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Anthropology and Epistemology of Complexity

PhD Thesis, cycle XXIII

Quantum Entanglement: Non-Local Implications

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La meccanica quantistica soffre di una fondamentale ambiguità che deriva dal fatto che nessuno sa esattamente cosa essa dica circa qualsiasi specifica situazione, perchè nessuno sa esattamente dove debba collocarsi il confine tra il vago mondo quantistico e il mondo preciso degli eventi specifici.
Questo per me è il vero problema della teoria.
Da un punto di vista pratico non c'è problema, in pratica siamo sempre in grado di scegliere questo confine giudiziosamente in modo che piccoli spostamenti in un verso o nell'altro non importino molto. Ma ogni volta che introduciamo questo confine, e dobbiamo collocarlo da qualche parte, noi stiamo dividendo arbitrariamente il mondo in due parti e usando due descrizioni del tutto diverse, una per una parte e l'altra per l'altra.
John S. Bell

Sappiamo oggi come si possa dimostrare che la luna non è là quando nessuno la guarda.
D. Mermin

Whole is not known by knowing its parts.
C. Samhita

Not only does God play dice, but he plays with nonlocal dice.
N. Gisin

0.1 Abstract

I sistemi quantistici entangled, se separati spazialmente, mostrano delle correlazioni cosiddette non locali, la conferma sperimentale e definitiva è avvenuta nel 1982. La non-località non richiede una revisione della teoria della relatività poiché tra i sistemi entangled non avvengono scambi di informazione. La convivenza pacifica fra le due teorie fisiche è momentaneamente garantita dalla nascita di un recente concetto in fisica: la non-separabilità o inseparabilità dei sistemi quantistici. La non-separabilità, nello stesso tempo, ci costringe, non solo a ricercare nuovi modelli interpretativi dei fenomeni quantistici, ma ripropone nuovamente il seguente problema: in che modo si separa o si partiziona un dato sistema quantistico? Allo stato attuale delle conoscenze, tale separazione resta arbitraria, quindi soggettiva, ma gli stati entangled eventualmente trovati hanno un carattere oggettivo solo se riferiti a quella separazione o partizione. Il problema è ancora irrisolto. Recenti lavori indicano che l'entanglement è un fenomeno che fa da sfondo a tutti i sistemi quantistici in quanto l'universo è in continua interazione (Torre,2010). I risultati sperimentali recenti, dimostrano dunque che la natura a livello microscopico, non è più pensabile come composta da oggetti separati e separabili dal proprio contesto. La metodologia scientifica per sfuggire a visioni parziali e talvolta persino fuorvianti, dovrebbe tener conto di questi nuovi elementi. Crediamo inoltre che l'inseparabilità non abbia legami con l'olismo; sarebbe come affermare che l'inseparabilità nel suo complesso è maggiore della somma delle sue parti inseparabili. La contraddizione non solo semantica nei termini utilizzati ci sembra evidente. E' la nozione stessa di somma algebrica che perde di significato, secondo l'entanglement quantistico (EQ) infatti 2 è diverso da 1 più 1. Non si tratta dunque di sommare oggetti, ma di diverse identità. Nella parte centrale del lavoro di tesi, viene proposto un esperimento teorico, che si basa principalmente sul cammino o catena di von Neumann. Questo esperimento ci conduce a riconsiderare i concetti di spazio e di tempo, in sintonia con alcuni lavori recenti di Suarez (Suarez et al 2007), nei quali si sostiene che l'entanglement è un fenomeno che avviene al di fuori dello spazio-tempo. I lavori di Suarez assumono una rilevanza ancor maggiore se comparati con quelli ottenuti sperimentalmente nel 2004 da Brukner e Vedral. Secondo questi autori, anche il tempo può essere messo in condizioni di entanglement. Il tempo viene trattato come semplice osservabile, come se fosse lo spin o la polarizzazione di una particella. L'istante di tempo precedente e l'istante di tempo successivo sarebbero sullo stesso piano. Riteniamo inoltre che i concetti di inseparabilità e di non località siano congruenti con il modello proposto da Bohm sull'ordine implicato ed esplicato. Nella seconda parte della tesi si affrontano le possibili implicazioni epistemologiche dell'EQ. In particolare, i suoi legami con l'Olomovimento e l'ordine esplicato/implicato di Bohm. Nel quadro così delineato, crediamo siano da rivedere i programmi di ricerca, quali le TOE e le teorie del Big Bang. Inseparabilità, non località ed ordine implicato ci proiettano anche verso concetti noti già da tempo nella filosofia Indiana, quali lo Spanda-Karika di Abhinavagupta. Viene proposto infine, nell'ultimo capitolo, un modello speculativo riguardante una possibile interpretazione della MQ della teoria Vedica della mente.

0.2 Pubblicazioni

La ricerca descritta nella tesi ha portato alle suguenti pubblicazioni:

- "Quantum Entanglement: Can We "See" the Implicate Order? Philosophical Speculations" Michele Caponigro, Xiaojiang Jiang, Ravi Prakash, Ram Vimal Prakash, Neuroquantoloy Journal Vol 8, No 3 (2010)
- "Quantum Interpretation of Vedic theory of Mind: an epistemological path and objective reduction of thoughts"
  M. Caponigro, R.Vimal,Journal of Consciousness Exploration Research Vol 1, no 4 (2010).
- "Interpretations of Quantum Mechanics: A Critical Survey" M. Caponigro,Prespacetime Journal (August 2010) Vol. 1 | Issue 5 | pp. 745-760.
- "Interpretations of Quantum Mechanics and Emptiness."
  M.Caponigro, R.Prakash,NeuroQuantology, June 2009 , Vol 7 , Issue 2, Page 198-203.
- "Inner Light Perception as a Quantum Phenomenon-Addressing the Questions of Physical and Critical Realisms, Information and Reduction.
  R.Prakash, M.Caponigro,NeuroQuantology,| March 2009 , Vol 7 Issue 1, Page 188-197
- "Approach to Physical Reality: a note on Poincare Group and the philosophy of Nagarjuna"
  M.Caponigro, P. Tandan,http://arxiv.org/abs/0704.1665 (Cornell University Library) 2008
- "Tomograms and the quest for single particle nonlocality" M. A. Anisimov, M. Caponigro, S. Mancini, V. I. Man'ko Journal of Physics: Conference Series 70, 012002 (2006).

-The article, "Quantum Entanglement: Can We "See" the Implicate Order? Philosophical Speculations, has been accepted by Tucson conference Stockholm May 1-8, 2011. (Toward a science of consciousness, Brain mind and reality).
-The article "Quantum Interpretation of Vedic theory of Mind: an epistemological path and objective reduction of thoughts", has been accepted by Tucson conference, Tucson April 13-17, 2010 (Toward a science of consciousness).

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0.3 Abbreviations

MQ.............Meccanica Quantistica
EQ.............Entanglement Quantistico
NL..............Non-Località
FAPP...........For All Practical Purposes
IO................Implicate Order
MWI............Many Worlds Interpretation
QE.............Quantum Entanglement
QM.............Quantum Mechanics
QS..............Quantum System
RQM...........Relational quantum mechanics
SR..............Special Relativity
GR.............General Relativity

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Introduzione

1.0.1 La MQ: Fapp

Un recente lavoro bibliografico che raccoglie buona parte degli studi sui fondamenti della meccanica Quantistica (MQ) non relativistica (Cabello,2004) riporta un numero impressionante di voci: circa 11000 riferimenti. E' una situazione forse unica e dopo quasi 90 anni dalla nascita della teoria, è lecito chiedersi se sia necessario discutere ancora o se tutto è stato già detto. La MQ da un punto di vista sperimentale è una teoria di grande successo ed accuratezza. Le rilevanti questioni nascono dall'interpretazione del suo formalismo. Parafrasando Bell, non possiamo accontentarci delle sole procedure FAPP (For All Practical Purposes)[1]. Bell chiarisce in qualche modo l'acronimo con la seguente affermazione:

> I am a quantum engineer, but on Sundays I have principles.

In un qualsiasi lavoro scientifico, e non solo, sono proprio le assunzioni filosofiche (hidden assumptions) di base che necessitano una accurata analisi. Tuttavia sappi-

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[1] Secondo Bell la procedura FAPP sul problema della misura in MQ lascia comunque aperto un problema di principio: individuare in modo preciso il confine tra ciò che deve descritto per mezzo di stati quantistici ondulatori da una parte, e per mezzo di termini "classici" nel senso di Bohr dall'altra. L'eliminazione, secondo Bell, di questo confine sfuggente ha sempre costituito l'attrattiva principale della descrizion in termini di "onda pilota". Il riferimento alla MQ proposta da Bohm è evidente.

amo che non è stato mai semplice rispondere alla seguente domanda: è **possibile per il pensiero umano fare totalmente a meno dell'apriori?** A causa della sterminata lettetura scientifica sui fondamenti della MQ preferiamo sin da subito specifare gli ambiti di ricerca a cui questo lavoro **non** si rivolgerà:

- **Non verrà proposta una nuova interpretazione della MQ.**
- **Non simpatizziamo, in modo particolare, per nessuna delle interpretazioni della MQ finora avanzate.**
- **Non ci addentreremo su questioni meramente epistemologiche riguardanti l'evoluzione storica della MQ, a parte una breve (e dovuta) introduzione iniziale, necessaria a contestualizzare la teoria fisica.**

Il lavoro di tesi si concentrerà invece sul fenomeno fisico dell'EQ e delle sue possibili implicazioni fisiche e filosofiche.

L'entanglement è una delle caratteristiche più affascinanti della MQ. Esso **non** ha un corrispettivo nel mondo classico. L'entanglement è anche una vera è propria spina nel fianco della fisica moderna, e nello stesso tempo una importante risorsa applicativa e tecnologica (i.e. computazione quantistica, teletrasporto). Crediamo che il fenomeno dell'entanglement come fenomeno fisico (ormai accertato ed accettato), ci dica qualcosa di molto più profondo rispetto all'interpretazione della teoria quantistica.

Nella struttura della tesi schematizzata a pag. XLIII, assumeremo l'EQ come uno degli elementi primari nella descrizione della possibile sottostante realtà fisica. Tale assunzione di base ci condurrà ad indagare concetti fondamentali quali la non-separabilità, la non-località. La figura 1.1 nella pagina successiva riporta alcune delle possibili implicazioni.

1.0.2 I due problemi in campo: l'Entanglement ed il processo di Misura

Anticipiamo qui brevemente, i due grandi problemi presenti nella MQ:

- l'entanglement
- il processo di misura.

Il seguente esempio mostra il primo dei problemi. Supponiamo di avere due particelle che interagiscono ad un istante di tempo t_1. Ora portiamo le particelle lontane

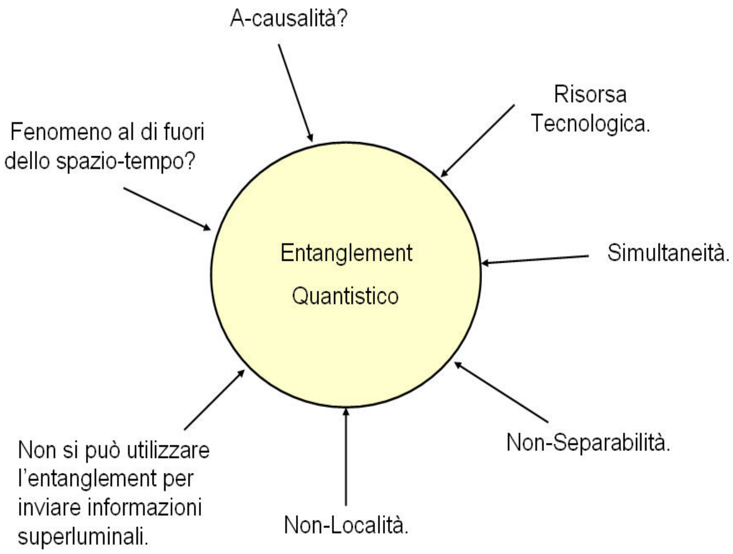

Figure 1.1: Alcune delle implicazioni fisiche e filosofiche dell'EQ.

(si intende spazialmente) dal punto in cui avevano interagito. Ad un successivo istante t_2 , effettuando una misura, troviamo che le due particelle dimostrano una correlazione molto forte: cioè quello che accade ad una è correlato a quello che accade all'altra[2]. Su queste imbarazzanti conclusioni ci poniamo una serie di domande.

La prima domanda è: questa correlazione ha le sue radici nell'istante t_1, cioè è stabilita quando le due particelle erano vicine? I dati sperimentali ci dicono di no. Essi confermano che le due particelle sono invece legate fra di loro all'istante tempo t_2. Un legame che non diminuisce di intensità con l'aumentare della distanza esso è inoltre istantaneo.

La seconda domanda è: tale fenomeno deriva in qualche modo da una "errata" divisione del mondo operata dalla teoria MQ? Qui le cose iniziano a complicarsi.

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[2] Il fenomeno dell'entanglement associato al processo di misura **non consente** di utilizzare queste strette correlazioni tra gli esiti di misure sui costituenti di sistemi composti **per comunicare a velocità superiore a quella della luce**. Per questo motivo si parla di una coesistenza pacifica della non località (NL) della MQ e la relatività ristretta. Infatti nell'ipotesi di due particelle di spin 1/2 spazialmente separate nello stato di singoletto, supponiamo che un osservatore che detiene la particella A voglia mandare un messaggio a quello che detiene la particella B mediante il processo di misura dello spin. L'osservatore A non sarà in grado di farlo. Sono le leggi della MQ che impediscono questo, infatti l'osservatore A non può controllare l'esito della misura essendo quest'ultima completemante casuale. L'osservatore A potrà inviare segnali all'osservatore B, ma questi saranno completamente casuali (sarebbe come non inviarli). In poche parole, le leggi della MQ non consentono di inviare **informazione** a velocità superiore a quella della luce.

Infatti questo problema rimane tuttora aperto. Ci ritroviamo il misterioso caso in cui l'eventuale correlazione trovata a seguito di una (possibile) suddivisione del mondo, sia legata e dipendente proprio da quel tipo di suddivisione (meglio Partizione)(Zandardi, 2001). Entrano qui in gioco in modo preponderante elementi fortemente epistemici i quali ci inducono ad indagare sul concetto stesso del fenomeno "entanglement".
L'ultima domanda è: esiste uno sconosciuto legame tra l'entanglement e le osservabili?[3] Proprio quelle osservabili scelte per definire lo stato entangled?
In pratica, ci chiediamo se il fenomeno dipenda non dalla natura degli oggetti correlati ma dal modo in cui sono teoricamente correlate le due variabili (scelte). Dunque una correlazione di variabili scelte non di oggetti. Evidentemente quest'ultima domanda ammette implicitamente una differenza di base tra proprietà (in questo caso l'osservabile[4]) ed il possibile oggetto quantistico sottostante. Su quest'ultimo punto ci sono alcune interpretazioni della MQ dette informazionali le quali sostengono che non esiste una tale differenza tra realtà ed informazione (Zeilinger, Fuchs). Esse coincidono[5]. Una semplice obiezione filosofica porterebbe ad affermare che si confonde l'epistemico con l'ontico. Il fatto che in MQ un oggetto è caratterizzato solo da alcune proprietà determinate e da altre che vengono ascritte sulla base di una distribuzione di probabilità[6] ci conduce ad alcune considerazioni di natura ontologica su tali oggetti:

- Esiste un problema epistemico, in realtà siamo solo noi che ignoriamo quelle

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[3] Ricordiamo il forte imbarazzo di Bell riguardo il concetto di osservabile, egli infatti contrappose il concetto di esseribili. Vedere la nota successiva.

[4] Bell sul concetto di osservabile osserva: nei libri di MQ si parla molto di osservabili. E da alcune presentazioni divulgative il pubblico generico potrebbe avere l'impressione che l'esistenza stessa del cosmo dipenda dal nostro essere qui a osservare le osservabili [....]Penso che non sia giusto raccontare al pubblico che nella fisica moderna faccia parte integrante, con un ruolo centrale, la mente cosciente. O che l"informazione" rappresenti il vero oggetto di una teoria fisica. [....] Il solo osservatore che è essenziale nella MQ pratica e ortodossa è l'apparato inanimato che amplifica gli eventi microscopici a livello di conseguenze macroscopiche.

[5] In generale ci si aspetta che lo stato di un certo oggetto fisico sia definito dall'insieme delle sue proprietà. Questa ipotesi seppure forte potrebbe non essere sufficiente a definire l'oggetto fisico, poiché si ammetterebbe che la somma delle sue proprietà sia l'oggetto. Infatti la domanda conseguente è: conoscendo le sue proprietà conosciamo l'oggetto fisico? Se questo problema, comunque irrisolto anche nella fisica classica, diviene ancor più problematico in MQ. Tutto questo richiama la cosiddetta metafisica del realismo il quale riteneva possibile inglobare una totalità definita di tutti gli oggetti e una totalità definita di tutte le proprietà.

[6] Infatti sappiamo che un oggetto quantistico è caratterizzato da diverse variabili (osservabili), le quali non possono essere determinate tutte simultaneamente, solo quanto andiamo a misurarle, troviamo un valore determinato anche per le variabili che nel sistema preparato erano indeterminate.

proprietà. Quelle proprietà avevano un valore determinato fin dall'inizio, solo che a noi era inaccessibile. Queste sono le interpretazioni a variabili nascoste, come quella di Bohm (problemi della non-località e della contestualità che sono fortemente controintuitivi).

- La MQ come le altre teorie della fisica in generale è in grado di descrivere adeguatamente solo ciò che è strettamente misurabile. Tutti i termini teorici sono dei semplici strumenti di calcolo che si introducono per comodità (FAPP). Le proprietà indeterminate sono solo realtà possibili[7].
- Punto di vista standard, secondo il quale per qualche ragione a noi sconosciuta dobbiamo descrivere gli oggetti macroscopici con la fisica classica e quelli microscopici con la teoria quantistica.

Per il secondo problema il **processo di misura** vi sono stati molti tentativi di soluzione:

- 1) Indroduzione di variabili nascoste che trasformano la sovrapposizione in una miscela statistica classica.
- 2) La coscienza dell'osservatore interviene fisicamente a favorire il collasso. Questa è l'idea di London e Bauer, Wigner (Wigner, 1989),von Neumann.
- 3) Si modifica la dinamica. Questa è la soluzione di Ghirardi, Rimini e Weber (Ghirardi,2005). Ma la loro diversa equazione è servita solo a risolvere questo problema. Non ha portato altre conseguenze empiricamente interessanti.
- 4) Si afferma che in realtà il collasso non è mai avvenuto. E allora il problema è quello di spiegare perché a noi risulta empiricamente. A questo punto ci sono diverse strade (MWI)[8].

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[7] Questa è la posizione di van Fraassen il quale professa agnosticismo sulla realtà di tutto ciò che non è direttamente misurabile. Naturalmente viene da chiedersi, se entità matematiche ma non empiricamente osservabili esistono? Infine si potrebbe sostenere che il mondo quantistico è caratterizzato da entità inosservabili descrivibili solo in modo matematico, completamente avulse dalle nostre capacità intuitive. Questo è il punto di vista di molti fisici, che però dà origine al cosiddetto problema della misurazione, che consiste proprio nel dare una spiegazione del rapporto fra questi oggetti non intuitivi e quelli che invece percepiamo normalmente.

[8] E' l'indirizzo di ricerca inaugurato da Everett, che però non fornisce nessuna buona ragione per spiegarci perché noi abbiamo accesso solo a uno dei valori della variabile. In pratica noi non vediamo la sovrapposizione per qualche misteriosa e sconosciuta ragione, Zurek sostiene questo su base evoluzionistica, egli sostiene che che noi non vediamo la sovrapposizione o coerenza o interferenza, perché è biologicamente inutile, il quantum darwinism

- 5) La decoerenza: i nostri strumenti di misura sono sistemi aperti in contatto con l'ambiente nel quale si disperde la sovrapposizione[9].
- 6) Oppure stabiliamo un confine arbitrario fra micro e macro e diciamo che il macro nel suo rapporto con il micro è caratterizzato dalla master equation e allora ricadiamo nei problemi della visione ortodossa.
- 7) La MQ, pur essendo una teoria straordinaria, per la sua eleganza e per le sue capacità predittive, non è teoria definitiva, essa verrà superata solo da un cambiamento rivoluzionario.

1.0.3 I punti essenziali della tesi

Come appare ora chiaro da queste prime fasi, i sistemi quantistici entangled, se separati spazialmente, mostrano delle correlazioni cosiddette non locali[10] . La non-località non richiede una revisione della teoria della relatività poiché tra i sistemi entangled non avvengono scambi di informazione. La convivenza pacifica fra le due teorie fisiche è attualmente garantita dalla nascita di un recente concetto in fisica: la non-separabilità o inseparabilità dei sistemi quantistici.

La non-separabilità, nello stesso tempo, ci costringe, non solo a ricercare nuovi modelli interpretativi dei fenomeni quantistici, ma ripropone nuovamente il seguente dilemma: in che modo si separa o si partiziona un dato sistema quantistico? Allo stato attuale delle conoscenze, tale separazione resta arbitraria (Zanardi 2001, L. Viola 2010), quindi soggettiva, ma gli stati entangled eventualmente trovati hanno un carattere oggettivo solo se riferiti a quella separazione o partizione. Il problema è ancora irrisolto.

Recenti lavori indicano che l'entanglement è un fenomeno che fa da sfondo a tutti

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[9] Si può anche dire che l'ambiente opera una sorta di superselezione, cioè rende irrilevanti tutte quelle osservabili che sono portatrici della sovrapposizone. Così l'ambiente rende stabili solo due posizioni dello strumento di misura. O meglio rende visibili le due posizioni del puntatore, che però di fatto resta nella sovrapposizione

[10] Bell (Bell, 1987) ci mostra in modo semplice la differenza tra una possibile correlazione classica e una quantistica, nelle sue stesse parole: le correlazioni quantistiche sono in qualche modo diverse? Per Einstein, se ho inteso correttamente il suo pensiero, non lo sono affatto. Nell'esempio di una moneta testa e croce erano tali fin dall'inizio, anche mentre erano (le monete) nascoste. Chi ha guardato per primo era semplicemente il primo a saperlo. Ma in effetti tutto era stato determinato nel momento in cui si erano distribuiti i due pezzi di moneta (e persino prima, in una teoria classica completamente deterministica). **La MQ rende misteriosa una situazione perfettamente semplice proprio perchè non contiene esplicitamente il valore, testa o croce, (oppure "su" o "giù") delle "variabili nascoste" anche prima dell'osservazione.**

i sistemi quantistici (Torre, 2010) in quanto l'universo è in continua interazione. I risultati sperimentali recenti, dimostrano dunque che la natura a livello microscopico, non è più pensabile come composta da oggetti separati e separabili dal proprio contesto. La metodologia scientifica per sfuggire a visioni parziali e talvolta persino fuorvianti, dovrebbe tener conto di questi nuovi elementi. Crediamo inoltre che l'inseparabilità non abbia legami con l'olismo; sarebbe come affermare che l'inseparabilità nel suo complesso è maggiore della somma delle sue parti inseparabili. La contraddizione non solo semantica nei termini utilizzati ci sembra evidente. E' la nozione stessa di somma algebrica che perde di significato, secondo l'EQ infatti 2 è diverso da 1 più 1. Non si tratta dunque di sommare oggetti, ma di diverse identità. Mentre una visione relazionale dei sistemi potrebbe ancora reggere. Nella parte centrale del lavoro di tesi, viene proposto un esperimento teorico, che si basa principalmente sul cammino o catena di von Neumann. Questo esperimento ci conduce a riconsiderare i concetti di spazio e di tempo, in sintonia con alcuni lavori recenti di Suarez (Suarez et al.,2007), nei quali si sostiene che l'entanglement è un fenomeno che avviene al di fuori dello spazio-tempo. I lavori di Suarez assumono una rilevanza ancor maggiore se comparati con quelli ottenuti sperimentalmente nel 2004 da Brukner e Vedral. Secondo questi autori, anche il tempo può essere messo in condizioni di entanglement. Il tempo viene trattato come semplice osservabile, come se fosse lo spin o la polarizzazione di una particella. L'istante di tempo precedente e l'istante di tempo successivo sarebbero sullo stesso piano. Riteniamo inoltre che i concetti di inseparabilità e di non località siano congruenti con il modello proposto da Bohm sull'ordine implicato ed esplicato. Nella seconda parte della tesi si affrontano le possibili implicazioni epistemologiche dell'EQ. In particolare, i suoi legami con il potenziale quantistico di Bohm, con l'Olomovimento e l'ordine implicato. Per concludere crediamo che, nel quadro così delineato, siano da rivedere i programmi di ricerca, quali le TOE e le teorie del Big Bang. Inseparabilità, non località ed ordine implicato ci proiettano anche verso concetti noti già da tempo nella filosofia Indiana, quali lo Spanda-Karika di Abhinavagupta. L'ultimo capitolo è dedicato ad una interpretazione della MQ della teoria Vedica della mente.

1.0.4 Formalismo e Realtà

Il formalismo della MQ è **solo un ricettario** che ci consente di computare la probabilità in un esperimento? Il formalismo della MQ a quali oggetti si riferisce? Esiste o non esiste una sua controparte? La riposta di Hawking (Hawking,1996) è molto chiara al riguardo, la "contraparte" non ci sarebbe, esistono solo le misurazioni:

Non chiedo che una teoria corrisponda alla realtà perché non so cosa sia la realtà. La realtà non è qualcosa che potete misurare con la cartina di tornasole. Tutto ciò che mi interessa è che la teoria preveda risultati delle misurazioni.

Naturalmente è lecito chiedersi questo: i risultati delle misure a che cosa si riferiscono? Bell sostiene, che non si può essere in disaccordo sulla struttura formale della MQ, ma si può essere in disaccordo sul suo significato fisico. Inoltre egli aggiunge:

> Si può sostenere che, cercando di guardare dietro le previsioni formali della teoria quantistica, ci stiamo mettendo nei guai da soli.

La posizione di Einstein è invece riassunta nella seguente citazione (1953):

L'essenza della situazione attuale io la vedo così: riguardo al formalismo matematico della teoria non esiste alcun dubbio, ma molti ce ne sono sulla interpretazione fisica delle sue asserzioni. In quale relazione sta la funzione con la situazione concreta individuale, cioè con la situazione individuale di un singolo sistema? Ovvero: che cosa dice la funzione sullo "stato reale" (individuale)? Ora si può anzitutto dubitare che si possa in generale attribuire un senso a queste domande. Si può infatti assumere il seguente punto di vista: "reale" ‘e solo il singolo risultato dell'osservazione, non un qualcosa di ***esistente obbiettivamente nello spazio e nel tempo indipendentemente dall'atto dell'osservazione****. Se si assume questo netto punto di vista positivistico, non c'‘e bisogno evidentemente di fare alcun pensiero su come lo "stato reale" debba essere interpretato nell'ambito della teoria dei quanti. Tale sforzo appare infatti come un tirar di scherma contro un fantasma. Questo punto di vista positivistico netto ha tuttavia - se conseguentemente sviluppato - un'irreparabile debolezza: esso conduce a dichiarare vuote di significato tutte le proposizioni esprimibili col linguaggio. [.....] Ora il concetto di "realtà fisica" ‘e diventato problematico e si son poste le do- mande, che cosa essa veramente sia, che cosa cerchi di descrivere la fisica teorica (mediante la MQ), e a che cosa si riferiscano le leggi da essa enunciate. A queste domande vengono date risposte assai diverse.*

> Ed in una lettera a Schrödinger, datata 1935, Einstein scriveva: *"la vera difficoltà sta nel fatto che la fisica è un tipo di metafisica; la fisica descrive "la realtà". Ma noi non sappiamo cosa sia "la realtà", se non attraverso la descrizione fisica che ne diamo di essa".*

Da queste prime autorevoli posizioni capiamo che il problema ontologico nel formalismo quantistico è un problema aperto. E' un problema che richiede la nostra attenzione e che solleva nuove questioni a più livelli. In pratica, la questione può essere posta in questi termini: ha senso chiedersi se un sistema quantistico possegga qualche proprietà indipendentemente dai nostri procedimenti per misurarla?[11] I problemi nell'interpretazione della MQ si possono ridurre a tre punti della teoria:

- Completezza della teoria.
- Principio di Sovrapposizione.
- Il processo di macro-oggettivazione.

Ogni interpretazione della MQ lascia inspiegato almeno uno dei tre punti. Le peculiarità della MQ, rispetto alla visione classica, hanno origini soprattutto nel principio di sovrapposizione. Questo principio, come sappiamo, è una diretta conseguenza del carattere lineare della teoria. Anche il singolare comportamento dei sistemi composti è una conseguenza di tale principio. Il problema della misura, e più in generale la descrizione quantistica dei sistemi macroscopici (macro-oggetivazione) è ancora una diretta conseguenza dello stesso principio.

In MQ è il concetto stesso di sistema quantistico composto che viene messo in discussione. Infatti un sistema composto è "scelto" arbitrariamente dallo sperimentatore come arbitrariamente sono scelti i suoi componenti. Uno sperimentatore può vedere un singolo sistema dove un altro ne vede molti sottosistemi. Questo pone dei problemi anche per i cosiddetti stati entangled (stati non-separabili). Infatti la scelta del sistema, come dicevamo è soggettiva, mentre lo stato entangled, eventualmente trovato, è si oggettivo ma solo verso quel tipo di scelta (partizione). Questo problema sarà trattato nel capitolo 5, attraverso recenti ricerche portate avanti da Torre et.al, Viola et.al, Zanardi (2001, 2007,2010).

Analizzeremo le importanti implicazioni tra i sistemi quantistici composti ed entanglement. Supponiamo di avere un sistema composto che inizialmente è in uno stato fattorizzato; i suoi costituenti hanno allora qualche proprietà oggettiva. Se lasciamo evolvere il sistema[12],supponendo che i costituenti interagiscano tra di loro,

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[11] In Einstein, come vedremo, nel non dover necessariamente negare, per esempio, che una particella, sebbene ad essa non siano sperimentalmente assegnabili in maniera simultanea posizione e velocità se non nei limiti imposti dalle relazioni di indeterminazione, non possieda oggettivamente valori perfettamente definiti di queste grandezze, comporta una concezione che assegna alla teoria scientifica il compito non già di descrivere soltanto i fenomeni, bensì anche di spiegare la "realtà", di cui si intende fornire una rappresentazione "oggettiva", ovvero logicamente indipendente dal ruolo del soggetto e dai suoi apparati di rilevazione.

[12] Ghirardi 1996,2005 "Un'occhiata alle carte di Dio" Il saggiatore.

il sistema per effetto di questa interazione si porta in uno stato che non più fattorizzato (appunto entangled) con una conseguente perdita di proprietà oggettive dei suoi costituenti. Questo rimane valido anche se i costituenti vengono allontanati l'uno dall'altro. Il solo fatto di avere interagito in passato ha fatto **perdere qualsiasi proprietà individuale oggettiva** ai costituenti: solo il sistema composto, **considerato come un tutto** ne possiede qualcuna. Ma poiché alla fine tutto interagisce con tutto, la visione che emerge dall'assunzione che il formalismo quantistico governi tutti i processi naturali (**universalità della MQ**) è quella che è stata ben elaborata da Bohm e Hiley (Bhom,Hiley 1993) nel lavoro "The undivided universe". Tale visione quantistica porterebbe ad una concezione dell'universo come un unbroken whole. Una totalità che ha qualche precisa proprietà, ma le cui parti non ne hanno alcuna. Quindi il fenomeno dell'**entanglement comporta in generale una perdita di qualsiasi proprietà dei costituenti di un sistema composto. L'universo in quest'ottica ci appare come un'unità indivisibile** le cui parti non possono venire caratterizzate se non con riferimento al tutto, di cui essi fanno parte. Questo fenomeno pone inevitabili difficoltà all'idea stessa di analizzare sistemi quantistici isolati. E' su questi elementi, vedremo che si innesterà l'argomento EPR (EPR, 1935) e le successive disuguaglianze di Bell. Queste ultime hanno rappresentato una vera e propria svolta concettuale nell'analisi del formalismo quantistico, non a caso Shimony (Shimony, 1983) ha definito il teorema di Bell come un esempio di **metafisica sperimentale**.

1.0.5 Il singolo evento quantistico

Le interpretazioni della MQ sono divise da questo fondamentale punto: non è possibile la descrizione completa del singolo evento. Un punto controverso a cui lo stesso Einstein ha dedicato molte energie. A differenza dell'interpretazione Standard, ogni altra interpretazione fallisce quando tenta una descrizione completa di un singolo evento. Ricordiamo che ad un livello sperimentale tutte le interpretazioni sono in accordo. D'altra parte tutte partono dallo stesso formalismo. Prendiamo come esempio l'interpretazione Standard. Il sistema quantistico qui è visto come un'entità unica che comprende sia il sistema quantistico che l'apparato di misura. Secondo Copenhagen, non ha alcun senso definire un sistema quantistico senza specificare in modo esplicito gli strumenti di misura. Allo stesso modo, non ha senso attribuire ad un sistema quantistico variabili complementari, in quanto gli apparati necessari per determinarli si escluderebbero reciprocamente. Dunque è impossibile costruire un apparato che misuri simultaneamente, ad esempio, la posizione ed il momento con una precisione arbitraria, di conseguenza, le richieste di precisi valori simultanei di quantità complementari non hanno significato. La funzione d'onda in questa interpretazione si riduce ad essere una nostra rappresentazione della conoscenza della storia di un sistema quantistico: **essa assume solo un significato epistemico**.

Il motivo che sta a monte è che il formalismo della MQ non fornisce affatto un punto di partenza nella descrizione del singolo evento e tutte le altre interpretazioni fanno riferimento ed uso dello stesso formalismo (escludendo un sistema quantistico in un autostato dell'osservabile scelta).

La MQ fa dunque previsioni solo riguardo a un insieme di molti eventi singoli, previsioni che sono molto precise circa la media, la distribuzione dei risultati di misure aspettati. In pratica, la MQ non sarebbe in grado di "spiegare perché eventi (singoli eventi specifici) accadono. Per fare un esempio preciso, non è in alcun modo possibile prevedere attraverso quale fenditura passerà una particella quando incontra un sistema a doppia fenditura.

L'impossibilità di prevedere il singolo evento, appare abbastanza presto nel corso dello sviluppo della MQ. Tale impossibilià fu subito elevata a principio fondamentale: la natura era puramente statistica (probabilità ontiche).

Con il teorema di Bell è divenuto possibile escludere fin da subito una descrizione più dettagliata (esclusione delle variabili nascoste). Vedremo in dettaglio la questione nelle prossimi capitoli. In generale, l'impossibilità di descrivere il singolo processo viene accettata dalla comunità scientifica come una conseguenza delle regole quantistiche e come una limitazione della possibilità classica di descrivere il mondo.

Secondo Copenhagen non è possibile, né ragionevole, ricercare le proprietà di un sistema quantistico in quanto tale. Dal momento che possiamo solo comunicare cosa abbiamo trovato attraverso il **nostro linguaggio classico**. Questioni quindi riguardanti le proprietà dei sistemi hanno solo senso in ambito classico, in quanto il nostro appararato è classico. In pratica, un fenomeno quantistico comprende sia il sistema quantistico che l'apparato di misura. A questo riguardo Wheeler sostiene che noi, come osservatori, siamo liberi di decidere in quale modo portare a conclusione un fenomeno quantistico. Noi scegliendo l'apparato di misura, decidiamo quale fenomeno può divenire realtà e quale no. Decidiamo quale fenomeno quantistico far "emergere". Quello che non possiamo fare è influenzare lo specifico valore ottenuto attraverso la misurazione (Zeilinger chiama questa cicostanza la nostra semi-libertà)(Zeilinger 2008). Infine, dal momento che facciamo parte dell'universo, secondo Wheeler, l'universo crea se stesso osservandosi attraverso di noi (fig.1.2)

In tale visione si riporterebbe gradualmente il ruolo dell'osservatore al centro della discussione, un ruolo espresso da Clauser, nella sua analisi fatta assieme a Shimony

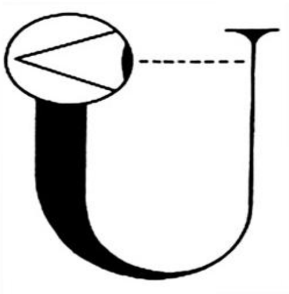

Figure 1.2: L'universo osserva se stesso

della presente situazione EPR-Bell:

> "forse un albero non sentito cadere in una foresta dopotutto non produce alcun suono".

Zeilinger (Zeilinger, 2010), uno degli esponenti della interpretazione informazionale della MQ propone che questa impossibilità di descrivere in modo completo il singolo processo casuale all'interno della MQ sia una fondamentale limitazione del programma della scienza moderna di arrivare ad una descrizione del mondo in ogni suo dettaglio. In altre parole, egli propone, che la descrizione della natura sfugge ad una razionale e dettagliata dissezione nelle parti costituenti.

1.0.6 I fondamenti della MQ nella sua evoluzione storica

Vediamo un breve excursus storico relativo ai problemi fondazionali della MQ. Abbiamo visto che la MQ, per come è presentata nei vari libri di testo, è sostanzialmente un'insieme di regole, un ricettario, per calcolare le distribuzioni di probabilità dei risultati di qualunque esperimento nel mondo microscopico. In quanto tale, non ci fornisce direttamente una descrizione della realtà cioè una ontologia. Sulla correttezza del formalismo quantistico vi è un accordo generale, il punto controverso resta il problema l'ontologia del suo formalismo. Si è sostenuto e si sostiene ancora che la teoria quantistica ci costringa ad abbandonare la realtà di un mondo esterno che esiste oggettivamente, indipendentemente dalla mente umana. In questi ultimi anni è poi emersa, grazie allo sviluppo teorico e sperimentale della teoria della informazione e computazione quantistica, una visione della MQ basata sulla teoria dell'informazione (Fuchs 2002, Zeilinger 2005). Secondo questa interpretazione la realtà è informazione, il quanto d'informazione è un bit, quel bit è la nostra conoscenza che non è diversa dalla proprietà del sistema preso in esame. Ma già Schrödinger nel 1935, metteva in guardia contro l'idea di ridurre la MQ a semplice rappresentazione della nostra conoscenza. Schrödinger, è sempre stato fortemente motivato dalla convinzione circa la necessità di salvare la continuità spazio-temporale della descrizione fisica, quindi salvare una certa visualizzazione dei processi fisici anche a livello microscopico. Dalle sue stesse parole possiamo capire più in dettaglio il suo pensiero:

"Non si deve attaccare alcun significato speciale al cammino dell'elettrone [....] ed ancor meno alla posizione di un elettrone sul suo cammino. L'onda non solo riempie tutto il cammino simultaneamente, ma si estende addirittura notevolmente in tutte le direzioni. Questa contraddizione è sentita così fortemente che si è persino posto in dubbio che quello che accade in un atomo possa inquadrarsi in uno schema spazio-temporale. Da un punto di vista filosofico, io considererei una decisione conclusiva in questo senso come una resa incondizionata. Infatti, poiché noi non possiamo assolutamente evitare di pensare in termini di spazio e tempo, quello che non possiamo ricondurre a siffatti concetti, non possiamo comprenderlo".

Per questa posizione Schrödinger sarà tra i pochissimi scienziati a cogliere più avanti il significato più profondo del lavoro EPR (EPR, 1935). Possiamo dire che Schrödinger si muove lungo la linea di pensiero indicata da de Broglie ed Einstein. Egli assegna un ruolo assolutamente prominente agli aspetti ondulatori, ed indica una interpretazione della funzione d'onda in termini di densità di massa o di carica dell'elettrone. Sappiamo sappiamo poi superata dalla interpretazione in termini di probabilità da Born. Anticipiamo brevemente,e per sommi capi, le due più significative posizioni rispetto all'interpretazionde della funzione d'onda: 1)la standard e 2) quelle in dissacordo con la prima, vediamo la prima:

- La funzione d'onda fornisce una descrizione completa di ogni singolo oggetto quantistico.
- Tutti gli oggetti quantistici rappresentati dalla stessa funzione d'onda sono fisicamente identici.
- L'informazione circa un oggetto non misurato, semplicemente non è disponibile.

Quelle in disaccordo sono:

- La funzione d'onda fornisce solo una descrizione statistica di un insieme di oggetti quantistici, e dunque una descrizione necessariamente incompleta di ogni singolo oggetto di questo tipo.

- Oggetti quantistici rappresentati dalla stessa funzione d'onda possono non essere fisicamente identici.
- L'ignoranza dell'osservatore circa gli attributi di un oggetto non misurato è dovuta all'effetto di certe variabili "nascoste", che la teoria quantistica non consente di rappresentare.
- Oggetti con la stessa funzione d'onda possono mostrare delle differenze quando vengono osservati, perché erano fisicamente diversi prima della misurazione.

I teorici delle variabili nascoste aderiscono dunque ad una visione classica della realtà. Secondo questa interpretazione una volta conosciute le proprietà ed i valori di queste variabili (nascoste) l'oggetto quantistico sarebbe completamente individuato. Niente di diverso rispetto ad una particella newtoniana. Tale visione evita di porre il processo di misura in una posizione privilegiata. Osserviamo in generale che le differenti interpretazioni della teoria quantistica nascono dal tentativo di salvare uno dei postulati della teoria. Ad esempio, la teoria di Everett (MWI) vuole rendere "classico" il principio di sovrapposizione.

1.0.7 Le proprietà sono informazioni?

Zeilinger (Zeilinger, 2008) sostiene che la realtà è informazione. In pratica quello che serve è "leggere" una proprietà del sistema. Il sistema è completamente definito da questo bit di informazione. Quindi la MQ, per Zeilinger, è il risultato delle nostre domande. Il quanto delle informazioni sono le proposizioni. Le leggi della natura non possono fare alcuna differenza tra realtà ed informazione. L'informazione è dunque una risposta ad una nostra domanda, il limite sotto il quale non si può scendere per porre questa domanda è proprio la particella elementare d'informazione (bit). Vi è una struttura ad un certo livello discreta, a grana fine, sotto il quale non si può scendere. I fenomeni quantistici sono allora una conseguenza del fatto che il mondo rappresenta le nostre affermazioni che necessariamente si presentano appunto quantizzate. Perché il mondo è quantizzato (Wheeler,1999)? Secondo questa teoria, lo è perché l'informazione sul mondo è quantizzata. Questo ha portato i sostenitori di questa tesi ad affermare che, l'informazione è la materia primordiale dell'universo. I progressi raggiunti secondo Fuchs (un altro eminente esponente di questa interpretazione) nella comprensione dei fenomeni quantistici sono evidenti, e scherzosamente aggiunge che questa presa di coscienza eviterebbe di fare ogni anno seminari inutili sulle interpretazioni della MQ a spese del contribuente.

Secondo questa tesi lo stato di un oggetto fisico è definito dall'insieme delle sue proprietà o bits. Quello che ci chiediamo e se una volta acquisiti i bits relativi siamo in grado di definire l'oggetto quantistico? Crediamo in generale che questa ipotesi seppure molto forte potrebbe non essere sufficiente a definire l'oggetto fisico. Perchè? Se ammmettiamo che la somma delle sue proprietà sia l'oggetto, la domanda conseguente è: conoscendo le sue proprietà conosciamo l'oggetto fisico? Questo è un problema crediamo controverso anche in fisica classica, di più lo è in MQ. In MQ un oggetto è caratterizzato da diverse variabili (osservabili), le quali non possono essere determinate tutte simultaneamente. Tali oggetti quantistici, sono caratterizzati solo da alcune proprietà determinate e da altre che vengono ascritte sulla base di una distribuzione di probabilità.

1.0.8 Il costruttivismo radicale della MQ

Vi sono posizioni che definiamo estreme, come quella espressa da Diner (Diner, 1986) da egli stesso definita come costruttivismo radicale. Nelle sue stesse parole:

> Every quantum mechanist has his own interpretation of QM. I have mine. It is a radical constructivist point of view; QM is a cybernetic model for input (preparation) and output (measurement) of an abstract black box.

Possiamo rappresentare tramite la seguente figura, l'operazione di estrarre informazione da un sistema quantistico.

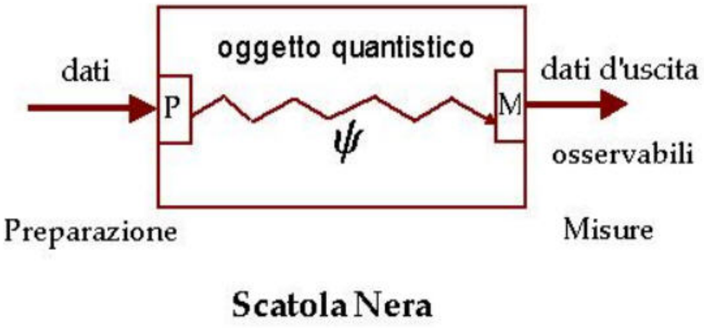

Figure 1.3: Quantum black box

1.0.9 Interpretazione Standard ed il dibattito Einstein-Copenhagen

Riassumiamo i punti essenziali dell'interpretazione Standard della MQ[13]:

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[13] Riassunte in Logiurato 2004

- (1) Completezza della funzione d'onda: essa costituisce una descrizione completa dello stato di un sistema fisico individuale. Essa determina la distribuzione di probabilità dei risultati di una misurazione di qualunque grandezza osservabile. Oggi vi sono fisici che sostengono con forza tale assunzione (Zeilinger), sostenendo che tale descrizione completa dello stato è un bit di informazione.
- (2) La nostra conoscenza della realtà fisica non può essere espressa se non per mezzo di un linguaggio classico. La descrizione completa dei fenomeni fisici richiede però l'uso di concetti classici contrapposti, quali ad esempio quelli di onda e di particella. Nessuna contraddizione nasce dal loro uso poiché concetti incompatibili descrivono fenomeni che si presentano in situazioni sperimentali incompatibili (complementarietà).
- (3) Il principio d'indeterminazione di Heisenberg (Heisenberg 1958)nega l'esistenza simultanea di valori definiti per le osservabili complementari.
- (4) L'atto di misurazione produce un cambiamento discontinuo del vettore di stato non descritto dall'equazione di Schrodinger. Nella misurazione lo stato del sistema collassa in uno degli autostati dell'osservabile misurata: lo stato finale può essere previsto solo probabilisticamente. L'apparato di misura deve essere descritto in termini classici.

L'assunzione fondamentale dell'interpretazione di Copenaghen è certamente la **completezza dello stato quantistico**: esso esprime tutto ciò che può essere detto riguardo allo stato fisico del sistema, e al contrario della descrizione classica dello stato di un sistema nello spazio delle configurazioni, dà soltanto le probabilità che le misure abbiano un certo esito (probabilità epistemiche).
La figura (fig. 1.4 pag. XXVI) sintetizza il problema della completezza del vettore di stato ed i percorsi legati alla sua interpretazione. Il ricorso alle probabilità non è il riflesso della nostra mancanza di conoscenza e non è dovuto all'aver trascurato dei dettagli nella descrizione della dinamica: è invece il processo di misurazione stesso ad essere intrinsecamente non deterministico (probabilità ontiche). Anche le relazioni d'incertezza esprimono non la nostra ignoranza circa valori di posizione ed impulso ben definiti ma sconosciuti, ma l'impossibilità stessa di definire simultaneamente quei concetti.
Come è ben noto Einstein non accettò mai questa pretesa completezza della teoria quantistica[14]. Questo dibattito sui fondamenti della MQ, dai primi anni della sua

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[14] E' interessante come il filosofo Howard (2007) con uno studio su Einstein finisce per attribuirgli una serie di atteggiamenti che siamo soliti considerare conflittuali circa le teorie e le entità della fisica,

formulazione durò fino a metà degli anni '60, vede contrapposti sostanzialmente due punti di vista. La posizione di Einstein da una parte e quella di Bohr e Heisenberg dall'altra. Einstein riteneva che la MQ fosse una teoria "provvisoria" ed "incompleta". Secondo Einstein, il "completamento" della teoria doveva necessariamente passare attraverso una reintroduzione dei ben noti concetti classici. Bohr e Heisenberg pensano invece che la descrizione dei fenomeni microscopici non poteva essere fatta in termini classici. Einstein riassume tale posizione in modo seguente: (Einstein,1949):

Se i sistemi parziali A e B formano un sistema totale che è descritto dalla sua funzione ψ, cioè dalla ψ_{AB}, non c'è ragione di attribuire un'esistenza reciprocamente indipendente (stato di realtà) ai sistemi parziali A e B considerati separatamente, neppure se i sistemi parziali sono separati spazialmente l'uno dall'altro nel momento particolare che viene considerato. Dire che, in quest'ultimo caso, la reale situazione di B non possa essere (direttamente) influenzata, da nessuna operazione di misura compiuta su A è quindi, nel quadro della teoria quantistica, un'affermazione infondata e (come dimostra il paradosso) inaccettabile. Considerando la questione in questo modo, risulta evidente che il paradosso ci costringe ad abbandonare una delle due seguenti affermazioni: 1) la descrizione compiuta per mezzo della funzione $\tilde{A}$ è completa, 2) gli stati reali di oggetti spazialmente separati sono indipendenti l'uno dall'altro.

L'unico modo dunque per Einstein di evitare le famose azioni "spettrali a distanza" implicate dal collasso della funzione d'onda, considerato come un reale processo fisico, è ammettere che gli oggetti quantistici abbiano simultaneamente le osservabili posizione ed impulso ben definite, anche se da noi non conoscibili a causa delle relazioni d'incertezza, e accettare che la funzione d'onda non si riferisca a sistemi individuali ma ad insiemi di sistemi.

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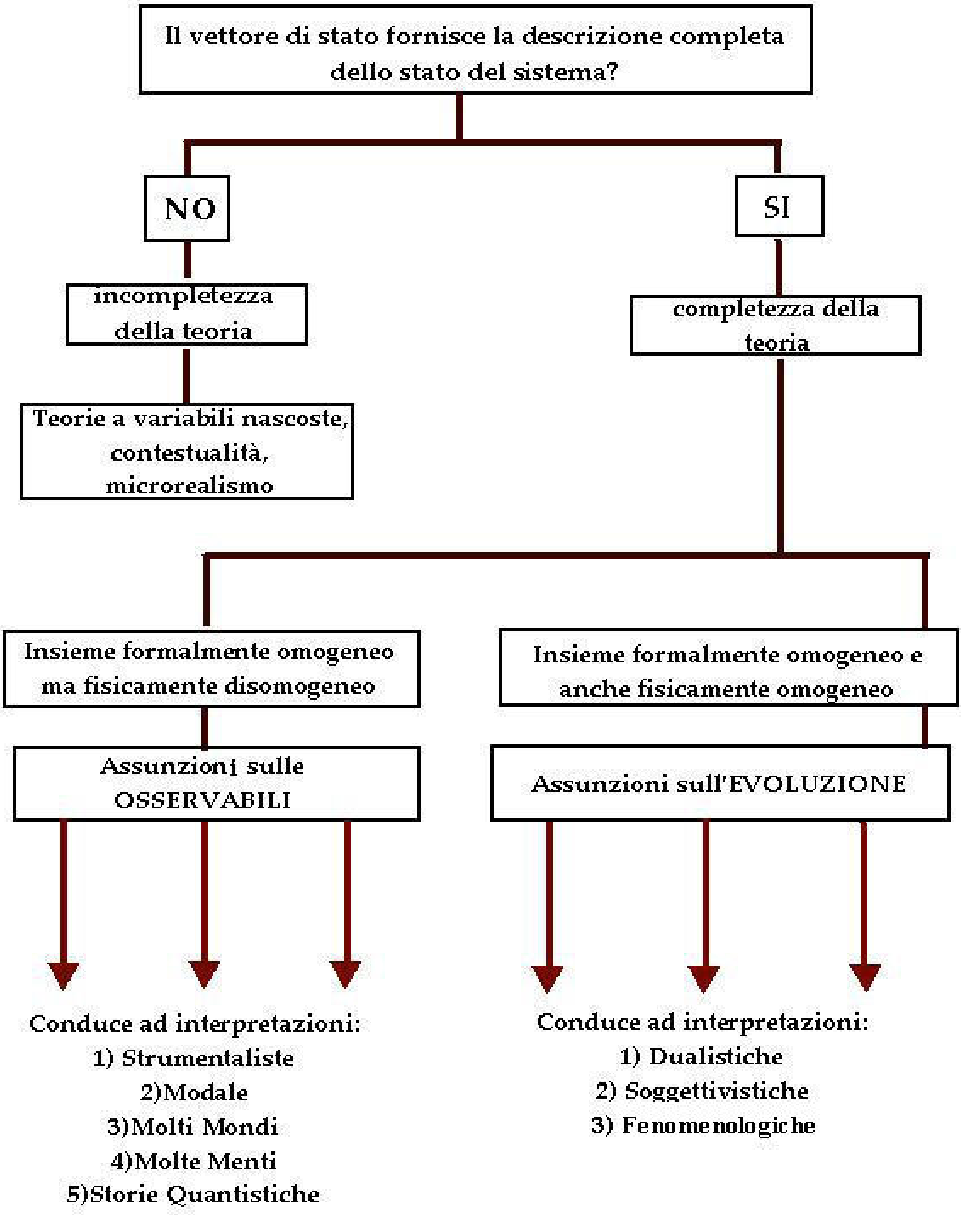
infatti secondo Howard, Einstein appare come:

- a) **realista** nella misura in cui cerca di descrivere un mondo indipendente dagli atti di percezione
- **idealista** nella misura in cui guarda ai concetti e alle teorie come libere invenzioni dello spirito umano
- **positivista** nella misura in cui considera i concetti e le sue teorie giustificate soltanto in quanto forniscono una rappresentazione logica delle relazioni tra esperienze sensoriali
- **platonista** nella misura in cui considera il punto di vista della semplicità logica come indispensabile ed efficace strumento di ricerca



Problema del formalismo della MQ:
breve schema a blocchi che riassume le interpretazioni.

Figure 1.4: Completezza del vettore di Stato: Interpretazioni

Secondo Bohr invece i nuovi fenomeni microscopici ci inducono ad abbandonare l'idea di una descrizione classica e ad accettare una situazione nuova che può essere riassunta appunto nel "principio di complementarità". Tale disputa si attua in due fasi.

In una prima fase Einstein rifiuta il principio di indeterminazione sia nel suo aspetto formale che concettuale, e tenta di dimostrarne l'erroneità escogitando degli esperimenti mentali con i quali misurare simultaneamente, e con infinita precisione, variabili complementari come la posizione e l'impulso.

Sul tema dell'incertezza Pitowsky, (Pitowsky,1989) dà due formulazioni del principio di indeterminazione, uno che chiama debole e l'altro forte, così definiti:

1) debole: se posizione e impulso hanno un valore ben definito, allora la misura della posizione di una particella disturba il valore del suo impulso e la misura del suo impulso introduce un'indeterminazione nella sua posizione. Tale disturbo non può essere arbitrariamente ridotto. E' il classico principio di indeterminazione.

2) forte: grandezze fisiche come "posizione", "impulso", "energia" ecc. tipicamente associate ai sistemi fisici esistono e sono ben definite solo nel contesto di particolari esperimenti. Quando viene effettuata una misura di posizione molto accurata il valore dell'impulso è semplicemente non definito, e viceversa. Secondo questo principio (forte) non esistono "disturbi" dovuti alle misure, ma l'indeterminazione risiede nel fatto che posizione e impulso sono due grandezza "complementari" e non può quindi esistere una descrizione comune.
E' stata proprio la messa in discussione del principio di indeterminazione che ha condotto alla possibilità di completare teoricamente (in senso classico, hidden variables) la MQ. In pratica, il principio di indeterminazione veniva ad assumere non più un carattere ontico ma epistemico. In una seconda fase Eistein invece ammette l'impossibilità di falsificare tale principio, ma rimane ancora profondamente insoddisfatto dell'origine non epistemica delle probabilità quantistiche. E' con l'argomento EPR (EPR,1935) che attacca la pretesa completezza della MQ. EPR pone in evidenza una possibile interpretazione realistica della MQ. Vi sono molte ragioni che rendono l'argomento di EPR fondamentale per il dibattito sul realismo in MQ (ed in generale sulle teorie fisiche). Esso infatti stabilisce, in primo luogo, la necessità di basare il realismo degli "oggetti" fisici non su argomenti filosofici a priori ma su esperimenti e misurazioni. In secondo luogo, fu proprio a partire dall'argomento di EPR che Schrödinger introdusse il concetto di "correlazione a distanza" (entanglement) che rappresenta una delle peculiarità fondamentali del formalismo quantistico. In altre parole, l'entanglement mostra che gli oggetti microscopici sono caratterizzati da proprietà che hanno natura **fondamentalmente relazionale**.

1.0.10 EPR ontico vs epistemico?

EPR si chiedono se la descrizione della MQ possa essere considerata "completa", nel senso che ad ogni "elemento di realtà deve corrispondere un elemento della teoria. Essi utilizzano il concetto classico di completezza in base al quale si presume che tutte le variabili che caratterizzano un sistema abbiano, in ogni istante, un valore ben definito. Essi non danno una definizione precisa di realtà[15], ne potrebbero darla, ma affermano che una condizione sufficiente per la realtà di una grandezza fisica è la possibilità di predirne con certezza il valore senza in alcun modo disturbare il sistema.

La versione originale dell'argomento EPR solleva il problema della completezza della teoria sostenendo che è possibile in via teorica attribuire un valore simultaneo alla posizione e all'impulso di una particella (attribuzione vietata dal principio di indeterminazione). Una formulazione più semplice di EPR è quella di Bohm (Bohm,1951). Questa versione utilizza solo variabili discrete (variabili di spin) e non variabili continue come posizione ed impulso. E' su questa versione che si basa il fondamentale lavoro di Bell del 1964 (Bell,1964). Bell trasforma il lavoro EPR in un argomento stringente sulla possibilità di una interpretazione classica della MQ. Le ipotesi alla base di tale lavoro sono di natura logico-probabilistica ed il confronto con la MQ avviene solo sulla base delle sue previsioni sperimentali. Bell analizza il modello di Bohm per due particelle di spin 1/2 e mostra come esso presenti in generale delle caratteristiche non locali, cioè di dipendenza della misura di un'osservabile (con separazione space-like) in una certa regione dalla possibile scelta di effettuare una misura in un'altra regione arbitrariamente distante (le due particelle sono entangled). A questo punto egli si chiede se ogni modello probabilistico, che riproduca le aspettazioni della MQ debba avere tali caratteristiche. La risposta a tale quesito è affermativa. Egli mostra che ogni modello probabilistico classico che descriva tutte le possibili misure di spin su di un sistema di due particelle di spin 1/2 soddisfa delle disuguaglianze (correlazioni tra misure con separazione space-like). Tali disuguaglianze vengono violate dalle correlazioni predette dalla MQ. Da questo confronto nasce una discussione che contrappone "determinismo" e "località". Bell afferma che, se le previsioni della MQ sono esatte, non esiste una "teoria deterministica locale" che riproduce tali previsioni. Se si trova una teoria deterministica questa dovrà essere non locale (un esempio è l'interpretazione di Bohm, dove

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[15] Tarozzi et al, 2009

viene recuperato il classico concetto di campo). Il risultato di Bell viene solitamente espresso nella forma negativa "non esistono teorie probabilistiche classiche locali che riproducono i risultati della MQ". Da un punto di vista filosofico la MQ si oppone dunque al realismo locale. In conclusione possiamo dire che per riprodurre gli stessi risultati della MQ, una teoria a variabili nascoste deve essere non locale.

1.0.11 Teorema di Bell: un esempio di metafisica sperimentale.

E' dall'analisi del modello di Bohm che Bell ha ricevuto importanti suggerimenti per lo sviluppo del proprio lavoro sulle teorie a variabili nascoste. Il teorema di Bell rappresenta certamente uno dei più grandi contributi al chiarimento dei problemi concettuali della teoria quantistica. Bell è stato in grado di dedurre una disuguaglianza per le correlazioni di osservabili che ogni tipo di modello a variabili nascoste locale deve soddisfare ma che è violata dalla teoria quantistica. A Bell va il grande merito di aver scoperto una formulazione matematica della posizione epistemologica di EPR e di averne mostrata l'incompatibilità con le predizioni statistiche della MQ. Contro ogni aspettativa, Bell è riuscito a trasformare un quesito che appariva puramente metafisico ed epistemologico in un problema di fisica, suscettibile di una soluzione nel campo dell'esperienza. Come già accennato Shimony (Shimony,1999) l'ha definata come un esempio di metafisica sperimentale. Le conclusioni raggiunte da Bell sono di estrema generalità, non importa la forma e il livello di complessità del modello a variabili nascoste escogitato: nessuna teoria soddisfacente, i criteri di realismo e località desiderati da Einstein, sarà capace di replicare tutti i risultati della MQ. Anche se oggi abbiamo una minoranza di oppositori a tale teorema, la fisica sperimentale per ora dà ragione a Bell. Durante il suo studio dei modelli a variabili nascoste e dei teoremi che ne tentavano di dimostrare l'impossibilità, l'attenzione di Bell era stata attratta dal carattere intrinsecamente non locale della teoria di Bohm: in essa la traiettoria di una particella localizzata in una regione dello spazio può dipendere istantaneamente da quel che accade in un luogo a lei arbitrariamente lontano. Bell si chiese allora se la NL che appariva nella trattazione causale di Bohm del paradosso EPR fosse non un difetto del modello teorico, ancora parziale essendo non relativistico, ma una caratteristica necessaria che ogni teoria a variabili nascoste, in grado di riprodurre perfettamente il formalismo quantistico deve contenere. Questa geniale intuizione portò Bell ad elaborare il famoso teorema di impossibilità delle teorie a variabili nascoste locali.

Teorema di Bell: Nessuna teoria deterministica locale a variabili nascoste può riprodurre tutte le predizioni della MQ.

A Clauser, Horne, Shimony e Holt (CHSH, 1969) è dovuta la prima notevole generalizzazione del lavoro di Bell. Ispirandosi al lavoro di CHSH, nel 1971 Bell generalizza il suo teorema conseguendo un ulteriore notevole risultato. Egli dimostra come sia possibile dedurre disuguaglianze violabili dalla teoria dei quanti dalle sole ipotesi di realismo e località, senza la condizione di determinismo. Come osservato da alcuni autori, tra i quali Popper (Popper,1998), l'eventuale incompatibilità tra teorie a variabili nascoste locali deterministiche e MQ, poteva forse ascriversi alla sola ipotesi di determinismo [Clauser, Horne 1974]. Il nuovo teorema chiarisce definitivamente come l'impossibilità di replicare i risultati della MQ sia da imputarsi esclusivamente alle sole richieste di località e realismo. Inoltre esso è applicabile tanto a teorie intrinsecamente stocastiche, non deterministiche, che a teorie deterministiche nella quale sono assunti parametri non controllabili associati agli strumenti di misurazione.
Teorema generale di Bell[16](1971): Nessun modello che soddisfi le ipotesi di realismo e località può riprodurre tutte le predizioni della teoria dei quanti.
Grazie alla disuguaglianza di Bell abbiamo finalmente la possibilità di distinguere sperimentalmente tra le predizioni delle teorie realistiche locali e quelle della teoria dei quanti. Dunque è comprensibile come il risultato di Bell abbia dato impulso ad un notevole numero di lavori sperimentali. La maggior parte degli esperimenti eseguiti è stata dedicata alla verifica delle correlazioni quantistiche tra le polarizzazioni di coppie di fotoni con spin totale nullo. Nel 1982 Aspect (Aspect et al. 1982) e collaboratori provano l'esistenza della non-località in modo definitivo.
La NL delle correlazioni quantistiche non appare solo nei sistemi entangled delle osservabili di spin o di polarizzazione, ma essa è del tutto generale e condivisa da qualunque tipo di stato non fattorizzabile. Gli attuali progressi tecnici permettono infatti la preparazione di sistemi entangled relativi ad osservabili differenti dallo spin o dalla polarizzazione e aprono quindi la strada a verifiche più generali della disuguaglianza di Bell. L'importante teorema di Bell-Kochen-Specker (Bell et al,1967), esprime l'impossibilità di assegnare valori alle osservabili quantistiche prima dell'atto di misurazione in maniera indipendente dal contesto sperimentale. Vedremo che esiste anche un rapporto tra NL e contestualità. Nello specifico descriveremo l'interessante lavoro di Greenberger, Horne e Zeilinger (Greenberg et al.

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[16] Secondo Zanghì (Zanghì, 2005) per poter parlare di località si deve presuppore l'esistenza di un'arena,lo spaziotempo, in cui gli eventi fisici accadono. L'argomento di Bell dà per scontato che le misure quantistiche abbiano risultati, per cui non si applica a qualunque versione della MQ in cui questo non vale. Nell'interpretazione a molti mondi il teorema non è applicabile.

1990). Questi autori, grazie all'introduzione di nuove forme di stati entangled, hanno dedotto una dimostrazione del teorema di Bell che non necessita di disuguaglianze. Concludiamo la sezione con un cenno al fondamentale teorema di Bell, Kochen e Specker sebbene meno famoso rispetto al teorema di Bell sulla NL, ha implicazioni non meno profonde per l'interpretazione del formalismo quantistico. Uno tra i più dibattuti problemi che affliggono i fondamenti della teoria dei quanti è se le proprietà degli oggetti quantistici possiedano o meno valori prima di un'osservazione. Bell, Kochen e Specker (BKS) trasformano quella che poteva apparire un'arbitraria presa di posizione filosofica, dei padri fondatori, in un'interpretazione della misurazione quantistica la cui giustificazione risiede nella struttura formale della teoria stessa. Essi dimostrano infatti in modo rigoroso l'impossibilità di assegnare valori ad un'osservabile prima dell'atto di misurazione indipendentemente dalle osservabili compatibili con essa congiuntamente misurate, giungendo ad una definitiva confutazione della forma di realismo professato da Einstein e da Popper.

Pertanto, in accordo con Bohr, il valore assunto da un'osservabile A deve dipendere dalla completa specificazione del contesto sperimentale. Più in generale, il teorema dimostra l'incompatibilità tra il formalismo quantistico e una sua interpretazione in termini di teorie a variabili nascoste di tipo non contestuale. Quindi una teoria a variabili nascoste che si propone di riprodurre i risultati della MQ deve necessariamente essere contestuale: il valore assegnato ad un'osservabile A da tale teoria deve dipendere dalle osservabili congiuntamente misurate con A e perciò dalla completa specificazione dell'apparato sperimentale. Il risultato di un'osservazione può ragionevolmente dipendere non solo dallo stato del sistema (includente le variabili nascoste), ma anche dalla completa disposizione dell'apparato [Bell 1966]. In definitiva, possiamo assumere che, almeno in condizioni simili a quella appena descritta, la richiesta di non contestualità segua dalla condizione di località:

$$\text{Condizione di località} \Rightarrow \text{Condizione di non contestualità}$$

Il primo studio sul legame esistente tra NL e contestualità si deve a Heywood e Redhead (Heywood, Redhead 1983), il teorema di Heywood e Redhead dimostra anche la NL: dunque la teoria quantistica è allo stesso tempo sia contestuale che non locale.

1.0.12 Non-località Einsteiniana vs non-località causale

I fisici preferiscono fare chiarezza su questo termine "non locale" utilizzato nella MQ a causa del fenomeno dell'entanglement. Una teoria si dice locale se prevede che non esistano segnali superluminali. Un segnale superluminale è uno scambio di informazione che avviene a velocità superiori alla velocità della luce. Da qui alcune definizioni. La "vera" NL e cioè la possibilità di trasmettere segnali a velocità superiori a c viene detta NL einsteiniana, tale NL è detta a-causale, in essa non vale il principio di causalità. Una teoria locale è anche causale, cioè vale il principio di causalità. La NL della MQ viene definita come non-località causale, in quanto è possibile creare correlazioni tra due sistemi A e B anche a velocità superluminali, ma tali correlazioni non permettono di trasmettere segnali tra A e B[17]. Poiché non vi è scambio di informazioni, non vi può essere un rapporto causale tra A e B. di conseguenza la non-località causale è compatibile con la causalità. In conclusione una teoria non-locale causale è locale in senso einsteiniano. Su alcuni di questi punti non siamo completamente d'accordo, il punto è che non conosciamo la natura dell'entanglement quindi non conosciamo che tipo di scambio avviene tra i due sistemi presi in considerazione. Qui la causalità viene salvata dal non scambio di informazione, al momento però non siamo in grado di capire la natura di questa famosa azione spettrale a distanza. In sintesi abbiamo queste possibilità:

- 1) Se la MQ è incompleta allora ⇒ è non locale (hidden variables)
- 2) Se la MQ è non oggettiva (cade principio di realtà)⇒lo stato quantistico è solo informazione (visione epistemica)
- 3) Se la MQ è non locale⇒lo stato quantistico è reale, alla fine l'intero universo è entangled, si può parlare solo delle proprietà del sistema non del singolo oggetto

E' importante sottolineare la differenza tra uno stato fattorizzato ed uno stato entangled. Se abbiamo un sistema composto da 2 particelle con certe proprietà P1 e P2, il sistema può essere rappresentato in uno stato fattorizzato in cui le particelle 1 e 2 possiedono oggettivamente e distintamente le rispettive proprietà P1 e P2. Se

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[17] I problemi che solleva la non-località in MQ son ben lungi lungi dal trovare una chiara comprensione in un coerente quadro razionale della natura (Figliuzzi,2008), come lo è il suo possibile legame con la causalità. Nella MQ mentre è lecito parlare di non-località "superluminale" in merito a eventi separati da un intervallo di tipo spaziale, non sarebbe lecito invece ammettere per tale fenomeno una relazione causale. A tal riguardo Laudisa (Laudisa,2007) si chiede, se non risulti possibile considerare causale anche il primo tipo di connessione (quella space-like) "sia pure al prezzo di introdurre una nozione fortemente non convenzionale di causalità. Una domanda, questa, la cui risposta in ogni caso dipende, da come viene presentato il rapporto tra lo spazio-tempo e la causalità nella teoria di Einstein. Le osservazioni di Laudisa fanno riferimento agli studi di Maulin (1997). Qui si propone la definizione di mutua implicazione causale e cioè di una direzione privilegiata, secondo cui "una coppia di eventi A e B si implicano causalmente a vicenda quando l'evento B non si sarebbe verificato se l'evento A non si fosse verificato, e viceversa"

però, ad un determinato istante, le due particelle interagiscono, da quell'istante in poi le due particelle formeranno un stato entangled e saranno legate dalla cosidetta non-separabilità quantistica. Non si potrà parlare di proprietà oggettivamente posseduta dall'una o dall'altra particella ma solo della proprietà del sistema entangled. L'entanglement è una costruzione che sposta le proprietà dal singolo oggetto al sistema. Dalla ricerca delle proprietà del singolo oggetto si passa alle proprietà di un sistema. Come sottolineava Bell in fin dei conti potremmo, ritrovarci con una macroscopica non-separabilità dell'universo. Come faceva rilevare Bell, visto che alla lunga tutto interagisce con tutto, l'intero universo potrebbe essere visto come un unico stato entangled. Di conseguenza non avrebbe senso discutere di proprietà oggettivamente possedute da un solo oggetto. Un universo dunque senza una proprietà individuale. Il tentativo (poi rivelatosi falso) di ridare dignità al singolo oggetto, indipendente dal fatto che esso possa successivamente formare uno stato entangled con altri è quello di proporre che le proprietà di un oggetto sono già possedute prima della misura. Bisogna analizzare più in dettaglio le differenze tra sistemi entangled (non-separabili) ed il misterioso fenomeno della non-località.
Dato un sistema quantistico, la procedura FAPP per arrivare a stabilire eventuali connessioni non-locali sono:

- 1) bisogna verificare formalmente se tale sistema è entangled (stato non fattorizzabile)
- 2) bisogna verificare se viola le disuguaglianze di Bell (in ipotesi space-like).
- 3) se tali disuguaglianze vengono violate abbiamo una connessione di tipo non-locale
- 4) se tali disuguaglianze non vengono violate pur essendo il sistema entangled non abbiamo nessun tipo di connessione non-locale.

Inoltre bisogna sottolineare che per stabilire il fenomeno della non-località di un processo quantistico, i due "osservatori" che effettuano le due misure sul sistema entangled, devono poi a **posteriori** confrontare gli esiti delle loro misure. E' da questo confronto a posteriori che essi si rendono conto delle correlazioni. I dati che a prima vista sembrano essere distribuiti casualmente appaiono invece esattamente correlati. Dati che potremmo definire psuedo-random sincronizzati a posteriori. In pratica si potrebbe essere in stato entangled senza esserne a conoscenza. Qui le possibili implicazioni filosofiche potrebbero essere molto interessanti.

1.0.13 L'Osservatore e la Misura

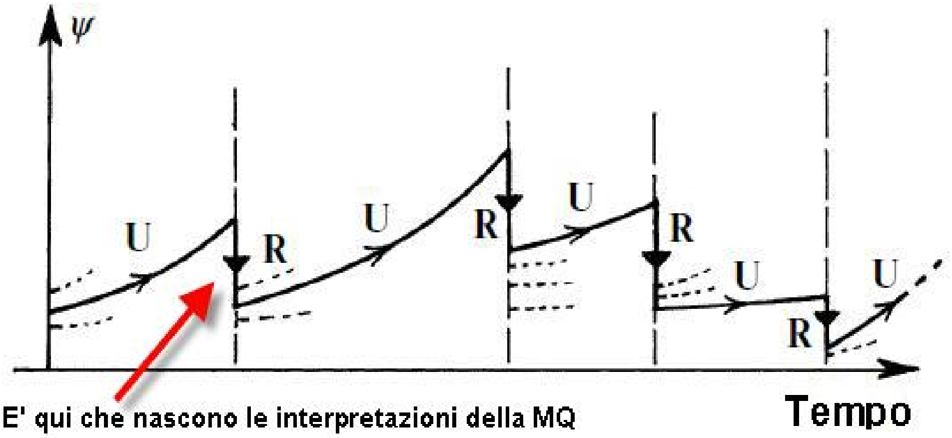

Figure 1.5: L'evoluzione della funzione d'onda si alterna tra due fasi diverse: 1) evoluzione unitaria **U** (eq. di Schrödinger) continua e deterministica e quella di riduzione dello stato **R** (discontinua e probabilistica).

La figura 1.5 (Penrose, 2005), pone in evidenza i due processi distinti che avvengono in MQ: il processo di evoluzione di Schrödinger **U**, e quello di riduzione di stato **R**. Secondo Penrose, il mistero degli stati che sono entangled si complica se facciamo solo riferimento al processo **U**, cioè alla solo equazione di schrodinger. Tale equazione tende a complicare le cose. Attraverso il suo utilizzo, un numero sempre più grande di parti dell'universo diviene entangled con il nostro sistema di partenza. Secondo Penrose, conviene dunque rivolgersi all'altro processo quello **R** (riduzione). Egli ritiene che è questo il processo che ci libera dagli stati entangled. E' la misurazione che recide gli entanglement. Penrose crede che la natura stessa metta in atto continuamente effetti di processo R, senza alcuna deliberata intenzione da parte dello sperimentatore o un qualsiasi intervento da parte di un osservatore cosciente. La domanda che naturalmente ci poniamo ora è: che cosa significa "osservatore cosciente", e che ruolo esso svolge nel processo **R** di riduzione. Quasi tutte le interpretazioni convenzionali della MQ dipendono dalla presenza di un essere che percepisce. La MQ sembra richiedere dunque una definizione di un essere percipiente. Poichè la misura richiede sempre una "osservazione".
Nella figura 1.6, a pag XXXVI, viene riporta una efficace rappresentazione fatta da Bell, dove si pone questo problema: dov'è il confine tra mondo microscopico ed il mondo della esperienza sensibile (ns.proposta nel cap.1.1 pag. XLV)[18]. Cercare di ridurre tutto all'apparato (classico) di misura non risolve il problema in

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[18] Dove avviene il collasso della funzione d'onda? Dov'è la sua frontiera? Nella figura Bell sottolinea

modo definitivo. Poiché lo stesso apparato è costituito da elementi quantistici e non si comporterebbe in modo classico se facciamo valere il processo U (problema del gatto di Schrodinger) anche per l'apparato. Il ricorso al fenomeno della decoerenza ambientale potrebbe risolvere il problema? Anche questa ipotesi potrebbe essere un ripiego, poiché l'inaccessibilità dell'informazione perduta nell'ambiente non significa che essa si effettivamente perduta in senso oggettivo. Ma se la perdita fosse soggettiva, torniamo di nuovo alla questione del "soggettivamente percepito", e da chi? Il problema ritorna all'osservatore cosciente. Nella storia dei fondamenti della MQ ricordiamo che una intepretazione (Wigner, 1989) basa sulla coscienza la violazione del processo U facendo riferimento esplicitamente al ruolo della mente. Per la precisione Wigner parte dalle osservazioni di von Neumann. In pratica, possiamo creare tutta una successione di stati di sovrapposizione, la cosiddetta catena di Von Neumann, che inizia dall'oggetto e finisce con continui ed indefiniti osservatori. Tale cammino, secondo Von Neumann, non può avere termine che con l'osservatore: egli, infatti, è l'unico strumento di misura in grado di misurare se stesso. Vediamo più in dettaglio la catena di von Neumann. Von Neumann assume la validità di quello che chiama il parallelismo psico-fisico, vale a dire che ogni processo mentale può essere descritto in termini fisici[19]. Egli parte dal presupposto che la MQ è caratterizzata da due diverse leggi di evoluzione:

- 1) quella governata dall'equazione di Schrödinger (deterministica)
- 2) quella indeterministica del postulato di proiezione.

Secondo von Neumann, ogni processo di misurazione può essere compreso solo mediante il punto 2. Da molti questo è considerato un grave difetto della teoria. Von Neumann ci indica questa giustificazione. Ci sono due descrizioni incompatibili, quella oggettiva (1) e quella soggettiva (2), secondo von Neumann la descrizione 1 ci permette di passare al 2, senza per questo che venga violato il parallelismo psico-fisico[20]. Questo non implica un intervento del soggetto sull'oggetto, perché la

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come la situazione si complichi ulteriormente, se si prova ad inglobare nel sistema parti sempre più grandi dell'ambiente di misurazione e cioè: la parte sensibile dello strumento, l'intero apparato, l'occhio dell'osservatore, il suo cervello, la sua mente, l'intero universo. Bisogna sottolineare che Bell si è rifiutato di cercare nella mente (o nell'intero universo) il limite invalicabile della riducibilità alla MQ e quindi il "luogo" del collasso. Nelle sue stesse parole: chi scrive condivide con la maggior parte dei fisici un certo imbarazzo all'idea che la coscienza sia coinvolta nella fisica, come pure l'usuale sensazione che considerare l'universo come un tutt'uno sia perlomeno immodesto, se non blasfemo.

[19] Lasciamo aperta questa questione, nel cap. 8, introdurremo un esperimento teorico che non assume tale condizione, lasciando al cammino stesso l'indicazione di una sua possibile conclusione.

[20] la sua violazione (come abbiamo già in precedenza accennato) il cosiddetto integrazionismo è invece

divisione fra oggetto e soggetto è arbitraria, in pratica possiamo porre il taglio dove vogliamo. Von Neumann si sforza di dimostrare che se "dividiamo" fra oggetto e soggetto in due modi diversi lo stesso sistema misurato il risultato non cambia, certo è contestabile che esistano due descrizioni inconciliabili del mondo, quella oggettiva e quella soggettiva.
Per tali motivi Von Neumann e Wigner hanno concluso che è la coscienza dello sperimentatore a provocare la riduzione del pacchetto d'onde. In questo caso il problema è stato risolto facendo ricorso a qualcosa di apparetemene di più misterioso della misurazione quantistica stessa. Il gatto di shrodinger è l'esempio emblematico di tale problema.
Una delle interpretazioni che non dipende necessariamente da qualche concetto di osservatore cosciente è quella di de Broglie-Bohm che va a cambiare i processi U ed R, ritenuti in questa intepretazione approssimazioni a qualche evoluzione fisica oggettivamente reale. Ritornado a Penrose, da qualche tempo egli si schiera per un nuovo processo che definisce OR. Dove gli stati oggettivi, dovuti ad effetti gravitazionali rimpiazzerebbero il processo U. Questo processo OR gravitazionale avrebbe

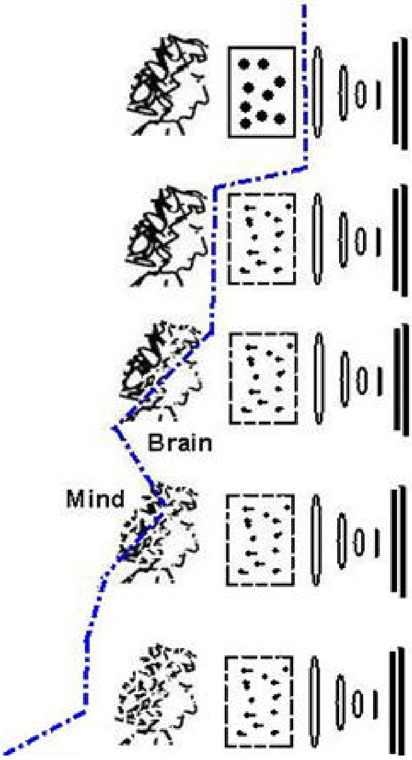

Figure 1.6: Una rappresentazione di Bell.

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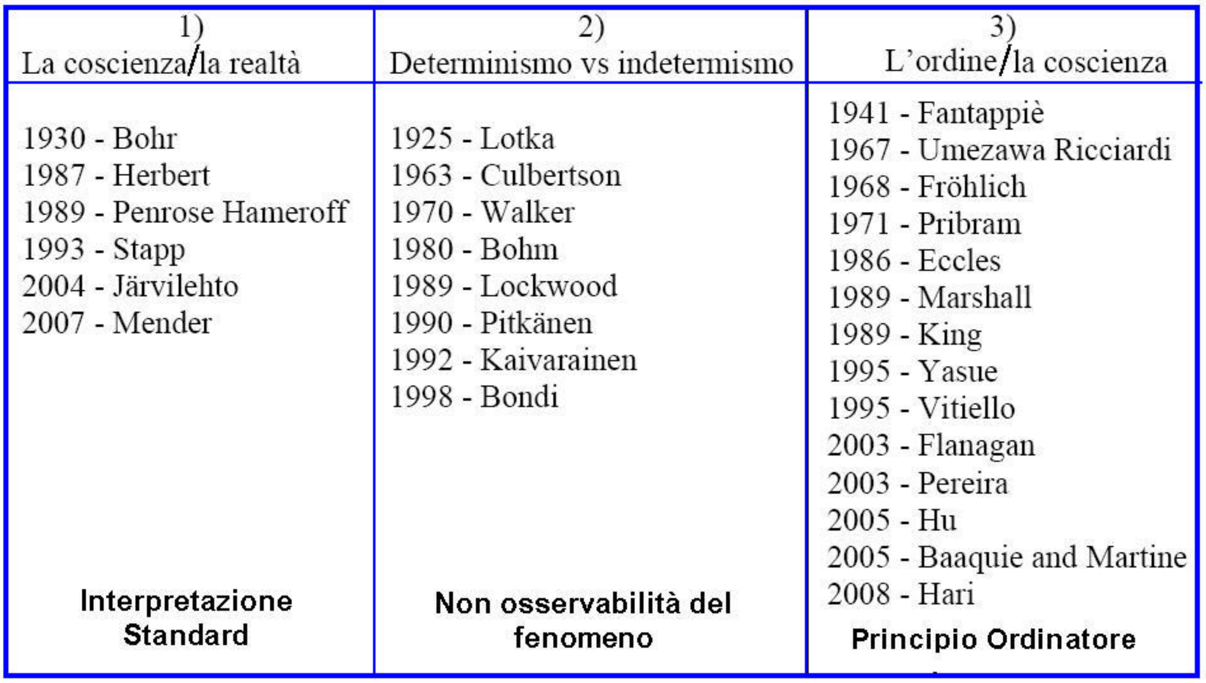
la strada seguita da London e Bauer e da Wigner: è la coscienza dell'osservatore che fisicamente favorisce il collasso della funzione.

luogo spontaneamente e non esigerebbe che un osservatore cosciente faccia parte del processo. Penrose finora non ha ancora elaborato una teoria completa al riguardo.
Per chiudere questa sezione, sul problema dell'osservatore e la MQ , riportiamo sinteticamente una tabella che racchiude i vari modelli quantistici della coscienza (Vannini, 2008) proposti fin dal 1924 fino ad oggi. Inizialmente tale indirizzo di ricerca non fu reputato oggetto di indagine scientifica in quanto imperniata su concetti metafisici. Solo dagli anni 80' con il progresso delle neuroscienze e alle conferme sperimentali, l'indagine sulla mente e sulla coscienza ha cessato di essere considerata un argomento di pura speculazione filosofica.
Le teorie sulla coscienza proposte negli ultimi decenni vanno dai **modelli fondati sulla fisica classica** (come i modelli avanzati da Churchland, Damasio, Dennett, Edelman, Varela e Searle) ai modelli più recenti che tentano di fondare una spiegazione delle dinamiche coscienti sui principi della MQ, quali i concetti fondamentali di dualismo onda-particella, collasso della funzione d'onda, retrocausalità, non-località e campo unificato (come i modelli proposti da Eccles, Hameroff (Hameroff, 1999), Penrose e Chris King (King,2003)). Malgrado i progressi finora ottenuti, una profonda comprensione dei fenomeni mentali appare ancor oggi un traguardo lontano. E' possibile suddividere i modelli proposti in tre gruppi:

- 1) Modelli che collocano la coscienza nella posizione di un principio primo dal quale discende la realtà.
- 2) Modelli che fanno discendere la coscienza dalle proprietà indeterministiche e probabilistiche dalla MQ.
- 3) Modelli che individuano nella MQ un principio d'ordine dal quale discendono e si organizzano le proprietà della coscienza.

La tabella seguente (fig. 1.7) mostra in quale categoria rientra ciascun modello. I modelli che rientrano nella prima categoria si rifanno, in modo più o meno esplicito, all'interpretazione di Copenhagen. Tali modelli sfuggono, per definizione, alla verifica sperimentale, in quanto fanno discendere i loro assunti dal fatto che la coscienza stessa si pone a monte della realtà osservata e la determina. In questo senso, i modelli che rientrano nella prima categoria potrebbero essere considerati non tanto dei modelli della coscienza, quanto piuttosto dei modelli che cercano di spiegare l'emergere della realtà osservabile da processi panpsichisti. I modelli del secondo gruppo partono dall'assunto che la coscienza risieda in un dominio non osservabile con le attuali tecnologie della ricerca, come ad esempio i processi che avvengono a scale di misura al di sotto della costante di Planck. Anche questi si pongono al di



1) La coscienza/la realtà	2) Determinismo vs indetermismo	3) L'ordine/la coscienza
1930 - Bohr 1987 - Herbert 1989 - Penrose Hameroff 1993 - Stapp 2004 - Järvilehto 2007 - Mender	1925 - Lotka 1963 - Culbertson 1970 - Walker 1980 - Bohm 1989 - Lockwood 1990 - Pitkänen 1992 - Kaivarainen 1998 - Bondi	1941 - Fantappiè 1967 - Umezawa Ricciardi 1968 - Fröhlich 1971 - Pribram 1986 - Eccles 1989 - Marshall 1989 - King 1995 - Yasue 1995 - Vitiello 2003 - Flanagan 2003 - Pereira 2005 - Hu 2005 - Baaquie and Martine 2008 - Hari
Interpretazione Standard	**Non osservabilità del fenomeno**	**Principio Ordinatore**

Figure 1.7: Classificazione dei modelli quantistici della coscienza.

là del criterio di falsificabilità. I modelli del terzo gruppo si basano sulla ricerca in natura di un principio di ordine che possa giustificare le proprietà della coscienza, si richiamano a principi e fenomeni che hanno già portato alla realizzazione di incoraggianti applicazioni in campo fisico (come, ad esempio, i condensati di Bose-Einstein, i superconduttori e il laser). Per questo motivo tali modelli possono essere più facilmente tradotti in ipotesi operative da verificare in campo sperimentale. Oltre al criterio della falsificabilità scientifica, va aggiunto, un secondo criterio relativo alla compatibilità del modello con le caratteristiche tipiche dei sistemi biologici. Si vede che i principi di ordine rinvenuti nella terza categoria propongono soluzioni spesso palesemente incompatibili con le caratteristiche dei sistemi biologici, come ad esempio, i condensati di Bose-Einstein i quali richiedono, per manifestarsi, temperature prossime allo zero assoluto. Applicando questo secondo criterio di selezione vengono progressivamente esclusi buona parte dei modelli proposti. In conclusione, sembra che tutti i modelli della coscienza, proposti nell'ambito della MQ, non sono traducibili in proposte sperimentali perché sono o incompatibili con il criterio della falsificabilità e/o incompatibili con le caratteristiche dei sistemi biologici. Tra i modelli presentati appartenenti alla seconda categoria, menzioniamo brevemente quello proposto da Bohm.

Bohm sviluppò la cosiddetta teoria dell'onda pilota. Questa teoria è in grado di fornire una descrizione **causale** dei processi quantistici. Bohm mostrò che il movimento della particella sotto la guida dell'onda avviene in accordo ad una legge che ha la forma della seconda legge di Newton, con la sola differenza che nella sua teoria la particella è soggetta, oltre ad una forza classica, anche ad una forza quantistica. Questa forza è legata a una forma di energia denominata potenziale quantistico. La funzione d'onda, secondo Bohm, agisce proprio come un'onda pilota che guida la particella corrispondente attraverso l'azione del potenziale quantistico. Il potenziale quantistico non opera come i campi elettromagnetici classici ma agisce in maniera istantanea (sincronica) e solo come pura "forma". Secondo Bohm, è proprio il potenziale quantistico a determinare la non-località dei processi quantistici. Questo potenziale informerebbe istantaneamente ogni particella. Secondo Bohm, dietro alla realtà fenomenica spazio-temporale esisterebbe, un livello a noi nascosto che guida la particella. In tale concezione non ci sarebbe più spazio per il cosiddetto ordine cartesiano. Non solo, anche i concetti spazio e tempo assumerebbero un ruolo diverso. Nel 1960 già Chew (Chew, 1960) sottolineava che non vi è alcuna necessità di spiegare i fenomeni quantistici sulla base di una struttura spazio-temporale (caratteristica della relatività speciale). Se infatti lo spazio-tempo fosse assunto (come Einstein riteneva) come elemento base, allora giustamente si richiederebbe alla località una validità assoluta. Così non accade, poichè come sappiamo le particelle manifestano delle correlazioni che sono non-locali. In tale contesto sono dunque da rivedere ed approfondire i concetti di spazio e di tempo. Bohm suggerì che per spiegare il carattere non locale dei fenomeni quantistici è necessario introdurre nuovi diversi livelli di realtà. Egli introdusse la distinzione tra foreground e background: ordine esplicato ed ordine implicato. Il risultato della misura quantistica è l'ordine esplicato (il mondo macroscopico). Quello che avviene in tale ordine rappresenta tuttavia una proiezione di un livello più fondamentale e nascosto: l'ordine implicato. Quest'ultimo è caratterizzato dalla non-località e dalla non-separabilità. Nelle sue stesse parole:

> si è condotti ad una nuova concezione di totalità indivisa che nega l'idea classica della possibilità di analizzare il mondo in parti esistenti in maniera separata e indipendente: la realtà fondamentale è l'inseparabile connessione quantistica di tutto l'universo e le parti che hanno un comportamento relativamente indipendente sono solo forme particolari e contingenti dentro questo tutto.

Per chiudere questa sezione osserviamo, in ultimo, che oggi vi sono ricerche in Italia (Conte et al, 2008) dove si cerca di verificare se vi possano essere significative violazioni delle disuguaglianze di Bell nei fenomeni cosiddetti percettivi (i.e. formazione di una immagine cosciente). Queste possibili violazioni indicherebbero la **presenza di effetti non locali di tipo EPR. Queste possibili violazioni indicano che effetti quantistici su grande scala possono far parte della percezione cosciente.**

1.0.14 Non-Località e Spazio-Tempo

Secondo Suarez, gli esperimenti in MQ, dopo il teorema di Bell, dimostrano che le correlazioni non-locali tra eventi separati spazialmente non possono essere spiegati per mezzo di influenze relativistiche, essendo queste ultime vincolate dalla costanza della velocità della luce. Questo significa che bisogna rinunciare alla visione secondo la quale i risultati delle misure quantistiche rivelino delle proprietà pre-esistenti al processo di misura. Le particelle non hanno alcuna proprietà prima di lasciare la sorgente EPR. Suarez insieme a Scarani (Suarez-Scarani, 1997), attraverso un esperimento chiamato "the before-before experiment" dimostrano che le correlazioni non locali non possono essere spiegate in termini di "prima" e "dopo". In pratica non esistono influenze non locali ordinate nel tempo.Secondo Suarez, rinunciare al concetto di località non è sufficiente per essere coerente con gli esperimenti della MQ, si deve rinunciare anche al determinismo non-locale. Bisogna cioè abbandonare l'opinione secondo la quale, un evento che si verifica per prima nel tempo è causa, e l'altro che avviene dopo nel tempo è effetto. **Le correlazioni non locali non possono essere spiegate attraverso una storia nello spazio-tempo, esse provengono al di fuori dello spazio-tempo.**

Secondo Suarez tali risultati sperimentali confermano l'interpretazione Standard della MQ. La teoria di Suarez-Scarani, fa riferimento alla necessità di introdurre delle "entità" esterne allo spazio-tempo. Su questo ultimo punto, il presente lavoro proporrà una propria tesi. L'esperimento su cui basano le loro deduzioni è il seguente: un fascio di luce, proveniente da una sorgente (denotata con S, figura 1.8), viene diviso da uno specchio semitrasparente (BS1) in due fasci (T ed R) che percorrono due diverse distanze; i due fasci, a loro volta, vengono fatti incidere su un secondo specchio semitrasparente (BS2), dal quale emergono, per sovrapposizione, altri due fasci che vengono rivelati da due detector D1 e D2 (figura 1.8). La MQ è in grado di predire quante volte scatta ciascun detector se si esegue l'esperimento per un tempo molto lungo, ma non può dire quale dei due detector sarà il prossimo a scattare (ved. Zeilinger il problema del singolo evento). Secondo Suarez-Scarani non è possibile trovare una spiegazione causale che ci indichi un ordine dei vari clicks dei detectors. Tale ordine ha una provenienza esterna allo spazio-tempo. Si

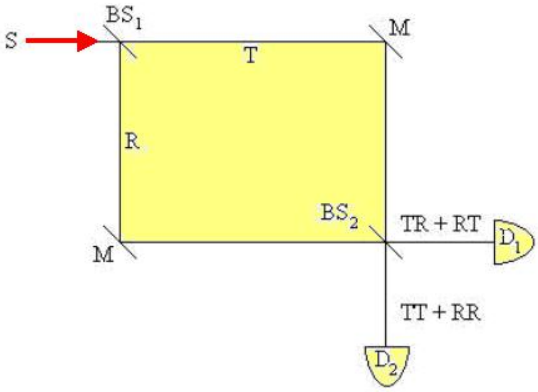


Figure 1.8: Suarez-Scarani Experiment.

rimanda a nuove "entità" esterne fuori dallo spaziotempo la sua spiegazione. Un terreno che dovranno affrontare, secondo Suarez, filosofi e forse teologi nei prossimi anni.

1.0.15 Entanglement degli stati temporali.

Bruker (Brukner et al,2004) hanno teoricamente dimostrato (si attendono i riscontri sperimentali) che è possibile porre in uno stato entangled anche gli istanti di tempo. Effettuando misurazioni successive su uno stato quantistico, essi hanno trovato che una seconda misura ad un istante t2 influenza (caso di fotoni polarizzati) il modo in cui lo stesso stato veniva polarizzato nell'istante precedente t1. In questo lavoro del 2004, essi hanno derivato le disuguaglianze di Bell temporali, partendo da due assunzioni quella di realismo (classico) e località temporale. Secondo gli autori la MQ viola tali disuguaglianze. La MQ sarebbe in contrasto con tali assunzioni. Vediamo di analizzare più in dettaglio tale risultato. Da un punto di vista formale e concettuale, lo spazio ed il tempo sono descritti in modo diverso nella MQ. Mentre il tempo è un parametro esterno alla dinamica (evoluzione del sistema) della MQ, le coordinate spaziali sono considerate osservabili in MQ. Inoltre il concetto di non-località, come è inteso nella letteratura scientifica, è una peculiarità degli stati composti entangled, questi stati non-separabili sono indipendenti dalla separazione spaziale dei suoi componenti. In questo caso parliamo di entanglement nello spazio. La località (spaziale) e il realismo come abbiamo visto impongono dei precisi vincoli, le famose disuguaglianze di Bell, che la MQ viola, con tutte le sue importanti applicazioni tecnologiche. In analogia con le assunzioni da cui deriviamo le disuguglianze di Bell (spaziali), Brukner et al. derivano le disuguglianze di Bell temporali. L'analisi viene fatta su un singolo sistema sottoposto a più misure in diverse istanti di tempo. Le assunzioni da cui essi partono sono le seguenti:

- 1) Realismo: i risultati di una misura sono determinati da proprietà nascoste che le particelle hanno già prima ed indipendente dalla loro osservazione;
- 2) Località nel tempo, i risultati di una misura eseguita al tempo t2 sono indipendenti da qualsiasi misura eseguita (precedente o successivamente) al tempo t1.

Gli autori osservano che contrariamente alle correlazioni spaziali, dove i vincoli della relatività ristretta vengono invocati al fine di garantire la località nello spazio, per le assunzioni di località temporali questo principio non esiste. In altre parole, non abbiamo vincoli per garantire la località nel tempo. Questo lavoro ci proietta ad indagare nuove relazioni tra la struttura dello spazio e del tempo nel formalismo della MQ. Da tale violazione (località temporale), possiamo dedurre che, la struttura spaziale e quella temporale devono convogliare in una teoria più profonda, in cui i due devono essere trattati su un piano paritario (la Quantum Field Theory non è sufficiente per questo). Bisogna ancora indagare per capire come i due (tipi) entanglement spaziali e temporali se relazionano tra loro. Per concludere ci sembra di capire che sia la nozione stessa di causalità ad essere messa seriamente in discussione.

1.1 La struttura della tesi

La struttura della tesi è rappresentata nella seguente figura. La nostra ipotesi di fondo è che l'EQ rappresenti un elemento base della possibile realtà fisica sottostante. Come sappiamo a causa della linearità della MQ, il fenomeno dell'entanglement discende direttamente dal principio di sovrapposizione. I passi che seguiremo nella tesi sono i seguenti:

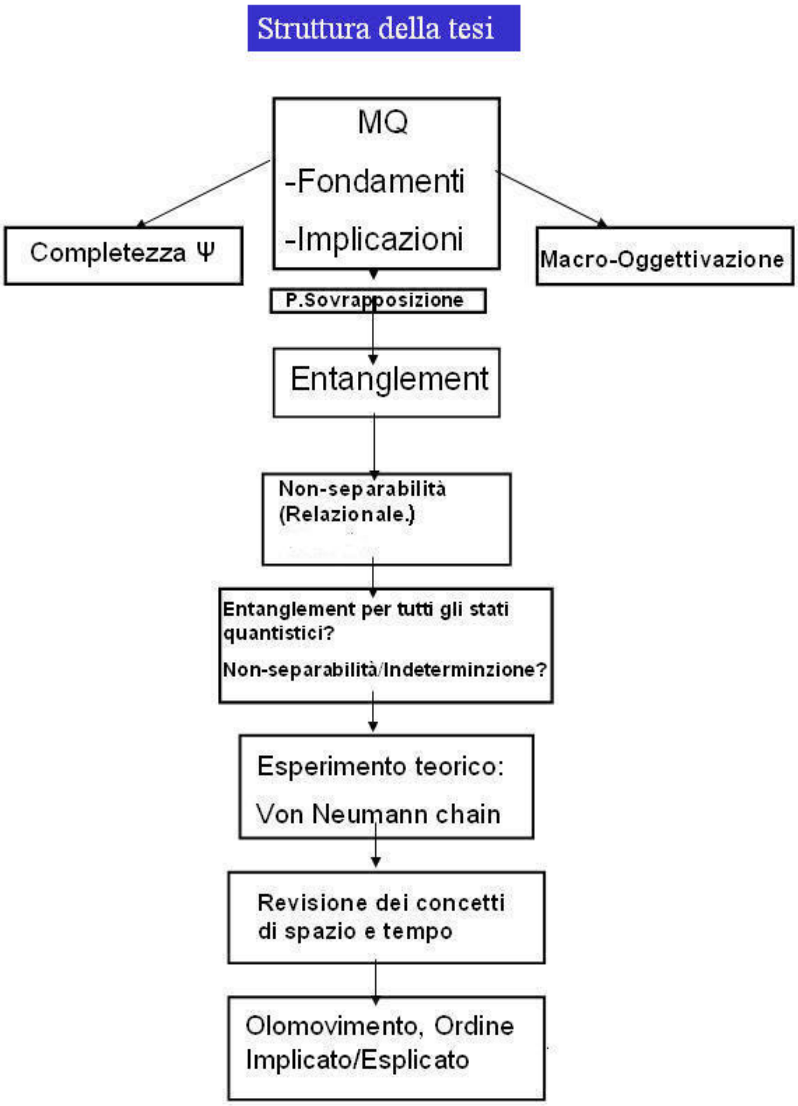


Figure 1.9: La struttura della tesi.

- 1) L'Entanglement (per sistemi quantistici separati spazialmente) implica⇛la non-località (i.e. cioè i sistemi non sono separabili).

- 2) La non-separabilità ci conduce⇛ad una visione Relazionale dei sistemi quantistici.

- 3) Si sostiene che l'entanglement è un fenomeno diffuso e presente in tutti i sistemi quantistici.
- 4) Viene proposto un esperimento teorico (grazie al cammino di von Neumann) in cui l'entanglement gioca un ruolo fondamentale. Esso ci consente di trovare un collegamento tra l'ordine esplicato e l'ordine implicato teorizzato da Bohm.
- 5) Tale risultato ben si sposa con le dimostrazioni di Suarez e Brukner, in cui si sostiene che non-località è un fenomeno che avviene al di fuori dello spazio-tempo e che il tempo stesso deve essere visto come semplice osservabile.
- 6) Nel contesto così delineato sono da rivedere i concetti di spazio e tempo: essi devono essere messi sullo stesso piano.
- 7) Queste conclusioni erano già note da tempo nella filosofia Indiana, come nello Shivaismo del Kashmir e precisamente nello Spanda-Kārikā di Abhinavagupta.

Nella figura seguente, viene proposto in sintesi uno degli obbiettivi della tesi: l'ordine implicato teorizzato da Bohm, emerge naturalmente dal cammino di von Neumann. Nel capitolo 8 sarà proposto un esperimento teorico a supporto di tale tesi.

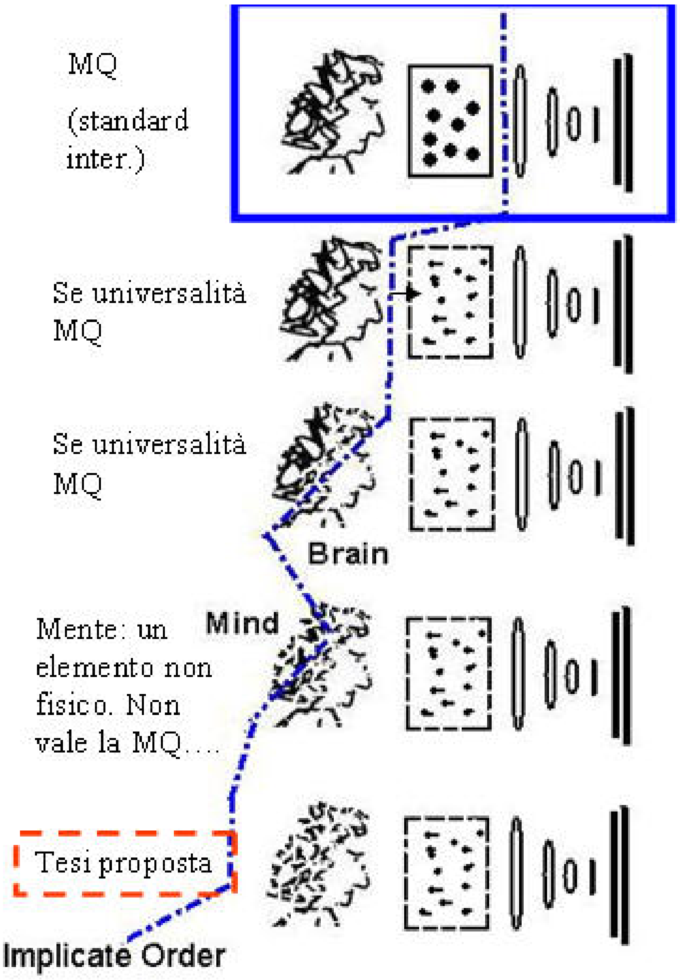


Figure 1.10: Implicate Order individuato dal cammino di von Neumann.

2

PART 1: Formal Structure and Interpretations of Quantum Mechanics

We start with a basic philosophical question that involves physics and epistemology: can we explain what the world is through a fundamental physical theory? This question corresponds to the historic disagreement among scientists and epistemologists concerning how to regard physical theories to which people commonly refer as the realist/antirealist debate. The position of the antirealist is the one according to which we should not believe that physics reveals to us something about reality but rather we should be content with physics to be, for example, just empirically adequate. In contrast, the realist is strongly inclined to say not only that physics tells us about reality, but also that it is our only way to actually do metaphysics. In few words, the question is: is there an ontology? We are interested to show through a logical pathway the existence of a possible ontology in Nature, assuming two basic hypotheses which the Greek thinkers made about Nature: 1) the existence of a real external world, 2) this external world is accessible through the existence of laws of nature(the reality is intelligible).

The abstract mathematical structure of the Lorentz transformations was deduced through simple physical principles. Thanks to the existence of these physical principles we do not have a significant debate on the interpretation of the theory of special relativity. The formulation of QM, on to the contrary, is based on a number of rather abstract axioms without a clear motivation for their existence (see the following Primas' synthesis, 2003):

1. Quantum mechanics refers to individual objects.
2. The probabilities of quantum mechanics are primary.
3. The placement of the cut between observed object and the means of observation is left to the choice of the experimenter.
4. The observational means are to be described in classical terms.
5. The act of observation is irreversible.
6. The quantum jump is a transition from the potentially possible to the actual.
7. Complementary properties cannot be revealed simultaneously.
8. Pure quantum states are objective but not 'real.'

Despite its success, the absence of elementary physical principles has determined a broad discussion about the interpretation of the theory. For this reason, and not only, Bell called the ordinary QM with the abbreviation FAPP (for all practical purposes). We will start presenting in this chapter, first, the basic formalism and postulates of QM, and will continue our overview by presenting main features of historical interpretations of QM. Historically QM began with two mathematical formulations, Heisenberg's Matrix Mechanics and Schrödinger's Wave Mechanics, and these were later found by Schrödinger to be mathematically equivalent. John von Neumann, in 1926, realized that a quantum system (QS) could be represented as a vector in Hilbert space, which lead to his development of an axiomatized formulation of quantum theory (von Neumann, 1932). The central feature of quantum theory is the wavefunction (ψ), which represents the state of a particle or system. Schrödinger tried a realist interpretation of ψ. Schrödinger's initial conception of the wavefunction was an extended volume charge (the "mechanical field scalar") that was centered on the atom. This interpretation had several problems, the most important of which was the continued experimental support for the notion that the electron was localized over a very small region of space, as if a point. For this and other reasons, Schrödinger later rejected his model (and its interpretations) and continued searching for a better theory.

In 1926-27, Louis de Broglie offered an interpretation he called the "double-solution" in which a particle is a singularity in a wave field (Jammer, 1974). Here, the particle retains much of its classical nature, but it is "guided" by an extended pilot wave given by Schrödinger's formalism, and thus subject to wave effects such as diffraction. This synthesis of wave and particle views would later be expanded upon by both David Bohm and John Bell. Another major class of interpretations are those that assume the formalism of quantum theory but reject that the wavefunction offers a complete description of a QS. Notably the theory of David Bohm postulates hidden variables that guide a QS according to deterministic laws (Bohm, 1951). Although Bohm's work presented a different explanation for quantum phenomena, it was criticized for offering no predictive value outside of the standard interpretation of quantum theory. However, Bohm argued that on a small enough scale, his interpretation might offer predictable discrepancies (Jammer, 1974). As we know, the most widely accepted interpretation of the formalism is Born's statistical interpretation, published in 1926. Born sought to account for the empirical results that the electron was a localized particle (corpuscle) but otherwise wanted to take advantage of Schrödinger's formalism. As a result, he interpreted the wavefunction as the probability density of finding a particle within a specific region. Standardly interpreted, particles do not possess discrete dynamical properties such as position, momentum, or energy, until the particle is measured. The probability of measuring a particular value is given by the statistical interpretation of the wavefunction, i.e. it is normalized and the probability is determined by the resulting distribution. Upon measurement, the wave function is said to collapse such as to yield a particular value of the measured dynamical property. Some problems arise within this interpretation respect a scientific realism view. The central premise of scientific realism is the existence of an external world independent of consciousness. Yet, the statistical interpretation of the wavefunction poses a problem, in that it offers no description of the state of a system before it is measured. It merely gives statistical information regarding the result of a measurement on the system. A scientific realist is prone to believing that a concrete state must exist before measurement. What actually constitutes this state is open to some discussion, but a realist will typically hold that a singular physical state exists; and that an experiment measures that state. Another serious problem for scientific realism is the phenomenon of quantum entanglement (QE). Such nonlocal interactions are not prima facie worrisome for most scientific realists. The implications are troubling when it is recognized that special relativity is the limiting velocity for any kind of causal propagation, and nonlocality violates special relativity. But the form of interaction between these particles is rather unlike other forms of causal contact, since information cannot be sent from one particle to another. The behavior of the particles is statistical, but correlated such that they are believed to interact during measurement. Thus, some hypothesize that this is an allowed form of superluminous interaction (Griffiths, 2003). In this field today, there are many works with the objective to find a causal correlation between two entangled particles. We argue in this thesis that is not possible to reintroduce the classical causality.

2.1 Basic formalism and postulates of quantum mechanics.

QM is a mathematical model of the physical world that describes the behavior of QS. A physical model is characterized by how it represents *physical states*, *observables*, *measurements*, and *dynamics* of the system under consideration. A quantum description of a physical model is based on the following concepts:

A *state* is a complete description of a physical system. QM associates a ray in *Hilbert space* to the physical state of a system.

- Hilbert space is a complex linear vector space. In Dirac's ket-bra notation states are denoted by *ket vectors* $|\psi\rangle$ in Hilbert space.
- Corresponding to a ket vector $|\psi\rangle$ there is another kind of state vector called *bra vector*, which is denoted by $\langle\psi|$. The *inner product* of a bra $\langle\psi|$ and ket $|\phi\rangle$ is defined as follows:

$$\begin{aligned}\langle\psi|\{|\phi_1\rangle + |\phi_2\rangle\} &= \langle\psi \mid \phi_1\rangle + \langle\psi \mid \phi_2\rangle \\ \langle\psi|\{c\,|\phi_1\rangle\} &= c\,\langle\psi \mid \phi_1\rangle\end{aligned} \tag{2.1}$$

  for any $c \in \mathbf{C}$, the set of complex numbers. There is a one-to-one correspondence between the bras and the kets. Furthermore

$$\begin{aligned}\langle\psi \mid \phi\rangle &= \langle\phi \mid \psi\rangle^* \\ \langle\psi \mid \psi\rangle &> 0 \text{ for } |\psi\rangle \neq 0\end{aligned} \tag{2.2}$$

- The state vectors in Hilbert space are normalized which means that the inner product of a state vector with itself gives unity, i.e.,

$$\langle\psi \mid \psi\rangle = 1 \tag{2.3}$$

- Operations can be performed on a ket $|\psi\rangle$ and transform it to another ket $|\chi\rangle$. There are operations on kets which are called *linear operators*, which have the following properties. For a linear operator $\hat{\alpha}$ we have

$$\begin{aligned} \hat{\alpha}\left\{|\psi\rangle + |\chi\rangle\right\} &= \hat{\alpha}\,|\psi\rangle + \hat{\alpha}\,|\chi\rangle \\ \hat{\alpha}\left\{c\,|\psi\rangle\right\} &= c\hat{\alpha}\,|\psi\rangle \end{aligned} \tag{2.4}$$

for any $c \in \mathbf{C}$.

- The sum and product of two linear operators $\hat{\alpha}$ and $\hat{\beta}$ are defined as:

$$\begin{aligned} \left\{\hat{\alpha} + \hat{\beta}\right\}|\psi\rangle &= \hat{\alpha}\,|\psi\rangle + \hat{\beta}\,|\psi\rangle \\ \left\{\hat{\alpha}\hat{\beta}\right\}|\psi\rangle & \end{aligned} \tag{2.5}$$

  Generally speaking $\hat{\alpha}\hat{\beta}$ is not necessarily equal to $\hat{\beta}\hat{\alpha}$, i.e. $\left[\hat{\alpha}, \hat{\beta}\right] \neq 0$

- The *adjoint* $\hat{\alpha}^{\dagger}$ of an operator $\hat{\alpha}$ is defined by the requirement:

$$\langle\psi \mid \hat{\alpha}\chi\rangle = \left\langle\hat{\alpha}^{\dagger}\psi \mid \chi\right\rangle \tag{2.6}$$

  for all kets $|\psi\rangle$, $|\chi\rangle$ in the Hilbert space.

- An operator $\hat{\alpha}$ is said to be *self-adjoint* or *Hermitian* if:

$$\hat{\alpha}^{\dagger} = \hat{\alpha} \tag{2.7}$$

Hermitian operators are the counterparts of real numbers in operators. In QM, the dynamical variables of physical systems are represented by Hermitian operators. These operators are usually called *observables*.

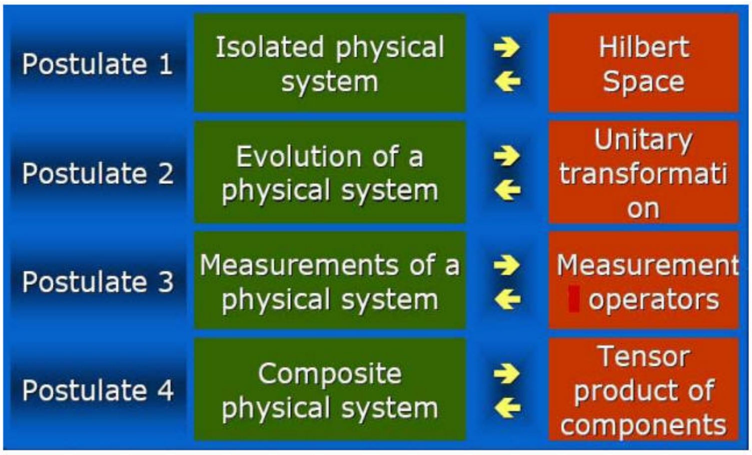
Postulates of quantum mechanics:

Quantum theory is based on the following postulates: **Postulate 1**: To any physical isolated system is associated a complex vector space, where is define an inner product (Hilbert space) which is called state space of the system. The system is completely described by a state vector.

This postulate give us the universal mathematical model of any physical system: a vector Hilbert space on the complex numbers?.

Postulate 2: The evolution of a closed QS is described by an unitary transformation. That is, the state, $|\psi(t)\rangle$ of the system at time t is related to the state $|\psi(t_0)\rangle$ a time t_0 by a unitary operator U which depends only on the time t and t_0 : $|\psi(t)\rangle = U\ |\psi(t_0)\rangle$.
The second postulate describes the temporal evolution of a closed physical system.
Postulate 3: *This postulate is about the "quantum measurement? ":*

- Mutually exclusive measurement outcomes correspond to orthogonal *projection operators* $\left\{\hat{P}_0,\ \hat{P}_1, ...\right\}$ and the probability of a particular outcome i is $\left\langle\psi \mid \hat{P}_i \mid \psi\right\rangle$. If the outcome i is attained the (normalized) quantum state after the measurement becomes:



Postulate 1	Isolated physical system	→ ←	Hilbert Space
Postulate 2	Evolution of a physical system	→ ←	Unitary transformation
Postulate 3	Measurements of a physical system	→ ←	Measurement operators
Postulate 4	Composite physical system	→ ←	Tensor product of components

Figure 2.1: Quantum Postulates

$$\frac{\hat{P}_i\,|\psi\rangle}{\sqrt{\langle\psi \mid P_i \mid \psi\rangle}}. \tag{2.8}$$

Measurement made with orthogonal projection operators $\left\{\hat{P}_0,\ \hat{P}_1, ...\right\}$ is called *projective measurement.*
Postulate 4: The state space of a composite physical system is the tensor product of the state spaces of the component physical systems. Moreover, if we have a QS $H_i, i = 1, ...n$ and system H_i is prepared in the state $|\psi_i\rangle$, then the joint state of the total system is: $|\psi_1\rangle\otimes\ |\psi_2\rangle\ \otimes.......\otimes\ |\psi_n\rangle\ = H_1\ \otimes.......\otimes H_n$.
Last postulate formalizes the interaction of many physical systems with the combination of different Hilbert spaces coming to a unique Hilbert space.

2.2 The EPR Argument: Objective Reality?

The Einsteinian research programme can be summarized in the following way:

> **Physical theories are attempts at saying how things are. The world is comprehensible.**

The above statement is a very general one, indeed this statement seems to be not enough to characterize uniquely Einstein's programme. In fact, that statement is also perfectly adaptable to the Galilean, Cartesian, Newtonian, Leibnizian, Maxwellian and several other scientific programmes. According to Einstein, quantum objects are concrete entities existing in a space-time where causality holds. In the following statement the Einstein's thought is more precise:

> Physical theories (including QM) are attempts at saying how things are (including quantum objects). The objective world is comprehensible. By the simultaneous help of space-time and causal conceptual categories we can study this comprehensible world.

To make explicit Einstein's claims in favor of objectivity and independence of reality[1]. In this framework we need to insert the EPR argument. In EPR work they demonstrated an inconsistency between the premises that go under the name of *local realism* and the notion that QM is complete. EPR never regarded it as a paradox, but as an argument to prove the incompleteness of QM.

A passage in a letter from Einstein to Max Born, dated March 24, 1948, illuminates some of the key issues for Einstein that lie behind the EPR paradox and what is at issue for him in his commitment to separability:

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[1] Instead, Bohr's scientific research programme can be summarized in the following way: Classical theories are attempts at saying how things are. The objective classical world is comprehensible. By using both space-time and causal categories we can study the classical world, but not the quantum world. According to Bohr, quantum phenomena are not comprehensible in the same sense as classical phenomena. In classical physics, objects are spatial and temporal entities that are ruled by causal laws. In this way, classical phenomena are comprehensible according to causal laws (conservation laws) in space-time. Thus in a classical context, the conceptual categories of space-time and cause can be used together to study physical phenomena. However, according to Bohr the situation changes drastically when we are dealing with quantum phenomena. In microphysics, the categories of space-time and cause can be used only in a mutually exclusive manner, according to Bohr's complementarity principle. According Bohr, quantum theory must be interpreted, not as a description of nature itself, but merely as a tool for making predictions about observations appearing under conditions described by classical physics. In other words, although **quantum phenomena cannot be described by simultaneous use of the space-time and causal concepts**, the use of these and other classical physics concepts is unavoidable.

> I just want to explain what I mean when I say that we should try to hold on to physical reality [....] That which we conceive as existing ("actual") should somehow be localized in time and space. That is, the real in one patt of space, A, should (in theory) somehow "exist" independently of that which is thought of as real in another part of space, B [....] What is actually present in B should thus not depend upon the type of measurement carried out in the part of space, A; it should also be independent of whether or not, after all, a measurement is made in A [... .]

Einstein maintained a belief in separability[2]as the very condition for the possibility of objectivity. According Howard, (Howard, 2007) Einstein's belief in separability in terms of a literal externality relation, the spatial separation between observer and observed:

> Like so many realists before him, Einstein speaks of the real world which physics aim to describe as the real "external" world, and he does so in such a way as to suggest that the independence of the real, its not being dependent in any significant way on ourselves as observers-is grounded in this "externality." For most other realists this talk of "externality" is at best a suggestive metaphor. But for Einstein, it is no metaphor. "Externality" is a relation of spatial separation, and the separability principle, the principle of "the mutually independent existence of spatially distant things," asserts that any two systems separated by so much as an infinitesimal spatial interval always possess separate states. Once we realize that observer and observed are themselves just previously interacting physical systems, we see that their independence is grounded in the separability principle along with the independence of all other physical systems.

In this first part of thesis, will be analyzed the EPR argument in detail because it contains the primitive notion of local causality used in discussions of Bell's theorem and the notion of quantum non-separability (Cavalcanti, 2008).
The original EPR paradox was based on position and momentum observables. Bohm in 1951 extended the example of EPR to the case of discrete observables (the case of two spin-1/2 particles). That is the version that was used by Bell in deriving his famous inequalities. It has played a central role in our understanding of QE. Both the original argument of EPR and Bohm's version, however, rely on perfect

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[2] Bohr rejects the separability condition.For Bohr, the quantum postulate and the material embodiment of concepts are at the root of quantum nonseparability (what Bohr often refers to as the "individuality" of phenomena).

correlations. For EPR-entanglement, local realism can only be reconciled with QM if one accepts the existence of an underlying localized *hidden variable* (non-quantum) state. In few words, **if one can accept *only quantum* states, then the EPR correlation implies nonlocal effects**[3]**.**

The EPR paper starts (see below quotation) with a distinction between reality and the concepts of a theory, followed by a critique of the operationalist position (the Copenhagen school).

> "Any serious consideration of a physical theory must take into account the distinction between the **objective reality, which is independent of any theory**, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves. In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) 'Is the theory correct?' and (2) 'Is the description given by the theory complete?' It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience.

EPR argue that we must distinguish those concepts from the reality they attempt to describe. One can see the physical constructs of the theory as mere calculational tools (operationalist position or FAPP). But according EPR the theory must

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[3] As we will see in details, in QM the term "nonlocality" refers to the failure of a certain relativity-theory-based locality assumption. This assumption is that no information about which experiment is freely chosen and performed in one spacetime region can be present in a second spacetime region unless a point traveling at the speed of light (or less) can reach some point in the second region from some point in the first. This assumption is valid in relativistic classical physics. Yet quantum theory permits the existence of certain experimental situations in which this information-based locality assumption fails. The simplest of the experiments pertinent to this issue involve two measurements performed in two spacetime regions that lie so far apart that nothing traveling at the speed of light or less can pass from either of these two regions to the other. We will see that Bell's work, based on EPR argument, refer only to performable actions and observable outcomes. Bell's work do not analyze any notions of "microscopic", "invisible", or other "hidden variables". The assumptions are expressed at the macroscopic level. These assumptions cannot be consistently reconciled with the predictions of QM. Bell (1971) and others (Clauser et al,1969) went on to consider, instead of deterministic local hidden-variable theories, rather probabilistic local hidden variable theories. But, as shown by Stapp (1978), and independently by Fine (1982), this change does not substantially change the situation, because the two detailed formulations are equivalent.

strive to furnish a complete picture of reality. The position **advocated by Einstein, is that the existence of physical events is independent of observers or reference frames and that those events can be associated to points in a relativistic space-time**. This framework makes explicit, as EPR desired, that events are among those things which are part of the objective reality[4], which is independent of any theory. EPR follow the previous considerations with a *necessary condition for completeness:*

> **EPR's necessary condition for completeness:** "Whatever the meaning assigned to the term *complete,* the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory.*".

After they they note that this condition only makes sense if one is able to decide what are the elements of the physical reality. Contrary to a common belief, they did not then attempt to *define* element of physical reality. Instead, they provide a *sufficient condition of reality*:

> **EPR's sufficient condition for reality: "The elements of the physical reality cannot be determined by *a priori* philosophical considerations**, but must be found by an appeal to results of experiments and measurements. A comprehensive definition of reality is, however, unnecessary for our purpose. We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.*".

EPR follow the analysis and they explicit a criterion that can be "regarded not as a necessary, but merely as a sufficient, condition of reality". This is followed by a discussion that, in QM, if a system is in an eigenstate of an operator A with eigenvalue a, by this criterion, **there must be an element of physical reality corresponding to the physical quantity** A. "On the other hand", they continue, if the state of the system is a superposition of eigenstates of A, "we can no longer speak of the physical quantity A having a particular value". After a few more considerations, they state that "the usual conclusion from this in QM is that *when*

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[4] Regarding the objective reality, the quantum non-locality denies the philosophical thesis that reality can be fully understood; and it seems to rejects the philosophical principle of sufficient reason, which goes back to classical Greek philosophy and says that every event has a cause.

the momentum of a particle is known, its coordinate has no physical reality". We are left therefore, according to EPR, with two alternatives:

> **EPR's central dilemma:** "From this follows that either (1) *the quantum-mechanical description of reality given by the wave function is not complete* or (2) *when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality.*

They justify this by reasoning that "if both of them had simultaneous reality, and thus definite values,these values would enter into the complete description, according to the condition for completeness". And in the crucial step of the reasoning: "If then the wave function provided such a complete description of reality it would contain these values (i.e. these would then be predictable).

2.3 Quantum Entanglement, Bell Inequality

The phenomenon of QE is widely considered to be central to the field of quantum computation and information. This phenomenon can be traced back. As we have seen, EPR argued that quantum mechanical description of *physical reality* can not be considered *complete* because of its rather strange predictions about two particles that once have interacted but now are separate from one another and do not interact. QM predicts that the particles can be *entangled* even after separation. Entangled particles have correlated properties and these correlations are at the heart of the EPR paradox. Mathematically, the entanglement is described as follows. For a system that can be divided into two subsystems QM associates two Hilbert spaces $\mathcal{H}_A$ and $\mathcal{H}_B$ to the subsystems. Assume that $|i\rangle_A$ and $|j\rangle_B$ (where $i, j = 1, 2, ...$) are two complete orthonormal basis sets for the Hilbert spaces $\mathcal{H}_A$ and $\mathcal{H}_B$, respectively. The tensor product $\mathcal{H}_A \otimes \mathcal{H}_B$ is another Hilbert space that QM associates with the system consisting of the two subsystems. The tensor product states $|i\rangle_A \otimes |j\rangle_B$ (often written as $|i\rangle_A |j\rangle_B$) span the space $\mathcal{H}_A \otimes \mathcal{H}_B$. Any state $|\psi\rangle_{AB}$ of the composite system made of the two subsystems is a linear combination of the product basis states $|i\rangle_A |j\rangle_B$ i.e.:

$$|\psi\rangle_{AB} = \sum_{i,j} c_{ij} |i\rangle_A |j\rangle_B \tag{2.9}$$

where $c_{ij} \in \mathbf{C}$. The normalization condition of the state $|\psi\rangle_{AB}$ is $\sum_{i,j} |c_{ij}|^2 = 1$. The state $|\psi\rangle_{AB}$ is called *direct product* (*or separable*) *state* if it is possible to factor it into two normalized states from the Hilbert spaces $\mathcal{H}_A$ and $\mathcal{H}_B$. Assume that $\left|\psi^{(A)}\right\rangle_A = \sum_i c_i^{(A)} \left|i\right\rangle_A$ and $\left|\psi^{(B)}\right\rangle_B = \sum_j c_j^{(B)} \left|j\right\rangle_B$ are the two normalized states from $\mathcal{H}_A$ and $\mathcal{H}_B$, respectively. The state $\left|\psi\right\rangle_{AB}$ is a direct product state when:

$$\left|\psi\right\rangle_{AB} = \left|\psi^{(A)}\right\rangle_A \left|\psi^{(B)}\right\rangle_B = \left(\sum_i c_i^{(A)} \left|i\right\rangle_A\right)\left(\sum_j c_j^{(B)} \left|j\right\rangle_B\right) \tag{2.10}$$

Now a state in $\mathcal{H}_A \otimes \mathcal{H}_B$ is called *entangled* if it is not a direct product state. In other words, entanglement describes the situation when the state of 'whole' cannot be written in terms of the states of its constituent 'parts'. Generally, it is a very hard problem to decide whether a quantum state is entangled or not. Fortunately, there are operational criteria, relying on measurements of correlations, with a possible outcome from which one can conclude that the state is entangled: the Bell inequality. A Bell inequality is satisfied by all states which are not entangled. Thus, if a violation of a Bell inequality is observed the state which describes the results is entangled. Interestingly, Bell inequalities were first introduced in a context of **foundations of QM**. Not only, Bell inequalities was a relations between conditional probabilities valid under the locality assumption. Hence, apriori they have nothing to do with quantum physics (and thus should not be written using quantum operators). However, it is the fact that quantum physics predicts a violation of these relations that makes them interesting. The original Bell inequality is, strictly speaking, not a Bell inequality according to the modern terminology. The original inequality required, besides locality, another assumption about perfect correlations. Shimony[5]recognized that this auxiliary assumption made the entire enterprize non testable and searched for an inequality involving only measurable quantities. This led him and his co-workers to find the CHSH inequality. Speaking about Bell inequality, QM gives predictions in form of probabilities. Already some of the fathers of the theory were puzzled with the question whether there can exist a deterministic structure beyond QM which recovers quantum statistics as averages over "hidden variables". In this way, it was hoped, one could get a classical-like description which would solve the problems with the interpretations of QM. In his famous impossibility proof Bell made precise assumptions about the form of a possible underlying hidden variable structure. Spatially separated systems and laboratories were assumed to be independent of one another. He derived an inequality which must be satisfied by all such (local realistic) structures. Next, he presented example of quantum predictions which violate it. In this way the famous Einstein-Podolsky-Rosen (EPR,1935) paradox was solved. Bell proved that EPR elements of reality cannot be used to

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[5] In 1983, Abner Shimony invented the expression, "passion at a distance," to characterize the distinctive relationship of two entangled quantum mechanical systems

describe quantum mechanical systems.The noncommutativity of quantum theory precludes simultaneous deterministic predictions of measurement outcomes of complementary observables. For EPR this indicated that "the wave function does not provide a complete description of "physical reality". They expected the complete theory to predict outcomes of all possible measurements, prior to and independent of the measurement (realism), and not to allow “spooky action at a distance” (locality). A more general version of Bell’s theorem for two qubits (two-level systems) was given by Clauser, Horne, Shimony, and Holt (CHSH, 1969), and extended by Clauser and Horne (CH)(Clauser et al, 1969). The important feature of the CHSH and CH inequalities, which hold for *all* local realistic theories, is that they can not only be compared with ideal quantum predictions, but also with experimental results. The three or more qubit versions of Bell’s theorem were presented by Greenberger, Horne, and Zeilinger (GHZ) (Greenberg et al. 1990). Starting from the assumptions of realism and locality, in 1964 Bell derived an inequality which was shown later to be violated by the quantum mechanical predictions for entangled states of a composite system. As we have seen, Bell’s theorem (Peres, 1993) is the collective name for a family of results, all showing the impossibility of local realistic interpretation of QM. Later work (Peres, 1993)has produced many different types of Bell-type inequalities. The Bell inequality is expressed as follow: let $A(a)$ and $A(a')$ be the two observables for observer A in the an EPR experiment. Similarly, let $B(b)$ and $B(b')$ be the two observables for the observer B. In general, the observables $A(a)$ and $A(a')$ are incompatible and cannot be measured at the same time, and the same holds for $B(b)$ and $B(b')$. It is assumed that the two particles that reach observers A and B in EPR experiments possess hidden variables which fix the outcome of all possible measurements. These hidden variables are collectively represented by λ, assumed to belong to a set Λ with a probability density $\rho(\lambda)$. The normalization implies:

$$\int_{\Lambda} \rho(\lambda) d\lambda = 1. \tag{2.11}$$

Because a given λ makes the four dichotomic observables assume definite values, we can write:

$$A(a,\lambda) = \pm 1; \quad A(a',\lambda) = \pm 1; \quad B(b,\lambda) = \pm 1; \quad B(b',\lambda) = \pm 1 \tag{2.12}$$

That is, the physical reality is marked by the variable λ. Now introduce a *correlation function* $C(a,b)$ between two dichotomic observables a and b, defined by:

$$C(a,b) = \int_{\Lambda} A(a,\lambda)B(b,\lambda)\rho(\lambda)d\lambda \tag{2.13}$$

For a linear combination of four correlation functions, define *Bell's measurable quantity* Δ as:

$$\Delta = C(a,b) + C(a',b') + C(a',b) - C(a,b') \tag{2.14}$$

Only four correlation functions, out of a total of sixteen, enter into the definition of Δ. We can write:

$$\begin{aligned}&\left|C(a,b) + C(a',b') + C(a',b) - C(a,b')\right| \\ &\leq \int_{\Lambda} \left\{|A(a,\lambda)| \left|B(b,\lambda) - B(b',\lambda)\right| + \left|A(a',\lambda)\right| \left|B(b,\lambda) + B(b',\lambda)\right|\right\} \rho(\lambda)d\lambda.\end{aligned} \tag{2.15}$$

Since:

$$|A(a,\lambda)| = \left|A(a',\lambda)\right| = 1 \tag{2.16}$$

we have:

$$\begin{aligned}&\left|C(a,b) + C(a',b') + C(a',b) - C(a,b')\right| \\ &\leq \int_{\Lambda} \left\{\left|B(b,\lambda) - B(b',\lambda)\right| + \left|B(b,\lambda) + B(b',\lambda)\right|\right\} \rho(\lambda)d\lambda\end{aligned} \tag{2.17}$$

Also $|B(b,\lambda)| = |B(b',\lambda)| = 1$, so that:

$$\left|B(b,\lambda) - B(b',\lambda)\right| + \left|B(b,\lambda) + B(b',\lambda)\right| = 2 \tag{2.18}$$

and the inequality (2.17) reduces to:

$$\left|C(a,b) + C(a',b') + C(a',b) - C(a,b')\right| \leq 2 \tag{2.19}$$

which is called CHSH form (CHSH, 1969) of Bell's inequality.

2.4 What are the problems?

QM was initially formulated in what appeared to be two fundamentally distinct ways, as Matrix mechanics, and Wave mechanics with the function ψ. The former developed by Heisenberg, Born and Jordan and the latter by Schrödinger. Dirac, Jordan, Pauli, and Schrödinger subsequently provided arguments for the equivalence of these two approaches. From a technical point of view, QM is a set of mathematically formulated prescriptions that serve for calculations of probabilities of different measurement outcomes. The calculated probabilities agree with experiments. But most serious problems that QM would have to face was its inability to demarcate with mathematical precision just where microscopic processes leave off and where macroscopic processes begin[6]. This ambiguity has played an important role in the debate since 1930 in QM. Many of the solution proposed to rescue the formalism (from Bohr to von Neumann, and Wigner to more recent attempts) **are based on the possibility of setting this line of demarcation at any point one pleases**[7]. The explicit consideration of such interpretation of the quantum formalism can be historically traced back at least to Einstein's consideration at the 1927 Solvay conference of two alternative understandings of quantum theory, which he called "interpretation I" (his own proto-interpretation, in which the quantum description is an incomplete one for the specification of state for individual systems) and "interpretation II" (Bohr's interpretation, in which the quantum description is understood to be as complete a description of quantum phenomena as can be given). This distinction reflects Einstein's philosophical preoccupations and a fundamental disagreement with Bohr. Mittelstaedt has identified, in addition to the Copenhagen interpretation, three classes of interpretation that he has identified as probably the most important:

- the Minimal interpretation, which "does not assume that measuring instruments are macroscopic bodies subject to the laws of classical physics. Instead they are considered proper quantum systems with respect to measuring instruments. Replaces Bohr's position with von Neumann's approach but on the other hand "refers to observed data only merely the values of a 'pointer' of a measurement apparatus"

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[6] Since the pioneering work of von Neumann, the observer of a quantum state $|S\rangle$ has been treated as a physical system that becomes entangled with $|S\rangle$. The fact that observers report definite outcomes of experiments has, therefore, been a mystery. Explanations of this mystery have supplemented QM with a wide variety of additional assumptions, **but have not questioned the fundamental premise of system: observer entanglement**. Fields (Fields,2011), proposed in his paper (as fundamental assumption for QM) to consider the "observer" not as a system, but as a functional requirement. Treating observation as a functional requirement naturally leads to the concept of a minimal observer, a concept fully formed by classical automata theory over 50 years ago. A minimal observer functions in a quantum environment exactly as would be expected for a system with finite observational and memory resources.

[7] We argue that this line of demarcation is not a problem but a resource (see chap. 8 pag.85)

- the Realist interpretation, which is similar to the minimal interpretation but "is concerned not only with measurement outcomes but also with the properties of an individual system"
- the 'Many worlds' interpretation which, like the previous two, considers QM to be universal but "avoids any additional assumption that goes beyond the pure formalism, even the very few weak assumptions that are made in the minimal interpretation"

A more recent illustration of the desire to consider the quantum formalism 'self-interpreting' is the information-focused approach vigorously advocated by Fuchs and Peres (Interpretation without interpretation for QM, 2000). They affirm:

> "*The thread common to all the nonstandard 'interpretations' is the desire to create a new theory with features that correspond to some reality independent of our potential experiments. But, trying to fulfill a classical world view by encumbering QM with hidden variables, multiple worlds, consistency rules, or spontaneous 'collapse', without any improvement in its predictive power, only gives the illusion of a better understanding. Contrary to those desires, quantum theory does not describe physical reality. What it does is provide an algorithm for computing probabilities for the macroscopic events ('detector clicks') that are the consequence of our experimental interventions. This strict definition of the scope of quantum theory is the only interpretation ever needed, whether by experimenters or theorists.*"

This position is today called: Radical Bayesian interpretation. The fact that Radical Bayesianism has appeared in the era of quantum information science is not accidental. It explicitly interprets quantum theory almost entirely as a theory of information rather than of physical objects.The revolutionary nature of quantum theory, we think is not linked to the interpretation of theory but at the observation of violations of Bell-type inequalities. This leads physicists to seek new ways of interpreting QM. Independently from philosophical position, we agree with Maudlin's words (Maudlin, 2002):

> "*Realism in philosophy of science is generally contrasted with instrumentalism or empiricism, which views assert that one can have no grounds to believe that the unobservable ontology of a theory is accurate. In this sense, theories are neither realistic nor non-realistic,*

> *only interpretations of (or better: attitudes toward) theories.[....] The beauty of Bell's theorem, of course, is that it is insensitive to the details of the theory suggested: any theory which can save the phenomena (if the phenomena include claims about the behavior of macroscopic devices located in space and time) must be non-local. Even a classical instrumentalist would be forced to accept non-locality.*"

The problem, as we have seen, is that the standard interpretation of QM, tells us nothing about the underlying reality. It provides just the essential mathematical formalism in order to make extremely accurate predictions, to compute the probabilities of different outcomes. The state vector represents our knowledge of the system, not its physics.

The basic support of the standard interpretation is that "measurement process" is an interaction between system and apparatus. This interpretation divides the world in apparatus and system but do not tell us nothing about these two "abstracts" concepts. More in details, the position regarding the measurement theory can be summarizing as following:

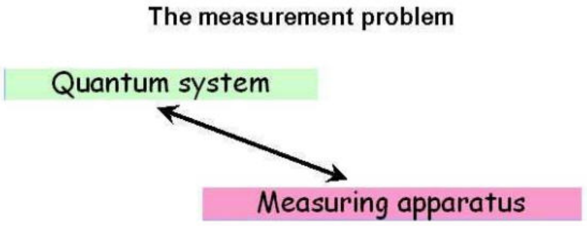


Figure 2.2: What is a measurement apparatus?

- Measurement is an interaction between system and apparatus.
- Measurements do not uncover some preexisting. physical property of a system. There is no objective property being measured.
- The record or result of a measurement is the only objective property.
- Quantum mechanics is nothing more than a set of rules to compute the outcome of physical tests to which a system may be subjected.

This interpretation solve most pragmatic problems but does not solve the measurement problem, how and why occurs the collapse of the wave function during the measurement process. The famous Schrödinger's cat paradox is exactly this. Why the measurement apparatus behave classically? After all it is constituted of particles that are governed by QM rules. Where is the limit between quantum and classical world? Next considerations put in evidence the problem. Consider a two-state microsystem whose eigenfunctions are labelled by ψ_+ and ψ_-. Furthermore, there is a macrosystem apparatus with eigenfunctions ϕ_+ and ϕ_- corresponding to an output for the microsystem having been in the ψ_+ and ψ_- states, respectively. Since prior to a measurement we do not know the state of the microsystem, it is a superposition state given by

$$\psi_0 = \alpha\psi_+ + \beta\psi_-, \qquad |\alpha|^2 + |\beta|^2 = 1. \tag{2.20}$$

Now, according to the linearity of Scrödinger's equation, the final state obtained after the interaction of the two systems is

$$\Psi_0 = (\alpha\psi_+ + \beta\psi_-)\phi_0 \longrightarrow \Psi_{out} = \alpha\psi_+\phi_+ + \beta\psi_-\phi_- \tag{2.21}$$

where it is assumed that initially the two systems are far apart and do not interact. It is obvious that, the state on the far right side of the last equation does not correspond to a definite state for a macrosystem apparatus. In fact, this result would say that the macroscopic apparatus is itself in a superposition of both plus and minus states. Nobody has observed such macroscopic superpositions. This is the so-called measurement problem, since the theory predicts results that are in clear conflict with all observations. It is **at this point** that the standard program to resolve this problem invokes the reduction of wave packet upon observation, that is,

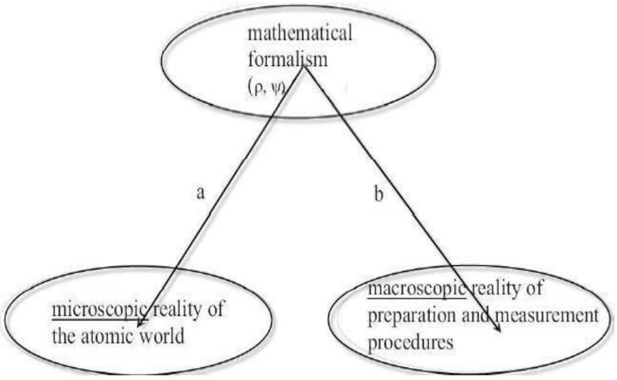
$$\alpha\psi_+\phi_+ + \beta\psi_-\phi_- \longrightarrow \begin{cases} \psi_+\phi_+, & P_+ = |\alpha|^2; \\ \psi_-\phi_-, & P_- = |\beta|^2. \end{cases} \tag{2.22}$$

Various attempts (interpretations) to find reasonable explanation for this reduction are at the heart of the measurement problem.

In relation to the standard interpretation, de Muynck (de Muynck, 2002) fix some fundamental points (see next table and figure): According to de Muynck (de Muynck, 2002) scheme, in the first realist case (a)QM is thought to describe microscopic reality most in the same way classical mechanics is generally thought to describe macroscopic reality.

In the empiricist case b) state vector and density operator are thought to correspond to preparation procedures, and quantum mechanical observables correspond to measurement procedures and the phenomena induced by a microscopic object in the macroscopically observable pointer of a measuring instrument. We mention,

Positive features	Negative features
+1. pragmatism	-1. pragmatism
+2. crucial role of measurement	-2. confusion of preparation and measurement
	-3. classical account of measurement
	-4. completeness claims
	-5. ambiguous notion of correspondence
	-6. confused notion of complementarity



Realist (a) and empiricist (b) interpretations of the mathematical formalism of quantum mechanics.

Figure 2.3: Realist (a) and empiricist (b) interpretations of the mathematical formalism of quantum mechanics.

here, another interpretation of QM called Many worlds (MWI) or relative state (see chap.3.7), this interpretation has no collapse. All possible outcomes co-exist in different branches of the 'universe'.These different branches cannot interfere or communicate in order to protect the theory itself from producing illogical situations. This theory 'resolves' the cat paradox assuming that the cat is alive in one branch and dead in the other. Also all the observers in these branches are in the states that agree with their observation of the state of the cat. Many worlds interpretation is suitable to those who try to describe the whole Universe with a wavefunction, assuming no **external observers**, and there have been serious efforts about this program.

As we have seen above, recently, with the development of quantum information theory, several scientists have given to the information a fundamental role in the description of the Nature. All these approaches (quantum theoretic description of physical systems) start in general from the assumption that we live in a world in which there are certain constraints on the acquisition, representation, and communication of information. They play on the ambiguous ontology of quantum states. They affirm that quantum states are merely states of knowledge (or of belief); this idea has led to the claim that quantum theory "needs no interpretation" (Fuchs, 2002). More in details, the field of quantum information theory opened up and expanded rapidly, QE[8]began to be seen not only as a puzzle, but also as a resource which can yield new physical effects and techniques. New insight into the foundations of quantum physics, suggesting that information should play an essential role in the foundations of any scientific description of Nature. The primitive role of the information seem to explain, according to some authors, the deep nature of physical reality. In this context, the description of a state of a QS (in this case, the measurement is **not** a physical process). The quantum state is a construct of the observer and not an objective property of the physical system. Some radical positions (Fuchs, 2002) claims that the nature of reality can be explained as subjective knowledge. On the other hand, others authors have argued that quantum theory is fundamentally just a theory of relations or of correlations?. For instance, the relational approach to probability suggest that probability should be thought of as a relation between a present and a possible future.

2.5 Interpretations of QM.

The problem linked to the collapse postulate (chap.2) is given in this term: we have to consider on the one hand the temporal evolution of the wave function **U**, provided by the rigorously causal, deterministic and time-reversal Schrödinger equation, and on the other the reduction processes of the state vector, that we call **R**. Different standpoints are possible about the role of the processes **R** in QM. We will analyze most important positions. We can individuate three main standpoints about **R**:

1. The wave function contains the available information on the physical world in probabilistic form; the wave function is not referred to an "objective reality", but due to the intrinsically relational features of the theory, only to what we can say about reality. Consequently, the "collapse postulate" is simply an expression of our peculiar knowledge of the world of quantum objects; (**this is the group of**

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[8] Entanglement recently come to play an essential role for physicists in their development of quantum information theory, moreover the entanglement of two or more states seem to be a basis for the discussion of the possible holism in quantum physics.

Copenhagen and neo-Copenhagen (de Muynck, 2002) interpretations[9])

2. The wave function describes what actually[10]happens in the physical world and its probabilistic nature derives from our perspective of observers.[**the group of Everett, (Everett, 1959), Deutsch (Deutsch, 1985), Bohm (Bohm, 1951) theories**]

3. The wave function partially describes what happens in the physical processes; in order to comprehend its probabilistic nature and the postulate R in particular, we need a theory connecting **U** and **R**. (This view includes all those theories which tend to reconcile U with R by introducing new physical process: **[**(Penrose,2005);(GRW, 2005)theories]

3. The wave function describes and represents an individual agent's subjective degrees of belief. In few words, the physical reality is a subjective information. (**Informational approaches group(Fuchs, 2002)**)

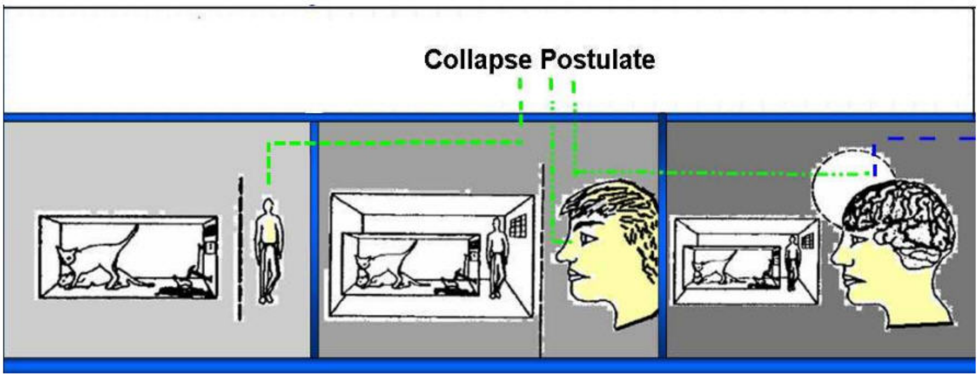

Figure 2.4: Measurement Problem.

The figure put in evidence the measurement problem through Schrödinger's cat again. The leftmost panel gives the standard Schrödinger cat story. There is a single observer, to be called Ob1, outside the box. Before Ob1 opens the window to look, the cat is in a superposition of being both alive and dead. By opening the

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[9] One of the most imposed points of view in the physicist community is to conclude that QM is merely an algorithm that provides the right answers to our questions; i.e. QM should be taken solely as an instrumentalistic theory about our observations.

[10] Realism is the assumption that there exists an objective external world independent of our perception of it. In a realistic physical theory, one thus requires a clear ontology of the basic "objects" used for example fields which are really fields, particles which are really particles, etc. Locality means that these objects are defined locally with no instantaneous action at a distance. Local realism may thus be defined by the combination of the principle of locality with the assumption that all objects must objectively have their properties already before they are observed. The paradigmatic example is that of local hidden variables.

window and looking, Ob1 "collapses the wave-packet" so that the cat is now in a unique state of being alive or dead. The story gets more interesting if we place O1 in a second box as shown in the second panel. If we, the second observer, are not looking, then O1 is in a superposition of states seeing an alive cat and seeing a dead cat. Once we make an observation, Ob1 collapses to one state or the other. The third panel removes the split even further, placing it in our brain.

A possible physical reality inferred from measurement process

We try to do a theoretical speculation on a possible relationship between the objectivity/subjectivity nature of measurement process and the underlying physical reality inferred. We build the following scheme:

Measurement process	Physical reality
1. ontic measurement ⟶	of ontic reality
2. ontic measurement ⟶	of epistemic reality
3. epistemic measurement ⟶	of ontic reality
4. epistemic measurement ⟶	of epistemic reality

Considerations. First case, is a realist position (without determinism), the second, a non-completely idealistic position, like the standard interpretation, last case is a pure idealistic view, third position is very intriguing, we do an epistemic measurement process but of ontic reality probably close d'Espagnat's conception of veiled reality(d'Espagnat 2003), a position supported from the discovery of non-separability in QM. According d'Espagnat the "veiled reality" is supported from the discovery of nonseparability in QM, he introduced the concept of the "veiled reality" which refers to something that cannot by studied by traditional scientific methods. d'Espagnat defines his philosophical view as "open realism"; existence precedes knowledge; something exists independently of us even if it cannot be described.

2.6 Interactions and von Neumann chain

The introduction of Stapp's book[11] put in evidence the fundamental problems in QM in relation to Mind/Matter problem.

According Stapp, the basic problem in the interpretation of QM is to reconcile the quantum features of the mathematics with the fact that our perceptual experiences

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[11] Mind, Matter and Quantum Mechanics, 2003

are described in the language of classical physics. Observed physical objects appear to us to occupy definite locations, and we use the concepts of everyday life, refined by the ideas of nineteenth-century physics, to describe both our procedures for obtaining information about the systems we are studying, and also the data that we then receive, such as the reading of the position of a pointer on a dial. Yet our instruments, and our physical bodies and brains, are in some sense conglomerates of atoms. The individual atoms appear to obey the laws of QM, and these laws include rules for combining systems of atomic constituents into larger systems. Insofar as experiments have been able to determine, and these experiments examine systems containing tens of billions of electrons, there is no apparent breakdown of the quantum rules. Yet if we assume that these laws hold all the way up to visible objects such as pointers, then difficulties arise. The state of the pointer would, according to the theory, often have parts associated with the pointer's being located in visibly different places. **If we continue to apply the laws right up to, and into, our brains, then our brains, as represented in QM, would have parts corresponding to our seeing the pointer in several visibly different locations.** Inclusion of the effects of the environment does not remove any of these parts, although it does make it effectively impossible to empirically confirm the simultaneous presence of these different parts. **The orthodox solution to this problem is simply to postulate, as a basic precept of the theory, that our observations are classically describable.** This postulate is incorporated into the theory by asserting that any conscious observation will be accompanied by a "collapse of the wave function" or "reduction of the wave packet" that will simply exclude from the prior physically described state all parts that are incompatible with the conscious experience. This prescription works beautifully. When combined with the rule that the probability that this perception will occur is the ratio of the quantum mechanical weighting of the reduced state to the quantum mechanical weighting of the prior state, one gets predictions never known to fail. This ad hoc injection, in association with "consciousness", of "classical" concepts into a theory that is mathematically incompatible with those concepts, is the origin of the mysteriousness of QM. There is mounting evidence from neuroscience that our conscious thoughts are associated with synchronous oscillations in well-separated sites in the brain. This opens the door to a natural way of understanding, simultaneously, both the mind-brain and quantum-classical linkages. Oscillatory motions play a fundamental role in QM, and they embody an extremely tight quantum-classical connection. This connection allows the quantum-classical and mind-brain connections to be understood together in a relatively simple and direct way.

We think that this central question is linked with Bohm's model of the Implicate Order (IO) (see chap. 8).

2.6.1 Observer and von Neumann chain

Bondoni (Bondoni,2010) analyze the possible relationship between two fundamental elements, **the measurement process and the von Neumann chain[12]**. We introduce briefly his pathway.

Bondoni start his analysis from the problem nested in Ozawa's effort to block von Neumann's chains and in his attributing the wave-collapse to a interaction between systems. Ozawa's analysis suggests to distinguish (sharply) the mathematical world from the phenomenological one. In Ozawa's own words:

> The orthodox view (of the wave-collapse) confuses the time at which the outcome of measurement is obtained and the time at which the object is left in the state determined by the outcome. (...) it confuses the time just after the reading of the outcome and the time just after the interaction between the object and the apparatus. There is no causality relation between the outcome and the state just after measurement.

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[12] We recall that von Neumann's quantum theory is a a formulation in which the entire physical universe, including the bodies and brains of the conscious human participant/observers, is represented by the basic quantum state. The dynamics involves three processes. **Process 1** is the choice on the part of the experimenter about how he will act. This choice is sometimes called the "Heisenberg choice", because Heisenberg emphasized strongly its crucial role in quantum dynamics. At the pragmatic level it is a "free choice", because it is controlled, at least at the practical level, by the conscious intentions of the experimenter/participant: neither the Copenhagen nor von Neumann formulations specify the causal origins of this choice, apart from the conscious intentions of the human agent.**Process 2** is the quantum analog of the equations of motion of classical physics, and like its classical counterpart is local (i.e., via contact between neighbors) and deterministic. This process is constructed from the classical one by a certain quantization procedure, and is reduced back to the classical process by taking the classical approximation. It normally has the effect of expanding the microscopic uncertainties demanded by the Heisenberg uncertainty principle into the macroscopic domain: the centers of large objects are smeared out over large regions of space. This conflict with conscious experience is resolved by invoking Processes 1 and 3. **Process 3** is sometimes call the "Dirac choice". Dirac called it a "choice on the part of Nature". It can be regarded as Nature's answer to a question effectively posed by the Process 1 choice made by the experimenter. This posed question is: will the intended consequences of the action that the agent chooses to perform actually be experienced? (e.g.,will the Geiger counter be observed to be placed in the intended place? And, if so, will the specified action of that device be observed to occur?) Processes 1 and 3 act on the variables that specify the body/brain of the agent. According Stapp, the "Yes" answer actualizes the neural correlates of the intended action or associated feedback.

This analysis according Bondoni is correct, otherwise, he argue, we would have a regress at infinity[13], a sort of hegelian *odd* infinity as von Neumann points out:

> we must always divide the world in two parts, the one being the observed system, the other the observer. (...) That this boundary (i.e. between the observed system and the observer) can be pushed *at will* deeply in the interior of the body of the real observer is the content of the principle of the psycho-physical parallelism.

Bondoni, retain that surely the word used "at will" is the source of such problem. This way, the counsciousness can enter in the description of a measurement. **On the other hand, we must distinguish the *measurement* and the *reading* of this measurement**; i.e. the entanglement of the object with the observer and the reading of this interaction by the experimenter. In this way, we can no longer assert that the mind causes the collapse, as the given collapse is occurred earlier.
Moreover Ozawa demonstrates that the wave-collapse occurs in a time interval $t + \Delta t$, while the perception of this collapse is at $t + \Delta t + \tau$, interval in which the two systems (object and observer) can no longer be in a relation.
On the other hand, we can observe that exists only that is perceivable in a *phenomenon*. **A measurement which is not perceived (by a reading) is not a real measurement.** It is a logically possible interaction which doesn't belong to the reality. From the difference between the above mentioned intervals**Ozawa infers a difference between measurement and perceiving of this measurement.** But it is a logical inference. How can someone experience a measurement without interact with it (with a reading)?[14] And if this collapse is not experienceable, then we are making *meta*-physics (we are going *beyond* physics). Therefore, is not usefull putting aside a non physical entity as the mind to leave room for something more abstract, as a measurement without reading, also if this *something* has a definite grade of mathematical reality. Moreover, Ozawa doesn't answer the main question.

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[13] Instead, in this thesis we retain that the infinity regress is not a problem but a resource, see Chap. 7 "Can wee see the IO".

[14] One can interacts with an object *without* knowing the result of this interaction. For example, an observer can know that he is interacting with an object, without knowing the eigenstate in which the object jumped. The observer knows that surely by *this* interaction the system-object jumped in an eigenstate $|\phi_i\rangle$ and that an observable $\mathcal{O}$ must have in $|\phi_i\rangle$ an eigen-value λ_i. But the observer cannot, without a reading, know in *which* eigenstate the system is. Obviously, knowing the wave-function of the system, he knows too the amplitudes of the probabilities associated to its vectors, but this is only a mathematical (statistic) forecasting, not a perception. In this sense, the fact that at $t + \Delta t$ the system-object is in an eigenstate is only an *inference*.

The reading of a measurement is invoked to explain the collapse; now, if this cannot be more the cause of the collapse, what is the real cause? Apparently, the interaction between subject and object, but we have no direct experience of it. It is a *perceived* measurement in a given context to determinate the wave-collapse. Von Neumann *seems* adhering to this position, stating:

> experience only permits statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value.

Obviously it is higly questionable the *subjective* character of our perception. Our perception is on the contrary *objective* in a phenomenological point of view. What is more objective than the fact that we have in front of us a *given and no other* experimental set-up, built in a *given* way, with *given* pointers?
Using Bohr's own words:

> (...) in actual experiments all evidence pertains to observations obtained under reproducible conditions and is expressed by unambiguous statements referring to the *registration* of the point at which an atomic particle arrive on a photographic plate (...).

And:

> (...) the problem of explanation that is embodied in the notion of complementarity suggests itself in our position as conscious beings and recalls forcefully the teaching of ancient thinkers that, in the search for a harmonious attitute towards life, it must never be forgotten that we ourselves are both actors and spectators in the drama of existence.

Obviously, it is one thing asserting that reality must be confined to the realm of experience and one other asserting that the cause of the wave-collapse, which oughts to belong to our experience, must coincide with the act of registration of a measure. Ozawa successfully shows that this act cannot cause the collapse. But, where is, then, the real cause of this collapse? If this is the measurement, where is, ontologically speaking, this measurement?

Quoting Planck:

> it is impossible (...) that the development of the knowledge in Physics until now aimed at a fundamental and radical division between the processes in the external nature and the processes in the human world of feelings.

Being no clear distinction between subject and object, it is best adopting an *holistic* view and consider as fundamental the perceived phenomenon. I.e. there are not in reality subject and object as two clear distinct entities, but a relation which *founds* it. Subject and object are only in a relation, in a totally entangled *Gestalt*. The measurement seen as interaction is such a Gestalt. But not meaning that observer and object *enter* in relation, but that the relation *founds* relate and correlate.
What it is this relation in the measurement? The totality of the experimental arrangement which permits speaking of measurement. A totality which lives in our perception and is made of perceiving devices and tools of measurement. This is the *kantian* position of Bohr which sees in the experiment the real cause of any result: the *a-priori*, a sort of *category* which makes possible speaking of measurements, particles, collapses and so on. A frame in which the observer arranges his experiences. Planck observes:

> **what we can measure, that it exists.**

The act of measuring, the registration of measurement, not the measurement without observer. What a measurement could be without observer, Bondoni add: I don't dare to say.
Bondoni, concludes his paper, with two distinct questions:

1. the reading of a measurement cannot be the cause of the wave-collapse

2. attributing the wave-collapse to the interaction observer-object *before* the reading of the measurement stops von Neumann's chain

According Bondoni, Ozawa successfully demonstrates 1. Bondoni, is not sure that stating 1 rules out completely the problem hidden in 2. That is, the rôle of the subject in the act of knowing. In particular, it is not clear the *phenomenological* correlate of the measurement. In absence of a precise phenomenological correlate of a measurement, we can infer that this process amounts to an *observation without observer*. We disagree with this conclusion, **the universality of QM is not a problem but a resource**, to us the real question is: where we can stop the von Neumann chain? We think that the IO is a possible answer, **we retain that QE is the medium between the explicate order and the implicate Order.**

2.7 Reality as Information?

Probability has played an important role in the foundations of QM from the beginning and continues to play an important role today. The choice of an interpretation of probability **affect** the interpretation of QM. Recent developments in Quantum information theory has led to new way to look at the foundations of QM, including a greater emphasis on possible role of subjective probability in QM. Several works claims that the QM can be view as information theory. According these works ,the description of physical systems in terms of information and information processing, is the only way to describe physical system. For instance, according Bub's words (Bub, 2008): *I argue that QM is fundamentally a theory about the representation and manipulation of information, not a theory about the mechanics of nonclassical waves or particles. The notion of quantum information is to be understood as a new physical primitive.* The author give at the information an **ontic statute**, in this context it is possible, for instance, deduce the physical laws and the matter from the information. We note others extreme positions on this topic, for instance, Zeilinger (Zeilinger,2005), where he claims that: *"The discovery that individual events are irreducibly random is probably one of the most significant findings of the twentieth century, even for single particles, it is not always possible to assign definite measurement outcomes independently of and prior to the selection of specific measurement apparatus in the specific experiment. For this reason, the distinction between reality and our knowledge of reality, between reality and information, cannot be made.*[15] The same position is the following statements of von Baeyer (von Baeyer, 2005) : **Information as physical reality**:*in 1905 Einstein proposed that the world is not what it seems. He suggested that is not continuous but atomistic, not absolute but relative, not classical but quantized. In the ensuing century his euristic hypothesis were confirmed as facts. They define what might be called the " atomic world view" Today we stand on the threshold of a new era: the information age. Far from replacing the atomic view of the world, the concept of information can be enlisted to build upon our current understanding of nature, and fill in remaining gaps.* We think that the possible relationship between reality and information is

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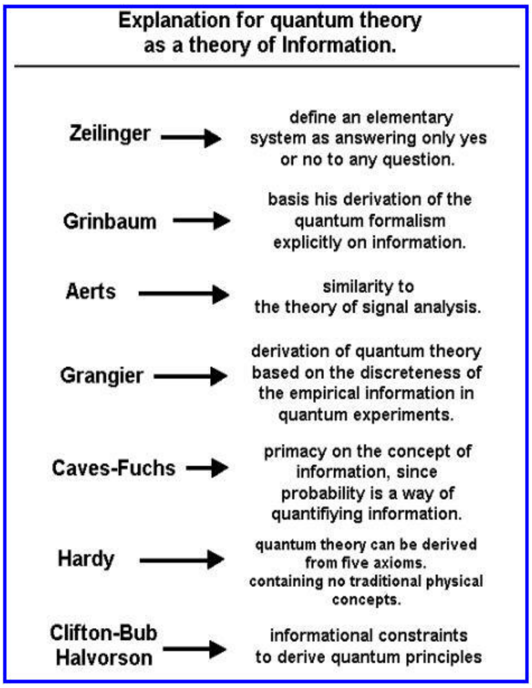
[15] According Zeilinger this simple principle play a role in QM similar to that of the Principle of Relativity in Special Relativity, or to the Principle of Equivalence in General Relativity. In particular, he suggests this principle provides an explanation for the **irreducible randomness in quantum measurement and for the phenomenon of entanglement.** A form of phenomenalism to physical object (they objects are taken not to exist in and of themselves, but to be mere constructs relating sense impressions) and a form of instrumentalism about the quantum state.



Explanation for quantum theory as a theory of Information.

Zeilinger	define an elementary system as answering only yes or no to any question.
Grinbaum	basis his derivation of the quantum formalism explicitly on information.
Aerts	similarity to the theory of signal analysis.
Grangier	derivation of quantum theory based on the discreteness of the empirical information in quantum experiments.
Caves-Fuchs	primacy on the concept of information, since probability is a way of quantifiying information.
Hardy	quantum theory can be derived from five axioms. containing no traditional physical concepts.
Clifton-Bub Halvorson	informational constraints to derive quantum principles

Figure 2.5: QM as Quantum Information?

very delicate problem and it seem quite approximate to say that information is the reality. This conclusion simply contradicts the everyday belief that physics is concerned with the physical structure of objects and that is the laws which govern the physical structure.

2.7.1 Reality as particles?

According Blood (Blood, 2008), it is remarkable that the particle-like properties which have led physicists to postulate the existence of particles mass, energy, momentum, spin, charge, the photoelectric and Compton effects, localized perception, particle-like trajectories (in bubble chambers, and atomic discreteness can all be explained by QM alone (wave function/state vector alone). This means there is no need to postulate the existence of particles (because QM can account for all the evidence). The net result is that **there is no evidence for particles**. Wave-particle duality arises because the state vector alone has both classical wave-like and classical particle-like properties. If only the state vector exists, then some of results of the Bell-Aspect and Wheeler delayed-choice experiments are easily and naturally understood.

According Blood, the relative ease of interpretation of the Bell-Aspect and Wheeler delayed-choice experiments, and the severe difficulties encountered in constructing viable theories of particles underlying QM, strongly suggest that the physical world consists solely of wave functions/state vectors. Seeing that the wave-particle conundrum can be resolved within QM is a step towards demystifying the theory. But we still do not know why our perceptions correspond to the characteristics of a particular quantum version of reality, and we still do not know the origin of the probability law.

For these reason, Blood do not interpret subatomic reality in terms of particles. To conclude this section we cite Wilczek (nobel prize 2004) about the notion of particle:

> Particle physics is not really about particles anymore, but about the mathematica relationship, in particular, symmetries, aspects of nature that remain invariant under different circumstances; the world of elementary particles is an intercative world whose constituents derive their identities and properties from one another in endless negotiations.

2.7.2 Relational Realism: Rovelli's Interpretation

Rovelli (Rovelli, 1996) departs radically from such strict Einstein realism, the physical reality is taken to be formed by the individual quantum events through which interacting systems (objects) affect one another. **Quantum events exist only in interactions and the reality of each quantum event is only relative to the system involved in the interaction.** In Relational QM, the preferred observer is abandoned. Indeed, it is a fundamental assumption of this approach that nothing distinguishes, a priori, systems and observers: any physical system provides a potential observer, and physics concerns what can be said about nature on the basis of the information that any physical system can, in principle, have. Different observers can of course exchange information, but we must not forget that such information exchange is itself a quantum mechanical interaction. An exchange of information is therefore a quantum measurement performed by one observing system A upon another observing system B. The physical theory is concerned with relations between physical systems. In particular, it is concerned with the description that observers give about observed systems. Following this hypothesis, all systems are equivalent. Nothing a priori distinguishes observer systems from quantum systems. If the observer O can give a description of the system S, then it is also legitimate for an observer O' to give a quantum description of the system formed by the observer O. It is rejected any fundamental or metaphysical distinctions as: system/observer, QS/classical system, physical system/consciousness. Rovelli (Rovelli, 1996) assume the existence of an ensemble of systems, each of which can be equivalently considered as an observing system or as an observed system. A system (observing system) may have information about another system (observed system). Information is exchanged via physical interactions. Rovelli's position, lead us to consider the following epistemological implications:

- rejection of the individual object
- rejection of individual intrinsic property

For these reasons, the consequences are: (a) it is not possible to give a definition of the individual object in a spatio-temporal location; (b) it is not possible to characterize the properties of the objects, in order to distinguish from the other ones. In other words, if we adopt the interaction like basic level of the physical reality, we accept the philosophy of the relations.

3

History and Philosophy of Quantum Entanglement: brief overview

In this chapter we will introduce a brief history of QE interpretations (included recent papers). We refer our introduction to two excellent works:
Jaeger (Jaeger et al, 2010) and Emerson (Emerson, 2009).

3.1 Non-locality: background

As we have seen, QM has posed philosophical problems from its beginnings. Main discussions deals with the notion of quantum state. Some philosophers of science argue that quantum states represent potential, not reality. but, quantum nonlocal entanglement, one of these problematic states, is a demonstrated fact and it is not a potentiality. Quantum entangled systems are probabilistically correlated across distances.
The entanglement phenomenon is as an extraordinary degree of correlation between states of quantum systems. This correlation cannot be given an explanation in terms of common cause. As we have seen before, QE can occur between two or more quantum systems. Most interesting is the case when the correlations occur between systems that are space-like separated. This means that changes made to one system are immediately correlated with changes in a distant system (even

though there is no time for a signal to travel between them). We speak in this case of non-local correlations. From mathematical point of view, two particles, 1 and 2, whose states (pure) can be represented by the state vectors ψ_1 and ψ_2. We can represent the composite two-particle system by wave-function ψ_{12}. Now, if the particles are unentangled, the composite state is the tensor product of the states of the components,

$$\psi_{12} = \psi_1 \otimes \psi_2 \tag{3.1}$$

This state is said to be factorable or separable. The state is entangled if an only if it cannot be factored:

$$\psi_{12} \neq \psi_1 \otimes \psi_2 \tag{3.2}$$

For mixed states, which must be represented by density operators rather than state vectors, the definition of entanglement is generalized: an entangled mixed state is one that cannot be written as a convex combination of products:

$$\rho_{12} = \sum_i p_i (\rho_{1i} \otimes \rho_{2i}) \tag{3.3}$$

where the sum of the p_i is equal to unity. This definition is for a bipartite system, that is, a composite system of only two parts, 1 and 2. For multipartite mixed quantum systems the situation is more complicated; **there is no single acceptable entanglement measure applicable to the full set of possible states** of systems having a greater number of parts. **The search for a fully general definition and measure of entanglement remains an active area of research**. As we know, despite the fact that the phenomenon of entanglement was recognized very early on in the development of QM, it remains one of the least understood aspects of quantum theory. A few philosophers of science and theoretical physicists explain these apparently counterintuitive phenomena as evidence of an acausal relational rather than causal dynamic world. Others approaches propose an atemporal models, superluminal models. **Physics has struggled with non-locality for centuries**. In its current guise, QE poses fundamental questions. Several contemporary philosophers, physicists, and mathematicians suggest that quantum non-locality requires us **to revise many of our basic notions**.

In Western science, the philosophical problem of action-at-a-distance or non-locality is at least four hundred years old. In the 17th century, Newton had introduced non-local action at a distance by suggesting that gravity is exerted between masses according to an inverse square law instantaneously at any distance.

Almost two hundred years later, studying rotational motion, Mach restated the problem, hypothesizing that each particle in the universe is instantaneously affected by every other particle.

In 1916, Einstein sought to remove action-at-a-distance in General Relativity (GR). In that formulation, local effects expressed as gravity (space-time curvature) were propagated at the speed of light. **But the statistical nature of QM required the reemergence of non-locality**. In the 20th century, non-locality appeared as a necessary corollary of the probabilistic nature of QM. As we know, in 1927, Max Born reemphasized the probabilistic nature of QM. He argued that the Schrödinger equation did not represent an electron (or other particle) as spread out over an area of space, but was instead a probabilistic estimate of its location. Following Born's interpretation, the entanglement (after Bell Theorem) is not only probabilistic correlation, but a real phenomenon. Although QM is the widely accepted probabilistic view of the world, some theorists continue to wonder if we could describe reality more concretely (i.e EPR argument, see Bohm's Interpretation)[1] In fact, EPR paper was the first that drew attention to the phenomenon of entanglement. As we have seen, in the introduction of thesis, the phenomenon of entanglement in MQ was taken by EPR as reductio ad absurdum. They show that there is a fundamental flaw with the theory: "since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system". Since QM implies such an "absurd" situation, QM must be incomplete at best. QE, however, precisely is such a non-classical relationship between quantum particles whereby changes made to one particle of an entangled pair can lead to changes in the other particle even though they no longer interact. Shortly after the appearance of the EPR paper, Schrödinger coined the term "entanglement" (Verschränkung) to describe this phenomenon. The first published occurrence of the term is in an article of his, written in English, which appeared in October of 1935. In this article, Schrödinger places the phenomenon of entanglement at the center of quantum theory:

When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endow-

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[1] In the Bohmian Mechanics (BM) interpretation of QM, particles maintain a specific position and velocity but they cannot be detected. Any measurement destroys the pilot wave (and information) associated with the particle. Like orthodox QM, Bohmian mechanics is in many respects, nonlocal. The "hidden variables" supplies information shared by entangled particles. A change in any state (for example "up spin") of one particle of an entangled pair is immediately made in the corresponding state of the other (for example, "down spin").

> *ing each of them with a representative of its own. I would not call that one but rather the characteristic trait of QM, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled (Schrödinger 1935).*

Despite this early recognition of the importance of the phenomenon, very little effort or progress was made over the next thirty years in developing a theory of entanglement or in answering Schrödinger's concerns regarding how this phenomenon could be consistent with relativity. It would be almost thirty years before another significant step toward a theory of entanglement would be made with John Bell's seminal (1964) paper on quantum non-locality. In that paper Bell considered a pair of particles in the singlet state that had interacted in the past, had become entangled, and then had separated. He derived an inequality involving the probabilities of various outcomes of measurements performed on these entangled particles that any local definite (i.e., hidden-variable) theory must satisfy. He then showed that QM violates this inequality; that is, the experimentally well-confirmed quantum correlations among entangled particles cannot be locally explained. BellŠs theorem does not rule out the possibility of hidden-variable theories in general, only those hidden-variable theories that are local. Indeed, Bell took the lesson of his theorem to be that any theory that reproduces the experimentally well-confirmed predictions of QM must be non-local. He writes:

> *It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty . . . This [non-locality] is characteristic, according to the result to be proved here, of any theory which reproduces exactly the quantum mechanical predictions (Bell 1964).*

Bell (Bell, 1964) showed that no physical theory of local hidden variables could produce the results of QM. Bell showed that either QM must be reconciled with nonlocality (not necessarily contravening SR) or the objective reality of particle properties (e.g., quantum states) had to be denied. Modifying the EPR thought experiment, Bell proposed a two measurement experiment of a pair of distant, entangled particles. The first would test predictions of "quantum theory", the second would test "local reality" predictions, espoused by the EPR paper Bell's predictions were so explicit that they were later tested and verified. Although his theory has been interpreted that way, Bell did not totally dismiss "hidden variables.'" His inequalities (only) demonstrate that "local" hidden variables contradict predictions of QM. Bell affirming that causality at the quantum level must be nonlocal.

What is remarkable about Bell's theorem is that it is a general result arising from an analysis of the relevant probabilities of various joint measurement outcomes, and **does not depend on the details of any hidden-variable theory** or even on the details of QM itself. Since then a number of different Bell-type inequalities have been derived, such as the Clauser, Horne, Shimony, and Holt (CHSH, 1969) inequality, which has proven particularly useful for experimental tests of non-locality. Following Bell, a number of experiments demonstrated not only that **non-locality is a genuine physical phenomenon characteristic of our world** (e.g., Aspect et al. 1982), **but also that non-locality can be experimentally produced,controlled, and harnessed for various applications**.

Another theoretical development came with Jarrett's (Jarrett, 1984) analysis showing that Bell's locality condition can be viewed as the conjunction of two logically independent conditions: a "controllable" locality, which if violated would conflict with special relativity, and an "uncontrollable" locality whose violation might "peacefully coexist" with relativity (Shimony,1984 and an opposing point of view see Maudlin (1994)). Hence, the violation of Bell's inequality could logically be due to a violation of one, the other, or both of these locality conditions. Jarrett's analysis has been taken by some to provide the solution to Schrödinger's worries about a conflict between quantum theory and relativity, as long as one assumes that the violation is in fact solely a violation of the uncontrollable locality.

3.2 Quantum Nonlocality After Bell: Not only does God play dice, but he plays with nonlocal dice.

From experimental point of view until 1990 no one paid much attention to quantum nonlocality. But in the 1990's two things changed. First, a conceptual breakthrough happened thanks to Ekert and to his adviser Deutsch (Deutsch, 1985). They showed that quantum nonlocality could be exploited to establish a cryptographic key between two distant partners and that the confidentiality of the key could be tested by means of BellŠs inequality. This was the first time that someone suggested that quantum nonlocality is not only real, but that it could even be of some use. Today, according Gisin (Gisin,2005), we can say that "**not only does God play dice,**

but he plays with nonlocal dice!". According Gisin, QM predicts the existence of a totally new kind of correlation that will never have any kind of mechanical explanation. And experiments confirm this: Nature is able to produce the same randomness at several locations, possibly space-like separated. The standard explanation is "entanglement", but this is just a word, with a precise technical definition. Still words are useful to name objects and concepts. However, it remains to understand the concept. Entanglement is a new explanation for correlations. Quantum correlations simply happen. Entanglement appears at the same conceptual level as local causes and effects. It is a primitive concept, not reducible to local causes and effects. Entanglement describes "correlations without "correlata" in a holistic view. In other worlds, **quantum correlation is not a correlation between 2 events, but a single event that manifests itself at 2 locations**. Historically this was part of the suspicion that entanglement was not really real, nothing more than some exotic particles that live for merely a tiny fraction of a second. But today we see a growing number of remarkable experiments mastering entanglement. In few words, entanglement exists and is going to affect future technology. **It is a radically new concept, requiring new words and a new conceptual category.**

From foundational point of view, years after Bell demonstrated the need for quantum nonlocality, theoreticians continued to ask about a relationship between the structures described by QM and local reality. Zukowski (Zukowski et al 2008)and Brukner (Brukner et.al 2004)(Institute for Experimental Physics, Vienna) notes, "No local realistic theory agrees with all predictions of QM as quantitatively expressed by violation of Bell's inequalities. Local realism [...] is based on everyday experience and classical physics [...] and supposes that measurement results are predetermined by the properties the particles carry prior to and independent of observations. Locality supposes that these results are independent of any action at "spacelike separations". After Bell, quantum nonlocality was the practical basis for quantum computing and quantum cryptography. In 1967, Simon Kochen and Ernst Specker (Kochen et al 1968) developed a strong position against Bohmian and similar hidden variable arguments for interpreting QM as deterministic. Kochen and Specker showed that the apparently QM equivalent statistical results of Bohmian hidden variables "do not take into account the algebraic structure of quantum observables. Kochen-Specker advanced the position that QM mathematics represented probabilities instead of physical reality. The Kochen-Specker proof demonstrates the impossibility of Einstein's assumption, made in the famous EPR paper, that quantum mechanical observables represent "elements of physical reality". More generally

does the theorem exclude hidden variable theories requiring elements of physical reality to be noncontextual (i.e. independent of the measurement arrangement).
In 1982, Aspect (at the Institut d'Optique in Paris) and co-workers verified Bell's theory of inequalities. A pair of photons created as a single decay event was emitted by the source. They traveled in opposite directions for a distance until they hit variable polarizers, the results of their interaction with the polarizers was recorded at each end. When the outcome was analyzed, the results verified QM nonlocality and showed a correlation that could not be supported by hidden variables A few years later (1986), Ghiraldi, Rimini, and Weber (Ghirardi et al 2005) proposed a solution to the collapse and nonlocality problem by changing QM. Their approach allows the quantum state of a QS to develop according to Schrodinger's equation. At random instants, development stops and the quantum state spontaneously collapses into a single local state. But like Bohm's formulation, GRW assumes instantaneity. Random collapses occurs faster superluminally, violating Special Relativity (SR).
In 1997, Zeilinger (at the University of Innsbruck in Austria) and collaborators conducted a "quantum teleportation." The essential information contained within one of two entangled photons was transmitted instantaneously over a distance, materializing in the form of a third photon identical to the first. At the same instant, the first photon disappeared. Again, the influence causing the nonlocal change occurred at a superluminal speed. Quantum nonlocality is now empirically verified.

3.3 Interpretations of Non-Locality

Some theoreticians argue that property theory has a role in interpreting quantum phenomena. Others suggest that quantum nonlocality may be interpreted as a holistic, nonseparable relational issue.
Summarizing Einstein's famous objection to entanglement, in the EPR paper, Richard Healey (Healey, 1989)reminds us that he assumed a classical physics understanding of the state of a whole system as combining individual component states, not adding something. Fifty years after EPR, Howard (Howard, 2007) equivalently restates the EPR principle as "The real state of the pair AB consists precisely of the real state of A and the real state of B, which states have nothing in to do with one another". In this EPR-like perspective, there is no supervenience of the whole system upon its components. Because the EPR deduction of nonlocal entanglement implies supervenience and contradicts separability, the paper argued that some unknowns (Bohm's "hidden variables") are missing in QM. Healey finds convincing explanations of quantum nonlocality as either "metaphysical property holism" or

"spatiotemporal nonseparability." The former implies that an entangled system is more than the sum of its parts. As EPR stressed, the whole (quantum state) seems to determine values of some of its parts. This threat to state separability was "one reason why Einstein denied that a QS's real state is given by its quantum state. This leads, according to Healey, to "physical property holism." The composite determines the state of its components.

In Healey's view, "nonseparability" can be interpreted as possibly varying magnetic field values extending "between" theoretically separated points in spacetime. And, he notes that yet-to-be-proven string theory does not eliminate the quantum nonseparability problem. Esfeld (Esfeld 2004) develops a metaphysical interpretation of physical relations which significantly diminishes or eliminates a role for intrinsic properties in QM. For Esfeld, QM presents us with two alternatives:

> either physical phenomenon have unknown intrinsic properties or they are only relations. QM inclines us to the second view. "Quantum theory supports metaphysics of relations by speaking against intrinsic properties on which the relations [...] supervene.

Esfeld proposes a "metaphysics of relations that dismisses intrinsic properties of relata which are a supervenience basis for the relations." He points to Wheeler's "geometrodynamics" (1962) which described everything as configurations of the "four-dimensional continuum." Although, as Esfeld notes, Wheeler's scheme was later rejected as incomplete, it does demonstrate that we can have a relational model of objects such as particles and quantum states "without intrinsic properties."

A few theoreticians suggest that there is no space between apparently separated entangled particles. For example, Brian Greene (Greene, 2005) notes that:

> space cannot be thought of as [...] intervening space[....] (distance) does not ensure that two objects are separate [.. .][because of] entanglement.

Karakostas (Karakostas, 2006) interprets quantum nonlocality holistically. Although quantum level interaction produces entanglement, entanglement itself does not require interaction. According Karakistas, entanglement:

> does occur in the absence of any interactions [...] entangled correlations among the states of various physical systems do not acquire the status of a causally dependent relation [...] their delineation is rather determined by the entangled quantum state itself which refers directly to the whole system. [This is] a genuine quantum mechanical instance of holism: there exist properties of entangled quantum systems which [...] characterize the whole

> system but are neither reducible to nor implied by or causally dependent on the local properties of its parts.

The parts of an entangled system depend upon the whole rather than the reverse. Karakostas additionally argues that:

> physical systems are realized as context-dependent. Quantum entities are not "things-in-themselves." Their wholeness is mind-independent and "veiled" from perception. "Any discussion concerning [...] whole is necessarily [...] ontological, metaphysical[...] the only confirmatory element about it [is] the network of interrelations which connect its events.

Richard Healey finds that nonlocal entangled systems can be interpreted holistically:

> When one performs measurements of spin or polarization on certain separated quantum systems. The results ... exhibit patterns of statistical correlation that resist traditional causal explanation.

These correlations suggest "spatiotemporal non-separability.

Berkovitz-Hemmo (Berkovitz-Hemmo,2005)argue that quantum phenomena can be interpreted from a "relational modal" perspective. They claim that this point of view enables them to "solve the measurement problem and [...] reconciles QM with the special theory of relativity." In the process, they reject local properties and argue that entities should be viewed in **terms of relations**. The assumption of a local property was basic to the EPR argument for QM incompleteness. Esfeld argues that QE necessitates relational descriptions. The empirical verification of entanglement (for example, Aspect, 1982) **means that there are no individual intrinsic properties of entangled particles**, instead there are "only correlations between the conditional probability distributions of the state-dependent properties of the quantum systems." In addition, the relation of hidden variables to the components of an entangled system "requires intrinsic properties on which these correlations supervene. Relational quantum mechanics (RQM) restates several basic QM principles. From an RQM perspective, a statement about a quantum event such as "A has a value x" must be rephrased as "A has the value x for B." By itself, "A has a value x" is meaningless. Discussing the impact of Bell's Inequalities on a hidden variables interpretation, Esfeld finds that "Bell's theorem does not rule out hidden variables that satisfy separability[....] If (we postulate) hidden variables that establish a causal connection with any of these [explanations: superluminal, backwards causation, or a joint cause], then [these] hidden variables [...] provide for intrinsic properties which are a supervenience basis for the correlations Esfeld finds that David Mermin's interpretation of QM which presents a "world of correlations without describing intrinsic properties of the correlate" is reasonable but unempirical. Instead, Esfeld finally argues that we must accept the empirically given evidence of QM and not expect additional factors. Filk (Filk, 2006) tries to avoid the nonlocal implications of Bell's Inequalities and finds "hidden variable" explanations feasible. Arguing that QM entanglement may be interpreted as local, he points out that "the wave function itself is interpreted as encoding the 'nearest neighbor' local relations between a QS and spatial points." This means that spatial position is "a purely relational concept[...] a new perspective onto quantum mechanical formalism where many weird aspects, like particle-wave duality, nonlocality of entanglement, and the 'mystery' of the double-slit experiment, disappear. This perspective circumvents the restrictions set by Bell's inequalities [...] a possible (realistic) hidden variable theory based on these concepts can be local and at the same time reproduce the results of QM "

Similarly, we could say that accurate probabilistic predictions of measurement results for an entangled pair can be made without specifying the separating distance between the members of the pair. Focusing on the relations between the members of the pair, enables us to more acceptably express a hidden variable explanation for the now-local entanglement phenomena. This non-spatial or a-spatial perspective can be seen in another relational approach to quantum theory explained by Rovelli (Rovelli, 1998) and Laudisa (Laudisa, 2004) and as one that "discards the notions of absolute state of a system, absolute value of its physical quantities, or absolute event[s] [...] [and] describes [...] the way systems affect each other [...] in physical interactions. The physical content of quantum theory is [...] the net of relations connecting all different physical systems. Bitbol (Bitbol, 1998)suggests that these theories could be naturalistic if they focus on relations as the collective probabilistic prediction several physical observers. However these relational QM views are held by a minority. Conventional interpretations (e.g., Copenhagen) of quantum theory accepted the predictions of EPR and welcomed the probabilistic verification of nonlocality in Bell's theorem. However, their explanations for QM nonlocality vary:

- Nonlocality is an integral feature of QM.
- Nonlocality indicates geometric relational acausality
- Nonlocal effects are atemporal

- Apparently nonlocal events are actually local
- There are superluminal causal links
- Nonlocal quantum events are relations between causal processes.

Each approach attempts to resolve philosophic questions raised by QM nonlocality. Some of these views are summarized above.

Nonlocality is Integral to Quantum Reality

Many theoreticians assume that entanglement involves no "hidden variables" and there are no undetected connections (e.g., no Bohmian "pilot wave") between distantly entangled particles." Bohr, Heisenberg, and many others accepted the predictions of EPR as consistent with QM.

Nonlocal Events are Atemporal

Recent articles by Suarez (Suarez, 2003, 2007) and others at the Center for Quantum Philosophy in Zurich (articles published in the Physical Letters) suggest that nonlocality necessitates timelessness. "Experiments with moving beam-splitters demonstrate that there is no real time ordering behind the nonlocal correlations. In Bell's world there is no 'before' or 'after.'" A few suggest that measurement notifications travel instantly across distances separating entangled particles. Entangled particles can be subject to a superluminal causal link. According to Ray-Murray, "It may be possible to avoid the [EPR] paradoxes [...] while accepting the existence of superluminal causal links [...] because we have no real control over the links. We cannot, for instance, use them to send superluminal signals of any kind." Mauldin (Rutgers University) also finds that "Superluminal signals must[...] propagate into the past: the signal is received before it is sent. The conditions required for the possibility of such paradoxes are more complex than merely the existence of superluminal signals. Accordingly, violations of Bell's inequality predicted by QM do not allow superluminal signals. [However] even though nature may not allow superluminal signally, it does employ, according to Bell, superluminal causation [...] this will pressure us to add more structure to space-time than Relativity says there is." Here, relativity theory is not challenged because no signal passes between the separated, entangled particles. However, Barbour interprets Aspect's experimental results as evidence of superluminal, causal contact. But a deeply troubled John Bell wrote the verified superluminal causal effect of nonlocal entanglement was "for me[.. .]the real problem of quantum theory.

3.4 Entanglement vs non-locality?

Despite these important advances, it was still only a handful of physicists who were deeply interested in entanglement. Philosophers of physics recognized the importance of entanglement and Bell's work, but many continued to think of entanglement as an "all or nothing" phenomenon and described entanglement as simply a spooky action-at-a-distance or mysterious holism. In the last two decades new discoveries, many of which are associated with the investigation of quantum information, have shown that much philosophical and foundational work remains to be done to deepen our understanding of entanglement and non-locality.

Toward the end of the 1980s and the beginning of the 1990s a number of important transformations in our understanding of entanglement took place. First, it was recognized (e.g., Shimony,1995) **that entanglement can be quantified**; that is it comes in degrees ranging from "maximally entangled" to not entangled at all. Moreover, entanglement can be manipulated in all sorts of interesting ways. For example, Bennett et al. (Bennett, 1996) have shown that one can take a large number of electrons that are all partly (that is, "a little bit") entangled with each other, and concentrate that entanglement into a smaller number of maximally entangled electrons, leaving the other electrons unentangled (a process known as entanglement distillation). Conversely, one can take a pair of maximally entangled electrons and spread that entanglement out over a larger number of electrons (so that they are now only partly entangled) in such a way that the total entanglement is conserved (a process known as entanglement dilution). The notion of a "degree of entanglement" seems to have been first recognized through the related notion of a degree of violation of the Bell inequalities, indeed, this was used as the first measure of entanglement in the case of **pure states: the greater the degree of violation of the inequalities, the greater the amount of entanglement.** There are, however, limitations to using a violation of Bell's inequality as a general measure of entanglement. First, there are Bell-type inequalities whose largest violation is given by a non-maximally entangled state, so entanglement and non-locality do not always vary monotonically. Werner (Werner, 1989) showed that there are some mixed states (now referred to as Werner states) that, though entangled, do not violate Bell's inequality, so we can have entanglement without non-locality. Popescu (1995) has shown that even with these local Werner states one can perform a non-ideal measurement (or series of ideal measurements) that "distills" a non-local entanglement from the initially local state. The Horodecki family (Horodecki, 2009) subsequently showed that not all entanglement can be distilled in this way there are some entangled states that are "bound." These bound entangled states are ones that satisfy the Bell inequalities (i.e., they are local) and cannot have maximally entangled states violating Bell's inequalities extracted from them by means of local operations. **Not only can one have entanglement without non-locality**, but also, as Bennett et al. (1999) have shown, **one can have a kind of "non-locality without entanglement."** There are systems that exhibit a type of non-local behavior even though entanglement is used neither in the preparation of the states nor in the joint measurement that discriminates the states (see Cerf et al, 1997). This work highlights another facet of the concept of non-locality, which, rather than involving correlations for space-like separated systems, involves instead a kind of indistinguishability based on local operations and classical communication. The relationship between this new notion of non-locality and the traditional one involving space-like separated systems remains to be worked out.

These recent developments point to the need for a new, more adequate way of measuring and quantifying entanglement. They show that the concepts of entanglement and non-locality are much more subtle and multifaceted than earlier analyses based solely on Bell's theorem realized. Much philosophical and foundational work remains to be done on understanding precisely how the important notions of entanglement and non-locality are related.

These questions of how to quantify entanglement and non-locality and the need to clarify the relationship between them are important not only conceptually, but also practically, insofar as entanglement and non-locality seem to be different resources for the performance of quantum information processing tasks. As Brunner (Viola, Brunner 2007) and colleagues have argued, it is important to ask "whether in a given quantum information protocol (cryptography, teleportation, and algorithm, it is better to look for the largest amount of entanglement or the largest amount of non-locality" (Brunner et al. 2007).

3.5 Entanglement and Information

Arguably it is this new emphasis on the exploitation of entanglement and non-locality for the performance of practical tasks that marks the most fundamental transformation in our understanding of these concepts. The newly formed field of quantum information theory is devoted to using the principles and laws of QM to aid in the acquisition, transmission, and processing of information. In particular, it seeks to harness the peculiarly quantum phenomena of entanglement, superposition, and non-locality to perform all sorts of novel tasks, such as enabling computations that operate exponentially faster or more efficiently than their classical counterparts (via quantum computers) and providing unconditionally secure cryptographic systems for the transfer of secret messages over public channels (via quantum key distribution). By contrast, classical information theory is concerned with the storage and transfer of information in classical systems. It uses the "bit" as the fundamental unit of information, where the system capable of representing a bit can take on one of two values (typically 0 or 1). Classical information theory is based largely on the concept of information formalized by Shannon in the late 1940s. Quantum information theory, which was later developed in analogy with classical information theory, is concerned with the storage and processing of information in quantum systems, such as the photon, electron, quantum dot, or atom. Instead of using the bit, however, it defines the fundamental unit of quantum information as the "qubit." What makes the qubit different from a classical bit is that the smallest system capable of storing a qubit, the two-level QS, not only can take on the two distinct values $|O\rangle$ and $|1\rangle$,but can also be in a state of superposition of these two states:

$$\psi = \alpha_0|0\rangle + \alpha_1|1\rangle. \tag{3.4}$$

Quantum information theory has opened up a whole new range of philosophical and foundational questions. The first cluster of questions concerns the nature of quantum information.A second cluster of important philosophical questions concerns how it is that quantum information protocols are able to achieve more than their classical counterparts. A third important cluster of philosophical questions concerns what new insights recent work in quantum information theory might provide into the foundations of QM. Some authors have argued that an information-theoretic approach may provide a new axiomatic basis for QM and provide deeper insight into what makes QM different from classical mechanics. Zeilinger (Zeilinger,1999) has proposed a new information-theoretic "foundational principle" which he believes can explain both the intrinsic randomness of quantum theory and the phenomenon of entanglement.In another approach, Fuchs (Fuchs,2002) has adopted a Bayesian approach and argued that QM just is quantum information theory a more sophisticated gloss on the old idea that a quantum state is just a catalogue of expectations. Bub (Bub,2008) in particular has taken this ("CBH") theorem to show that quantum theory is best interpreted as a theory about the possibilities of information transfer rather than a theory about the non-classical mechanics of waves or particles. Much philosophical work remains to be done assessing these various claims that quantum information provides a new, more adequate way of conceiving quantum theory.

The second contribution in this thesis focuses on the concept of entanglement and how the notion of entanglement might be generalized for situations in which the overall system cannot be easily partitioned into separated subsystems A and B. The standard definition of entanglement for pure states depends on being able to define two or more subsystems for which the state cannot be factored into product states. For strongly interacting quantum systems, such as indistinguishable particles (bosons or fermions) that are close enough together for quantum statistics to be important, the entangled systems cannot easily be partitioned into subsystems in this way. In response to this problem, Viola and Barnum (Viola, 2007)(see chap.5) have developed a notion of "generalized entanglement", **which depends on the expectation values of a preferred set of observables, rather than on a partitioning of the entangled system into subsystems**. The intuition behind their approach is that entangled pure states look mixed to local observers, and the corresponding reduced state provides expectation values for a set of distinguished observables. They define a pure state as "generalized unentangled" relative to the distinguished observables if the reduced state is pure and "generalized entangled" otherwise (Barnum et al. 2004). Similarly a mixed state is "generalized unentangled" if it can be written as a convex combination of unentangled pure states. Their hope is that this new approach will lead to a deeper understanding of entanglement by allowing it to be defined in more general contexts. Recent developments in quantum information theory have renewed interest in finding a new axiomatic formulation of QM. In his paper for this volume, D'Ariano takes up this challenge of finding a new axiomatization. D'Ariano argues that a more promising approach to an operational axiomatization involves situating QM within the broader context of probabilistic theories whose non-local correlations are stronger than QM and yet are still non-signaling.

Another way in which considerations of probability have been at the center of foundational debates in quantum information theory is in the analogy that has been drawn between Bayesian conditionalization and quantum state updating upon measurement (e.g., Bub and Fuchs (2002)). In the Bayesian approach, named for the eighteenth-century mathematician and theologian Thomas Bayes, probabilities are interpreted as subjective degrees of belief, rather than frequencies.

Speaking of information, it has been argued that quantum information (QI) theory may hold the key to solving the conceptual puzzles of QM. Timpson (Timpson,

2006) takes stock of such proposals, arguing that many are just the old interpretative positions of immaterialism and instrumentalism in new guise. Immaterialism is the philosophical view that the world at bottom consists not of physical objects but of immaterial ones, in this context, the immaterial stuff of the world is information. As Timpson shows, this immaterialist view can be seen underlying Wheeler's (1990) "It from bit" proposal and Zeilinger's "foundational principle" (1999). Similarly, instrumentalism is another philosophical approach that it has long been popular to invoke in the context of QM, and has found new life in the context of quantum information theory. Instrumentalism is the view that the task of scientific theories is simply to provide a tool for making predictions not to be a description of the fundamental objects and laws actually operating in the world. In this context instrumentalism argues that the quantum state is merely a representation of our information, one that allows us to make predictions about experiments, but which should not be thought of as a description of any objective features of the world. Timpson (Timpson, 2006)argues that merely re-dressing these well-worn philosophical positions in the new language of information theory does not in fact gain any interpretive ground. After providing a detailed critical analysis of Zeilinger's foundational approach, Timpson concludes that there is indeed great promise for gaining new insights into the structure and axiomatics of QM by focusing on information-theoretic phenomena, as long as one steers clear of the non-starters of immaterialism and instrumentalism.

As we have seen in this brief overview, quantum information science is in the process of transforming our understanding of both QM and information theory.

3.6 Entanglement and Uncertainty principle

It is known that quantum mechanics is problematic in the sense that it is incomplete and needs the notion of a classical device measuring quantum observables as an important ingredient of the theory. Due to this, one accepts that there exist two worlds: the classical one and the quantum one. In the classical world, the measurements of classical observables are produced by classical devices. In the framework of standard theory, in the quantum world the measurements of quantum observables are produced by classical devices, too. Due to this, the theory of quantum measurements is considered as something very specifically different from classical measurements.

It is psycologically accepted that to understand the physical meaning of a measurement in the classical world is much easier than to understand the physical meaning of analogous measurement in the quantum world. Using the relations of the quantum states in the standard representation and in the classical one (described by classical distributions), one can conclude that complete information on a quantum state is obtained from purely classical measurements of the position of a particle made by classical devices in each reference frame of an ensemble of classical reference frames, which are scaled and rotated in the classical phase space.

These measurements do not need any quantum language if we know how to produce, in the classical world (using the notion of classical position and momentum), reference frames in the classical phase space differing from each other by rotation and scaling of the axis of the reference frame and how to measure only the position of the particle from the viewpoint of these different reference frames.

Thus, we avoid the paradox of the quantum world which requires for its explanation measurements by a classical apparatus accepted in the framework of standard treatment of QM. The problem of wave function collapse reduces to the problem of a reduction of the probability distribution which occurs as soon as we “pick” a classical value of the classical random observable in the classical framework. This means that we "solved” the paradox of the wave function collapse reducing it to the problem of standard measurement of a classical random variable used in the probability theory. The measurement on a reference frame affects the distributions on the others (due to the underlying uncertainty principle). Can the nonlocal character of QM to be intrinsically present in a single system to emerge as subtle correlations among distributions of different reference frames?[2] We are going to analyze from another point of view this delicate question in the next section.

3.6.1 Entanglement in single system? A tomographic approach.

By using a tomographic approach (Mancini et al. 2003) to quantum states, we rise the problem of nonlocality within a single particle (single degree of freedom).

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[2] Wehner-Oppenheim (Wehner,Oppenheim,2010) have uncovered a fundamental link between the two defining properties of quantum physics: non-locality and uncertainty principle. According the authors, previously, researchers have treated non-locality and uncertainty as two separate phenomena. Now they have shown that two phenomenon are intricately linked. Moreover they show that this link is quantitative and have found an equation which shows that the "amount" of non-locality is determined by the uncertainty principle. The surprising result by Wehner and Oppenheim is that the uncertainty principle provides an answer. Two parties can only coordinate their actions better if they break the uncertainty principle, which imposes a strict bound on how strong non-locality can be. Oppenheim argue that it a surprising and perhaps ironic twist: Einstein and his co-workers discovered non-locality while searching for a way to undermine the uncertainty principle. Now the uncertainty principle appears to be biting back.

We propose (Asinimov,Caponigro,Mancini,Man'ko, 2007) a possible way to look for such effects on a qubit. Although a conclusive answer is far from being reached, we provide some reflections on the foundational ground. QE is associated with the specific *nonlocal* correlations among the parts of a QS that has no classical analog. This assumes that the entangled system should consist of two or more parts. Although recently much interest has been dedicated to single particle entanglement, it relies to different degrees of freedom, hence to different parts of the system (subsystems). Typical Bell-type experiments involve, beside entangled (singlet) states, non commuting observables (on each subsystem). Thus, the nonlocal character might not solely be ascribed to the property of states (entanglement), but also to uncertainty principle (e.g. correlations that arise due to the noncommuting chararcter of observables). As such it could somehow emerge even in a single system (single degree of freedom). Here, we address this possibility by resorting to quantum tomography in order to fix the meaning of *nonlocality* in this context. Results along this direction might shed light on the basic principles of QM, like the uncertainty principle, perhaps pointing out some form of self entanglement.The tomographic description can be applied to the systems with both continuous and discrete variables. Here we are interested in case of discrete variables, because we are going to deal with the "smallest" system-a qubit. As we have seen previous section, the problem of wave function collapse reduces to the problem of a reduction of the probability distribution which occurs as soon as we "pick" a classical value of the classical random observable in the classical framework. Nevertheless, measurement on a reference frame instantaneously affects the distributions on the others (due to the underlying uncertainty principle). In this sense nonlocality seems intrinsically present in a single system and should emerge as correlations among distributions on different reference frames (i.e. correlations of noncommuting observables measurement results). It immediately follows the question of whether such correlations can be reproduced by any hidden variable theory.

To address the above question, we consider the simultaneous measurement of spin projection along two directions specified by vectors $\vec{a}, \vec{b} \in \mathbb{R}^3$. We get the POVM elements for such a joint measurements as

$$\Pi_{r,s}\left(\vec{a}, \vec{b}\right) = \left(\frac{1}{4} + rs\,\vec{a}\cdot\vec{b}\right)\mathbb{I} + \left(r\vec{a} + s\vec{b}\right)\cdot\vec{\sigma}/2, \tag{3.5}$$

where $r, s = \pm 1/2$ are the possible measurement results and $\vec{\sigma} \equiv (\sigma_x, \sigma_y, \sigma_z)$ represents the vector of Pauli operators.

Due to the unsharpness of the measurements, the vectors $\vec{a}, \vec{b}$ are constrained by

$$\left\|\vec{a} + \vec{b}\right\| + \left\|\vec{a} - \vec{b}\right\| \leq 2. \tag{3.6}$$

If we consider a qubit state ρ, the probability of outcomes r, s along $\vec{a}, \vec{b}$ reads

$$P_{r,s}\left(\vec{a},\vec{b}\right) = \mathrm{Tr}\left[\rho\, \Pi_{r,s}\left(\vec{a},\vec{b}\right)\right]. \tag{3.7}$$

Then, we can write the correlation of measurement results. In doing so we suppose to have outcomes of the type ± 1 (rather than $\pm 1/2$), thus obtaining

$$E\left(\vec{a},\vec{b}\right) = \sum_{r,s=\pm 1/2} 4\, rs\, P_{r,s}\left(\vec{a},\vec{b}\right). \tag{3.8}$$

Given the measurement correlations (3.8) one can test the nonlocal character of the quantum state through some Bell like inequality.

Let us consider the CHSH inequality (CHSH, 1969)

$$\left|E\left(\vec{a},\vec{b}\right) + E\left(\vec{a},\vec{b'}\right) + E\left(\vec{a'},\vec{b}\right) - E\left(\vec{a'},\vec{b'}\right)\right| \leq 2. \tag{3.9}$$

We restrict our attention to the $x - z$ plane and consider

$$\begin{aligned} \vec{a} &\propto (0,0,1), & (3.10)\\ \vec{a'} = \vec{b} &\propto (\sin\phi, 0, \cos\phi), & (3.11)\\ \vec{b'} &\propto (\sin(2\phi), 0, \cos(2\phi)), & (3.12) \end{aligned}$$

with $0 \leq \phi \leq \pi/2$. Moreover, we take $\rho \equiv |\psi\rangle\langle\psi|$ with

$$|\psi\rangle = \cos\frac{\theta}{2}|+1/2\rangle + \sin\frac{\theta}{2}|-1/2\rangle, \quad 0 \leq \theta < 2\pi. \tag{3.13}$$

We are now going to distinguish the four possible correlations (3.8). In each case we assume the condition (3.6) satisfied with equality and the two vectors having the same norm.

i)

$$\begin{array}{l} \vec{a} \equiv \frac{1}{\sqrt{1+\sin\phi}}\,(0,0,1) \\ \vec{b} \equiv \frac{1}{\sqrt{1+\sin\phi}}\,(\sin\phi, 0, \cos\phi) \end{array} \quad \Rightarrow E(\vec{a},\vec{b}) = \frac{\cos\phi}{1+\sin\phi}. \tag{3.14}$$

ii)

$$\begin{array}{l} \vec{a} \equiv \frac{1}{\sqrt{1+\sin(2\phi)}}\,(0,0,1) \\ \vec{b'} \equiv \frac{1}{\sqrt{1+\sin(2\phi)}}\,(\sin(2\phi), 0, \cos(2\phi)) \end{array} \quad \Rightarrow E(\vec{a},\vec{b}) = \frac{\cos(2\phi)}{1+\sin(2\phi)}. \tag{3.15}$$

iii)

$$\begin{array}{l} \vec{a'} \equiv (\sin\phi, 0, \cos\phi) \\ \vec{b} \equiv (\sin\phi, 0, \cos\phi) \end{array} \Rightarrow E(\vec{a},\vec{b}) = 1. \tag{3.16}$$

iv)

$$\begin{array}{l} \vec{a'} \equiv \frac{1}{\sqrt{1+\sin\phi}}\,(\sin\phi, 0, \cos\phi) \\ \vec{b'} \equiv \frac{1}{\sqrt{1+\sin\phi}}\,(\sin(2\phi), 0, \cos(2\phi)) \end{array} \Rightarrow E(\vec{a},\vec{b}) = \frac{\cos\phi}{1+\sin\phi}. \tag{3.17}$$

Putting together Eqs.(3.14), (3.15), (3.16), (3.17) into Eq.(3.9), it is easy to see that the inequality is always verified (for any pure state of the qubit).

Some Foundational Reflections

Although we have not found violations of Bell inequality, we cannot draw firm conclusions about the rised problem. In fact many other Bell-type inequalities could be considered, and moreover the effect could be sought in systems living in larger Hilbert spaces, even in continuous variable systems (which is an ongoing work).
However, we can provide some reflections on the foundational ground. We can conceptually analyze the two possible scenarios:

- (**Case A**) impossibility to violate any Bell inequality;
- (**Case B**) possibility to violate some Bell inequality.

These scenarios bring us to the following reflections:
Case A: Entanglement as basic level. The Case A would be favorable to

the assumption that the basic level of physical world could be the entanglement. This simple position may have important epistemological implications, like the rejection of individual object, and the rejection of individual intrinsic properties. As consequence, it is not possible to give a definition of the individual object in a spatio-temporal location and it is not possible to characterize the properties of the objects, in order to distinguish it from other ones. In other words, if we adopt the entanglement as basic level, we accept the philosophy of the relations and we renounce at the possible existence of intrinsic properties while we accept relational properties. We remember, for instance, that a mathematical model based on the relationist principle accept that the position of an object can only be defined respect to other matter. We do not venture in the philosophical implications of the relationalism, as the monism which affirm that there are not distinction a priori between physical entities. An important advantage of these approach is the possibility to eliminate the privileged role of the observer. This is Rovelli's approach to QM where the founding postulate is the impossibility to talk about properties of systems in the abstract, but only of properties of systems relative to one system (we can never juxtapose properties relative to different systems). RQM is not the claim that reality is described by the collection of all properties relatives to all systems, rather, reality admits one description per each (observing) system, and any such description is internally consistent. As Einstein's original motivation with EPR was not to question locality, but rather to question the completeness of QM, so the relation interpretation can be interpreted as the discovery of the incompleteness of the description of reality that any single observer can give. In this particular sense, RQM can be said to show the "incompleteness" of single-observer Copenhagen interpretation.

Case B: Uncertainty principle as basic level. The Case B would show a sort of self-entanglement and would be favorable to the assumption that the basic level of physical world could be the uncertainty principle. As we know, Heisenberg's relation express ontological restrictions on the experiments that we can perform on quantum systems. The relation introduce a subject-object separation metaphorically called "the Heisenberg cut". For these reasons, there are many interpretations of the uncertainty principle. First, we note that the usual formalism of quantum theory does not incorporate notion such a “simultaneous observations", and thus no statement about them can be deduced from the same formalism. The question if the theoretical structure or the quantitative laws of quantum theory can be indeed derived on the basis of the uncertainty principle, as the same Heisenberg wished, is open. Recently, a proposal to construct QM as a theory of "principle" was provided by Bub; but this proposal does not use the uncertainty principle as one of its fundamental principles. Heisenberg's relation cut acts as a boundary between potentiality and actuality, a definite boundary between a QS and a classical apparatus. According to this position, in the world of potentiality should be possible to have precise value of measurable quantities: we see an evident contradiction with the assumption that physical quantities do not exist before a measurement process. In the perspective of the above relational approach to QM, Dickson (Dickson, 1996) proposes an original interpretation of uncertainty principle based on a refreshing reminder on the foundations of dynamics. According Dickson, the formulation of dynamical laws requires the notion of inertial frames. The tomographic approach seems in line with this idea.

We retain that the basic problem is how uncertainty principle consider the fundamental concept of “individuality" of a quantum event. First, we need to understand the definition of a quantum process, and not only to focus our attention on the unavoidable “disturbance" or "physical influence" of the observer on the observed. However, the new concept of nonlocality would change our vision of physical reality; probably we cannot anymore speak about simple individuality. The concept of individuality should be revisited. For instance, a forced equivalence between information and individuality (underlying a physical reality) is claimed by Zeilinger, putting forward an idea which connects the concept of information with the notion of elementary systems.

3.7 Entanglement and MWI

The meaning given to an entangled state by the many-worlds interpretation (Everett, 1959) could add new elements useful in our analysis. According to this interpretation, the terms of an entangled state describe something that really exist; the state does not just refer to the probabilities of results that would be obtained if measurement takes place. The different terms in an entangled state can be interpreted as showing that the universe branches into a number of different worlds. What are really important are the *correlations*. The main ingredient is thus the relative state.

Let us say that an observer O is going to perform a measure of the observable B on the system S being in a superposition state: $|\mathrm{S}\rangle = \alpha|\varphi_B\rangle + \beta|\phi_B\rangle$; where $|\varphi_B\rangle$ and $|\phi_B\rangle$ are eigenstates of B. Before the measurement is performed, the state of the composite system (Observer plus System) is

$$|\mathbf{O}{+}\mathbf{S}\rangle^0 = |Ready\rangle_O(\alpha|\varphi_B\rangle_S + \beta|\phi_B\rangle_S).$$

After the measurement (according to Shrödinger equation evolution) the composite system will be in a state

$$|\mathbf{O}{+}\mathbf{S}\rangle^1 = \alpha|\varphi_B\rangle_O|\varphi_B\rangle_S + \beta|\phi_B\rangle_O|\phi_B\rangle_S,$$

where the observer results entangled with the observed system. The physical meaning, according this interpretation, relies on the *correlations*. Each component of the wave function is called branch [fig. 3.1], and the branching is responsible for our experiences. These are the consequences of the fact that there is not interaction between branches, but every subsystem can only interact with the other subsystems

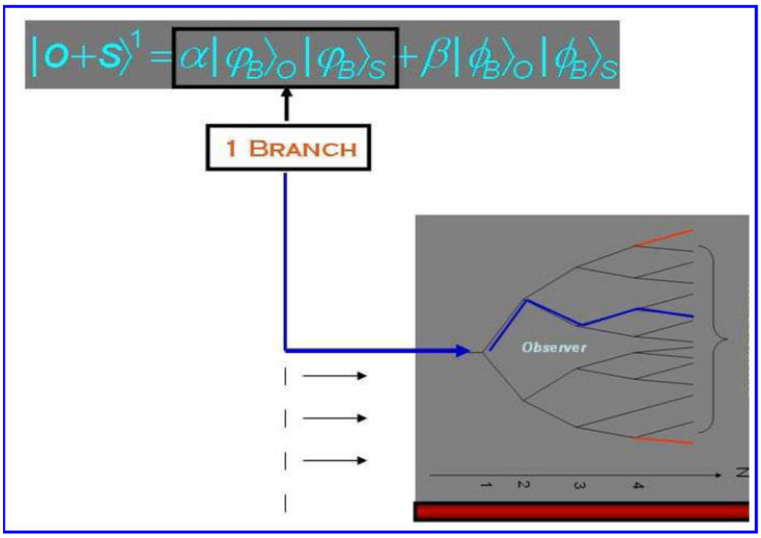

Figure 3.1: Branches.

states that are in the same branch. In this way, the quantum “world" is always decomposable into system and observer. The basic idea is that their correlations defines a preferred set of basis vectors. The relevance of quantum correlations has been stressed also in Cerf.(Cerf, 1997). There, it was claimed that only correlations, not the correlata of a QS, are physically accessible, but we have to include the observer as one of its parts. As a consequence, quantum reality is "real" in the sense that QM completely and deterministically describes the evolution of a closed system (not just its wavefunction), and that the statistical character arises from the fact that an observer, because he is part of the closed system, is offered an incomplete view of the QS he attempts to measure. Therefore, the quantum universe is deterministic as Einstein’s physical reality demands, but must include the observer as one of its parts due to the inseparability of entangled quantum states.

As we have seen this interpretation, the world we live in is continually branching, into multiple near-copies corresponding to different possible measurement outcomes. Unitary quantum dynamical laws describe the evolution of all these branches simultaneously. The definite measurement records that we observe, remember and communicate, are just characteristics of individual branches. Then, the development of all quantum systems are governed by the same unitary dynamical laws and hence develop completely deterministically and linearly. In this context, the wavefunction describes real properties, so that all speculations about determinism, causality, quantum jumps and collapse of wavefunction are unnecessary. When a microscopic QS interacts with a macroscopic apparatus, decoherence drives the "collapse" of the wave function (FAPP for all practical purposes). All possible outcomes of any measurement are regarded as real but we perceive only a specific outcome, because the state of my brain as part of the QS is strongly **correlated** with the outcome. In this context, the evolution of the wave function is deterministic, we are unable to predict with certainty the outcome of an experiment to be performed in the future. We do not know what branch of the wavefunction we will end up on, so we are unable to predict our future state of mind, thus, while the global picture of the universe is in a sense deterministic from my own local perspective from within the system we perceive quantum mechanical randomness. There is problem, within this approach is not yet fully explained the quantum mechanical rules to computing probabilities. The main problem is the derivation of the Born rule. **The problem of probability in this view of QM arises because the splitting of worlds seem unrelated to the Born probabilities.** The challenge of this interpretation is, therefore, to show that it predicts the existence of probability in the context of completely unitary time evolution. The debate on this question remain open, for instance **(objective) Bayesian interpretation** of quantum probability could be an interesting approach to solve the question.

4

PART 2: Structure of Thesis

4.1 Our Pahtway

In this Chapter, we introduce briefly the pathway of our thesis. We will fix as ontic level the phenomenon of QE. Staring from this assumption, we will derive a series of philosophical implications. The next figure shows our pathway.

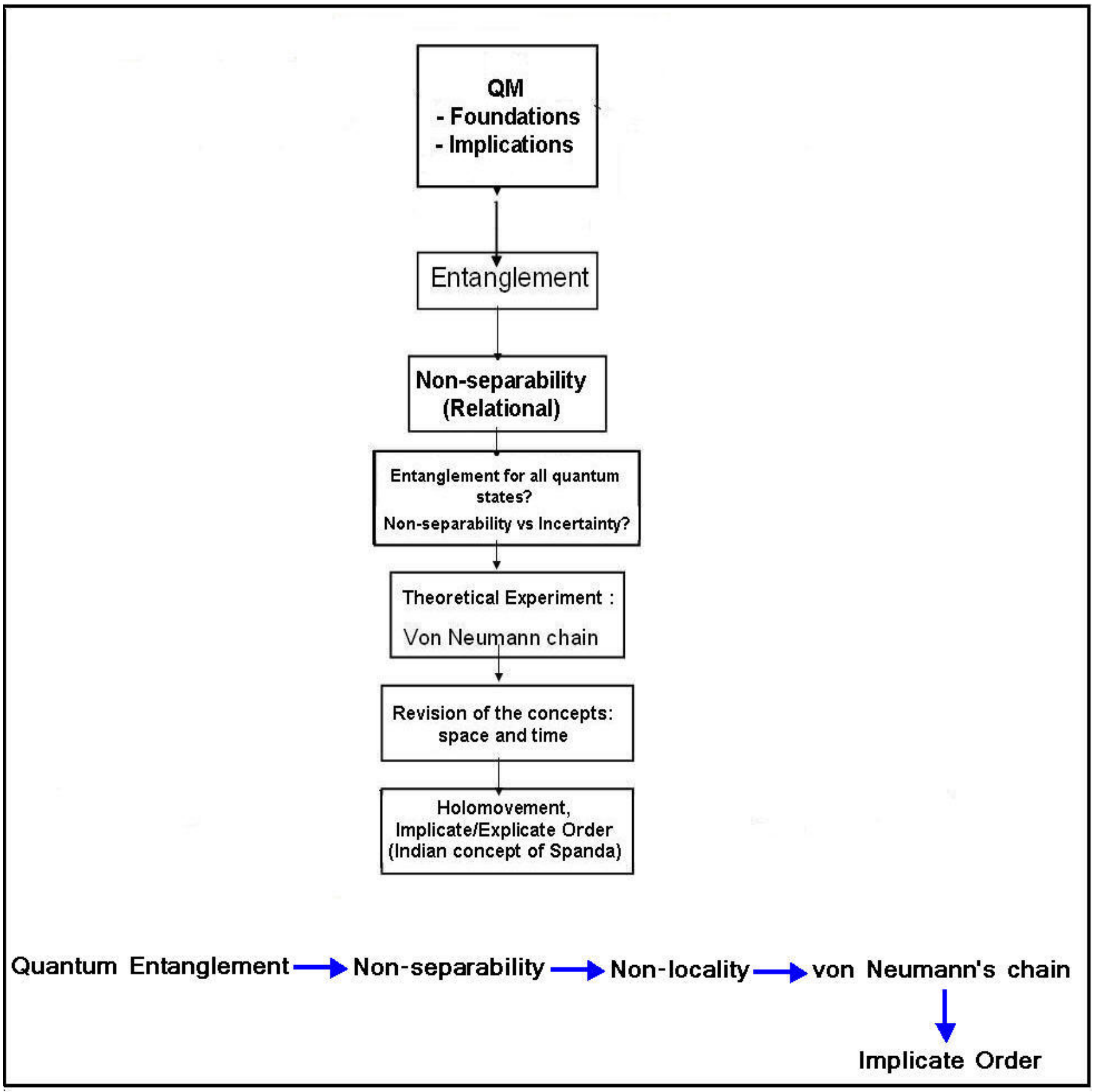

Figure 4.1: The structure of Thesis.

Our logical steps are summarized here:

- Entanglement⇒non-separability⇒non-locality.
- A relational approach to non-separability.
- Ubiquitous of Quantum Entanglement?
- Entanglement and Uncertainty?
- Entanglement and time.
- Entanglement and von Neumann chain: we will propose a theoretical experiment (see chap. 8).
- Entanglement and the Implicate Order
- Implicate order and Spanda Karika (Kashmir Shaivism Philosophy)

Basically our main objective is to find the possible links between these elements[1]:(i) *entanglement*, (ii) *non-separability*, (iii)*non-locality*, (iv)*space-time*,(v)*holomovement* and (vi)*implicate order*.
We will argue that the underlying physical reality (i.e. IO) is a structure inferred by the explicate order and that non-locality plays an important in this process. Finally, we will argue that the "observer"[2] is not a separated part of the explicate order (physical word) as well as is not a separated of the IO. The next scheme shows the possible pathway.

$$\begin{tikzcd}
\textbf{Underlying Physical Reality}: & \textit{Implicate Order} \arrow[d, Leftrightarrow] & & \\
& & \Longleftarrow & \text{Holomovement(by Entanglement)} \\
& \textit{Explicate Order} & &
\end{tikzcd}$$

In order to understand the problems linked at the interpretations of QM based on entanglement, we cite the following table (Drechsel 2009). This table (fig. 4.2) shows the fundamental difference between Classical Physics (CM), Quantum Physics (QM) and the Standard Model and Quantum physics based on Entanglement:

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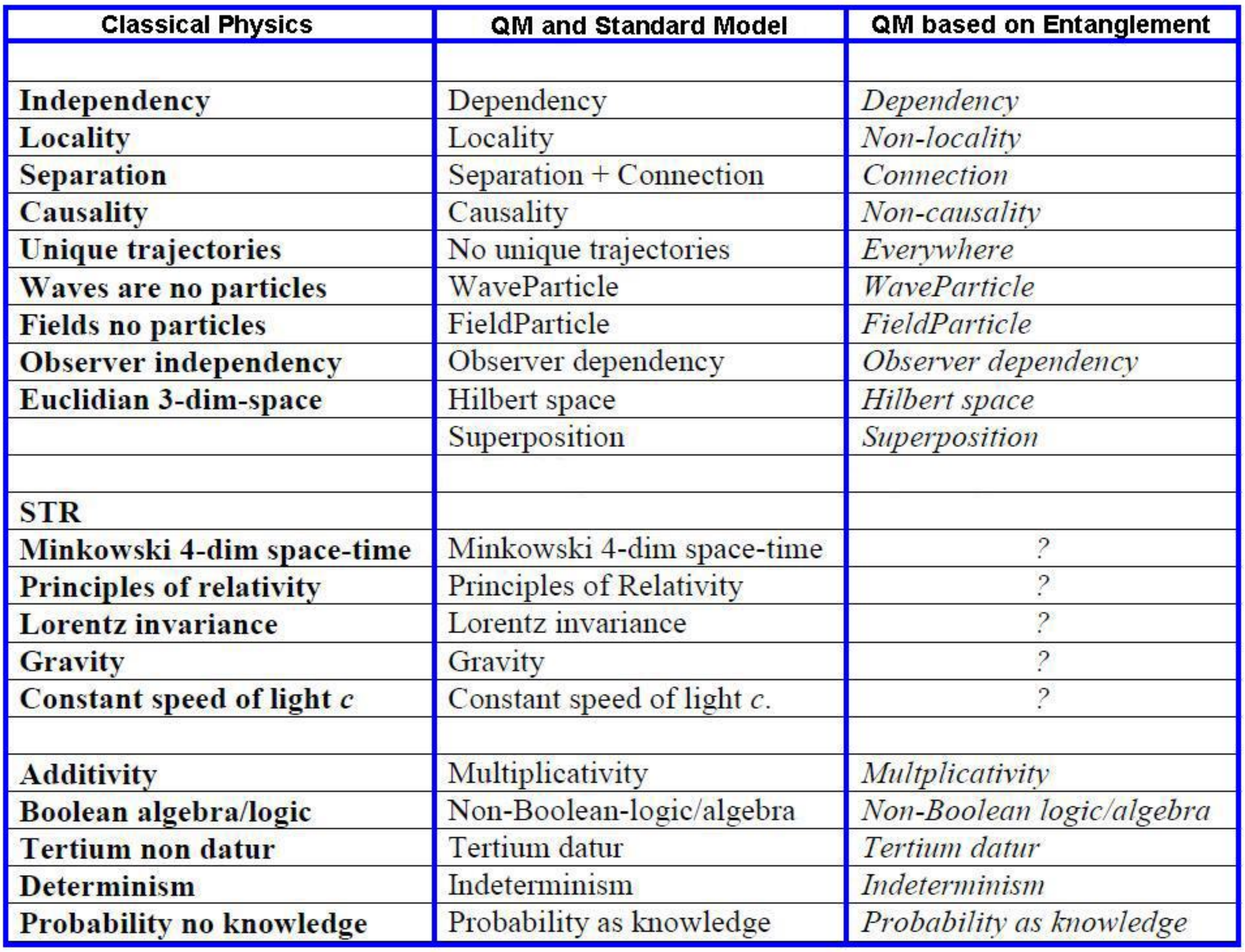
[1] i.e.: **entanglement ⇒non-separability⇒non-locality ⇒holomovement⇒implicate order**

[2] We call Observer or mind or consciousness



Classical Physics	QM and Standard Model	QM based on Entanglement
Independency	Dependency	*Dependency*
Locality	Locality	*Non-locality*
Separation	Separation + Connection	*Connection*
Causality	Causality	*Non-causality*
Unique trajectories	No unique trajectories	*Everywhere*
Waves are no particles	WaveParticle	*WaveParticle*
Fields no particles	FieldParticle	*FieldParticle*
Observer independency	Observer dependency	*Observer dependency*
Euclidian 3-dim-space	Hilbert space	*Hilbert space*
	Superposition	*Superposition*
STR		
Minkowski 4-dim space-time	Minkowski 4-dim space-time	?
Principles of relativity	Principles of Relativity	?
Lorentz invariance	Lorentz invariance	?
Gravity	Gravity	?
Constant speed of light c	Constant speed of light c.	?
Additivity	Multiplicativity	*Multplicativity*
Boolean algebra/logic	Non-Boolean-logic/algebra	*Non-Boolean logic/algebra*
Tertium non datur	Tertium datur	*Tertium datur*
Determinism	Indeterminism	*Indeterminism*
Probability no knowledge	Probability as knowledge	*Probability as knowledge*

Figure 4.2: Drechsel's Table

5

Entanglement and Subsystems: A relative concept

In spite of continuous progress, the current state of entanglement theory is still marked by a number of outstanding unresolved problems. These problems range from the complete classification of mixed-state bipartite entanglement to entanglement in systems with continuous degrees of freedom, and the classification and quantification of multipartite entanglement for arbitrary quantum states. At an even more fundamental level, recent indications show that the very definition of entanglement as given thus far may be too restrictive to embrace relevant physical and information-theoretic settings in their full generality.

5.1 Systems and Partitions

The relationship between QE and QS is very delicate. There are many efforts to understand this dynamics. Zanardi (Zanardi, 2001) argue that the partitions of a possible system has not an ontological superior status with respect to any other. We retain this conclusion very significative in order to understand the same notion of entanglement.

In his analysis, Zanardi argue that given a physical system S, the way to subdivide it in subsystems is in general by no means unique. On the contrary it is a widespread praxis in theoretical physics to consider different partitions into subsystems in dependence of both the physical regime and the the necessities of the description. It is is indeed a quite common experience to refer sometimes to a system (e.g., an atom, as elementary and sometime as composite e.g., made out electrons and nucleons). The emergence of a distinguished multi-partite structure is strongly dependent of the physical regime e.g., the energy-scale, at which one is working and on the set of observations (experiments) the observer is interested in. Clearly even the notion of entanglement is affected by some ambiguity being relative to the selected multi-partite structure. States that are entangled with respect to a given partition in subsystems can be separable with respect to another. In other words: states of a system S that is regarded as elementary can be viewed as entangled once S is endowed with a multi-partite structure. In this case one is in the, somehow paradoxical, situation of having entanglement seemingly without entanglement.

The above ambiguity is removed as soon as, according to some criterion, a preferred multi-partite structure is selected among the family of **all possible partition into subsystems**. In other terms, it is the set of "available" interactions that individuates the relevant multi-party decomposition and not an a priori, god-given partition into elementary subsystems. In his work Zanardi (Zanardi, 2001) try to provide a satisfactory algebraic definition of what a quantum subsystem is in an operationally motivated framework.

He concludes that some the consequences of the **non uniqueness of the decomposition of a given system S into subsystems** (such non-uniqueness) implies, at the quantum level, a fundamental ambiguity about the very notion of entanglement that accordingly becomes a relative one. One can parametrize the space of all possible partitions i.e, tensor product structures, of a n-dimensional quantum state-space by the points of a set T_n. The fact of considering all the points in T_n on the same footing (that amounts to establishing a democracy between different TPS's) provide a **relativization of the notion of entanglement**. Without further physical assumption, **no partition has an ontologically superior status with respect to any other**. The subsystems associated with all these possible i.e, potential multi-party decomposition were referred to as virtual.

Generalized Entanglement

Starting from previous statements, in general, how can entanglement be understood in an arbitrary physical system, subject to arbitrary constraints on the possible operations we may perform for describing, manipulating, and observing its states? Viola and Barnum (Viola-Barnum, 2007,2010) proposed answer builds on the idea that entanglement is an inherently **relative concept**, whose essential features may be captured in general in terms of the relationships between different observers, as specified through expectations of quantum observables in different, physically relevant sets. The role of the observer must be properly acknowledged in determining the distinction between entangled and unentangled states has been stressed by various authors in various contexts. We believe that the richness of applications as well as the numerous questions raised by the GE program[1]to date speak for themselves about the significance and potential of GE for properly capturing the unavoidable relativity of entanglement. We hope that the GE approach will provide fresh stimulus for the exploration of entanglement to be extended into still-unexplored physical, mathematical, and philosophical regions.

5.2 Entanglement for all quantum states?

In this section, we will argue that the classification of quantum systems is based on a subjective description (choice of their degrees of freedom). Starting from Torre's (Torre, 2010) work, we argue that there are not two classes of quantum states: entangled and factorizables. The factorizables state becomes entangled for a different choice of their degrees of freedom, they are entangled with respect to other observables. Thus, the subject (by his choice) introduces epistemic elements in the classification of quantum systems, for these reasons we conclude that all quantum states exhibit an entangled nature. Quantum systems admit a variety of tensor product structures depending on the complete system of commuting observables chosen for the analysis, as consequence we have different notions of entanglement associated with these different tensor product.

Torre's paper (Torre et al,2010), is a fundamental paper about the nature of entanglement.

It is shown that a state that is factorizable in the Hilbert space corresponding to

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[1] GE stand for generalized entanglement, the key realization underlying the GE approach is that the distinctive features of entanglement are determined by the expectation values of a distinguished subspace of observables of S.

some choice of degrees of freedom, becomes entangled for a different choice of degrees of freedom. Therefore, entanglement is not a special case but is ubiquitous in quantum systems. Simple examples are calculated and a general proof is provided. The physical relevance of the change of tensor product structure is mentioned. According Torre, one may erroneously think that there are two classes of states for the QS, entangled and factorizable, that correspond to qualitative difference in the behaviour of the system, close to classical in one case and with strong quantum correlations in the other. Torre in his work argue that this is indeed wrong because factorizable states also exhibit entanglement with respect to *other* observables. In this sense, all states are entangled; **entanglement is not an exceptional feature of some states but is ubiquitous in QM.**

Consider two exclusive properties of a QS, A_1 and A_2, corresponding to two different eigenvalues of some observable (for instance, spin up and spin down) and also another unrelated pair of exclusive properties, B_1 and B_2 (for instance, located here or there). Furthermore, imagine two possible states of the system: ψ_1, corresponding to the simultaneous appearance of the properties A_1 and B_1 and the other state, ψ_2, corresponding to the appearance of the properties A_2 and B_2. The superposition, $\psi_1 + \psi_2$, is an entangled state of the system. In this state, none of the properties A_1, A_2, B_1, B_2 are objective (in the sense that the state is *not* an eigenvector corresponding to any of these eigenvalues) but there are strong quantum correlations among them because the observation of one property, say A_1, forces the appearance of B_1 although they may be totaly unrelated (like spin and location). In entangled states all sort of astonishing quantum effects appear, like violations of Bell's inequalities, EPR (so called) paradox, Schrödinger cat, nonlocality, contextuality, teleportation, quantum cryptography and computation, etc. The principle of superposition, that generates the entanglement, contains perhaps the central essence of QM and almost all pondering concerning the foundations of QM involve entangled states. As we know, the opposite to the entangled states are the factorizable states, for instance ψ_1 or ψ_2 above, where the properties are objective and the behaviour of the system is closer to classical expectations; for instance, the correlations found are understood as a direct consequence of the preparation of the system.

The fact that factorizability and entanglement are not preserved in a change of the degrees of freedom used to describe the system has been analysed by experts, specially those involved in quantum computation research (Zanardi, 2001), but this important feature of QM is ignored. Torre, in his work present simple calculations that emphasize this remarkable feature. In his paper Torre define entanglement and factorizability with rigor and he will prove that every factorizable state becomes entangled in a different factorization of the Hilbert space.

Entanglement and Compound Systems

The relationship between QE and compound system is the key to understand the root of entanglement (Viola et al. 2007). As we know, the state of a compound QS, $S = (S_1, S_2)$, belongs to a Hilbert space build as the tensor product of spaces corresponding to each subsystem: $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$. This decomposition, denoted as a *Tensor Product Structure* (TPS), may correspond to two individual physical subsystems like, for instance, one electron and one proton building a hydrogen atom, or to different degrees of freedom or coordinates of one system. The degrees of freedom are expected to be independent in the sense that the assignment of one value to one degree of freedom is compatible with an arbitrary assignment of *any* value for the other one. For QM, this means that, in the Hilbert space, the two degrees of freedom A and B will correspond to two observables whose operators act individually in each factor space, that is, they are of the form $A \otimes \mathbb{I}$ and $\mathbb{I} \otimes B$ and therefore they commute. If we define bases in each factor space, $\{\varphi_k\} \in \mathcal{H}_1$ and $\{\phi_r\} \in \mathcal{H}_2$, the most general state in the Hilbert space is given by an expansion in the basis $\{\varphi_k \otimes \phi_r\}$ as

$$\Psi = \sum_{k,r} C_{kr} \ \varphi_k \otimes \phi_r \ . \tag{5.1}$$

This state Ψ is factorizable if there exist $\Psi_1 \in \mathcal{H}_1$ and $\Psi_2 \in \mathcal{H}_2$ such that $\Psi = \Psi_1 \otimes \Psi_2$. Otherwise it is entangled. Notice that in the determination of whether a state is factorizable or entangled, the factorization of the Hilbert space (that is, the TPS) is crucial and this factorization depends on the choice of the observables corresponding to the degrees of freedom. From the mathematical point of view, every TPS is equivalent but from the physical point of view, the TPS are determined operationally by the measurements and operations that are accessible under given physical circumstances. For instance, if our composite system consists of two particles that are spatially separated, the most natural TPS is given by the tensor product of the single-particle Hilbert spaces associated with the individual particles. However if in this same system, the overall motion is uninteresting and only the relative motion is relevant we may prefer a TPS corresponding, not to the position of the individual particles, but instead, to the center of mass and relative position. A relevant question is whether some arbitrary state of a system, analyzed with different choices of the degrees of freedom, that is, with different TPS, still maintains the property of been factorizable or not. In other words, is factorizability an objective property of the system or is it a feature of our description of the system. In order to approach this question we recall a useful tool provided by the Quantum Covariance Function that relates a state Ψ and two observables A and B.

Factorizability of a state as Epistemic Property?

An important question is related at the property of factorizability of quantum state. Is the factorizability an objective property? In few words, is factorizability an objective property of the system or is it a feature of our description of the system (i.e. an epistemic property, see fig. 5.1).
With reference to previous work (Torre, 2010), the authors show that factorizability and entanglement are not preserved in a change of the degrees of freedom used to describe the system, in details they demonstrate that the factorizability of a state is a property that is **not** invariant under a change of the degrees of freedom that we use in order to describe the system. From mathematical point of view (Torre, 2010), they consider a QS with two subsystems $S = (S_A, S_B)$ that may correspond to two degrees of freedom A and B. The state of the system belongs then to the Hilbert space $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$ and the two degrees of freedom are represented by operators $A \otimes \mathbb{I}$ and $\mathbb{I} \otimes B$. Given a factorizable, non entangled, state $\Psi = \Psi_A \otimes \Psi_B$ with Ψ_A and Ψ_B arbitrary states (not necessarily eigenvectors of A and B) in the spaces $\mathcal{H}_A$ and $\mathcal{H}_B$. Then there exists a transformation of the degrees of freedom $F = F(A, B)$ and $G = G(A, B)$ that suggests a different factorization, $\mathcal{H} = \mathcal{H}_F \otimes \mathcal{H}_G$, where the state is no longer factorizable: $\Psi \neq \Psi_F \otimes \Psi_G$ with $\Psi_F \in \mathcal{H}_F$ and $\Psi_G \in \mathcal{H}_G$.

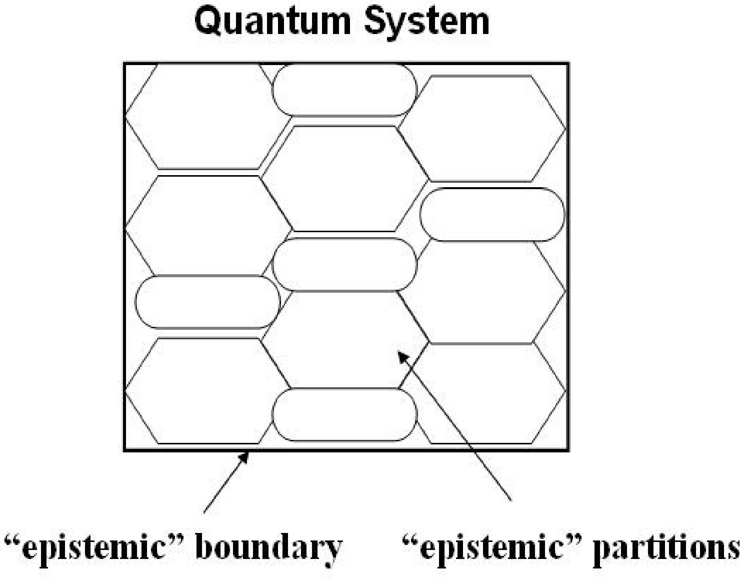

Figure 5.1: Quantum Partitions.

The state becomes entangled in these new degrees of freedom; the factorizability of *states* is not invariant under a different factorization of the Hilbert space. To conclude, they have showed that for any system in a factorizable state, it is possible to find different degrees of freedom that suggest a different factorization of the Hilbert space where the same state becomes entangled, for this reason every state, even for those factorizable, it is possible to find pairs of observables that will violate Bell's inequalities.

In conclusion, we have seen that the factorizability of a state is a property that is not invariant under a change of the degrees of freedom that we use in order to describe the system.

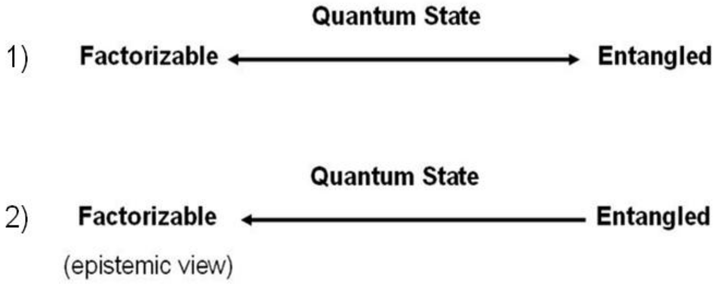

Figure 5.2: 1) de la Torre's thesis ; 2) Our position.

The fact that the appearance of entanglement depends on the choice of degrees of freedom can find an interesting application in the "disentanglement" of a state. One can, sometimes, transform an entangled state into a factorizable one by a judicious choice of the degrees of freedom. Perhaps the most important manifestation of quantum correlations, that is, those that can not be explained in terms of some classical interaction, involves the violations of Bell's inequalities. Furthermore, it has been shown that in every nonfactorizable or entangled state there are observables that violate Bell's inequalities. In this work, we have seen that for any system in a factorizable state, we can find different degrees of freedom that suggest a different factorization of the Hilbert space where the same state becomes entangled. As a consequence of this we can conclude that in every state, even for those factorizable, we can find pairs of observables that will violate Bell's inequalities. This violation of the classical behaviour is then not exceptional but is ubiquitous in quantum systems. We notice that in the determination of whether a state is factorizable or entangled, the factorization of the Hilbert space is crucial and this factorization depends on the choice of the observables corresponding to the degrees of freedom. In this paper, we are interested to analyze the possible epistemic elements related to the choice of QS and their subsystems. In other words, if the choice of degree of freedom of

QS contains subjective elements. We will refer often to recent and relevant work by de la Torre. These authors, in their paper, showed that a state that is factorizable in the Hilbert space corresponding to some choice of degrees of freedom, becomes entangled for a different choice of degrees of freedom. According the authors,in every state, even for those factorizable, we can find pairs of observables that will violate Bell's inequalities. Also they analyze the inverse problem: the fact that the appearance of entanglement depends on the choice of degrees of freedom can find an interesting application in the "disentanglement" of a state, one can, sometimes, transform an entangled state into a factorizable one by a judicious choice of the degrees of freedom. From philosophical point of view we agree with first analysis, instead we disagree with the second statement.

The figure 5.2 showed the two positions. We will analyze in the next section that factorizable state is an epistemic view of quantum state and that all QS exhibit an entangled nature, the real ontic nature. Conclusions We can conclude that the epistemic approach to QS do not always exhibit the entangled nature of quantum states (i.e. apparent factorizability). We retain instead that the ontic nature of quantum states is entangled. The underlying physical reality exhibit an intrinsic quantum entangled nature.

6

Entanglement and Time

6.1 Temporal Bell Inequalities

Brukner et.al (Brukner et al, 2004) derive the temporal Bell inequalities from simple principles. These temporal Bell inequalities are derived from the assumptions of realism and locality in time. The authors shown that QM violates these inequalities and thus is in conflict with the two assumptions. This can be used for performing certain tasks that are not possible classically. Their results open up a possibility for introducing the notion of entanglement in time in quantum physics.

Conceptually, as well as mathematically, space and time are differently described in QM. While time enters as an external parameter in the dynamical evolution of a system, spatial coordinates are regarded as quantum-mechanical observables. Moreover, spatially separated quantum systems are associated with the tensor product structure of the Hilbert state-space of the composite system. This allows a composite QS to be in a state that is not separable regardless of the spatial separation of its components. We speak about *entanglement in space*. On the other hand, time in QM is normally regarded as lacking such a structure.

Entanglement in space displays one of the most interesting features of QM (called nonlocality). As we know, *Locality in space* and *realism* impose constraints, Bell's inequalities, on certain combinations of correlations for measurements of spatially separated systems, which are violated by QM. Furthermore, entanglement in space is considered as a resource that allows powerful new communication and computational tasks that are not possible classically. Because of different roles time and space play in quantum theory one could be tempted to assume that the notion of *"entanglement in time"* cannot be introduced in quantum physics.

The authors will explicitly derive *temporal Bell's inequalities.* (the notion of temporal Bell's inequalities was first introduced by Leggett and Garg (Leggett et al. 1985) in a different context) in analogy to the spatial ones. There are constraints on certain combinations of temporal correlations for measurements of a *single* QS, which are performed at *different* times. Brukner explicitly shows that QM violates these inequalities.

The temporal Bell's inequalities are derived from the following two assumptions:

> (a) *Realism:* The measurement results are determined by "hidden" properties the particles carry prior to and independent of observation, and
> (b) *Locality in time:* The results of measurement performed at time t_2 are independent of any measurement performed at some earlier or later time t_1.

It should be noted that in contrast to spatial correlations, where the special theory of relativity can be invoked to ensure locality in space, no such principle exists to ensure locality in time for temporal correlations. Nevertheless, it is meaningful to ask whether or not the quantum-mechanical predictions are compatible with the assumptions (a) and (b). Ultimately we expect to learn more about the relation between the structure of space and time and the abstract formalism of quantum theory.

In conclusion, the difference between the spatial and temporal structure may ultimately be fundamental, or it may be an indication that we need a deeper theory in which the two need to be treated on a more equal footing (quantum field theory does not suffice in this sense). Either way, it appears that the next step should lie in exploring the consequences of combining entanglement in space and time in order to study how they relate to each other.

6.2 Entanglement as Nonlocal Determinism

As we have seen quantum correlations in space-like separated, according Einstein, imply particles carrying hidden variables, which determine the particle's behavior. In this way Einstein concluded that the quantum mechanical description of the physical reality cannot be considered complete. Bell (1964) showed that if one only admits relativistic local causality the correlations occurring in two-particle experiments should fulfill clear locality conditions ("Bell's inequalities"). Bell experiments conducted in the past two decades (in spite of their loopholes), suggest a violation of local causality: statistical correlations are found in space-like separated detections; violation of Bell's inequalities ensure that these correlations are not predetermined by local hidden variables. Nature seems to behave nonlocally, and QM predicts well the observed distributions. So, the QM predicts correlated outcomes in space-like separated regions for experiments using two-particle entangled states. Bell experiments demonstrate nonlocal correlations[1] between space-like separated events, which cannot be explained by means of relativistic influences bounded by the velocity of light. According Suarez, **giving up the concept of locality is not sufficient to be consistent with quantum experiments. One has to give up also nonlocal determinism** (i.e. the view that one event occurring before in time can be considered the cause, and the other occurring later in time the effect.).

In other words, this means that one has to give up the view that the outcomes at each part of the setup result from properties preexisting in the particles before measurement: outcomes in Alice's (respectively Bob's) cannot be explained by the properties the photon carries when leaving the source and the settings of Alice's (respectively Bob's) measuring devices. According the before-before or Suarez-Scarani[2]. The time-notion makes sense only in the domain of the relativistic local phenomena. The nonlocal correlations cannot be explained by any history in spacetime, they come from outside spacetime. Putting together the results of these experiments types one can conclude that in entanglement experiments local random events experience influences from outside spacetime to produce nonlocal order. Quantum correlations unite in the same phenomena full local randomness and nonlocal timeless order. According, Suarez the before-before experiment demonstrates that quantum randomness can be controlled by influences from outside spacetime, and therefore by immaterial free will. Rather than looking at quantum physics as the model for explaining free will, one should look at free will as a primitive principle for explaining why the laws of Nature are quantum. QM actually means that in nature this ordering activity comes about without flow of time.

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[1] According Suarez-Scarani (Suarez-Scarani, 1997), the experiments demonstrates that these nonlocal correlations cannot be explained in terms of "before" and "after".

[2] They argued that recent experiments with moving beam-splitters demonstrate that there is no real time ordering behind the nonlocal correlations: In Bell's world there is no "before" and "after"

7

Quantum Entanglement and the Implicate Order

7.1 Implicate Order and Quantum Theory

Before to introduce the possible link between QE and the IO, we need to analyze the concept of IO. Historically Bohm proposed originally in 1951 (Bohm, 1951) the ontological interpretation of QM based on an interpretation of quantum theory and later developed especially in cooperation with his long-time colleague Hiley (Bohm,Hiley 1993).

Bohm[1]felt that the ontological interpretation can do two things to make the IO more

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[1] Buckley-Peat (Buckley, Peat 1996) Bohm explain to connection between QM and the notion of observer: This idea of implicate and explicate order obviously involves wholeness, because, in the IO, everything has its origin in the totality, it is folded into the totality. Moreover, the separation of the observer and the observed is no longer basic in this view. **The observer is essentially an IO, and so is the observed**. Everything that is observed is really the intersection of two streams of energy: one stream which belongs to the thing observed, the other which belongs to the observer. The 'phenomena' are the result of the intersection of these two streams. Both streams come ultimately from the same total reality. It suggests a structure in which mind and matter are not very different. Anyone can see that our thought has this character, that a large part of it is implicit or folded up. When one part is explicit, a tremendous amount is implicit. This IO is common to mind and to matter, so it means that we have much of a parallelism between the two sides. The things which are well defined and explicate have to be seen as special features of the IO. The underlying

specific: firstly, to show how the explicate order arises out of the IO, and secondly, to provide a more specific idea about how mind and matter are related. According Pylkkänen (Pylkkänen,2007):

> To see how the explicate order arises out of the IO, it is useful to consider the "field theory", that is, the ontological interpretation of the electromagnetic field. Roughly, one thinks of the electromagnetic field being in an IO (as we indeed mentioned above when saying that the movement of light waves in, for example, every region of the room enfolds information about the whole room). When one applies the ontological interpretation of quantum theory to this field, one then sees how the explicate order arises. The explicate order here is the famous "quantum", that is, a bullet of light, which in Bohm's theory has to be seen as a momentary, particle-like manifestation, rather than as a continuously existing particle. This, of course, is very much in the spirit of what we have said above about the IO.

Bohm in his paper (Bohm,1990)[2] developed in detail the notion of IO. His essential idea is that the whole Universe is in some way enfolded in everything, and that each thing is enfolded in the whole. According Bohm, everything enfolds or implicates everything. In his words:

> The basic proposal is then that this enfoldment[3] In this sense, the whole universe is enfolded in everything, and everything is enfolded everywhere in the whole universe. The IO thus prevails as the most fundamental order of the universe currently known to us. relationship is not merely passive or superficial. Rather, it is active and essential to what each thing is. The external relationships are then displayed in the unfolded or explicate order in which each thing is seen, as has already indeed been indicated, as relatively separate and extended, and related only externally to other things. The explicate order, which dominates ordinary experience as well as classical (Newtonian) physics, thus appears to stand by itself. But actually, **it cannot be understood properly apart from its ground in the primary reality of the IO**. Because the IO is not static but basically

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reality is the IO, and the explicate order is a very special case of the IO.

[2] In that article Bohm to provide a basis for a non-dualistic theory of the relationship of mind and matter.

[3] This idea of "enfoldment" of the whole universe in each part, resonates with Leibniz's idea of monads. According Bohm the enfoldment is taking place in a wide range of domains, each region or "part" of the universe enfolds information about the whole universe.

> dynamic in nature in a constant process of change and development, I called its most general form the holomovement. All things found in the unfolded, explicate order emerge from the **holomovement**[4] in which they are enfolded as potentialities and ultimately they fall back into it. [.....] It takes only a little reflection to see that a similar sort of description will apply even more directly and obviously to mind. The general implicate process of ordering is **common both to mind and to matter**[5]. This means that ultimately mind and matter are at least closely analogous. Therefore, it seems reasonable to go further and suggest that the IO may serve as a means of expressing consistently the actual relationship between mind and matter without introducing something like the Cartesian duality between them.

Accoding Bohm the Non-locality (Bell's Inequality violation) lead us to new notion of quantum wholeness which implies that the world cannot be analyzed into independently and separately existent parts. **Quantum wholeness is what is primary.** In particular, such wholeness means that in an observation carried out to a quantum theoretical level of accuracy, the observing apparatus and the observed system cannot be regarding as separate. Rather, each participates in the other to such an extent that it is not possible to attribute the observed result of their interaction unambiguously to the observed system alone.
With Bohr, he shared the view that quantum theory emphasizes undivided wholeness, as well as the more philosophical idea that it is important to carefully consider the role of language and communication in physics. According Bohm, Bohr treats the entire process of observation as a single phenomenon which is a whole that is

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[4] Accordin Pylkkänen the IO is not static but rather basically dynamic in nature, in a constant process of change and development. This is why he called its most general form the holomovement. Bohm's ontology takes movement as fundamental, and here he connects with the tradition of "process philosophers" from Heraclitus to Whitehead. Bohm's IO ontology contrasts with the ontology that has been prevalent in Western philosophy and science. This is **the atomistic ontology,** which assumes that everything consists of some fundamental elements (i.e. particles and/or fields) that are only externally related to each other. Atomistic ontology dominates much of contemporary science and philosophy. Bohm claims that physics strongly suggests that the atomistic ontology does not fit with the experimental facts of relativity and quantum theory. If he is correct, we need a new more fundamental ontology or theory of reality, and this is indeed what he tried to develop. He also thought that the IO framework can be extended to the domain of biological and psychological phenomena, making it into a proposal about the general architecture of existence as a whole, instead of just about physical existence.

[5] Bohm was led to propose that the general implicate process of ordering is common to both mind and matter.

not further analyzable. For Bohr, this implies that the mathematics of the Quantum Theory is not capable of providing an unambiguous (i.e., precisely definable) description of an individual quantum process. But rather, it is only an algorithm yielding statistical predictions concerning the possible results of an ensemble of experiments. Bohr further supposes that no new concepts are possible that could unambiguously describe the reality of the individual quantum process. Therefore, there is no way intuitively or otherwise to understand what is happening in such processes. Only in the Newtonian limit can we obtain an approximate picture of what is happening. And this will have to be in terms of the concepts of Newtonian physics. Bohr's approach has the merit of giving a consistent account of the meaning of the Quantum Theory. Moreover, it focuses on something that is new in physics (i.e., the wholeness of the observing instrument and what is observed). The question is clearly also of key importance in discussing the relationship of mind and matter. But Bohr's insistence that this wholeness cannot be understood through any concepts whatsoever – however new they may be – implies that further progress in this field depends mainly on the development of new sets of mathematical equations without any real intuitive or physical insight as to what they mean apart from the experimental results that they may predict. It seems very important to question Bohr's assumption that no conception of the individual quantum process is possible.

7.2 Quantum Entanglement and Holomovement: an unfragmented epistemology

In this section we argue about the natural revision of the notions of space and time started by general theory of relativity and QM (i.e entanglement). In the light of QE (quantum correlations which transcends our notions of space and time), we suggest to consider the viewpoint that spatio-temporal relations between objects are emergent properties in the explicate order, and that Bohm's holomovement concept has no space-time structure. For these reasons, we cannot relying the space-time as primitive notions (i.e. the ontic level). The primary elements in our approach will be considered the holomovement which unfolds and enfolded (via Entanglement) by space-time. In the last section of paper, we will speculate about a possible link between the Holomovement and Spanda, a central notion in the tradition of Kashmir Shaivism philosophy (Dyczkowski,1996).

Our pathway in this section

In order to support our main thesis, we will focus on non-local features of entangled quantum systems. The entanglement is a correlation related to the indivisible wholeness of quantum systems which transcends our physical concepts of space-time.

As we know, this correlation is made responsible for the instantaneous determinacy of certain aspects also of the distant part when the local part is determined by measurement. Although there are some speculations about "non-locality in time" the usual understanding of non-locality is restricted to space. In this short paper, we argue that whole space-time nature arise in the Explicate order and that the Bohm's holomovement represent, in this view, the ontic level of underlying physical reality. For these reasons, we agree with the following quotation?:

> **"One important feature concerning the holomovement is that *it is not described in space-time but from it space-time is to be abstracted.* Thus we no longer start with an a priori space-time manifold in order to discuss physics; rather we construct space-time from the underlying process. Is not, as Wheeler and Hawking suggests, a progression for the continuum via fluctuations to the space-time foam: rather it is the simplicial description of the relative invariant features of the holomovement that become the foam from which the continuous space-time is abstracted. Thus locality is no longer a primary concept but is also abstracted so that quantum non-local correlations could be explained as remnant of the basic underlying complex."**

As we know, Bohm introduced the quantum potential in the standard QM. In virtue of the features of quantum potential, Bohm introduced a new order for understand quantum phenomena, in particular the quantum non-locality. According this new order subatomic particles are instantaneously connected through space which functions as an immediate information medium between them. We will not use here the quantum potential to explain quantum correlations. We will accept the feature of the entanglement as theorized by standard QM.

The starting point according Bohm (Bohm, 1980) is the understanding of the universe as an unbroken, undivided whole. Every attempt to analyze the whole by breaking it into seemingly independent parts is in principle incomplete and in the last consequence doomed to failure. Bohm very strongly points out that everything or, better, the whole is in constant motion, is evolving, and that nothing ever is

fixed or reaches an ultimate, final form. Some of the notions and phrases underlying the processuality in his thinking are "undivided wholeness in flowing movement" or "holomovement", "the enfolding- unfolding universe"; he also stresses that Şknowledge should be considered as a **process**". In details, the holomovement is a dynamics holistic pulsation in which orders unfold and enfold. This fundamental process is not a movement within space-time but rather a process in which ultimately **space-time and its contents are created**. In this context, we have difficulty to fit contemporary physics into a pure reductionist framework, QE lead us to consider a non-reductionistic wholeness approach in physics.
Very interesting is the definition of entanglement stated by Hu (Hu,2006):

> So what is then the essence of QE? We propose that QE is not merely the correlations of certain observable physical parameters in the process of measurement but a genuine interconnectedness and inseparableness of once interacting quantum entities. It is the quantum "glue" holding once interacting quantum entities together in pre-spacetime and can be directly sensed and utilized by the entangled quantum entities [...] It can be diluted through entanglement with the environment, i.e.,decoherence.

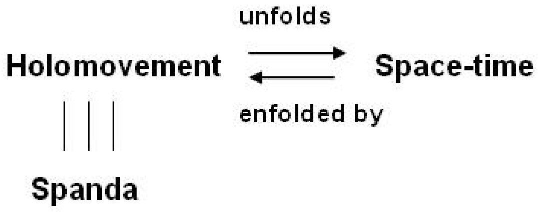


Figure 7.1: Our pathway: holomovement unfolds and enfolded **(via Entanglement)** by space-time. Spanda is assimilable with holomovement.

In few words, we have to do with these fundamental elements:

1. Non-locality
2. space-time
3. Implicate/Explicate Order
4. Holomovement

We argue that these are not separable elements and that the Holomovement unfolds and enfolded by space-time via Entanglement (see Fig. 7.1). Moreover, we argue that this flux called Holomovement has a common ground with the concept of Spanda (not physical flux) a central notion in the philosophy of Kashmir Shaivism.

Introduction

Today, most important studies in these fields are carried forward by Pylkkänen and Hiley. In the present paper, often we will refer to these works. Bohm, calls IO the primary reality, this reality exists ’folded up’ in nature and gradually unfolds as the universe evolves, enabling organization to emerge, in this way, the implicate becomes explicate over time. Against the Copenhagen interpretation of QM, he began to suspect that there was a deeper order underlying the complex behavior of particles, giving rise to his theory of an ’IO’ in the universe, an ’undivided wholeness’ that governs all reality. The theorization of the existence of a ’quantum potential’, which determined the motion of particles was the main support for the existence of the IO. We remember that, in this brief paper, we are not going to utilize this concept. According Bohm the whole universe can be thought of as a holomovement (see Fig. 7.2 and 7.3), in which a total order is contained. The explicate order is a projection from **higher dimensional levels of reality**, and the apparent stability and solidity of the objects and entities composing it are generated and sustained by a ceaseless process of enfoldment and unfoldment, for subatomic particles are constantly dissolving into the IO and then recrystallizing. According Globus (Globus, 2007) "Bohmian wholeness is dynamical: a continuous holomovement. The holomovement has two simultaneous processes: implication and explication. In implication the ordinary Cartesian order is enfolded to the whole where it "exists" in potentia, while in explication the Cartesian order is unfolded from the whole. Hiley (Bohm-Hiley, 1993), affirm that:

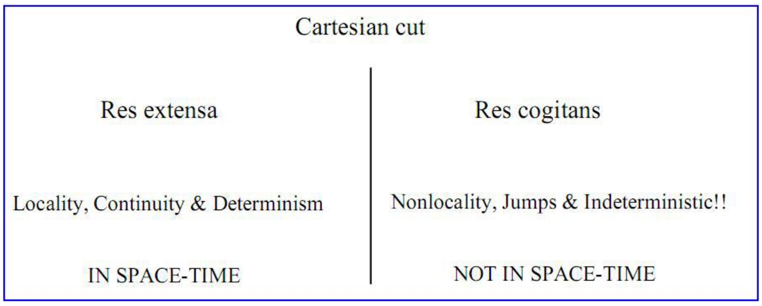


Figure 7.2: According Hiley: Cartesian division between res extensa and res cogitans.

> Is spacetime primary? Could space-time merely be an appearance, a feature that has to be abstracted from some deeper structure, a structure where

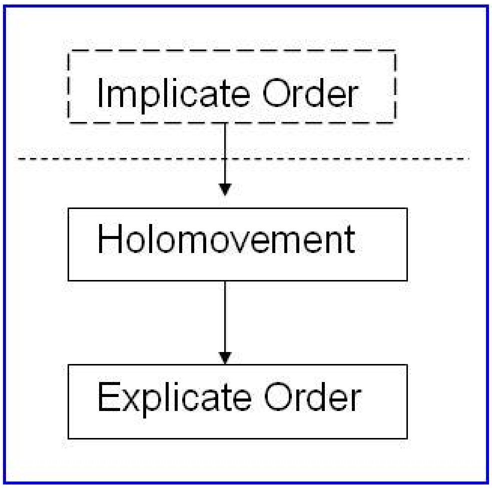


Figure 7.3: Holomovement as flux between the Implicate and Explicate Order.

> space-time itself is not taken as basic? If we adopt this radical view, we can see that it is not necessary to insist on the Cartesian division between res extensa and res cogitans. Matter actually has its origins in a deeper structure, **a structure where space-time and hence extension is not primary**. If such an approach were viable then matter and mind need no longer be separated by space-time constraints as illustrated in the picture above (Fig. 7.2)".

According Hiley, this is fundamentally the wrong view. **Something new is needed, and this new order must not take space-time as basic and fundamental.**

7.3 Unfragmented Mind-Matter?

Bohm is convinced that metaphysical realities need to be embraced in our understanding of quantum non-locality. The separation of the two mind and matter is an abstraction. **The ground is always one.** The non-locality principle embedded in QM is therefore highly suggestive of a universe that is a holistically interconnected reality, in which, at the quantum level, particles interact interdependently according to some guiding principle, or 'hidden variable'. The notion of QE, as for chaos, complexity and chance, should not be interpreted in terms of disorder: on the contrary, it directs us to a view of reality which, at the ultimate level, is remarkably unfragmented.
Time, like space, is therefore to be regarded as a secondary, rather than a primary, order, derived from the multidimensional reality of the 'holomovement'. Globus (Globus, 2007) in a work dedicated to Pylkkänen's book affirm that

the holomovement (Bohm's Ontology) has a "double aspect" theory, reminiscent of Spinoza, with mind and matter as aspects of a neutral reality. The tertium quid for Bohm is the holomovement. Globus add that although Bohm considers the IO to be the fundamental order and the explicate order to be derivative; the processes of implication and explication are at parity. Pylkkänen presents Bohm's theory of the mind-matter relationship, which is called "soma-significance". In the theory of soma-significance, all matter has a mental aspect, which is a Bohmian version of panpsychism. And all mind has a material aspect. But mind and matter are basically abstractions. Since nothing is purely mental or purely physical, Bohm thinks the problem of mind/matter interaction is elided. Mind and matter are aspects of the same level, "correlated projections of an underlying ground". **This implies no causal relationship between them at the same level**. On the other hand, there are causal relationships between levels. Mind affects matter at a less subtle level and matter affects mind at a more subtle level. Mind is both implicate and explicate. Matter is implicate and explicate, too. In other words, the fundamental concepts in Bohm's view is contained in the notion of "holomovement", a term he coined wherein he posits the "unbroken wholeness", and enfolded order of the material universe. We are unable to distinguish Matter and Mind because they are an integral feature of the holomovement. From philosophical point of view, this basic unity is the same as the underlying wholeness of Bohm's "IO" and is similar to **Jung's theory of a collective unconscious, the unus mundus** (Giannetto-Pozzi, 1998). In the last section of paper, we argue that Holomovement flux is similar to Spanda, the fundamental concept in the philosophy of Kashmir Shaivism by Abhinavagupta.

7.4 Space-Time in Bohm's Ontology

According Bohm, the space could be considered more fundamental more real than the objects in it, but if we take the view that space is what is real than we have to say that the measure of space is not what is real, the measure of space is what matter provides, so space goes beyond the measure of space. As said before, the IO has to be regarded as a process of enfoldment and unfoldment in a higher-dimensional space. The processes of enfoldment and unfoldment in three dimensions (as with the famous ink-in-fluid analogy and the hologram) are simplifications that only apply under certain conditions. For example, strictly speaking, the electromagnetic field (which underlies holography) obeys quantum laws and is thus a multidimensional reality. In Bohm's words:

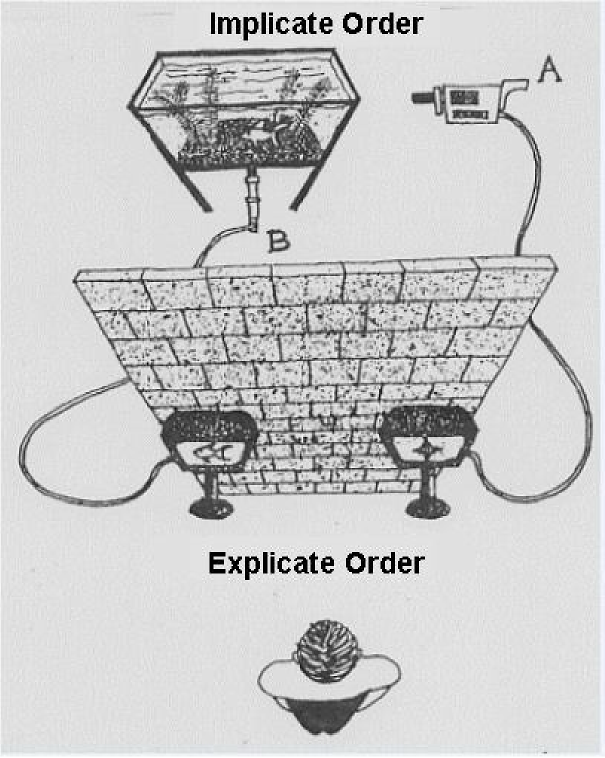


Figure 7.4: The Implicate and Explicate Order.

> Quite generally, then, the IO has to be extended into a multidimensional reality. In principle this reality is one unbroken whole, including the entire universe with all its "fields" and "particles". Thus we have to say that the holomovement enfolds and unfolds in a multidimensional order, the dimensionality of which is effectively infinite.

Bohm next considers together quantum non-locality and the relativistic notion of space and time, which gives rise to some further interesting proposals:

> What is crucial in the present context is that, according to the theory of relativity, a sharp distinction between space and time can not be maintained (except as an approximation, valid at velocities small compared with that of light). Thus, since the quantum theory implies that elements separated in space are generally **non-causally and non-locally** related projections of a higher-dimensional reality, it follows that moments separated in time are also such projections of this reality.

According Pylkkänen in the previous statement Bohm means that because space and time cannot be sharply distinguished, what appears as a non-local correlation between spatially separated elements at a given moment in a certain frame of reference may instead appear as a correlation between elements at two different moments in another frame of reference. Given that one was using the idea of correlated projections from the higher-dimensional reality to account for the non-local correlations in space, it seems natural to offer the same suggestion to account for the correlation between the moments. After all, one is examining the same correlated elements from different frames of reference. Moreover, Pylkkänen add in his analysis:

> Evidently, this leads to a fundamentally new notion of the meaning of time. Both in common experience and in physics, time has generally been considered to be a primary, independent, and universally applicable order, perhaps the most fundamental one known to us. Now, we have been led to propose that it is secondary, and that like space [. . .] it is to be derived from a higher-dimensional ground, as a particular order. Indeed, one can further say that many such particular time orders can be derived for different sets of sequences of moments, corresponding to material systems that travel at different speeds. However, these are all dependent on a multidimensional reality that cannot be comprehended fully in terms of any time order, or set of such orders.

7.4.1 Entanglement and Mind-Matter relationship

Bohm suggests that the relationship of mind and body is analogous to the relationship between the systems in an EPR situation. Bohm next raises a very interesting and radical possibility: the relationship between matter and consciousness is similar to the relationship **between quantum systems that are non-locally correlated**. In connection with quantum non-locality, he introduced, the notion of a higher-dimensional reality, which projects into lower-dimensional elements that have not only a non-local and non-causal relationship but also just the sort of mutual enfoldment that we have suggested for mind and body. Strictly speaking, mind and body are not separate, but "**ultimately one**".

7.5 Holomovement as Spanda

The concept of Spanda (Dyczkowski, 1998) is the essence of the monistic Kashmiri Saiva text the Spandakarika, or the Stanzas on Vibration which is a medieval Hindu Tantric text. Ksemaraja, a disciple of Abhinavagupta defines it as follows: Spanda literally means a throb. It connotes dynamism or the dynamic aspect of the divine, the divine Creative Pulsation. Ksemaraja cites the pre-eminent Hindu scholar Abhinavagupta to clarify this ambiguity. Spandana means some sort of movement. According Ksemaraja: "Movement or motion occurs only in a **spatio-temporal framework**. The "Supreme" transcends all notions of space and time. Spanda, therefore, in the case of the Supreme is **neither physical motion, nor psychological activity like pain and pleasure, nor pranic activity like hunger or thirst**. It is the throb of the ecstasy of the divine I-consciousness (vimarsa). In this context that the Bohm's Holomovement is assimilable with Spanda, the common ground which transcend the space-time framework. Moreover we argued that two orders (i.e.explicate and IO) are mediated by **quantum entanglement.**

Conclusion

Today we feel the difficult to fit contemporary physics into a reductionist framework, and that a non-reductionistic wholeness is essential in physics. We have seen how the central idea in Bohm's view was that every thing is in some sense enfolded into the whole and that the whole is unfolded into every thing. Bohm called this dynamics, the holomovement which is a holistic pulsation in which orders unfold and enfold. Emphasis should be put on the fact that this fundamental process is not a movement within space-time (like in the example of the ink-drop) but rather a process in which ultimately space-time and its contents are created. We argued that this creation is due to the Holomovement (the primary element)mediated by QE. Moreover we have speculate on the possible relationship between Holomovement and Spanda a not physical flux, the central notion in the Philosophy of Kashmir Shavism.

To conclude this chapter, the next figure 7.5 (W.Russell, 1927) shows an interesting view of physical reality.

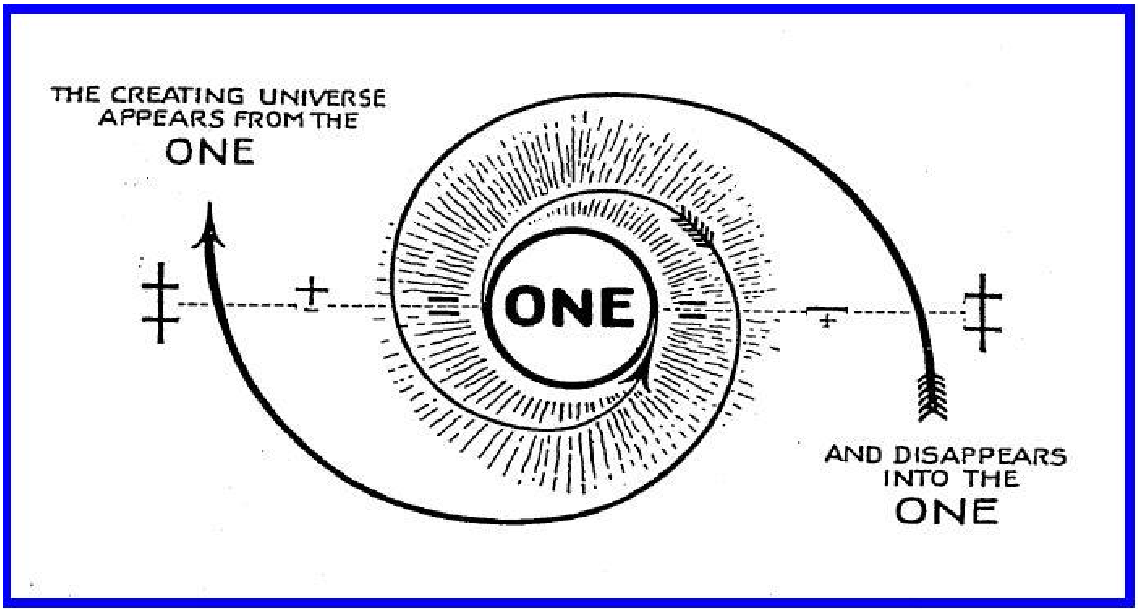


Figure 7.5: Russell's Oneness

8

Can we ”see” the Implicate Order?

In this chapter we argue about a possible philosophical description of the IO starting from a simple theoretical experiment. Utilizing an EPR source and the human eyes (as biological detectors) of a "single" person, we try to investigate the philosophical and physical implications of QE in terms of implicate order (IO). We know, that most specialists still disagree on the exact number of photons required to trigger a neural response, although there will be many technical challenges, we assume that neural response will be achieved in some way. The objective of paper is to investigate possible links between: QM, quantum cognitive science, brain and mind. At the moment, the questions are more than the answers. We argue that we are perennially immersed in the IO and that the "real path" of QE process is from the IO towards explicate order, not vice versa. Finally, we speculate about the common ground between the IO and chitta (Vedic theory of Mind).

8.0.1 Introduction

In all of classical physics, the description of a system’s state depends only on itself and its immediate surroundings, in other words, classical physics is local. This is not the underlying reality described by QM. QM exhibits non-locality when it remains contextual even in this spatially separated setting. The phenomenon of QE is among the most counterintuitive concepts in QM. Today the study of entanglement occupies a prime position in the field of quantum information processing. This term was first introduced by Schrödinger as the essence of QM, the term describes a system composed of two or more particles, which exhibits the property that the results of measurements on one particle cannot be specified independently of the parameters of the measurements on the other particles. Although the different measurements can take place in spacelike separated regions, the results of each measurement depend on the complete experimental context of the whole system. From physical point of view, the entanglement is considered to be an objective property of the QS, but some experimental tests can demonstrate that the entanglement depends on the measurement context and therefore this entanglement becomes an entangled property itself. From philosophical point of view, there are possible "subjective" elements on the choice of the QS and their subsystems. As we have seen (chap. 5.2),(Torre,2010) it is showed that a state that is factorizable in the Hilbert space corresponding to some choice of degrees of freedom, becomes entangled for a different choice of degrees of freedom. Therefore, entanglement is not a special case but is ubiquitous in quantum systems. According this work, as a consequence of this they conclude that in every state, even for those factorizable, we can find pairs of observables that will violate Bell's inequalities. The philosophical implications are that the appearance of entanglement depends on the **choice of degrees** of freedom can find an interesting application in the "disentanglement" of a state. Moreover, because of the fragility of entanglement, any interaction with the environment, which distinguishes between the entangled sub-systems, collapses the quantum state. Therefore the decoherence (via interaction with the system's environment) play a central role in understanding the emergence of our classical world from QM. Today an entanglement can be created, manipulated and quantified, bi-partite entanglement is well understood and, it is also, accessible from an experimental viewpoint. Very interesting for the philosophical implications is the Entanglement swapping, a method that enables one to entangle two quantum systems that do not have **direct** interaction with one another. To conclude this brief survey, we can say that surely with the violation of Bell's inequality is started a tension between QM and space-time theory. According Shimony there are other sources of tension, like the difficulty of quantizing general relativity and the difficulty of maintaining the very concept of a space-time continuum at the Planck level. He adds that a solution to the nonlocality problem created by Bell must be a deep solution. He believes that nonlocality is here to stay, but so far we only have a phenomenological account of it. What is needed is a deep theory underlying the phenomenology, in the way that Boltzmann's statistical account of thermodynamic processes provided the conceptual underpinning of the second law of thermodynamics.

8.0.2 Our framework

In this chapter we are interested to address the question: can the human eyes (left and right eye) detect QE? According Sekatski (Sekatski et al. 2009) "one" person could not detect entanglement by simply observing photons, for this reason they discuss about the possibility to test the QE for several observers in order to demonstrate entanglement in a Bell-type experiment. The authors conclude that close to perfect threshold (human) detectors can be used to test quantum nonlocality without the need of any supplementary assumption. Our framework is different, we argue from theoretical point of view (without any specific technical discussion) about the possibility to test the QE in a single person (his left and right eye as detectors). The picture (Fig. 8.1) show how we can perform this test:

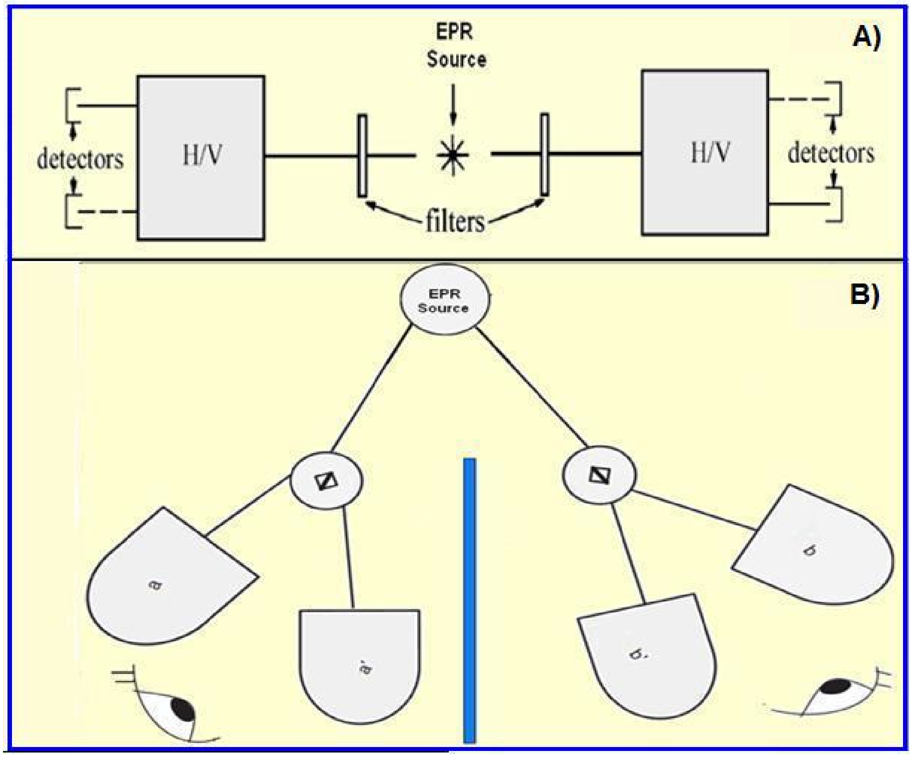


Figure 8.1: In A) Classic EPR source application. In B) Details of EPR source (entangled photons) and human eyes of single observer.

The "two" observers in this case are: Alice (left eye) and Bob (right eye). They receive entangled particles emitted by some source, each eye choose a measurement setting, a and b respectively, and then record their measurement outcomes values, say A and B. The measurement process in this special case take place in the brain (Fig. 8.2), but the real and interesting question is: "where the entanglement

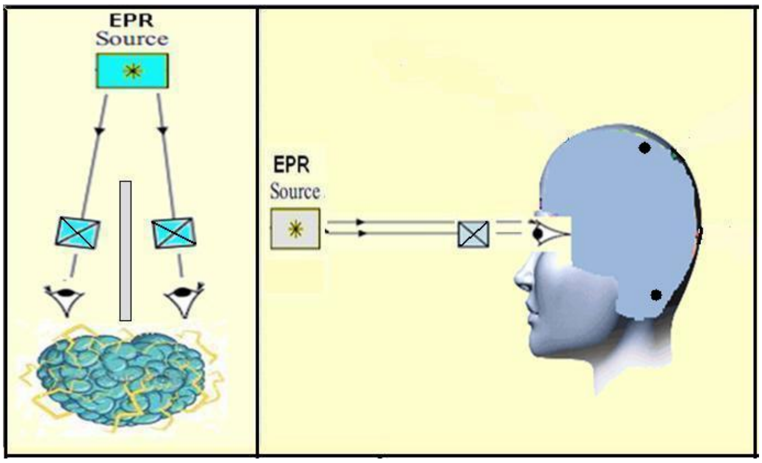
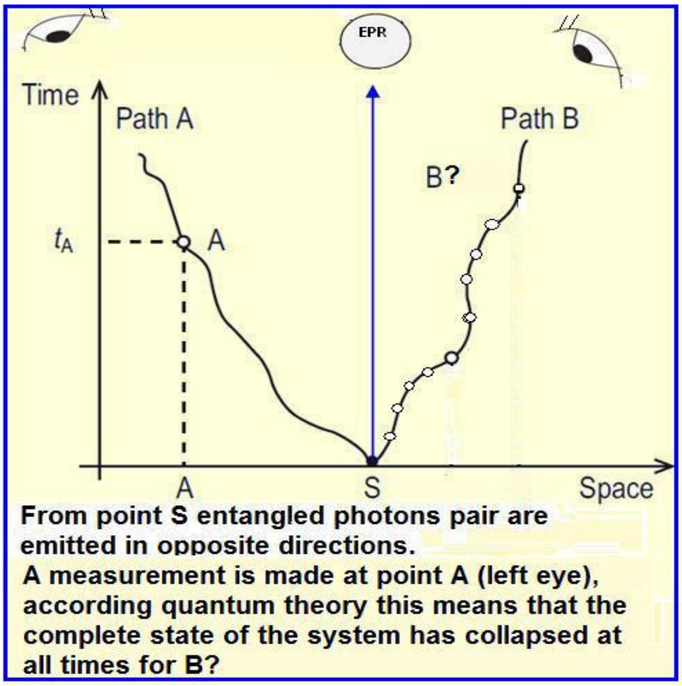


Figure 8.2: The theoretical test.

take place?" We will speculate philosophically on the (possible) QE in terms of mind/brain and not in terms of quantum model of dissipative brain?. We know that, at the moment the questions are more than the answers, for example:



From point S entangled photons pair are emitted in opposite directions.
A measurement is made at point A (left eye), according quantum theory this means that the complete state of the system has collapsed at all times for B?

Figure 8.3: When an where exactly does the state function of the system collapse?

1. What we can say, in this case, about spacelike seperation?
2. The measurement process is simultaneously (left eye and right eye, see Fig. 8.3)?
3. Where the entanglement take place (Fig. 8.4)?

4. What we can say about the notion of space-time?

We will argue in then sections, that "real" physical process of the QE start from an IO towards the relevant explicate order. This is in the "inverted", "opposite", or "reverse" direction with respect to the classical QE explanation, which from an explicate order to the related IO. Concisely, we argue that the entanglement takes place in the IO before the subject's visualization (subjective experience),i.e., the brain processes involved before conscious subjective experience. The subjective experience (SE) can be considered as an explicate order, which seems to involve disentanglement, and the physical neural network in the brain (the neural correlate of the related SE) seems to be responsible because of the decoherence via the interaction of the brain's cognitive fronto-parietal feedback signals with environmental stimulus dependent feed forward signals. The concept of implicate/explicate order can be applied at any level of complexity. In other words, in the above example we considered an IO at neural-network level (such as chitta or memory formation and recall, attention, re-entry, brain processes involved in bringing the system to wakefulness and so on). One could argue that this IO is the explicate order for lower levels (such as neural-signal, neurotransmitter, synaptic-level, chitta/memory-formation processes, and genetic-level that are responsible for the formation of chitta/memory), which, in turn, has IO in terms of elementary particles. The fermions and bosons (elementary particles) are explicate orders and strings (string theory) or loops (loop quantum gravity) are related implcate orders. These can be considered as explicate orders and related sub-quantum field, unified field (consciousness unfied with all four fundamental forces), or Paramatman as fundamental IO.

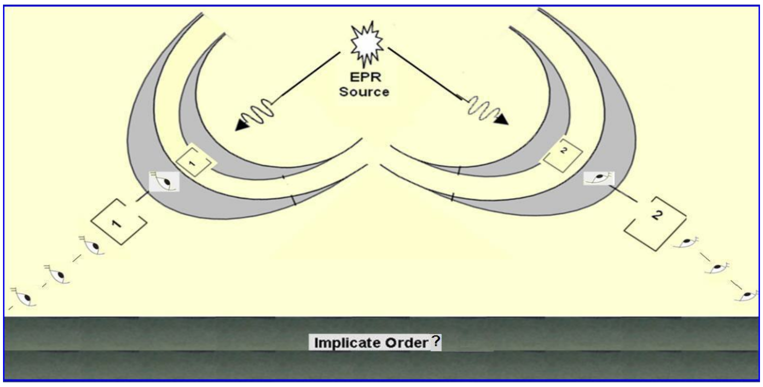


Figure 8.4: When does the entanglement take place?

8.1 Quantum Entanglement in Composite Systems

We recall the QE for composite systems. From an information theoretic point of view, the most remarkable feature of entanglement is the fact that in a maximally entangled state, all information is encoded in joint properties of the individual systems while the individuals themselves carry no information whatsoever (Zeilinger, 2005). From a phenomenological point of view, the phenomenon of entanglement is quite simple. When two physical systems come to an interaction, some correlation of a quantum nature is generated between the two of them, which persists even when the interaction is switched off and the two systems are spatially separated. QE describes a non-separable state of two or more quantum objects and has certain properties which contradict common physical sense. While the concept of entanglement between two quantum systems, which was introduced by E. Schrödinger in 1935, is well understood, its generation and analysis still represent a substantial challenge. Especially entanglement between **objects of different nature like atoms and photons** was achieved only very recently and is subject of current research. The quantification of entanglement is a long standing problem in quantum information theory. Any good measure of entanglement should satisfy certain conditions. An important condition is that entanglement cannot increase by local operations and classical communications. Entanglement can be realized by having two entangled particles emerge from a common source, or by allowing two particles to interact with each other. Yet, another possibility to obtain entanglement is to make use of a projection of the state of two particles onto an entangled state. This projection measurement does not necessarily require a direct interaction between the two particles. When each of the two particles is entangled with another particle, an appropriate measurement (for example, a Bell-state measurement) of the partner particles will automatically collapse the state of the remaining two particles into an entangled state. This striking application of the projection postulate is referred to as entanglement swapping or teleportation of entanglement. Also, we can have, atom-photon entanglement. When a single atom is prepared in an excited state $|e\rangle$ it can spontaneously decay to the ground level $|g\rangle$ and emit a single photon. Due to conservation of angular momentum in spontaneous emission the polarization of the emitted photon is correlated with the final quantum state $|g\rangle$ of the atom. For a simple two-level atom, after spontaneous emission, the system is in a tensor product state of the atom and the photon. But for multiple decay channels to different ground states the resuling state of atom and photon is entangled. The physical process of spontaneous emission can not be explained by a semiclassical treatment of the light field but only by a quantum field approach. Today, a considerable effort is put into the research on entanglement with no restriction too, but a strong emphasis on, **two-level systems, i.e. qubits**. Bipartite entanglement is well understood and has been prepared in many different physical systems. The math definition of entanglement varies depending on whether we consider only pure states or the general set of mixed states. Only for pure states, we say that a given state $|\psi\rangle$ of n parties is *entangled* if it is not a tensor product of individual states for each one of the parties, that is,

$$|\psi\rangle \neq |v_1\rangle_1 \otimes |v_2\rangle_2 \otimes \cdots \otimes |v_n\rangle_n \ . \tag{8.1}$$

For instance, in the case of 2 qubits A and B (sometimes called "Alice" and "Bob") the quantum state

$$|\psi^+\rangle = \frac{1}{\sqrt{2}}[(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B)] \tag{8.2}$$

is entangled since $|\psi^+\rangle \neq |v_A\rangle_A \otimes |v_B\rangle_B$. On the contrary, the state

$$|\phi\rangle = \frac{1}{2}[(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |0\rangle_B + |0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |1\rangle_B)] \tag{8.3}$$

is not entangled, since

$$|\phi\rangle = \left(\frac{1}{\sqrt{2}}\left(|0\rangle_A + |1\rangle_A\right)\right) \otimes \left(\frac{1}{\sqrt{2}}\left(|0\rangle_B + |1\rangle_B\right)\right) \ . \tag{8.4}$$

A pure state like the one from Eq.8.2 is called a *maximally entangled state of two qubits*, or a *Bell pair*, whereas a pure state like the one from Eq.8.4 is called *separable.*

In the general case of mixed states, we say that a given state ρ of n parties is *entangled* if it is not a probabilistic sum of tensor products of individual states for each one of the parties, that is,

$$\rho \neq \sum_k p_k \ \rho_1^k \otimes \rho_2^k \otimes \cdots \otimes \rho_n^k \ , \tag{8.5}$$

with $\{p_k\}$ being some probability distribution. Otherwise, the mixed state is called *separable.* The essence of the above definition of entanglement relies on the fact that entangled states of n parties cannot be prepared by acting locally on each one of the parties, together with classical communication (telephone calls, e-mails, postcards...) among them. As said before, this set of operations is often referred to as “local operations and classical communication”, or LOCC. Entanglement is a genuine quantum-mechanical feature which does not exist in the classical world. It carries non-local correlations between the different parties in such a way that they cannot be described classically.

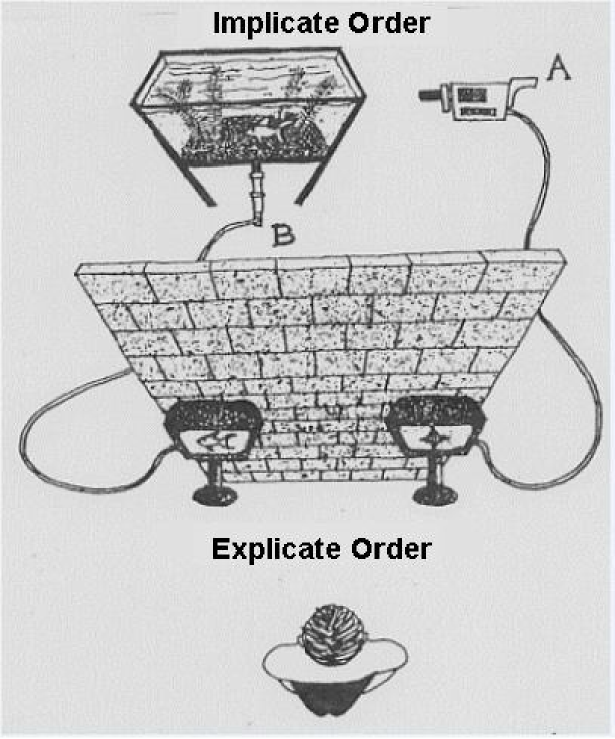


Figure 8.5: The Implicate and Explicate Order according David Bohm.

8.2 The Implicate Order

As we have seen, today, most important studies in these fields are carried forward by Pylkkänen and Basil Hiley. Bohm, calls IO the primary reality, this reality exists ’folded up’ in nature and gradually unfolds as the universe evolves, enabling organization to emerge, in this way, the implicate becomes explicate over time. Against the Copenhagen interpretation of QM, he began to suspect that there was a deeper order underlying the complex behavior of particles, giving rise to his theory of an ’IO’ in the universe, an ’undivided wholeness’ that governs all reality. The

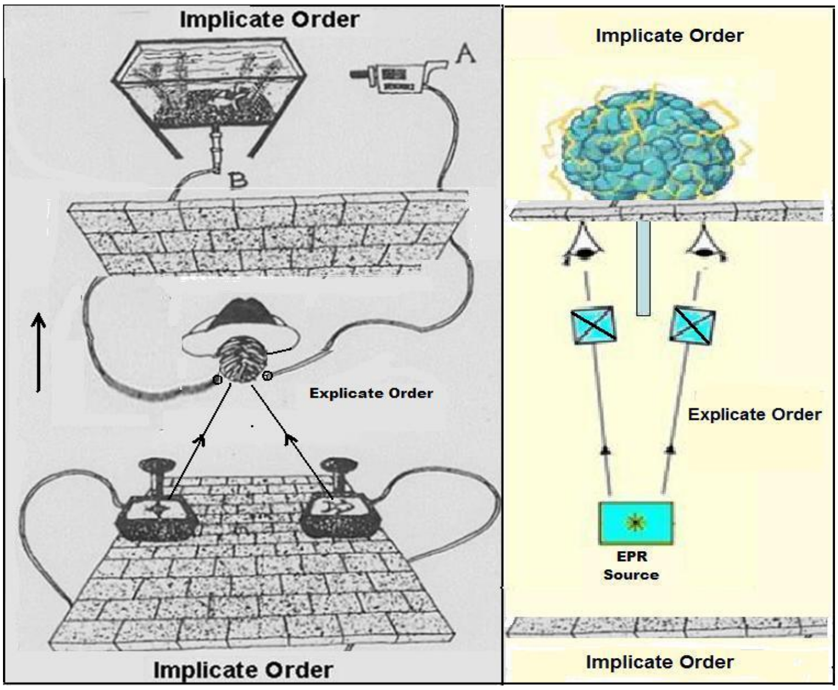


Figure 8.6: We are perennially "immersed" in the Implicate Order according our thesis.

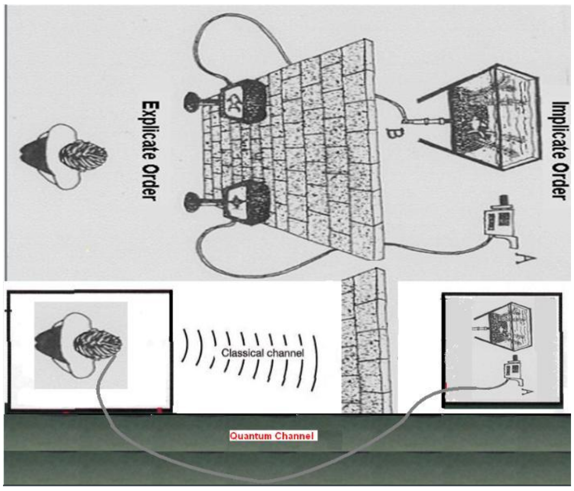


Figure 8.7: We named "quantum channel" the hidden implicate order.

theorization of the existence of a 'quantum potential', which determined the motion of particles was the main support for the existence of the IO. According Bohm the whole universe can be thought of as a holomovement (see Fig. 8.5), in which a total order is contained. The explicate order is a projection from **higher dimensional levels of reality**, and the apparent stability and solidity of the objects and entities composing it are generated and sustained by a ceaseless process of enfoldment and unfoldment, for subatomic particles are constantly dissolving into the IO and then recrystallizing. According Globus "Bohmian wholeness is dynamical: a continuous holomovement. The holomovement has two simultaneous processes: implication and explication. In implication the ordinary Cartesian order is enfolded to the whole where it "exists" in potentia, while in explication the Cartesian order is unfolded from the whole.

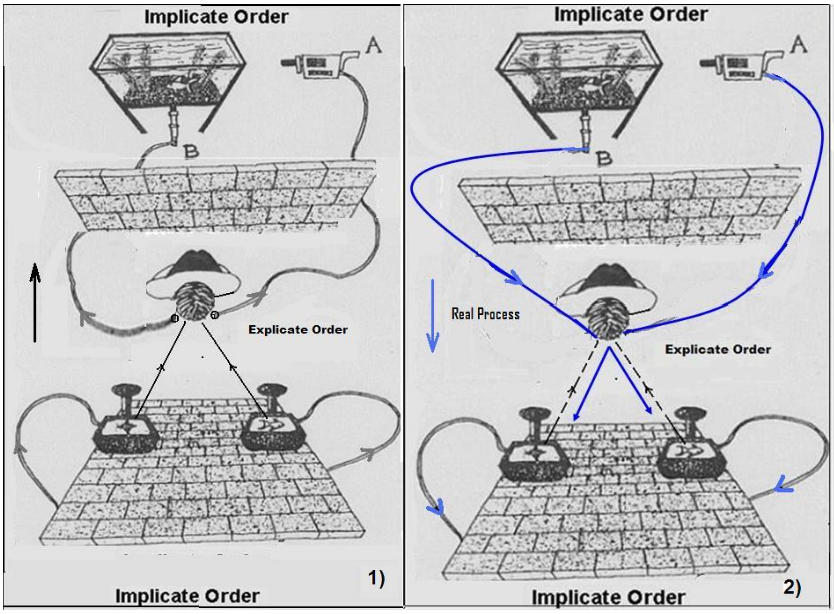


Figure 8.8: "Classic" quantum entanglement 2) Disentanglement the real physical process: from implicate order towards explicate order by mind.

8.3 Philosophical Speculations: the ”real” process of quantum entanglement

In order to give a correct context of describing the underlying physical reality, according our analysis (Fig. 8.6), it is necessary to review the notions of space-time, QE phenomenon, implicate/explicate order and decoherence. We retain that physical reality (explicate order) must be linked to:

1. The foundation of implicate order has a "structure" without any spatial and temporal connotation.
2. The physical brain is responsible of disentanglment.
3. The phenomenon of decoherence as a means to produce classicity: the explicate order (Fig. 8.7)

4. The "real" path of QE is from implicate order towards explicate order. This is the "opposite" or "reverse" direction with respect to the classical-quantum concept of entanglement. In other words, the classical-QE is from explicate order towards implicate order (Fig. 8.8).

To sum up, we retain that the entanglement takes place before subject's visualization or subjective experience in the IO. The visualization (the explicate order) has to do with disentanglement and the brain is responsible for that. This view fits well with our previous paper on the possible relationship between IO and Chitta or memory, a fundamental category in the Vedic theory of Mind.

8.4 Implicate/Explicate order, Vedic science, and the dual-aspect-dual-mode PE-SE framework

According to (Caponigro et al, 2010, see next chap.9): the five Vedic entities Chitta, Manas, Buddhi, Ahamkara, and 'Paramatman→ Atman→Purush↔Prakriti→ Brahma→Jivatma or 'Paramatman→ ParamPurush/MahaPurush↔Prakriti→ ParamBrahma→Atman/Jivatman' are assimilable with Bohm's Implicate and Explicate order at various levels and the holomovement framework. For example, the entities 'Paramatman→Atman→Purush↔Prakriti can be considered equivalent to Bohm's enfolded IO at fundamental level; whereas Brahma, Jivatman, Chitta, Manas, Buddhi, and Ahamkara can be considered as unfolded Explicate Order at various levels. For example, Chitta is assimilable with the holomovement that does not have the structure of space-time; the holomovement (via entanglement) unfolds and enfolds via space-time; in the same way Chitta unfolds and enfolds (via entanglement) with Manas, which represent the Explicate Order of Vedic theory of Mind. Bohm and J. Krishnamurthi (Vedic scholar and a great Indian thinker) communicated with each other, and Bohm's Implicate/Explicate and enfolding/unfolding is a sort of linked with the dual-aspect part of Vedic science; he is clearly a dual-aspect philosopher, which is consistent with the dual-aspect-dual-mode PE-SE framework. Stapp's framework is closer to Dvait Advait Vedic framework.

Vamadeva (David Frawley) suggested that we would have to discriminate between individual chitta or mind from cosmic chitta or cosmic mind, Mahat or cosmic buddhi and Chit or pure consciousness beyond manifestation. If QM could find evidence of either chitta on a cosmic level or chit as the unmanifest background of the cosmos, it would be quite a breakthrough. To address Vamadeva's comment, we propose the following hypothesis: In dual-aspect-dual-mode PE-SE framework, individual chitta (memory bank), manas (different from western term 'mind'), buddhi, Ahamkara are part of single brain/mind based individual consciousness, which is based on the interaction between environment (in terms of stimulus dependent feed forward signals along quantum and classical pathways) and individual cognition (attentional feedback signals) as detailed in. When many brains/minds and respective environments interact, social or group consciousness emerges (such laws, political views, religion, economics, and so on). When all brains/minds of all living beings (human, animals, plant life, and so on) and their respective environments interact, higher order cosmic consciousness (cosmic chitta, cosmic manas, Mahat or cosmic buddhi, and Mahat ahankar; or pure consciousness beyond manifestation or dual-aspectShiva-Shakti) emerges. One could argue for Trika Kashmir Shaivism where Shiva (mental aspect) and Shakti (physical aspect) are the two aspects of same entity. Dvait-Advait Vedanta is closer to Stapp's orthodox QM framework. According to Von Neumann (von Neumann, 1932)(orthodox) QM is thus dualistic in the pragmatic and operational sense that it involves aspects of nature that are described in physical terms and also aspects of nature that are described in psychological terms, and these two parts interact in human brains in accordance with laws specified by the theory. This is all in close accord with classic Cartesian dualism. On the other hand, and in contrast to the application to classical mechanics, in which the physically described aspect is ontologically matterlike, not mindlike, in QM the physically described part is mindlike. So both parts of the quantum Cartesian duality are fundamentally mindlike. Thus QM conforms at the pragmatic/operational level to the precepts of Cartesian duality, but reduces at a deep ontological level to a fundamentally mindlike nondual monism." Although, so far, there is no concrete QM evidence of either chitta on a cosmic level or chit as the unmanifest background of the cosmos, one could argue that quantum bounce model of loop quantum gravity suggest that universe may have some memory (chitta) of previous big-bounce cycle and maintains recall, although it is controversial and references there in). In addition, if Stapp's framework is correct, then perhaps mind-brain dualism at pragmatic/operational level reduces at a deep ontological level to a fundamentally mindlike nondual monism at cosmic level. This is somewhat consistent with Trika Kashmir Shaivism with dual-aspect Shiva-Shakti framework at cosmic level.

8.5 Commentaries

1) Mikhail Mikhailov (personal communication to the authors in May 2010) commented as follows: "I think that the research area of this article defined as philosophy and the interpretation of QM deserves special attention. My focus is very close to Epistemology and Hermeneutics but I am far from Physics. So, I must restrain from any comments. But I can formulate some suggestions and thoughts concerning the most important terms of Indian philosophy. I heard about the QE and the idea sounds good to my unprofessional ear. But as to the possible links between quantum physics and Indian philosophy I am very skeptical. Yes, indeed, the ancients had a quantum theory, they strictly defined the particles starting from 1-17 mm and time moments starting from one trillionth of a sec. They developed the concept of universal vyapti and built mathematical logic, theory of binary encoding and ciphering. But as I can understand, for the purpose of congruous Eternal Calendar (Kaala-yantra instrument of Time). A mechanical prototype of the Vedic recital-mnemonic analogue-digital Calendar-Chronometer seemingly had been found under the sea and is popularly called Antikitera Mechanism. To my mind, ancients studied Physics not statically as a dead body but dynamically through the concept of time. Time was the highest God Mahaa-Kaala and the highest scientific principle. Time governs the movements of planets, pulsate in our heart, vibrates in our tongue, thoughts, fillings, breath, movements, which were used for its measurement. The Laws of Time are the Laws of True Physics embracing subjective (citta) and objective (mana) consciousness. Moreover, I treat the so-called psychological phenomena (citta, mana buddhi, ahamkara) primarily in the ontolological perspective of Samkhya philosophy. Citta is sensitivity in cosmological sense embracing primarily all physical and chemical reactions. Buddhi is excitation (excitement, actuation, fermentation, energization). Ahamkara is self-movement of primordial matter or vital energy (praNa) and subjectivity. Mana and indriyas represent objectification. Concentration of mind on citta gives you the sense of Quantum State, where the ideas of things and their movements are born. The concept and ideas about Emptiness and Interpretation of QM have sound ground. One can not only "see" the IO, but actively determine its behavior. Vedic Theory of Mind must be seen and correctly understood in the perspective of parama-advaita of Kashmirian monistical shivaism. The idea about epistemological path of objective reduction of thoughts must be supplemented with the expansion of feelings and intuitions, movements and actions. Otherwise, it can lead into a blind alley. Furthermore, I have translated the first part of my book "Key to the Vedas" into English. It deals with Indian philosophy of Sciences (Vedas) and Vedic Hermeneutics of Eternal Calendar-Chronometer. It shows many lacunas, deadlocks and pitfalls of modern Indology (its Western and Eastern views) and explains the right ways of interpreting the different Vedic disciplines in a homogenous perspective of precise Time-measurement and Eternal Calendar."

Our response: There could be different interpretations depending on the metaphysical frameworks. Our framework is the dual-aspect dual-mode PE-SE framework that has the least number of problems, which is close to Trika Kashmir Shaivism, where Shiva (mental aspect) and Shakti (physical aspect) are the two aspect of the same entity.

2) One reviewer argued that the present formalism of quantum theory is not adequate, even when the equations work well in connection with applications. Therefore, from our point of view any philosophical implication and interpretation, respectively, that is based on conventional quantum theory is problematic and has obviously nothing to do with that what we call "truth".

Our response: If the definition of "truth" is mind-independent reality (MIR) then MIR is always unknown as per Kant. In physics, we assume MIR = mind-dependent reality (MDR), which is debatable and in our view incorrect. Application of quantum physics to consciousness is not new. For example, According to, Von Neumann (orthodox) QM is thus dualistic in the pragmatic and operational sense that it involves aspects of nature that are described in physical terms and also aspects of nature that are described in psychological terms, and these two parts interact in human brains in accordance with laws specified by the theory. This is all in close accord with classic Cartesian dualism. On the other hand, and in contrast to the application to classical mechanics, in which the physically described aspect is ontologically matterlike, not mindlike, in QM the physically described part is mindlike. So both parts of the quantum Cartesian duality are fundamentally mindlike. Thus QM conforms at the pragmatic/operational level to the precepts of Cartesian duality, but reduces at a deep ontological level to a fundamentally mindlike nondual monism." Stapp bypasses some of the problems of substance dualism, but it still has problems (Vimal, 2010). This framework seems is the same or close to Dvait (dualism)/Advait (mentalistic monism) Vedanta (Stapp, 2007). Our approach follows the dual-aspect-dual-mode PE-SE framework that has the least number of problems, namely just one problem of the justifiable brute fact of dual-aspect. In addition, we have theoretical support that physics is invariant under PE-SE transformation.

3)Rajat kumar Pradhan commented (personal communication in May 2010), "The manuscript is really very speculative and requires some deep thought. Many of the views presented by you and co-researchers tallies with those of mine expressed in my paper available at http://arxiv.org/abs/0907.4971, an abridged version of which has been accepted for publication in a forthcoming issue of Neuroquantology (2010,vol-8,No.3). These articles elaborate a mechanism involved in the process of individualization of the cosmic consciousness. Especially I fully agree with your observation that the cosmic consciousness is realizable through meditational techniques. The mechanism responsible for this god-realization is an entanglement of the subject with the object in the singlet $|0, 0>$ state, wherein simultaneous knowledge becomes possible of the entire Universe! Bohm's IO is more objective in nature and is rather a melted amalgamation of all the objective phenomena before they become fully manifest as distinct i.e. explicate. As far as I understand, the role played by the individual consciousness in making the implicate explicate is a latter addition to his original idea. His IO can keep objectively unfolding itself even without an observer to do the trick. Thus, although Bohm's ideas are Vedic they are not fully Vedantic.

Our response: Pradhan's metaphysical view appears close to Stapp's framework. If this is correct then both frameworks are close to Dvait-Advait Vedanta as elaborated in response to commentary of Schommers. These frameworks have more problems than our dual-aspect dual-mode PE-SE framework [17] and. B**ohm's implicate/explicate order is clearly dual-aspect view** (a dual-aspect interacting entities, where each entity has mental aspect and physical aspects). Our framework is somewhat close to Trika Kashmir Shaivism, where Shiva (Purush, consciousness) is mental aspect and Shakti (Prakriti, energy) is the physical aspect of the same entity, in analogy to the two sides to the same coin. Thus, physical/material aspect cannot be separated from its mental aspect because these two aspects are permanently "glued" to each other. In this article, Vedic theory (Dvait-Advait Vedanta) and dual-aspect view are somewhat mixed and may lead to confusion to readers. Therefore, readers are encouraged to read with appropriate context. We tried to interpret Bohm's view in term of Vedic theory, but Bohm's view is dual-aspect. Therefore, gap remains.

9

Quantum Interpretation of Vedic theory of Mind

In this chapter we argue about a possible quantum interpretation of Vedic Theory of Mind. Chitta, Manas, Buddhi and Ahamkara, in our quantum approach will be considered respectively as: common ground, quantum superpositions, observer (quantum collapsing) and measurement outcomes eingvalues,Povm. We suggest that through the continue interactions between these four components, we are able to understand the formation of Ahamkara (Ego). Chitta (by vrittis) is linked to Manas via entanglement. The unsolved problem is the nature of Buddhi component and his right collocation in this process. Moreover, we argue that our approach can be supported by Zeilinger's interpretations of QM. Finally, we will speculate about possible analogy between Chitta and Bohm's Holomovement.

9.1 Introduction

The Samkhya is the oldest school of Hindu Philosophy, for it is the first attempt to harmonize the philosophy of the Vedas through reason. The Samkhya teaches that the phenomenal universe is considered as a dynamic order, **an eternal process of unfolding/enfolding**, without beginning or end. All has evolved out of an Uncaused cause which is not consistent with a rational solution. The Samkhya leaves the Uncaused cause undefined as being impossible to be conceived by the intellect. This absolute is beyond time, space and thought, it is without difference, attribute and form. True evolution, according to Samkhya system, does not exist in the phenomenal world, but only in the chain of causation from the cosmic substance (prakrti) to the gross elements (mahabhutas). According Kak's work the Sankhya and the Yoga systems take the **mind** as consisting of five components:

1. Chitta
2. Manas
3. Buddhi
4. Ahamkara
5. *Paramatman →Atman→Purush↔
   Prakriti→Brahma→ Jivatman

Manas is the **lower mind** which collects sense impressions. Ahankara (the **individual Ego**, which feels itself to be a distinct, separate entity) is the sense of I-ness that associates some perceptions to a subjective and personal experience. Once sensory impressions have been related to I-ness by ahamkara, their evaluation and resulting decisions are arrived at by **buddhi, the intellect**. **Chitta is the memory bank of the mind**. These memories constitute the foundation on which the rest of the mind operates. But chitta is not merely a passive instrument. The organization of the new impressions throws up instinctual or primitive urges which creates different emotional states. This mental complex surrounds the innermost aspect of consciousness, which is called atman, the self, or Brahman.

In our approach, we will analyze first four entities in detail. **The set of entities in fifth component of mind is beyond the scope of current article**. However, concisely, our hypothesis is that entities **Paramatman is assimilable with the Bohm's IO**. This is because this entity is in enfolded form and is the fundamental sub-quantum dual-aspect unified field; it pervades all Atmans and Prakriti. In the fifth component (Paramatman→Atman→ Purush↔Prakriti→Brahma→ Jivatman), the arrow → indicates that the entity on its right side is 'derivable' from that on its left side and ↔ refers to bi-directional interaction. Furthermore, Paramatman is 'quantized' in to Atmans, each of which pervades Prakriti. The entity Atman when it is in excited state with energy is called Purush, which when interacts with un-manifested (un-evolved) Prakriti (vacuum) is called Brahma, which, in turn is when embodied (after co-evolution and co-development) in an individual, is called Jivatman. However, this type of successive step-by-step derivation seems to be metaphysical-view dependent and appears to be designed for 'dualism from eastern perspective' (Dvait Vedanta) and/or neutral monism (Advaita Vedanta). To make Vedic theory of mind (VTOM) 'independent of' or 'not committed to' any metaphysical-view, we might need a minor modification as follows: (Paramatman$\rightarrow$ParamPurush/MahaPurush $\leftrightarrow$Prakriti$\rightarrow$ParamBrahma$\rightarrow$ Atman/Jivatman)).

In other words, one can investigate if such modification will allow VTOM to be applicable to all views including materialism. For example, in the case of materialism, we have implicitly assumed that 'Paramatman → ParamPurush/MahaPurush' plays a role of say perturbation in Prakriti in string theory, which is then eventually capable of creating SEs including self (Atman/Jivatman) in humans and animals. In such modification, Paramatman when it is in excited state with energy can be called ParamPurush or MahaPurush, which when interacts with un-manifested (un-evolved) Prakriti (vacuum) is called ParamBrahma. Then, long after Big Bang or Big Bounce (perhaps during Cambrian evolutionary explosion about 540 millions years ago the mental aspect of ParamBrahma is 'quantized'[1] in to Atmans (also called Jivatmans) by the process of co-evolution, co-development, sensori-motor tuning, and embodiment in an individual. Jivatman is also called self or subjective experience of subject. Unfolding or Explicate Order starts when MahaPurush/Purush and Prakriti interact with each other (or 'Prakriti is infused/joined with Purush') and ParamBrahma/Brahma starts 'creation' at the onset of classical Big Bang or quantum Big bounce; for further detail see. Eventually, after a long period of co-evolution and co-development, Brahma is embodied in an individual subject, which is then called Jivatman. The embodied entity Jivatman interacts with entities Chitta, Manas, Buddhi, and Ahamkara (the topic of current article). Furthermore, in previous article (Vimal, 2010), the empirical data of samadhi state was interpreted in terms of various metaphysical views and science, especially with respect to the dual-aspect dual-mode optimal framework. In addition, it was argued that there is a need for a new Veda in Vedic science (perhaps, it can be called "Vigyan Veda"), which is close to science (=Vigyan), such as neuroscience and quantum physics. The Vigyan Veda tries to remove "the inconsistencies and speculative hypotheses related to consciousness research from Vedic science that

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[1] Here, the term 'quantized' is used metaphorically and needs unpacking because it could be different from say the 'quantization' of materialistic classical electromagnetic field in to quantum electrodynamics to change the description of a physical system from classical to quantum-mechanical.

includes ancient four Vedas (Rigveda, Yajurveda, Samaveda, and Atharvaveda). In subjective experiences (SEs) are derived from a proto-experience and three gunas (qualities: Sattva, Rajas, and Tamas guna) of Vedic science in the dual-aspect-dual-mode framework with hypothesis H_2. The current article can be considered another chapter of Vigyan Veda. To conclude this brief introduction, Bhakta (Bhakta, 2006) put in evidence in the next figure (Fig.9.1) the importance of quantum theory to rediscover the origin of Vedas.

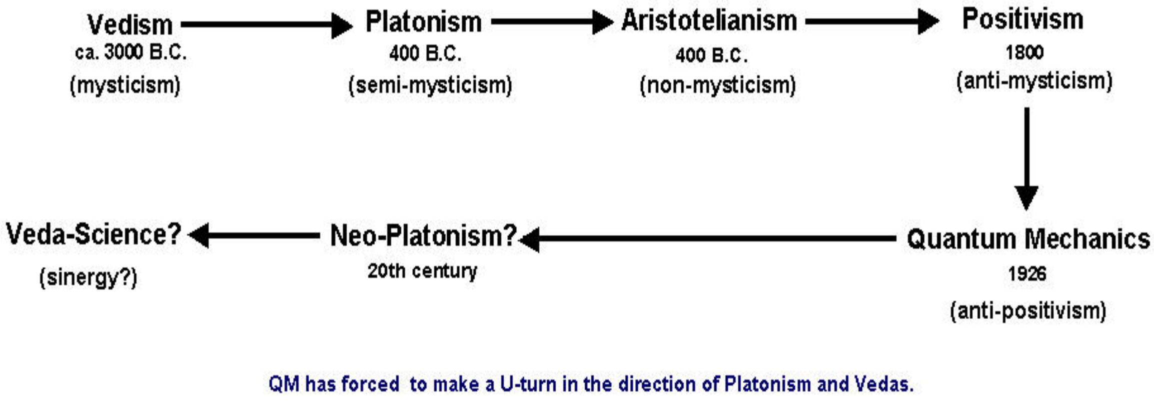
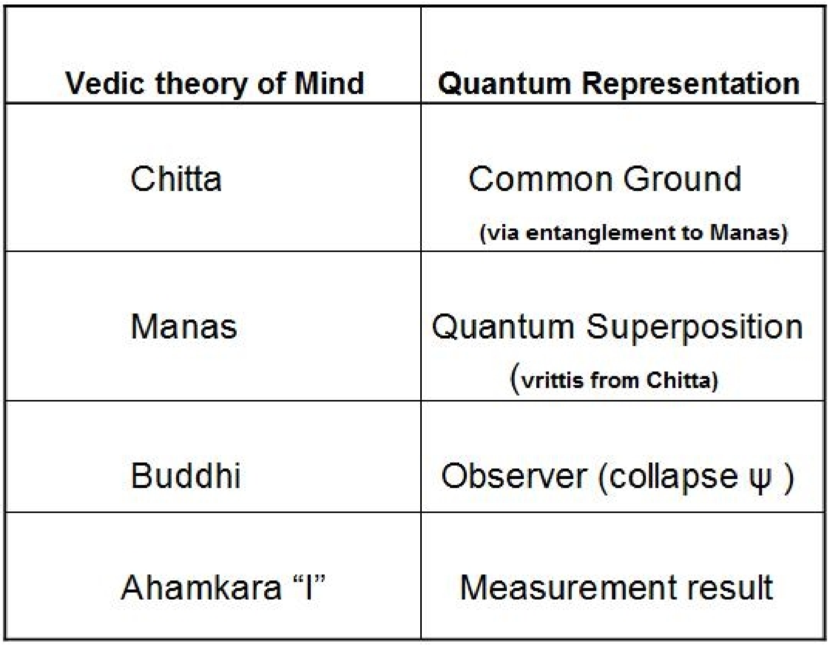


Figure 9.1: QM make a U-turn toward Platonism/Vedas

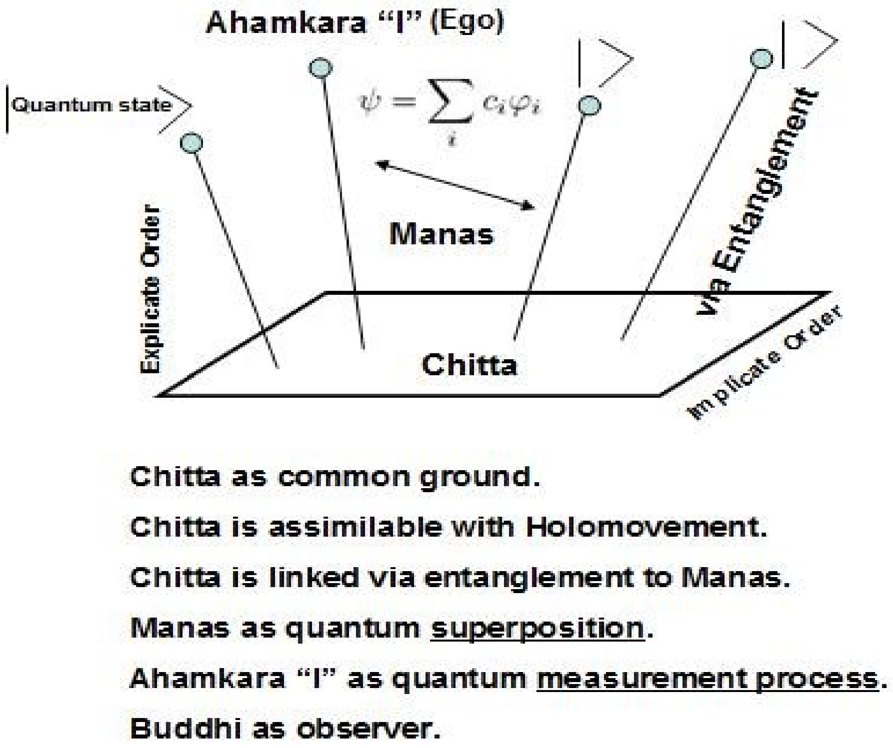
9.2 Our pathway

In order to support our main thesis, we have drawn two pictures. On the basis of the tables 1 and 2 (see respectively Fig. 9.2 and Fig 9.6, pag.116), we have drawn Fig. 9.3. As we see, the role of Chitta is fundamental, it is the common ground. We suggest that Chitta is linked via Entanglement with Manas. Manas is represented by quantum superpositions of phase-entangled thought-waves arising from Chitta. According to this view, **the Ahamkara is built time by time through Buddhi's choices (i.e., collapse)**. Ahamkara is the sense of "I-am-ness," the individual Ego, which feels itself to be a distinct, separate entity. It provides identity to our functioning, but Ahamkara also creates our feelings of separation, pain, and alienation as well.Ahamkara is the strong wave that declares "I am"." Ego can have negative energy (such as in aversion) or positive energy (such as Sankalp shakti or energy of determination), **Concisely, Chitta is continuously emitting Vrittis** (are thought waves in vedic tradition) **towards Manas who acts on them.** This process leads to the superposition of phase-entangled thought-waves and subjective experiences (SEs) embedded in neural-networks via developmental neural Darwin-



Vedic theory of Mind	Quantum Representation
Chitta	Common Ground (via entanglement to Manas)
Manas	Quantum Superposition (vrittis from Chitta)
Buddhi	Observer (collapse ψ)
Ahamkara “I”	Measurement result

Figure 9.2: Table of correspondences see Details Pag. 114



Chitta as common ground.

Chitta is assimilable with Holomovement.

Chitta is linked via entanglement to Manas.

Manas as quantum superposition.

Ahamkara “I” as quantum measurement process.

Buddhi as observer.

Figure 9.3: Our theoretical thesis

ism and sensorimotor interaction and tuning as Manas.

To sum up, we have:

1. Chitta (the ground)
2. Vrittis arise from Chitta (via entanglement)
3. Manas act on them by Buddhi's choice (collapse)
4. Ahamkara is built as quantum measurement outcomes.

The Waves of vrittis (that arise from Chitta) is an information from outer world, we will see that this information is **the same concept** utilized in Zeilinger's interpretation of QM. In the last section, we will see that the ground (Chitta) is assimilable to Bohm's Holomovement which has no space-time structure (our previous work).

9.2.1 Quantum superposition of thought waves and SE(s) as Manas.

As we know, in the standard interpretation of QM, the essential difference of quantum mechanical concept of reality from usual classical reality is that in QM the properties of material systems, as they are observed in a measurement, may not exist **before** the observation (measurement process). In the context of Vedic theory of Mind[2] means that **without Buddhi component Chitta is not perceived**. We show a simple example of quantum superposition. To see how this plays out in real physics, consider the quantum superposition:

$$\psi = \sum_i c_i \varphi_i \tag{9.1}$$

in case of simple quantum superposition of two eigenstates φ_1, φ_2, we find the following state of the particle before the measurement: $\psi = c_1\varphi_1 + c_2\varphi_2$, this superposition of states is localized correspondingly in in A_1 and A_2. According to reduction postulate the system having been previously in the state ψ goes over into **one** of the states ψ_1 and ψ_2, with the corresponding probabilities $|c_1|^2$ and $|c_2|^2$. Thus, before the measurement we do not know where this particle is located; it could be at A_1, A_2, or both. This postulate corresponds to what is observed in real measurements, the reduction postulate is accepted as the basis for the quantum-mechanical calculations. In our approach, **the Ahamkara component of Vedic theory of Mind is represented by eigenvalues (or Povm)[3]**. For example, 'I experience redness of red-rose'.

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[2] In this article, the term 'theory of Mind' includes theories of 'my own mind' and 'others mind'.

[3] POVM = Positive Operator Valued Measure

9.3 Zeilinger's Interpretation of Quantum Mechanics: reality as information

Recently, with the development of quantum information theory, several scientists have given to the information a fundamental role in the description of the Nature. Quantum information theory has led to new way to look at the foundations of QM, including a greater emphasis on possible role of **subjective probability** (Fuchs,2002) in QM. Several works claims that the QM can be viewed as an information theory. These works states that the description of physical systems in terms of information and information processing, is the only way to describe physical system. For instance, according Bub's words (Bub, 2008):

> I argue that quantum mechanics is fundamentally a theory about the representation and manipulation of information, not a theory about the mechanics of nonclassical waves or particles. The notion of quantum information is to be understood as a new physical primitive.

Concisely, the information is taken at ontic level. We are interested to illustrate Zeilinger's position as an evidence. His thesis is quite simple:

> "The discovery that individual events are irreducibly random is probably one of the most significant findings of the twentieth century, even for single particles, it is not always possible to assign definite measurement outcomes independently of and prior to the selection of specific measurement apparatus in the specific experiment. For this reason, the distinction between reality and our knowledge of reality, between reality and information, cannot be made".

All these approaches (called quantum theoretic description of physical systems) start in general from the assumption that we live in a world in which there are certain constraints on the acquisition, representation, and communication of information. According these approaches, the description of physical systems in terms of information and information processing, is complementary (or the only way) to the conventional description of physical system in terms of the laws of physics. The notion of quantum information is to be understood as a new physical primitive. The primitive role of the information seems to explain, according some authors, the deep nature of physical reality. In this framework, the description of a quantum state is a description of the **information possessed by the observer about the system**.) According to Zeilinger and Brukner the information is the most fundamental notion in QM. Based on this observation they suggest new ideas for a foundational principle for quantum theory. They proposed, that the foundational principle for quantum theory may be identified through the assumption that the most elementary system **carries one bit of information only**. Therefore an elementary system can only give a definite answer in one specific measurement. The irreducible randomness of individual outcomes in other measurements and quantum complementarity are then necessary consequences. Moreover, they affirm that the objective randomness of the individual quantum event is a necessity of a description of the world in view of the significant influence the observer in QM has. In other words, the quantum level can be considered as subjective because of **observer's choice**. Starting from these premises the Buddhi component assumes the role of observer, his choice[4]causes the collapse, thus causes Ahamkara. Moreover, we suggest that Zeilinger's interpretation give us only an apparent randomness of measurement outcomes but only in the explicate order.

9.4 The central Role of Buddhi component

The central role of Buddhi, is supported by Zeilinger's interpretation of QM. The Buddhi component by his continue choices is able to build time by time the Ahamkara.
In general, the five components of mind, namely, (i) Chitta, (ii) Manas, (iii) Buddhi, (iv) Ahamkara, and (v)Paramatman→Atman→Purush ↔Prakriti→Brahma→ Jivatman or Paramatman→ ParamPurush/MahaPurush↔Prakriti → ParamBrahma→ Atman/Jivatman' are not well defined in literature including Rig-Veda, and have overlapping meanings/attributes; and various Vedic scholars use these terms and their interactions differently. Chitta, Manas, Buddhi, and Ahamkara are not fundamental entities and lack inherent existence. Therefore, according to Nagarjuna, there is no causation (Buddhi does not cause Ahamkara and vice-versa) and they dependently co-arise, which is consistent with re-entry hypothesis.
In other words, they all interact with each other in re-entrant manner for having subjective experiences, thoughts, perception, and action. The Vedic theory of mind (VTOM) that includes yoga is an elegant framework because it appears to be independent of various metaphysical views. This means VTOM can be interpreted in terms of idealism (matter emerges from mind), dual-aspect (mind and matter are two aspects of the same entity), neutral-monism (∼ Advait Vedanta, mind and mat-

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[4] How the 'choice' or 'selection' is precisely and rigorously made is given in using the dual-aspect-dual-mode optimal framework.

ter are derived from or reduced to a neutral entity), (substance) dualism ($\sim$ Dvait Vedanta: mind and matter are on equal footing and independent of each other but interact with each other via a liaison perhaps via Manas), and materialism (mind emerges from matter). For example, the **fig. 9.4** shows one of the interpretations of Vedic theory of Mind: Ahamkara seems to acts as an efficient condition for Buddhi, but other conditions might be involved[5]. On the other hand, Fig.9.5 shows another interpretation: Buddhi seems to acts as an efficient condition for Ahamkara. One (such as Descartes) could be tempted to interpret Fig. 9.5 "I am, therefore I think", where the term "I am" refers to Ahamkara and the term 'I think' refers to Buddhi. There, we emphasize that one should observe caution in the interpretations of VTOM. For example, both interpretations can be derived from this elegant Vedic theory of Mind and Nagarjuna's dependent co-origination[6]. Furthermore, in the above example, one could argue that 'I' or 'true Self' is Jivatman, 'I-maker' or the 'false self' is Ahamkara, and 'thinker'/'decision maker' is Buddhi. One could further argue that the term 'Self' can be referred to Atman/ Purusha/ Brahman/Jivatman depending on the specific context and the framework. One could also argue that all entities (Chitta, Manas, Buddhi, Ahamkara, and Jivatman) interact in re-entrant manner in a neural-network for SEs, thoughts, perception, and action. Further research is needed to make them precise and to link VTOM with the current trend of neuroscience.

9.5 Chitta as Holomovement

The starting point according Bohm is the understanding of the universe as an unbroken, undivided whole. Every attempt to analyze the whole by breaking it into seemingly independent parts is in principle incomplete and in the last consequence and is doomed to fail. Bohm very strongly points out that everything or, better, the whole is in constant motion, is evolving, and that nothing ever is fixed or reaches an ultimate, final form. Some of the notions and phrases underlying the processuality

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[5] "From an eastern perspective, Nagarjuna argued that the real causes should have powers as their essential properties and should have inherent existence, but causality does not have these attributes. Therefore, he proposes four 'conditions' (efficient, percept-object, immediate, and dominant conditions) instead of causality to explain phenomena in conventional reality: (i) an efficient condition explains the occurrence of successive events; (ii) an object is the percept-object condition for its perception; (iii) an immediate condition explains the various steps involved in a phenomena; (iv) a dominant condition is the purpose for which an action is undertaken".

[6] Historically, Vedic science was opposed by atheists Buddhism (Nagarjuna was Buddhist philosopher), Jainism, and materialists Lokâyata (or Cârvâka: http://en.wikipedia.org/wiki/Lokayata).

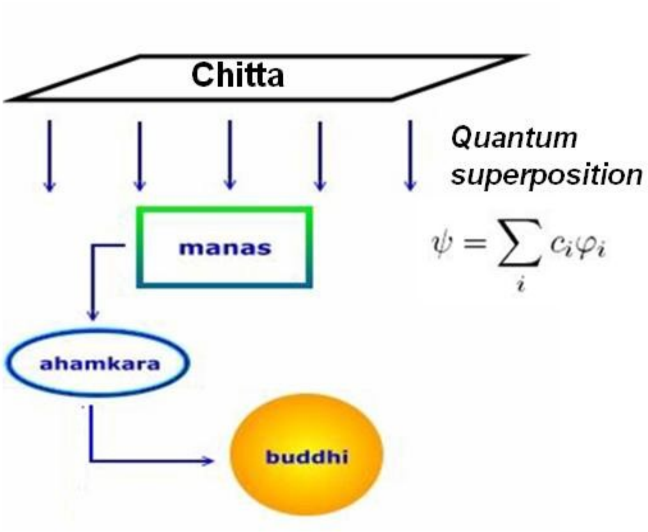
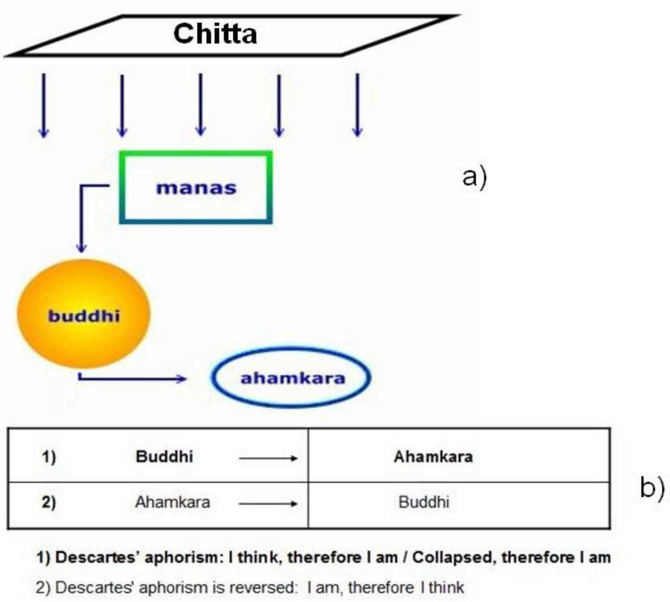


Figure 9.4: The secondary role of Buddhi component.



1)	**Buddhi** ⟶	**Ahamkara**
2)	Ahamkara ⟶	Buddhi

1) Descartes' aphorism: I think, therefore I am / Collapsed, therefore I am

2) Descartes' aphorism is reversed: I am, therefore I think

Figure 9.5: a) The central role of Buddhi: the ego is built through a Buddhi's choice, b) "Collapsed, therefore, I am".

in his thinking are undivided wholeness in flowing movement or holomovement, the enfolding- unfolding universe; he also stresses that "knowledge should be considered as a **process**". In details, the holomovement is a dynamics holistic pulsation in which orders unfold and enfold. This fundamental process **is not a movement within space-time** but rather a process in which ultimately **space-time and its contents are created**. The following quotation put in evidence the dynamics of space-time creation:

"One important feature concerning the holomovement is that *it is not*

> *described in space-time but from it space-time is to be abstracted.* Thus we no longer start with an a priori space-time manifold in order to discuss physics; rather we construct space-time from the underlying process. Is not, as Wheeler (Wheeler, 1999) and Hawking suggests, a progression for the continuum via fluctuations to the space-time foam: rather it is the simplicial description of the relative invariant features of the holomovement that become the foam from which the continuous space-time is abstracted. Thus locality is no longer a primary concept but is also abstracted so that quantum non-local correlations could be explained as remnant of the basic underlying complex."

All five entities Chitta, Manas, Buddhi, Ahamkara, and 'Paramatman →Atman→Purush ↔Prakriti →Brahma
→Jivatman' or 'Paramatman→ParamPurush/MahaPurush
→ Prakriti→ParamBrahma→Atman/Jivatman' **are assimilable with Bohm's Implicate and Explicate order** at various levels and the holomovement framework. For example, the entities Paramatman→Atman→ Purush↔Prakriti can be considered equivalent to Bohm's enfolded IO, whereas Brahma, Jivatman, Chitta, Manas, Buddhi, and Ahamkara can be considered as unfolded Explicate Order at various levels. For example, Chitta is assimilable with the holomovement that does not have the structure of space-time; the holomovement (via entanglement) unfolds and enfolds via space-time; in the same way Chitta unfolds and enfolds (via entanglement) with Manas, which represent the Explicate Order of Vedic theory of Mind.

9.5.1 Conclusion

To sum up, at sub-quantum fundamental level, **both Vedic theory of mind and Bohm's Implicate/Explicate Order can be interpreted as similar**. One could argue that the latter might be derived from the former to the some extent. Both are elegant frameworks because they can be interpreted as independent of metaphysical views, even though Bohm was clearly dual-aspect philosopher and a great physicist. Furthermore, at quantum and classical level, Vedic theory of mind can be interpreted in terms of global workspace framework, neural Darwinism and reentrant processing, and of course the dual-aspect dual-mode framework. One could argue that it would be the difficult to fit contemporary materialistic reductionistic neuroscience framework with non-reductionistic wholeness. However, the boundary between both frameworks might melt as consciousness and neuroscience researches progress, say, by extending materialism to physicalism (= materialism + SEs) via dual-aspect dual-mode framework.

9.5.2 Commentaries

1) According to Chandrasekar (personal communication to the authors in June 2010), "I find that your article on vedic theory of mind uses different understanding from Samkhya, Yoga, Buddhism and Advaita. I personally feel that this way of taking different standpoints is tricky and troublesome. For example, Samkhya talks only of Purusha and Prakrti (note: it does not talk of parabrahman). Advaita talks of Atman and Brahman. Buddhism denies permanence of soul. Hence I say that a combination of the understanding of these four philosophical schools might be tricky. Regarding Descartes' I think therefor I am'. Please be informed of the Existentialist, Soren Kierkegaard, who philosophized in the way you have projected this statement as I am therefore I think (Kierkegaard also refutes DescartesŠ position with this statement to establish his existentialist position."

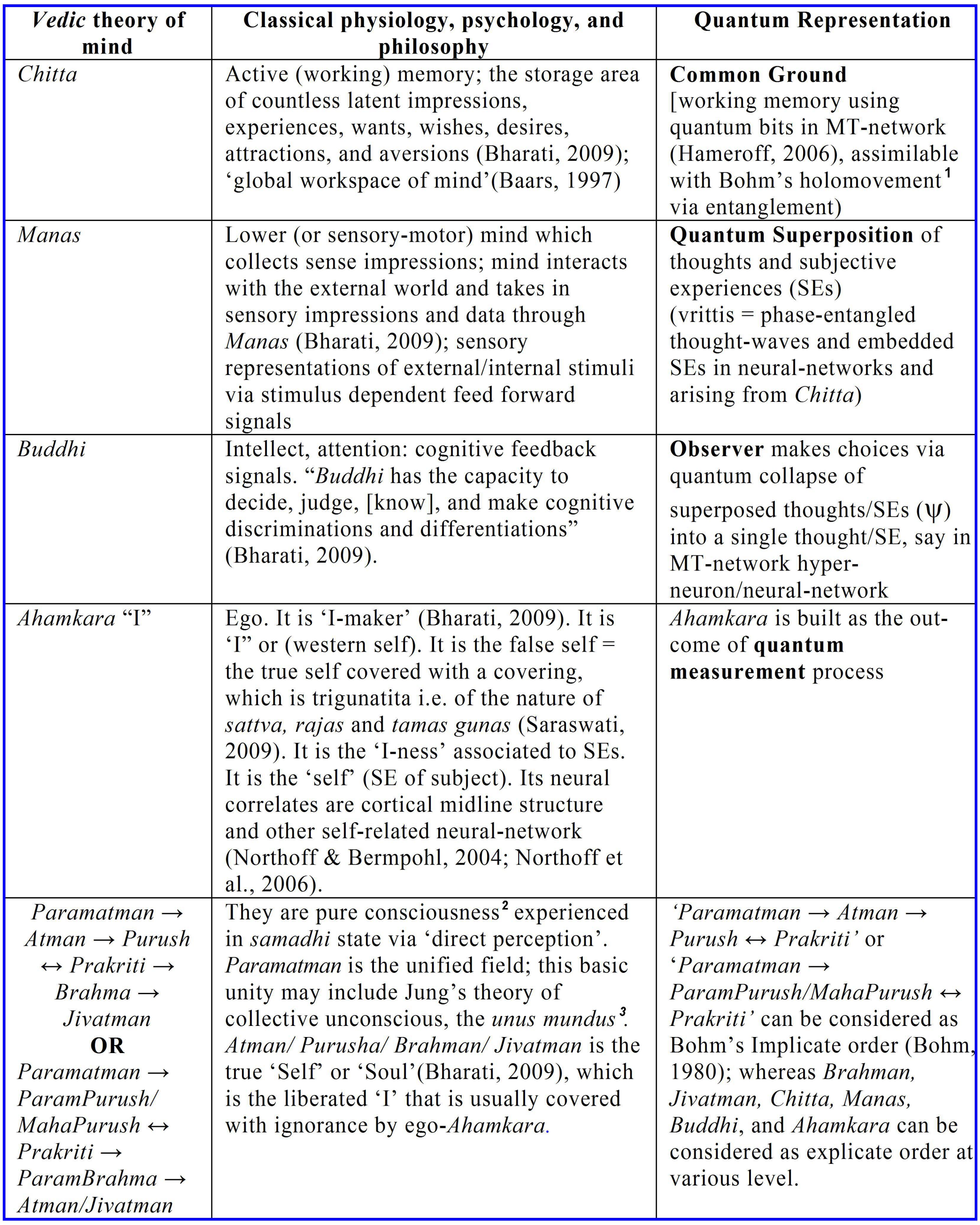
Response: We agree with Chandrasekar that there are differences between Samkhya, Yoga, Buddhism and Advaita and each of them has problems. Therefore, we follow the dual-aspect-dual-mode PE-SE framework that is optimal (which has the least number of problems) and is close to Trika-Kashmir-Shaivism, where Shiva is the mental aspect and Shakti is the physical aspect of the same entity.

2) Narayan Kachhara (personal communication in June, 2010) commented, "Application of QM to explain mind concepts appears to be a progressive approach. However, not going into its merit, I would like to make some observations from the point of view of Jain philosophy. Atman is non-physical and is different from physical mind. Jain philosophy describes two componentsof mind, one Dravya Manas, the physical mind, and two Bhava Manas which is Atman counterpart of physical mind. Atman having intrinsic property of consciousness thinks, experiences, knows, perceives and acts. The Dravya Manas acting in parallel with Atman works in the physical plane to execute the intents of Atman. The components Chitta, Manas, Buddhi and Ahamkara are parts of Dravya Manas and have functions more or less similar to the Vedic concepts. Jain philosophy does not subscribe to the concept of Paramatman as IO of Bohm. Paramatman is the pure form of Atman, a state reached when all karmic matter has been eliminated. This state is not derived from Prakriti thatis physical. Jivatman refers to individual Atman, all Atman are independent and not a part of Brahma. Brahma is not supposed to cause creation, in

fact no substance, physical likematter or energy, and non-physical like Atman, can be created or destroyed; their fundamental forms are eternal. They, however, undergo transformation according to some set of rules, scientific laws in case of matter and doctrine of karma in case of Atman."

Response: Jain philosophy seems close to substance dualism, in analogy to Vedic system. Therefore, this view has problems related to substance dualism, which are detailed in (Vimal, 2010). Our metaphysical view is dual-aspect dual-mode PE-SE framework as detailed in close to Trika Kashmir Shaivism, and has the least number of problems, namely, only one justifiable problem of brute fact of dual-aspect assumption.

To conclude the Unus mundus in the following table, is a term which refers to the concept of an underlying unified reality from which everything emerges and returns, Jung's concepts of the archetype and synchronicity (Giannetto-Pozzi, 1998) are related to the unus mundus.



***Vedic* theory of mind**	**Classical physiology, psychology, and philosophy**	**Quantum Representation**
Chitta	Active (working) memory; the storage area of countless latent impressions, experiences, wants, wishes, desires, attractions, and aversions (Bharati, 2009); 'global workspace of mind'(Baars, 1997)	**Common Ground** [working memory using quantum bits in MT-network (Hameroff, 2006), assimilable with Bohm's holomovement[1] via entanglement)
Manas	Lower (or sensory-motor) mind which collects sense impressions; mind interacts with the external world and takes in sensory impressions and data through *Manas* (Bharati, 2009); sensory representations of external/internal stimuli via stimulus dependent feed forward signals	**Quantum Superposition** of thoughts and subjective experiences (SEs) (vrittis = phase-entangled thought-waves and embedded SEs in neural-networks and arising from *Chitta*)
Buddhi	Intellect, attention: cognitive feedback signals. "*Buddhi* has the capacity to decide, judge, [know], and make cognitive discriminations and differentiations" (Bharati, 2009).	**Observer** makes choices via quantum collapse of superposed thoughts/SEs (ψ) into a single thought/SE, say in MT-network hyper-neuron/neural-network
Ahamkara "I"	Ego. It is 'I-maker' (Bharati, 2009). It is 'I" or (western self). It is the false self = the true self covered with a covering, which is trigunatita i.e. of the nature of *sattva, rajas* and *tamas gunas* (Saraswati, 2009). It is the 'I-ness' associated to SEs. It is the 'self' (SE of subject). Its neural correlates are cortical midline structure and other self-related neural-network (Northoff & Bermpohl, 2004; Northoff et al., 2006).	*Ahamkara* is built as the out-come of **quantum measurement** process
Paramatman → Atman → Purush ↔ Prakriti → Brahma → Jivatman **OR** *Paramatman → ParamPurush/ MahaPurush ↔ Prakriti → ParamBrahma → Atman/Jivatman*	They are pure consciousness[2] experienced in *samadhi* state via 'direct perception'. *Paramatman* is the unified field; this basic unity may include Jung's theory of collective unconscious, the *unus mundus*[3]. *Atman/ Purusha/ Brahman/ Jivatman* is the true 'Self' or 'Soul'(Bharati, 2009), which is the liberated 'I' that is usually covered with ignorance by ego-*Ahamkara*.	*'Paramatman → Atman → Purush ↔ Prakriti'* or *'Paramatman → ParamPurush/MahaPurush ↔ Prakriti'* can be considered as Bohm's Implicate order (Bohm, 1980); whereas *Brahman, Jivatman, Chitta, Manas, Buddhi*, and *Ahamkara* can be considered as explicate order at various level.

Figure 9.6: Table of correspondences in details:

(1)See also for Bohm's Implicate/Explicate order and holomovement.

(2)There are many meanings (or aspects) attributed to the term 'consciousness', such as 'pure consciousness', 'subjective experiences', (multidimensional) physical/neurobiological processes, and so on.

(3)"Unus mundus, lit. "One world", is a term which refers to the concept of an underlying unified reality from which everything emerges and returns.

9.6 Māyāvada and Quantum Entanglement

We conclude this speculative chapter, with a recent work by Parkin (Parkin, 2008). In order to conciliate the doctrine of mayavada[7]with the reality of material world, Parkin utilize the feature of QE. According Parkin, the best argument for the plausibility of world-affirming mayavada is based on emergence due to the entangled state of the universe, and like all good arguments it is based on empirical evidence. The second aim of his work, is to show that world-affirming mayavada is a plausible metaphysical position which should be taken seriously in contemporary metaphysical debate. To achieve this some pluralist arguments against **nondualism are rejected**, and it is explained how world-affirming mayavada is preferable to pluralism when accounting for the ontological problems that arise **from limitless decomposition and emergence due to QE**. His starts from these points:

- 1)At the quantum level, the whole universe is entangled.
- 2)If the whole universe is entangled, then the whole possesses emergent properties.
- 3) If the whole possesses emergent properties, then the whole does not supervene on its parts, in that the whole displays properties greater than the sum of its parts.
- 4) If the whole does not supervene on its parts, then whole must be logically prior to part.
- 5) Therefore, whole is prior to part.

Parkin, in other words affirm that since entanglement is a truth about quantum wholes, and that this truth can be applied to the entire universe, it follows that the universe displays qualities of emergence. Hence the whole displays properties greater than the sum of its parts. If the whole displays properties greater than the sum of its parts, then whole is prior to part, and thus world-affirming m?y?vada must be a plausible ontological position.

A brief comment on this theoretical speculation. We retain that the problem is to affirm: the whole displays properties greater that the sun of its parts (holism), instead until now we have presented the QE as non-separability. Non-separability has a different ontological status with respect holism.

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[7] According to Māyāvada philosophy, all living entities are one with brahman, but at present, are covered by illusion, and therefore temporarily seperated from brahman. When the illusion is gone, the living entity becomes again one with the brahman and loses its identity.

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Conclusioni

I risultati sperimentali recenti, dimostrano che la natura a livello microscopico, non è più pensabile come composta da oggetti separati e separabili dal proprio contesto. Crediamo che il concetto di inseparabilità mina in qualche modo le stesse basi della metodologia scientifica finora adottata (i.e. il metodo riduzionista). Nella parte centrale del lavoro di tesi, è stato proposto un esperimento teorico. Un esperimento teorico che si è basato sul cammino o catena di von Neumann. Il cammino di von Neumann è stato visto, in questo contesto, **non come un problema ma come una risorsa**. Una risorsa che ci ha condotto a valutare positivamente il modello proposto da Bohm nel 1980 (i.e. ordine esplicato/implicato). Questo esperimento inoltre ci suggerisce una revisione dei concetti di spazio e di tempo, in sintonia con alcuni lavori recenti di Suarez, nei quali si sostiene che l'entanglement è un fenomeno che avviene in realtà al di fuori dello spazio-tempo. I lavori di Suarez-Scarani hanno assunto una rilevanza ancor maggiore quando sono stati comparati con quelli ottenuti sperimentalmente nel 2004 da Brukner e Vedral. Secondo questi ultimi, anche il tempo può essere messo in condizioni di entanglement. Il tempo viene trattato come una semplice osservabile, come se fosse lo spin o la polarizzazione di una particella. L'istante di tempo precedente e l'istante di tempo successivo sarebbero in tale modello sperimentale sullo stesso piano. Nella seconda parte della tesi si sono affrontati le possibili implicazioni epistemologiche dell'EQ. In particolare i legami con l'Olomovimento e l'ordine implicato di Bohm. Nel quadro così delineato, crediamo siano da rivedere i programmi di ricerca, quali le TOE e le teorie del Big Bang.

Inseparabilità, non località ed ordine implicato ci proiettano anche verso concetti noti già da tempo nella filosofia Indiana, quali lo Spanda-Karika di Abhinavagupta. Nell'ultimo capitolo è stato proposto un modello molto speculativo riguardante una possibile interpretazione della MQ della teoria Vedica della mente.

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