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The Macro-Objectification Problem and Conscious Perceptions

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ABSTRACT

We reconsider the problem of the compatibility of our definite perceptions with the linear nature of quantum theory. We review some proposed solutions to the puzzling situation implied by the possible occurrence of superpositions of different perceptions and we argue that almost all are not satisfactory. We then discuss the way out which makes explicit reference to consciousness and we underline its pros and cons. In the second part of the paper we reconsider this problem in the light of the recently proposed collapse models, which overcome the difficulties of the standard theory by adding nonlinear and stochastic terms to the evolution equation and, on the basis of a unique dynamical principle, account both for the wavy behaviour of microsystems as well as for definite macroscopic events. By taking into account that different microscopic situations can trigger different displacements of an enormous number of particles in our brains which, in turn, lead to different and definite perceptions, we make plausible that such models do not assign a peculiar role to the conscious observer. Simply, the characteristic amplification mechanism leading to the collapse implies the suppression of all but one of the nervous stimuli corresponding to different perceptions. Thus, collapse models, at the nonrelativistic level, qualify themselves as theories which can consistently account for all natural processes, among them our definite perceptions.

Part I

1 A sketch of the quantum description of physical processes

Since the galilean revolution, the natural language of any scientific theory has been mathematics. In particular, different physical situations characterizing an individual physical system are usually described by appropriate mathematical entities which uniquely specify the “state” of the system under consideration. A paradigmatic example is given by

Newtonian mechanics: the state of a system is uniquely specified by the assignment of the positions and velocities of all its constituents. Besides the states, a crucial role is played by the physically observable quantities, such as the momentum, the energy and so on. In classical mechanics these quantities are simply functions of the positions and the velocities of the constituents and, as such, they always possess precisely definite values. Finally, any theory must have a predictive character. This is usually embodied in an evolution equation for the "state" of the system which uniquely assigns a state at any time t once the initial state (at time 0) is specified. Obviously the formal scheme must also contain the prescription which, once the state is known, allows one to infer the value he will get when subjecting the system to a "measurement" of the physical observable he is interested in.

To supply, in a quite elementary way, the reader who is not familiar with quantum theory with the formal elements which are necessary to understand what follows, we consider it appropriate to summarize the "rules of the game" in the case of quantum mechanics. In reading this section it may be useful to give a look at Fig.1 which puts in evidence all formal aspects we are going to describe, by making reference to the oversimplified case of a linear vector space of dimension 2.

- The states of the system are associated to normalized (i.e. of length 1) vectors (which, for this reaason are also called statevectors) of a linear vector space. Let us denote, following Schrödinger, as $|\psi\rangle$, $|\phi\rangle$ two such states. The linear nature of the space of the states implies that if the two just mentioned states are possible states for a system, then also any normalized combination of them with complex coefficients $\alpha|\psi\rangle + \beta|\phi\rangle$, $|\alpha|^2 + |\beta|^2 = 1$ is also a possible state of the system.

- The physical observables of the system are associated to appropriate operators acting on the state space. Here, an extremely important and innovative aspect of the formalism consists in the emergence of the phenomenon of quantization: the physical observables (in general) cannot assume any value in appropriate continuos intervals (as it happens in classical physicis) but they can take only some discrete values, called eigenvalues, which are the values for which the eigenvalue equation, Eq.(1) below, admits a solution. If we denote as Ω the operator corresponding, within quantum mechanics, to an appropriate classical observable (like the angular momentum and similar) then we must look for values ω_i and states $|\phi_i\rangle$ satisfying:

$$\Omega|\phi_i\rangle = \omega_i|\phi_i\rangle. \tag{1}$$

  The eigenvalues ω_i (due to some precise formal requests on the operators representing observables) turn out to be real, they are usually discrete, the eigenvectors turn out to be pairwise ortogonal and, as a set of states, they are "complete", a technical expression to stress that any vector of the space can be expressed as a linear combination of them. Accordingly, the eigenstates of an observable yield an orthogonal system of axes for the space itself.

- The evolution equation is a deterministic differential equation, the celebrated Schrödinger's equation. Its most relevant feature, for what interests us here is that it is linear, i.e., if $|\psi, 0\rangle$ and $|\phi, 0\rangle$ are two initial states and $|\psi, t\rangle$ and $|\phi, t\rangle$ are their evolved at time t, then the evolved of the initial state $\alpha|\psi, 0\rangle + \beta|\phi, 0\rangle$ is $\alpha|\psi, t\rangle + \beta|\phi, t\rangle$.

- The predictions of the theory are fundamentally probabilistic and are embodied in the following rule. If the system is described by the state $|\Psi\rangle$ and if one is interested in the predictions concerning the outcome of a measurement of an observable Ω, one must express the state as a linear combination of the eigenstates of the observable itself (something we know that is always possible):

$$|\Psi\rangle = \sum_i c_i |\phi_i\rangle. \tag{2}$$

Then the theory makes precise probabilistic predictions concerning any outcome, let us say ω_k, which one can get in a measurement of Ω (and the same procedure allows to determine the probabilities of the outcomes for the other observables). Actually, the probability $P(\Omega = \omega_k || \Psi\rangle)$ of such an outcome for such an observable when the system is in the indicated state is simply given by the modulus square of the corresponding coefficient c_k of Eq.(2) (Note that since the vector has length one the sum of the squares of all its components equals one, i.e., one of the possible outcomes is obtained with certainty). From this rule one sees that when one and only one of the c_i's is different from zero (and therefore it equals 1) we can predict with certainty the outcome itself. In such a case we say that the observable Ω, possesses with certainty the value ω_k.

- It has to be stressed that, in general, different operators do not commute $\Omega\Gamma \neq \Gamma\Omega$. The most relevant implication of this fact is that, in general, the eigenvectors of a pair of such operators are not aligned. This means that if one prepares the system in a state that corresponds to a definite value of an observable (and therefore it is an eigenstates of the observable itself) the corresponding statevector will have non zero projections on at least two (in general many) eigenstates of the other noncommuting observable. As a consequence there are nonzero probabilities of getting one among various outcomes for it: the considered variable does not have a precise value. Accordingly, making sharp the value of an observable makes indefinite the value of other observables.

  This is the uncertainity principle which holds, in particular, between the position and momentum variables: the more precise we make one of the two observables, the less precise we make the other.

  It has to be stressed that if we consider a set of observables which commute among themselves (a set having this property is called an abelian set) then a theorem ensures that they admit precisely the same eigenstates. There obviously follows that, when such a common eigenstate describes the state of the system, all the considered observables possess precisely definite values.

- The theory specifies also the effect of the measurement process: if we make a system in a state like the one of Eq.(2) (with various c_i different from zero), to interact with the measuring apparatus, and we obtain the outcome, let us say ω_j, the state of the system changes instantaneously from $|\Psi\rangle$ to the eigenstate corresponding to the eigenvalue of the measured observable: $|\Psi\rangle \rightarrow |\phi_j\rangle$. Note that, contrary to the standard evolution, which is linear and deterministic, the change induced by the measurement process is nonlinear (since the probabilities are given by the squares of the moduli of the coefficients) and stochastic (since all outcomes corresponding to non zero coefficients may occur with the specified probabilities).

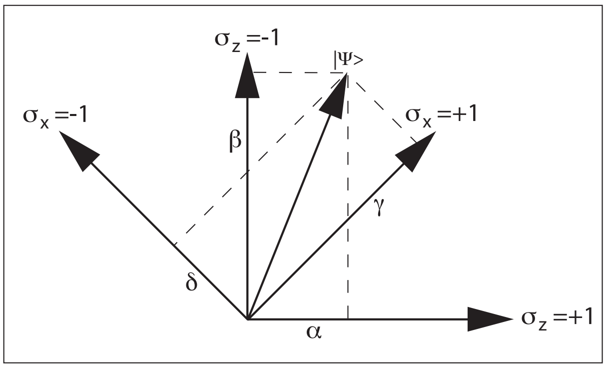

Figure 1: The formal structure of quantum mechanics in a pictorial form.

As already anticipated, we have chosen to depict, in Fig.1, the situation we have just described by making reference to the simplest vector space which occurs in the theory, the one related to the spin degree of freedom of a spin 1/2 particle. In such a case the vector space is two dimensional. Moreover, the observables corresponding to the projections of the spin along any given direction can take only the values ± 1, in units of $h/2\pi$, h being Planck's constant.

Each operator corresponding to the spin component in a given direction is uniquely associated to two orthogonal unit vectors, its eigenstates. These vectors are different for different directions. In the figure, we have indicated the state $|\Psi\rangle$ associated to the system, and two pairs of orthogonal axes (the horizontal and vertical ones and those at 45^0 and 135^0 degrees). They correspond to the observables σ_z, the projection of the spin along the z-axis (in the indicated units), and σ_x, the projection of the spin along the x-axis, respectively. From the figure one can grasp all relevant points of the formalism: the modulus square of the components α (β) of the statevector along the horizontal (vertical) axis give the probability of getting the outcome $+1$ (-1) when the spin is measured along the z-axis. Similarly, the modulus square of γ and δ yield the probabilities of getting the two above mentioned outcomes in a measurement of the spin component along the x-axis.

As one clearly sees, making precise and equal to $+1$, e.g., the value of the spin component along the x-axis, which means aligning the statevector $|\Psi\rangle$ with the line at 45^0, implies, since this unit vector has components $1/\sqrt{2}$ along the horizontal and vertical axes that, for such a state, there is a probability 1/2 of getting the outcome $+1$ or -1 in the measurement of the z-spin component. Making absolutely precise one observable, i.e. σ_x, renders thus maximally indeterminate the other one since equal probabilities are attached to its two possible outcomes. We also recall that, within the standard theory, a measurement changes instantaneously the state of the system. In our case, if we measure the x-component of the spin and we get the result $+1$, the statevector $|\Psi\rangle$ is transformed into the unit vector at 45^0.

2 The position representation

To allow the reader to follow the discussion in the second part of the paper we are compelled to make an important specification: not all observable quantities are quantized, some of them can take any value within a continuous interval. This implies some formal mathematical refinements which we will not discuss in detail. Typical examples of this situation are the position and the momentum observables; both of them can assume, just as in classical mechanics, all values lying between $-\infty$ and $+\infty$. Let us consider the analogous, in the continuous case, of the discrete case discussed above. For the moment, let us assume that we are dealing with a one-dimensional problem, i.e. a particle moving along a line, and let's denote as X its position variable.The eigenvalue equation (1) will be replaced by:

$$X|x\rangle = x|x\rangle, \tag{3}$$

x being the value of the position occupied by the particle, while Eq.(2) will be replaced by:

$$|\Psi\rangle = \int_{-\infty}^{+\infty} dx\psi(x)|x\rangle. \tag{4}$$

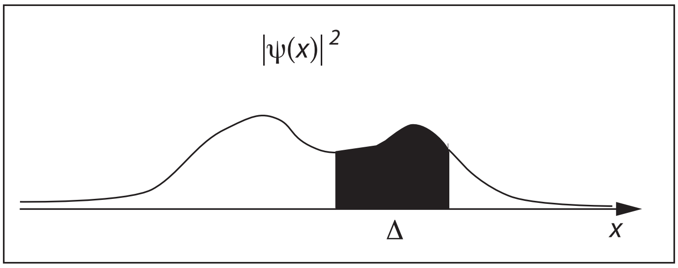

Figure 2: The probability of finding the particle within the interval Δ is given by the black area in the figure.

It is important to clarify the physical meaning of the coefficient (the wavefunction) $\psi(x)$ appearing in this equation. First of all, the normalization condition (the fact that $|\Psi\rangle$ has length 1) now reads:

$$\int_{-\infty}^{+\infty} dx|\psi(x)|^2 = 1. \tag{5}$$

Secondly, just as the squares of the moduli of the coefficients c_i give the probabilities of getting the outcome ω_i in a measurement of the observable Ω, now the modulus square of the wavefunction $|\psi(x)|^2$ yields the probability density of finding the particle at x in a position measurement. Physically this means that the area subtended by the modulus square of this quantity in a given interval Δ of the x-axis, gives the probability of finding the particle in the indicated interval when subjected to a position measurement. We have depicted the situation in Fig.2.

3 The quantum measurement problem

With the above premises, we can now formulate in a precise way the quantum measurement problem. The idea is quite simple. Suppose we have a microscopic system in an eigenstate of a specific observable, and we want to ascertain its value, which, as we know, coincides with certainty with the associated eigenvalue. If we denote as usual as $|\phi_i\rangle$ the eigenstate of the micro-observable Ω we are interested in, and we assume that we can get knowledge of its definite value ω_i, we must consider an apparatus A characterized by a "ready state" $|A_0\rangle$ and a micro-macro interaction leading to the evolution:

$$|\phi_i\rangle \otimes |A_0\rangle \quad \rightarrow \quad |\phi_i\rangle \otimes |A_i\rangle, \tag{6}$$

where the macrostates $|A_i\rangle$ are macroscopically and perceptually disinguishable. The standard example is the one of a macroscopic pointer that, after the measurement, will "point" at the obtained value i.

Equation (6) deserves some comments. In it the product of two states, referring to two different systems appears (the use of the circled cross makes reference to the formal fact that the space of the composite system is the direct product of the spaces of the constituents). However, from a physical point of view, the states appearing in Eq.(6) have a precise meaning: at the l.h.s we have a microsystem in the state which corresponds to its having the precise value ω_i for an appropriate observable, while the macroscopic apparatus is in a "ready" state in which its pointer points at 0. Concerning the state at the r.h.s. the microsystem is in the same state and still has the property $\Omega = \omega_i$, while the macroscopic pointer is also in a definite, different from the previous one, state: its pointer points at i on the scale. We have ascertained the possessed value of the observable Ω.

Here comes the problem. In fact we can easily prepare the microsystem in a state which, instead of being an eigenstate of the observable we are interested in, is a linear superposition of eigenstates belonging to different eigenvalues (the reader should remember that the eigenstate of the σ_x component of the spin associated to the eigenvalue $+1$ is a linear superposition, with equal coefficients of the two eigenstates of σ_z belonging to the eigenvalues $+1$ and -1). Moreover, we can put the microsystem in such a superposition into interaction with the macroapparatus designed to "measure" Ω. At this point we are in troubles since we can argue as follows. The unfolding of the process which implies the micro-macro (system-apparatus) interaction must be governed by our fundamental theory, quantum mechanics. In fact, what reason whatsoever there could be for all micro-constituents of the universe to be governed by the quantum laws, while a macrosystem, which is nothing more than an assembly of nuclei, atoms, molecules and so on, should be ruled by different laws? However, as we have repeatedly stressed, due to the linear character of the evolution, if the microsystem-macroapparatus interaction is described by

Eq.(6) when the triggering state is an eigenstate of the observable Ω, then, in the present case, one has:

$$\sum_i c_i|\phi_i\rangle \otimes |A_0\rangle \equiv \sum_i c_i[|\phi_i\rangle \otimes |A_0\rangle] \quad \rightarrow \quad \sum_i c_i|\phi_i\rangle \otimes |A_i\rangle. \tag{7}$$

The final state is not a product (factorized) state of the system and the apparatus, but a linear superposition of such states. Technically it is referred as an entangled system-apparatus state. The puzzle arises from the fact that, as the theory tells us, such a state does not describe neither a microsystem with a definite property for Ω (and this is not particularly problematic) nor a macroscopic object whose pointer points at a precise position. Actually the theory implies that the pointer "does not have a precise location" and only if we decide to "measure its position" we will get one of the potentially possible outcomes: the pointer will be found to point at, let us say, k. Which meaning can be attached to a state in which a superposition of macroscopically and perceptually different states appears? How to interpret this state of affairs?

As we have already anticipated, the "orthodox" way out is to claim that the final situation is described, with probability $|c_i|^2$, by one of the terms of the superposition, all of which correspond to the pointer "pointing at a precise position". So, standard quantum mechanics contains two evolution laws, the linear one typical of microsystems and the nonlinear and stochastic one corresponding to Wave Packet Reduction (WPR), and accounting for the measurement processes. The big problem derives from the fact that the theory does not contain any formal element which identifies when one or the other type of evolution occur. Actually, macroscopic systems which require a genuinely quantum treatment exist. The problem has been emphasized with admirable lucidity by the late J. Bell:

> *Nobody knows what quantum mechanics says exactly about any situation, for nobody knows where the boundary really is between wavy quantum systems and the world of particular events.*

4 The von Neumann chain

John von Neumann has been the first to dig deeply into the measurement problem. He made an important remark. If one takes into account Eq.(7), one cannot consider it as exhaustively describing the measurement process. In fact, as it is obvious, the final state leads to the natural question: what actually is the outcome of the measurement? (i.e. where does the pointer point?). The answer is obvious: we must consider a further process aimed to ascertain which one of the eigenstates $|A_i\rangle$ actually occurred. In this way the so-called von Neumann's chain finds its origin. The r.h.s of Eq.(7) must be enriched by taking into account the further measuring apparatus (let us call it B) devised to identify in which of the macrostates the pointer A is. Accordingly, we must consider successive measurement procedures aiming to identify what the actual state of affairs is:

$$\sum_i c_i|\phi_i\rangle \otimes |A_0\rangle \otimes |B_0\rangle \otimes .... \rightarrow \sum_i c_i|\phi_i\rangle \otimes |A_i\rangle \otimes |B_i\rangle \otimes ...., \tag{8}$$

and so on. The chain never ends but it exhibits a quite interesting feature. No matter at which point one chooses to break it, if the linear superposition is replaced by one of its terms (let us say the ith) one gets a consistent set of outcomes: the particle is found in state $|\phi_i\rangle$, the macroapparatus has its macroscopic pointer pointing at the value i of the scale, the apparatus B reveals that the macroapparatus A actually points at i and so on. In brief, there is a full "final" consistency provided one breaks (at a certain level) the chain.

Some remarks are at order:

- This approach leaves open the stage at which the breaking must be assumed to occur, provided it occurs at some point. In this sense, it is not surprising that von Neumann and Wigner have chosen (see below) to break it at the level in which consciousness enters into play.
- von Neumann's has tacitly made some quite drastic assumptions concerning the unfolding of the process (typically that the measurement has 100% efficiency, that the final states are strictly ortogonal etc., a set of assumptions which are very difficult to be verified in actual experiments) and this is why one usually refers to the just described scheme as "The Ideal von Neumann's Measurement Process".

5 The unavoidability of the problem

Some authors (Primas, 1990) have suggested that the previous argument arises from having described the measurement process by a too idealized scheme. That this is not the case has been proved in absolute generality in a recent paper (Bassi & Ghirardi, 2000), in which it has been shown that, if quantum mechanics has unrestricted validity, the occurrence of the embarrassing superpositions of macroscopically and perceptually different states of macrosystems cannot be avoided.

The original paper by Bassi and Ghirardi has given rise to a stimulating debate with B. d'Espagnat: (d'Espagnat, 2001). The relevant conclusion of this author, for what concerns us here, is:

> *What Bassi & Ghirardi has proved is that we must either accept the break* [i.e. to abandon the superposition principle] *or grant that man-independent reality - to the extent that this concept is meaningful - is something more "remote from anything ordinary human experience has access to" than most scientists were up to now prepared to believe.*

In the appendix the author has felt the necessity to state, as Bassi and Ghirardi have argued, that there are only two ways out of this *impasse*: either one accepts the break or one must assume that it is consciousness that leads to WPR.

6 Some attempts to overcome the difficulties

The measurement problem has seen an alive and never ending debate as well as many attempts for a consistent solution in the last 90 years. The actors of this "drama" have been scientists of the level of Bohr, Einstein, de Broglie, Schrödinger, Born, Jordan, von Neumann, Wigner and many others.

6.1 Superselection rules

An interesting proposal (Daneri et al. 1962), strongly supported by Rosenfeld, assumes that *in principle* the set of all conceivable observables of a macroscopic object is an abelian set, so that, when macrostates enter into play, the state (2) cannot be distinguished from the statistical mixture ensuing to WPR i.e., to the situation in which one has an ensemble of systems the fraction $|c_k|^2$ of which is in the state $|\phi_k\rangle \otimes |A_k\rangle$. In fact, if all observable quantities commute, they have a common set of eigenstates so that the implications of the assumption that one has an ensemble of systems in these eigenstates distributed according to the probabilistic law $|c_k|^2$, makes the ensuing situation indistinguishable from the one associated to the state (4). This has been made more precise by Jauch (Jauch, 1964). The proposal meets serious difficulties since, if the assumption is correct, also the hamiltonian should commute with all observables, and, as a consequence, it could not drive a pointer state from one to a macroscopically different state. However, this certainly occurs, because the state $|A_0\rangle$, corresponding to the ready state of the apparatus, is transformed by the measurement process in the state corresponding to a position of the pointer which differs from 0. This fact in turn implies that the energy of the whole system is not an observable, a quite peculiar and nonsensical fact.

6.2 Many Universes and Many Minds

Important proposals are "The Many Universes Interpretations" of Everett III (Everett, 1957) and DeWitt (de Witt, 1971) and "The Many Minds Interpretation" of Albert and Lower (Albert & Loewer, 1988). The first proposal suggests that all potentialities of the state, referring to different macroscopic situations, become actual in different universes. There is a continuous multifurcation of the Universe associated to superpositions of macroscopically different states. So, when a state like the one of Eq.(7) is dynamically brought into play by the measurement interaction, one must think that there are infinitely many universes, each of them corresponding to one and only one of the perfectly meaningful terms of the superposition.

The Many Minds Interpretation assumes that in place of all potentialities becoming actual in different universes, all possible perceptions occur in appropriately correlated different "sheets" of our brains.

I will not discuss these proposals here. I will limit myself to stress that all of them are affected by an unsatisfactory vagueness. In fact it is not clear when the superselection rules of (Daneri et al. 1962) become effective, as well as when a splitting of the universe or of the brain should occur.

6.3 Bohmian Mechanics

The basic idea (Bohm, 1952a,b) of this approach is that quantum mechanics is an incomplete theory and that, in order to characterize the state of a system, further variables (hidden and inaccessible) are necessary. The hidden variables that supplement the wavefunction are the initial positions of the particles of the system. The general scheme goes then as follows: one starts with a given wavefunction $\psi(\mathbf{r}_1, ...\mathbf{r}_2, ..., 0)$ at time $t = 0$, one solves the Schrödinger equation and derives the wavefunction at time t. In terms of the known wavefunction at the various times one introduces a velocity field which drives the various particles. The fundamental feature of the theory is that it is constructed in such a way that, if the initial density distribution of the particles agrees with $|\psi(\mathbf{r}_1, ...\mathbf{r}_2, ...; 0)|^2$, then, at any subsequent time the quantum density distribution of the particles which propagate deterministically from their precise initial positions in agreement with the velocity field, is given by $|\psi(\mathbf{r}_1, ...\mathbf{r}_2, ...; t)|^2$, and, as such, it coincides with the one implied by standard quantum mechanics. The theory is completely deterministic, it fully agrees with the quantum predictions concerning the probability density distributions of the positions and it claims that what the theory is about are exclusively the positions of all particles of the universe. The scheme overcomes the difficulties related to WPR and it is mathematically precise. For our purposes it is important to stress that this approach does not meet any difficulty with the psycho-physical correspondence if one accepts that our perceptions are fully determined by the locations of the particles in our brain.

6.4 Decoherence

A lot of attention (Zurek, 1981, 1982, 1991; Griffiths, 1984, 1996; Gell-Mann & Hartle, 1990) has been paid to approaches making a precise reference to the decoherence induced on any quantum system, and in particular on macroscopic ones, by the unavoidable interaction with the environment. The idea is rather simple, and can be depicted by enriching the von Neumann chain by taking into account that the different macrostates $|A_i\rangle$ become correlated with ortogonal states $|E_i\rangle$ of the environment. One should then replace Eq.(7) by the more physically appropriate equation:

$$\sum_i c_i|\phi_i\rangle \otimes |A_0\rangle \otimes |E_0\rangle \quad \rightarrow \quad \sum_i c_i|\phi_i\rangle \otimes |A_i\rangle \otimes |E_i\rangle. \tag{9}$$

Since the experimenter has no control of the degrees of freedom of the environment, i.e. of the states $|E_i\rangle$, he must disregard them. Doing this one ends up dealing, as in the case of Daneri et al. and of Jauch, with a statistical mixture, precisely the one implied by WPR.

This argument characterizes Zurek's approach. Griffiths, Gell-Mann and Hartle "Decoherent Histories" scheme is a more refined approach based on analogous considerations. Some remarks are appropriate.

- These approaches make clear that the unavoidable interactions with the environment and, subsequently, with the whole universe, make extremely difficult to put into evidence the superpositions of different macroscopic states. In this sense they show that the standard theory with the inconsistent WPR postulate works well FAPP, *For All Practical Purposes.*

- It does not seem acceptable to claim that linear superposition of states corresponding to different perceptions occur but that this fact is irrelevant because each of them is associated, e.g., to a different location of a molecule of the environment (the argument actually rests entirely and simply on the orthogonality of the states $|E_i\rangle$ of the environment).

- The proposal deals essentially with ensembles. But in practice one mostly deals with individuals physical systems.
- Contrary to the classical case, in quantum mechanics, different statistical ensembles may give rise to precisely the same physics. In particular the ensemble containing an equal number of states "$|PointerHere\rangle$" and "$|PointerThere\rangle$" is physically indistinguishable from the one containing an equal number of states "$|PointerHere\rangle + |PointerThere\rangle$" and "$|PointerHere\rangle - |PointerThere\rangle$". Both attach the same probabilities to all conceivable outcomes of prospective measurements (Obviously, these probabilities differ from those implied by the quantum formalism when the state is the final one of Eq.(7)). This being the situation, what makes legitimate to make the first choice and to ignore the possibility of a mixture of states involving the superposition of macroscopically and perceptively different states?

Even the more convinced supporters of decoherence have been compelled to face this problem and have been lead to recognize (Joos & Zeh, 1985) that:

> *Of course, no unitary treatment of the time dependence can explain while only one of these dynamically independent components is experienced.*

6.5 von Neumann and Wigner

von Neumann himself and, subsequently, Wigner, have taken a clear cut attitude: in nature "physical processes" and "conscious acts of perception" occur and they obey different laws. In brief, they accept that quantum mechanics governs only the first set of processes. von Neumann stresses that, in his chain, the final state always refers to the act of perception of a conscious observer, a process which, in his view, is not governed by quantum mechanics but by WPR. The idea is fascinating and it has a certain consistency. Its limitation derives from the fact that it does not make precise the borderline between the two levels. As J. Bell has put it:

What is conscious? The first living cell or a Ph.D student?

This concludes the first part of our analysis and leads us to consider modifications of the standard theory.

Part II

7 Collapse or GRW models

Quite recently a new approach to the problem of interest has been proposed. It is based on the idea that (Bell, 1990):

Schrödinger's equation is not always true.

One adds to the standard evolution equation nonlinear and stochastic terms which strive to induce WPR at the appropriate level, leading to states which correspond to definite macroscopic outcomes. The theory, usualy referred as the GRW theory (Ghirardi et al. 1986), is a rival theory of quantum mechanics and is experimentally testable against it. Its main merits are that it qualifies itself as a unified theory governing all natural processes, in full agreement with quantum predictions for microscopic processes and inducing the desired objectification of the properties of macroscopic systems. Let us be more precise.

- A first problem concerns the choice of the preferred basis: if one wants to objectify some properties, which ones have to be privileged? The natural choice is the one of the position basis, as suggested by Einstein (Einstein, 1926):

  > *A macrobody must always have a quasi-sharply defined position in the objective description of reality*

- A second problem, and the more difficult, is to embody in the scheme a triggering mechanism implying that the modifications to the standard theory be absolutely negligible for microsystems while having a remarkable effect at the macroscopic level.

The theory is based on the following assumptions:

- Let us consider a system of N particles and let us denote as $\psi(\mathbf{r}_1, ..., \mathbf{r}_N)$ their configuration space wavefunction. The particles, besides obeying the standard evolution, are subjected, at random times with a mean frequency λ, to random and spontaneous localization processes around appropriate positions. If a localization affects the i-th particle at point $\mathbf{x}$, the wavefunction is multiplied by a Gaussian function $G_i(\mathbf{x}) = (\frac{\alpha}{\pi})^{3/4} exp[-\frac{\alpha}{2}(\mathbf{r}_i - \mathbf{x})^2]$.

- The probability density of a localization for particle i at point $\mathbf{x}$ is given by the length (< 1) of the wavefunction immediately after the hitting: $G_i(\mathbf{x})\psi(\mathbf{r}_1, ..., \mathbf{r}_N)$. This implies that localizations occur with higher probability where, in the standard theory, there is a larger probability of finding the particle.

- Obviously, after the localization has occurred the wavefunction has to be normalized.

It is immediate to realize that a localization, when it occurs, suppresses the linear superposition of states in which a particle is well localized at different positions separated by a distance larger than $1/\sqrt{\alpha}$. The situation is depicted in Fig.3.

The most important feature of the model stays in the trigger mechanism. To understand its role, let us consider the superposition of two macroscopic pointer states $|H\rangle$ and $|T\rangle$, corresponding to two macroscopically different locations of the pointer. Since the pointer is "almost rigid" and contains an Avogadro's number of microscopic constituents one immediately realizes that a localization of any one of them suppresses the other term

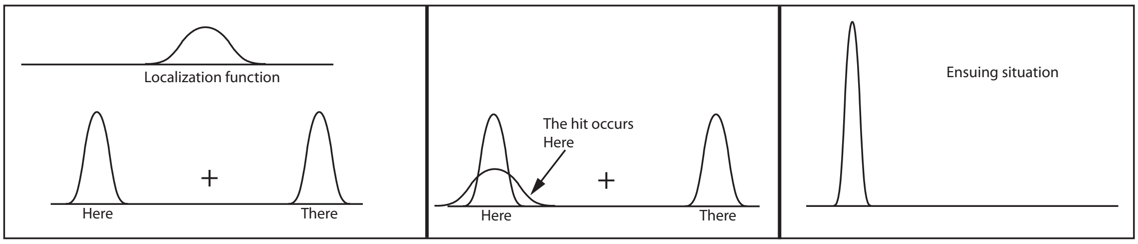

Figure 3: The localization affecting a particle in the superposition of two far-away position states.

of the superposition: the pointer, after the localization of one of its constituents, is defintely either Here or There (see Fig.4 for an intuitive understanding of the process).

With these premises we can choose the values of the parameters of the theory (which Bell has considered as new constants of nature): the mean frequency of the localizations λ and their accuracy $1/\sqrt{\alpha}$. In the original proposal these values have been chosen (with reference to the processes suffered by nucleons, since the frequency is proportional to the mass of the particles) to be:

$$\lambda = 10^{-16} sec^{-1}, \quad \frac{1}{\sqrt{\alpha}} = 10^{-5} cm \tag{10}$$

So, a microscopic system suffers a localization, on average, every hundred milions years. This is why the theory agrees to an extremely high level of accuracy with quantum mechanics for microsystems. On the other hand, due to the trigger mechanism, one of the constituents of a macroscopic system, and, correspondingly, the whole system, undergoes a localization every 10^{-7} seconds.

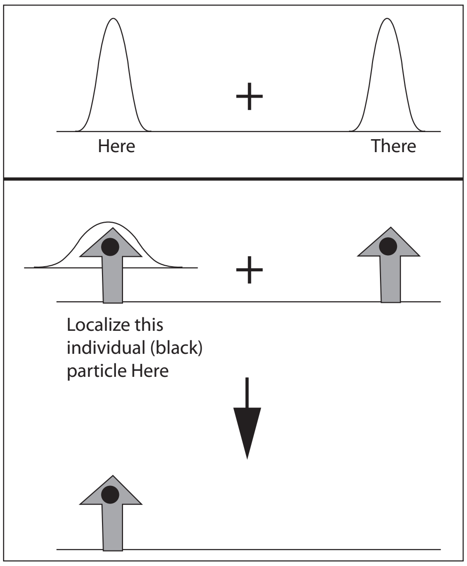

Figure 4: The trigger mechanism: in the case of a macroscopic body, localizing one of its constituents amounts to localizing the system itself.

Few comments are at order:

- The theory allows to locate the ambiguous split between micro and macro, reversible and irreversible, quantum and classical. The transition is governed by the number of particles which are well localized at positions further apart than 10^{-5} cm in the two states whose coherence is going to be dynamically suppressed.

- The theory is testable against quantum mechanics. Various proposals have been put forward (Rae, 1990; Rimini, 1995; Adler, 2002; Marshall et al. 2003). The tests are difficult to be performed with the present technology. The theory identifies appropriate sets of mesoscopic processes which might reveal the failure of the superposition principle.

- Most of the physics does not depend on both parameters, but on their product $\alpha\lambda$. A change of one or two orders of magnitude of this value will already conflict with experimentally established facts. So, in spite of its appearing "*ad hoc*", if one chooses to make objective the positions (and no other alternatives are practicable), almost no arbitrariness remains.

An interesting feature deserves a comment. Let us make reference to a discretized version of the model. Suppose we are dealing with many particles and, accordingly, we can disregard Schrödinger's evolution of the system because the dominant effect is the collapse. Suppose that we divide the universe in elementary cells of volume $10^{-15}cm^3$, the volume related to the localization accuracy. Denote as $|n_1, n_2, ...\rangle$ a state in which there are n_i particles in the i-th cell and let us consider the superposition of two states $|n_1, n_2, ...\rangle$ and $|m_1, m_2, ...\rangle$ which differ in the occupation number of the various cells. It is then quite easy to prove that the rate of the dynamical suppression of one of the two terms is governed by the quantity:

$$exp\{-\lambda t \sum_i (n_i - m_i)^2\}, \tag{11}$$

the sum running over all cells of the universe.

It is interesting to remark that, being $\lambda = 10^{-16} sec^{-1}$, if one is interested in time intervals of the order of perceptual times (i.e. about $10^{-2} sec$) this expression implies that the universal dynamics characterizing the theory does not allow the persistence for perceptual times of a superposition of two states which differ for the fact that 10^{18} nucleons (a Planck's mass) are differently located in the whole universe. This remark suggests a relation with the idea of Penrose who, to solve the measurement problem by following the quantum gravity line, has repeatedly claimed that it is the Planck mass which defines the boundary between the wavy quantum universe and the world of our definite perceptions.

8 Collapse theories and definite perceptions

An interesting objection to GRW has been presented (Albert & Vaidman, 1989; Albert, 1992). By taking advantage of the extreme sensitivity of our perceptual apparatuses, the authors have remarked that one can devise situations leading to definite perceptions which do not involve the displacement of a sufficient number of particles (such as those of a pointer) in order that the GRW mechanism enters into play.

Albert and Vaidman have considered a spin 1/2 particle with the spin along the x-axis which goes through a Stern-Gerlach apparatus devised to test the value of the z-spin component. The particle ends up in the superposition of moving along a trajectory pointing upwards and one pointing downwards (see Fig.5). After the apparatus there is a fluorescent screen such that when it is hit by the particle at a given point, about 10 atoms with an extremely short life-time are excited and decay immmediately. In this way, we produce the linear superposition of two rays originating from two points A and B, differently located on the screen.

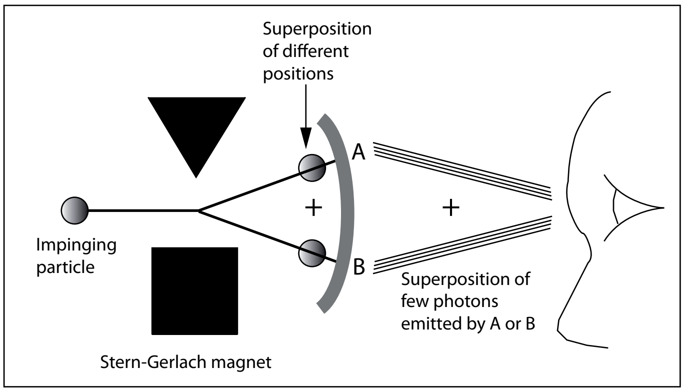

Figure 5: The set up suggested by Albert and Vaidman which should prove that also the GRW theory must attach a specific role to conscious perceptions.

The argument goes on: due to the fact that the process is triggered by a single particle and that it involves few photons, there is no way for the GRW dynamics to induce reduction on one of the two states. On the other hand we know that, due to the sensitivity of our visual apparatus, an observer looking at the screen will have a definite perception concerning the fact that the luminous signal comes from A or from B. Accordingly, in Albert and Vaidman's opinion, collapse theories must accept reduction by consciousness in order to account for definite perceptions by the observer.

Note that since microscopically different situations usually trigger macroscopic changes in the material world, only in exceptional cases one should resort to consciousness. Apart from this fact (which has not been appropriately recognized by the above authors) we have taken the challenge represented by the smart suggestion of Albert and Vaidman. Our counterargument goes as follows:

- We agree that the superposition of the considered microstates persists for the time which has to elapse before the eye is stimulated (actually it must persist because in place of observing the rays we could make them interfere, proving that the superposition is there).

- However, to deal with the process in the spirit of the GRW theory, one has to consider all systems which enter into play (triggering particle, screen, photons and brain). A quite prudential estimate of the number of ions (Na and K ions going through the Ranvier nodes and trasmitting the electrical signal to the lateral geniculate body and to the higher visual cortex) which are involved, makes perfectly reasonable (we refer the reader to (Aicardi et al. 1991) for details) that a sufficient number of particles are displaced by a sufficient spatial amount (recall that the myelin sheet is precisely $10^{-5}cm$ thick) to satisfy the conditions under which, according to the GRW theory, the suppression of the superposition of the two signals will take place within the perception time scale.

- We are not attaching any particular role to the conscious observer. The observer's brain is the only system which is present in which a superposition of two states involving different locations of a large number of particles occur. As such, it is the only place where the reduction can and actually must occur according to the theory. If in place of the eye of a conscious observer one puts in front of the photon beams a spark chamber or a device leading to the displacement of a macroscopic pointer, reduction will equally take place. In the example, the human nervous system is simply a physical system, a specific assembly of particles, which performs the same function as one of these devices, if no other device interacts with the photons before the human observer does.

Before concluding we feel the need of a specification. The above analysis could be taken as indicating a naive and oversimplified attitude towards the deep problem of the mind-brain correspondence. There is no claim and no presumption that the GRW theory allows a physicalistic explanation of conscious perceptions. We only point out that, for what we know about the purely physical aspects of the process, before the nervous pulse reaches the higher visual cortex, the conditions guaranteeing, according to collapse models, the suppression of one of the two electric pulses are verified. In brief, a consistent use of the dynamical reduction mechanism accounts for the definiteness of the conscious perception, even in the peculiar situation devised by Albert and Vaidman.

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