AN OUTLINE OF AN INTERPRETATION OF QUANTUM MECHANICS

Gennaro AULETTA

November 5, 2012

Abstract

The main thesis of this article is that Quantum Mechanics consists in the Basic formalism (Schrödinger equation) plus the Measurement theory (or the theory of open systems).

1 Introduction

My approach is mainly a philosophical one. I sum up some results developed more extensively in my book [2].

In section 2 we begin with a short presentation of that what decoherence is. In section 3 we summarize the specific features of the measurement process. In section 4 we discuss the ontological aspects, especially related to the complementarity wave/particle. In section 5 we critically examine the Many-World Interpretation and discuss the main philosophical lessons and consequences. In section 6 concluding remarks follow about the relationship between measurement and basic quantum theory.

2 Decoherence

2.1 The Reservoir

We begin with a definition of decoherence [41] [42]:

Definition 2.1 (Decoherence) *The decoherence consists in the loss of coherence (in the tendency to zero of the off-diagonal elements of a density matrix) of a (a relatively small) object system due to the action of a large reservoir on it.*

By tracing out the reservoir we can obtain a transition from an initial (pure) state to a mixture. This transition, the necessary condition of a measurement, is not an unitary evolution [34] [43]:

Theorem 2.1 (Shea/Scully/McCullen/Zurek) *The Measurement-required reduction can only be obtained with a partial trace, which* per definitionem *is not unitary.*

It is very important to distinguish between such a mixture, which is an 'improper' mixture, because it is generated by a partial trace with respect to a total system which remains in a pure state – and a proper mixture. Note that the statistical interpretation does not distinguish between them — see [3].

On the other hand we can formulate following theorem, synthesizing the analysis of Zeh and Joos [22]:

Theorem 2.2 (Joos/Zeh) *The correlations or off-diagonal terms of a density matrix cannot be destroyed, but only downloaded in the reservoir or environment.*

and by following corollary:

Corollary 2.1 (Off-diagonal terms) *The off-diagonal terms of the object system tend to zero in a decoherence process but they can never really be zero.*

In other words decoherence is not a sharp process where the quantum features of the object system are completely lost. Therefore, it can be very interesting to see what happens at a mesoscopic level, where strange creatures as Schrödinger Cats can be studied.

2.2 Schrödinger Cats

Let us now consider an experiment performed by the equip of Haroche [5].

First of all consider a easy description of a Schrödinger cat (= S-Cat). Consider a two-level atom (ground and excited state: $|g\rangle, |e\rangle$) coupled to an apparatus $\mathcal{A}$ represented by a quantum oscillator in a coherent state. The state vector $|\alpha\rangle$ defining it has a circular Gaussian distribution of radius unity due to quantum fluctuations which make the tip uncertain. Consider an ideal measurement in which the atom-oscillator interaction entangles the phase of the oscillator $\pm\varphi$ to the internal state of the atom leading to:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|e, \alpha e^{\imath\varphi}\rangle + |g, \alpha e^{-\imath\varphi}\rangle). \tag{1}$$

When the distance $l = 2\sqrt{N}\sin\varphi$ (where N is the photon number) is larger than 1, a S-cat is obtained.

In this case the mesoscopic S-Cat is obtained by sending a rubidium atom, prepared in a superposition of two circular Rydberg states, excited $|e\rangle$ and ground state $|g\rangle$ (quantum numbers 51 and 50 respectively), across a high quantum microwave cavity C storing a small coherent field $|\alpha\rangle$. The coupling between the cavity and the atom is measured by the Rabbi frequency ω. Each circular atom is prepared in a superposition of $|e\rangle$ and $|g\rangle$ by a resonant microwave $\pi/2$ pulse in a low quantum cavity R_1 before encountering cavity C. It then crosses C in which a small coherent field with average photon number N varying from 0 to 10 is injected by a pulsed source S. The field, which evolves freely while each atom crosses C, relaxes to a vacuum before being regenerated for the next atom. The field is left coherent. After leaving C, each atom undergoes another $\pi/2$ pulse in a cavity R_2 identical to R_1. R_1 and R_2 are fed by a cw source S$'$ whose frequency ν is swept across ν_0. The atoms are finally counted in $|e\rangle$ and $|g\rangle$ by detectors $\mathrm{D}_e, \mathrm{D}_g$. The $|e\rangle \rightsquigarrow |g\rangle$ transition (transition frequency $\nu_0 = 51.099$ GHz) and the cavity frequency are slightly off resonance (detuning δ), so that the atom and the field cannot exchange energy but only undergo $1/\delta$ dispersive frequency shifts. The atom-field coupling during time t produces an atomic-level dependent dephasing of the field and generates an entangled state, which, for $\omega/\delta \ll 1$, is given by Eq. (1) with $\varphi = \omega^2 t/\delta$.

The final probability distribution $\wp_g^{(1)}(\nu)$ (of finding an atom in $|g\rangle$ as a function of ν) exhibits Ramsey fringes (interference) typical of atoms subjected to successive pulses. In fact transitions $|e\rangle \rightsquigarrow |g\rangle$ occur either in R_1 or in R_2: hence the two 'paths' are indistinguishable, leading to an interference term between the corresponding probability amplitudes. The phase difference between these amplitudes is $2\pi(\nu - \nu_0)\tau$ (where $\tau = 230\mu s$ is the time between the two pulses). When δ is reduced, the contrast of the fringes decreases (and the 'paths' of the atoms become partially distinguishable) and their phase is shifted. The fringe contrast reduction demonstrates the separation of the field state into two components and provides a measurement of the 'separation' l^2. When an atom leaves C, the system is prepared in state (1), so that the field phase 'points' toward $|e\rangle$ and $|g\rangle$ at the same time: we obtain a S-Cat. Finally one can obtain a situation where the field components do not overlap at all and there is no longer any interference. In this sense this experiment is also a marvellous confirmation of which-paths or wave/particle experiments.

The coherence between the two components of the state and its quantum decoherence were revealed by a subsequent two-atom correlation experiment [5]. While a first atom creates a superpositional state involving the two field components, a second atom (the probe) crosses C with the same velocity after a short delay τ_2 and dephases the field again by an angle $\pm\varphi$. The two field components turn into three, with phases: $+2\varphi, -2\varphi, 0$. The zero component may be obtained via two different paths, since the atoms may have crossed C either in the (e, g) configuration or in the (g, e) configuration (i.e. the second atom undoes the phase shift of the first one). Since the atomic states are mixed after C in R_2, the (e, g) and (g, e) 'paths' are indistinguishable. As a consequence, there is an interference term in the joint probabilities $\wp_{ee}^{(2)}, \wp_{eg}^{(2)}, \wp_{ge}^{(2)}, \wp_{gg}^{(2)}$. The difference between conditional probabilities (the correlation between the two atoms)

$$\wp_{/}^{(2)} = \left(\frac{\wp_{ee}^{(2)}}{\wp_{ee}^{(2)} + \wp_{eg}^{(2)}}\right) - \left(\frac{\wp_{ge}^{(2)}}{\wp_{ge}^{(2)} + \wp_{gg}^{(2)}}\right) \tag{2}$$

is independent of ν, except around $\varphi = 0, \pi/2$. Equal to 0.5 at short times τ_2 when the quantum coherence is fully preserved, $\wp_{/}^{(2)}$ is shown to decay to 0 when the system I atom + field has evolved in a fully incoherent mixture. Hence we have obtained a decoherence.

3 Measurement

3.1 The Environment

However, if we desire an effective result, as it is presupposed by the Measurement theory, we need to add the environment $\mathcal{E}$ (and to consider the reservoir as an apparatus, or to take the reservoir as the environment and to add an apparatus).

Previously the influence of $\mathcal{E}$ was normally considered as a noise factor. Instead of we can understand the importance of this factor by formulating the following theorem (which synthesizes the analysis of both Zeh and Zurek):

Theorem 3.1 (Zeh/Zurek) *The Environment makes all information about the premeasured system unavailable with only one exception: when the Hamiltonian $\hat{H}_{\mathcal{AE}}$, which couples $\mathcal{A}$ and $\mathcal{E}$, commutes with an observable $\hat{O}^{\mathcal{S}}$ of the object system:*

$$[\hat{O}^{\mathcal{S}}, \hat{H}_{\mathcal{AE}}] = 0 \tag{3}$$

then this particular observable will not be disturbed, so that the pointer of the apparatus will contain the information about this observable and only this one.

The theorem guarantees the required correlation between system's and apparatus' observable. Obviously, such a theorem cannot be understood in the sense of a classicality of the pointer because, as we have already seen, interference terms are never destroyed and other observables which do not commute with the one measured, always enter, to a certain extent, in the result which is never 100% 'determined' — this is the POVM problematic.

Measurement can be then mathematically described as follows. Let $\mathcal{S}$ be a system of the form: $|\varsigma\rangle = \sum c_n|n\rangle$; then we have:

$$\begin{aligned}
|\Psi(t = t_0)\rangle\rangle &= |\varsigma\rangle \otimes |a_0\rangle \otimes |\mathcal{E}(t_0)\rangle\rangle && (4)\\
&\mapsto |\Psi(t = t_1)\rangle\rangle = \left[\sum_n c_n(|n\rangle \otimes |a_n\rangle)\right] \otimes |\mathcal{E}(t_1)\rangle && (5)\\
&\mapsto |\Psi(t > t_2) = \sum_n c_n|n\rangle \otimes |a_n\rangle \otimes |\mathcal{E}_n(t)\rangle. && (6)
\end{aligned}$$

The first transition [Eq. (5)] has provided $\mathcal{A}$ with information about $\mathcal{S}$ (it is what we named *Premeasurement*) and the second one [eq (6)] is indispensable in order to define the measured observable. If we express the process by using the reduced density matrix, we have:

$$\begin{aligned}
\hat{\rho}^{\mathcal{S}+\mathcal{A}+\mathcal{E}}_{\mathrm{Tr}_{\mathcal{E}}} &= \mathrm{Tr}_{\mathcal{E}}\left[|\Psi(t > t_2)\rangle\langle\Psi(t > t_2)|\right]\\
&\simeq \sum_n |c_n|^2 |a_n\rangle\langle a_n| \otimes |n\rangle\langle n|\\
&= \hat{\tilde{\rho}}^{\mathcal{S}+\mathcal{A}+\mathcal{E}}_{\mathrm{Tr}_{\mathcal{E}}}
\end{aligned} \tag{7}$$

Hence we have a change from an initial (pure) state to a mixture by tracing out the environment.

3.2 The Pointer

On the other hand, if one assumes the classicality of the pointer, following corollary can be proved:

Corollary 3.1 (Classicality of Pointer) *Let a Measurement scheme $\left\langle \mathcal{H}_{\mathcal{A}}, \hat{O}^{\mathcal{A}}, |\mathcal{A}\rangle, \hat{U} \right\rangle$ be a candidate for a $\mathcal{M}_U$ of a discrete sharp observable $\hat{O}^{\mathcal{S}}$ (where $\mathcal{H}_{\mathcal{A}}$ is the Hilbert space and $|\mathcal{A}\rangle$ the state vector of the apparatus, respectively). If the pointer $\hat{O}^{\mathcal{A}}$ is classical, then the coupling g cannot be generated by an observable of $\mathcal{S} + \mathcal{A}$, because in this case $\left\langle \mathcal{H}_{\mathcal{A}}, \hat{O}^{\mathcal{A}}, |\mathcal{A}\rangle, \hat{U} \right\rangle$ cannot fulfil the probability reproducibility condition.*

Therefore the pointer cannot really be classical. On the other hand, if we treat the pointer observable quantum-mechanically, following corollary can be proved:

Corollary 3.2 (Zurek) *The pointer observable $\hat{O}^{\mathcal{A}}$ commutes with the apparatus/environment interaction Hamiltonian $\hat{H}_{\mathcal{AE}}$:*

$$[\hat{O}^{\mathcal{A}}, \hat{H}_{\mathcal{AE}}] = 0. \tag{8}$$

3.3 Triorthogonal Decomposition

The combined $\mathcal{A}+\mathcal{S}$ system is now represented by a mixture diagonal in a particular product basis consisting of the eigenvectors of the pointer of $\mathcal{A}$ and the corresponding relative states of $\mathcal{S}$.

We now prove in a general form that, while biorthogonal decomposition (system + apparatus) suffers the basis degeneracy problem, this is not so for triorthogonal decomposition (system + apparatus + environment) [14].[1] First let us state the following lemma:

Lemma 3.1 (Elby/Bub) *Let* $\{|a_j\rangle\}$ *and* $\{|s_j\rangle\}$ *be linearly independent sets of vectors, respectively in* $\mathcal{H}_1, \mathcal{H}_2$ *for two generic systems* $\mathcal{S}_1, \mathcal{S}_2$*. Let* $\{|s'_j\rangle\}$ *be a linearly independent set of vectors that differs non trivially from* $\{|s_j\rangle\}$*. If* $|\Psi\rangle = \sum_j c_j|a_j\rangle \otimes |s_j\rangle$*, then* $|\Psi\rangle = \sum_j c'_j|a'_j\rangle \otimes |s'_j\rangle$ *only if at least one of the* $\{|a'_j\rangle\}$ *vectors is a linear combination of* (*at least two*) $\{|a_j\rangle\}$ *vectors.*

We omit the proof of the Lemma[2], but use it to prove *per contradictionem* the uniqueness of triorthogonal decomposition (in order to indirectly prove theorem 3.1 and its corollary, so that the required pointer objectification can be obtained).

Proof

Suppose a vector $|\Psi\rangle = \sum_j c_j|a_j\rangle \otimes |s_j\rangle \otimes |e_j\rangle$, where $\{|a_j\rangle\}, \{|s_j\rangle\}, \{|e_j\rangle\}$ are orthogonal sets of vectors respectively in $\mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3$ for three generic systems $\mathcal{S}_1, \mathcal{S}_2, \mathcal{S}_3$. Then, we claim that even if some of the $|c_j|$'s are equal, no alternative orthogonal sets $\{|a'_j\rangle\}, \{|s'_j\rangle\}, \{|e'_j\rangle\}$ exist such that $|\Psi\rangle = |a'_j\rangle \otimes |s'_j\rangle \otimes |e'_j\rangle$, unless each alternative set of vectors differs only trivially from the set it replaces. Assume, without loss of generality, that $\{|e_j\rangle\}$ differs not trivially from $\{|e'_j\rangle\}$, and let us write $|\Psi\rangle = \sum_j c_j|f_j\rangle \otimes |e_j\rangle$ (where $|f_j\rangle := |a_j\rangle \otimes |s_j\rangle$). Now supposing $|\Psi\rangle = \sum_j c'_j|f'_j\rangle \otimes |e'_j\rangle$ (where $|f'_j\rangle := |a'_j\rangle \otimes |s'_j\rangle$), we cannot rewrite the factorisable state $|a'_j\rangle \otimes |s'_j\rangle$ as an entangled state.

But according to lemma 3.1, since $|\Psi\rangle = \sum_j c_j|f_j\rangle \otimes |e_j\rangle$ and since $\{|e_j\rangle\}$ differs not trivially from $\{|e'_j\rangle\}$, then we have $|\Psi\rangle = \sum_j c'_j|f'_j\rangle \otimes |e'_j\rangle$ only if $|f'_k\rangle = \sum_j g_{jk}|f_j\rangle$, where at least two of the g_{jk}'s are non-zero. But since $|f_j\rangle := |a_j\rangle \otimes |s_j\rangle$, it follows that $|f'_k\rangle$ is an entangled state ($|f'_k\rangle = \sum_j g_{jk}|a_j\rangle \otimes |s_j\rangle$), which is the required contradiction. Q.E.D.

The above proof shows that one should not identify[3] the triorthogonal decomposition presupposed by decoherence with the von Neumann chain: in the second case, only successive measurements, in which each decomposition is biorthogonal, are considered. Note that, while the partial trace is a mathematical formalism — to be better analysed in the following subsection — which reflects our ignorance (our 'discarding') of the environment and that is therefore relative to the subsystem over which we perform such a partial trace, the triorthogonal decomposition — due to the introduction of a third factor such the environment — is not a relative property (not relative to an observer) but an absolute one[4].

3.4 Reversibility/Irreversibility

A clear evidence for the preceding analysis is the problem of reversibility/irreversibility. A recent proposed experiment of Mabuchi and Zoller shows that:

Theorem 3.2 (Jump operator) *The action of a jump superoperator cannot in general be inverted as such. Inversion is possible if one consider the system as pertaining to a subset of the original Hilbert space and the jump as unitary: but then no new information is obtained.*

One supposes [27] the action of a destruction operator (which causes the jump by photon absorption, for example) $\hat{a}$ which acts as a unitary operator on a subspace $\mathcal{H}_1^{\mathrm{Tr}=1;\geq 0}$ ($\mathcal{H}_1$ for the sake of simplicity, where the subscript '1' means here 1 photon) of the original problem:

$$\hat{a}|\psi\rangle = \hat{U}|\psi\rangle, \quad \langle\psi|\hat{a}^\dagger = \langle\psi|\hat{U}^\dagger. \tag{9}$$

Due to the unitarity of $\hat{U}$ we have:

$$\langle\psi|\hat{N}|\psi\rangle = 1, \tag{10}$$

where $\hat{N}$ is the number operator, which means that the expectation value of the photon number is equal to unity for an arbitrary state from the specified subset $|\psi\rangle \in \mathcal{H}_1$. If we expand $|\psi\rangle$ as follows

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle + \ldots + c_n|n\rangle, \tag{11}$$

where $|n\rangle$ is a (normalized) state with n photons, then Eq. (10) can be written:

$$\wp_1 + 2\wp_2 + 3\wp_3 + \ldots + n\wp_n + \ldots = 1, \tag{12}$$

---

[1] See also [6].

[2] See the original article of Elby and Bub.

[3] As sometimes happens: see [28].

[4] See also [6].

with positive numbers $\wp_n = |c_n|^2$. For this Eq. to be fulfilled, at least one of the numbers $\wp_1, \wp_2, \ldots$ must be non-zero. And therefore the state $|\psi\rangle \in \mathcal{H}_1$ cannot be the vacuum. Since a jump diminishes here the number of photons by single unity, the fact that a jump occurred gives the information that the initial state was not the vacuum: but we know this already, because the initial state belonged to the subset $\mathcal{H}_1$. But since $|\psi\rangle \in \mathcal{H}_1$ depends on the preparation, no new information is gained by such a reversible quantum jump. The same can be proven if we consider a double jump operator (for the absorption of two photons) and so on.

Nielsen and Caves provided [31] a powerful generalization of the preceding theorem by showing that an ideal measurement is reversible iff no information about the identity of the prior state is obtained from the measurement, since each state is equally likely, given some result j, and therefore it is not a measurement.

Practically QM system are never completely free from some form of dispersion or dissipation. Which is another form to say that QM systems are open systems. This signifies a natural irreversibility of QM systems.

In conclusion we can postulate what follows:

Postulate 3.1 (Irreversibility) *The reversibility of QM systems is only an ideal and limiting case of a series of irreversible behaviours, where a system is thought to be more and more isolated.*

Obviously there can be a partial reversibility only if there is no triorthogonal decomposition — i.e. in the case of a coupling between a system and a reservoir —, while, as has already been said, if three systems are coupled — which is the case when performing measurements [see theorem 3.1: p. 3, and its corollary] but also for some form of spontaneous interactions —, irreversible behaviour is stronger.

4 Ontology

4.1 Wave/Particle Dualism

Traditionally the Wave/Particle Dualism (= WPD) was understood as a yes/no complementarity (Copenhagen). Later a permanent copresence of a wave and a particle was proposed (de Broglie/Bohm). In the light of recent proposed and performed experiments we can state:

Proposition 4.1 (Wave/Particle Ontology) *The wave-like and the corpuscular behavior of microentities are only two extreme forms of being of the same ontological entity.*

The starting point was a Greenberger/Yasin study [18], in which following inequality was derived:

$$\mathcal{P}^2 + \mathcal{V}^2 \leq 1, \tag{13}$$

where $\mathcal{P}$ means the path determination (in an interferometer, for example) and $\mathcal{V}$ the visibility of the fringes (of the interference).

It is a POVM treatment. We can see it by following example [29]. First let us introduce a path projector $\hat{P}_{\mathcal{P}}$ and an interference-pattern projector $\hat{P}_{\mathcal{V}}$ (both sharp), which are orthogonal on the Poincaré sphere [see figure 1].

Then consider all sharp measurements of an arbitrary observable $\hat{O}$ such that $\hat{P}_{\hat{O}}$ lies on the arc going from $\hat{P}_{\mathcal{P}}$ to $\hat{P}_{\mathcal{V}}$, where $\hat{P}_{\hat{O}}$ satisfies: $[\hat{P}_{\hat{O}}, \hat{P}_{\mathcal{P}}] \neq 0$ and $[\hat{P}_{\hat{O}}, \hat{P}_{\mathcal{V}}] \neq 0$. The outcomes of these $\hat{O}$–experiments can be considered as joint measurements of $\hat{P}_{\mathcal{P}}$ and $\hat{P}_{\mathcal{V}}$.

Mittelstaedt a,d co-workers proposed the following interferometry experiment: an incoming photon $|\psi\rangle$ passes a first BS and is subjected to a phase shift $\delta\varphi$ in the full transmitted component, becoming $1/\sqrt{2}(|\mathcal{P}\rangle + e^{\imath\delta\varphi}|\neg\mathcal{P}\rangle)$, where $\hat{P}_{\mathcal{P}} = |\mathcal{P}\rangle\langle\mathcal{P}|$ and $\hat{P}_{\neg\mathcal{P}}$ represents the opposite point with respect to $\hat{P}_{\mathcal{P}}$ in the Poincaré sphere, whereas $\hat{P}_{\neg\mathcal{V}}$ represents the antifringes of the diffraction. The transparency of the second BS is expressed by the variable parameter $\eta \in [0, 1]$, which thus determines the observable $\hat{P}_{\hat{O}}(\eta)$. If $\eta = 0$, then the path is completely determined:

$$\hat{P}_{\hat{O}}(0) = \hat{P}_{\mathcal{P}}; \tag{14}$$

and the same for $\eta = 1$ ($\hat{P}_{\hat{O}}(1) = \hat{P}_{\neg\mathcal{P}}$); but if $\eta = \frac{1}{2}$, then one measures the interference observable

$$\hat{P}_{\hat{O}}\left(\frac{1}{2}\right) = \hat{P}_{\mathcal{V}} = \frac{1}{2}\left(\hat{I} + |\mathcal{P}\rangle\langle\neg\mathcal{P}| + |\neg\mathcal{P}\rangle\langle\mathcal{P}|\right). \tag{15}$$

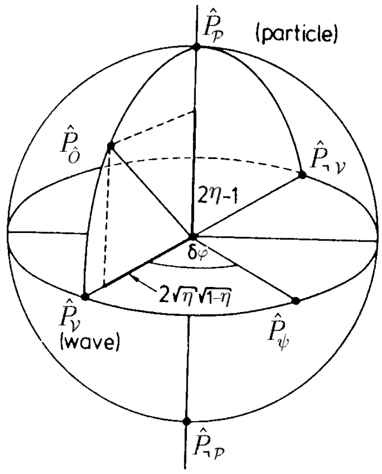

Figure 1: Poincaré-sphere representation of a stochastic measurement of which-path/visibility — from [29].

In the general case $0 \leq \eta \leq 1$ we have:

$$\begin{aligned} \hat{P}_{\hat{O}}(\eta) &= (\eta - \sqrt{(1-\eta)\eta})\hat{I} + 2\sqrt{(1-\eta)\eta}\hat{P}_{\mathcal{V}} + (1-2\eta)\hat{P}_{\mathcal{P}} \\ &= \left(\eta - \frac{1}{2}\mathcal{V}(\eta)\right)\hat{I} + \mathcal{V}(\eta)\hat{P}_{\mathcal{V}} + (1-2\eta)\hat{P}_{\mathcal{P}}, \end{aligned} \tag{16}$$

with the visibility given by $\mathcal{V} = 2\sqrt{(1-\eta)\eta}$.

The study of Mittelstaedt, Schieder and Prieur presents a very easy model which, by means of the Poincaré sphere and POVMs, demonstrates in a direct way the smoothness of the Complementarity which-path/visibility.

4.2 Two Limits

Therefore, the ontological basic entity of QM is something which oscillates between a wave-like and a particle-like behaviour. The tendency toward a particle-like behaviour is some form of localization or individuation: at the limit it is a classical situation; while the other direction is an increment of entanglement where at the end we have the system is disappeared in the environment.

We have grounds to understand the basic QM entity as an *extended particle* or *Quantum particle*. In other words the superposition is never completely lost also in a corpuscular behavior, but the 'particle' conserves a form of fuzziness and intrinsic imprecision which makes it nature only a different degree of the wave behavior. Hence QM becomes intrinsic stochastic and all localization is always imperfect.

4.3 Individuation

The localization of macro-objects can be understood as a continuous scattering process produced by the environment. On the other hand it is not the number of microsystems which guarantees as such the transition to the macroscopic domain: in fact the entanglement between a system and the apparatus happens very quickly if there is a large number of involved quanta.

In consequence of this situation, the macro world is not so 'determinate' as it seems. Evidently there is nothing wrong in the senses and perceptions as such: they serve to the scope of the survival struggle, and it is normal that living beings interpret their environment in selective and instrumental way. What is wrong is the arbitrary scientific generalization, which takes the 'determinate' beings of the everyday experience as the primary and perhaps absolute experience — as the Copenhagen interpretation does.

Individuals are not static beings or data but processes; and it is a never ended process: they are quasi-individuals (never reduction to zero of off-diagonal elements).

4.4 Omnimoda determinatio

It is the end of the philosophical category of *omnimoda determinatio*, i.e. the complete determination of all properties which can be assigned to individuals or systems. It is the basis of classical physics [24]. In classical mechanics q and $\dot{q}$ are on the same footing, so that both can have determined values at the same time. But it is dubious that one can measure with infinite precision the velocity of a particle at a given point. It can be said only that *in a small space interval* it has a velocity $\dot{q}$, but it is surely conceptually erroneous to assign to it both a perfectly determined velocity $\dot{q}$ and a perfectly determined position q. Landsberg showed with a concrete example that it is possible to deduce some uncertainty relations, similar in structure to those of QM, also in the classical case.

5 Many-World Interpretation and the World

5.1 Presentation

One could say that the Many-World Interpretation (= MWI) is the solution. In fact many supporters of the decoherence are also supporters of the MWI.

The main point of the MWI (independently from the different positions) is that there is a universal wave function with no separated systems: all is entangled with all.

5.2 Degeneracy problem

But the MWI presents a great problem. Zurek pointed out that after this theory the apparatus $\mathcal{A}$, by virtue of being correlated with the state of the system $\mathcal{S}$, contains not only all the information about the measured observable, but it must equally well contain all the information about many other observables in spite of the fact that generally the latter ones do not commute with the former, and this is in QM surely impossible (basis degeneracy problem). It is also possible to conceive experiments where it would be the case. In conclusion we can formulate Zurek's conclusion about Everett's proposal by means of the following theorem:

Theorem 5.1 (Zurek) *QM, when applied to an isolated composed object consisting of an apparatus and a system, cannot in principle determine which observable has been measured.*

In fact there is not only an infinity of terms in a single expansion but perhaps there are also infinitely many possible expansions (each one in terms of eigenfunctions of some observable). Now it is impossible to believe that the system is diagonalized for all observables together – this would be again, apart from other considerations, a violation of UP. And that the latter is a consequence of the MWI can be proved (sse original article of Zurek for details). We call such a problem the *basis degeneracy problem* [14].

Hence, for respecting UP, we are forced to admit that, when measured, the system is in a state whose components are diagonalized only *relatively to one observable*, while the others are indeterminate — contrary to the MWI.

But suppose that it is possible to maintain MWI allowing some form of choice between different basis. Then we are faced with other difficulties:

- in this way we have shifted the problem from a choice between the components of a basis to a choice between basis;
- we are now faced with the impossible problem to individuate the subject able to make such a choice;
- we ascribe to the measurement a power greater then the Standard interpretation does[5], because it would have the power to decide between which superbranching of universes (choice between basis) we are called to live and to act in.

5.3 Ensemble

It seems that we live in a universe constituted of an ensemble of quasi individual interacting systems.

A new insight comes from quantum information: the real world is unlikely to supply us with unlimited memory or unlimited Turing machine tapes [23]. The individuals of our universe (product of localization processes) are only

---

[5] See [38].

a special physical realization of an information potentially infinite (given by the superposition or the entanglement) but not available as such, i.e. each time only a finite amount of information is really available. Moreover: not all information physically present in our universe is available for one of its components or parts, because there is always some form of dispersion and because each gain in information is a local interaction which partly destroys the input.

5.4 No Reductionism and No Appearance

In the light of the previous discussion reductionism cannot be accepted. If we understand *reductionism* as the idea that the world can be explained in some form in terms of its 'components'[6], then it is surely false. Firstly, there is no guarantee at all that one day we shall find the 'last elements'. In so far as we know now, this is a mythology.

Secondly, the 'last elements', as far as we know them, i.e. photons, electrons, quarks, are characterized by the features of entanglement and superposition, which make them completely inadequate to serve as 'elements'. And here we return to the point that the environment cannot be understood as a 'sum' of individuals. It is also just as difficult to consider particles as elements in quantum field theory.

Furthermore, what the experiments on S-Cats show, is also that macroscopic behaviour, though not different in nature from microscopic behaviour, emerges as a process of complication and localization[7], which is completely quantic at its starting point, but capable of producing a new form of being in its results[8]. But then the macroscopic world cannot be understood as a '*simulacrum*', i.e. as a phenomenon of the underlying atomic or subatomic structure. Complication, localization and individualisation are not 'illusions' — as the MWI postulates —, but depend on physical interactions which are surely 'real': in fact triorthogonal decomposition is an absolute property and not relative to a specific system. In other words: it is a fact of experience that there are (partly fuzzy) individuals and localisations. And there are no grounds to reject such experience.

The history of the pair of concepts *appearance/reality* is very long, stemming from ancient Platonism up until our own times. We certainly cannot discuss the problem fully in this present context. It suffices to remark that, within the framework of modern physics, it also had and partly has some place. It is well known that Galilei thought [16] that 'qualities' as colour, taste, sound, and flavour were all merely illusory and not 'objective'. After the birth of optics and of acoustics, and after the technological and industrial production of tastes and flavours, such a supposition now seems a little unsound.

On the other hand, at a philosophical level, the supposition itself of illusory things, or of ontologically inferior realities is surely a theoretical dinosaur. Therefore one can postulate that no realities of the second order exist, but all that which exists exists. Hence we postulate:

Postulate 5.1 (Appearance) *There are not illusory things.*

5.5 No Subjectivism

But I do not propose some form of subjectivism. The measurement is only a special case of the interaction. This signifies that the basic form of reality in our universe is not the static being but the interaction (in our case the physical interaction).[9] Now it is not necessary that there are interacting humans: we know in fact that there are also spontaneous transitions to decoherence. Hence QM provides us with a new form of thinking which is neither 'realistic' (in the classical sense of the term) nor 'subjectivistic'.

We can also state: *to be is to interact*, and: *individuals are operations*. More than two thousand years of Platonism and Aristotelism are at an end. The first thinker to have searched for a new path in this direction was Whitehead [40]. It is true that Aristotle spoke of a *dynamics*; but it was conceived either as a univocal evolution — for example the development of a tree from the seed — in the sense of a program, or as a pure possibility depending upon the subjective action of a human being — for example the marble block which can become a statue or a bank or some other thing. He did not conceive the interaction as the mode of being itself: for him the basic beings are the substances. Here, on the contrary, the ground entities are 'events', i.e. interaction modes [19] [36] [37].

Therefore, we can understand what Zurek says: the correlations are ontologically precedent to individuals [43]: in fact individuals are 'extracted' from entanglement and superpositions. In this sense *to know is to separate.*

---

[6] Examinations in [33] [9].

[7] See also [8].

[8] See also [4] [26].

[9] See also [15].

This is the measurement (or subjective) form of *to be is to interact*. Hence the knowledge perfectly corresponds to the dynamics of being: it is an aspect of this dynamics [35]. Regarding the level of definition we already need a choice or a strategy. Another way of saying the same thing is that we are, in principle, not completely separated from the rest of the world. But if we wish to know we must separate. In conclusion the knowledge is not only 'knowledge of interactions' but is itself an operation: To measure a system is to single out some degrees of freedom — in order to define and observe it [21]. There is no longer place for a detached sensorial experience of the world.

With Wheeler's words one can also say: *it from bit* [39]. We understand this point not as a subjective proposition, but as the fundamental idea that the organization is ultimately information, and that without some form of information there would be no place for physical interaction.

5.6 Three Levels

In summing up, we can say that we have three different aspects of the 'world': the correlations, the (quasi-)individuals, and, between these two extremes, the interactions or the dynamics. The interactions (measurements, spontaneous decoherence, and so on) are a junction between the extremes and are at the same time complementary to both extremes, since the localization can be understood in a dynamical way (like the measurement process itself) or as the final result (individualisation) of measurement. It is the dynamics which, on the one hand, limits the correlations and, on the other, makes the emergence of individuals possible. But it is also the dynamics which prevents a full individualisation — here we remember that also in classical mechanics kinematics is to a certain extent complementary to dynamics. It is interesting to observe that, as a consequence of the latter point, if the individuals were perfectly determined beings (hence uncorrelated), as was believed in classical mechanics, then the world would be 'frozen' and no dynamics would be possible.

From the perspective of a quantum system, the individualisation is a noise: in fact it is a decoherence process by means of which some information is lost — here we remember that some channels which transmit classical information cannot transmit quantum information and the decoherence process in quantum computation. But, also from the perspective of an individual, quantum correlations appear as noise — see the discussion about the S-Cat. In the first case it is a 'classical' noise; in the second case a 'quantum' noise.

It is also interesting to note that, historically speaking, the three 'levels' of the world have been studied and discovered in this sequence: individuals, dynamics and correlations. In fact the first physical science to be born was kinematics — with Galilei, Descartes, Newton. It has always remained as the basis of classical mechanics. It was kinematics that introduced the idea of perfect individuals and conceived physical states as the sum of perfectly determined properties. Then dynamics — with Newton, Lagrange, Hamilton — followed, but nobody thought that such a new development could radically change the basic assumptions of kinematics — the only one was Leibniz. Finally Maxwell discovered a new reality: the fields, which are in open conflict with classical mechanics — as was acknowledged by Einstein [10] [11] [13]. However, with only QM, the correlations have acquired a central theoretical status. Note that historically Leibniz was the first philosopher to discuss the problem of the correlations (*Harmonia praestabilita*), but he gave exclusive importance (though he was a nominalist in his youth) to the correlations by eliminating the level of individuals[10]. On the other hand, he understood, and very well, that the perfection of our world consists of a compromise between the unity of laws (correlations, QM basic laws) and the variety of beings (individuals) [25].

5.7 Operational Approach

On this basis I defend an operational approach. At an epistemological level one may ask if an operational interpretation is less universal and less fundamental than an 'objective' one[11]. If so, then QM would imply a fundamental new limitation with respect to classical mechanics. As a matter of fact a part of the Copenhagen interpretation goes in this direction, and surely the three-valued logic approach as well. But the problem is that one usually conceives the operational approach as centered on the measurement[12]. On the contrary, as said, we interpret the measurement process as a particular realization of an 'ontology' based on interactions. For the interpretation here proposed, the operations are 'objective' processes in the sense that they do not necessarily depend on the human consciousness. It is another form of objectivity, which is not 'classic'.

A philosophical expression of the operational approach can be the pragmatism[13].

---

[10] On this point see examination in chapters III and IV of [1].

[11] Bunge poses the problem and answers 'yes' [7].

[12] See again [7]. Consequently he thinks that, due to the problems of the Measurement theory, an operational interpretation is unsound.

[13] See [32].

6 Conclusions

In the which-path/visibility experiments we experience a Complementarity between the superposition of the system (the visibility of interference fringes) and a (partial) localization due to a measurement. In other words, this complementarity has the following features:

- it joins the two fundamental aspects of the theory (formalism and Measurement theory) and acknowledges that both are fundamental for QM;
- simultaneously it points out that both aspects are exclusive;
- finally this Complementarity is a smooth one, which allows us to consider closed and reversible systems as a special case of open and irreversible systems.

On a foundational level we have two parts of the theory which traditionally seemed in conflict since one is founded on reversible laws, while the other (the Measurement theory) on irreversibility. Hence the problem of the relationship between reversible basic QM laws and irreversible measurement arises.

Now the space-time order that is created by interactions is not a universal connection, but local, as is evident by the existence of antiparticles which fly in the other direction of time, we never have to deal with a past defined once and for all, following which not only prediction, but also retrodiction is impossible (delayed choice). In other words: each order is a local topological structure. But, and this is the most important thing, though the order is absolutely local and relative, nobody can change it arbitrarily: in other words, nobody can go forward and backward 'in the time', because the time originates from interactions which *per definitionem* are irreversible — if not, there would be no individualisation and no order at all. Hence we must distinguish the theoretical possibility of going in one or the other direction of time, and the possibility to physically change the time direction. While the latter is impossible, because we cannot change 'our point of view' with that of antimatter, the former is exactly the content of the 'reversible' laws of QM and of physics in general. More exactly one should not speak of reversibility, but of 'time isotropic laws'. And the theory of delayed choice is exactly the physical content of this isotropy.

It is true that the fundamental laws of QM (for example the Schrödinger Eq.) are reversible. But this is only true if assuming isolated systems, which, as we have shown, is never really the case. One can say that an individual system, in order to exist, must have interacted with something, and hence *per definitionem* is not isolated. Even the interesting experiments on QM reversibility can never completely eliminate some form of dispersion. Hence QM systems can go 'forward' or 'backward', but every time they do so they produce some form of irreversibility (dispersion).

In conclusion QM implies a more radical form of ontological relativity than the one we are accustomed to admit by the relativity theory, though in the same spirit; and Bohr was really disappointed that Einstein did not see the analogy between the consequences of QM and that of the relativity theory[14].

References

[1] AULETTA, Gennaro, *Determinismo e contingenza. Saggio sulla filosofia leibniziana delle modalità*, Napoli, Morano, 1994

[2] —, *Foundations and Interpretation of Quantum Mechanics. In the Light of a Critical-Historical Analysis of the Problems and of a Synthesis of the Results*, Singapore, World Scientific, 1999

[3] BALLENTINE, Leslie E., "The Statistical Interpretation of Quantum Mechancis", RMP **42** (1970): 358–81

[4] BRODSKY, S. J./DRELL, S. D., "Anomalous Magnetic Moment and Limits on Fermion Substructure", *Physical Review* **D22** (1980): 2236–43

[5] BRUNE, M./HAGLEY, E./DREYER, J./MAÎTRE, X./MAALI, A./WUNDERLICH, C./RAIMOND, J. M./HAROCHE, S., "Observing the Progressive Decoherence of the 'Meter' in a Quantum Measurement", *Physical Review Letters* **77** (1996): 4887–90

[6] BUB, Jeffrey, *Interpreting the Quantum World*, Cambridge, University Press, 1997

[7] BUNGE, Mario, "Physics and Reality", *Dialectica* **19** (1965): 195–222

[8] D'ESPAGNAT, Bernard, *Veiled Reality*, Reading, Mass., Addison/Wesley, 1995

[9] DUMMETT, Michael, *Logical Basis of Metaphysics*, London, Duckworth, 1991, 1995

---

[14] See [30].

[10] —, "Physik und Realität", *Journal of Franklin Institute* **221** (1936): 313–47; eng. tr. in [12, 59–97]

[11] —, "Remarks Concerning the Essays Brought Together in This Co-operative Volume", in SCHILPP, Arthur (ed.), *Albert Einstein. Philosopher-Scientist*, La Salle (Illinois), Open Court, 1949, III ed. 1988: pp. 665–88

[12] —, *Out of My Later Years, Estate of A. Einstein*, 1956, 1993: New York, Wings Books

[13] —, *Mein Weltbild*, Frankfurt, Ullstein, 1993

[14] ELBY, A./BUB, J., "Triorthogonal Uniqueness Theorem and its Relevance to the Interpretation of Quantum Mechanics", *Physical Review* **A49** (1994): 4213–16

[15] FINKELSTEIN, David R., *Quantum Relativity*, Berlin, Springer, 1996

[16] GALILEI, Galileo, *Il Saggiatore*, Opere v. IV

[17] GIULINI, D./JOOS, E./KIEFER, C./KUPSCH, J./STAMATESCU, I.-O./ZEH, H. D. (ed.s), *Decoherence and the Appearance of a Classical World in Quantum Theory*, Berlin, Springer, 1996

[18] GREENBERGER, D. M./YASIN, A.,, "Simultaneous Wave and Particle Knowledge in a Neutron Interferometer", *Physics Letters* **128A** (1988): 391–94

[19] HAAG, Rudolf, "Fundamental Irreversibility and the Concept of Events", *Communications in Mathematical Physics* **132** (1990): 245–51

[20] —, "An Evolutionary Picture for Quantum Physics", *Communications in Mathematical Physics* **180** (1996): 733–43

[21] JOOS, E., "Decoherence Through Interaction with the Environment", in GIULINI *et al.* (ed.s), *Decoherence and the Appearance of a Classical World in Quantum Theory*, Berlin, Springer, 1996: pp.35–136

[22] JOOS, E./ZEH, H. D., "The Emergence of Classical Properties Through Interaction with the Environment", *Zeitschrift für Physik* **B59** (1985): 223–43

[23] LANDAUER, Rolf, "The Physical Nature of Information", *Physics Letters* **217A** (1996): 188–93

[24] LANDSBERG, P. T., "Why Quantum Mechancis?", *Foundations of Physics* **18** (1988): 969–82

[25] LEIBNIZ, Gottfried W., *Discours de Metaphysique*, in *Philosophische Scriften* (ed. Gerhardt), Halle, 1875; rep. Hildesheim, Olms, 1978: IV, pp. 427–63

[26] LYONS, Louis, "An Introduction to the Possible Substructure of Quarks and Leptons", *Progress in Particle and Nuclear Physics* **10** (1983): 227–304

[27] MENSKY, Michael B., "A Note on Reversibility of Quantum Jumps", PL **222A** (1996): 137–40

[28] MITTELSTAEDT, Peter, *The Interpretation of Quantum Mechanics and the Measurement Process*, Cambridge, University Press, 1998

[29] MITTELSTAEDT, P./PRIEUR, A./SCHIEDER, R., "Unsharp Particle-Wave Duality in a Photon Split-Beam Experiment", *Foundations of Physics* **17** (1987): 891–903

[30] MURDOCH, Dugald, *Niels Bohr's Philosophy of Physics*, Cambridge, University Press, 1987

[31] NIELSEN, M. A./CAVES, C. M., "Reversible Quantum Operations and their Application to Teleportation", *Physical Review* **A55** (1997): 2547–56

[32] PEIRCE, Charles S., *Toward a Logic Book*, in *Writings*, Bloomington, Indiana Univeristy Press, 1986: III, pp.

[33] PRIMAS, Hans, *Chemistry, Quantum Mechanics and Reductionism*, Berlin, Springer, 1983

[34] SCULLY, M. O./SHEA, R./MCCULLEN, J. D., "State Reduction in Quantum Mechanics: A Calculation Example", *Physics Reports* **43C** (1978): 485–98

[35] —, "Reality, Causality, and Closing the Circle", in *Search for a Naturalistic Point of View*, Cambridge, University Press, 1993: I, pp. 21–61

[36] STAPP, Henry P., "Whiteheadian Approach to Quantum Theory and the Generalized Bell's Theorem", *Foundations of Physics* **9** (1979): 1–25

[37] —, "Nonlocal Character of Quantum Theory", *American Journal of Physics* **65** (1997): 300–304

[38] VON NEUMANN, John, *Mathematische Grundlagen der Quantenmechanik*, Berlin, Springer, 1932, 1968, 1996

[39] WHEELER, John A., "Information, Physics, Quantum: The search for Links", in ZUREK (ed.), *Complexity, Entropy and the Physics of Information*, Redwood City, Addison-Wesley, 1990: pp. 3–28

[40] WHITEHEAD, Alfred N., *Process and Reality*, London, Macmillan, 1929, 1957, corrected ed. 1978

[41] ZEH, H. D., "On the Interpretation of Measurement in Quantum Theory", *Foundations of Physics* **1** (1970): 69–76

[42] ZUREK, Wojciech H., "Pointer Basis of Quantum Apparatus: Into What Mixture Does the Wave Packet Collapse?", *Physical Review* **D24** (1981): 1516–25. {4, 5, 12}

[43] —, "Environment-induced Superselection Rules", *Physical Review* **D26** (1982): 1862–80