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SPONTANEOUS WAVE PACKET REDUCTION [1]

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1. Introduction

With his research activity, with his deep investigations and with his stimulating suggestions of new experiments J. A. Wheeler has given extremely relevant contributions to the debate on the foundational problems of quantum mechanics. Some of his penetrating remarks focussing in a lucid and concise way the challenge that quantum mechanics represents for the scientific enterprise constitute an ideal starting point to elucidate the motivations for the so called spontaneous localisation program.

Let us consider one of his preferred sentences[1]: *No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon.* This phrase, which concludes the presentation of the delayed choice experiments, is accompained by the remark that[2] *it makes no sense to talk of the phenomenon until it has been brought to a close by an irreversible act of amplification.* The argument acquires a greater strength when combined with the brilliant and picturesque way of stressing the enigma we have to face by resorting[3] to the image of the *Great Smoky Dragon*, with a sharply defined tail and mouth and a fog of uncertainty in between.

We consider it appropriate to compare the above sentences with the desiderata put forward[4] by J.S. Bell for an "exact theory": ... *it should allow electrons to enjoy the cloudiness of waves, while allowing tables and chairs, and ourselves, and black marks on photographs, to be rather definitely in one place rather than another, and to be described in "classical terms".* The cloudiness of waves parallels the fog of uncertainty of the Smoky Dragon and the definiteness, the particularity of the world of experience parallels the sharp definiteness of its tail and mouth, which is due to the irreversible acts of amplification involved in the preparation and detection procedures.

With reference to the above, we consider it appropriate to stress that the fundamental attitude behind the spontaneous localisation approach we are going to analyse in this paper (contrary to the position taken by, e.g., the supporters of hidden variables theories) is to accept that, in general, microphenomena are basically *foggy* and *cloudy* demanding however that such fogginess disappears as a consequence of specific events whose occurrence and effects are clearly identified and described in a mathematically precise way.

Even though it is very seldom mentioned, we would like to recall that even A. Einstein was, in a sense, prepared to accept the foggy nature of microscopic phenomena. In his[5] *Reply to Criticisms*, he remarks that in the case of the decay of a radioactive atom, the orthodox quantum theorist would claim that *it is not reasonable even to posit the existence of a definite point of time for the transformation of a single atom* (i.e. the microworld is cloudy). He states clearly that such a position is sensible. However he also stresses that Schrödinger taught us that the question about the time of decay can be straightforwardly transformed (by simply coupling the atom to an appropriate apparatus) into the question of the presence of a macroscopic registration mark on a paper strip. And he states: *the location of the mark is a fact which belongs entirely within the sphere of macroscopic concepts* ... and there is hardly likely to be anyone inclined to accept that the existence of that location is essentially dependent upon the carrying out of an observation. In fact: *in the macroscopic sphere it is simply considered certain that one must adhere to the program of a realistic description in space and time* (i.e. the macroworld is definite)*; whereas in the sphere of microscopic situations one is more readily inclined to give up, or at least to modify this program* (!). Few pages later he comes back to this point and he stresses that his realistic attitude does not derive from a philosophical prejudice: *the real in physics is to be taken as a type of program, to which we are, however, not forced to cling a priori. No one is likely to be inclined to attempt to give up this program within the realm of the "macroscopic" (location of the mark on the paper strip "real")*. And then he draws his conclusion: *But the "macroscopic" and the "microscopic" are so interrelated that* ***it appears impracticable*** *to give up this program in the realm of the "microscopic" alone.*

We have chosen to devote so much space to this quotation to call attention on the fact that, within the context of our analysis, the crucial problem of our best theory is to succeed in accounting for the smooth merging of the cloudy microworld with the definite macroworld; stated differently, to make precise where and how acts occur which can be unambiguously identified as[2] *irreversible acts of amplification*. Quite appropriately, in our opinion, J. A. Wheeler held, with Bohr, that locating the shifty split cannot be related to acts of empirical assertions. On the contrary, the occurrence of the irreversible acts of amplification must be part of the physical description and one should not ascribe to them any exceptional position above the rest.

Nowadays this position is shared by almost all scientists seriously involved in the foundational problems of quantum mechanics. Many interesting attempts along this line have appeared recently, ranging from detailed critical investigations about the possibility of a deterministic completion of the theory, to the consideration of the so called environment induced superselection rules, to the interesting features of the so called Quantum Histories Approach. All such lines, as well as many others deserving attention, are represented in this conference; we refer the reader to the pertinent papers in this proceeding for a general view of the status of the matter. From now on we deal with the line of research which is the subject of this paper.

The Spontaneous Wave Packet Reduction program represents an attempt to answer the puzzling questions raised above by identifying in a precise way within a strictly quantum context (i.e., by assuming completeness of the Hilbert space description of the states of individual physical systems) the shifty split between micro and macro, reversible and irreversible. The very existence of precise dynamical reduction models shows that, contrary to Einstein's expectations, the program of building up a consistent and unified theory allowing the microsystems to be foggy and nevertheless implying the definiteness of the macroscopic world is viable. It is important to stress that the emergence of such definiteness is implied and precisely described by the formalism so that, to account for it, there is no need to invoke (as many other attempts do) the practical impossibility of revealing interference effects at the macroscopic level. We leave to the reader the evaluation of the potential relevance of the approach and to identify its advantages and drawbacks with respect to the many interesting recent proposals. At any rate, it seems to us that having the explicit proof that a theory exhibiting such features is possible has, by itself, a certain relevance for the investigations about the foundations of quantum mechanics.

2. General remarks about Spontaneous Localizations.

As stressed above the motivation for this line of research derives from the desire of forbidding the embarrassing superpositions of macroscopically different states without requiring to consider measuring apparata and, more generally, macroscopic objects as peculiar systems differing from all other physical systems. Since the most characteristic differences between standard quantum evolution and wave packet reduction consist in the fact that the first is linear and deterministic, while the second is nonlinear and stochastic, one entertains the idea of modifying the standard quantum dynamics by adding stochastic and nonlinear terms to the evolution equation. Such modifications are assumed to describe universal mechanisms governing all physical processes.

Several attempts have been made[6-10], but they did not lead, up to recent times, to a real breakthrough due to some crucial problems which had been left unsolved. The first one is that of the choice of the preferred basis: which specific properties of individual physical systems should one require to be dynamically and spontaneously objectified? Secondly, how can the dynamical modifications satisfy the two diverging desiderata of having a practically negligible effect for all microsystems (a necessary requirement due to the extremely high degree of accuracy of tested predictions of quantum theory) and simultaneously to be able to induce an extremely rapid suppression (the amplification mechanism) of the superpositions of macroscopically distinguishable states? The solution[11,12] came from the identification of the appropriate preferred basis, i.e. the one associated to positions.

Before proceding, with reference to the celebrated sentence by J. A. Wheeler quoted previously and calling attention to the crucial role of the irreversible act of amplification in making legitimate to speak of a phenomenon, we point out that the stochastic and nonlinear features of the theory introduce irreversibility at the very fundamental level. Thus, as we will see, **irreversible acts** making an elementary phenomenon a phenomenon can occur and actually occur (even though with extremely low probability) already at the genuinely microscopic level. To elucidate this point let us consider the famous cosmological example[2] of the gravitational lens effect pointed out by J. A. Wheeler. If the elementary particle coming from the quasar and following two far away routes would be a massive particle rather than a photon, then, due to the extremely long time (billion of years) it has to spend travelling, it would surely suffer at least one spontaneous localisation process (see below) before reaching us, thus being compelled "to choose a specific route". However, it is appropriate to remark that within the model, while a microphenomenon takes hundreds of millions of years to become a phenomenon in J. A. Wheeler's sense, the elementary and very tiny irreversibility built in it is such to imply a tremendous **amplification** when such a microscopic system triggers macroscopic changes. Thus, irreversibility and amplification are two distinct elements of the formalism but they combine just in such a way as to make appropriate both J. A. Wheeler's statements about microphenomena and his sharing Bohr's view that the central point is not the observer's consciousness but the experimental device, bringing the phenomenon to a close. What is relevant about the models under discussion is that, while to account for this process standard quantum mechanics has to embody the (inconsistent) postulate of

wave packet reduction, within such models the universal dynamical laws governing all natural processes do the desired job.

3. A concise review of dynamical reduction models.

As already stated, a satisfactory elaboration of the spontaneous localisation program at the nonrelativistic level has required various steps[11-15]. In order to grasp the conceptually relevant points as well as to understand precisely how the new dynamics works it turns out to be useful to start by discussing the simplest model of this type: Quantum Mechanics with Spontaneous Localisation (QMSL).

3.1. The QMSL Model.

The first model of spontaneous reduction[11,12], QMSL, is based on the assumption that, besides the standard evolution, physical systems are subjected to spontaneous localisations occurring at random times and affecting their elementary constituents. Such processes, which we will call "hittings", are formally described in the following way. When the i-th constituent of the system suffers a hitting the wave function changes according to

$$\Psi(\mathbf{r}_1, ..., \mathbf{r}_N) \rightarrow \Psi_{\mathbf{x}}(\mathbf{r}_1, ..., \mathbf{r}_N) = \Phi_{\mathbf{x}}(\mathbf{r}_1, ..., \mathbf{r}_N) / \| \Phi_{\mathbf{x}} \|$$
$$\Phi_{\mathbf{x}}(\mathbf{r}_1, ..., \mathbf{r}_N) = (\alpha/\pi)^{3/4} \exp[-(\alpha/2)(\mathbf{r}_i - \mathbf{x})^2] \Psi(\mathbf{r}_1, ..., \mathbf{r}_N). \quad (3.1)$$

The localisation processes occur at randomly distributed times with a mean frequency $\lambda = 10^{-16}$ sec^{-1}. The probability density of the process occurring at point $\mathbf{x}$ is given by $\|\Phi_{\mathbf{x}}\|^2$. The localisation parameter $1/\sqrt{\alpha}$ is assumed to take the value 10^{-5} cm.

To understand the physical relevance of the hitting processes as well as the reasons for which QMSL meets the requirements imposed on it, let us consider first the case of a single particle in one dimension in the superposition of two far away states (See Figs.1a,b,c). The separation between the two regions L and R in which the configuration space wave function is appreciably different from zero is assumed to be much larger than the characteristic localisation parameter $1/\sqrt{\alpha}$. In Fig.1b we have supposed the localisation to occur* around the point L and we have shown

* We have also considered, in Fig. 1c the effect of the occurrence of one of the extremely improbable localizations, i.e. at a point where the wave function practically vanishes. One sees from the figure (as one can easily understand from the precise rules governing localisation processes) that even if it occurs, such a process leaves the state practically unaffected.

how such a process leads to a state which is well localised around L. This is an example of the irreversible acts which take place according to the model. Obviously, in the case of a single elementary particle, even when the separation L-R is of thousands of light years, a spontaneous localisation has an appreciable probability of occurring only after about 10^8 years. At any rate, if the process occurs, the microsystem has to choose in which space region it is.

To understand why all those measurement-like processes we are compelled to recognise as occurring almost all the time, almost everywhere in the universe lead to the definiteness of the world of our experience, i.e. to allow the reader to grasp the basic role of the amplification mechanism, we have considered, in Fig.2, the case of the superposition of two far away states of a macroscopic pointer. Would such a state occur, as it is evident both from Eqs.(3.1) and from the figure, a localisation process affecting just one of the particles of the pointer would lead to a suppression of the linear superposition. In fact in the state corresponding to the pointer being around L, all its constituent particles are around L, while in the state at R they are all around R. Hitting one of the particles at left means to multiply the whole wavefunction times a Gaussian centred around L in the position variable of the particle suffering the localisation. It is obvious that after normalisation of such a function the R-term in the superposition (practically) disappears. One then simply remembers that the pointer contains about 10^{24} particles so that one of them will suffer a hitting in about 10^{-7} secs. This is the way in which the elementary irreversible processes are amplified whenever a measurement like process takes place.

The QMSL mechanism does not respect the symmetry properties of the wave function in the case of identical constituents. Its generalisation satisfying such a requirement, the Continuous Spontaneous Localisation model (CSL), has been presented and discussed in various papers[13-15].

3.2. The CSL Model.

The model is based on a linear stochastic evolution equation for the statevector. The evolution does not preserve the norm but only the average value of the square norm. The equation, in the Stratonovich version, is:

$$\frac{d|\Psi_w(t)>}{dt} = [-\frac{i}{\hbar}H + \sum_i A_i w_i(t) - \gamma \sum_i A_i^2] |\Psi_w(t)> \tag{3.2}$$

In Eq. (3.2), the quantities A_i are commuting self-adjoint operators, while the quantities $w_i(t)$ are c-number stochastic processes with probability of occurrence satisfying

$$P_{Cook}[w(t)] = P_{Raw}[w(t)] \| |\Psi_w(t)> \|^2. \tag{3.3}$$

Here $P_{Raw}[w(t)]$ is equal to

$$P_{Raw}[w(t)] = \frac{1}{\mathcal{N}} e^{-\frac{1}{2\gamma}\sum_i \int_0^t d\tau w_i^2(\tau)}, \tag{3.4}$$

($\mathcal{N}$ being a normalisation factor) i.e., to the probability density of a white noise process satisfying

$$<<w_i(t)>>=0, \quad <<w_i(t)\, w_j(t')>>= \gamma\delta_{ij}\delta(t-t'). \tag{3.5}$$

To clarify the physical meaning of the model, let us assume, for the moment, that the operators A_i have a purely discrete spectrum and let us denote by P_σ the projection operators on their common eigenmanifolds.

Then we make the following precise assumption: if a homogeneous ensemble (pure case) at the initial time t=0 is associated to the statevector $|\Psi(0)>$, then the ensemble at time t is the union of homogeneous ensembles associated with the normalised vectors $|\Psi_w(t)>/\| |\Psi_w(t)> \|$, where $|\Psi_w(t)>$ is the solution of Eq.(3.2) with the assigned initial conditions and for the specific stochastic process $w(\tau)$ which occurred in the interval (0,t). The probability density for such a subensemble is that given by Eq. (3.3).

One can prove[14,15] that the map from the initial ensemble to the final ensemble obeys the forward time translation semigroup composition law (once more we see that irreversibility is built in the model from the very beginning). It is also easy to prove that the evolution, at the ensemble level, is governed by the dynamical equation for the statistical operator

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H,\rho(t)] + \gamma \sum_i A_i \rho(t) A_i - \frac{\gamma}{2}\{\sum_i A_i^2, \rho(t)\}, \tag{3.6}$$

from which one immediately sees that, if one disregards the Hamiltonian evolution, the off-diagonal elements $P_\sigma \rho(t) P_\tau$ $(\sigma \neq \tau)$ are exponentially damped.

For our concerns, the relevant feature of the dynamical process (3.2) with the prescription (3.3) is that it drives the statevector of each individual member of the ensemble into one of the common eigenmanifolds of the operators A_i, with the appropriate probability. To clarify this, we consider[13] a simplified case in which only one operator A appears in Eq. (3.2). The solution of this equation corresponding to the particular initial condition (involving only two eigenmanifolds of A with eigenvalues α,β)

$$|\Psi(0)\rangle = P_\alpha|\Psi(0)\rangle + P_\beta|\Psi(0)\rangle, \tag{3.7}$$

when the Hamiltonian is disregarded* , is:

$$|\Psi_B(t)\rangle = e^{\alpha B(t)-\alpha^2\gamma t}P_\alpha|\Psi(0)\rangle + e^{\beta B(t)-\beta^2\gamma t}P_\beta|\Psi(0)\rangle. \tag{3.8}$$

Here B(t) is the Brownian process

$$B(t) = \int_0^t d\tau w(\tau). \tag{3.9}$$

Taking into account Eq.(3.8) and the cooking prescription, one gets the cooked probability density for the value B(t) of the Brownian process at time t:

$$\begin{aligned} P_{Cook}[B(t)] &= \|P_\alpha|\Psi(0)\rangle\|^2 \frac{1}{\sqrt{2\pi\gamma t}} e^{-\frac{1}{2\gamma t}(B(t)-2\alpha\gamma t)^2} \\ &+ \|P_\beta|\Psi(0)\rangle\|^2 \frac{1}{\sqrt{2\pi\gamma t}} e^{-\frac{1}{2\gamma t}(B(t)-2\beta\gamma t)^2}. \end{aligned} \tag{3.10}$$

From (3.10) it is evident that for $t\to\infty$, the Brownian process B(t) can assume only values belonging to an interval# of width $\sqrt{\gamma t}$ around either the value $2\alpha\gamma t$ or the value $2\beta\gamma t$. The corresponding probabilities are $\|P_\alpha|\Psi(0)\rangle\|^2$ and $\|P_\beta|\Psi(0)\rangle\|^2$, respectively. The occurrence of a value "near" to $2\alpha\gamma t$ for the random variable B(t) leads, according to Eq.(3.8), to a state vector that, for $t\to\infty$, lies in the eigenmanifold corresponding to the eigenvalue α of A. In fact, one gets:

$$\frac{\|P_\beta|\Psi_B(t)\rangle\|^2}{\|P_\alpha|\Psi_B(t)\rangle\|^2} \equiv e^{-2\gamma t(\alpha-\beta)^2}\frac{\|P_\beta|\Psi(0)\rangle\|^2}{\|P_\alpha|\Psi(0)\rangle\|^2} \xrightarrow[t\to\infty]{} 0. \tag{3.11}$$

* In Eq. (3.8) and following we have changed the notation for the statevector from the one labelled by the white noise symbol w as in Eq.(3.2) to the one labelled by the Brownian motion symbol B, to stress the fact that, under our assumptions, the state at time t does not depend on the specific sample function $w(\tau)$ in the interval (0,t) but only on its integral Eq.(3.9).

Note that, even though the spread $\sqrt{\gamma t}$ tends to ∞ for $t\to\infty$, its ratio to the distance $2(\alpha-\beta)\gamma t$ between the two considered peaks of the distribution tends to zero.

Analogously, when the random variable B(t) takes a value "near" to $2\beta\gamma t$, for $t\to\infty$, the state vector is driven into the eigenmanifold corresponding to the eigenvalue β of A.

It is then clear that the model establishes a one-to-one correspondence between the "outcome" (the final "preferred" eigenmanifold into which an individual statevector is driven) and the specific value (among the only ones having an appreciable probability) taken by B(t) for $t\to\infty$, a correspondence irrespective of what $|\Psi(0)\rangle$ is*. In the general case of several operators A_i, a similar conclusion holds for the "outcomes" α_i of A_i and the corresponding Brownian processes $B_i(t)$.

This concludes the exposition of the general structure of the CSL model. Obviously, to give a physical content to the theory one must choose the so-called preferred basis, i.e. the eigenmanifolds on which reduction takes place or, equivalently, the set of commuting operators A_i. The specific form that has been presented and shown to possess all the desired features, is obtained[13-15] by identifying the discrete index i and the operators A_i of the above formulae with the continuous and discrete indices (**r**,k) and the operators

$$N^{(k)}(\mathbf{r}) = \left(\frac{\alpha}{2\pi}\right)^{\frac{3}{2}}\sum_s\int dq e^{-\frac{\alpha}{2}(q-r)^2} a_k^+(q,s)a_k(q,s). \tag{3.12}$$

Here $a_k^+(\mathbf{q},s)$ and $a_k(\mathbf{q},s)$ are the creation and annihilation operators of a particle of type k (e.g. k= electron, proton, ...) at point **q** with spin component s, satisfying the canonical commutation or anticommutation relations. Correspondingly, one has a continuous family of stochastic Gaussian processes satisfying:

$$\langle\langle w_k(\mathbf{r},t)\rangle\rangle=0, \quad \langle\langle w_k(\mathbf{r},t)w_j(\mathbf{r}',t')\rangle\rangle=\gamma\delta_{kj}\delta(\mathbf{r}-\mathbf{r}')\delta(t-t'). \tag{3.13}$$

The parameter α is assumed to take the same value (10^{10} cm^{-2}) as in the case of QMSL, while γ is related to the frequency $\lambda=10^{-16}sec^{-1}$ of that model according to $\gamma=\lambda(4\pi/\alpha)^{3/2}$.

3.3. How does Dynamical Reduction Work?

Due to the choice of the parameters for QMSL and the corresponding ones for CSL, the considered dynamics has the following nice features[15]:

* Obviously $|\Psi(0)\rangle$ plays a crucial role in determining the probability of occurrence of the Brownian processes B(t).

-In the case of microscopic systems the nonhamiltonian terms have negligible effects.
-On the contrary, in the macroscopic case the reduction mechanism is extremely effective in suppressing linear superpositions of states in which a macroscopic number of particles are displaced by more than the characteristic localisation length. Such a suppression occurs at the individual level, so that any individual macroscopic system acquires[16] *in a split second* definite macroscopic properties.

This feature has already been analysed in great detail with reference to the QMSL model. To discuss the decoherence properties of CSL ensuing from the choice (3.12), even though the reduction processes occur at the individual level, one can limit his considerations to the evolution equation for the statistical operator:

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H,\rho(t)] + \gamma\sum_k \int dr N^{(k)}(r)\rho(t)N^{(k)}(r) - \frac{\gamma}{2}\sum_k \{\int dr N^{(k)2}(r),\rho(t)\}. \quad (3.14)$$

For sake of simplicity here we will further restrict ourselves to a simplified version of CSL obtained by disregarding the hamiltonian term and discretizing the space. This allows us to derive in a straightforward way[14,15] the main consequences which are of interest for the subsequent discussion.

We divide the space into cells of volume $(\alpha/4\pi)^{-3/2}$ and we denote by $N_i^{(k)}$ the number operator counting the particles of type k in the i-th cell. As follows from the discussion of the preceding Subsection, in the considered case the dynamical evolution drives the statevector into a manifold such that the number of particles present in any cell is definite. The simplified equation for the statistical operator reads:

$$\frac{d\rho(t)}{dt} = \gamma\left(\frac{\alpha}{4\pi}\right)^{\frac{3}{2}}\sum_k\left(\sum_i N_i^{(k)}\rho(t)N_i^{(k)} - \frac{1}{2}\{\sum_i N_i^{(k)2},\rho(t)\}\right). \quad (3.15)$$

In accordance with the relation of Subsection 3.2 we will often use the QMSL frequency parameter λ in place of the expression $\gamma(\alpha/4\pi)^{-3/2}$. If we denote by $|n_1^{(k)},n_2^{(k)},...,n_i^{(k)},...>$ the state with the corresponding occupation numbers for the various types of particles and for the various cells, the solution of Eq.(3.15) reads, in the considered basis:

$$< n_1^{(k)},n_2^{(k)},...|\rho(t)|m_1^{(k)},m_2^{(k)},...> = e^{-\frac{\lambda}{2}\sum_k\sum_i (n_i^{(k)}-m_i^{(k)})^2 t} < n_1^{(k)},n_2^{(k)},...|\rho(0)|m_1^{(k)},m_2^{(k)},...>. \quad (3.16)$$

Equation (3.16) shows that linear superpositions of states containing a different number of particles in the various cells are dynamically reduced to one of the superposed states with an exponential time rate depending on the expression $\frac{\lambda}{2}\sum_k\sum_i (n_i^{(k)} - m_i^{(k)})^2$.

The amplification process in going from the micro to the macroscopic case and the preferred role assigned to position make it clear how also CSL, like QMSL, overcomes the difficulties of quantum measurement theory. This is easily understood by remarking once more that in measurement processes different eigenstates of the measured micro-observable trigger (through the system-apparatus interaction) different displacements of a macroscopic pointer from its "ready" position. The unique dynamical principle of CSL leads then, in extremely short times, to the dynamical suppression, with the appropriate probability, of all but one of the terms in the superposition, i.e., to the emergence of an outcome.

The above analysis should have made evident that Dynamical Reduction Models describe in mathematically precise terms when, where and how a microphenomenon becomes a phenomenon as a consequence of the occurrence of an irreversible act and how it is brought to a close by an amplification process.

4. General implications of dynamical reduction.

In the previous Section we have concisely presented the precise formal aspects of QMSL and CSL, and we have clarified how such models overcome the difficulties of the formalism. We stress that the considered models represent truly rival theories of standard quantum mechanics (in fact they can, in principle, be tested against it) but they exhibit, at the microscopic level, empirical divergences from it which are so small that they can claim all the same experimental support. Said differently, they meet the two divergent desiderata for dynamical reduction theories which have been mentioned previously, i.e., they imply no appreciable changes in the behaviour of such systems and at the same time they induce an extremely rapid suppression of the unwanted superpositions at the macroscopic level.

Due to the (present) impossibility of performing *experimenta crucis* allowing to discriminate between dynamical reduction models and quantum mechanics, to accept or to refuse the dynamical reduction philosophy is, to a large extent, a matter of taste. At any rate we consider of some conceptual interest to have shown that one can follow such a line of thought to overcome the "difficulties" met by quantum mechanics. In a recent interesting paper[17], on the basis of a comparison of the effects of the CSL dynamics with those due to the environment, it has been stated that, in absence of possible experimental tests, the consideration of new physical principles which are not motivated by the necessity of explaining new phenomena makes the dynamical reduction program vulnerable to Occam's razor.

We disagree on this point for two reasons. One has been sharply expressed by J.S. Bell[18]: *I think that theoretical physics owes much to insisting on more than agreement with experiment.* The second emerges naturally when one takes into account the specific context, the conceptual problems which motivate the reduction program. The central issue is the conceptual implications of quantum formalism for what concerns the possibility of adopting a macrorealistic position about nature.

A quite natural way to grasp the core of the question is to consider the hidden variable models which have played and continue to play (quite appropriately in our opinion) an important role for the debate on the conceptual foundations of quantum mechanics. Within such approaches one requires from the very beginning the theory to be in complete agreement with quantum mechanics. In spite of this, it would be quite unappropriate to deny the conceptual relevance of having been able to prove that a deterministic completion of quantum mechanics is possible and of having identified the price (i.e. contextuality) that one has to pay for this.

Having stated this we will, in this Section, call attention to recent developements of the dynamical reduction program. As we will see, the investigations furthering the considered line have led to some interesting general results about the requests that one has to respect when attempting to modify quantum mechanics and have required a reconsideration of nonlocality and of the criteria for property attribution to individual physical systems. We will also review briefly some experimental aspects of the new dynamics and we will call attention to some open problems on which active research is still going on.

4.1. Some general results concerning the role of nonlinearity and stochasticity.

As is well known[19] standard quantum mechanics exhibits nonlocal features which, however, allow[20] its *peaceful cohexistence* with relativity, since quantum nonlocality is of the uncontrollable type. It can be proved[15,16] that also QMSL and CSL satisfy the no faster-than light signalling constraint.

In connection with this problem it is appropriate to call attention to a quite general result by N. Gisin[21]. It can be summarized by stating that the

inclusion of nonlinear elements in the Schrödinger equation unavoidably leads to violations of the above constraint.

On the other hand, it is worth mentioning that one can prove[15,22] that, even though the inclusion of stochastic features in the dynamics may lead to ensemble reduction (i.e. to diagonalization of the statistical operator in the preferred basis), it cannot induce, by itself, individual reductions (i.e. the fact that the statevector of each individual system is driven into one of the preferred eigenmanifolds). It goes without saying that the very reason for considering the dynamical reduction program is the desire of accounting for individual reductions.

The conclusion of this Subsection is that it is just the combined interplay of nonlinearity and stochasticity which makes possible for CSL to *peacefully cohexist* with relativity, and at the same time to satisfy the fundamental desideratum that individual macroprocesses have outcomes.

4.2. Locality from the dynamical reduction point of view.

It goes without saying that since CSL reproduces the quantum correlations about measurement outcomes at the two wings of the apparatus in an EPR-like situation, it also exhibits nonlocal features, just as standard quantum mechanics does. Thus one is led to raise the problem of the precise nature of the nonlocal aspects of the theory. Immediately after the formulation of QMSL, J.S. Bell has felt the necessity of discussing this problem and has reached the conclusion[16] that the model *is as Lorentz invariant as it could be in the nonrelativistic version.*

This problem has been reconsidered in great detail in two recent papers[23,24]. In them the two different kinds of nonlocality which can characterize a theory and which are usually denoted as parameter dependence (PD) and outcome dependence (OD) have been taken into account. For those who are not familiar with this problem one can state that a theory violates locality by exhibiting PD when the outcome at one wing can depend on the settings at the other wing, while in theories exhibiting OD, the outcome at one wing can depend only on the outcome at the other wing.

It is appropriate to recall that[23] while quantum mechanics exhibits OD, all deterministic hidden variable theories exhibit PD. In refs.(23,24) it has been shown that both QMSL and CSL violate locality by exhibiting only OD. This is of some relevance, since, as extensively discussed in ref (18) and in the papers under consideration, the two just mentioned nonlocal features have a completely different status from the point of view of the possibility of getting relativistic generalizations of the theory itself. In fact it is easily proved[23] that all theories exhibiting PD, admit at most what J. S. Bell has called[18] non-genuinely relativistic generalizations, this specification making reference to the fact that while physics turns out to be the same for all observers there is nevertheless a hidden preferred reference frame. On the contrary, the violation of locality by OD does not preclude the possibility of a relativistic generalization in the[18] true Lorentz sense.

4.3. Are experimental tests of dynamical reduction possible?

In spite of the fact that we have repeatedly stressed the extreme difficulty to devise experimental tests of CSL against quantum mechanics, it is appropriate to mention that there have been various investigations aimed to identify possible ways of tackling such a problem.

Let us list some of the effects of the modified dynamics which deserve to be discussed:

-The theory is fundamentally irreversible; as such it implies a continuous increase of the energy with the elapsing of time. This is easily understood by taking into account that localising a system implies inducing high momentum components. The corresponding energy increase can be explicitly evaluated[15] and turns out to be quite negligible and well below experimental testability.

-A quite natural area to search for effects of the modified dynamics is the one of the so called macroscopic quantum effects, typically superconductivity and the like. There have been various interesting investigations[25-27] about this point, the conclusion being that the theory actually implies a change in the resistivity of a superconductor with respect to the quantum mechanical value. Once more, however, testing such an effect is not possible with the present technology.

-Another effect is particularly interesting and its investigation has recently led to some relevant conclusions about CSL. Consider a bound system like, e.g., a hydrogen atom and suppose that its electron suffers a localisation process. One can easily evaluate[15,28,29] the probability that such a process leads to the excitation or to the dissociation of the atom. Due to the fact that the localisation accuracy is orders of magnitude larger than the dimensions of the atom, even if such a process occurs, the corresponding probability turns out to be extremely small. When one takes into account the extremely low probability that a microscopic system suffers a localisation one reaches the conclusion that, on the average, one atom per second per mole will be excited or dissociated as a consequence of the modifications of the dynamics. This seems to be a too improbable event to be tested. In spite of this, investigations[30] on this effect have brought a new understanding of the

phenomenon and have suggested a modification of CSL along the lines we are going to discuss.

The argument of ref.(30) goes as follows. Let us suppose that the CSL mechanism is operative at the level of quarks and that it makes sense to apply it to the quark model for nucleons (both these assumptions are by no means obvious). Then one can go through a calculation strictly similar to the previous one for the atom. In spite of the fact that the probability of dissociation is much smaller than before (due to the extremely small dimensions of a nucleon), nevertheless, if reduction is governed by the number of displaced particles in accordance with the CSL parameters λ and α, one gets a lifetime for the proton appreciably shorter than the one already confirmed by experiments. To avoid this problem one should change the parameters of the model. This in turn would imply violating the other requests that it must meet (typically the suppression of the superpositions of macroscopically different states would require an unacceptably long time to occur).

The authors of ref.(30) then make an important remark. If one replaces the number density operators of the CSL model by the corresponding mass density operators and one assumes the reduction rates to be those of CSL for nucleons, the excitation and/or dissociation probabilities are depressed by large factors. The advantages are remarkable. First of all the dissociation rate for the proton turns out to have a value well below the experimental bound while the reduction rates for macroscopic objects coincide practically with those of CSL, the decoherence being governed by the nucleons in ordinary matter, the contribution from electrons becoming negligible. Moreover, in doing so one relates reduction to gravity, an interesting possibility which has been suggested by various authors[6,31-34]. Actually, a model exhibiting this feature and having the further advantage of replacing one of the two parameters of CSL with Newton's gravitational constant had been presented[35] some years ago. Other advantages of taking such a position have been discussed in ref.(27).

4.4. Relativistic Generalizations and Property Attribution.

In spite of the fact that, as pointed out in Subsection 4.2, there is no reason of principle forbidding a relativistic generalization of CSL due to its nonlocality being of the O.D. type, it turns out not to be easy to reach such a goal. Several interesting attempts have been made in recent years[36-39], but they have not led to a satisfactory solution of the problem. Trying to embody stochastic elements in a quantum field theory context leads to intractable divergences. The considered investigations have, however, led to a better understanding of some crucial points and have thrown some light on relevant conceptual issues.

First they have led to a completely general and rigourous formulation[37,38] of the concept of stochastic invariance. Second, they have stimulated a critical revisitation of the problem of the criteria for the attribution of objective local properties to physical systems. A way to do this having the following implications has been proposed. In specific situations one cannot attribute any local property to a microsystem; any attempt to do so gives rise to ambiguities. However, in the case of macroscopic systems, the impossibility of attributing to them local properties (or, equivalently, the ambiguities about such properties) last only for time intervals of the order of those which are necessary for the dynamical reduction to take place.

The above picture has stimulated a deeper investigation of the problem and a critical reconsideration (taking appropriately into account the role of nonlocality within a relativistic context) of the logical structure of the EPR argument[40]. The conclusion is that, when the appropriate criterion is adopted, no objective property corresponding to a local observable can emerge, even for microsystems, as a consequence of a measurement-like event occurring in a space-like separated region. Such properties emerge only in the future light cone of the considered macroscopic event. Correspondingly it turns out to be impossible to establish, even conceptually, cause-effect relations between space-like events.

To conclude, if a way to circumvent the present difficulties (i.e. the intractable divergences) will eventually be found, we can anticipate that, even in the relativistic version, dynamical reduction models will allow microsystems to be foggy, while requiring macrosystems to always have definite macroproperties.

4.5. Closing the circle within the spontaneous reduction program.

The last point we consider worth mentioning is that the spontaneous localization models represent theoretical constructions allowing one to close the circle in A. Shimony's sense, i.e. to elaborate a worldview based on a genuinely quantum formalism (i.e. on the Hilbert space description of physical systems) which can accomodate our knowledge about microscopic phenomena and at the same time to account for our definite perceptions. This program has been proven to be viable in two recent papers[41,42].

Reference (41) gives an answer to a criticism[43] which had been raised, completely in general, against the dynamical reduction program. It is based on the remark that one can easily imagine situations leading to definite perceptions and which nevertheless do not involve the displacement

of a large number of particles. Typically, consideration has been given to a "measurement-like" process in which the two paths followed by a microsystem going through a Stern-Gerlach set up end on two different regions of a fluorescent screen and they excite a small number of atoms which decay by emitting a small number of photons. Then one is dealing with a superposition of two states corresponding to photons emerging from two different points. However the process involves such a small number of particles that the CSL dynamics cannot lead to its suppression. On the other hand, since the visual perception threshold is quite low (about 7 photons) the naked eye of a human observer is sufficient to detect the point from which the luminous spot originates. The conclusion is obvious: in the considered example no dynamical reduction can take place and thus the measurement is not over, the outcome is not definite, up to the moment in which a conscious observer perceives the signal.

This criticism is inappropriate. It is perfectly true that in the considered case the superposition persists for long times (actually it must do so since, due to the fact that the system under consideration is microscopic, one could perform on it inteference experiments which everybody would expect to confirm standard quantum predictions) but, if one takes seriously the above remark, one cannot avoid considering the whole system which brings about the definite "outcome", i.e. the unambiguos perception. One must then give a simple estimate of the number of ions which are involved in the visual perception mechanism. Such an analysis makes perfectly plausible[41] that in the process a sufficient number of particles are displaced of a sufficient spatial amount to satisfy the conditions which are necessary, according to CSL, for the suppression of the superposition of the two nervous signals to take place within the perception time.

It has to be stressed that this analysis, even though resorting to the mechanism of visual perception does by no means amount to attribute a special role to the conscious observer. The observer's brain is simply the only system which enters into the game in which a superposition of two states involving different locations of a large number of particles occurs. As such it is the only place where the amplification act bringing to a close the microscopic phenomenon can occur. But, if in place of the eye of a human being one puts in front of the photon beam a spark chamber or any device leading to the displacement of a macroscopic pointer or producing ink spots on a computer output, reduction will take place. Once more this example shows the appropriateness, within the considered theoretical models, of J. A. Wheeler's position that the central point is not the observer's consciousness but the experimental device bringing the phenomenon to a close.

Before concluding we would like to mention that in ref.(42) it has been shown how a reinterpretation of the considered model theory allows one to make a further relevant step towards closing the circle within a nonrelativistic framework One starts by defining at each fixed time t an average mass density function M(**r**,t) in the real three dimensional space. Such a function is simply the expectation value of the mass operator of a cell of volume 10^{-15} cm^3 centred at **r**, evaluated on the state vector $|\Psi,t>$ describing the physical system which represents "our universe". It is obvious that within standard quantum mechanics such a function cannot be endowed with an objective physical meaning precisely due to the occurrence of linear superpositions of macroscopically different mass distributions. One then considers a CSL model relating reduction to the mass density. The theory dynamically suppresses in extremely short times the embarrassing linear superpositions. Limiting his considerations to the set of states which are allowed (i.e. are dynamically stable) by the model one can give a description of the world in terms of the considered function M(**r**,t). Secondly, one can define an appropriate topology on such a set which allows a quite natural specification of macroscopic similarity of allowed Hilbert space states. In turn, this topology can be taken as a basis to define a sensible principle of psycho-physical correspondence for the theory.

5. Conclusions.

In this paper we have taken into account the main conceptual difficulties met by standard quantum mechanics in dealing with physical processes involving macroscopic system. We have stressed how J.A. Wheeler's remarks and lucid analysis have been relevant to pinpoint and to bring to its extreme consequences the puzzling aspects of quantum phenomena. We hope to have made plausible how the recently proposed models of spontaneous dynamical reduction represent a consistent way to overcome the conceptual difficulties of the standard theory. Obviously, many nontrivial problems remain open; the first and more relevant one being that of generalizing the model theories considered here to the relativistic case. This is the challenge of the dynamical reduction program.

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Figure Captions.

Fig.1. A typical spontaneous localisation process of the QMSL model for a microsystem in a superposition of far away states. (a) Initial state and hitting function. (b) A localisation around L leads to the suppression of the R component of the statevector. (c) A very improbable localisation has practically no effect.

Fig.2. The amplification mechanism of the QMSL model: any localization of one of the constituents of the pointer amounts to a localisation of the whole pointer.

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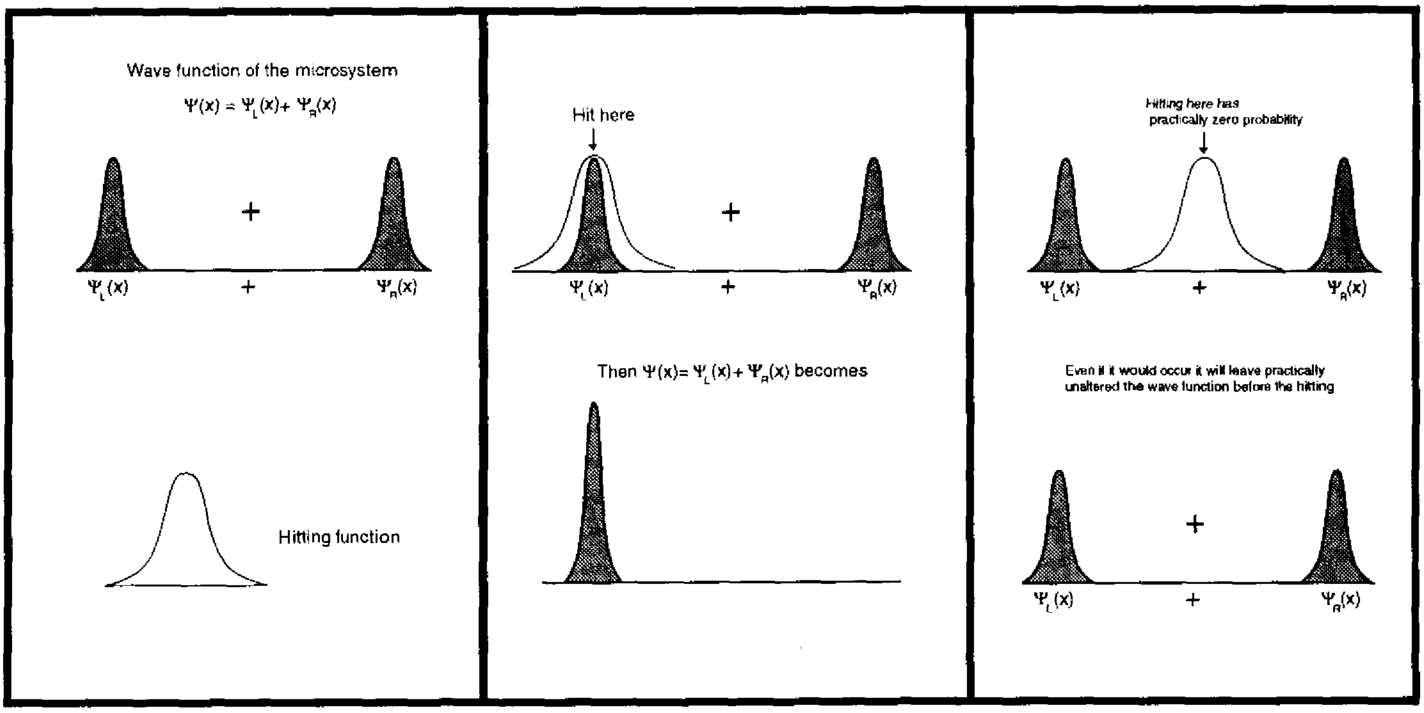

Fig.1a Fig.1b Fig.1c

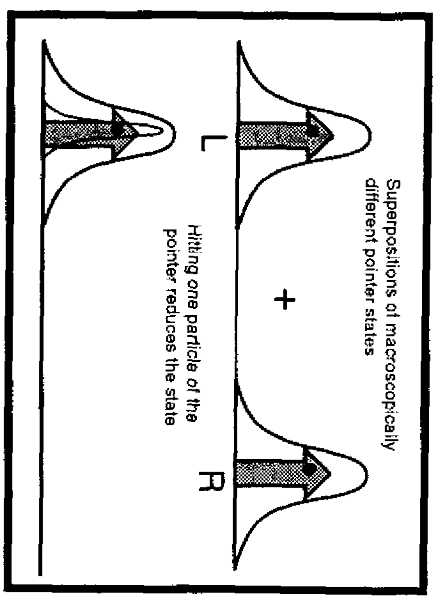

Fig.2

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