Spontaneous state vector collapse at large distances

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ABSTRACT. A structural interpretation for the quantum-mechanical state vector of an unbound system allows, at sufficiently large distances, spontaneous state reduction – not stimulated by measurements. Scenarios for spin-singlet breakdown are proposed that allow for a gentle deviation, at large distances, from the predictions of usual quantum mechanics.

RESUME. En donnant une interprétation structurale au vecteur d'état en mécanique quantique, on peut, pour un système non lié et à des distances suffisamment grandes, arriver à une réduction spontanée de l'état – non stimulée par une mesure. On propose des scénarios pour la décomposition du singulet de spin, qui entraînent une faible déviation, aux grandes distances, des prédictions de la mécanique quantique usuelle.

Suppose that, at some initial time, the quantum-mechanical state vector for an unbound system is represented by a normalized superposition of eigenstates of the operator associated with some observable. If the system remains unprobed then the state vector evolves unitarily, continuing as a superposition state. On the other hand, a measurement of the observable corresponds to a non-unitary reduction of the superposition state into a final state characterized by one eigenvalue, or a narrow range of eigenvalues. Thus a wave function with a spreading domain in position space continues, in principle, to expand indefinitely as long as the position remains unprobed. This poses no conceptual problem if the state vector is regarded as no more than a calculational tool. Then, wave packet spreading and reduction do not represent actual physical structures and processes but are merely aspects of a set of rules –quantum mechanics– for calculating the relative frequency of certain experimental outcomes.

Suppose instead one attempts a structural interpretation for the state vector. For a system which is always detected as a single particle, the state vector is then, even before any probe, a structural feature (albeit not an observable) of an actual physical entity –a quantum object (QO)[1]. An expanding wave function characterizes an expanding, undetected QO which acts as a coherent, irreducible unity over its extended spatial domain. The structural integrity of the undetected QO is maintained by internal physical processes that are faster than any external probe –that is, the time of interaction between a QO and another object is always greater than the time required for those internal processes to maintain the unified structure of the QO over its extended domain. Even though this unifying connection over the QO's domain must be superluminal, it does not constitute signalling between distinct objects separately identifiable by some external probe. The QO is quite unlike usual extended bodies composed of spatially distinct component "parts" that can be separately distinguished from each other by certain probes.

With a real-structure outlook, the usual, detection-related, reduction of the position space wave function corresponds to an actual physical process for the QO –a structural transformation, collapsing the QO's spatial domain. Even though this collapse is superluminal, naive relativity is not violated –the QO collapses as a whole and there are not separate (component) objects racing at superluminal, relative speeds with respect to each other. This lack of component parts and the constraint of a speed limit for signal/object transmission is elaborated in reference [1].

Now suppose there are no detectors around to stimulate reduction and the undetected QO continues to expand. There may well be some critical size beyond which the expanding QO becomes unstable and there occurs "spontaneous reduction". If the process of internal coordination over the undetected QO's extended domain occurs at a finite (albeit superluminal) rate, then a spatial coherence limit may be reached beyond which the QO's structural unity cannot be maintained. If so, internal instability –and not outside probes– may prompt deviations from the usual unitary development of the state vector. For certain interference phenomena, measurements beyond the spatial coherence limit would then show a deviation from the predictions of the usual quantum mechanics.

We examine here the physical consequence of spontaneous state breakdown for a system in a superposition state yielding two detected particles. Consider a zero-spin system initially in a spin-singlet state and whose final-state *detected* decay products are always two spin-half particles β_1, β_2 found in opposite directions along a line (x-axis). The spatial domain of the system is sufficiently large that the wave function becomes :

$$\Phi(1,2) = \phi_1(x_1)\phi_2(x_2)(\hbar^2/4)|\,\text{sing.}(1,2)\rangle \tag{1}$$

where the spin-singlet dependence is :

$$|\,\text{sing.}(1,2)\rangle \equiv [|\diamond_1 \cdot \mathbf{n}; +\rangle|\diamond_2 \cdot \mathbf{n}; -\rangle - |\diamond_1 \cdot \mathbf{n}; -\rangle|\diamond_2 \cdot \mathbf{n}; +\rangle]/\sqrt{2} \tag{2}$$

where $|\diamond_i \cdot \mathbf{n}; +\rangle\{|\diamond_i \cdot \mathbf{n}; -\rangle\}$ is the eigenvector corresponding to the eigenvalue $+1\{-1\}$ of the spin-component operator $\diamond_i \cdot \mathbf{n}$ for β_i along the direction of the unit vector $\mathbf{n}$.

$$\diamond_i \cdot \mathbf{n}|\diamond_i \cdot \mathbf{n}; +\rangle = |\diamond_i \cdot \mathbf{n}; +\rangle\{\diamond_i \cdot \mathbf{n}|\diamond_i \cdot \mathbf{n}; -\rangle = -|\diamond_i \cdot \mathbf{n}; -\rangle\} \tag{3}$$

The separation between the peaks of the spatial wave functions, ϕ_1, ϕ_2 grows with time.

Despite the factorized spatial dependence, the state function $\Phi(1,2)$ is not factorizable into a simple product each factor of which refers only to one of the particles β_1, β_2. The spin singlet involves a rather extreme superposition:

$$|\,\text{sing.}(1,2)\rangle = \int d\mathbf{n}[1/2\pi\sqrt{2}]|\diamond_1 \cdot \mathbf{n}; +\rangle|\diamond_2 \cdot \mathbf{n}; -\rangle \tag{4}$$

If the system remains unprobed, then the state vector evolves unitarily, maintaining the non-factorizable, superposition state.

On the other hand, a probe (placed on the positive x-axis) for the spin component of β_1 in the $\mathbf{a}$ direction requires a reduction of the state vector into a factorized form corresponding to a pair of spin anti-correlated β's :

$$|\,\text{sing.}(1,2)\rangle \overset{\text{stim.}}{\longrightarrow} \begin{cases} \text{either} & |\diamond_1 \cdot \mathbf{a}; +\rangle|\diamond_2 \cdot \mathbf{a}; -\rangle \\ \text{or} & |\diamond_1 \cdot \mathbf{a}; -\rangle|\diamond_2 \cdot \mathbf{a}; +\rangle \end{cases} \tag{5}$$

Another probe (on the negative x-axis and farther from the source than the probe on the positive x-axis) for the spin component of β_2 in the direction $\mathbf{b}$ requires a further reduction :

$$|\diamond_1 \cdot \mathbf{a}; +\rangle|\diamond_2 \cdot \mathbf{a}; -\rangle \overset{\text{stim.}}{\longrightarrow} \begin{cases} \text{either} & |\diamond_1 \cdot \mathbf{a}; +\rangle|\diamond_2 \cdot \mathbf{b}; -\rangle \\ \text{or} & |\diamond_1 \cdot \mathbf{a}; +\rangle|\diamond_2 \cdot \mathbf{b}; +\rangle \end{cases} \tag{6}$$

and similarly for $|\diamond_1 \cdot \mathbf{a}; -\rangle|\diamond_2 \cdot \mathbf{a}; +\rangle$.

Before any probe, the system consists of one undetected QO, characterized as a whole by the state vector $\Phi(1,2)$. It is *not* two distinct objects each having some definite spin orientation –notwithstanding the formulation of $\Phi(1,2)$ in terms of final state eigenvectors of the individual particles β_1, β_2. The widespread, tacit and unwarranted assumption that there are actually two objects in the singlet state –and not just one object with a private connection over spatially disparate public domains [2]– is incompatible with quantum mechanics and lies at the heart of the spin version [3] of the EPR paradox [4].

The probe of the spin component of β_1 stimulates the transformation of the expanding, singlet-state QO into two objects each with a definite spin orientation (as indicated in (5)). Before the probe, there is no question of superluminal signalling ; there is, however, a superluminal process, internal-to-the-QO, that maintains the structural identity of the QO in the singlet state until the external probe catalyses the QO's collapse into two distinct objects.

Now, what is expected if the two spin-component detectors are distanced farther and farther from the source of the singlet QO ? Canonical quantum mechanics allows no deviation from the predictions for the singlet state as long as the system is not disturbed before reaching the detectors. But what if the QO does have a limited stability domain and –without external disturbances– there does occur a spontaneous breakdown of the singlet state *before* anything reaches either detector ? The simplest possibility for such spontaneous singlet-state collapse is the Bohm-Aharonov proposal [5] wherein the singlet is spontaneously transformed into a spin anti-correlated pair of β states :

$$|\,\mathrm{sing.}(1,2)\rangle \xrightarrow{\text{spont.}} |\diamond_1 \cdot \mathbf{n}; +\rangle|\diamond_2 \cdot \mathbf{n}; -\rangle \tag{7}$$

with an isotropic distribution for the spin direction $\mathbf{n}$. The unprobed, singlet-QO breaks into a pair of $\beta - QO$s.

Experimental results over moderate distances contradict the Bohm-Aharonov proposal and are consistent with the predictions of usual quantum mechanics. But this is not surprising since the Bohm-Aharonov proposal should apply only for those, possibly huge, distances where the singlet-QO has necessarily and entirely fallen apart. A scenario more appropriate for the interim domain where spontaneous reduction is possible

–but not necessary– is :

$$|\,\mathrm{sing.}(1,2)\rangle \begin{cases} \xrightarrow{\text{usual evolution}} |\,\mathrm{sing.}(1,2)\rangle \text{ with probability } [1-|\eta|^2] \\ \xrightarrow{\text{spont}} |\diamond_1\cdot\mathbf{n};+\rangle|\diamond_2\cdot\mathbf{n};-\rangle \text{ with probability } [|\eta|^2/4\pi] \end{cases} \tag{8}$$

where $|\eta|$ is very small (near zero) for moderate separations between the source of the spin-singlet QO and the spin probes. $|\eta|$ grows larger as the source-to-nearest-probe distance is increased.

Another (seemingly different) scenario for spontaneous state vector reduction is the gradual erosion of the singlet-QO into a state that superposes both a singlet and an anti-correlated pair :

$$|\,\mathrm{sing.}(1,2)\rangle \overset{\text{spont.}}{\longrightarrow} |\psi(\mathbf{n})\rangle| \equiv \lambda|\,\mathrm{sing.}(1,2)\rangle + \eta|\diamond_1\cdot\mathbf{n};+\rangle|\diamond_2\cdot\mathbf{n};-\rangle \tag{9}$$

where there is no preference in the spin direction $\mathbf{n}$. The state vector normalization is maintained :

$$\langle\psi(\mathbf{n})|\psi(\mathbf{n})\rangle = 1 \tag{10}$$

giving the condition relating the complex parameters λ and η :

$$|\lambda|^2 + |\eta|^2 + \eta^*\lambda/\sqrt{2} + \lambda^*\eta/\sqrt{2} = 1 \tag{11}$$

Both of the mixed ensembles in (8) and (9) have the *same* density operator :

$$\mathbf{Dens.op} = [1-|\eta|^2]\,\mathbf{Dens.op}^{singlet} + |\eta|^2\,\mathbf{Dens.op}^{Bohm-Aharonov} \tag{12}$$

The likelihood for a detected final state, $|\diamond_1\cdot\mathbf{a};+\rangle|\diamond_2\cdot\mathbf{b};-\rangle$, becomes

$$P(\mathbf{a},\mathbf{b}) = [1+\mathbf{a}\cdot\mathbf{b}(1-4|\eta|^2/3)]/4 \tag{13}$$

This interpolates smoothly between the pure singlet result (when $|\eta|=0$) and the Bohm-Aharonov prediction (when $|\eta|=1$). Detected deviation from spin anti-correlation in a given ($\mathbf{a}=\mathbf{b}$) spin direction should occur in only $|\eta|^2/3$ of the trials.

The expectation value of the observable $[\diamond_1\cdot\mathbf{a}\otimes\diamond_2\cdot\mathbf{b}]$ becomes

$$C(\mathbf{a},\mathbf{b}) = -\mathbf{a}\cdot\mathbf{b}(1-2|\eta|^2/3) \tag{14}$$

and the quantity, $B(\mathbf{a}, \mathbf{a}', \mathbf{b}, \mathbf{b}') \equiv |C(\mathbf{a}, \mathbf{b}) - C(\mathbf{a}, \mathbf{b}')| + |C(\mathbf{a}', \mathbf{b}) + C(\mathbf{a}', \mathbf{b}')|$ takes on the maximum value

$$B^{max} = 2\sqrt{2}(1 - 2|\eta|^2/3) \tag{15}$$

For sufficiently small $|\eta|$ (not just for the pure singlet case), B^{max} violates the Bell inequality [6], $B \leq 2$. As $|\eta|$ grows the Bell inequality is eventually saturated. For $|\eta|^2\rangle 0.44$, B^{max} satisfies the Bell inequality (as does the Bohm-Aharonov result).

There are more elaborate possibilities for singlet breakdown –such as :

$$|\,\mathrm{sing.}(1,2)\rangle \overset{\mathrm{spont.}}{\longrightarrow} \begin{cases} |\psi(\mathbf{n})\rangle \text{ with probability } [P(\eta)/4\pi] \\ |\psi'(\mathbf{n})\rangle \text{ with probability } [1 - P(\eta)]/4\pi \end{cases} \tag{16}$$

where $\langle\psi'(\mathbf{n})|\psi(\mathbf{n})\rangle = 0$ and $P(\eta)$ is initially (i.e. up to moderate distances) close to unity –say, as in

$$P(\eta) = |\langle\psi(\mathbf{n})|\,\mathrm{sing.}(1,2)\rangle|^2 = [1 - |\eta|^2/2] \tag{17}$$

The essential features in all these scenarios, (8), (9), (16) is that they allow for a very gentle departure from the predictions of usual quantum mechanics and interpolate smoothly between usual quantum mechanics ($|\eta| = 0$) and the Bohm-Aharonov proposal ($|\eta| = 1$). Thus the successes of usual quantum mechanics can be retained for moderate size domains while allowing unexpected developments –resulting from spontaneous state reduction– at larger distances.

Even though measurements over moderate distances have shown the usual quantum mechanics to be adequate [7], it is important to devise and carry out experiments testing quantum mechanics for greater and greater detector separations to check whether $|\eta|$ systematically departs from zero. The successes of quantum mechanics over moderately-sized domains and the failure of models always satisfying Bell's inequality do not rule out those real-structure pictures that deviate from the predictions of quantum mechanics only in exceptional –and as yet unexplored– circumstances (such as for sufficiently large distances).

I have sketched here a possible physical basis for spontaneous state vector reduction and pointed out some of the phenonological implications for the spin-singlet system. There are mathematically well –formulated models of spontaneous reduction based on Hilbert space hitting processes or diffusion processes [8]. It may be worthwile to adapt the qualitative picture presented here to the formalism of reference [8].

References

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[2] To visualize such a private connection, consider a two-dimensional position space. The envelope of a single *QO* includes the disparate public domains of ϕ_1, ϕ_2 privately connected together off the public surface –say, by a tube.

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(Manuscrit reçu le 7 mai 1992)