Persistence of information in the quantum measurement problem

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It is here suggested that quantum statistics does not require a specific postulate about the outcome of a measurement process. It can be derived without any reference to either a collapse of the state vector or the macroscopic nature of the measuring apparatus. The entangled state of object system and measuring apparatus can be held to be valid throughout. But it is possible to show that the interference terms vanish, i.e. the entangled state is exactly equivalent to the corresponding classical mixture, for a large class of situations: all those in which some kind of recording of the measurement results takes place (at the microscopic or macroscopic level).

While this class certainly includes all the measurements we are ordinarily concerned with, it might be possible to envision "measurement-like" processes that do not belong to it. It might be possible, perhaps at an intermediate level between the macroscopic and the microscopic, to realize processes in which all information about the measurement results gets erased. It is here claimed, based on microscopic analogies, that in such a situation we should expect the interference terms not to vanish and the equivalence to a classical mixture not to hold. In other words, we should think of the quantum postulate describing the outcome of a measurement as a classical mixture merely as a practical device with limited validity.

The present argument is purely statistic and makes no claim about individual events. In this sense it is independent from any specific interpretation of quantum mechanics. It leaves open the question whether an individual result is determined by a hidden parameters theory or is intrinsically indeterminate.

Super-simplified version of the argument (degeneracy not taken into account, von Neumann chain consisting only of object system plus apparatus)

Object system with observable O, eigenstates ϕ_n
Measuring apparatus with "index observable" M, eigenstates Φ_n

$$U_t\phi_n \otimes \Phi_0 = \phi_n \otimes \Phi_n$$

$$U_t \sum_n c_n\phi_n \otimes \Phi_0 = \sum_n c_n\phi_n \otimes \Phi_n$$

In the language of statistical mechanics:

$$W_t = P_{\sum_n c_n\phi_n \otimes \Phi_n} \qquad (1)$$

The quantum measurement postulate requires:

$$\overline{W_t} = \sum_n |c_n|^2 P_{\phi_n \otimes \Phi_n} \qquad (2)$$

which is, strictly speaking, incompatible with the laws of motion.

Expectation value for a joint observation of the observable Q of the object system and the observable R of the measuring apparatus:

$$\langle Q \otimes R \rangle = Tr(WQ \otimes R)$$

If W is given by (1),

$$\langle Q \otimes R \rangle = \sum_{n,n'} c_n c_{n'}^{\;*} (\phi_{n'}, Q\phi_n)(\Phi_{n'}, R\Phi_n) \qquad (3)$$

If W is given by (2),

$$\langle Q \otimes R \rangle = \sum_n |c_n|^2 (\phi_n, Q\phi_n)(\Phi_n, R\Phi_n) \qquad (4)$$

The predictions of (1) and (2) differ by the presence of non diagonal terms (interference terms)

But the non diagonal terms vanish if

$$[Q,O]=0 \text{ or } [R,M]=0 \qquad (5)$$

Indeed, in that case it is possible to choose a common set of eigenstates for Q and O or R and M, so that the first or the second scalar product vanishes for $n \neq n'$. (This is true in particular if Q = I or R = I, i.e. if we perform an observation only on the object system or only on the measuring apparatus.)

The density matrix (2) therefore describes correctly the outcome of the measuring process for a subclass of observations performed on the object system plus apparatus: those that satisfy the condition (5). But not in general. If both

$$[Q,O]\neq 0 \text{ and } [R,M]\neq 0 \qquad (6)$$

the interference terms do not vanish. And they SHOULD NOT! Indeed in this case the observation of Q and R erases all traces of the previous measurement, and I will argue that in that case we should expect the interference terms NOT to vanish.

This result does not depend on the super-simplifications adopted in the above calculation. It holds with degenerate observables, an arbitrary von Neumann chain of systems, the initial state of the apparatus described as an ensemble. For a proof, see the paper quoted in the title (downloadable from http://www.shantena.com/en/physicslectures/quantummeasurement/).

In other words: the density matrix (1) always represents correctly the outcome of a measurement process. It can be replaced by the density matrix (2) for a subclass of observations performed on the object system plus apparatus, those in which information about the outcome of the measurement process is conserved.

It doesn't matter where the information is stored: it can be at the microscopic or macroscopic level. See the following examples.

Practically speaking, in all measurements involving a macroscopic measuring apparatus information about the outcome persists: no further observation erasing all traces of the previous measurement is actually doable. Therefore replacing the density matrix (1) with the density matrix (2) is an acceptable practical prescription.

But: in "measurement-like" processes at an intermediate level between micro and macro it might be possible to erase all traces of the measurement outcome. Then, I propose, the statistics would be correctly described by (1), not by (2).

Quantum beats
T. Hellmuth, H. Walther, A. Zajonc and W. Schleich, *Phys. Rev. A* **35**, 2532 (1987)

type I atoms: energy levels g, a, a'
type II atoms: energy levels g, g', a

illuminated by pulsing laser light, some atoms get excited, then decay
detector accepts one photon per pulse, insensitive to frequency
number of events vs. decay time
quantum beats superposed on exponential decay for type I, not for type II

Quantum eraser
M.O. Scully and K. Druhl, Phys. Rev. A **25**, 2208 (1982), etc.
This version: G. Greenstein and A. Zajonc, *The Quantum Challenge* (Jones and Bartlett Publishers, Boston, 1997)

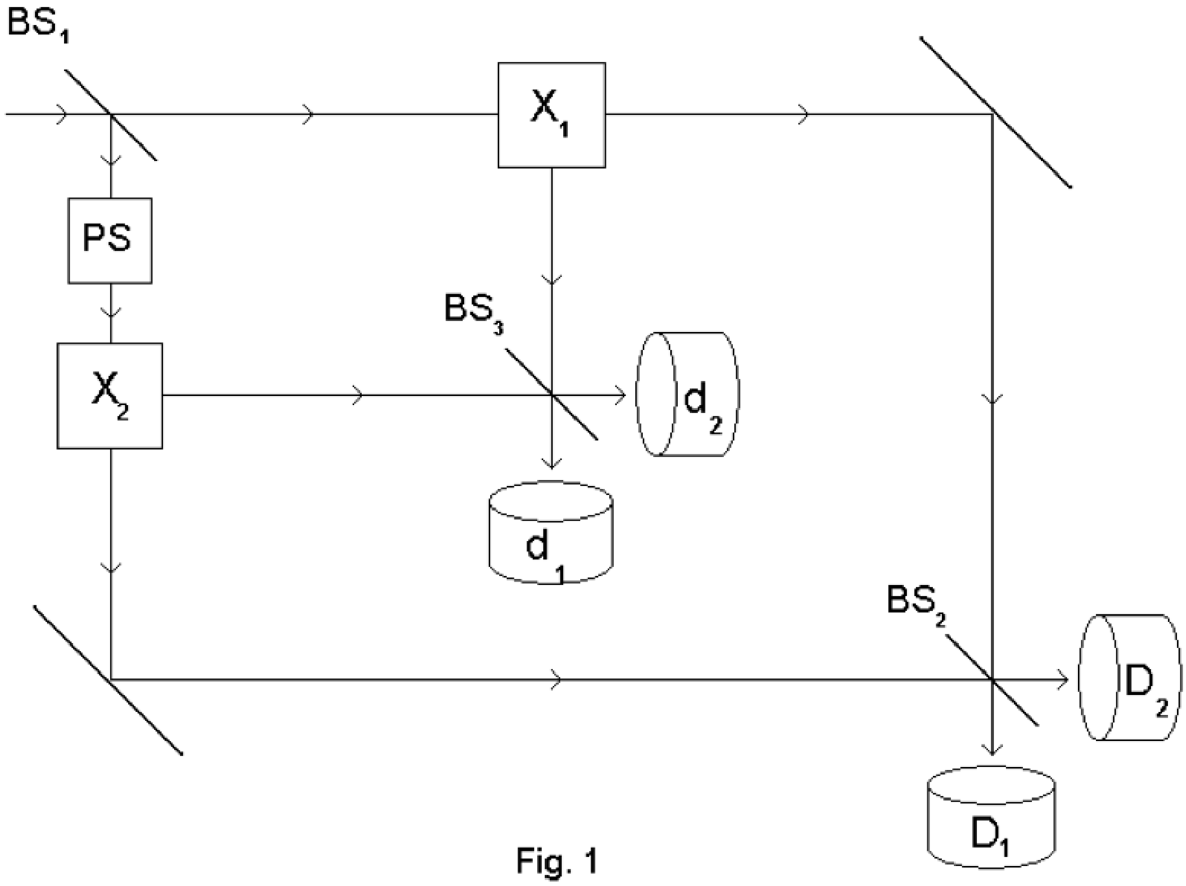

Fig. 1