State Vector Reduction in Quantum Field Theory

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(This talk presents some thoughts intended to get various discussions started.)

The Quantum Measurement Problem

Let S be an arbitrary quantum mechanical system (with states denoted by $|S\rangle$) and let M be another quantum mechanical system (with states denoted by $|M\rangle$) that is taken to be "macroscopic," a "measuring apparatus," or "me." If S and M interact, then quantum theory predicts that, generically, entanglement will occur between S and M, i.e., one will have evolution of the sort

$$|S_0\rangle|M_0\rangle \to c_1|S_1\rangle|M_1\rangle + c_2|S_2\rangle|M_2\rangle$$

(where, for simplicity, I imagine that only 2 such terms appear on the right side, that $|S_1\rangle$ is orthogonal to $|S_2\rangle$ and $|M_1\rangle$ is orthogonal to $|M_2\rangle$).

Although quantum theory predicts my final state to be as given above, I never feel this way! Rather, with probability $|c_1|^2$, I feel that I am in state $|M_1\rangle$ and, with probability $|c_2|^2$, I feel that I am in state $|M_2\rangle$. Why?

Possible explanations:

- Many Worlds: All alternatives do happen. The final state really is $c_1|S_1\rangle|M_1\rangle + c_2|S_2\rangle|M_2\rangle$ and there is a "me" who feels himself to be in state $|M_1\rangle$ and another "me" who feels himself to be in state $|M_2\rangle$. But the "Born rule" then has no meaning, and the fundamental mystery then becomes: Why am I always one of the "me's" that sees results consistent with the Born rule?

- Environmental Decoherence: Have an additional environment system, E, and the final state is really $c_1|S_1\rangle|M_1\rangle|E_1\rangle + c_2|S_2\rangle|M_2\rangle|E_2\rangle$, so that the final state of the original system S, M is described by the density matrix $|c_1|^2|S_1\rangle\langle S_1|\,|M_1\rangle\langle M_1| + |c_2|^2|S_2\rangle\langle S_2|\,|M_2\rangle\langle M_2|$. This explains why it typically is impossible to "re-interfere" the S, M system, and it may help provide "preferred bases" in which to expand the M system, but I don't see how it helps explain why I perceive only one of the alternatives $|M_1\rangle$ and $|M_2\rangle$.
- State Vector Reduction: The quantum state manages to evolve from $c_1|S_1\rangle|M_1\rangle + c_2|S_2\rangle|M_2\rangle$ to either

$|S_1\rangle|M_1\rangle$ (with probability $|c_1|^2$) or $+\ |S_2\rangle|M_2\rangle$ (with probability $|c_1|^2$). A violation of the ordinary quantum laws of evolution of states is needed for this "reduction" of the state vector to occur. Possible causes include (i) the macroscopic nature of M; (ii) the conscious nature of M; (iii) gravitational phenomena. However, unless the reduction is "immediate" and "complete," this doesn't really solve the problem, i.e., one still has to deal with superpositions, probabilities, etc. Without a sharp dividing line, it it hard to see how reduction can be immediate and complete.

What States Does One Reduce to in State Vector Reduction?

If "spontaneous" state vector reduction occurs, what states does one reduce to?

In Schrodinger quantum mechanics of a system of particles, the "positions of the particles" seems a natural choice. For example, in the GRW proposal, a spontaneous "collapse" occurs (very rarely) for each particle to a (nearly) position eigenstate, leading to a rapid collapse to a (nearly) position eigenstate of an entangled macroscopic collection of particles.

Quantum field theory should be closer to the "ultimate truth" than nonrelativistic Schrodinger quantum mechanics. Quantum field theory has the features that

- The observables are local (smeared) fields, $\phi(f), T_{ab}(f^{ab}), \ldots$.
- In all nonsingular states, the fields in highly localized regions fluctuate enormously: $\langle[\phi(f)]^2\rangle \to \infty$ as $f \to \delta$-function.
- In all nonsingular states fields at nearby spacetime points are highly entangled, e.g. $\langle\phi(x)\phi(y)\rangle \sim 1/\sigma(x,y)$ where σ denotes the squared geodesic distance between x and y.

Suppose that a quantum field is in a macroscopic but highly non-classical state. What states will the quantum field reduce to? Some possibilities are:

- States with (nearly) definite field values. But these are singular.
- States with a definite number of particles. But these are highly non-classical for a bosonic field.
- Coherent states. But these are not orthogonal.

So, it is far from clear to me what one would like state vector reduction to do in quantum field theory.