Wave function branching as a spacetime process

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The probabilistic collapse of the wave function,

$$\sum c_n\psi_n \longrightarrow \psi_n \text{ with probability given by } |c_n|^2 ,$$

representing a measurement, for example, is usually regarded as instantaneous. This would be unproblematic for a local state ψ, but for spatially extended systems it may lead to a conflict with the theory of relativity, as it appears to describe superluminal effects. Because of quantum nonlocality (entanglement between distant systems), this situation does even represent the generic case. Even though an instantaneous collapse does not allow one to send superluminal signals, its very definition would either require the choice of absolute simultaneities, or cause other inconveniences for its precise formulation.

This problem therefore forms a major obstacle to dynamical collapse theories, which would have to modify the Schrödinger equation in order to describe von Neumann's process 1 (for which no *direct* evidence has ever been found, but which has nonetheless to be *used* in practice regardless of its interpretation). If a measurement result did (according to the Copenhagen interpretation) instead appear "out of the blue" or "outside the laws of Nature", measurements performed on entangled systems would still require some kind of "spooky influence at a distance". Let me, therefore, emphasize that the usual lame textbook excuse, according to which the wave function is merely a tool to calculate probabilities, is not tenable (although it may be justified in a pragmatic sense – see below): superpositions are well known to describe individually observable ("real") properties, which depend on the complex phases of all their relative coefficients – hence on the wave function. This includes also nonlocal states, such as those defining a total spin or angular momentum of spatially separated particle pairs (general EPR states). Therefore, a collapse would even violate conservation laws if the latter are understood to hold not just statistically (in the mean).

The problem does *not* seem to arise in the Everett interpretation, since this assumes that the Schrödinger equation is universally valid and exact. The latter assumption is also responsible for decoherence, which can be defined as the uncontrollable dislocalization of superpositions – propagating according to the relativistic Schrödinger dynamics. Decoherence explains the formation of autonomous "branches" of the wave function, which have been confirmed to be identical with the phenomenologically used collapse components. However, decoherence does *not explain* a genuine collapse, since all components of the now global superposition would stay in existence according to this unitary description. Therefore, one has to *postulate* that the subjective observer also "splits" into his different branch versions in order to possess definite states of knowledge, and thus to become aware of definite measurement results, for example. This new form of a psycho-physical parallelism is the essential novel element of the Everett interpretation that allows us to avoid a superluminal collapse to become part of the dynamics. A transition of the wave function into one *definite* (though unpredictable) component is nonetheless always *taken into account* in order to describe the dynamics of that wave function which represents "our" quantum universe. It is important, for example, to prepare a definite initial quantum state in the laboratory. Would this transition, when explicitly formulated, then not necessarily lead into the same problems as a collapse?

Let me therefore formulate the complete process of decoherence and observation in spacetime. Although the wave function is nonlocal, that is, defined on a high-dimensional space that appears as a configurations space in a classical picture, quantum field theories are construed on a local Hilbert space basis corresponding to states of classical fields in space. This leads to general states represented by wave functionals $\Psi[F(\mathbf{r}),t]$ over some fundamental spatial fields $F(\mathbf{r})$ on arbitrary simultaneities characterized by a time coordinate t. These states form a tensor product of local states. We can, for example, write any global state in a form such as

$$\Psi = \sum_{njk} c_{njk}\, \Psi_n^{system}\, \Psi_j^{apparatus}\, \Psi_k^{environment} ,$$

for *all* subsystems that are spatially disjunct, and that cover the whole carrier of the wave function. So to which superpositions, in which representation, and when, does the phenomenological collapse apply? If we had started with an initial product state, and thereafter assumed only ideal interactions, we would simply have ended up with a *single* sum in the corresponding measurement basis. In order to analyze the resulting decoherence as a spacetime process, we may now further subdivide the environment into arbitrary spatial subregions. For example, if "near" describes a sphere with radius defined by the distance light could have traveled since the measurement began, and "far" the environment further away, we obtain for the mentioned case of ideal measurements

$$\Psi = (\sum_n c_n\, \Psi_n^{system}\, \Psi_n^{apparatus}\, \Psi_n^{near}\,)\, \Psi^{far} ,$$

where the far-region is not yet entangled with the "system". (In general, there will be additional, here irrelevant entanglement in other variables, too.) The radius of the near-region would thereby steadily grow, while very complex processes may be going on within it. If the branching of the wave function is *defined* by this decoherence process, it does not act instantaneously, but rather like a relativistic three-dimensional zipper. Nonetheless, all components must still exist according to the assumptions, while reasonable collapse models, which eliminate all but one components from the sum over n, would somehow have to reproduce the realistic border line between near and far regions in order to remain undetectable and compatible with the theory of relativity.

There has been much dispute about *when* the (real or apparent) collapse into a definite component occurs – that is, when the measurement has really been completed. We *may asume* that this is the case as soon as the dislocalization of a superposition has become irreversible (in practice – there is no *fundamental* irreversibility in this unitary description). However, we do not *have to* take a collapse into account before we have observed the outcome, or before we have been informed about it. This statement refers, strictly speaking, separately to each subjective observer – not yet even to his "friend" who acts as a mediator to tell him the result. We could *in principle* perform interference experiments with our "friends".

So what would this subjective observation (at the end of the measurement chain) mean in the quantum dynamical description? Clearly, the "near-region" must now include this observer. It would not suffice, though, if some of those uncontrollable (thermal) variables which are mostly relevant for decoherence had propagated beyond his position. It is necessary that some controllable variables, which may carry information in a usable form, have been registered by his senses, and the message transferred to his consciousness – so that the latter has become entangled with the variable n. Only then has the subjective observer split into the various branches caused by this quantum measurement. From an objective point of view (the "bird's perspective"), no branch is ever selected.

However, such a "subjective collapse" is definitely *not* what is usually assumed for the wave function that would describe "our world". The conventional picture identifies the collapse with the irreversible occurrence of decoherence. Thereafter, one assumes that the wave function has collapsed into a definite branch, although we may not yet *know* it. The superposition over n is thereby replaced by an effective esemble describing this incomplete knowledge. Since this replacement is merely a heuristic picture – not a physical process, this apparent collapse might even be assumed to propagate superluminally. The final observation then *seems* to represent a "mere increase of knowledge" – just as in a classical observation. This is the justification for the mentioned conventional textbook description, which is part of the Copenhagen interpretation. Strictly speaking, though, an observer does not enter a specific branch until he becomes entangled with n – as one may see from the last equation above.

– See also www.zeh-hd.de/nonlocality.html and www.zeh-hd.de/SolveMeas.html .