GRAVITATIONAL COLLAPSE OF THE WAVEFUNCTION: AN EXPERIMENTALLY TESTABLE PROPOSAL

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Summary

Arguments are given, suggesting that the enigmatic phenomenon of wavefunction collapse ought to be a *real* physical process, and that pure unitary evolution is therefore an approximation. Two specific reasons are provided to support the case that deviations from unitary evolution arise when gravitational effects begin to be important. Accordingly, wavefunction collapse comes about as a consequence of a *tension* between the principles of quantum mechanics and those of general relativity. A specific proposal for the rate of state reduction is given, and an experiment is suggested for testing this proposal.

1. Wavefunction collapse: a real gravitational effect?

I argue that the enigmatic phenomenon of wavefunction collapse is a *real* physical process, and that pure unitary evolution is therefore an approximation. Let us consider two specific reasons to support the case that deviations from unitary evolution must arise when gravitational effects begin to be important and that wavefunction collapse comes about as a consequence of a *tension* between the principles of quantum mechanics and those of general relativity. In the next section, I outline a specific proposal for the rate of state reduction, and an experiment is suggested for testing this proposal.

The first specific reason for this belief has to do with the evident time-asymmetry in the structure of space–time singularities: the big bang was extraordinarily highly constrained (leading to the existence of the second law of thermodynamics and of its particular nature), whereas the singularities of gravitational collapse are expected to be of a completely unconstrained nature. Since the structure of space–time singularities is supposed to be a consequence of the (still missing) theory of *quantum gravity*, this time-asymmetry in singularity structure suggests that the elusive quantum gravity theory must itself be time-asymmetric. We do not see such asymmetry either in general relativity or in the unitary-evolution part of quantum mechanics. However in the "state-reduction" part, there is a gross time asymmetry in the way in which probabilities are computed. It is accordingly argued that the sought-for theory of quantum gravity is indeed time-asymmetric and gets its time-asymmetry from the fact that it must be a theory in which *state-reduction* is somehow fused with unitary evolution.

For the other specific reason, consider a situation in which there is a lump of material, in one or other of two possible locations, as described by the respective quantum states $|\psi\rangle$ and $|\phi\rangle$. Each of these is to be a stationary state. Suppose that the energy eigenvalue E, for Schrödinger's time-evolution operator $i\hbar\partial/\partial t$, is the same for each state. Next, consider that they are put into linear superposition. According to standard quantum mechanics, each such linear superposition $w|\psi\rangle+z|\phi\rangle$, with complex amplitudes w and z, is just as stationary as are the original two states individually, every such superposition having the same energy eigenvalue E. When we consider the *gravitational field of the lump*, however, we encounter a profound difficulty. First consider a single lump location $|\psi\rangle$. We assume that the lump is large enough that its field can be treated as though it were a classical solution of Einstein's equation. Now, Schrödinger's $i\hbar\partial/\partial t$ must be replaced by $i\hbar \boldsymbol{T}$, where $\boldsymbol{T}$ is an appropriate Killing vector. The problem for a superposition $w|\psi\rangle+z|\phi\rangle$ is that we have a *different* killing vector $\boldsymbol{T}$ for each of the two states $|\psi\rangle$ and $|\phi\rangle$, so we cannot express the stationarity in the ordinary Schrödinger way. The problem is a deep one, because it is Einstein's principle of general covariance that prevents us from even *pointwise identifying* the two space–times associated with $|\psi\rangle$ and $|\phi\rangle$, let alone equating their respective "$\boldsymbol{T}$s".

My procedure for treating this situation is to allow a "cheat" in performing this identification, provided that we take into account the "error" in doing so. This error can be estimated, in a Newtonian limit, as the gravitational self-energy E_G of the *difference* between the mass distributions in the two lump locations, where these distributions are taken as the *expectation values* of the mass distributions in $|\psi\rangle$ and $|\phi\rangle$, respectively. Each of $|\psi\rangle$ and $|\phi\rangle$ is to be a stationary solution of the "Schrödinger–Newton equation", which is the Schrödinger equation with an additional Newtonian potential term whose source is the expectation value of the mass distribution in the state. The energy E_G is regarded as a *fundamental uncertainty* in the energy of the superposition $w|\psi\rangle+z|\phi\rangle$ (where w and z are taken to be of roughly the same size). Consistently with Heisenberg's uncertainty principle, as applied to the time/energy uncertainty of an unstable nucleus, we take the superposition $w|\psi\rangle+z|\phi\rangle$ to be an *unstable state* which will decay either to $|\psi\rangle$ or else to $|\phi\rangle$, in a time scale of about $\hbar/E_G$. (This proposal is close to one put forward by Diósi, but there are some significant differences, which remove a severe energy-conservation problem in Diósi's version, noted by Ghirardi, Grassi, and Rimini.)

2. A proposal for an experimental test

Although gravitational effects are usually thought of as being very tiny, we find that the proposal put forward in the previous section is on a plausible scale, which could account for all observed instances of wavefunction collapse. (For example, Schrödinger's cat, would reduce virtually instantaneously to being either alive or dead, but neutron interferometry and observed quantum superpositions of fullerenes would be unaffected.) In a suggested experiment, a tiny crystal of perhaps 10^{15} or 10^{17} nuclei would be put into a superposition of two slightly different locations, differing by about a nuclear diameter, by hitting it with a beam-split photon (or other coherent quantum projectile). The proposal being considered here suggests a decay time of some 10^{-1} or 10^{-3} seconds, depending on the nature of the crystal, during which time the photon would need to be kept coherent, after which the whole process would be reversed to see whether phase coherence is lost, this being a key implication of the present collection of ideas. In one version of the proposed experiment (FELIX) the whole experiment would be performed in space-orbit, in order that the beam-split photon, which is here an X-ray photon, may be kept coherent by reflecting it between mirrors of perhaps an Earth-diameter separation.

Acknowledgements

The author is grateful to NSF for support under grant PHY 93-96246 and to the Leverhulme foundation for an Emeritus Fellowship.

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