Penrose Decoherence

Kirk T. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544
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1 Problem

R. Penrose [1, 2] has proposed that macroscopic quantum systems that are coherent superpositions of spatially separated states undergo a quantum state reduction associated with the gravitational interaction between its component states. In particular, if system has mass m and two possible states separated by distance d, the interaction energy is $|U| = Gm^2/d$, where G is Newton's gravitational constant. Then, the characteristic time for the reduction of the wave function to one or the other of the two states is,

$$\tau \approx \frac{\hbar}{|U|}\,, \tag{1}$$

according to the theory of Penrose.[1]

Discuss the viability of this hypothesis in view of the experiment of Jaklevi̇c *et al.* [4] on quantum interference effects in a pair of Josephson junction.

2 Solution

In the Josephson effect, the quantum state is that of the Cooper pairs of a superconducting material. Roughly, there is one Cooper pair per atom, so the number density ρ of pairs is about $10^{23}/\mathrm{cm}^3$. We take the effective mass of a pair to be about m_e, the mass of an electron. If the superconducting material of the loop containing the pair of Josephson junctions has volume V, then the number of pairs is $n = \rho V$.

Penrose's time constant (1) can now be written as,

$$\tau = \frac{\hbar d}{G(nm_e)^2} = \frac{\hbar}{m_e c}\frac{c^2}{Gm_e}\frac{d}{cn^2} = \frac{\lambda_e}{R_e}\frac{d}{cn^2}, \tag{2}$$

where d is the diameter of the loop, c is the speed of light, $\lambda_e = \hbar/m_e c = 3.9 \times 10^{-11}$ cm is the Compton wavelength of the electron, and $R_e = Gm_e/c^2 = 6.7 \times 10^{-56}$ cm is the Schwarzschild radius of the electron.

The experiment of Jaklevi̇c *et al.* involved a circuit whose material had an area $wd \approx 10^{-4}$ cm^2 and thickness $t = 1000$ Å$= 10^{-5}$ cm, so its volume was $V = 10^{-9}$ cm^3. The number of Cooper pairs in the circuit was therefore $n \approx 10^{14}$. The diameter of the circuit was $d \approx 0.3$ cm. Penrose's characteristic time for this device is then,

$$\tau \approx \frac{4 \times 10^{-11} \cdot 0.3}{7 \times 10^{-56} \cdot 3 \times 10^{10} \cdot (10^{14})^2} \approx 6 \times 10^5 \text{ s} \approx 1 \text{ week}. \tag{3}$$

[1] A different view on gravity-induced decoherence has been given in [3], where effects of gravitational time dilation are considered.

While this is probably longer than the observation time of the original experiment, commercial superconducting quantum interference devices (SQUIDs) based on the same principle have functional lifetimes longer than one week.

It might be argued that if the Cooper pairs move through the loop too rapidly, Penrose's theory analysis would not apply. The Josephson current in the experiment of Jaklevič *et al.* was 10^{-3} A $= 2ev\rho wt$, where v is the velocity of the pairs, and wt is the area normal to the current. With $\rho = 10^{23}/\mathrm{cm}^3$, $w \approx 3 \times 10^{-4}$ cm, and $t \approx 10^{-5}$ cm, we find that $v \approx 10$ cm/s. The time for a pair to go once around the circuit is about 0.1 s, so there are about 10^7 traversals of the circuit during the time (3). If, somehow, the "decay clock" of the wave function is reset each traversal, then the experiment provides little constraint on Penrose hypothesis.

On the other hand, it appears that the existence of commercial SQUIDs with operating periods greater than one week argues against a simple reading of the hypothesis of Penrose (and of that of [3]).

The possible relevance of the Josephson effect to Penrose's hypothesis was suggested by P.J.E. Peebles.

References

[1] R. Penrose, *On Gravity's Role in Quantum State Reduction*, Gen. Rel. Grav. **28**, 581 (1996), http://kirkmcd.princeton.edu/examples/QM/penrose_grg_28_581_96.pdf

[2] R. Penrose, *Quantum State Reduction as a Gravitational Phenomenon: Theory and Experiment*, seminar at Princeton U. (Apr. 27, 1999).

Abstract: The problem of quantum state-vector reduction is addressed in many different ways by the various schools of thought in quantum mechanics. To support my own particular viewpoint that reduction is an actual objective physical process, I shall point out a fundamental conflict between the basic principles of general relativity and those of quantum mechanics. This leads to the conclusion that a quantum superposition – *i.e.*, a "Schrödinger's cat" – is *unstable* and will decay into one or the other of the two states in quantum superposition in a period of time that can be calculated from the gravitational energies involved. For a real cat, this time would be a tiny fraction of a second, which is why we do not actually see quantum-superposed Schrödinger's cats. But for a small enough object, like a very small crystal, this predicted effect should be measurable. A specific space-based experiment to detect this effect (now being actively investigated) will be described. Some recent theoretical developments will also be presented.

[3] I. Pikovski, M. Zych1, F. Costa1 and C.B̃rukner, *Universal decoherence due to gravitational time dilation*, Nature Phys. **11**, 668 (2015), http://kirkmcd.princeton.edu/examples/QM/pikovski_nphys_11_668_15.pdf

[4] R.C. Jaklevič *et al.*, *Quantum Interference Effects in Josephson Tunneling*, Phys. Rev. Lett. **12**, 159 (1964), http://kirkmcd.princeton.edu/examples/QM/jaklevic_prl_12_159_64.pdf