Universal decoherence due to gravitational time dilation

I. Pikovski, M. Zych, F. Costa, and C. Brukner - Nat. Phys.

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The physics of low-energy quantum systems is usually studied without explicit consideration of the background spacetime. Phenomena inherent to quantum theory in curved spacetime, such as Hawking radiation, are typically assumed to be relevant only for extreme physical conditions: at high energies and in strong gravitational fields. Here we consider low-energy quantum mechanics in the presence of gravitational time dilation and show that the latter leads to the decoherence of quantum superpositions. Time dilation induces a universal coupling between the internal degrees of freedom and the centre of mass of a composite particle. The resulting correlations lead to decoherence in the particle position, even without any external environment. We also show that the weak time dilation on Earth is already sufficient to affect micrometre-scale objects. Gravity can therefore account for the emergence of classicality and this effect could in principle be tested in future matter- wave experiments.

July 14, 2015

Layout

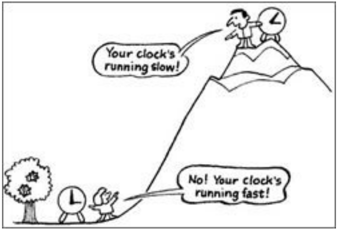
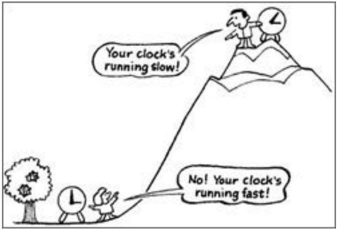


Figure : Gravitational time dilation – High clocks run fast



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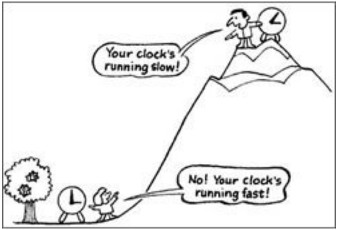

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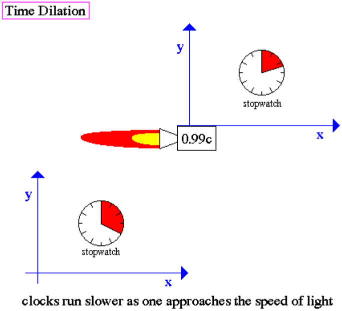
- Gravitational time dilation causes clocks to run slower near a massive object
- We show that even the weak time dilation on Earth is already sufficient to decohere micro-scale quantum systems



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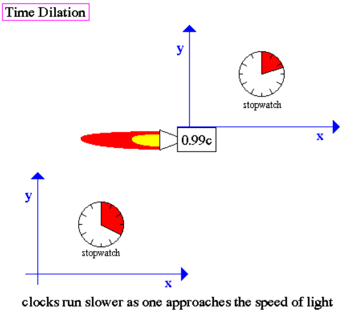

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- Special and general relativistic effects can combine (as noticed by astronauts)

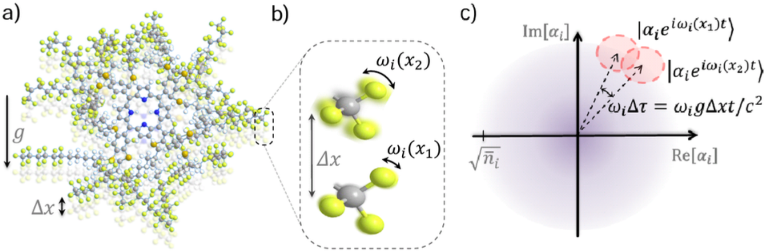

Figure : Gravitational time dilation causes decoherence of composite quantum systems. a, Illustration of a TPPF20 (tetrapentafluorophenyl porphyrin) molecule that has recently been used for matter-wave interference. Here we illustrate a vertical superposition of size Δx in Earth's gravitational potential $\Phi(x) = gx$. b, The frequencies ω_i of internal oscillations are modified in the gravitational field – that is, $\omega_i \to \omega_i(x) = \omega_i(1 + gx/c^2)$ – which correlates the internal states and the centre-of-mass position of the molecule.

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- This is the well-tested gravitational redshift to lowest order in c^{-2} (Hafele, J. C. and Keating, R. E. Around-the-world atomic clocks: Predicted relativistic time gains. Science 177, 166168 (1972), Chou, C. W., Hume, D. B., Rosenband, T. and Wineland, D. J. Optical clocks and relativity. Science 329, 16301633 (2010))

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- In quantum mechanics time dilation causes an additional, purely quantum mechanical effect: entanglement between the internal degrees of freedom and the centre of mass position of the particle resulting in decoherence
- Even though the time dilation on earth is very weak, it leads to a significant effect for composite quantum systems

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- First consider the case when the gravitational contribution to time dilation is dominant such that the velocity contributions can be neglected

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- Thus the total initial state is $\rho(0) = |\psi_{\mathrm{cm}}(0)\rangle\langle\psi_{\mathrm{cm}}(0)| \otimes \Pi_{i=1}^{N} \rho_i$

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Proposed experiments

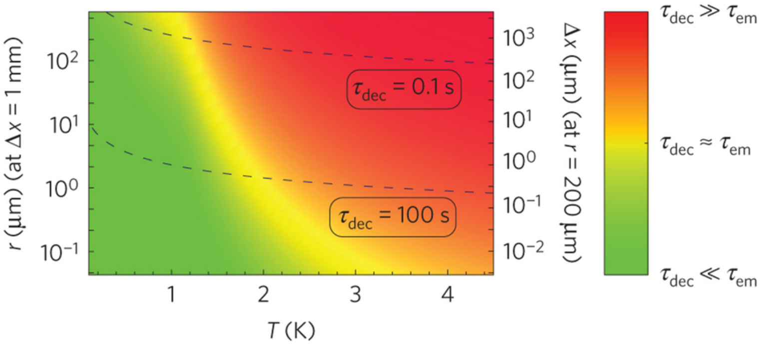

Figure : Decoherence due to gravitational time dilation as compared to decoherence due to emission of thermal radiation for sapphire microspheres. In the green region time dilation is the dominant decoherence mechanism. The left axis shows various sphere radii r (corresponding to particle numbers $N = 10^7$ to $N = 10^{18}$) for a fixed superposition size Δx, whereas the right axis shows various superposition sizes for a fixed particle radius. The dashed lines correspond to the respective time dilation decoherence time scales. Sapphire was chosen for its low emission at microwave frequencies.

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- However, we note that the simple model for the composition of the system, necessary to estimate the time dilation decoherence rate, is very crude and at low temperatures we expect the model to break down

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- Thank you for your attention !!!