Schrödinger 's Cats, remain afraid of gravity!

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Abstract

Standard quantum theory allows for superpositions of macroscopically different states of macroscopic objects. Such states, called Schrödinger's Cats, collapse under standard quantum measurements. Massive Schrödinger Cats are relevant and problematic in quantum gravity, and also remain problematic in the Newtonian non-relativistic limit. The speaker [1] and Penrose [2] have introduced a tiny universal decoherence - proportional to Newton's constant G - to modify the standard unitary qauntum dynamics. Accordingly, any Schrödinger Cat collapses spontaneously, without any measurement. After 30 years, dedicated tests using quantum nanomechanics are under construction or planning in earth- (e.g. [3]) as well as in space-based labs (e.g. [4]), results are expected in the coming years. Indirect tests were already reported (e.g. [5] based on Lisa Pathfinder's data) to constrain the short-length cutoff parameter of the theory. A most recent indirect test in the Gran Sasso underground lab [6], co-authored by the speaker, has led to headlines, raising the question whether collapse of Schrödinger Cats has anything to do with gravity.

[1] Diosi, PLA 120,377 (1987)

[2] Penrose, GRG 28, 581 (1996)

[3] Pontin et al, PRR 2, 023349 (2020)

[4] Kaltenbaek et al, EPJ Quant.Tech. 3:5 (2016)

[5] Helou et al, PRD 95, 084054 (2017)

[6] Donadi et al, Nat.Phys. https://doi.org/10.1038/s41567-020-1008-4 (2020)

Sept 2020

Donadi, Piscicchia, Curceanu, Diósi, Laubenstein, Bassi:
Underground test of gravity-related wave function collapse
Nat.Phys. Sept 7, 2020

- *One of quantum physics' greatest paradoxes may have lost its leading explanation* (Science)
- *Test of wave function collapse suggests gravity is not the answer* (phys.org)
- *The Fate of Schrödinger's Cat Probably Isn't in The Hands of Gravity* (sciencealert.com)
- *Schrödinger's Cat Need Not Worry About Gravity* (The Qubit Report)
- *Physicists place fresh limits on gravity's role in wavefunction collapse* (Physics World)

Massive Schrödinger 's Cats Are Problematic

Superposition of macroscopically different states of a "big" mass M:

$$|Cat\rangle = \frac{1}{\sqrt{2}}|x_1\rangle + \frac{1}{\sqrt{2}}|x_2\rangle$$

Positions x_1, x_2 are "macroscopically" different. Measurement of position $\hat{x}$ —*I look at M*— collapses $|Cat\rangle$ into $|x_1\rangle$ or $|x_1\rangle$ at random. The average state becomes mixed:

$$|Cat\rangle = \frac{1}{\sqrt{2}}|x_1\rangle + \frac{1}{\sqrt{2}}|x_2\rangle \Longrightarrow \frac{1}{2}|x_1\rangle\langle x_1| + \frac{1}{2}|x_2\rangle\langle x_2|$$

- The big M has two distant locations x_1, x_2 *until I look at it*.
- Gravity is sourced from two distant locations *until I look at M*.
- If *I look at M*, centre-of-mass jumps over a distance $|x_1 - x_2|/2$.

Let's Collapse Cats Before They Grow Up

The Concept of spontaneous collapse

- Don't assume: real measurements, real measuring devices, real observers
- Assume: fictitious measurements, hidden measuring devices (and OMG as universal observer, only if you like :)
- Hidden fictitious measuring devices (run by OMG., if you like :)
  - every where x and time t
  - measure mass distribution $\hat{\rho}(x,t)$ at all x and t
  - make measurement effective for large masses only

Prices: tiny irreversibility (decoherence) w.r.t. standard unitary quantum dynamics and tiny energy-momentum non-conservation.

An Ahistoric Approach to DP-Theory — Quantum Cosmology

- Hawking (1983): unitarity of scattering is lost due to space-time fluctuations (instantons) on Planck scale

$$|\Psi\rangle\langle\Psi| \Longrightarrow \hat{\rho} = \$\left(|\Psi\rangle\langle\Psi|\right) \qquad \neq \hat{S}|\Psi\rangle\langle\Psi|\hat{S}^\dagger$$

- Banks-Susskind-Peskin (1984): master equation, violation of energy-momentum conservation:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \int[\hat{\varphi}(x),[\hat{\varphi}(y),\hat{\rho}]]h(x-y)d^3xd^3y$$

- D. (1986): unitarity is lost due to gravitational fluctations much before the Planck scale, nonrelativistically:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{G}{2\hbar}\int[\hat{\varrho}(x),[\hat{\varrho}(y),\rho]]\frac{1}{|x-y|}d^3xd^3y$$

My Approach to DP-Theory — Collapse

Standard Collapse, when Hamiltonian $\hat{H}$ is measured:

$$|\Psi\rangle = \sum_n c_n |E_n\rangle \Longrightarrow \hat{\rho} = \sum_n |c_n|^2 |E_n\rangle\langle E_n|$$

Speculate! Underlying decoherence mechanism is stochastic unsharpness δt of time:

$$|\Psi(t)\rangle = \sum e^{-iE_n(t+\delta t)/\hbar} |E_n\rangle \Longrightarrow \hat{\rho} = \sum_n |c_n|^2 |E_n\rangle\langle E_n|$$

Dynamics? If fluctuation δt is a white-noise, $\langle(\delta t)^2\rangle = \gamma t$, then

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{\gamma}{2\hbar^2}[\hat{H}, [\hat{H}, \hat{\rho}]]$$

My Approach to DP-Theory — Collapse (cont.)

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{\gamma}{2\hbar^2}[\hat{H},[\hat{H},\hat{\rho}]]$$

Assumption of white-noise δt yielded dynamical collapse on $\hat{H}$.
Make this universal! In leading orders of c:

- local time flow: $(1+\Phi(x,t)/c^2)dt$ instead of dt. Choose

$$\langle\delta\Phi(x,t)\delta\Phi(y,\tau)\rangle = \frac{G\hbar}{|x-y|}\delta(t-\tau)$$

- local Hamiltonian density is $\hat{\varrho}(x)c^2$

Put these two together! c cancels! DP Master Equation obtained:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{G}{2\hbar}\int\frac{dxdy}{|x-y|}[\hat{\varrho}(x),[\hat{\varrho}(y),\hat{\rho}]]$$

Assumption of gravity's stochastic unsharpness yielded spontaneous collapse on $\hat{\varrho}(x)$.

Spontaneous Collapse of Massive Cats

$$|Cat\rangle = \frac{1}{\sqrt{2}}|x_1\rangle + \frac{1}{\sqrt{2}}|x_2\rangle \Longrightarrow \frac{1}{2}|x_1\rangle\langle x_1| + \frac{1}{2}|x_2\rangle\langle x_2|$$

This collapse happens spontaneously by DP master equation.
Characteristic time of collapse (D.87, P.96):

$$\tau_{DP} = \frac{\hbar}{U(x_1 - x_2) - U(0)} =: \frac{\hbar}{\Delta E_G}$$

$U(x_1 - x_2)$: gravitational interaction if M were both at x_1 and x_2.
To avoid divergence, DP needs short-length cutoff σ. Lowest value: nuclear size $\sim 10^{-13}$cm (strongest DP-effect). It can be higher!
Distant superpositions:

$$\tau_{DP} = \frac{\hbar}{-U(0)} \sim \begin{cases} 10^{-\mathbf{19}} s & M = 1g & (even\ for\ \sigma \geq 10^{-8} cm) \\ 10^{+\mathbf{16}} s & M = AU & (\sigma = 10^{-12} cm) \end{cases}$$

Massive Cats: death before life; Atomic systems: coherence forever.
NanoCats (e.g. 1μg) can exist even for *ms*'s.

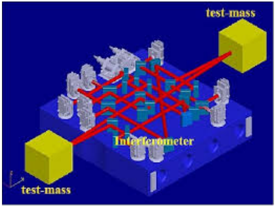
Tests?

- Interferometric tests on nano Cats: quantum controlled cantilevers, trapped probes, levitated dielectrics, etc. Not yet conclusive, results in coming years.
  - Optomechanics, Marshal et al.
  - Levitated dielectric, Ulbricht et al.
  - Electromechanics, Gely & Steele
  - Optomechanics in space, Kaltenbaek et al. MAQRO
- Non-interferometric tests on bulk probes, based on annoying side-effect of DP: noise, tiny vibration of masses.
  - Checking motional noise of large objects, Helou et al (2017)
  - Checking radiation of vibrating elementary charges, Donadi et al (2020), ICON, QUBO
  - Checking heat creation (Vinante & Ulbricht (2021)

Gasbarri, Belenchia, Carlesso, Donadi, Bassi, Kaltenbaek, Paternostro, Ulbricht (2021) *Testing the foundation of quantum physics in space via interferometric and non-interferometric experiments with mesoscopic nanoparticles*

GW People's Test in Space Lab

Helou, Slagmolen, McClelland, Chen: *LISA pathfinder appreciably constrains collapse models*
Phys.Rev. D95, 084054 (2017)



- Preparatory mission to Laser Interferometer Space Antenna
- Detection of relative acceleration between two free falling masses
- Record upper bound $5.2 * 10^{-13} cms^{-2}/\sqrt{Hz}$ on noise

Conclusion: Extreme low noise yields higher bound on cutoff:

$$\sigma \geq 4.0 * 10^{-12} cm$$

Larger than the size of any nucleus.

Our Test in Underground Lab

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Nat.Phys. Sept 7, 2020

- Gran Sasso Lab: under 1500m rock, against cosmic radiation
- Detector: tea cup size pure germanium ($375cm^3$)
- Shields: pure copper and led layers
- Data taking: 62 days
- MC calculated background: 506 photons in range $1.0 - 3.8$keV
- Detected photons: 576

Conclusion: 70 spontaneous photons yield higher bound on cutoff:

$$\sigma \geq 5.4 * 10^{-9} cm \quad (valid\ at\ prob.\ 0.95)$$

Three orders of magnitude larger than previous bounds.
Rules out Penrose's $\sigma = 5.0 * 10^{-10}$, specific for germanium.

Omissions, Summary, Manifesto

Omissions:

- other collapse theories by Károlyházi, Ghirardi, Bassi et al
- works/thoughts of Jánossy, Lukács, Frenkel, Tilloy
- DP-related works in foundations, philosophy, cosmology, ...

Summary:

- DP: simple model of G-related spontaneous wf collapse
- has a single free parameter: short-length cutoff σ
- became, after 30yy, testable only recently.
- Non-interferometric tests have put higher bounds on σ.
- Interferometric tests are under preparation.

Manifesto:

- Gravity's impact on QM is even more likely than DP's validity
- Schrödinger's Cats, do remain afraid of gravity!

I.e.: Standard Quantum Mechanics Will Be Challenged by Gravity.