Probing the Quantum nature of Gravity

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Your passion for (AMO-)physics: What are you curious about?
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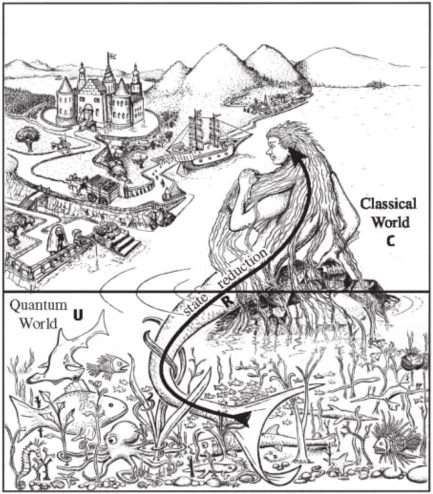
April 27, 2021

What is the discussion about?



[Fashion, Faith, and Fantasy in the New Physics of the Universe; Roger Penrose (2016)][1]

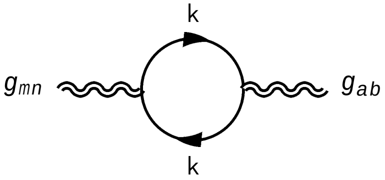
What is the discussion about?

- Gravity in local scales is well tested and well understood
  QT is well tested but not well understood?
- Gravity stands out among other forces
  QT has problems with formalism and/or measurement
- l_P where we realise quantized gravity.
  M_P is massive enough to expect breakdown of QT -behave gravitationally
- Are these problems related?
  Why should we be sure about their influence on each other?
- Lets first see some theoretical motivations and flaws and then look into the few experimental directions to test the above questions.

What is the discussion about?

Quantizing Gravity

- Begin with a notion that 'quantum' is fundamental theory.
- EH action way too simple? $S \quad {}^3x \; ? \; \overline{\quad g}R$
  Pure gravity is renormalizable in 1 loop
  With matter it is not renormalisable. [G.t'Hooft, M.Veltman (1974)][2].
- 1 loop matter correction: No counter terms in the EH action.[J.Donoghue (1997)][3]



- The non-renormaliziblity concerns the UV-behaviour of the theory and **does not lead to any new prediction**.
- We can already see quantum correction for Newton Potential etc in an effective theory.

Quantizing Gravity

Where is the Problem?

- Quantum field theory of Gravity : local field operators.
- Small distances or large momenta : divergences show up in calculations of integrals in momentum space.

We may not make have a theory in the most fundamental level.

But

- Effective Field Theory of Gravity
- Extra dimensions, Emergent Gravity, String Theory
- Lower dimensions: (2+1)D Gravity, (Canonical) Loop Quantum Gravity

Quantizing Gravity

- We shall not dive in detail into various ways we could try to quantize gravity rather treat it as Effective Field Theory
- EFT: Quantum theory of General Relativity at low energy. Any deviation detected then we need to look for UV completion.

If there is a quantum aspect of gravitation then,

- Single Graviton
- Excite an electron in Hydrogen atom. [Rothman, Boughn(2006)] [4]
- Entanglement

Dyson conjectured, detecting a single graviton is not realistic. [Dyson(2013)] [5]

Can we detect a Graviton?

- Sensitivity of LIGO : Detects if more than 3.10^{37} gravitons.

Mirrors of LIGO

- We already use quantum mechanics to detect the gravitons!

- Electron excitation in H-atom by a graviton: Cross-sections
  (graviton - electron) - 10^{65} sq.cm
  (p-p at 7 TeV) - 10^{25} sq.cm
  (Higgs - 10^{38}sq.cm)

Discussion

Fundamental Problems with QM

- Superposition principle breaks down for macroscopic objects.
- QM is a **two step process**: Unitary evolution - State reduction
- QM gives us **probability connections**: 2 step measurements
- Formalism Problems
- Gravity might not be quantized but they might play a role in wave function collapse.

"My own point of view is that as soon as a 'significant' amount of space time curvature is introduced, the rules of quantum linear superposition must fail"
-R. Penrose

Gravitizing Quantum Mechanics

- Semi-Classical : Classical gravity coupled to quantum matter

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4}\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle \Longrightarrow \nabla^2\Phi_N = 4\pi G_N\langle\psi|\hat{\rho}_{\mu\nu}|\psi\rangle$$

- Schrodinger-Newton Equation

$$i\hbar\partial_t|\psi\rangle = (H_M + \underbrace{H_N}_{\text{Gravitational Potential}})|\psi\rangle$$

$$H_N = -G\int_{\vec{r}} \frac{m_1 m_2|\psi_1(t,r)\psi_2(t',r')|}{|\vec{r}' - \vec{r}|}$$

- Non-linear equation: Matter fields $|\psi\rangle$ determine the Newtonian potential and potential determines the evolution of $|\psi\rangle$.
- Stochastic Collapse and Penrose Collapse

Stochastic Collapse

- Gravity is considered as a stochastic **noise** background.
- Replace H_N ÝÑ H_S given by stochastic variable $\Phi \mathrm{p} r, t \mathrm{q}$ which is, independent of $|y\mathrm{y}$. Its statistical correlation function is defined as,

$$\Phi_N \mathrm{p} t_1, r \mathrm{q} \Phi_N \mathrm{p} t_2, r^1 \mathrm{q} \;\; \text{¡} \quad G_N \frac{d \mathrm{p} t_1 \quad t_2 \mathrm{q}}{|\vec{r} \quad \vec{r}^1|}$$

- for a local mass distribution $M \mathrm{p} r \mathrm{q}$, SN equation for stochastic variable $y \mathrm{p} t \mathrm{q}$ is

$$i \mathrm{B}_t y \mathrm{p} t \mathrm{q} \quad H_M \quad \overset{»}{\underset{r}{}} \; \Phi_N \quad M \mathrm{p} r \mathrm{q} \quad y \mathrm{p} t \mathrm{q}$$

Stochastic Collapse: Gravitational Decoherence

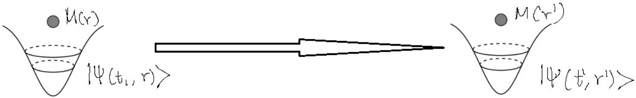
- In terms of density matrix it reads,

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H_M, \rho(t)] - \underbrace{\frac{G}{2\hbar}\int d\vec{r}\, d\vec{r}'\, \frac{[M(\vec{r}),[M(\vec{r}'), \rho(t)]]}{|\vec{r}-\vec{r}'|}}_{\text{Non-Unitary, Off-diagonal Damping Lindbladian}}$$

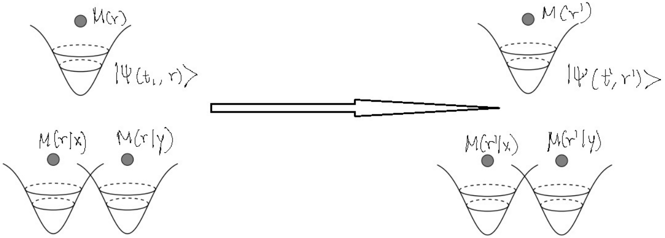
- This is the evolution equation from $(t_1, \rho) \to (t_2, \rho')$ in the noisy background. To know the influence of damping term we will go to coordinates x and y to see the correlations of configurations of $M(r)$.
- **Decoherence time (τ)**: $M(r|x)$ being the corresponding mass distribution at x, we can define,

$$\tau(x,y)^{-1} \equiv \frac{G}{2\hbar}\int d\vec{r}\, d\vec{r}'\, \frac{[M(\vec{r}|x) - M(\vec{r}|y)][M(\vec{r}'|x) - M(\vec{r}'|y)]}{|\vec{r}-\vec{r}'|}$$

Stochastic Collapse: Spatial Superposition



Stochastic Collapse: Superposition



Stochastic Collapse: Gravitational Decoherence

- We had,

$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H_M, \rho(t)] - \Gamma\rho$$

- Decoherence implies decay of the **off-diagonal density matrix elements**.

$$\rho_{xy}(t) = \langle x|\rho|y\rangle = \rho_{xy}(0)e^{-\Gamma t}$$

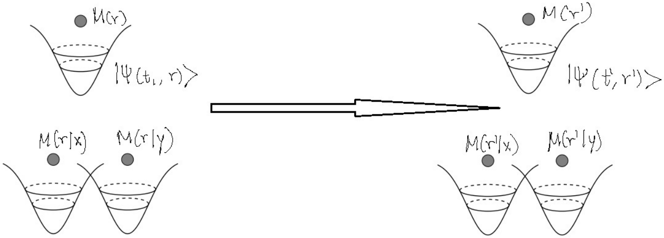
- The integral above will diverge for a point particle.
- $\tau = \Gamma^{-1}$ is the time taken by a wave function of a massive object in spatial superposition to collapse.
- We can define a length scale $R_D = \hbar^2/Gm^3$ from coefficients of SN equation.
- This is a critical parameter within which the system acts like coherent particle and beyond which there is decoherence.
- R_D for a proton would be 10^6!

Stochastic Collapse: Spatial Superposition

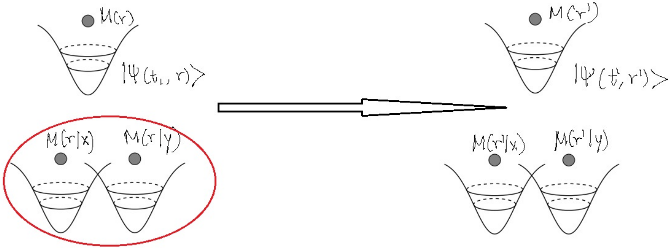
Wait a minute

- Massive object in superposition? Can we really see it?
- Example: We have seen 10^5 Rb atoms (m 10 ^{25}kg) spatial superposition at Δx 0.5m collapse, for 1sec

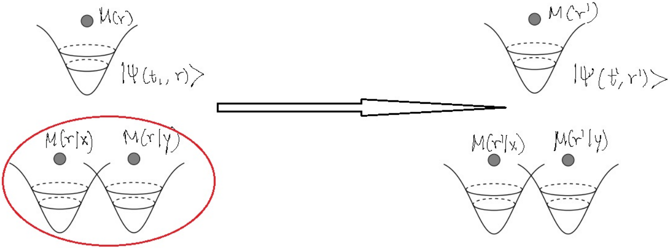
Superposition: Observations

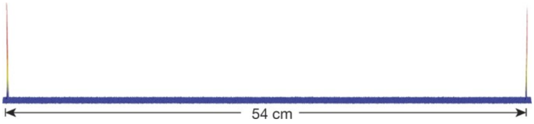


Superposition: Observations



Superposition: Observations

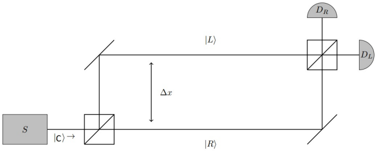


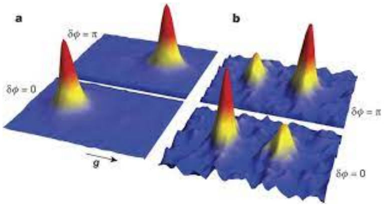


[Kasevich et.al (2015)]

Interference: Observations

|*C*y |*L*y |*R*y





[Kasevich et.al (2015)][6]

Problems

Experimental

- Neutral masses, Low internal temperature: No Casimir only Gravity.
- Cannot distinguish the source of collapse

We may not make predictions in the most fundamental level.

Stochastic Collapse

- Normalisation problems (generic to semi-classical SN)
- Mass distribution dependence: only by varying the mass distribution we get many predictions of the theory.
- The nature of noise or the source is not explained.
- Unrealistic predictions: For simple matter distribution, $t \quad \Gamma^{\ 1} \quad \frac{\hbar R_D}{G_N m^2}$ for Rb atoms, would be 10^9 seconds!

Discussion

Penrose Collapse

- Lets start with stationary states (ignoring gravity), ψ_L, ψ_R with corresponding space-time associated

$$|\Psi\rangle = \alpha_L |\psi_L; g^L_{\mu\nu}\rangle + \alpha_R |\psi_R; g^R_{\mu\nu}\rangle$$

- Stationarity implies associated killing vectors (timelike)
- Schrodinger time-evolution operator $\partial/\partial t$ acting on such a stationary state,

$$i\hbar \frac{\partial}{\partial t} |\Psi\rangle = E |\Psi\rangle$$

- But matter distributions associated with the two states are different, in the presence of a background gravitational field $\psi_L g^L_{\mu\nu} \neq \psi_R g^R_{\mu\nu}$.

Penrose Collapse

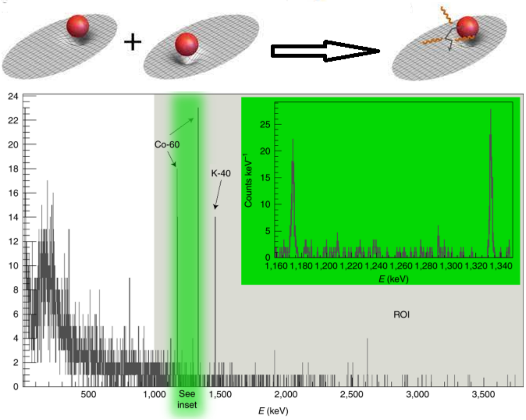
- Assume approximate isometry between g^L_{mn} Ñ g^R_{mn}. That means they are equal upto an error term.
- This corresponds to slight difference in Schrodinger operator ù ñ **uncertainty in Energy**.
- In weak field limit,

$$\Delta E_{LR} \quad 4pG_N \int_{r,r^1} \frac{\Delta M_{LR} \text{p} r \text{q} \Delta M_{LR} \text{p} r^1 \text{q}}{|\vec{r} \quad \vec{r}^1|}$$

- This is the energy uncertainty which is associated with Decoherence/Collapse time $\Delta t_{LR} \quad \frac{\hbar}{\Delta E_{LR}}$

$$t^{\ 1} \quad \text{r} \Delta t_{LR} \text{s}^{\ 1} \quad \Gamma \quad \frac{G_N m^2}{\hbar R_P}$$

Penrose Collapse



[Donadi et.al(2020)] [7]

Penrose Collapse

- Is Brownian-like diffusion an unavoidable consequence of gravity-induced collapse of wave-function of charged massive objects?
- Energy range: $10 \quad 10^5$keV
  Wavelength: $10^{\ 5} \quad 0.1$nm
- 62 days, Germanium Detector (375 c.c), 3100m water equivalent shield.
- R_P
  - Penrose : size of nucleus wave function $0.05 \; 10^{\ 10}$m
  - Experiment bound: ¡ $0.54 \; 10^{\ 10}$m

Discussion

Quantum Gravity mediated Entanglement

Consider 2 masses in two mass interferometers with a spin
Center of mass state of the masses

$|Cy_j \quad |Ly_j \quad |Ry_j \quad ; j$ P t1, 2u

spin-1/2 dof as markers, $|L\{R$y Ñ |Ò { Óy

$|Cy_j \quad |$Ò$y_j \quad |$Óy_j

state at t 0, split them using a magnetic field

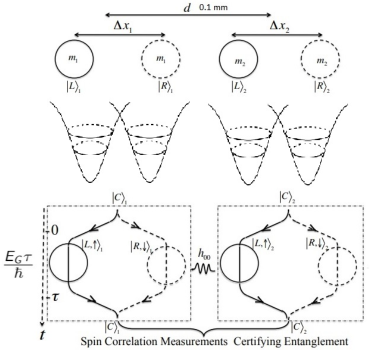
$|y$pt 0qy_{12} $\frac{1}{?\,2}$p|Òy_1 |Óy_1q $\frac{1}{?\,2}$p|Òy_2 |Óy_2q

Hold the superposition till t t, refocus using Unitary transformation

$|y$pt tqy_{12} $\frac{1}{2}$ |Òy_1 p|Òy_2 $e^{i\,f}$ |Óy_2q |Óy_2 p$e^{i\,\bar{f}}$ |Òy_1 |Óy_1q

Not Product States;ENTANGLED STATES

Quantum Gravity mediated Entanglement



- M_P is accessible mass scale.
  Work with mesoscopic test masses 10 14kg
- Send it through beam splitter and then recombine: state evolution from pt 0q ÝÑ pt tq under mutual gravitational interaction
- Entanglement ù ñ impart phases to components of superposition Ñ only from graviton [Bose et.al (2017)][8]

Quantum Gravity mediated Entanglement

- The differential phases $f \quad \frac{Gm^2 t}{\mathrm{p}d \quad \Delta x \mathrm{q}\hbar}$ and $\overline{f} \quad \frac{Gm^2 t}{\mathrm{p}d \quad \Delta x \mathrm{q}\hbar}$.
- $f \quad \overline{f} \quad 2n p$ for $n \quad 0$, the equation is separable - coherence : not entangled
- Other wise we cannot factorise them - decoherence : entangled. $f \quad \overline{f}$ P r0, ps so, the condition to have entanglement is

  $$\boxed{f \quad \overline{f} \quad O\mathrm{p}1\mathrm{q}}$$

- To see it explicitly we can use any tool : Check the Entropy or Just see the violation of Bell inequality.
- If the states turned out to be entangled, **then gravitational field has some quantum behaviour**.

Summary

- Quantizing Gravity: Theoretically quest to treat gravity equally like other fundamental forces. Local tests are **not feasible**, may have cosmological implications.

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- Gravitizing Quantum Theory: Try to solve the wave function **collapse problem**. The **non-linearity** in SN equations pose many problems. Two models:
  1. Stochastic Collapse: Gravitational noise in quantum experiments.
     Significant noise for large mass distribution radius
     Unreal decoherence time
     Theory depends on mass distribution
     No explanation on noise (nature and source)

Summary

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  1. Stochastic Collapse: Gravitational noise in quantum experiments.
  2. Penrose Collapse: The massive particle in spatial superposition curve the spacetime.
     Time evolution of such systems Ñ energy uncertainty Ñ decoherence time.
     Collapse Ñ radiation Ñ test

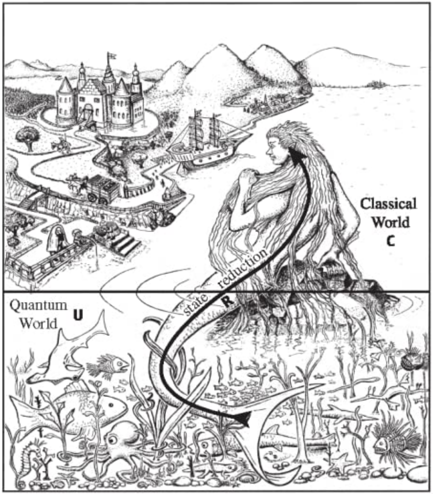
Summary

- Quantizing Gravity: Theoretically quest to treat gravity equally like other fundamental forces. Local tests are **not feasible**, may have cosmological implications.
- Gravitizing Quantum Theory: Try to solve the wave function **collapse problem**. The **non-linearity** in SN equations pose many problems. Two models:
  1. Stochastic Collapse: Gravitational noise in quantum experiments.
  2. Penrose Collapse: The massive particle in spatial superposition curve the spacetime.
  3. Entangled Diamonds: To see if gravity has any quantum nature at all. Does it interact with the quantum world.

What we will see, what we may know?

- First direct detection of quantum nature of gravitational interactions.
- Gravity can be viewed as an effective quantum field theory, may not be UV complete, but perfectly capable of making predictions for tabletop experiments.
- More enthusiasm in Table top experiments - gravitational waves etc!
- Scope for new theoretical models (Emergent gravity etc), study of existing models, theoretical tests.
  Still the problem of 'interpretation' remains.
- Better control of non-gravitational decoherence: helps Quantum Computing etc.

THANK YOU (Discussions)



[Fashion, Faith, and Fantasy in the New Physics of the Universe; Roger Penrose (2016)]

Appendix

The two masses are interacting only through gravity. The overall phase factor should be multiplied for completeness $e^{i j}$

$$j \quad \frac{E_G t}{\hbar} \quad \frac{G_N m^2 t}{d \hbar} \quad 60 \quad \frac{m}{1\text{ng}} \quad \frac{t}{1\text{s}} \quad \frac{1\text{mm}}{d}$$

The condition to see Entanglement is,

$$W \quad | \quad s_x^1 s_z^2 \;\text{¡} \qquad s_y^1 s_z^2 \;\text{¡} \;| \;\text{¥}\; 1$$

Reference

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