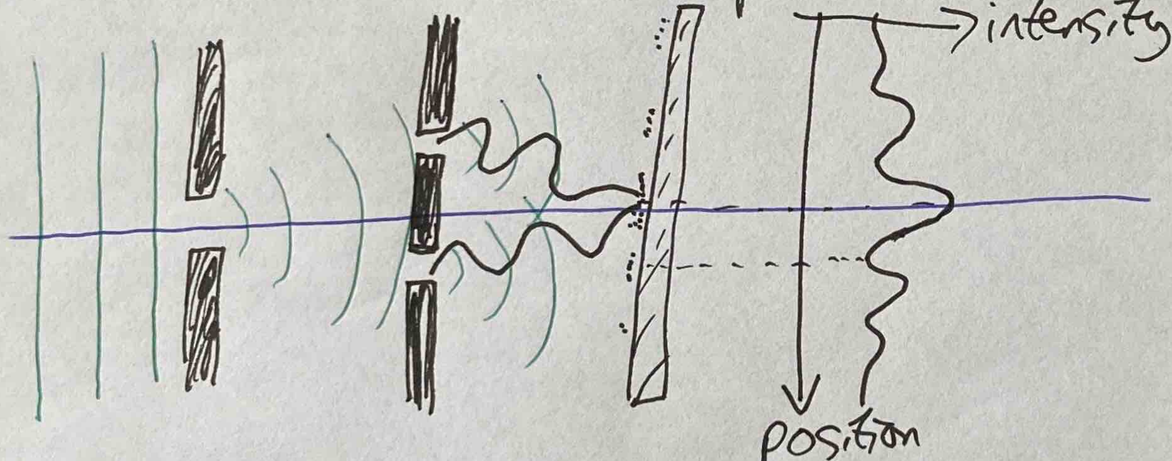
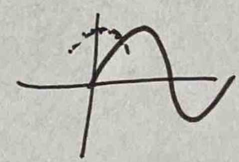
CAN WE TEST THE GRAVITATIONAL EFFECT OF A MASS IN A SUPERPOSITION?

MACROSCOPIC QUANTUM SUPERPOSITIONS TO TEST QUANTUM GRAVITY

QUANTUM MECHANICS

- INTERFEROMETRY
  - Quantum 2-slit experiment





- WAVEFUNCTION

↓

SPATIAL SUPERPOSITION

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

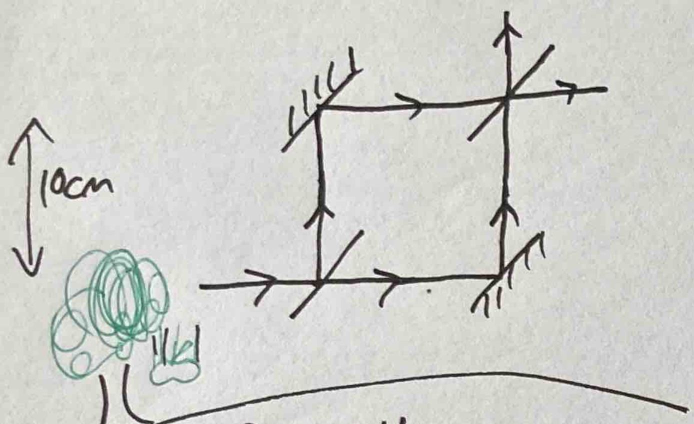
↓

INTERFERENCE

$(p = h/\lambda)$

☆ MOLECULES MADE UP OF 2000 ATOMS [1]

S.E.: $\left[\frac{\hat{p}^2}{2m} + \hat{V}\right]|\psi\rangle = i\hbar\frac{\partial}{\partial t}|\psi\rangle$



EARTH

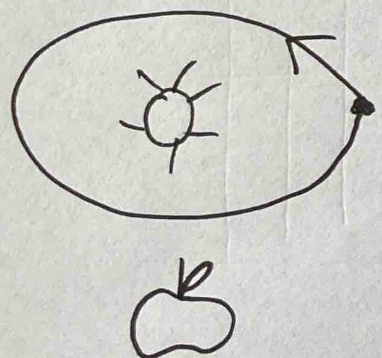
Interferometer

1975

COW [2]

GRAVITY

NEWTON



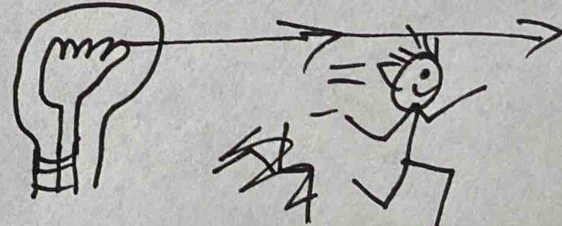
$$F = \frac{GMm}{r^2} \approx mg$$

$$V = \frac{-GMm}{r} \leftarrow \text{GRAVITATIONAL POTENTIAL ENERGY}$$

$$V_{Earth} \approx mgh$$

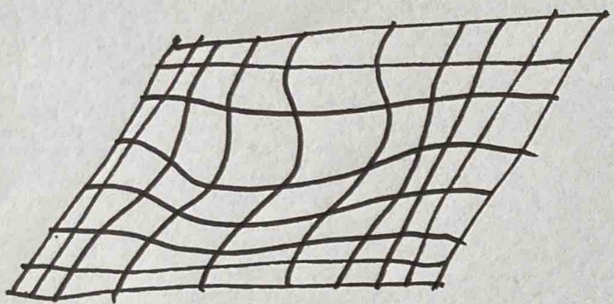
PROBLEMS

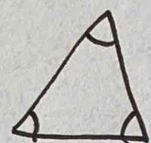
- mediator? ×
- instantaneous? ×



GENERAL RELATIVITY

MASS CURVES SPACETIME



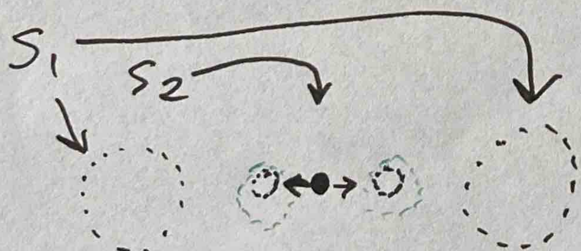


180°? ×

1936
BRONSTEIN
[3, 4, 5]

1957 CHAPEL HILL
FEYNMAN [6]

NANOPARTICLE: $10^8 - 10^{12}$ atoms



$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

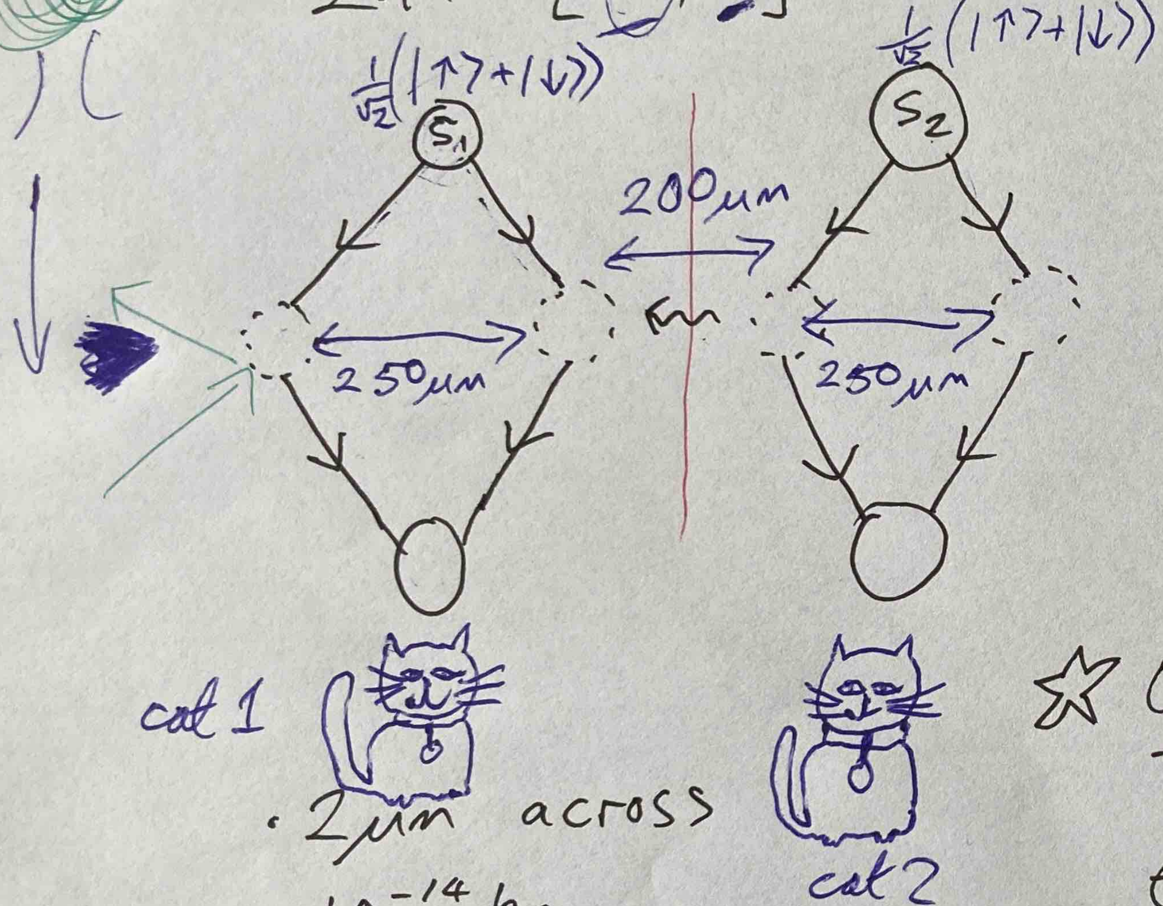
$$|\psi_1\rangle|\psi_2\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)|\psi_2\rangle$$

$$\Downarrow$$

IF WE HAVE QUANTUM GRAVITY: $|\psi_{entangled}\rangle = \frac{1}{\sqrt{2}}\left(|L,L\rangle + |R,R\rangle\right)$

Schrodinger Cats Proposal

2017 [7, 8]



DECOHERENCE

- 2μm across
- 10^{-14} kg
- 10^{12} atoms
- 1s coherence time

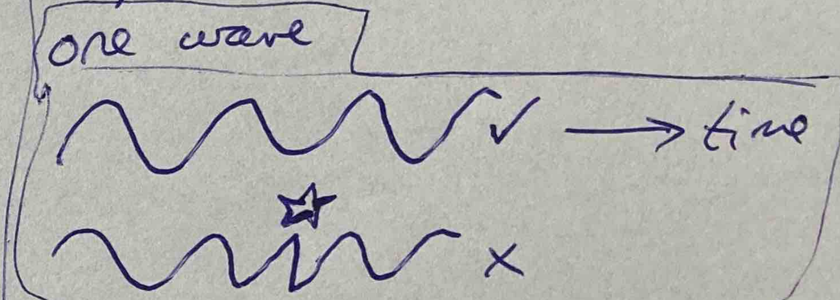
☆ ONLY A QUANTUM THING CAN ENTANGLE THINGS

Lecture 2 Decoherence & Experimental Progress

Decoherence is:
- quantum noise
- entanglement you don't like

[9-12]

Coherence is a fixed relative phase



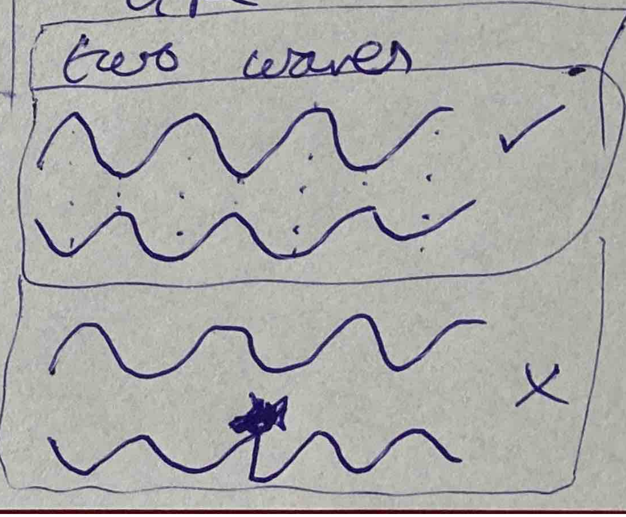
Entanglement

Coin1	Coin2
H	T
T	T
T	T
T	T
H	H
T	H
H	H

Spin1	Spin2
↑	↑
↓	↓
↓	↓
↑	↑
↓	↓
↑	↑

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle\right)$$

Noise is an interaction you dont like



Decoherence for nanoparticles

- potential energy noise
- collisions – gas atoms
  - photons (blackbody radiation – emission, absorption, scattering)
  - collapse models (CSL, DP...)

[13]

☆ ~2 μm particle: if we want ~1 s coherence time

⇒ need ~10^{-16} mbar

need ~5K internal temperature

more details: [14, 15]

Quantum Harmonic Oscillator

$$E = KE + PE$$

$$= \frac{(\Delta p)^2}{2m} + \frac{1}{2} m\omega^2 (\Delta x)^2$$

$$\frac{dE}{d(\Delta x)} = 0$$

+ HUP

$$\Delta x \Delta p = \frac{\hbar}{2}$$

$$\Delta x = \sqrt{\frac{\hbar}{2m\omega}}$$

Zero Point motion

$$E_0 = \frac{\hbar\omega}{2}$$

Ⓑ Feedback cooling of LIGO mirror [19]

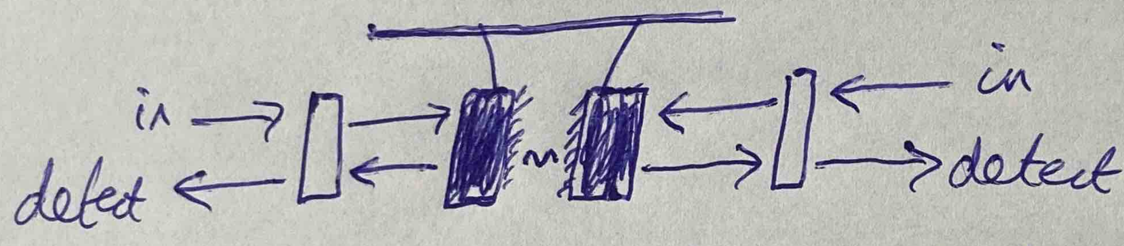
Ⓒ Gravitational interaction between two 90mg masses

Experiments

Ⓐ Ground-state cooling [16–18] of nanoparticles

Lecture 3 — Extensions to the Schrodinger Cats Proposal

- Use aLIGO [21]



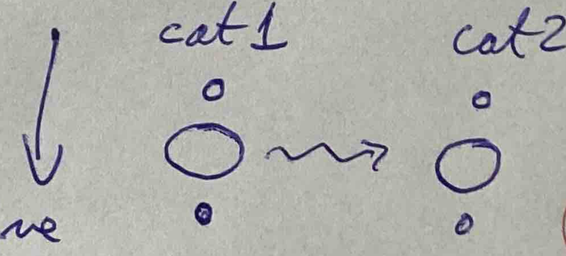
NEEDS: * 2 mirrors back-to-back
* Needs more COM cooling (x1000?) than ref [19]

- Control potential to expand wavefunction [22]
[instead of creating $\frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$]

potential: V → ∩ → U → ∩ → U

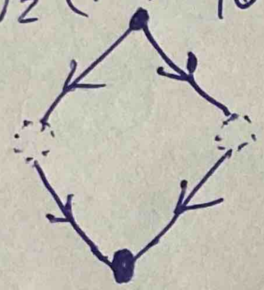
⟶ time

'squeezing'



- Experiments with a closed-loop Stern-Gerlach interferometer with atoms

[23, 24] $\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$



BEC: ~10^7 atoms in one quantum state

$$|\psi\rangle_{cat} = \frac{1}{\sqrt{2}}\left(|\text{all left}\rangle + |\text{all right}\rangle\right)$$

$$|\psi\rangle = \left[\frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)\right]\left[\frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)\right]$$

$$\cdots + \cdots$$

- Motional dynamic decoupling [25]
  ... based on
  spin dynamic decoupling
  ... based on
  spin echo

<u>Summary:</u> Macroscopic superpositions could test the gravitational ~~effect~~ effect of matter.
testing quantum gravity