Fundamental Tests of Quantum Mechanics

Perspectives on Quantum Sensing and Computation for Particle Physics
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The trouble with quantum mechanics

Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing.
Albert Einstein

I’m not as sure as I once was about the future of quantum mechanics.
Steven Weinberg

I believe that one must strongly consider the possibility that quantum mechanics is simply wrong when applied to macroscopic bodies.
Roger Penrose

If you push quantum mechanics hard enough it will break down and something else will take over – something we can’t envisage at the moment.
Anthony J. Leggett
Quantum superpositions

Microscopic superpositions
Experimentally verified

Cats are made of atoms + linearity of the theory

Macroscopic superpositions
Never seen
The Copenhagen interpretation assumes a **mysterious division** between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics […]
A solution: Models of spontaneous wave function collapse

The Schrödinger equation is **modified**. The new dynamics is **nonlinear** in such a way to describe the quantum micro-world, the classical macro-world, as well as the transition from one to the other.

A unique, modified, quantum world

**The dynamics of collapse models**


\[
d|\psi_t\rangle = \left[ -\frac{i}{\hbar} \hat{H} dt + \int d^3x \left( \hat{M}(x) - \langle \hat{M}(x) \rangle_t \right) dW_t(x) \right. \\
\left. -\frac{1}{2} \int \int d^3x d^3y \mathcal{G}(x - y) \left( \hat{M}(x) - \langle \hat{M}(x) \rangle_t \right) \left( \hat{M}(y) - \langle \hat{M}(y) \rangle_t \right) dt \right] |\psi_t\rangle
\]

Quantum mechanics + collapse in space

**Nonlinear**

**Stochastic**

**Collapse operator** ~ position

\[
M(x) = ma^\dagger(x)a(x) \quad \langle M(x) \rangle_t = \langle \psi_t| M(x) |\psi_t \rangle
\]

**CSL model**


**DP model**


\[
\mathbb{E}[dW_t(x)] = 0 \quad \mathbb{E}[dW_t(x) dW_t(y)] = \mathcal{G}(x - y) dt
\]

Noise driving the collapse

\[
\mathcal{G}(x) = \frac{\lambda}{m_0^2} e^{-x^2/4r_C^2}
\]

\[
\mathcal{G}(x) = \frac{G}{\hbar} \frac{1}{|x|}
\]
Collapse dynamics in a nutshell

**Microscopic superposition in space.** Collapse very weak, modulo tiny deviations

**Macroscopic superposition in space.** Collapse very strong. The larger the delocalization in space and the number of particles, the faster the collapse

**Many-body single-particle superpositions in space.** Collapse very weak, modulo tiny deviations

**Superpositions in other d.o.f.** Very weak if they do not imply delocalization in space
Penrose and collapse


... for the superposed state we are considering here we have a serious problem. For we do not now have a specific spacetime, but a superposition of two slightly differing spacetimes. How are we to regard such a ‘superposition of spacetimes’? ... It will be shown that there is a fundamental difficulty with these concepts, and that the notion of time-translation operator is essentially ill defined.

Penrose’s idea: quantum superposition ➔ spacetime superposition ➔ energy uncertainty ➔ decay in time

The DP master equation, previously shown, is the simplest way to implement these ideas into a dynamical model.
How to test collapse models

Interferometric experiments

Create a large superposition, in terms of mass, distance and duration, and perform a "double slit" experiment.

Prediction of quantum mechanics (no environmental noise)

Prediction of collapse models (no environmental noise)

Non interferometric experiments

A collapse of the wave function changes the position of the center of mass → Collapse-induced Brownian motion.

Prediction of quantum mechanics (no environmental noise)

Prediction of collapse models (no environmental noise)
Advantages and disadvantages

Interferometric experiments

These are a direct test of the quantum superposition principle and of collapse models.

They are difficult. The whole field of quantum optomechanics boomed also with the aim of creating macroscopic quantum states.

Non interferometric experiments

They are a direct test of collapse models and an indirect test of the quantum superposition principle.

They are easier because no quantum superposition is needed to test the collapse-induced Brownian motion.
How to test the collapse noise

Quantum Mechanics

A gas will expand (heat up) faster than what predicted by QM

Collapse models

Charged particles will emit radiation, whereas QM predicts no emission

A cantilever’s motion cannot be cooled down below a given limit
The model needs to be **regularized** (particles with finite size), otherwise integrals diverge.

How do we choose the size?

**Penrose**: Solution of the Schrödinger-Newton equation

**Diòsi**: Compton wavelength (original idea, later abandoned)
The photon emission rate - number of emitted photons per unit time and unit frequency $\omega_k$ - to first perturbative order is:

$$\frac{d\Gamma_t}{d\omega_k} = \frac{2}{3\pi^{3/2}\varepsilon_0c^3R_0^3}\frac{Ge^2N^2N_a}{\omega_k}$$

valid for $\lambda \in (10^{-5}\text{–}10^{-1})$ nm, i.e. energies $E \in (10\text{–}10^5)$ keV.

where a sum over all polarizations and direction of propagation of the the emitted photons is taken.

$G =$ gravitation's constant, $e =$ electric constant, $\varepsilon_0 =$ dielectric constant, $c =$ speed of light

$N =$ atomic number, $N_a =$ total number of atoms, $R_0 =$ DP’s free parameter, $\omega_k =$ photon’s frequency
### Schematic representation of the experimental set-up.

The experimental apparatus is based on a coaxial p-type high-purity germanium detector, with the dimensions of 8.0 cm diameter and 8.0 cm length; the active volume is 375 cm$^3$. The detector is shielded by layers of electrolytic copper and pure lead. The inner part of the apparatus consists of the following main elements: 1, germanium crystal; 2, electric contact; 3, plastic insulator; 4, copper cup; 5, copper end-cup; 6, copper block and plate; 7, inner copper shield; 8, lead shield. In order to minimize the radon contamination an air-tight steel casing (not shown) encloses the shield and is continuously flushed with boil-off nitrogen from a liquid nitrogen storage tank.
The analysis


**Comparison between the measured and the simulated background spectra.** The measured emission spectrum is shown in the ROI as a dark-grey histogram. The simulated background distribution is shown in green for comparison. The simulation is based on a Geant4 validated MC characterization of the whole detector. The MC has as input the measured activities of the residual radionuclides for each material present in the experimental set-up.

The simulation accounts for the emission probabilities and the decay schemes, the photon propagation and interactions in the materials of the apparatus and the detection efficiencies.
The results

**Lower bounds on the spatial cutoff $R_0$ of the DP model.**

According to Penrose, $R_0 = 0.05 \times 10^{-10}$ m for the germanium crystal used in the experiment (red circle on the horizontal scale).

Our experiment sets a lower bound on $R_0$ at $0.54 \times 10^{-10}$ m (green bar and arrow).

The figure shows also previous lower bounds in the literature:
- data analysis from gravitational wave detectors*, $R_0 \geq (40.1 \pm 0.5) \times 10^{-15}$ m, red bar and arrow
- Data from neutron stars**, $R_0 \approx 10^{-13}$ m, blue bar and arrow.

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The conclusion


The DP model, which is the simplest way to model dynamically Penrose’s idea of gravity-induced wave function collapse, where the free parameter $R_0$ is chosen according to Penrose’s prescription, is excluded.

Possible ways out:

• Let the parameter $R_0$ completely free. The price to pay is that it is not clear how to give a meaning to it
• Enrich the dynamics = add new parameters. This is possible, as done for other collapse models
• Devise a new theory, which goes beyond quantum theory - the solution invoked by Penrose. This is ambitious work in progress
• Others ...
Tests of the CSL model

Two phenomenological parameters. $\lambda$ measures the strength of the collapse, $r_C$ the space resolution of the collapse. $m_0$ is a reference mass, equal to that of a nucleon.

$$G(x) = \frac{\lambda}{m_0^2} e^{-x^2/4r_C^2}$$

- Theoretical guesses

Lower bound: for such values of the parameters, the collapse is too weak and ineffective at the “macroscopic” level.

Working assumption: a graphene disk with $N = 10^{11}$ amu, delocalized over $d = 10^{-5}$ m, should collapse in $T = 10^{-2}$ s.
To improve interferometric tests, it will likely be necessary to go to micro-gravity environment in outer space → MAQRO
Non - Interferometric Experiments

Cold atom gas

M. Bilardello et al., Physica A 462, 764 (2016)
Non-Interferometric Experiments

+ several more
Non-Interferometric Experiments

Auriga

Ligo

Lisa Pathfinder

Non - Interferometric Experiments

We present a scheme to measure the displacement of a nanomechanical resonator at cryogenic temperatures. The technique is based on the use of a superconducting quantum interference device (SQUID) and microwave cavities. Unlike conventional interferometric techniques, our detection scheme does not involve displacement sensors. Other techniques have been recently demonstrated to be more compatible with ultralow temperatures. In particular, both single electron transistors and microwave cavities have demonstrated outstanding displacement sensitivity. Other techniques have been recently demonstrated to be more compatible with ultralow temperatures. In particular, both single electron transistors and microwave cavities have demonstrated outstanding displacement sensitivity.

We demonstrate its potential by cooling an ultrasoft silicon cantilever to a temperature range from magnetic resonance force microscopy (MRFM) experiments to fundamental physics experiments. The technique is based on the use of a SQUID read-out of a subattonewton force sensor operating at millikelvin temperatures. The superconducting quantum interference device is used to detect the magnetic flux change induced by a magnetized particle attached on the end of the mechanical resonator. Our method involves attaching a ferromagnetic particle to the end of the resonator, which, whenever the resonator moves, causes a change in the magnetic moment. This change results in a flux through the SQUID coil and a current flowing in the detection loop, which is proportional to the magnetic moment of the ferromagnetic sphere. The constant $x$ in this equation is $0.75$ T. The frequency of the resonator is measured by the dc SQUID amplifier via a superconducting flux transformer of total inductance $L$. The motion of the resonator is detected by measuring the current in the coil and a current flowing in the SQUID coil. The SQUID coil has a quality factor of $3.8 \times 10^{10}$ Hz. © 2011 American Institute of Physics.
Non - Interferometric Experiments

Cantilever - Update 2

Radiation – Update 1
K. Piscichia et al., Entropy 19, 319 (2017)

Gravitational Wave detectors – Update 1
M. Carlesso et al., N. Journ. Phys 20, 083022 (2018)
Non - Interferometric Experiments

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www.tequantum.eu
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The Group (www.qmts.it)

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The GRW model

Systems are described by the wave function. This evolves according to the Schrödinger equation, except that at random times (with frequency $\lambda$) they undergo spontaneous collapses:

$$|\psi\rangle \rightarrow \frac{\hat{L}_x^i |\psi\rangle}{||\hat{L}_x^i |\psi\rangle||}$$

$$\hat{L}_x^i = \left( \frac{1}{\pi r_C^2} \right)^{\frac{3}{4}} e^{-\frac{(q_i-x)^2}{2r_C^2}}$$

The probability (density) for a collapse to occur around $x$ is given by $||\hat{L}_x^i |\psi\rangle||^2$

- Collapses are random in space and time
- Two parameters defining the model: $\lambda$ and $r_C$
The jump

Initial wavefunction $|\psi\rangle$

Jump operator $\hat{L}_x^i$

Final wavefunction $\frac{\hat{L}_x^i |\psi\rangle}{\|\hat{L}_x^i |\psi\rangle\|}$

Jump probability $r_C$
Example: “large” superposition

Initial wavefunction $|\psi\rangle$

Jump operator $\hat{L}_x^i$

Final wavefunction $\frac{\hat{L}_x^i|\psi\rangle}{\|\hat{L}_x^i|\psi\rangle\|}$

Jump probability $= 1/2$
Example: “small” superposition

Initial wavefunction $|\psi\rangle$

Jump operator $\hat{L}_x^i$

d $<< r_c$

Final wavefunction $\frac{\hat{L}_x^i |\psi\rangle}{\|\hat{L}_x^i |\psi\rangle\|}$
Amplification mechanism

Initial “2-particle” wavefunction

Rigid object: system left + system right

Jump operator on “particle” 2

Entangled state

\[ \psi_1^L \otimes \psi_2^L + \psi_1^R \otimes \psi_2^R \]

Such jumps are twice as frequent, because each ‘particle contributes to them

Final wavefunction
However

Initial “2-particle” wavefunction

Ideal gas: particles are independent

Jump operator on “particle” 2

Factorized state

The jump on one particle did not affect the state of the other particle!

Final wavefunction