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Classification of macroscopic quantum effects

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ABSTRACT

We review canonical experiments on systems that have pushed the boundary between the quantum and classical worlds towards much larger scales, and discuss their unique features that enable quantum coherence to survive. Because the types of systems differ so widely, we use a case by case approach to identifying the different parameters and criteria that capture their behaviour in a quantum mechanical framework. We find it helpful to categorise systems into three broad classes defined by mass, spatio-temporal coherence, and number of particles. The classes are not mutually exclusive and in fact the properties of some systems fit into several classes. We discuss experiments by turn, starting with interference of massive objects like macromolecules and micro-mechanical resonators, followed by self-interference of single particles in complex molecules, before examining the striking advances made with superconducting qubits. Finally, we propose a theoretical basis for quantifying the macroscopic features of a system to lay the ground for a more systematic comparison of the quantum properties in disparate systems.

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1. Introduction

One of the most fascinating questions in quantum physics is whether large objects, say cats, can show features of the strange quantum behaviour of atoms and particles. When Erwin Schrödinger thought-up his Gedanken experiment in 1935 about a cat in a quantum superposition of states, so that it is dead and alive at the same time, he wanted to highlight the seeming contradictions – not to say the absurdity – of apprehending large objects through the framework of quantum mechanics.

Because Planck's constant is so small, quantum effects become imperceptible as objects grow in mass and complexity. Yet, there is nothing stopping us, in theory, from designing experiments where massive objects behave as if they were atoms in at least one degree of freedom. The boundary where quantum effects stop and classical physics takes over is blurry. Determining where that boundary lies is one of the most fascinating questions in physics and excites ongoing interest [1–8]. The challenge is largely technological, and as we will see, astounding experiments continue to push the quantum limit into the realm of macroscopic objects previously reserved for classical treatment.

It is extremely difficult to isolate massive objects from the environment as they constantly interact by exchanging photons, which leads to heating and therefore decoherence (i.e. the disruption of the constant phase relationship required for quantum states). The

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experimenter's challenge, then, is to find a macroscopic degree of freedom whose energy levels are separated by more than k_BT, where k_B is Boltzmann's constant and T is the temperature. To maintain the separation, the system is usually cooled to cryogenic temperatures that ensure the quantum state survives long enough for a measurement to be made.

We can identify at least two criteria that a macroscopic quantum state should meet: first, the state must be entangled and this entanglement must be verifiable experimentally, and second, it should be *macroscopically distinguishable* [8,12], i.e. it must have macroscopic observables that we can use to discriminate different states that are combined into the overall entangled states. Although a systematic way of comparing the quantum features of disparate systems is currently lacking, we review and make some suggestions as to how this can be tackled in the section “Discussion and conclusions”.

Let us now explore some recent experiments that have pushed the quantum limit to ever larger scales. They cover a wide variety of systems and cannot be easily described within a single framework. This imposes a case by case approach because no two systems can directly be compared when they are quantised in different degrees of freedom and use a wide variety of different macroscopic metrics. This accounts for the current lack of a clear measure of macroscopic quantumness.

2. Massive objects

Here, we explore the quantum properties of macroscopic bodies with a comparatively high fixed centre of mass. We look at interference experiments where macromolecules undergo diffraction at a grating, and then turn our attention to micromechanical resonators approaching the size of a human hair that operate in the quantum regime.

2.1. Molecular interference

Sending molecules one at a time at two slits can produce an interference pattern on a screen positioned beyond the slits. This signature of wave behaviour underpins de Broglie's theory on the joint wave and particle character and propagation of massive objects. Since its inception in 1923, many experiments have successfully recovered the interference pattern due to objects at ever higher masses, starting with electrons, neutrons, atoms, dimers, and nowadays macromolecules. Some of the largest molecules to have been interfered are C_{60} buckminster fullerenes (football-shaped carbon lattices) called buckyballs.

In the experimental set-up [9,10], a hot molecular beam of C_{60} molecules is produced by sublimation from an oven. The beam passes through rotating choppers that select the velocity of the molecules before they undergo collimation. The buckyballs finally impinge on a diffraction grating with 55 nm-wide slits and periodicity 100 nm. Detection of the interference pattern takes place not on a traditional screen, but by ionisation detection: molecules are ionised with a laser and detected in a vacuum chamber mounted on a translational scanning stage. Eventually, an interference pattern builds up showing a characteristic central peak and up to three higher-order peaks on both sides of the central maximum (limited by spectral coherence due to fluctuations in the velocity of the molecules).

The de Broglie wavelength, λ_B, associated with a massive object is $\lambda_B = h/p$, where h is Planck's constant and p is the momentum. In the case of C_{60} under experimental conditions, $\lambda_B(C_{60}) \approx 3pm$, which is more than 300 times smaller than the diameter of the buckyball ($\approx 10^{-9}$ m) [10], and more than 50 times smaller than the slit width. Single molecules enter the grating one at a time (given a low flux) such that two separate molecules can never interfere. That an interference pattern can build-up under these conditions is deeply surprising because we are used to thinking of particles and molecules as point-like objects. In the quantum physical picture, however, they are treated as a wave during time-of-flight – which we can in turn think of as a superposition of position states – becoming point-like again at detection. Another quantum feature is that the position at arrival of individual incident molecules is entirely random and unpredictable.

This raises a fascinating question. Let us imagine that our senses were so sophisticated that we could resolve distances on the Planck scale. Would we then perceive objects, especially macroscopic ones, as behaving quantum mechanically?

Bohr's complementarity principle tells us that knowing which slit a particle enters destroys the interference pattern. During time-of-flight, hot molecules can emit thermal photons from the hundreds of mechanical degrees of freedom in their structure. They can give away potential information about their path and the slit they enter. But, for this to happen, the wavelength of the photons must be short enough to resolve the separation between neighbouring slits. So far, this has not been the case in experiments with C_{60} due to the long wavelength attributed to thermal photons [10]. We cannot exclude the possibility that heavier and more complex molecules could leak useful information, which would kill the contrast in the interference pattern. The question is at what mass does this happen? Efforts are currently underway to interfere large proteins with order magnitude heavier masses than C_{60}, and which require more sophisticated interferometers [11].

So far our only constraint has been that the molecule should not give access to which-path information as it grows in size and complexity. Another constraint is the sophistication of laboratory equipment. Because massive objects have very short de Broglie wavelengths, diffraction gratings must be fabricated to stringent parameters ranging in the tens of nanometres, which poses a significant technical challenge. A historical perspective allows us to be optimistic that advances in interferometry and detection technologies will further extend the quantum limit to larger bodies.

This is a natural point to ask if we can set an objective limit on the size of a body beyond which quantum superpositions collapse into classical mixtures. In 1964, Peres and Rosen [12] took an operational view of the problem by setting an upper bound on the time it takes interference fringes to form when a massive body impinges on two slits. It can easily be shown (using the Fraunhofer limit of diffraction and the de Broglie wavelength of a massive object of momentum mv) that an approximate value of the time, t, that it takes to build up an interference pattern on a screen, is given by

$$t \approx \rho a^4 d/h \tag{1}$$

where ρ is the density of the body, d is the distance between interference fringes, h is Planck's constant, and a is the size of the body (comparable to the separation between two slits). Assuming that $t < 10^{18}$ s (the age of the universe) and $\rho \approx 1$ g cm^{-3} (a universal constant), we can estimate that a_{max} and m_{max} (the maximum size and mass of the body) are: $a_{max} < 1$ cm and $m_{max} < 1$ g. Hence, objects whose mass and size exceeds those bounds cannot show quantum interference in a double slit experiment. Below this bound, and in different contexts, setting the boundary between the quantum and classical pictures may remain subjective and limited by other practical considerations.

2.2. Micromechanical resonators

Remarkable breakthroughs have been made in the field of micro-mechanical resonators [13–15] over the last five years. These devices are currently enabling the study of quantum

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