Physicists propose quantum entanglement for motion of microscopic objects

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Researchers at the California Institute of Technology (Caltech) have proposed a new paradigm that should allow scientists to observe quantum behavior in small mechanical systems.

Their ideas, described in the latest online issue of the Proceedings of the National Academy of Sciences, offer a new means of addressing one of the most fascinating issues in quantum mechanics: the nature of quantum superposition and entanglement in progressively larger and more complex systems.

A quantum superposition is a state in which a particle, such as a photon or atom, exists simultaneously in two locations. Entanglement, which Albert Einstein called "spooky action at a distance," allows particles to share information even if they are physically separated.

A key challenge in observing quantum behavior in a small mechanical system is suppressing interactions between the system and its noisy environment — i.e., the surrounding material supporting the system or any other external contact. The random thermal vibrations of the system's surroundings, for example, can be transferred to the mechanical object and destroy its fragile quantum properties. To address this issue, a number of groups worldwide have begun to use cryogenic setups in which the immediate environment is cooled down to a very low temperature to reduce the magnitude of these random vibrations.

The Caltech team suggests a fundamentally different approach: using the forces imparted by intense beams of light to "levitate" the entire mechanical object, thereby freeing it from external contact and material supports. This approach, the researchers show, can dramatically reduce environmental noise, to the point where diverse manifestations of quantum behavior should be observable even when the environment is at room temperature.

Among the scientists involved in the work are Darrick Chang, a postdoctoral scholar at Caltech's Institute for Quantum Information; Oskar Painter, associate professor of applied physics; and H. Jeff Kimble, Caltech's William L. Valentine Professor and professor of physics.

The idea of using optical forces to trap or levitate small particles is actually well established. It was pioneered by Arthur Ashkin of Bell Laboratories in the 1970s and 1980s, and has since formed the basis for scientific advances such as the development of "optical tweezers" — which are frequently used to control the motion of small biological objects — and the use of lasers to cool atoms and trap them in space. These techniques provide an extremely versatile toolbox for manipulating atoms, and have been employed to demonstrate a variety of quantum phenomena at the atomic level.

In the new work, Chang and his colleagues demonstrate theoretically that similar success can be achieved when an individual atom is replaced by a much more massive — but still nanoscale — mechanical system. A related scheme has been presented simultaneously by a group at the Max Planck Institute of Quantum Optics in Garching, Germany [http://arxiv.org/abs/0909.1469].

The system proposed by the Caltech team consists of a small sphere made out of a highly transparent material such as fused silica. When the sphere comes into contact with a laser beam, optical forces naturally push the sphere toward the point where the intensity of light is greatest, trapping the sphere at that point. The sphere typically spans about 100 nm in diameter, or roughly a thousandth the width of a human hair. Because of its small size, the sphere's remaining interactions with the environment — any that don't involve direct contact with another material, because the sphere is levitating — are sufficiently weak that quantum behavior should easily emerge.

For such behavior to appear, however, the sphere must also be placed inside an optical cavity, which is formed by two mirrors located on either side of the trapped sphere. The light that bounces back and forth between the mirrors both senses the motion of the sphere and is used to manipulate that motion at a quantum-mechanical level.

The researchers describe how this interaction can be used to remove energy from, or cool, the mechanical motion until it reaches its quantum ground state — the lowest energy allowable by quantum mechanics. A fundamental limit to this process is set by the relative strengths of the optical cooling and the rate at which the environment tends to heat (return energy to) the motion, bringing it back to the ambient temperature.

In principle, the motion of the well-isolated sphere can be cooled starting from room temperature down to a final temperature that is ten million times lower; in that super-cooled state, the center of mass of the sphere moves by only the minimum possible amount set by intrinsic quantum fluctuations.

The researchers also propose a scheme to observe a feature known as entanglement, which lies at the heart of quantum mechanics. Two remotely located systems that are quantum entangled share correlations between them that are stronger than classically allowed. In certain circumstances, entanglement can be a very valuable resource; it forms the basis for proposals to realize improved metrology and more powerful (quantum) computers.

The proposed scheme consists of sending a pair of initially entangled beams of light — the production of which was first accomplished by Kimble's group at Caltech in 1992 —into two separate cavities, each containing a levitated sphere. Through a process known as quantum-state transfer, all of the properties of the light —in particular, the entanglement and its associated correlations — can be mapped onto the motion of the two spheres.

While the sizes of these nanomechanical objects are still very far from those we associate with everyday experience, the Caltech researchers believe that their proposal presents an exciting opportunity to realize and control quantum phenomena at unprecedented scales — in this case, for objects containing approximately 10 million atoms.

More information: *PNAS* paper: "Cavity optomechanics using an optically levitated nanosphere"

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