Making Quantum Behavior Observable Using Optical Levitation

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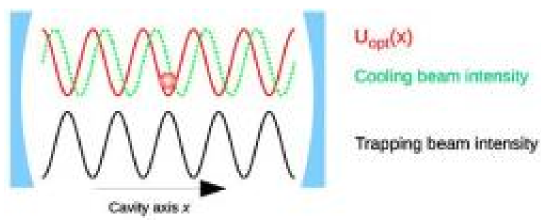

A dielectric sphere trapped in an optical cavity can enable quantum behavior to emerge. The large trapping beam intensity (red) provides an optical potential that traps the sphere near an antinode. A second, weaker cavity mode (green) cools the motion of the sphere. Image credit: D. E. Chang, et al.

(PhysOrg.com) -- Perhaps one of the biggest challenges of modern physics is figuring out how to realize and take advantage of strange quantum behaviors in progressively larger and more complex systems. Progress along this front is expected to shed insight into the nature of quantum mechanics and lead to many novel applications. With this goal in mind, scientists have recently proposed a unique approach that involves optically levitating a nano-mechanical system in order to cool it to its quantum ground state, where the amount of motion of the system reaches the fundamental minimum set by intrinsic quantum fluctuations.

The researchers, Darrick E. Chang, et al., from institutions in the US and Austria, are publishing their study in an upcoming issue of the Proceedings of the National Academy of Sciences. A similar proposal has simultaneously been put forth by researchers at the Max Planck Institute in Garching, Germany.

“Over the next several years, there will be a concerted effort by a number of groups worldwide to observe and manipulate quantum behavior in progressively larger and more complex mechanical systems,” Chang, from the California Institute of Technology, told *PhysOrg.com*. “A major obstacle is the interaction between these systems and their environments, which tends to ‘leak away’ the quantum nature of these systems and return them to classical states. We've proposed a technique that can allow these interactions to be dramatically suppressed, by using optical forces to levitate such systems and remove them from any direct contact with material surroundings. We have shown in detail that this enables quantum behavior to emerge in the case of a levitated nanosphere, but we anticipate that these ideas can also be applied to a wide class of other systems and over a large range of system size scales.”

As the scientists explain, in order to make a system’s quantum behavior observable, the system must be actively cooled to temperatures much colder than the surrounding environment. A key challenge to this cooling is overcoming the tendency of the environment to re-heat the system back to the ambient temperature. One possible solution is to work in cryogenic environments where the ambient temperature itself is reduced, an approach that is being taken by a number of groups worldwide.

“Using cryogenic setups is certainly a viable approach to reduce the effects of the environment,” Chang said. “As one attempts to observe more exotic quantum effects and use larger systems, however, it is likely that moving to cryogenic environments alone will not be sufficient. This motivates the search for other techniques to suppress environmental interactions, which can be applied as an alternative or in conjunction with cryogenics.”

In the new study, Chang and his coauthors have proposed a novel approach in which one isolates the system from the environment to such a degree that re-heating becomes a very inefficient process, even when the environment sits at room temperature. In this scheme, isolation is achieved by optically levitating an entire nano-mechanical system inside an optical cavity, which removes direct contact of the system with any other material. An optical cavity consists of an arrangement of mirrors that confines light inside of it by repeatedly reflecting the light waves off the mirrors. The force from the light is powerful enough to counteract the force of gravity, creating an optical trap that can suspend small, light-weight objects inside the cavity.

The researchers calculated that an optically levitated silica nanosphere can be optically self-cooled to its ground state starting from room temperature. In this scenario, the nanosphere would interact with two optical modes of the cavity. One mode would provide an optical trap for the sphere, while a second, weaker mode would provide a radiation pressure cooling force. The scientists explain that this system is an extreme example of environmental isolation in which the nanosphere is mechanically isolated as well as thermally decoupled from its surroundings. In fact, the isolation is so good that quantum mechanical effects should be able to persist for times much longer than in conventional nano-mechanical systems, even those in cryogenic environments.

While ground-state cooling should also be achievable in the near future with other systems, the scientists believe that the levitated system is an elegant example of how quantum effects can emerge and be robust even at room temperature. For example, the scientists predict that quantum entanglement initially shared between two light modes could be transferred onto the motion of two nanospheres trapped in separate cavities, which could then be observed. Other potential applications include exploring fundamental material limits, investigating nanoscale properties, and realizing novel quantum hybrid architectures.

“There are a number of potential applications for quantum opto-mechanical systems,” Chang said. “One can imagine coupling such systems to other quantum systems to enable tasks such as quantum information transfer or quantum state manipulation. For example, work along these lines has been done by Dan Rugar at IBM, who has pioneered techniques to detect single electron spins in solid-state environments using opto-mechanics. It is also possible that opto-mechanical systems can be used as a novel platform for realizing nonlinear optical processes, by suitable manipulation of the interaction between light and mechanical motion.”

More information: D. E. Chang, et al. “Cavity opto-mechanics using an optically levitated nanosphere.” *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.0912969107