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Physicists demonstrate controlled expansion of quantum wavepacket in a levitated nanoparticle

Quantum mechanical effects, such as wave-particle duality, typically manifest themselves at the scale of photons, electrons and atoms. However, scientists are seeking ways to extend these counterintuitive phenomena to bigger systems, such as large molecules, nanoparticles and, ultimately, macroscopic objects. In a Physical Review Letters article, researchers at ETH Zurich and ICFO have now proposed and implemented a technique to increase the distance over which the wave-like behavior of an optically levitated nanoparticle remains well-defined. This marks a step forward in bringing truly macroscopic objects to the quantum regime.

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Quantum mechanics theory predicts that, in addition to exhibiting particle-like behavior, particles of all sizes can also have wave-like properties. These properties can be represented using the wave function, a mathematical description of quantum systems that delineates a particle's movements and the probability that it is in a specific position.

While physicists have been able to prepare the wave functions of many small particles, preparing those of larger particles has so far proved challenging. This is mainly because the wave-like behavior of larger particles is more prone to being destroyed by unwanted interactions than their classical particle-like behavior.

Researchers at ETH Zurich and ICFO, **Dr. Andreu Riera-Campeny** and **ICREA Prof. at ICFO Oriol Romero-Isart**, recently introduced a new method that could help to delineate the wave function of larger particles. Their proposed approach, outlined in a paper published in Physical Review Letters, leverages a technique known as quantum squeezing to increase the coherence length, which is the distance over which the wave-like behavior of an optically levitated nanoparticle remains well-defined.

"One of the most beautiful demonstrations of quantum physics is matter-wave interference," Massimiliano Rossi, first author of the paper, told Phys.org. "It shows that massive objects, which we normally expect to behave like particles, can also behave like waves-like ripples on the water. In theory, this wave-like behavior applies not only to atoms but also to much larger and more 'ordinary' objects.

"Nanoparticles are a perfect example: they're everywhere in nature, similar in size to viruses, and we think of them as tiny bits of dust. But if you take a single nanoparticle, isolate it extremely well from its surroundings, and control its motion, quantum mechanics predicts it should also show interference."

Rossi and his colleagues, along with other physicists focusing on the optomechanical levitation of particles, have been trying to realize this idea experimentally for years. So far, however, the observation of interference in individual nanoparticles has proved difficult to achieve.

"A key milestone achieved a few years ago was cooling a nanoparticle to its quantum ground state, which means placing it in a well-defined wavepacket of motion," said Rossi. "The problem is that this wavepacket is very narrow-only a few picometers wide. To observe interference, you would need a diffraction grating of that same tiny scale, which is hard, i not impossible, to build. That led to the idea behind this work: instead of making a smalle grating, why not make the wavepacket larger?

How to make a nanoparticle's wavepacket larger

The primary objective of the team's recent study was to try to increase a nanoparticle's quantum wavepacket of motion. If they could sufficiently expand this wavepacket, they might be able to open the door for interference experiments with optically levitated nanoparticles.

"The basic principle is simple and comes straight from textbooks," explained Rossi. "In a harmonic potential, like that of an optical tweezer, a Gaussian wavepacket stays tightly confined (around 10 pm in our case). But if you suddenly remove the potential, there is delocalization: the wavepacket spreads out over time, increasing its 'size'. Of course, in practice we can't just switch off the trap, because then the nanoparticle would simply fall."

To overcome this challenge, Rossi and his colleagues temporarily made the optical trap they were using weaker. When they did this, they found that the particle's wavepacket initially expanded, but was then recompressed by the trap, returning to its original size.

"The trick is to switch back to the tight trap before that happens," said Rossi. "This way, the wavepacket retains its expanded size, giving us a larger delocalization. With this method, we managed to increase the nanoparticle's delocalization to 70 pm-more than double the coherence length of the ground state. In absolute terms, this is still small for diffraction experiments, but it proves that the idea works."

Using their newly devised method, the researchers were able to reach beyond the narrow ground-state limit reported in earlier experiments and actively enlarge a nanoparticle's quantum wavepacket in a controlled way. In principle, their approach could also be scaled up, which could ultimately enable interference experiments with massive objects.

"If we repeat the process with multiple pulses, the delocalization can grow exponentially-assuming that decoherence is kept low," said Rossi. "That makes it realistic to one day reach coherence lengths comparable to the nanoparticle's own size. Achieving that would be a major step toward matter-wave interference with massive objects."

The recent work by Rossi and his colleagues could soon inspire other physicists to devise similar approaches to realize the quantum delocalization of levitated particles. As part of their next studies, the researchers hope to devise effective strategies to suppress decoherence in the optical system they used.

"Right now, the main source of decoherence comes from photons scattered by the optical tweezer," added Rossi. "To overcome this, in our group we are developing a hybrid approach to levitation: we'll combine the optical tweezer with an electrical quadrupole trap, similar to those used for ions.

"Such traps can provide confinement with extremely low decoherence rates-much lower than what's possible with optical tweezers alone. This will allow us to push the delocalization even further, ultimately aiming for quantum interference with truly macroscopic objects."

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Reference:

M. Rossi et al, Quantum Delocalization of a Levitated Nanoparticle, Physical Review Letters (2025). DOI: 10.1103/2yzc-fsm3.