# Quantum Ground State of Rotation: for the First Time in Two Dimensions

Researchers cool a levitated silica nanorotor to its librational quantum ground state in two rotational degrees of freedom simultaneously, reaching the fundamental limit set by quantum uncertainty.

**Quantum mechanics tells us that a particle can never be perfectly still. But how precisely can it be oriented? A research team at the University of Vienna, together with colleagues at TU Wien and Ulm University, has now cooled the rotational motion of a levitated silica nanorotor all the way to its quantum ground state - in two orientational degrees of freedom. Reporting in Nature Physics, they show how optical cooling confines the nanoparticle's orientation to within the bounds of quantum zero-point fluctuations, the unavoidable orientational uncertainty imposed by Heisenberg's uncertainty principle. Such quantum-limited alignment is an important milestone towards rotational matter-wave interferometry and ultra-sensitive quantum torque sensing.**

## Rotation at the quantum limit

In our everyday world small particles are always jiggling and rotating with thermal energy, and temperature is a measure of this motion. While classical physics suggests that it should be possible to cool particles to a stand still and perfect orientation, quantum mechanics predicts that every particle will always maintain some finite energy and always be inherently somewhat disoriented, even when it is trapped at the absolute zero temperature.

When silica nanoparticles are trapped by focused laser light in ultra-high vacuum, they are almost perfectly isolated harmonic oscillators, swinging back and forth both in their center of mass and in their angular motion, simultaneously realizing a perfect linear and torsional pendulum.

When cooled to less than one ten-thousandth of a degree Celsius above absolute zero their energy can no longer be changed continuously, but rather in discrete, quantized energy steps, which are fundamentally limited at the bottom by the quantum ground state – a finite energy they maintain even at absolute zero temperature. Cooling to the quantum ground state has already been achieved for levitated nanoparticles before, for instance by the team around Uroš Delić and Markus Aspelmeyer at the University of Vienna (Science 2020). Cooling the rotational motion has proven more challenging and has so far only been achieved in one dimension by the team around Lukas Novotny at the ETH Zürich (Nat. Phys. 2025).

In the new experiments, led by Markus Arndt (University of Vienna), Uroš Delić (TU Wien) and Benjamin Stickler (Ulm University), a nano-dumbbell rotor, composed of two 150 nm diameter silica spheres, is trapped and oriented by the laser's electric field like by an invisible spring. Initially, the trapped glass rotor still exhibits thermal angular oscillations, known as libration. Optical cooling reduces its temperature to a few ten microkelvin above absolute zero, where energy quantization becomes relevant and the particle is cooled to the lowest of these energies, the quantum ground state. Doing this in two axes, the new study is the first to achieve quantum limited alignment of the rotor's orientation, where its direction remains fundamentally uncertain with about 20 µrad.

"The tip of the rotor then moves less than one hundredth of the diameter of a single atom," says Stephan Troyer, lead author of the study. "This is like a compass needle oriented to better than the width of a bacterium".

## A new window into the quantum world

The ability to control rotation with this accuracy is more than a laboratory record; it is a prerequisite for a new generation of quantum technologies. While most quantum experiments today use single atoms, ions or molecules, these silica nanorotors are massive, consisting of about 100 million atoms and they are still quantum limited.

Rotating particles shall offer new insights and capabilities in future versions of the experiment: After each turn, a rotor ends up in the same orientation. This can give rise to quantum effects that have no analogue in linear motion: when the trapping light is switched off, the nanorotor can rotate in all directions at once, in a quantum superposition of orientation. If the particle evolves undisturbed, its initial alignment will first lose its definition entirely before reviving after a well-defined time, in a new form of rotational matter-wave interferometry. This revival time becomes accessible when the object size is scaled down, to the scale of a tobacco mosaic virus, about 100 times lighter than demonstrated in this work.

“The beauty of our 2D cooling method is that it works across scales,” says Stephan Troyer. “Cooling is easier for larger bodies but applying our techniques to smaller structures we hope to be able to observe this rotational quantum interference. This is an interesting system for probing the interface between quantum physics and phenomena of our daily lives.”

The technology also pushes the field of quantum enhanced torque sensing: a cold nanorotor is an extremely sensitive detector for tiny torques, the rotational equivalent of tiny forces.

## How it works: intense light can cool the motion

To reach these extremely low temperatures, the researchers use coherent scattering cooling. The nanoparticles are trapped in a staggering light intensity of 100 MW/cm$^2$ and scatter this light into an optical resonator. In this process a single scattered photon can carry away a single quantum of mechanical energy from the particle’s rotation into the optical resonator field, thus cooling the rotor.

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**The experiment is embedded into the**

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**Summary:**

- **Achievement:** For the first time, researchers have cooled two rotational axes of a trapped nanoparticle to its quantum ground state.
- **Precision:** The particle's alignment was cooled to 20 μK and to an orientation of 20 μrad**,** close to the fundamental limits of quantum mechanics.
- **Future:** This platform is the basis for future rotational matter-wave interferometry and for testing quantum physics at the interface to classical phenomena.
- **Applications:** the systems are promising for quantum assisted torque sensing, with applications in inertial navigation and materials research.

**About the University of Vienna:**

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**SEO keywords:**

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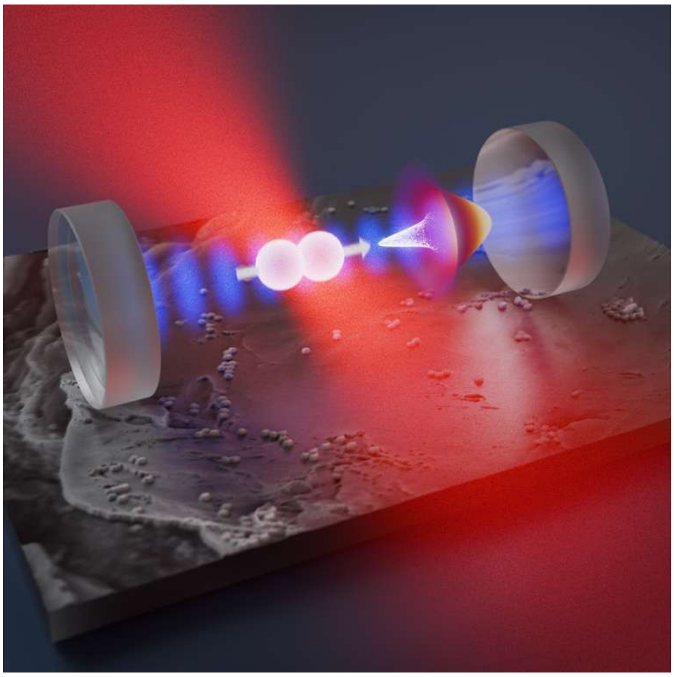

**Quantum-controlled nanorotor**

A silica nanorotor is trapped by an optical tweezer (red) inside an optical resonator (blue) formed by two opposing mirrors. Cooled close to its two-dimensional quantum ground state of trapped rotation, the rotor alignment in the trapping potential approaches its quantum uncertainty limit (white cone).

(Image rights: University of Vienna/Stephan Troyer)