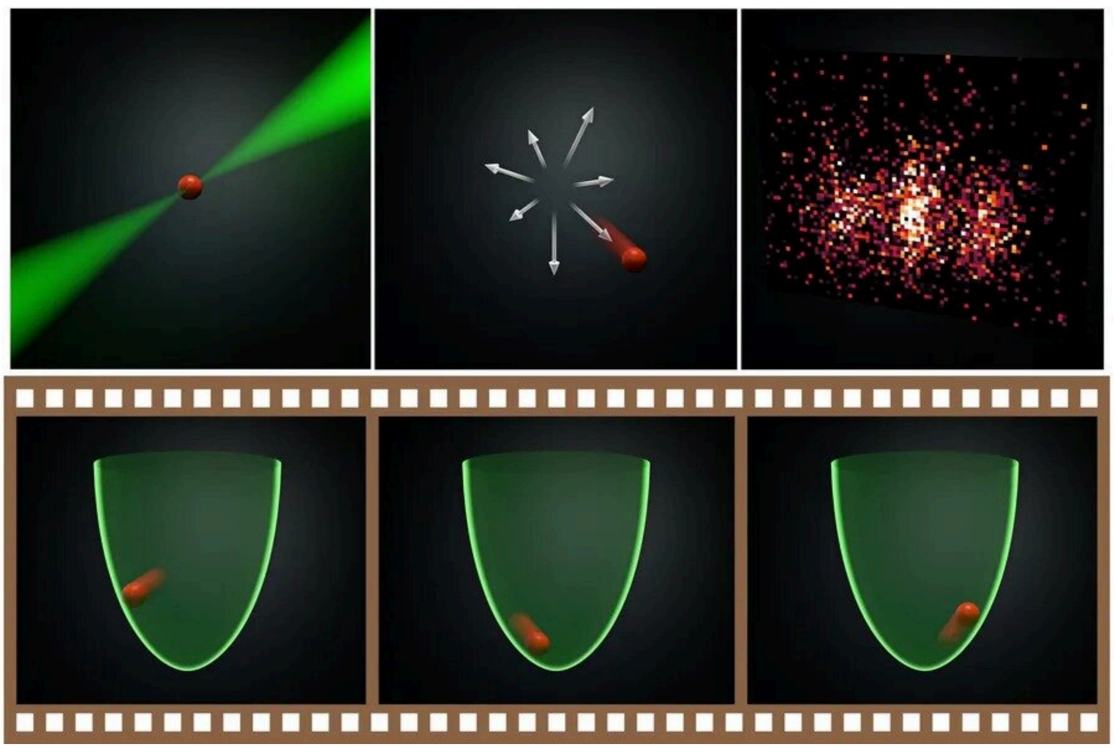
# A quantum video reel: Time-of-flight quantum tomography of an atom in an optical tweezer

January 24 2023, by Kenna Castleberry



Using all of images from the video reel, the team could then estimate the quantum states of the atom. Credit: University of Innsbruck

When it comes to creating ever more intriguing quantum systems, a constant need is finding new ways to observe them in a wide range of physical scenarios. JILA Fellow Cindy Regal and JILA and NIST Fellow Ana Maria Rey have teamed up with Oriol Romero-Isart from the University of Innsbruck and IQOQI to show that a trapped particle in the form of an atom readily reveals its full quantum state with quite simple ingredients, opening up opportunities for studies of the quantum state of ever larger particles.

In the quantum realm an atom does not behave as a point particle; instead it behaves more as a wave. Its properties (e.g., its position and velocity) are described in terms of what is referred to as the wavefunction of the atom. One way to learn about the wavefunction of a particle is to let the atom fly and then capture its location with a camera.

And with the right tricks, pictures can be taken of the particle's quantum state from many vantage points, resulting in what is known as quantum tomography ("tomo" being Greek for slice or section, and "graphy" meaning describing or recording). In the work published in *Nature Physics*, the authors used a rubidium atom placed carefully in a specific state of its motion in a tightly focused laser beam, known as an optical tweezer. And they were able to observe it from many vantage points by letting it evolve in the optical tweezer in time. Like a ball rolling in a bowl, at different times the velocity and location of the particle interchange, and by snapping pictures at the right time during a video reel of the ball, many vantages of the particle's state can be revealed.

The researchers used multiple time-of-flight camera pictures as a tomography tool and reconstructed the quantum state of their trapped atom without any other aids. The quantum tomography revealed features one would not find for an atom in a classical state, but that required instead a genuine quantum description for understanding the combined measured patterns.

## Flying particles

Atoms that are trapped and behaving quantum mechanically are nothing new to JILA, and time-of-flight is a way in which experimenters often learn about the momentum spread of a collection of atoms.

One reason the researchers started thinking about this experiment with a single atom was actually a result of protocols proposed for large trapped particles, where many atoms in a solid are stuck together, moving as one. "Nanoparticles are solid objects containing billions of atoms and can be used to test quantum mechanics at large scales," Oriol Romero-Isart explained. "Some of the ideas and protocols we have theoretically devised in this context can be tested with single atoms, using the exquisite control that the team of Cindy Regal has with single atoms in their lab."

Romero-Isart proposed in a 2011 paper that time of flight combined with letting a single particle roll coherently in a trap could result in full quantum tomography. And, in contrast to many techniques that are often used for quantum tomography, it would be applicable to any particle, as long as it could be seen on a camera.

"Quantum tomography has been accomplished in many different ways for a variety of particles and systems," explained Regal. The technique used by the researchers, however, is intriguingly simple because you just wait for the right time during the video reel, and let the atom fly.

"Quantum tomography is a protocol that aims to determine the full quantum state of a system," explained JILA and NIST Fellow Ana Maria Rey. As Romero-Isart, added: "Since in quantum mechanics a single measurement perturbs the state of the system, quantum tomography requires the ability to repeat the experiment under identical conditions."

Regal, Rey, and Romero-Isart set out to see if an optical tweezer trap was a controlled enough platform to see a provable quantum behavior for a single particle, the single particle being an atom for these experiments, using Romero-Isart's proposed video reel technique

## Operating the camera

Using the optical tweezers, Cindy Regal and her team were able to record the atom's time of flight after releasing the atom from the trap. "For this experiment, we looked at rubidium atoms," Regal added. "What we do is create many single identical atoms, around 60,000 times, each time creating the atom nominally in the same state." In repeating this over and over, the researchers could create a type of image that reveals the velocity, or momentum, of the atom at the time when it was released from the trap.

"Imagine, for example, a particle that has very low momentum," Rey posited, "If we release it, then the particle will barely move and we will find it very close to its initial position after time evolution. On the other hand, a very energetic particle will move very fast after we release it from the trap, and we will find it very far away. So, the map of the positions of the particles after a long time of evolution allows us to determine the momentum at the time of release."

The camera used to take these images was different from what Regal used in the past to help create these informative images. "Because we had to take images of the atoms quickly during their flight, it is important to capture as many photons from the atom as possible and optimize the camera for low noise," said Regal.

A new video reel is then taken by repeating the experiment sequence again, but capturing the system at a different point in time in the optical tweezer video reel.

## Imaging quantum states

Using all of images from the video reel, the team could then estimate the quantum states of the atom. "One key contribution of the theory was to be able to reconstruct what is called the Wigner function of the state (which connects the wave function of a quantum state to a probability distribution in position-momentum space) from experimental measurements," explained Rey.

"One key outcome of the work was to prepare the atom in a state that is fully quantum and cannot admit a classical description," Rey added. "We were able to demonstrate that even accounting for small imperfections and systematic errors unavoidable in the experiment, the state retains a negative Wigner function which can only happen for genuine quantum states."

The capability to prepare and measure a single atom wavefunction featuring a negative Wigner function revealed the success of the quantum protocol implemented by the researchers. The measurement idea will be useful for benchmarking the performance of quantum state control in optical tweezers, which is increasingly important for quantum computing and metrology in neutral atom arrays.

As much of quantum physics revolves around isolating and manipulating atomic states, the results of this experiment offer promising new avenues for further explorations. "There are exciting directions ahead," Rey said. Regal, Rey, and Romero-Isart will continue their collaboration by not only drawing parallels between how one images quantum states of neutral particles, but also in creating arbitrary motional quantum states, and expanding concepts to more traps and more atoms. These explorations will further push the boundaries of quantum control afforded by optical tweezers.

**More information:** M. O. Brown et al, Time-of-flight quantum tomography of an atom in an optical tweezer, *Nature Physics* (2023). [DOI: 10.1038/s41567-022-01890-8](https://dx.doi.org/10.1038/s41567-022-01890-8)

Provided by University of Innsbruck