Quantum dark states lead to an advantage in noise reduction

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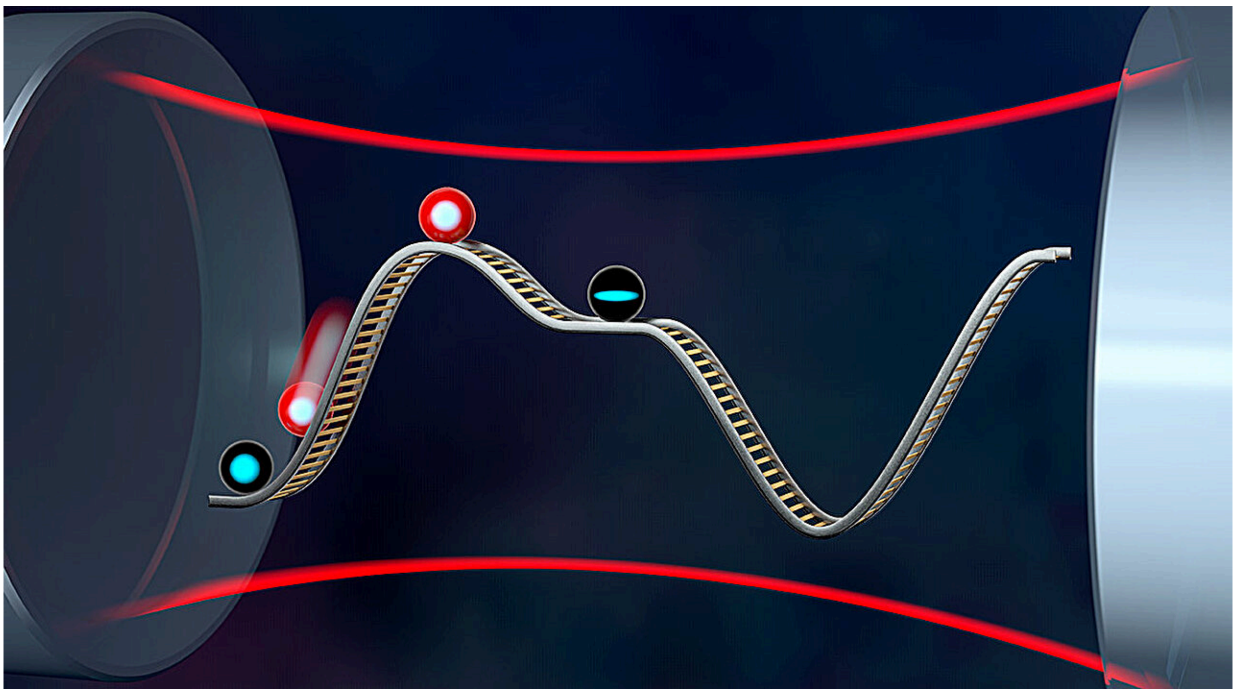

Multilevel atoms on a superradiance potential "rollercoaster" inside an optical cavity. The system can be tuned to generate squeezing in a dark state where it will be immune to superradiance. Credit: Steven Burrows/Rey Group

While atomic clocks are already the most precise timekeeping devices in the universe, physicists are working hard to improve their accuracy even further. One way is by leveraging spin-squeezed states in clock atoms.

Spin-squeezed states are entangled states in which particles in the system conspire to cancel their intrinsic quantum noise. These states, therefore, offer great opportunities for quantum-enhanced metrology since they allow for more precise measurements. Yet, spin-squeezed states in the desired optical transitions with little outside noise have been hard to prepare and maintain.

One particular way to generate a spin-squeezed state, or squeezing, is by placing the clock atoms into an optical cavity, a set of mirrors where light can bounce back and forth many times. In the cavity, atoms can synchronize their photon emissions and emit a burst of light far brighter than from any one atom alone, a phenomenon referred to as superradiance. Depending on how superradiance is used, it can lead to entanglement, or alternatively, it can instead disrupt the desired quantum state.

In a prior study, done in a collaboration between JILA and NIST Fellows, Ana Maria Rey and James Thompson, the researchers discovered that multilevel atoms (with more than two internal energy states) offer unique opportunities to harness superradiant emission by instead inducing the atoms to cancel each other's emissions and remain dark.

Now, reported in a pair of new papers published in *Physical Review Letters* and *Physical Review A*, Rey and her team discovered a method for how to not only create dark states in a cavity, but more importantly, make these states spin squeezed. Their findings could open remarkable opportunities for generating entangled clocks, which could push the frontier of quantum metrology in a fascinating way.

Rolling into a dark state on a superradiant roller coaster

For several years, Rey and her team have studied the possibility of harnessing superradiance by forming dark states inside a cavity. Because dark states are unique configurations where the usual paths of light emission interfere destructively, these states do not emit light. Rey and her team have shown that dark states could be realized when atoms prepared in certain initial states were placed inside a cavity.

Prepared in this way, the quantum states could remain impervious to the effects of superradiance or light emission into the cavity. The atoms could still emit light outside the cavity, but at a pace that is much slower than superradiance.

Former JILA postdoctoral researcher Asier Piñeiro Orioli, the lead researcher in the prior study with Thompson, and also a contributor to the two recently published studies, found a simple way to understand the emergence of a dark state in a cavity in terms of what they called a superradiant potential.

Rey says, "We can imagine the superradiant potential as a roller coaster where atoms ride. As they fall down the hill, they emit light collectively, but they can get stuck when they reach a valley. At the valleys, the atoms form the dark states and stop emitting light into the cavity."

In their previous work with Thompson, the JILA researchers found that the dark states must be at least a little bit entangled.

"The question we aimed to address in the two new works is whether they can be both dark and highly entangled," explains first author Bhuvanesh Sundar, a former JILA postdoctoral researcher. "The exciting part is that we not only found that the answer is yes, but that these types of squeezed states are rather straightforward to prepare."

Creating highly entangled dark states

In the new studies, the researchers figured out two possible ways to prepare the atoms in highly entangled spin-squeezed states. One way was by shining the atoms with a laser to energize them above their ground state and then placing them into special points on the superradiant potential, also known as saddle points. At the saddle points, the researchers let atoms relax in the cavity by switching off the laser, and interestingly, the atoms reshape their noise distribution and become highly squeezed.

"The saddle points are valleys where the potential has zero curvature and zero slope simultaneously," Rey elaborates. "These are special points because atoms are dark but on the verge of becoming unstable and therefore tend to reshape their noise distribution to becoming squeezed."

The other proposed method involved the transfer of superradiant states into dark states. Here, the team also found other special points where the atoms are close to special "bright" points—not in a valley of the roller coaster, but at points with zero curvature—where the interplay between superradiance and an external laser generates spin-squeezing.

"The neat thing is that the spin squeezing generated at these bright points can then be transferred into a dark state where, after appropriate alignment, we can turn off the laser and preserve the squeezing," Sundar adds.

This transfer works by first driving the atoms into a valley of the superradiant potential and then using lasers with appropriate polarizations (or directions of light oscillations) to coherently align the squeezed directions, making the squeezed states immune to superradiance.

The transfer of squeezed states into dark states not only preserved the reduced noise characteristics of the squeezed states, but also ensured their survival in the absence of being driven by an external laser, a crucial factor for practical applications in quantum metrology.

While the study published in *Physical Review Letters* used only one polarization of the laser light to induce spin squeezing, generating two squeezed modes, the *Physical Review A* paper took this simulation further by using both polarizations of laser light, resulting in four spin-squeezed modes (two modes for each polarization).

"In these two papers, we considered multilevel atoms with many internal levels," says Piñeiro Orioli, "and having many internal levels is harder to simulate than having two levels, which is often studied in the literature. So, we developed a set of tools to solve these multilevel systems. We worked out a formula to calculate entanglement generated from the initial state."

The findings of these studies can have far-reaching implications for atomic clocks. By overcoming the limitations of superradiance via the generation of dark entangled states, physicists either store the entangled states using the atoms as a memory (allowing for the retrieval of information from these states) or inject the entangled state into a clock or interferometer sequence for quantum-enhanced measurements.

More information: Bhuvanesh Sundar et al, Squeezing Multilevel Atoms in Dark States via Cavity Superradiance, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.033601. On *arXiv*: DOI: 10.48550/arxiv.2302.10828

Bhuvanesh Sundar et al, Driven-dissipative four-mode squeezing of multilevel atoms in an optical cavity, *Physical Review A* (2024). DOI: 10.1103/PhysRevA.109.013713. On *arXiv*: DOI: 10.48550/arxiv.2309.10717

Provided by JILA

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