Levitated Quantum Optomechanics

Aurelio Fusco, Grey Golus, Lucas Sabatini

The Institute of Optics

Introduction

A ~100nm particle is levitated using a 1064nm laser and feedback-cooled to its ground state in a high vacuum. The particle's motion is driven by momentum transfer from photons in the laser light. Polarization adjusts the elliptical focal plane, modifying the electromagnetic field and causing vibrations in the particle at higher frequencies along specific axes. This enables the particle to mimic quantum properties on a larger scale in a more controlled environment.

Team Roles

Aurelio Fusco - Scribe
Grey Golus – Poster Designer
Lucas Sabatini – Researcher

No one has the specific role of project leader, we are a team, and we are all collectively responsible for the research and work done.

Light can levitate particles with a diameter smaller than the wavelength of the laser. An easy way to think of this levitation is by using elastic collisions. While a photon carries no mass, it does have momentum. With a particle of small enough mass and many photons, enough momentum can be imparted to keep the particle in place. While this is not the exact physics behind levitated particles it is a good way to think about this.

When isolated from the environment by levitation and a high vacuum, the particle can be feedback cooled down to its ground state. This state is the minimum amount of energy possible. The particle vibrates in all directions. This motion can be modeled as if the particle had springs connected to it on the negative and positive sides of all its axes, making it carry out harmonic motion in each direction. The amount of quantized energy each direction experiences is controlled using the elliptical focal plane of the laser. The focal plane is rotated, causing a flip in the energy. The rotation in the focal plane is caused by changing the direction of the light's polarization and the electromagnetic wave. The measured cycling of energy between the two different states is known as Rabi Oscillations. This and other properties, such as Ramsey Fringes and Hahn Echoes, can be observed in these particles along with quantum particles. This process allows scientists to model quantum phenomena with greater ease and test the boundaries between classical physics and quantum physics.

Experiment

The experiment uses a 100nm silica particle, chosen for its smoothness and ease of trapping. It's trapped by a 1064nm laser in a vacuum chamber to minimize interactions with the environment and measured with a 532nm laser. The trapping laser passes through two Electro Optical Modulators (EOMs): the first modulates intensity, while the second modulates the polarization direction of the trapping beam, resulting in reduced oscillation frequency in x-axis compared to y-axis. A spatial filter shapes the beam to a Gaussian profile and expands it to overfill the numerical aperture (NA). The 532nm beam is telescoped to adjust its divergence angle, aligning its focus with the trapping laser. Both beams are overlaid, collimated, and focused on the particle using a NA of appropriate size, then collimated again after passing through an identical NA. The particle's motion is measured by reflecting the trapping laser and analyzing the measuring beam with photodiodes along the positive and negative X and Y axes.
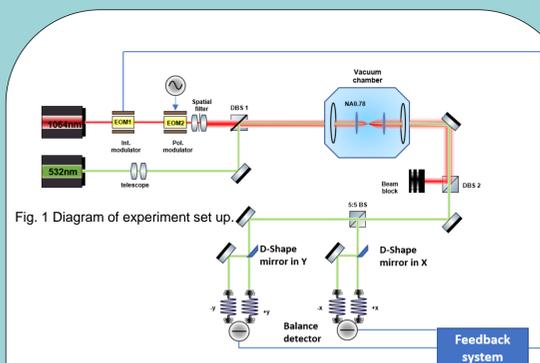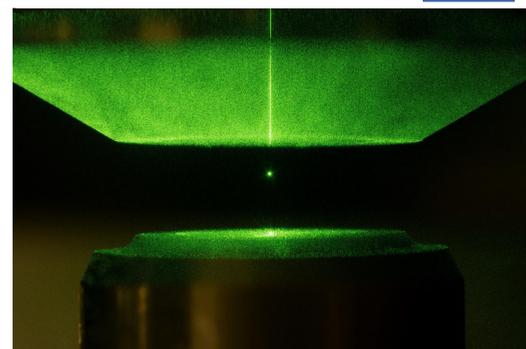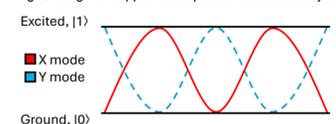

Fig. 1 Diagram of experiment set up.

Fig. 2 Image of trapped silica particle illuminated by 532nm laser

Excited, |1)
■ X mode
■ Y mode
Ground, |0)

Rabi Oscillations are a quantum phenomena where something oscillates back and forth between 2 states. This diagram shows how this model can be used across multiple applications. This is comparable to the experiment, when one mode peaks this parallels a qubit being a |1), or an electron being in its excited state.

Fig. 3 Two level system analogy diagram

Results
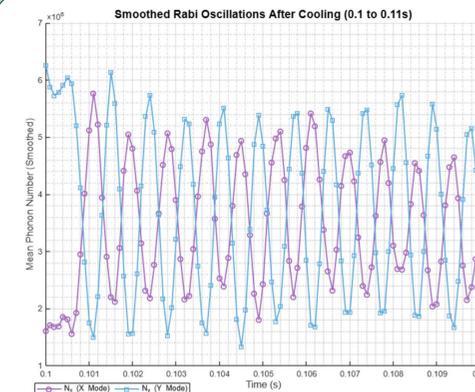
Since we have 100ms of data after cooling plotting that all on one graph would look very chaotic so by only plotting 10ms at a time we can visualize the energy transfer much easier. Despite only graphing 1/10th of the data the other 9/10ths follows the same pattern.

The raw data for this experiment is collected in volts, it represents the motion signal of the X and Y modes, but the data must first be converted to exemplify the oscillatory behavior of the energy transfer. The volts turn into the mean phonon number, a classical measurement to a quantum. By using the calibration factor and the provided formula $\langle N_i \rangle = M\omega_i\langle q_i^2 \rangle / \hbar$, the collected data can be visualized as Rabi Oscillations. The N_i is the average phonon number. You can imagine phonons as the quantized units of vibrational energy, so the mean phonon number would represent the average number of vibrational energy quanta per mode. Due to the frequency of the Rabi Oscillations being about 10kHz the periods(f^{-1}= T) needs to be 0.1ms or less. Using 0.1ms intervals allows us to be able to visualize the energy transfer better. This method of converting classical to quantum measurements enables the visualization of the Rabi Oscillations. The resulting graph of the mean phonon number over time illustrates the Rabi Oscillations after cooling after preparing the X mode into a relative lower energy, clearly showing the alternating dominance of the X and Y vibrational modes.

Discussion
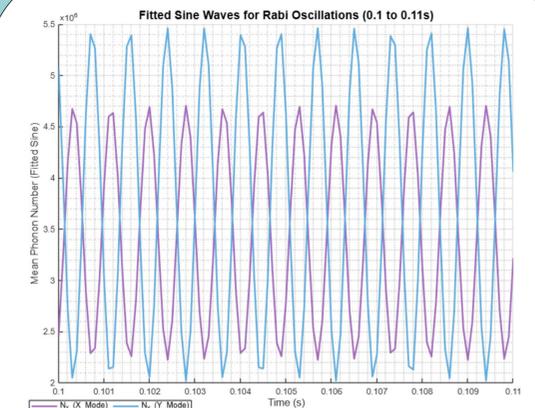
By fitting the graph to a sine wave, we can visualize what the theoretical expectation of the data should look like.

This experiment is one which bridges the gap between classical and quantum mechanics. This system can be considered as semiclassical, the particle's motion and vibrational modes are described classically, but the quantization of vibrational energy, represented by phonons, is quantum mechanical. By measuring voltage signals-a classical quantity-and analyzing them, it can uncover the underlying quantum behavior. This is significant because quantum mechanics is complex, expensive, and difficult to test directly, whereas semiclassical systems allow us to isolate quantum properties in a simpler, more cost-effective way. In the experiment, the coupling between the X and Y vibrational modes mirrors the behavior of a quantum system oscillating between two states, such as a qubit in quantum computing. Manipulating coupling in a system can be used to stop or adjust energy transfer between modes, and theoretically, the coupling in qubits can be controlled to swap states, equalize energy levels, or achieve superposition. Semiclassical systems, such as this one, provide valuable insights into quantum behavior and contribute to the development of tools for advanced quantum technologies.

References
Fig.1 Provided by Kai Zhang
Fig. 2 Image by Yifan Bu
Fig. 3 Created by Grey Golus

Nick Vamivakas, Mishkat Bhattacharya, and Peter Barker, "Levitated Optomechanics," Optics & Photonics News 27(7), 42-49 (2016). https://opg.optica.org/opn/abstract.cfm?uri=opn-27-7-42
Martin Frimmer, Lukas Novotny; The classical Bloch equations. Am. J. Phys. 1 October 2014; 82 (10): 947–954. https://doi.org/10.1119/1.4878621
Frimmer, M., Gieseler, J., & Novotny, L. (2016). Cooling Mechanical Oscillators by Coherent Control. Physical Review Letters, 117(16). https://doi.org/10.1103/physrevlett.117.163601