

Cavity QED with a Bose-Einstein Condensate

Based on a paper of the same title by Brennecke *et al.* (2007)

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Introduction.

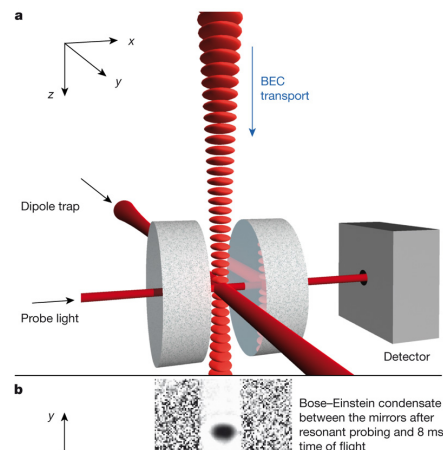
Quantum Electrodynamics (QED) is a highly successful theory that describes the ways in which matter interacts with light. Cavity QED is the study of light and matter within the confines of a resonant cavity. Brennecke's team used an ultra-high finesse (nearly perfectly reflective) cavity, which allowed the atoms to absorb and emit photons many times without dissipation.

Traditional cavity QED experiments have focused on single atoms or groups of atoms behaving as separate particles. Brennecke's team expanded the cavity QED body of knowledge to include Bose-Einstein condensates (BEC). Bose-Einstein condensates are groups of atoms that have been cooled to the point that their wave functions significantly overlap. Essentially, a BEC interacts with light as though the group of atoms were a single particle.

The purpose of the experiment was to find the energy spectrum of a Bose-Einstein condensate of rubidium atoms. The spectrum is a function of the cavity's resonance frequency ($\omega_c = c/2L$) and also of the number N of rubidium atoms. In the first experiment, the team held N constant and varied ω_c ; in the second experiment, the team held ω_c constant and varied N .

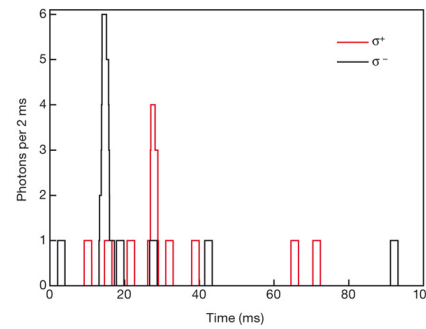
Experimental Methods.

The BEC was prepared from 3.5 million rubidium atoms in a two-step cooling process. First, the atoms were laser-cooled in a magneto-optical trap. The result was an ultra-cold cloud of Rubidium, about 6% of which were in the BEC phase. Second, the atoms were transported to the cavity by two counter-propagating waves. The atoms were carried at the group velocity of the wave system. While being transported, the atoms underwent evaporative cooling that purged the cloud of non-BEC atoms. After 8 milliseconds of flight time, the cloud was reduced to 220,000 rubidium atoms in the BEC phase.



Inside the cavity, a dipole trap induced a circular polarization within the BEC. A linearly polarized probe beam was then subjected to a quarter-wave plate in order to probe the BEC with either parallel ($\sigma+$) or anti-parallel ($\sigma-$) circular polarization. Data was taken for both $\sigma+$ and $\sigma-$.

For fixed values of both ω_c and N , an energy spectrum looks like the graph to the right. The vertical axis is the number of resonant photons above the dark count. The horizontal axis is labeled time, but really represents frequency because the probing laser is changing its frequency at 25 MHz per millisecond. The data points are the two resonant peaks, one for $\sigma+$ and one for $\sigma-$.



Once an intermediate data set like the above graph was obtained, the parameter under study (either ω_c or N) was varied slightly and the process was repeated until a full data set was obtained.

Results.

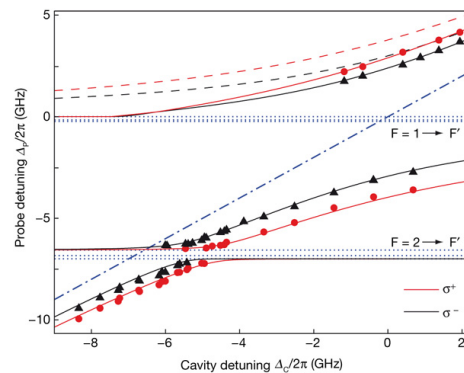
Energy Spectrum vs. cavity resonance frequency ω_c

A single rubidium atom absorbs a photon of frequency ω_a when it jumps from the ground state $|F = 1\rangle$ to the first excited state $|F' = 2\rangle$. Rather than plotting the energy spectrum as probe beam frequency ω_p versus cavity resonance frequency ω_c , the team chose to plot the detuning frequencies Δ_p and Δ_c . The detuning frequency is defined as the difference between the absolute frequency and ω_a :

$$\Delta_p = \omega_p - \omega_a$$

$$\Delta_c = \omega_c - \omega_a$$

When expressed this way, the energy spectrum with a constant N and a varied ω_c (hence, a varied Δ_c) looks like the graph to the right. The vertical axis is Δ_p , while the horizontal axis is Δ_c . The dash-dot-dash-dot line is simply the $y=x$ line. The upper family of horizontal dotted lines represents the single-atom transitions from a ground state $|F=1\rangle$ to other states $|F' = 1,2,3\rangle$. The lower family of horizontal dotted lines represents the single-atom transitions from $|F=2\rangle$ to other states $|F' = 1,2,3\rangle$. The solid lines are theoretical predictions. The red dots and black triangles represent points of resonance for $\sigma+$ and $\sigma-$ respectively.



There are two patterns to note here. First, as the cavity resonance frequency increases, the probe frequency must also increase in order to create resonance. Second, there are avoided crossings at the single-atom transition frequencies

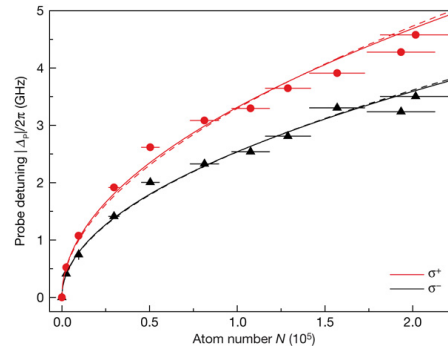
$|F=1\rangle \Rightarrow |F'\rangle$ and $|F=2\rangle \Rightarrow |F'\rangle$. These avoided crossings are caused by influences by higher-order transverse modes, which are resonances perpendicular to the axis of the cavity.

Energy Spectrum vs. number of atoms N

For this experiment, the cavity detuning frequency Δ_p is held constant at zero. The advantage of plotting the detuning frequencies rather than the absolute frequencies now becomes clear. Theoretical predictions suggest a simple relationship between Δ_p and N :

$$\Delta_p \sim \sqrt{N}$$

When the experimental data is plotted, the result looks like the graph to the right. The vertical axis is Δ_p , while the horizontal axis is N . The dotted and solid lines are the respective predictions from two theoretical models. The red dots and black triangles represent points of resonance for $\sigma+$ and $\sigma-$ respectively.



Although not all of the error bars pass through the theoretical prediction lines, the data for both $\sigma+$ and $\sigma-$ do approximate the theoretical $\Delta_p \sim \sqrt{N}$ curve.

Summary.

A Bose-Einstein condensate (BEC) of rubidium was transported into an ultra-high-finesse optical cavity. A dipole trap induced a circular polarization into the BEC. A circularly polarized probe laser measured the energy spectrum as a function of both the cavity resonant frequency ω_a and the number of rubidium atoms N . Data was taken for parallel ($\sigma+$) and anti-parallel ($\sigma-$) polarizations.

First, the spectrum was measured as a function of ω_a . Probe frequency increased as a nonlinear relation to ω_a . There were anti-crossings at the single-atom resonance frequencies. Second, the spectrum was measured as a function of N . The probe frequency increased with the square root of N . The results of both experiments confirmed theoretical predictions.

Bibliography

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2. Öttl, A., Ritter, S., Köhl, M., and Esslinger, T. Apparatus for Bose-Einstein condensation and cavity quantum electrodynamics: Single atom detection in quantum degenerate gases. *Rev. Sci. Instrum.* 77, 063118 (2006)
3. Cuccoli, A., Fubini, A., and Tognetti, V. Quantum fluctuations in one-dimensional arrays of condensates. *Phys. Rev. A*, 64, 061601(R) (2001)