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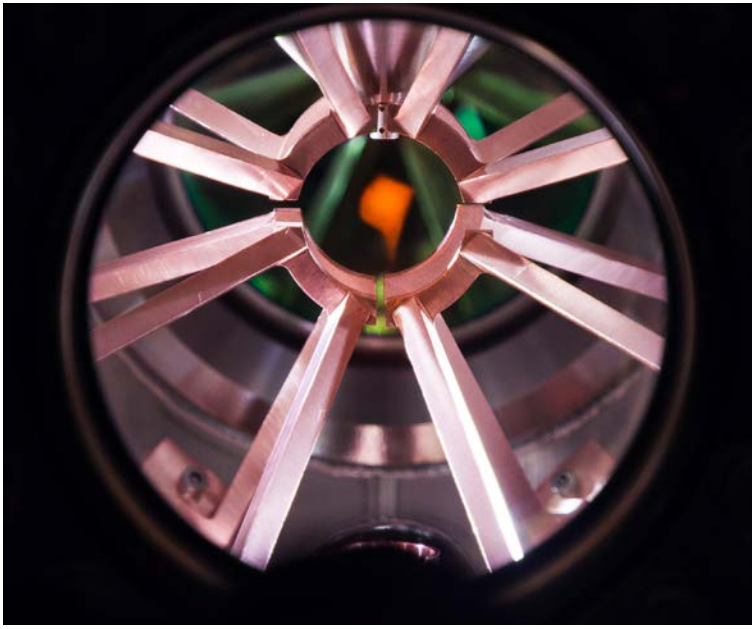
Author: Prof. Dr. Herwig Ott



[1]stands for **O**pen **S**ystem **C**ontrol of **A**tomic and Photonic Matte**R**; funded by the Deutsche Forschungsgemeinschaft since July 01, 2016.

Strong Purcell Effect on a Neutral Atom Trapped in an Open Fiber Cavity

J. Gallego, W. Alt, T. Macha, M. Martinzue-Dorantes, D. Pandey, and D. Meschede
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Physical concepts are often simple to sketch but experimentally challenging to realize. One example is the directed emission of a photon from an atom into an optical fiber. This forms the basic concept of a single photon source (SPS). Applications of SPS include optical quantum communication, quantum cryptography and quantum repeaters. In order to make such a SPS efficient, two challenges have to be overcome: first, the coherent interaction of the atom with the light field, denoted as *g*, has to be the dominant energy scale. This ensures that the atom-light interface is coherent and quantum information can be transferred via the emitted and absorbed photons. Such a strong coupling can be achieved with the help of optical cavities. Second, the decay rate of the cavity, denoted as κ, has to be much larger than the spontaneous decay rate γ of the atom. Both conditions together ensure that the emission of the photons is preferably into the optical cavity. As a result, the lifetime of the atoms is decreased. This is known as the Purcell effect, where

$$f_p = \frac{g^2}{\kappa\gamma}$$

is the Purcell factor. The two conditions impose $f_p > 1$. The modified emission properties of the atom can be understood from the modified mode structure of the electromagnetic environment and the strong coupling with the cavity modes.

In their experiment, the authors report a record value for the Purcell factor with single atoms. The setup consists of an optical fiber cavity assembly, in which single, laser–cooled rubidium atoms are placed. The cavity assembly consists of two opposite optical fibers with micro-machined mirrors on the entrance facets. The small distance between the two fiber facets leads to a very small mode volume of the cavity and thus a large coupling constant *g*. The photons emitted into the optical fiber are detected with a single photon counter.

Fig. 1 shows the measured linewidth of the atom with and without coupling to the fiber cavity. The authors observe that the coupling to the cavity broadens the atomic transition by a factor of 6. This means that the lifetime of the atom is reduced by the same factor and the atom can emit six times more photons into the cavity and the fiber than into free space. To verify that the broadening is homogeneous, the authors have also measured the correlation function between the emitted photons in a Hanbury Brown and Twiss experiment. From the antibunching signal of the photons lifetime shortening from 27 to 3.3 ns is observed, in very good agreement with the broadening.

The results are very promising for future applications as high repetition SPS. Optimizing their protocol, the authors estimate a maximum Purcell factor achievable in their setup of 195. Such a large Purcell broadening is important to match the bandwidth mismatch between photons coming from solid state emitters, such as quantum dots, and atoms.

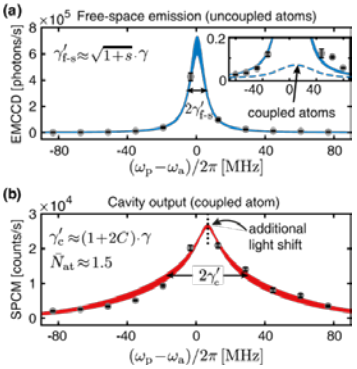

Fig. 1: Purcell broadening of a single rubidium atom in an optical fiber cavity. The upper panel shows the natural linewidth in free space, while the lower panel shows the broadening due to the coupling to the cavity.

Using non-equilibrium thermodynamics to optimize the cooling of a dilute gas

Daniel Mayer, Felix Schmidt, Steve Haupt, Quentin Bouton, Daniel Adam, Tobias Lausch, Eric Lutz, and Artur Widera

arXiv:1910.06188 (2019)

Laser cooling is one of the most important technological achievements in physics during the last decades. And without it, OSCAR would not exist!

In a standard magneto-optical trap, cooling is provided by a combination of dissipative and restoring light forces, thus providing an effective bath and establishing a "temperature". In a purely conservative trapping potential, atomic collisions provide thermalization, thus allowing for evaporative cooling. Imagine now an ensemble of non-interacting atoms in a conservative trapping potential, which are subject to laser cooling. Despite the absence of thermalizing collisions is there a way to reach a state with a well-defined global temperature? And how can the coupling to such an unusual bath, which acts only locally, be described?

The authors have addressed these questions by studying an ensemble of about ten cesium atoms in a very elongated, anharmonic trapping potential formed by two crossing laser beams (Fig. 2). The small atomic cloud is initialized in thermal equilibrium by optical molasses cooling at a temperature of 12 µK. Being able to measure the positions of all cesium atoms, the authors can infer that the spatial distribution of the atoms is that of a thermalized ensemble. The bath is now provided by three-dimensional degenerate Raman sideband cooling. Thereby, a set of three pairs of lasers is shown on the atomic cloud, leading to a three-dimensional optical lattice structure, in which vibrational cooling of the atoms takes place. After such a Raman pulse, the local "temperature" of each atom – defined as the distribution over the vibrational states – has dropped to 2.9 µK. However, the spatial distribution of the atoms is the same as before. Hence, the ensemble is far away from thermal equilibrium and effectively squeezed in phase space. After switching off the cooling lasers, the atomic motion in the anharmonic potential sets in and alters the phase space distribution of the atoms, but thermalization due to collisions is absent. Applying a second and a third Raman cooling pulse after an optimized delay time T, the authors manage to create an ensemble which is very close to thermal equilibrium at a temperature 2.9 µK. Due to the anharmonicity of the trap, the intuitive harmonic result of an optimal delay equal to a quarter trap period cannot be applied. Nevertheless, non-equilibrium thermodynamics offers a way to optimize the strategy to a cooler final thermal state.

The manuscript highlights the authors' superb control of the cooling process, tracing the full cooling dynamics in phase space. Moreover, the authors introduce the theoretical framework to characterize non-equilibrium phase space distributions and to quantify their overlap with a target state in thermal equilibrium. The results represent a major step forward in the large territory of non-equilibrium thermodynamics.

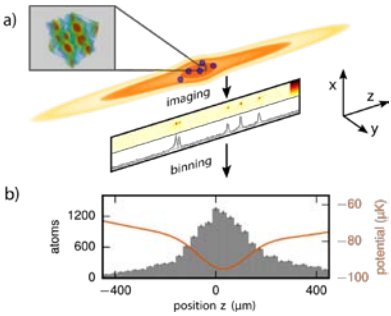

Fig.2: Experimental setup and readout of the atomic positions. (a) Optical dipole trap with a few cesium atoms. The laser pattern for the Raman sideband cooling is shown in the inset. The atomic distribution is imaged with single atom sensitivity. (b) Spatial distribution of the atoms along the z-direction for an ensemble in thermal equilibrium.

Rotational cooling of molecules in a BEC and angulon stability

Martin Will, Tobias Lausch, and Michael Fleischhauer

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The friction, which is experienced by an impurity moving in a medium, depends on the properties of that medium. Conservation laws enforce that the impurity, in order to relax, has to excite allowed combinations of energy and momentum in the environment. In a superfluid, such excitations are not present if the impurity moves slower than a critical velocity. A microscopic look at the impurity reveals that the physical picture is a bit more involved: the interaction of the moving impurity with the superfluid leads to the formation of a polaron, which is a quasiparticle composed of the impurity and phonons carrying linear momentum.

Recently, rotating impurities immersed in a superfluid have been studied, identifying a new quasiparticle, the angulon [1]. In analogy to polarons, an angulon is composed by the rotating impurity and phonons, which carry orbital angular momentum. So what is then the fate of a rotating impurity in a superfluid? Does it relax or does it rotate forever? How much of the physical picture known from the linear motion survives?
The authors have addressed this question by studying rotating homonuclear diatomic molecules in a weakly interacting Bose-Einstein condensate (see Fig. 3). The answer to these questions depends on the size of the molecule. In the context of an atomic Bose-Einstein condensate, a normal molecule is a point-like object, which can only interact with phonons of a wavelength which matches the size of the molecule. In other words, the phonons have to resolve the structure of the molecule. Such phonons are nothing else than high energetic single particles. A small rotating molecule therefore relaxes, spilling out individual atoms from the superfluid medium, eventually reaching the rotational ground state.
The really interesting part of the story is the behavior of molecules, which are larger than the healing length of the condensate. Note that the healing length is a measure of the smallest available phonon wavelength in the condensate. The authors find that such a molecule relaxes down to a critical rotational quantum number, where the relaxation stops. This criticial rotational quantum number is found to coincide with the naïve estimate where the classical orbital velocity of the two atoms roughly coincides with the critical velocity for superfluidity.
The results show, that for such large rotating molecules, the corresponding angulon is a stable quasiparticle. Diatomic molecules with a bond length larger than the typical healing length have already been prepared in experiments: Rydberg macrodimers or Feshbach molecules. The experimental verification of these predictions is within reach.

Fig 3: Rotating molecule (rotational quantum numbers j, m_j) immersed in a weakly interacting Bose-Einstein condensate. If the bond length ($2r_0$) is larger than the healing length, the excitation of phonons (angular momentum quantum numbers λ, μ) is suppressed below a critical value.

[1] Rotation of quantum impurities in the presence of a many-body environment. R. Schmidt and M. Lemeshko, Phys. Rev. Lett. **114**, 203001 (2015)