Quantum Manipulation of Ultracold Atoms

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1. Collective Cavity Cooling of Classical Atoms

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Laser cooling of atoms has not only enabled Bose-Einstein condensation, but has also resulted in a number of important applications and devices, many of which are tied to precision measurements and atomic clocks. However, laser cooling has so far been limited to atoms with a relatively simple internal structure, and the cooling of molecules or even of atoms with a more complicated level scheme has not been possible.

In Doppler cooling, the preferred absorption of photons from a beam counterpropagating relative to the atom's motion leads to slowing and cooling of the atom. Since the momentum "kick" associated with each photon absorption event is much smaller than the momentum of a thermal atom, several thousand absorption-emission events are required to significantly change the atom's velocity. Therefore laser cooling has only been demonstrated with atoms that can be optically cycled many times between two states. However, most atoms (and all molecules) have multiple ground states to which the excited state can decay. Once the atom reaches a different ground state, the laser no longer has the correct detuning relative to the atomic transition, and the cooling stops. In particular, molecules have many vibrational and rotational levels, and consequently no laser cooling of molecules has been demonstrated.

In analogy to proposals for two-level atoms [1], we have proposed a laser cooling method that is largely independent of the atomic level structure [2]. The basic idea is that energy is conserved in the scattering process, and that therefore events where the scattered photon carries away a larger energy than the incident-photon energy must be accompanied by a corresponding reduction of the atom's energy. Such scattering events can be enhanced in an optical resonator that is tuned to be resonant with a frequency that is higher than that of the incident light. The new cooling mechanism depends only on the finesse (i.e. on the reflectivity of the cavity mirrors) and on the detuning of the photons relative to the cavity resonance, while it is independent of the detuning relative to atomic transitions. Therefore this new technique should be generic and in principle applicable to all light scatterers. The target can be a multilevel atom, a molecule with different rotational and vibrational states, or possibly even a scattering center (impurity) inside a solid. The only requirement is that at the given intensity and laser frequency the emission rate by the scatterer is large enough to produce significant cooling. Here the cooling power is given by the product of the scattering rate and the energy difference between the incident and the scattered photon [2]

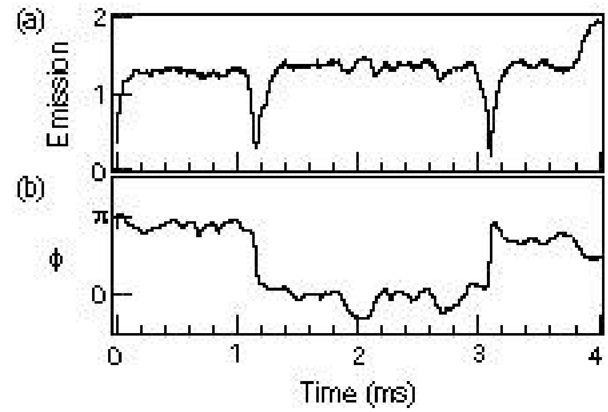

Fig. 1. Simultaneous traces of the intracavity intensity (a) and the field phase (b). The phase jumps of π in the emitted light indicated the switching of the atomic density grating between two equivalent, but spatially offset lattices.

When we performed what was to be a proof-of-principle experiment with cesium atoms inside an optical resonator, we found to our surprise that both the light emitted by the atoms into the cavity, and the cavity-emission-induced forces on the atoms were much larger than expected for independent atoms [3,4]. In some cases, the observed emission into the resonator exceeded the predicted single-atom value by a factor of one thousand, and the light-induced forces were more than a factor of 20 larger than the prediction for a single atom in the cavity [4].

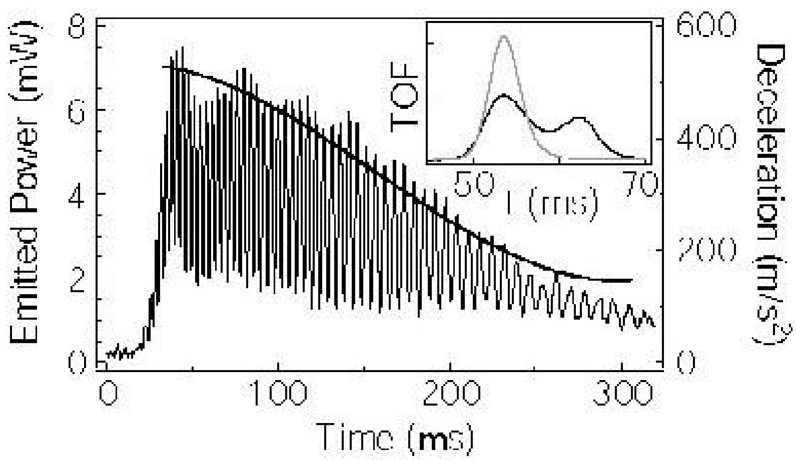

Fig. 2. The emitted power during the illumination of a falling atomic cloud. The beat frequency is due to the Doppler effect and reveals the changing velocity of the decelerating atomic cloud. The time-of-flight signal (inset) shows slowing of a substantial fraction of the atoms (delayed peak).

The observed superradiance-like collective emission by the atomic sample requires some mechanism that provides optical gain [5]. For not too large light-atom detuning, where the atomic multilevel structure is relevant, we obtained experimental evidence that the optical gain is, at least in part, Raman gain between differently populated magnetic sublevels [3]. In the limit of large detuning, where the atomic multilevel structure is negligible, and the atoms behave like classical light scatterers, Domokos and Ritsch at the University of Innsbruck suggested that the collective emission could be explained by a collective process where the atoms self-organize into a density grating [6]. Then the classical (Rayleigh) scattering rate of the individual atoms, proportional to the number of atoms N, would be transformed into collective Bragg scattering, proportional to N^2. They also predicted that the atoms could organize into one of two equivalent, but spatially offset density gratings. We have experimentally verified these predictions, in particular the self-organization process and the associated symmetry breaking, by measuring the phase of the light emitted into the cavity (Fig. 1). Furthermore, as Fig. 2 shows, we have observed a very strong cooling of the sample's center-of-mass motion [4].

We are next planning an experiment where the observed large off-resonant collective force will be used to stop a molecular beam. We are also modifying the experimental setup with cesium atoms to perform experiments on quantum information processing and sub-shot noise readout of atomic clocks and interferometers.

2. Bose-Einstein Condensates on Microfabricated Chips

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Bose-Einstein condensates in magnetic traps and waveguides produced by microfabricated structures hold great promise for new quantum devices exploiting atomic matter waves, such as Fabry-Perot resonators, interferometers, or Josephson junctions. It is of particular interest to reach the regime of quantum tunneling that would allow one to coherently couple two spatially separated condensates. Given a typical energy scale of $E = 7\times10^{-31}$J = h×1kHz= $k_B\times$50nK on which the energy of the condensate can be conveniently controlled, quantum tunneling requires potentials that vary abruptly on a length scale $L \approx h/(mE)^{1/2} \approx 1\mu$m, where m is the atom's mass. Such rapidly varying magnetic potentials can only be created at small distances d ≈ L from miniaturized field sources. Since the field sources are typically at room temperature, and in any case many orders of magnitude hotter than the condensate, it is a fundamental question whether it is even possible to bring a condensate to micrometer distances from a surface without destroying the condensate. Thus, we have experimentally explored fundamental limitations on condensate stability at small distances down to 0.5μm from dielectric and metal surfaces.

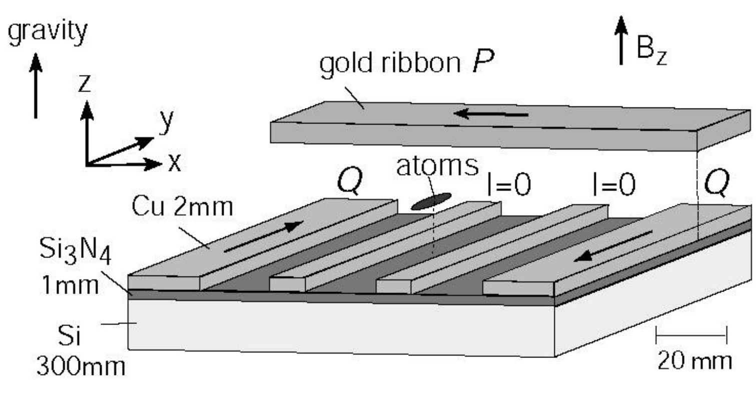

Fig. 3. Microfabricated chip. The outer Cu wires (*Q*) generate a 2D quadrupole field in the xz plane, the ribbon (*P*) in combination with an external field gradient creates the confinement along the y direction.

The power of microchips lies in the fact that conductor or permanent magnet structures patterned on a surface in combination with external magnetic fields can be used to produce three-dimensional magnetic confinement of atoms above the surface [7]. This not only allows for miniaturization of magnetic trapping potentials, but the substrate also represents an excellent heat sink for the microscopic conductors, resulting in current densities of 10^6 to 10^7 A/cm^2 in room temperature wires, exceeding those in superconductors. The corresponding magnetic traps are comparatively steep, with vibration frequencies of typically several kHz, which results in large densities and collision rates for the atomic sample, and both simplifies and accelerates the evaporative cooling necessary for Bose-Einstein condensation.

Fig. 3 shows the microfabricated chip that provides radial and axial vibration frequencies of 6kHz, and 70 Hz, respectively, at a distance of 50μm from the surface [8]. We typically load 3×10^6 atoms at an initial temperature of 300μK and an initial collision rate of 140s^{-1} into the trap, and evaporatively cool them in 3s to below the condensation temperature of 0.8μK. We then place the condensate or an ultracold atom cloud at various distances from either a metal or a non-conducting surface, and measure the cloud lifetime. As Fig. 4 shows, the behavior is very different for metals and insulators. Whereas for metals the trap lifetime is reduced already at distances of several micrometers from the 2μm thick film, the dielectric does not affect trap stability down to distances of 1.3μm. The different behavior is due to the fact that the strongest coupling of the trapped gas to its surroundings is via the electron magnetic moment, and that a room temperature conductor supports thermally excited currents that create magnetic fields. Radio frequency components of this magnetic field can drive transitions that change the orientation of the electron spin relative to the applied magnetic field, corresponding to transitions from trapped to untrapped states of the atom in the external magnetic potential. The lifetime associated with these thermal-field induced spin flip processes is well modeled (solid line) by currents due to Johnson noise (dotted line) in combination with a finite, distance-independent lifetime due to background gas collisions (dashed line). The effect of Johnson noise-induced currents can be reduced by decreasing the metal volume, and by using metals with higher resistivity.

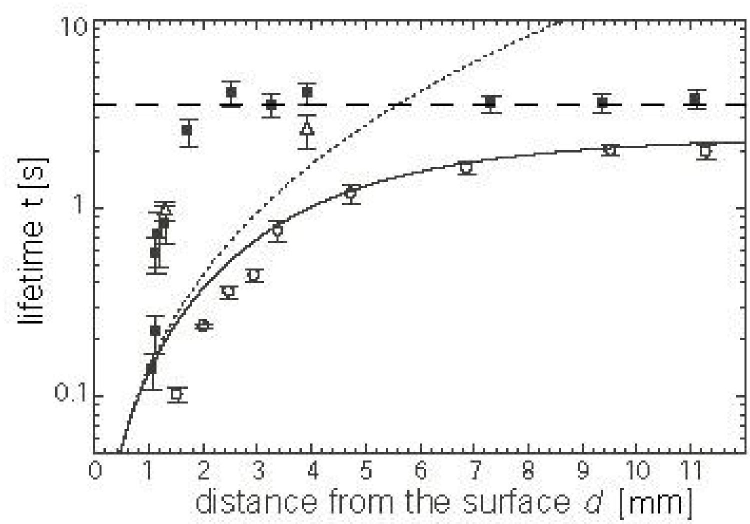

Fig. 4. Trap lifetime as a function of distance from a dielectric (solid squares) and metal (open circles) surface, for a temperature of 1μK. The dotted line is the calculated lifetime above the metal due to thermal magnetic fields only, the solid line includes the distance-independent one-body lifetime.

The insulating surface has no effect on the ultracold gas until the retarded van der Waals potential (Casimir-Polder potential) becomes so strong that it pulls the atoms out of the magnetic trap into the surface. For a condensate in a kHz vibration frequency trap, this occurs at distances smaller than 1.3μm. In order to keep a stable condensate at smaller distances from, e.g., a 100-nanometer size wire, it will be necessary to remove part of the nearby surface. Since the Casimir-

Polder potential can be associated with the image of the atomic dipole induced by quantum fluctuations, reducing the surface area will reduce the Casimir-Polder force. In the future, we plan to demonstrate traps where the condensate is stable at distances less then 1μm from a thin wire. In such traps, it should be possible to observe coherent tunneling, opening the door to microscopic quantum manipulation of atomic Bose-Einstein condensates.

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Accepted for Publication:

C. Chin, V. Vuletic, A.J. Kerman, S. Chu, E. Tiesinga, P.J. Leo, and C.J. Williams, “Ultracold Cs_2 Feshbach Spectroscopy”, Phys. Rev. A, forthcoming.

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Presented:

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