Cesium Atoms Bouncing in a Stable Gravitational Cavity

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A curved mirror for atoms was made from an evanescent wave, formed by internal reflection of a quasiresonant laser beam at a curved glass surface. A cold cloud of cesium atoms was dropped onto the mirror and observed to rebound more than 8 times. The mirror size and reflectivity were studied, and reasonable agreement with a simple theory obtained. With 800 mW of laser power and a mirror of 1 mm diameter, we observed up to 73% of the atoms returning after each bounce, the losses being mostly during the free flight between bounces.

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In recent years atoms have been held near stationary [1], thrown upwards without heating [2,3], made to produce quantum interference after macroscopic path separations [4], and trapped in quantum wells [5]. The aim of such experiments is not merely to demonstrate juggling with unusually small balls, or interference of waves associated with heavy particles. The important feature is that an atom is an object sufficiently complicated to have a rich internal structure, yet with a behavior sufficiently reproducible to produce observable quantum interference and to facilitate experimental techniques of the highest precision.

We present in this Letter an experimental demonstration of multiple bouncing of atoms on a reflective surface. This can be regarded as a first step towards an interferometer of Fabry-Pérot type for atomic de Broglie waves [6,7]. A cold cloud of cesium atoms has been released a few millimeters above a curved mirror, and we have observed the motion of the cloud during about ten successive bounces. The curvature of the mirror ensures that the classical trajectories close to the vertical axis are stable [7,8]. Previous demonstrations of atomic mirrors were limited to a single reflection of a fast atomic beam [9], or to two bounces [10,11] in a "trampoline" geometry like ours. Very recently we observed an improvement on this using cesium in a preliminary version of our current experiment [12]. We report here for the first time multiple bounces on a curved mirror of useful size and high reflectivity.

We used an atomic mirror formed by an evanescent light wave extending from a glass surface into the vacuum; see Fig. 1(a) [13]. The electric field in this wave gives rise to a potential for the atom which is simply the light shift of the atomic ground state:

$$U = \hbar\Omega^2/4\delta, \qquad \text{for } \delta \gg \Omega\,. \tag{1}$$

$\Omega = dE/2\hbar$ is the Rabi frequency *in the evanescent wave*, proportional to the electric field amplitude E and the atomic dipole moment d; $\delta = \omega_L - \omega_A$ is the detuning between the laser frequency ω_L and the atomic resonance frequency ω_A. The electric field falls off with distance z into the vacuum as $\exp(-\alpha z)$, the characteristic distance $1/\alpha$ (0.21 μm in our experiment) being of the order of the wavelength of the light over 2π. The potential is repulsive at positive detunings. Specular reflection can be achieved if no photons are scattered. The average number of scattering events during the reflection is given by [10,14]

$$n_p = \Gamma M v_0/\alpha\hbar\delta, \tag{2}$$

where v_0 is the speed of the atom on entering the evanescent wave, M is its mass, and Γ is the natural width of the transition. Thus, while Eq. (1) indicates that the potential is higher at small detunings, allowing faster atoms to be reflected, the condition $n_p < 1$ places a limit on the minimum detuning which is useful. Equation (2) is derived by integrating the scattering along the path followed by an atom in the potential U; this path depends on the intensity I and the detuning δ and this explains why n_p no longer depends on I and varies as $1/\delta$ instead of the usual $1/\delta^2$ for a scattering process. Equations (1) and (2) apply strictly to a simple two-level atom, but they yield good estimates for what can be achieved for alkalis such as cesium. They imply that with our typical power of 800 mW, in a Gaussian beam of $1/e^2$ radius 0.5 mm, and a detuning of 10 GHz, Cs atoms with velocities up to 0.4 m/s could be reflected from a spot of radius 0.5 mm, while scattering one photon every eleven bounces (per atom).

The experimental configuration, illustrated in Fig. 1(a), is described in [12]. A prism of BK7 glass has a concave spherical region, with radius of curvature 2 cm, polished into its top surface. The atomic mirror is formed by an 800 mW beam from a titanium-sapphire ring laser, reflected internally at an angle of 53° to the normal, at the center of the concave region. This laser beam is tuned between 1 and 10 GHz above the resonance transition $g = 6S_{1/2} \rightarrow e = 6P_{3/2}$, $F_g = 4 \rightarrow F_e = 5$ in cesium. To drop atoms onto the mirror, first of all about 10^7 cesium atoms are loaded from a laser-slowed atomic beam into a magneto-optical trap (MOT), for 1.5 s. The center of the MOT is 3 mm above the center of the mirror.

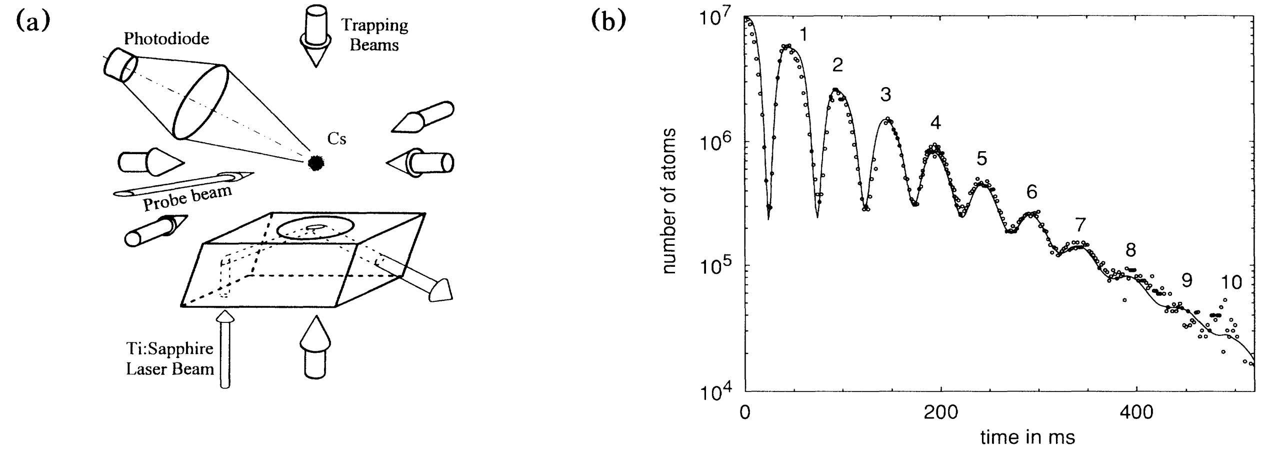

FIG. 1. (a) Experimental setup. Atoms from a magneto-optical trap are released above a curved mirror formed by an evanescent light wave. The number of atoms present in this stable gravitational cavity is measured as a function of time using the fluorescence induced by a probe beam. (The shown beam radii are not to scale.) (b) Number of atoms in the probe beam, for different times after their release (points). Background pressure 3×10^{-8} mbar, mirror power 800 mW, detuning 1.9 GHz, and waist 1×1.1 mm. The curve is a fit calculated by our Monte Carlo simulation of the experiment; the fitted parameters are loss per bounce, the temperature, the radius of the cloud when it is first dropped, and the drop height. The values used here are 39% loss per bounce, temperature 4 μK, initial cloud radius 0.25 mm (1 standard deviation of the Gaussian profile), and drop height 2.91 mm. The simulation assumed a reflective parabolic surface, elliptical in the horizontal plane, of major axes 2.1 by 2.3 mm (diameter). These diameters were obtained from measurements of the profile of the elliptical Gaussian beam used to form the mirror, combined with a calculation from Eq. (1).

After 1.5 s, the MOT loading is blocked and the intensity of the trapping beams is switched from 13 to 0.4 mW/cm^2, causing both the temperature and diameter of the trapped cloud to reduce. To achieve further cooling, the polarization of the horizontal beams is switched to linear, after 5 ms, using liquid crystal wave plates, and the trap magnetic field is turned off. In 20 ms the atoms thermalize to a temperature of 5 μK; then all the beams are blocked and the atoms fall. Weak repumping light on the $F_g = 3 \rightarrow F_e = 4$ transition is left on to ensure that the falling atoms are in the $F_g = 4$ ground state. The beam producing the evanescent wave mirror is switched on after another 5 ms, and the atoms are left bouncing, with the mirror always on. After a variable delay, the atoms present are detected by introducing a probe beam at the resonant atomic frequency, while the mirror is turned off to eliminate stray light. The probe is centered 3 mm above the mirror, and has vertical width 2 mm, horizontal width 3 mm. The fluorescence it produces is detected by a photodiode. This is a "destructive" detection method, in that the probe heats the atoms sufficiently to empty them from the gravitational cavity, so the experiment is cycled with different probe times to build up a picture of the motion.

Figure 1(b) gives an example result. It shows, on a logarithmic scale, the number of atoms between 2 and 4 mm above the mirror, for a range of times t after dropping them. Each bounce, or round trip in the cavity, takes 50 ms, for a drop height of 3 mm. In the figure, eight bounces are clearly visible, and the signal-to-noise ratio falls to about 1 at the tenth bounce, each point being a single cycle of the experiment. For the first two bounces, the signal falls off more rapidly because the width of the atomic mirror is smaller than that of the cloud of atoms falling onto it: the mirror performs a selection in horizontal position. Thereafter, the falloff in the series of maxima is close to exponential, and has two sources: loss of atoms from the cavity, and spreading of the peaks due to the finite initial spread in position and velocity of the atoms. A Monte Carlo simulation of the motion, with atoms moving on classical trajectories, reproduces our results very well (full curve), and enables us to separate these two effects. The former (i.e., loss) dominated for most of our studies, so the slope of the logarithmic plot indicates the all-important parameter of loss per bounce.

To gain more information on the atomic mirror, we observed the signal at a given time, $N \times 50$ ms after the atoms were dropped (i.e., at the Nth bounce peak), while varying the mirror detuning. This was carried out for various laser powers, spot sizes, and polarizations; Figs. 2(a) and 2(b) show example results. We fitted the curves by taking into account first the variation of the effective mirror size and second the losses due to photon scattering. The mirror size contribution is dominant at large detuning: it comes from the reduction, as detuning increases, of the radius at which the Gaussian laser beam intensity is just sufficient to reflect the atoms. Our fits to curves like those of Fig. 2(a) have an adjustable parameter c_U multiplying the right-hand side of Eq. (1), enabling us to compare our results with those expected

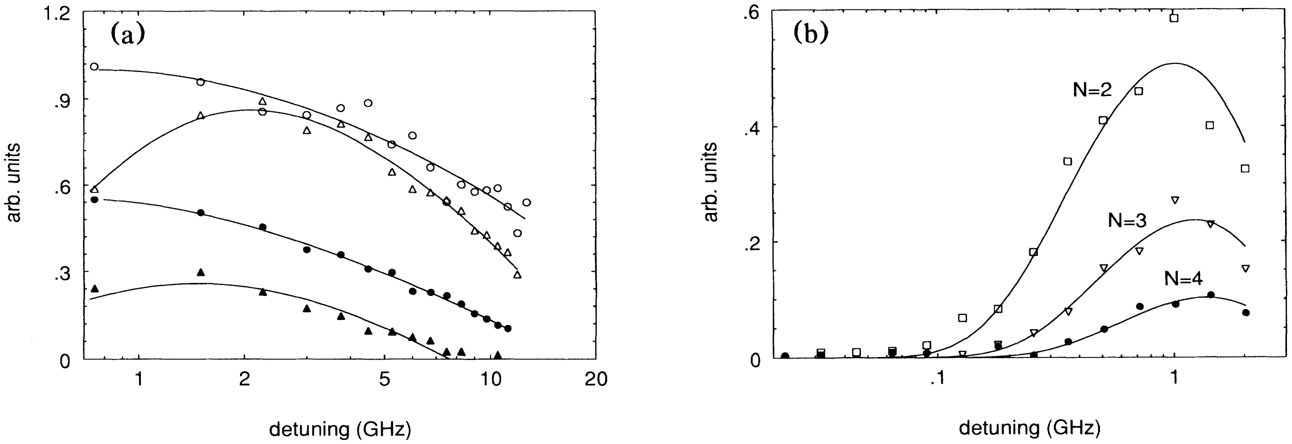

FIG. 2. Number of atoms present after a given number of bounces, as a function of mirror detuning. The curves are a simple fit taking account of loss by photon scattering, and of the effective radius of the mirror (see text). (a) Large detunings. Bounces 1 (○) and 4 (△) at 770 mW, and bounces 1 (●) and 4 (▲) at 400 mW, with mirror waist 0.5 by 0.7 mm. The fourth bounce signals here have been magnified by a factor 10. (b) Small detunings. Bounces 2, 3, and 4 with mirror waist 2 by 2.4 mm at 800 mW. The weak repumping light was present for these experiments.

for a two-level atom. We found $c_U = 0.4 \pm 0.2$; one expects c_U to be below 1 because of the Clebsch-Gordan coefficients for a ground state $F_g > 0$. Also, as expected from Fresnel's laws, we found that the mirror potential was about 2 times higher, through the Ω^2 term, when the incident laser beam was polarized in the plane of reflection, compared to polarization perpendicular to the plane [15].

The form of the detuning curves is dominated at low detuning by losses due to photon scattering. Photon scattering can cause loss either by heating the atoms, or by optically pumping them to a state which is not reflected. Such a state can be either an $F_g = 4$ Zeeman sublevel with a reduced spot size due to a smaller Clebsch-Gordan coefficient, or the $F_g = 3$ hyperfine level in the ground state if the detuning is below 9 GHz (the separation of the $F_g = 4$ and $F_g = 3$ hyperfine levels). In the latter case the atomic mirror produces an attractive potential for atoms in the $F_g = 3$ state, causing them to stick to the glass. Since about 1 in 5 scattering events from $F_g = 4$ leaves an atom in $F_g = 3$, this is the main source of loss by scattering during the reflection, at detunings below 9 GHz. Photon scattering associated with the mirror has two origins: either during the reflection itself [Eq. (2)], or during the free flight because of stray light originating from the beam forming the mirror. Other sources of stray light, and collisional losses, will be independent of the mirror detuning. We distinguished between the two contributions from the mirror light by shutting off the mirror for 30 ms every 50 ms, which reduces the loss during the free flight by 3/5. Also, the weak illumination of the $F_g = 3 \rightarrow F_g = 4$ transition is sufficient to repump the atoms during the 50 ms free fall but not during the $\sim 3\ \mu$s reflection. Without this repumping light the total losses were observed to increase slightly, giving more information on the intensity of the stray light. Our results were consistent with stray light from the mirror beam having an intensity $\eta = 2 \pm 1 \times 10^{-4}$ times that at the center of this beam before it enters the prism. The fits at low detuning in the presence of repumping during the free flight [Fig. 2(b)] were consistent with Eq. (2) with a multiplying factor between 1 and 2.

To summarize this study, we find that in a typical situation such as that of Fig. 1(b), the total loss per bounce [$(39 \pm 1)\%$] may be divided as follows: 5% due to photon scattering during the reflection, 10% due to stray light from the mirror beam, 10% due to background-gas collisions, and the remaining 20% due either to extra sources of stray light or to other causes such as residual misalignments of the mirror spot with respect to the vertical axis. The contribution from background-gas collisions was deduced from a set of bounce signals at various background pressures, which gave a collisional rate of escape of 2 ± 1 s^{-1} at 3×10^{-8} mbar. At higher detunings, the signal-to-noise ratio decreases, but the losses are reduced also. At a detuning of 10 GHz, and a mirror diameter of 1 mm, we observed a loss per bounce of $(27 \pm 2)\%$. This was dominated by losses during the free fall; at this detuning Eq. (2) predicts just 0.05 scattering events per bounce during the reflection itself.

We now consider a few perspectives. The gravitational cavity can be thought of as a shallow "trap" for atoms, in which the internal atomic state is perturbed only during a very small fraction of the motion, as in other neutral particle storage devices such as the hydrogen maser and neutron bottles. For our experiments the trap depth was $\sim 5\ \mu$K horizontally and 1 mK vertically. The loading could be improved by using the "dark funnel" method [16], and the detection made nondestructive by measuring the refractive index of the cloud. Also, the lifetime in the trap can be increased by using a more highly polished fused silica prism to reduce stray light and by enhancing the evanescent wave to enable one to work at higher detunings. An appropriate coating on the glass surface may help with the latter [17].

Finally, a fascinating, though still far off goal is the realization of an atomic Fabry-Pérot interferometer and the observation of its modes. To reduce loss not only of atoms but also of *coherence*, ultrahigh vacuums will be necessary, along with a very good mechanical stability of the mirror. Experimental techniques for matter-wave cavities can be envisaged by analogy with lasers. For instance, the use of a pulsed mirror is a method of mode locking the cavity. In cw operation, transverse mode selection can be achieved by reducing the size of the mirror, while longitudinal mode selection could be performed using Raman velocity selection [3] to adjust very precisely the maximal velocity of the atoms stored in the cavity.

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