Cooling of atoms on reflection from a surface light wave

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A decrease in the transverse kinetic energy of a beam of sodium atoms on reflection from a surface light wave has been observed. The decrease is associated with optical pumping between the ground-state hyperfine sublevels of the atoms. The initial transverse momentum of $42\hbar k$ decreased to $28\hbar k$ after one reflection. © *1995 American Institute of Physics.*

In Ref. 1 a mirror based on a surface light wave produced by total internal reflection of a laser beam from a vacuum–dielectric interface was proposed for neutral atoms. Efficient reflection of atoms from such a mirror was observed for a warm beam (Ref. 2), which is incident on the mirror at a glancing angle, and for cold atoms (Ref. 3).

A new trap for neutral atoms — a gravitational cavity — based on a surface wave was recently proposed in Ref. 4 and realized in Ref. 5 . In this trap spatial localization of Cs atoms falling in a gravitational field is achieved by periodic reflection of the atoms from a surface light wave propagating along a dielectric substrate.

The absence of cooling in such a trap, however, strongly limits its stability. Atoms in the trap are heated as a result of absorbing only several photons of the scattered light and escape from the trap within a time of the order of 100 ms.

A mechanism for cooling alkali atoms reflected from a surface light wave was studied in Refs. 6 and 7 . This mechanism involves the optical pumping of an atom between the its ground-state hyperfine sublevels. It is of interest because it makes it possible to combine low temperature with a high density of atoms, both of which are required in order to observe new physical effects and possibly Bose-Einstein condensation.[7]

First, we recall the basic idea of cooling in a surface light wave. The intensity of the field has the form $I_{ev}(y)=I_{ev}(0)\exp(-2y/\Lambda)$, where y is the coordinate perpendicular to the surface, and $\Lambda=\lambda/2\pi(n^2\sin^2\theta-1)^{-1/2}$ is the characteristic decay length which depends on the angle of incidence θ and the index of refraction n. Figure 1a shows the levels of the D_2 line of the sodium atom and the frequency ω of a surface wave detuned in the blue direction from the frequency ω_0 of the transition between the $|F=1\rangle$ sublevel of the ground state and the excited state $|e\rangle$ of the atom by the amount $\delta=\omega-\omega_0$. The main simplification of this scheme of levels is that the hyperfine structure in the excited state with a characteristic splitting of $\delta_e/2\pi\cong 50$ MHz between the sublevels is ignored, which is justified for $\delta\gg\delta_e$. It is convenient to study the interaction of the atoms with the field of the surface wave in the basis of "dressed states."[8] The dependence of the energy of the triplets of the dressed states of a three-level atom, which are a superposition

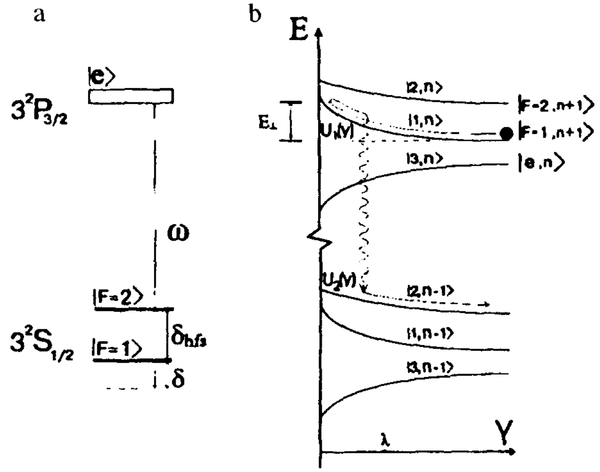

FIG. 1. a) Energy level scheme of the D_2 line of a Na atom and the frequency of the surface light wave; b) spatial dependence of the energy of the dressed states of an atom in a surface wave and the mechanism of removal of kinetic energy from the atom.

of the combined states $|F=1,\ n+1\rangle$, $|F=2,\ n+1\rangle$, and $|e,n\rangle$, where n and $n+1$ are the number of photons of the light field, on its position in the field of the surface wave is shown in Fig. 1b. For weak saturation of the transition,

$$s=\omega_R^2(y)/2\delta^2 \ll 1, \tag{1}$$

the energy of the dressed states 1 and 2 for a linearly polarized light field is determined by the expressions[7]

$$U_1(y)=\frac{2}{3}\frac{\hbar\omega_R^2(y)}{4\delta}, \tag{2a}$$

$$U_2(y)=\frac{2}{3}\frac{\hbar\omega_R^2(y)}{4(\delta+\delta_{hfs})}, \tag{2b}$$

where ω_R is the Rabi resonance frequency, and $\omega_R^2(y)=\omega_R^2(0)\exp(-2y/\Lambda)$. The gradient force $F_{\text{dip}}=-\nabla U_i$ acts on an atom in the dressed state $|i\rangle$.

We assume that the atom is initially in the $|F=1\rangle$ sublevel, and that its kinetic energy is $E_\perp=Mv_\perp^2/2<U_1(0),\ U_2(0)$. In the absence of spontaneous decays such an atom is reflected elastically from the potential $U_1(y)$. In the presence of spontaneous decays the atom can make a transition from the dressed state $|1,\ n\rangle$ into one of the states $|i,\ n-1\rangle$ with decay rates which, in the case of large detunings (1), have the form $\Gamma_{11}\cong q\Gamma s/3$, $\Gamma_{12}\cong(1-q)\Gamma s/3$, and $\Gamma_{13}\cong\Gamma(s/3)^2$, where $q=0.72$ is the coupling coefficient between the excited state and the sublevel[7] $|F=1\rangle$.

According to Eqs. (2), the amplitudes of the potentials of the states $|1,\ n\rangle$ and $|2,\ n-1\rangle$ can differ substantially because of the different detuning of the field with respect to the transitions $|F=1\rangle\rightarrow|e\rangle$ and $|F=2\rangle\rightarrow|e\rangle$. For this reason, the spontaneous

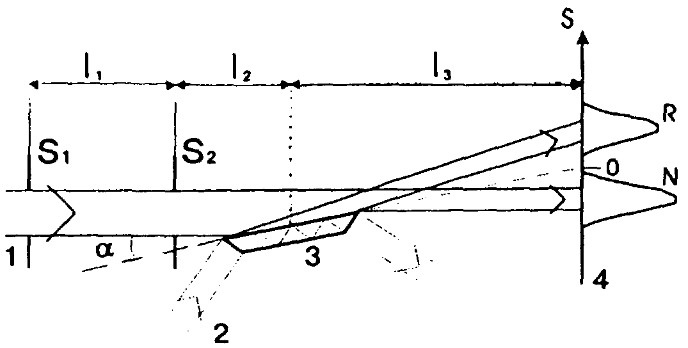

FIG. 2. Experimental arrangement: *1*—Atomic beam; *2*—laser beam; *3*—quartz plate; *4*—registration plane; *R*—peak of the reflected atoms; *N*—peak of the atoms passing by the atomic mirror.

transition $|1, n\rangle \rightarrow |2, n-1\rangle$ at the point y from a deep potential to a shallow potential is accompanied by the loss of the kinetic energy $\Delta E_\perp = U_1(y) - U_2(y)$ by the atom. Knowing the dependence of the decay rate Γ_{12} of the atom on the position of the atom in the surface wave, we can calculate the average energy lost by the atom in one reflection:

$$\langle \Delta E_\perp \rangle = -\int_{-\infty}^{\infty} [U_1(y) - U_2(y)] \Gamma_{12}(y) dt = -\frac{2}{3} \frac{\delta_{hfs}}{\delta + \delta_{hfs}} E_\perp (1-q) n_{sp}, \tag{3}$$

where

$$n_{sp} = \int_{-\infty}^{\infty} (\Gamma_{11} + \Gamma_{12}) dt = (2\Lambda\Gamma/v_\perp)(E_\perp/\hbar\delta)$$

is the total number of spontaneous decays per reflection with weak saturation of the transition (1).

The experimental arrangement for measuring cooling of atoms on reflection from a surface light wave is shown in Fig. 2. The beam of Na atoms was produced by a 0.14 mm in diameter circular diaphragm S_1, placed on the source of the atoms, and by a 0.5-mm-high and 0.24-mm-wide collimating diaphragm S_2. The diaphragms are separated by the distance $l_1 = 250$ mm. A 25-mm-long quartz plate was inserted vertically into the beam at a distance $l_2 = 33$ mm from the collimating diaphragm. The plate was 0.5 mm thick, and its entrance and exit faces were beveled at an angle of 45°, which made it possible to introduce into the plate at an angle a laser beam which by means of multiple reflection within the plate produced on the surface of the plate a penetrating surface wave. The radiation power of the laser beam was $P = 40$ mW, and the radius of the beam at $1/e$ of the intensity was $w = 0.4$ mm. The amplitude of the Rabi frequency in the surface wave is $\omega_R(0)/2\pi = (P\beta^2/2n\pi w^2 I_s)^{1/2}(\Gamma/2\pi) = 560$ MHz, where $I_s = 6$ mW/cm^2 is the saturation intensity of the transition, $\Gamma/2\pi = 10$ MHz is the uniform width of the transition, and $\beta^2 = 6.9$ is the Fresnel coefficient,[9] which relates the intensity of the field in the surface wave with the intensity of the wave in a plate for $n = 1.45$, angle of incidence $\theta = 45°$, and polarization parallel to the plane of incidence.

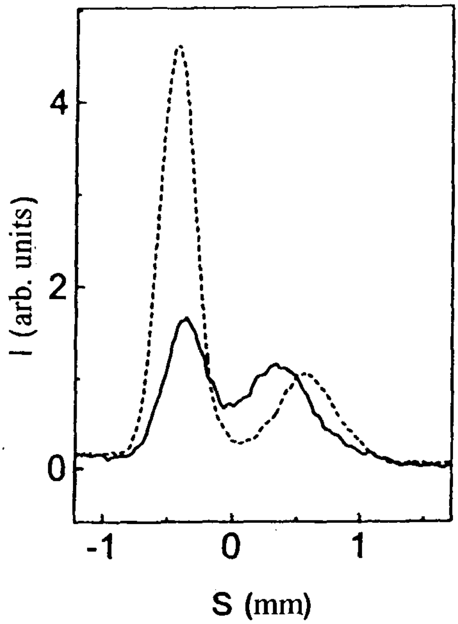

FIG. 3. Profiles of the transverse distribution of the atoms in the beam in the registration plane: dashed profile—mirror reflection, solid profile—reflection with cooling.

The fluorescence signal, recorded at a distance $l_3=322$ mm from the center of the plate, from the atomic beam reflected from the surface light wave was used to probe the spatial distribution of the reflected beam. An additional probe laser beam was used to intersect the atomic beam at an angle of 73°. The probe beam was focused into a spot, with dimensions of 0.5 mm along the atomic beam and 0.2 mm across the beam, and scanned horizontally perpendicular to the atomic beam. The small width ~10 MHz of the lasing line of the probe laser made it possible to tune the frequency of the laser within the Doppler contour of the atomic transition and to perform selective excitation of the atoms via their velocities. The fluorescence was recorded with a photomultiplier. This method makes it possible to detect atoms selectively either in the state $F=1$ or in the state $F=2$.

The measured profiles of the spatial distribution of the atomic beam are shown in Fig. 3. For each profile, the recorded velocity of the atoms is $v=700$ m/s, and the angle of inclination of the plate is $\alpha=1.8$ mrad. The dashed profile corresponds to the case in which the frequency of the surface wave is detuned from the transition $|F=2\rangle\rightarrow|e\rangle$ by the amount $\delta_2/2\pi=[\omega-(\omega_0-\delta_{hfs}+\mathbf{kv})]/2\pi=600$ MHz, where **k** is the wave vector in the surface wave, and $|\mathbf{k}|=(\omega n/c)\sin\theta$. The probe beam probed only atoms in the sublevel $F=2$. In this case normal mirror reflection of the atoms was observed.[2] The right-hand peak in the distribution corresponds to reflected atoms and the left-hand peak corresponds to the part of the initial beam that passed by the plate (Fig. 2).

To observe cooling of the atoms, the frequency of the surface wave was shifted in the blue direction relative to the transition $|F=1\rangle\rightarrow|e\rangle$ by the amount $\delta_l/2\pi=[\omega-(\omega_0+\mathbf{kv})]/2\pi=400$ MHz, and the atoms were recorded, as before, in the sublevel $F=2$. To increase the useful effect, part of the probe radiation was used to prepump all atoms incident on the surface wave into the sublevel $F=1$. Accordingly, only atoms undergoing the spontaneous decay $|1,n\rangle\rightarrow|2,n-1\rangle$, which leads to a transition of an atom from the $F=1$ into the $F=2$ sublevel of the ground state, were detected in the region of detection. The corresponding distribution of the atoms in the region of detection is shown in Fig. 3 (solid line). The left-hand peak corresponds to atoms in the initial beam which have passed by the plate. The presence of this peak is explained by the fact that the atoms passing next to the plate are partially pumped by the scattered light of the surface wave into the recorded sublevel $F=2$. The small shift and deformation of this peak are explained by the light pressure exerted by the pump beam. Comparing this profile with the dashed profile, we clearly see the shift of the peak of the reflected atoms in the direction of small angles. Measurement of the displacement of the center of gravity of the peak of the reflected atoms relative to the zero point, which corresponds to the intersection of the plane of the atomic mirror with the registration plane, gives the value $\Delta s_c=0.385$ mm. This shift corresponds to a reflection angle $\varphi_c=\Delta s_c/l_3\cong 1.2$ mrad. An analogous measurement for mirror-reflected atoms gives $\varphi_s=1.8$ mrad. Therefore, the decrease in the average transverse velocity of the atoms on cooling is $v_c/v_s=\varphi_c/\varphi_s=0.66$. In absolute units this corresponds to a decrease in the transverse momentum from the initial value $p_\perp\cong 42\hbar k$ to the value $p_\perp\cong 28\hbar k$. The relative loss of energy by the reflected atoms in this case is $\Delta E^c/E_\perp=1-(v_c/v_\perp)^2=0.56$. To derive the theoretical value of this ratio, we note that the factor $(1-q)n_{sp}$ in the expression (3) accounts for the probability of a transition between the dressed states $|1,n\rangle\rightarrow|2,n-1\rangle$, so that in analyzing the energy distribution of the atoms which have already undergone a transition, this factor must be set equal to 1. Taking this fact into consideration, we obtain $\Delta E^t/E_\perp=2\delta_{hfs}/3(\delta_{hfs}+\delta_l)=0.54$. As one can see, the measured magnitude of the cooling agrees well with the theoretical value.

The observed cooling of the atoms was maximum near the chosen detuning $\delta_l/2\pi=400$ MHz. Knowing the transverse velocity of the reflected atoms $v_\perp=\alpha v\cong 126$ cm/s and assuming Eq. (2a) is valid, we can determine the maximum penetration depth of an atom into the surface wave and the corresponding maximum value of the Rabi frequency $\omega_R^{\max}/2\pi=\delta_l(3Mv_\perp^2/\hbar\delta_l)^{1/2}/2\pi\cong 330$ MHz. Therefore, the approximation of weak saturation (1) of the transition is valid for the chosen detuning. As the detuning increased, the effect remained observable up to detunings $\leqslant 1.0$ GHz. A decrease in $\Delta E_\perp$ and a decrease in the number of atoms in the cooled peak as a result of the decrease in the probability for optical pumping of the atoms, which is proportional to n_{sp}, were found to be in complete agreement with the theory.

As the detuning decreased, we observed that the cooling effect vanished abruptly and auxiliary effects, associated with the resonance deflection of atoms scattered by the laser light, appeared. When the atomic transition saturates, the cooling effect becomes weaker for two reasons. First, because of the saturation of the transition, the atoms on the average undergo the transition $|1,n\rangle\rightarrow|2,n-1\rangle$ at large distances from the surface, where the potentials (2) are shallower and the momentum of the selected atom decreases.

Second, as the excitation probability of an atom increases, the induced heating of the momentum of an atom as a result of an increase in the rate Γ_{13} increases substantially.

We note that the complete cycle of cooling of the atoms should include the subsequent pumping into the initial sublevel $F=1$. This pumping makes it possible to close the cooling cycle, after which it can be repeated.[8] To return the atom into the initial sublevel $F=1$, after reflection from the surface wave, it is possible to apply a weak field tuned to resonance with the transition $|F=2\rangle \rightarrow |e\rangle$. An estimate shows that to pump an atom into the sublevel $F=1$, the atom must absorb $\cong 3$ photons; the momentum diffusion will be $\Delta p_d \cong \sqrt{3}\hbar k$, which is much smaller than the experimentally measured decrease, $14\hbar k$, in the momentum as a result of one reflection of an atom.

In contrast with the existing methods of cooling in standing light waves,[8,10] the method of cooling atoms by cyclic reflection from a surface wave differs by the fact that this method makes it possible to cool atoms from energies $\sim \hbar\omega_R^2/\delta$ to $\sim \hbar^2 k^2/M$. The parameters of the wave remain fixed. This occurs because as an atom is cooled, its penetration depth into the surface wave decreases and, correspondingly, the characteristic quantum $\sim \hbar\omega_R^2(v_\perp)/\delta$ of its exchange energy with the light field decreases.

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