Radiative collimation of an atomic beam by two-dimensional cooling by a laser beam

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(Submitted 11 August 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 6, 251–253 (25 September 1984)

Two-dimensional radiative cooling of a beam of sodium atoms by radiation-pressure forces has been studied in an axisymmetric standing light wave. The temperature of the transverse motion of the atoms was reduced to 3.5 mK.

Since the first observation[1] of the cooling of atoms by a laser beam, the most significant results have been achieved in the use of lasers to reduce the energy spread of and to cool atomic beams.[2,3] The longitudinal velocities and temperatures achieved in these studies have been comparable to the transverse values, so that the next logical step toward extremely low temperatures is a two-dimensional cooling of an atomic beam. Furthermore, the capability of compressing beams, reducing their dimensions, and reducing their momentum spread (in magnitude and direction)—in other words, the capability of collimating them—is of fundamental importance in many experiments.

Hänsch and Schawlow[4] have pointed out the possibility of using laser beams to reduce the transverse velocities of an atomic beam.

In the present letter we report the first achievement of radiative collimation and two-dimensional cooling of an atomic beam by means of an intense laser beam.

The idea of radiative collimation of an atomic beam can be summarized as follows. An atomic beam (Fig. 1) emerging from source 7 is illuminated by an axisymmetric light field whose frequency (ω) lies on the red side of the frequency (ω_0) of an atomic transition. An axisymmetric field is formed by reflecting a laser beam from a specular-conical surface 5 of a reflecting axion. In the axisymmetric field produced by the

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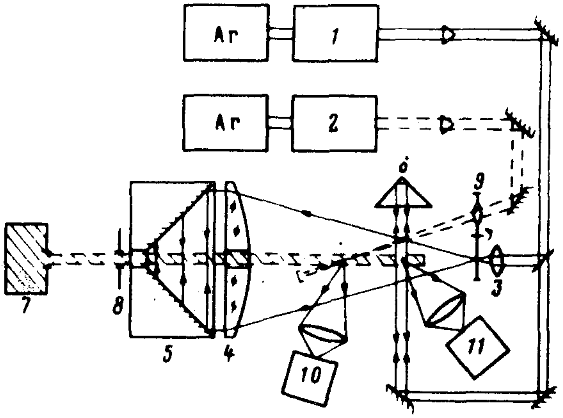

FIG. 1. The experimental layout. 1, 2—Dye lasers; 3, 4—telescope; 5—axion; 6—prism; 7—atomic gun; 8—diaphragm; 9—modulator; 10, 11—photomultipliers.

reflecting axion, a radiation-pressure force acts on an atom whose velocity is directed away from the axis of the cone; if $\omega < \omega_0$, this force is directed toward the axis of the cone. This force causes a rapid contraction of the distribution of atomic velocities in the direction transverse with respect to the cone axis in the region of the axisymmetric field. This contraction in turn causes a sharp decrease in the angular divergence of the atomic beam, i.e., collimates it.

The beam of sodium atoms is produced by two iris diaphragms 1 mm in diameter, one at the gun (7) and the other 14 cm away from it. The original divergence of the atomic beam is $\Delta\phi_0 = 1.4 \times 10^{-2}$. The cone is positioned 2 cm from the second diaphragm. The distance over which the atoms interact with the light in the cone is 35 mm. The distance from the gun to the detection zone is 52 cm. For a cyclic interaction we use the beam from a two-frequency dye laser 1 tuned to a component of the D_2 line of the sodium atom. We choose a frequency difference of 1712 MHz, so that one frequency excites atoms from the level $F = 1(3S_{1/2})$ to the level $F' = 2(3P_{3/2})$, while the other excites atoms from the level $F = 2(3S_{1/2})$ to the level $F' = 3(3P_{3/2})$. Part of the two-frequency beam, which intersects the atomic beam at an angle of 90°, is used to calibrate the frequency scale.

The transverse distribution of beam atoms is determined from the fluorescence signal created by a single-frequency probing field which is scanned over space. The probing beam intersects the atomic beam at an angle of 10°. The frequency of the probing field is tuned to the transition $F = 2(3S_{1/2}) - F' = 3(3P_{3/2})$ and is positioned at the center of the Doppler line of the atomic beam. In this manner we select the atoms with the most probable velocity. The fluorescence signal from the probing field is detected after the two-frequency beam is interrupted. The effective diameter of the probing beam in the detection zone is 0.5 mm.

Figure 2 shows profiles of the atomic beam before and after the interaction with the two-frequency light beam. Each curve reflects the total flux of atoms from the two sublevels of the ground state of the sodium atom. We see an increase in the atomic intensity by a factor of 3.5 and a contraction (collimation) of the atomic beam. Mea-

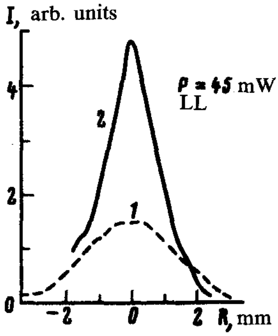

FIG. 2. Transverse distribution of the intensity of the atomic beam. 1—Before the interaction with the laser beam; 2—after.

surements of the diameter of the atomic beam before and after the interaction with the laser field can be used to calculate the change in the transverse velocity of the atoms in the course of their collimation. Calculations for the case in Fig. 2 show that the transverse velocity decreases from 5.5×10^2 cm/s to 1.6×10^2 cm/s. The corresponding decrease in the temperature of the transverse motion is from 42 mK to 3.5 mK.

We have measured the intensity of the atoms at the center of the beam as a function of the frequency of the collimating laser field (Fig. 3). We see from these results that a negative frequency difference leads to a collimation of the beam, while a positive frequency difference decollimates the beam. This behavior of the curves confirms our interpretation of the observed effect as a consequence of the radiation-pressure force, which has a dispersive dependence on the frequency of the laser field in the field of a standing light wave.[5] In addition to the radiation-pressure forces, a gradient

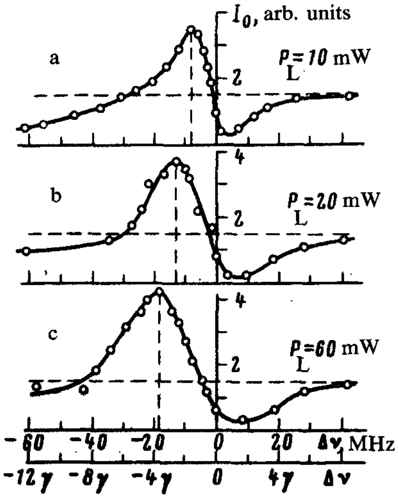

FIG. 3. Intensity of atoms at the center of the beam versus the difference between the frequencies of the laser beam and the frequency of the atomic transition at various power levels.

force influences the motion of the atoms; at high intensities, this force is used to focus atomic beams.[6] Estimates show that this gradient force is negligibly weak under these particular experimental conditions. Furthermore, the dependence of the gradient force on the light frequency is symmetric with respect to the frequency of an atomic transition in the field of a standing light wave. It can be seen from Fig. 3 that for each intensity there is a corresponding optimum frequency of the collimating field. Within the experimental errors, the optimum frequency deviation for the collimating field varies with the intensity of the laser field as $\gamma(1 + I/I_{\text{sat}})^{1/2}$, where I and I_{sat} are respectively the laser beam intensity and the saturation intensity, and γ is the radiative width of the transition. This behavior agrees with the calculations of Letokhov *et al.*[5]

We wish to emphasize that this collimation of an atomic beam has been achieved at a high thermal velocity of the beam and over a short interaction length. Estimates show that the use of a longer collimator or a slower atomic beam would result in (first) a substantial increase in the beam density and (second) an extremely low transverse temperature.

We wish to thank V. G. Minogin for useful discussion.

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Translated by Dave Parsons
Edited by S. J. Amoretty