Radiative slowing and reduction of the energy spread of a beam of sodium atoms to 1.5 K in an oppositely directed laser beam

S. V. Andreev, V. I. Balykin, V. S. Letokhov, and V. G. Minogin
Institute of Spectroscopy, Academy of Sciences of the USSR

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A reduction of the velocity spread of a beam of sodium atoms has been observed experimentally as the beam was slowed by an oppositely directed resonant laser beam. Over an effective slowing distance of 20 cm, the longitudinal velocity distribution of the atomic beam was contracted by a factor of 19; correspondingly, the relative-motion temperature of the atoms was lowered to 1.5 K.

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Laser methods for cooling ions[1] and atoms[2] are being developed actively. The method which has proved most successful so far is the laser cooling of ions in an electromagnetic confinement system, which has produced a temperature of 10^{-2} K (Refs. 3 and 4). The laser cooling of moving neutral atoms, for which no confinement method has been found so far, is a far more complicated problem.

Laser cooling of atoms was first observed experimentally in Ref. 5 in measurements of the deformation of the velocity distribution of a beam of sodium atoms bombarded by an oppositely directed laser beam. In the present letter we are reporting some experiments, carried out with a refined apparatus, which have yielded the first, direct observation of a contraction of the velocity distribution of sodium atoms by an oppositely directed, intense, two-frequency laser beam. The cooling effectively lowered the temperature to 1.5 K and contracted the velocity distribution by a factor $\mu \approx 19$.

The physical reason for the contraction of the velocity distribution is the sharp resonant dependence of the radiation-pressure force on the velocity, as a result of which the force effectively acts on only those atoms which are at resonance with the wave.[6] During the slowing of a thermal atomic beam, the limiting contraction, defined as the ratio of the width of the initial velocity distribution to the width of the final distribution with a zero average velocity, can reach $\mu = (M\bar{v}/\hbar k)^{1/2} \approx 100$ (Refs. 7 and 8). This value corresponds to a reduction of the relative-motion temperature of the atoms to $T = T_0/\mu^2 \approx 10^{-4}\, T_0$, where $\hbar k$ is the momentum of the photon, and M and $\bar{v}$ are the mass and average initial velocity of the atoms.

Figure 1 shows the key parts of the experimental apparatus. An argon laser, L_1, pumps two cw dye lasers, one of which, L_3, slows the atomic beam, while the other, L_2 (a Spectra-Physics Model 580A single-frequency scannable laser), is used as a probe to determine the longitudinal velocity distribution of the atomic beam. The beams from the two lasers enter the vacuum chamber in a collinear manner in the

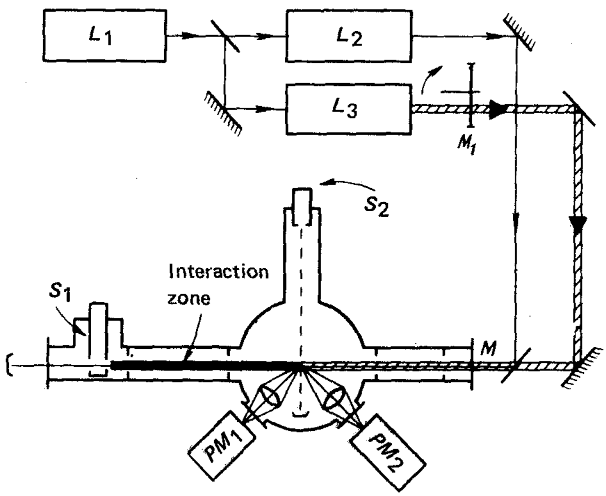

FIG. 1. The experimental arrangement (the zero in which the beam atoms interact with the intense, oppositely directed laser beam is blackened). L_1 –Argon laser; L_2 –probing laser; L_3 –two-frequency, high-power laser; S_1, S_2 –the sources of the parallel and perpendicular atomic beams, respectively; PM_1, PM_2 –photomultipliers; M_1 –mechanical chopper; M–semitransparent mirror.

direction opposite the main atomic beam. The velocity distribution of the atoms is determined from the fluorescence signal $\Phi_{1,2}$ excited by the probing laser. To keep the fluorescence signal from the strong field from interfering with the observation of the weak, fluorescence signal from the probing field, we took measures to separate the fluorescence signal caused by the probing beam from that caused by the strong slowing beam. Specifically, the beam from the high-power laser, L_3, was modulated periodically by a chopper M_1 with a duty factor of 1:1, and the fluorescence excited by the probing beam was measured only at times at which the strong field was cut off. A stroboscopic voltmeter was used to turn the detection system on and off periodically. An auxiliary atomic beam was directed perpendicular to the laser beam for a frequency calibration of the fluorescence signal excited by the probing beam. The output frequency from the high-power laser was tuned to maximize the fluorescence within the Doppler contour of the $3S_{1/2}$ - $3P_{3/2}$ transition ($\lambda = 5896$ Å).

Since the ground state of the sodium atom is split into two hyperfine sublevels, separated by $\Delta\nu = 1772$ MHz, we made the interaction of the atoms with the laser beam cyclic by arranging output from the laser L_3 simultaneously at two frequencies, separated by 1770 MHz. For this purpose we placed three Fabry-Perot etalons inside the laser cavity and adjusted the distance from the dye stream to the "total-reflection" mirror of the cavity to minimize the competition between pairs of axial modes separated by 1772 MHz (Ref. 9). The frequency of the probing laser was scanned along the Doppler contour of the $3S_{1/2}$ - $3P_{3/2}$ transition. The fluorescence in the sodium vapor and the fluorescence of the atomic beam in the absence of the strong laser field were both monitored to ensure a smooth scanning of the laser frequency.

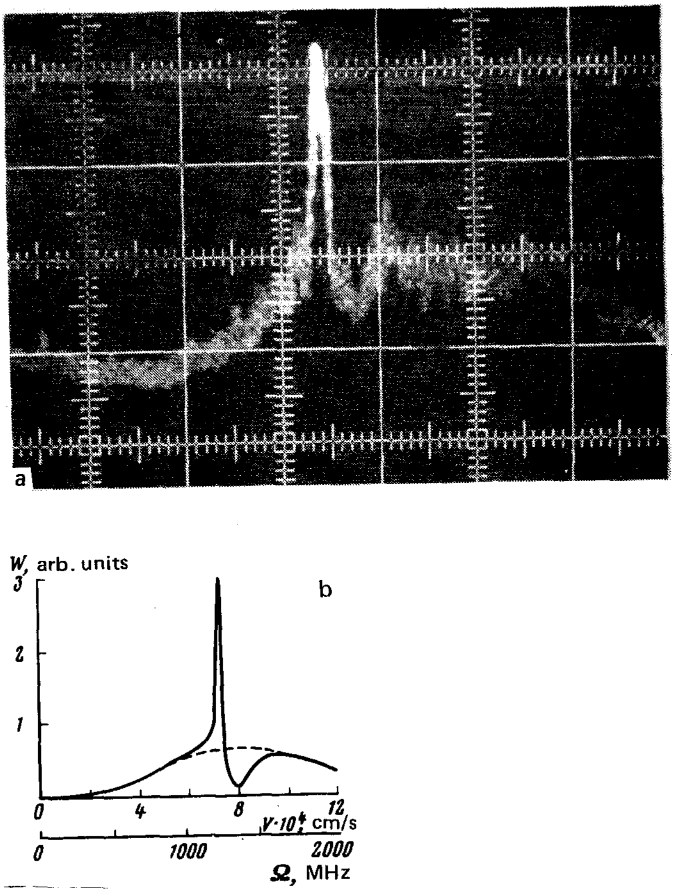

FIG. 2. (a) Experimental profile of the velocity distribution. (b) Calculated deformation of the velocity distribution $W(v)$ of a beam of sodium atoms. Dashed curve–Profile of the initial distribution at a temperature of 573 K. In part (a), the division along the frequency axis is 420 MHz.

The temperature of the source of the parallel atomic beam was 300 °C. The vacuum chamber was pumped down to (3-5) × 10^{-6} Torr. The diameter of the strong laser beam near the exit aperture of the atomic source was $d_s' = 1.1$ mm, and that in the measurement region was $d_s'' = 1.3$ mm; the corresponding diameters of the probing beam were $d_p' = 0.65$ mm and $d_p'' = 0.6$ mm. The geometric length of the interaction zone was 40 cm.

Figure 2a shows an oscilloscope trace of the fluorescence signal resulting from the probing beam as the frequency of this beam was scanned along the velocity distribution deformed by the strong laser beam. This trace clearly reveals a contraction of the longitudinal velocity distribution of the atoms in a region below the resonant velocity. We wish to emphasize that, since the fluorescence was detected only at times at which the strong field was turned off (by the chopper M_1), the characteristic dip and peak on the velocity distribution could not have been caused by joint effects of the two laser beams (for example, a matching of the frequencies at certain times). For the trace in Fig. 2a, the power level of the beam from the strong laser was 12 mW in both modes; the power of the beam from the probing laser was 0.1 mW; and the respective beam diameters were 1.3 and 0.6 mm.

The width of the distribution peak is 70 MHz (or 4.1×10^3 cm/s in velocity units), and with an initial beam temperature of 573 K this width corresponds to a contraction factor $\mu = \Delta\nu_0/\Delta\nu_{\text{cont}} \approx 19$ or to an effective relative-motion temperature of 1.5 K. The shift of the peak from the resonant frequency is 150 MHz, in good agreement with a simple calculation from the Liouville equation, which predicts a shift of 130 MHz (Fig. 2b).

In conclusion we wish to emphasize that the deformation of the velocity distribution was achieved over an effective slowing (interaction) distance of 20 cm. Estimates show that an increase in this distance to ~1 m would make it possible to slow a substantial fraction of the atoms and to reduce their velocity spread to essentially zero.

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