Cooling of sodium atoms by resonant laser emission

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(Submitted 4 October 1979)
Zh. Eksp. Teor. Fiz. **78**, 1376–1385 (April 1980)

Results are presented of an experimental investigation of cooling of sodium atoms in an atomic beam by resonant laser radiation using the light-pressure forces. The translational kinetic energy of the atoms was drawn from the scattered spontaneous radiation. To ensure multiple interactions of the atom with the radiation, the atom was optically oriented by circularly polarized (σ^+) laser radiation. As a result, the atom landed on the sublevel $F=2$, $m_F=2$ of the ground state, from which it interacts with the radiation as a two-level system. The atoms were cooled with a cw laser whose emission continuously attuned itself to the resonant frequency of the decelerating atom. The degree of cooling of the atoms in the beam was determined by the deformation of the Doppler contour of the absorption line.

PACS numbers: 32.90. + a, 41.80. − y

1. INTRODUCTION

The idea of the possibility of using intense laser radiation to cool atoms was advanced in Ref. 1, where it was proposed to act on the low-frequency part of the Doppler contour in low-pressure atom vapor. The translational kinetic energy is drawn in this case from the scattered spontaneous radiation. A different approach to cooling by laser radiation was proposed in Ref. 2. If the ions are localized first in an electromagnetic trap, then the absorption and emission spectra will be modulated via the Doppler effect at a radio frequency ν_1 when the ions move in the trap. When the ions are exposed to laser radiation, say at the frequency $\nu_0-\nu_1$ (ν_0 is the central frequency of the transition), the symmetrical emission of photons at the frequencies $\nu_0, \nu_0\pm\nu_1, \nu_0\pm 2\nu_1$ makes possible a redistribution of the energy between the radiation and the translational motion of the ions, as a result of which the ions are cooled.

Letokhov *et al.*[3] have proposed and devised a method of adiabatic cooling of atoms in a resonant laser field with a scanned frequency, in which the cooling is made possible by laser radiation that attunes itself continuously to the resonant frequency of the decelerating atom.

The first to be experimentally cooled were Ba^+ and Mg^+ ions[4,5] localized beforehand in electromagnetic traps and exposed to laser radiation. We have previously[6] reported briefly observation of cooling of sodium atoms in a resonant laser field with scanned frequency. In the present paper we report in greater detail further experiments on the cooling of free sodium atoms.

2. FORMULATION OF PROBLEM

The idea of the experiment is the following. When the atom is irradiated by an opposing resonant light wave, the two-level atom at resonance with the laser radiation is acted upon by the spontaneous light-pressure force (Fig. 1)[7]

$$F_{sp}=\hbar k\gamma\frac{G}{1+G+(\Omega-\mathbf{kv})^2/\gamma^2}, \qquad (1)$$

where $\hbar k$ is the photon momentum; $G=d^2\mathscr{E}_0^2/2\hbar^2\gamma^2$ is the saturation parameter; $\mathscr{E}=\mathscr{E}_0\cos(\omega t-\mathbf{kv})$ is the light-wave electric-field intensity; Γ is the natural half-width of the line of the transition under consideration; $\Omega=\nu-\nu_0$ is the difference between the frequency ν of the laser radiation and the central frequency ν_0 of the atomic transition; $\mathbf{v}$ is the velocity of the atom, and $\mathbf{k}$ is the wave vector. The force of the spontaneous light pressure of the opposing wave slows down the atom, and its absorption frequency goes off resonance with the laser field. If the frequency of the laser radiation is continuously attuned to the resonant frequency of the decelerating atom, then deep cooling of the atom can be obtained.[3] This cooling regime is called adiabatic.

The atoms in the beam have a velocity that corresponds to a Doppler absorption-line contour with a maximum corresponding to the most probable velocity of the atoms. If the frequency laser is scanned along the absorption-line contour of the sodium atoms by a sufficiently intense ($I_L \gg I_{sat}$) laser radiation, then this scanning should be accompanied by a slowing down of the atoms by the laser radiation, i.e., by a decrease of the fraction of fast atoms and by an increase of the fraction of the slow atoms, and consequently by a deformation of the absorption line contour. The narrow-band single-mode laser radiation interacts with a small group of atoms from the Doppler contour, within the limits of the homogeneous width of the absorption line. If the laser frequency is adiabatically scanned along the Doppler contour towards the lower frequencies, the velocity of this group of atoms decreases, and consequently the absorption frequency shifts to the long-wave part of the spectrum by an amount equal to the change of the laser frequency. New groups of atoms from the Doppler contour then become resonant with the radiation. In the ideal adiabatic-scanning case the slowing and "gathering" of the atoms should take place from the entire Doppler contour, beginning with the frequency ν in at which the scanning of the radiation initiated, and ending with the frequency ν_0 corresponding to atoms

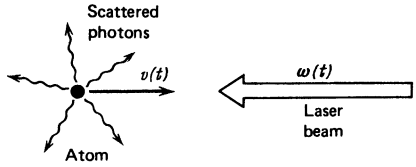

FIG. 1. Slowing down of an atom by an opposing resonant light wave: $\omega_{at}=\omega_0(1-v(t)/c)\equiv\omega_L$.

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with zero velocity. In a real experiment there are always factors that prevent such a continuous crowding of the atoms towards the frequency ν_0. These factors will be discussed later on.

The crucial requirement in cooling of atoms by the force of spontaneous light pressure when the laser frequency is scanned is to ensure continuous and cyclic excitation of the atom during its interaction with the radiation. The number of photons scattered by the atom determines in final analysis the change of the atom velocity. Continuity of the interaction is essential if the group of atoms interacting with the scanning radiation is to stay at resonance with the radiation.

In the present study, the interaction of the radiation with the sodium atom (its first and excited levels are shown in Fig. 2) was made cyclic by optically orienting the atom.[8] Intense circularly polarized (σ^+) laser radiation interacting with those atoms whose frequency of the transition $F=2 \rightarrow F'=3$ is at resonance with the radiation (Fig. 3) excites transitions with $\Delta m=+1$. As a result of these transitions, the atom lands very rapidly on the sublevel $F=2$, $m_F=2$. The only possible transition from this sublevel is to the sublevel $F'=3$, $m_F'=3$. The nonresonant transitions $F=2$, $m_F=2 \rightarrow F'=2$, $m_F'=-2, -1, 0, +1, +2$ are forbidden by the selection rules. The atom is thus assured of multiple cyclic interaction with the laser radiation on the sublevel $F=2, m_F=2$.

3. EXPERIMENTAL SETUP

The experimental setup is illustrated in Fig. 4. It consists of the following basic elements: A cw dye laser (*1*) (Spectra Physics model 580A), a cell with sources of the main (*11*) and reference (*10*) atom beams, a recording system, (*5,6*) for the fluorescence signal from the atoms (photomultiplier, oscilloscope), a system for scanning the laser frequency (*4*), based on a scanning block (Spectra Physics model 481A), a control cell with sodium vapor (*2*), and a system for monitoring the laser frequency and the scanning regime. The maximum scanning rate of the dye laser *1* was 370 MHz/msec, whereas for adiabatic cooling at a laser power $I_L=5I_{sat}$ the required frequency-scanning rate is 1360 MHz/msec. We have constructed on the basis of the 481A block a scanning system in which a rate up to 1400 MHz/msec could be achieved. The scanning rate could be varied discreetly and increased by a factor of 2 compared with the preceding one.

The main atomic beam was collimated by two diaphragms, with $d_1=1.2$ and $d_2=2$ mm, spaced 30 cm apart. In the experiment, the laser radiation was scanned from a frequency ν_{in}, such that $\nu_{in}-\nu_0=v_{pr}\nu_0/c=1380$ MHz, and corresponding to v_{pr} (v_{pr} is the most

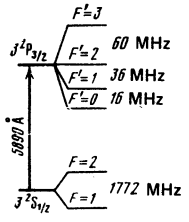

FIG. 2. Energy diagram of hyperfine structure of the D_2 line of sodium.

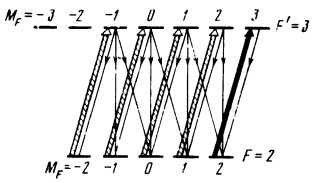

FIG. 3. Optical orientation of sodium atom by circularly polarized (σ^+) laser radiation.

probable atom velocity in a parallel beam at 300° C). The time of interaction of the radiation with the atoms was $t=v_{pr}/(F/m)=1.03\approx 1$ msec, and the interaction length (from the first diaphragm to the observation re-tion) was 38 cm. An image of the region of intersection of the main and reference atom beams was produced on the cathode of the photomultiplier. The registered fluorescent signal could be due to the atoms of the main beam, to those of the reference beam, or to both. The main atom beam was collinear with the laser beam and the reference beam was perpendiuclar to the laser beam. The reference atom beam was used for absolute and relative calibration of the frequency scale.

To obtain circularly polarized (σ^+) radiation, we used a Glan prism and a quarter-wave plate, paying particular attention to obtaining and monitoring the degree of polarization of the radiation. To this end, the source of the main atomic beam and the exit window of the cell were removed prior to the experiment, and the degree of polarization of the radiation was estimated from the laser beam reflected by a mirror behind the cell and passing in the opposite direction through the quarter-wave plate and the Glan prism. The cell in which the radiation interacts with the atomic beams was evacuated with diffusion pumps to a pressure $p=5\times10^{-6}$ Torr.

The temperature of the source of the main beam was 250–350° C, that of the reference beam 200° C. A weak magnetic field ($H\approx 1$ G) was applied along the laser beam in the cell to prevent redistribution of the populations of the magnetic sublevels by the scattered light.

4. RESULTS OF THE EXPERIMENTS

Figure 5a shows the absorption line contour of the atoms in a perpendicular beam used to calibrate the fre-

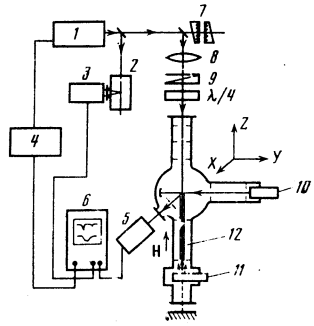

FIG. 4. Diagram of experimental setup: *1*—dye laser, *2*—monitoring cell with sodium, *3*, *5*—photomultipliers, *4*—laser-frequency scanning block, *6*—oscilloscope, *7*—interferometer, *8*—lens, *9*—polarizer, *10*, *11*—ovens of atomic beams, *12*—region of interaction of atomic and laser beams.

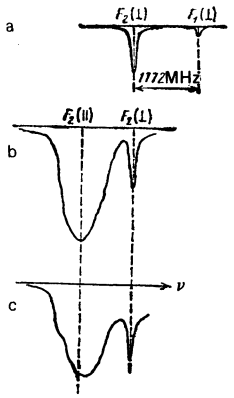

FIG. 5. Absorption line contours of atoms: a—in perpendicular beams, b, c—in parallel and perpendicular atomic beams. Scanning rates: b—46 MHz/msec, c—370 MHz/sec. Laser radiation intensity 50 mW/cm^2.

quency scale. The two absorption maxima correspond to the hyperfine splitting of the ground state of the sodium atom. The position of the maximum $F_2(\perp)$ on the frequency scale corresponds to the frequency of the absorption of the atoms from the parallel atomic beam with zero velocity.

Figure 5b shows the combined absorption contours of the atoms in the parallel and perpendicular beams at a slow rate (46 MHz/msec) of laser-radiation frequency scanning, i.e., in a regime far from adiabatic. At this scanning rate the effects of resonant action cannot influence the motion of the atoms, and the curves represent the atom absorption contours in both beams.

By way of example of the influence of the light pressure on the motion of the atoms, Fig. 5c shows the deformation of the contour in a parallel beam at a scanning rate 370 MHz/msec. When this contour is compared with the contour of Fig. 5b it is seen that the maximum of the absorption contour shifts into the frequency region corresponding to the slower atoms, and a fluorescence signal is observed from the parallel beam at frequencies corresponding to the slow atoms. That is to say, the laser radiation causes a redistribution of the atom velocities.

Figure 6 shows the absorption-line contours of the atoms in parallel and perpendicular beams at a laser-

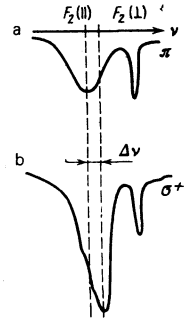

FIG. 6. Absorption-line contour in parallel and perpendicular atomic beams: a—excitation by radiation with linear π polarization, b—excitation by radiation with circular σ^+ polarization.

radiation frequency scanning rate $\Omega = 370$ MHz/msec and at different polarizations of the laser radiation.

In the case of linear (π) polarization of the radiation, under the conditions of our experiment, multiple interaction of the atom with the radiation is impossible because the atoms go off to the sublevel $F = 1$. If circular polarization (σ^+) is used, the atom becomes optically oriented and as a result it can interact with the radiation repeatedly. This can lead to the appearance of a noticeable light-pressure force on the atoms in the beam, i.e., to slowing down of the atoms, as is demonstrated by the displacement of the maximum of the absorption line contour in the parallel atomic beam.

We measured the dependence of the displacement of the maximum of the absorption line contour in a parallel beam on the rate of scanning of the radiation frequency. It is seen in Fig. 7 what with increasing scanning rate the displacement of the contour maximum is increased, and the largest displacement is attained in the adiabatic scanning regime and amounts to $\frac{1}{4}v_{pr}$.

The right-hand scale of Fig. 7 shows the average temperature of the atoms that interact with the radiation; this temperature was determined from the maximum of the absorption line contour in the atomic beam. The ensemble of atoms newly produced as a result of the interaction with the radiation is not necessarily an equilibrium thermodynamic system. Therefore, strictly speaking, it is no longer possible to assign an average temperature to the maximum of the absorption-line contour. It is more correct to define the temperature of the atoms in terms of the mean squared velocity of the ensemble of atoms:

$$T = \frac{m}{2k}\langle (v - \langle v\rangle)^2\rangle, \qquad (2)$$

where

$$\langle v\rangle = \frac{1}{N_0}\int_0^\infty vN(v)\,dv, \quad N_0 = \int_0^\infty N(v)\,dv,$$

$\langle v\rangle$ is the average velocity of the atoms and $N(v)$ is the atom velocity distribution that results from the interaction with the radiation. Equation (2) was used to determine by numerical integration the maximum change of the temperature of the atoms in the course of the interaction with the radiation. The change of the temperature was 73°.

It was of interest to estimate the number of laser photons reradiated by the sodium atom at the maximum observed displacement of the maximum of the absorp-

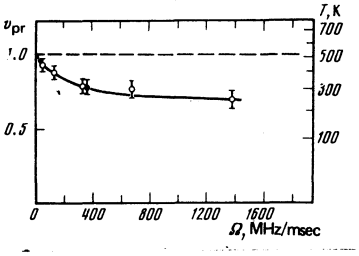

FIG. 7. Dependence of the shift of the center of the absorption contour in a parallel atomic beam on the rate of laser frequency scanning (the point ● corresponds to Fig. 5c).

tion line contour. It turned out to be

$$N=mv_{pr}/4\hbar k=6\cdot 10^3 \text{ photons.}$$

Figure 8b shows the changes of the absorption-line contours in combined parallel and perpendicular beams with changing laser-radiation intensity. To monitor the laser scanning regime, we scanned the absorption-line contour of the sodium atoms in vapor—see Fig. 8a (t = 90 °C; the laser-radiation intensity was constant in all three cases I–III: I_L = 0.3 mW/cm²). At high radiation power (cases II and III), to estimate the signal at the frequency corresponding to atoms at rest, we measured the absorption line contour only in the perpendicular beam (Fig. 8c) at the same values of the laser intensity as for the case of scanning the combined contours of the parallel and perpendicular atomic beams (Fig. 8b, cases II and III). All the measurements were made at a laser-frequency scanning rate Ω = 1400 MHz/msec. For cases b and c, the intensities of the laser radiation were the following: I—1.85 mW/cm², II—14.6 mW/cm², III—400 mW/cm².

A characteristic feature of the presented oscillograms is the following. A displacement of the maximum of the absorption line contour towards zeroth frequencies, analogous to the displacement produced when the scanning rate is changed, and an increase in the fluorescence signal at zeroth frequencies ν_0. A particularly s strong change of the contours observed at I_L = 400 mW/cm². At an intensity I_L = 14.6 mW/cm² the absorption line contour shows signal spikes, whereas the absorption line contour in vapor is smooth. The latter is evidence of a smooth change in the laser frequency, and that the possible instability of the frequency scanning rate is not the cause of these spikes. For cases I and II of Fig. 8, the rate of scanning of the frequency of the laser radiation exceeds the rate of deceleration of the atoms (owing to the insufficient intensity of the laser radiation), and therefore the resonant absorption frequency of the atoms does not manage to attune itself to the changing laser frequency. It is this which chops up the absorption line contour in case II of Fig. 8b.

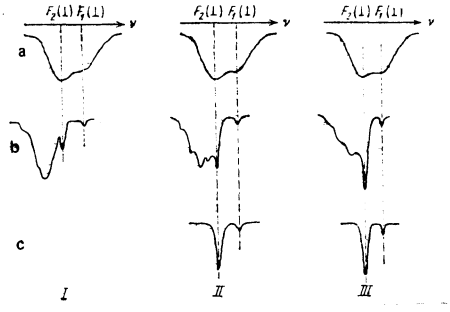

FIG. 8. Evolution of the absorption line contour in a parallel beam with varying intensity of the laser radiation (Ω = 1400 MHz/msec throughout): a—absorption line contour of sodium atoms in vapor (control cell, t = 90°C, the laser radiation intensity for all cases I–III is I_L = 0.3 mW/cm²); b—combined contour of absorption line in parallel and perpendicular atomic beams, c—absorption-line contour in perpendicular beam. For cases b and c, the laser radiation intensity is: I – I_L = 1.85 mW/cm², II – I_L = 14.6 mW/cm², III – I_L = 400 mW/cm². The absolute and relative calibration of this scale is against the position of the maxima of $F_2(1)$ and $F_1(1)$ (the frequency scale for case III differs from that for cases I and II).

Only for case III is the rate of change of the radiation frequency close to the change of the resonant frequency of the sodium atoms on account of the light-pressure force, and it is this which slows down the atoms. It should be noted that at such a high radiation power the atoms can go off very rapidly to the ground sublevel F = 1 on account of the fraction of π-polarized radiation, and it might seem that the atoms should not interact with the laser radiation if the broadening of the levels by the laser radiation is disregarded.

The absorbed laser-radiation power is given by[8]

$$I(\Delta\nu)=\frac{h\nu}{2T}\frac{I_D/4\tau^2}{(\Delta\nu)^2+(I_D+1)/4\tau^2}, \tag{3}$$

where $\tau = 1/A$, A is the Einstein coefficient for the spontaneous transition, $\Delta\nu$ is the frequency detuning, and $I_D = I_L/I_{L0}$ (I_{L0} = 6 mW/cm²).

The ratio of the absorbed power at the line center to the absorbed power at a frequency displaced by the width of the hyperfine structure (1772 MHz) is

$$I(\Delta\nu=1772 \text{ MHz})/I(\Delta\nu=0)=2.15\cdot 10^{-3};$$

i.e., at the frequency corresponding to the transition of the atom from the F = 1 sublevel, the spectral power of the radiation is 1/10 of the spectral power necessary to saturate the transition at I_L = 400 mW/cm².

Thus, at high radiation power it is possible to transfer the atom to a state with F = 2, in which it again interacts effectively with the laser radiation and is cooled. We note that the advantages of the strong-saturation regime and of the corresponding strong field broadening in systems for cooling and dragging of atoms was noted in Ref. 9.

5. DISCUSSION OF RESULTS

In adiabatic scanning of the laser frequency along the Doppler contour from the initial frequency ν_{in} to ν_0, and in continuous cyclic interaction of the radiation with the atoms, the fluorescence signal at the frequency ν_0 is given by the expression

$$I_{fl}(\nu_0)=\text{const}\cdot\int_{\nu_{in}}^{\nu_0} I(\nu)\,d\nu$$

$$=\frac{I_{max}}{\Delta\nu_{hom}}\int_{\nu_{in}}^{\nu_0}\left(\frac{\Delta\nu}{\Delta\nu_{pr}}\right)^3\exp\left[-\frac{3}{2}\left(\frac{\Delta\nu}{\Delta\nu_{pr}}\right)^2\right]d\nu=0.68\frac{I_{max}(\nu_{in}-\nu_0)}{\Delta\nu_{hom}} \tag{4}$$

where $I(\nu)$ is the Doppler contour of the absorption line in the parallel atomic beam, and I_{max} is the fluorescent signal at a fixed laser frequency at the center of the Doppler contour. The fluorescence signal at the frequency ν_0, relative to the fluorescence signal at the maximum of the Doppler contour, under the conditions of our experiment ($I = 5I_{sat}$ and t = 300°C), is equal to

$$I_{fl}'=0.68\frac{(\nu_{in}-\nu_0)I_{max}}{\Delta\nu_{hom}(1+I/I_{in})^{1/2}}, \tag{5}$$

i.e., in the ideal case we should observe in our experiment a displacement of all the particles of the Doppler contour (starting with the frequency ν_{in}) towards the central frequency ν_0, and a corresponding increase of the fluorescence signal by a factor of 60 compared with

the signal at the maximum of the absorption contour. In experiment one observes a shift of the maximum of the Doppler contour and a negligible increase of the signal at the central frequency.

We propose that the main causes that prevented us from realizing deep cooling of the atoms in this experiment were the following:

1. The presence of parasitic linear polarization (see Fig. 9b). The degree of polarization of the laser radiation at the entry to the cell is 99%, and in the inside of the cell it is 97%. One of us[10] calculated the departure of the atoms to the sublevel $F = 1$ due to the presence of a fraction of linear polarization in the laser radiation. At an interaction time 1 msec and at 3% linear polarization, the number of particles remaining on the sublevel $F = 2$ is 0.1 of the initial population of the level. Measurements at high power, case III of Fig. 8b, confirm the assumption that the linear polarization exerts an influence.

2. The resonance of the laser radiation with the atoms from the Doppler contour takes place in the scanning regime for a small group of atoms, whose number increases as the line center is approached, but within a range of ~20 MHz (with allowance for the field broadening). At a scanning rate 1400 MHz/msec the 20 MHz frequency interval is scanned in a time of 15 μsec. This means that if the laser frequency breaks down for a time 15 μsec (by acoustic vibrations, vibrations of the jet, etc.) while the mechanical elements continue to be scanned, then the radiation ceases to interact with the preceding group of atoms after the cessation of the perturbation that has led to the brief frequency deviation. This is equivalent to a new start of scanning, but only with a second initial frequency ($\nu'_{in} > \nu_{in}$), closer to the zeroth frequency ν_0. In our experiment we did not monitor the laser frequency stability in the indicated range of time and frequency.

3. Loss of cyclicity of the interaction, which occurs also during the initial stage of the orientation of the atom on account of the absorption line wing, Fig. 9a.

6. CONCLUSION

We have demonstrated in this paper the cooling of sodium atoms by circularly polarized laser radiation. We have analyzed the possible causes that prevent deep cooling of the atoms. It is clear from the results of this paper that realization of deep cooling of atoms calls for the use of a more effective scheme of multiple cyclic interaction of the atoms with the laser field. For sodium atoms, for example, it is possible to use scanned 2-frequency radiation, which excites the atoms from both sublevels F_2 and F_1. There is no doubt that it is simplest to cool atoms of those elements whose ground state is not split by the hyperfine interaction, and between the ground level and first excited state of which there are no metastable states, for example even isotopes of alkaline-earth elements. Unfortunately, at the present time the frequency range of dye laser does not extend to the ultraviolet, where the resonant transitions of most elements are located. However, taking into account the constant progress in laser technology, one can hope to perform cooling experiments with the indicated atoms.

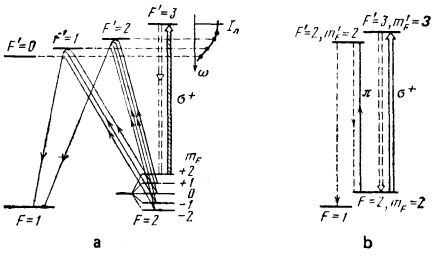

FIG. 9. Channels of loss of cyclic interaction of Na atoms with laser radiation. a—loss due to the presence of absorption-line wing of Na atoms, b—loss due to the presence of linear polarization in the laser radiation.

In conclusion, the authors are grateful to V. G. Minogin for helpful remarks during the discussion of the results and to L. A. Bol' shov for advice in the course of reading the manuscript.

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Translated by J. G. Adashko