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Collimation and Decollimation of Atomic Beams by Laser Radiation

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Abstract. Efficient collimation and decollimation of an atomic beam by spontaneous radiation pressure acting on the atoms in axially symmtric light fields has been accomplished. The on-axic atomic-beam intensity was changed by 800 times. The entire effect of collimation and decollimation takes place in a laser-frequency variation about the natural line width.

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Many experiments in physics are connected with the application of particle beams. The results of such experiments depend greatly on the degree of the compression of the particle beam in both coordinate and momentum spaces, that is, they depend on the degree of collimation. According to the nature of particles, the problem of particle-beam collimation has so far been solved to a variable degree. The collimation of charged particles, for example, is already in use in experimental set-ups but, at the same time, it is still unknown how to collimate neutral particle beams.

The analysis of different methods of collimation of charged particles (electrons, protons, heavy charged particles, etc.) shows that common to them is the use of *dissipative forces* when a part of the energy from the particles being collimated is transferred to an external system where the beam is transformed. It may be assumed that the application of dissipative forces may turn out to be useful in collimating neutral particle beams as well.

The possibility of action of the light pressure dissipative force on the transverse velocities of atoms in a beam was first mentioned in [1]. In our recent experiment [2] we demonstrated the possibility of collimating beams by laser-radiation light pressure.

The present paper continues studying the possibilities of atomic-beam collimation and decollimation. These phenomena are strong enough that significant applications can be envisioned. The action of the light-pressure *potential-gradient force* on the spatial parameters of atomic beams have been studied in [3, 4].

1. Principle of Collimation and Decollimation of Atomic Beams

Let an atomic beam interact with an axisymmetric light standing-wave formed by the laser radiation reflected from a mirror-conical surface (Fig. 1). If the laser frequency ω is less than the atomic transition frequency $\omega_0 (\omega < \omega_0)$, the atom whose transverse component of the ϑ_ϱ velocity is directed from the axicone axis is acted upon by a spontaneous light-pressure force directed to the axicone axis. At low velocities $(\vartheta_\varrho \ll |\Omega| / k)$ this force is reduced to a friction force [5]

$$F = -\beta m \vartheta_\varrho , \tag{1}$$

where β is the dynamic friction coefficient having the value

$$\beta = -\frac{4\hbar k^2}{m} \frac{\Omega}{\gamma} G \left(1 + \frac{\Omega^2}{\gamma^2}\right)^{-1} \times \left(1 + \frac{\Omega^2}{\gamma^2} + 2G\right)^{-1} . \tag{2}$$

Here k is the wave vector, 2γ is the natural line width, G is the saturation parameter of the atomic transition, $\Omega = \omega - \omega_0$ is the detuning of the laser frequency ω relative the atomic transition frequency ω_0, m is the

mass of the atom. Due to the action of this force the transverse-velocity distribution of atoms is narrowed in the region of an axisymmetric field. This, in turn, results in a decrease of the atomic-beam angular divergence, that is, beam collimation.

If the detuning of the laser frequency about the atomic transition frequency changes in sign ($\omega > \omega_0$), the light-pressure force changes its sign, too, and increases the transverse velocity of the atom. This means that now its action increases the angular divergence and causes the atomic beam to spread (to decollimate).

Thus, by varying the detuning sign one can both collimate and decollimate an atomic beam.

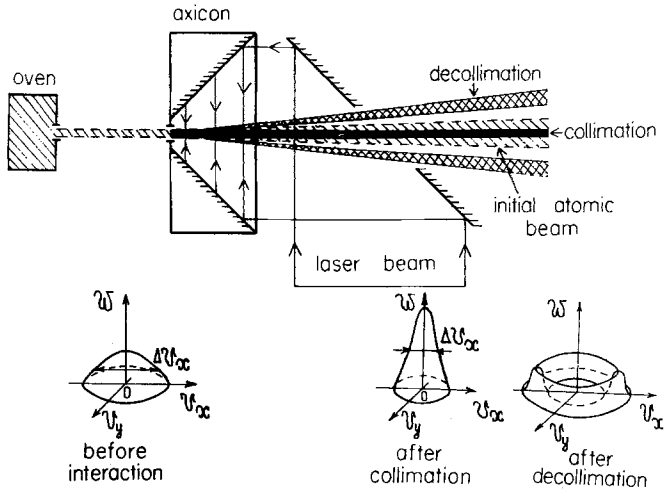

Fig. 1. Collimation and decollimation of an atomic-beam by laser radiation

2. Experimental Set-Up and Exitation Scheme

The experimental set-up has been described comprehensively in our previous paper [2, 7]. Here, we wish to call just its basic elements and the modifications which have been introduced.

The experiment was performed with sodium atoms. The atomic oven (the outlet diameter is 1 mm) was placed at 6.5 cm from the diaphragm 1.1 mm in diameter (Fig. 1). The distance between the diaphragm and the detection zone was 36 cm. The atomic beam divergence was originally $\Delta\varphi_0 = 3.2 \times 10^{-2}$ rad. The length of interaction between the atoms and the axisymmetric standing wave was 35 mm. A two-frequency cw dye laser with active stabilization of its frequency by an external Fabry-Perot etalon was used as a source of excitation [6]. Its frequency jitter and drift during the experiment was approximately $1 \div 2$ MHz.

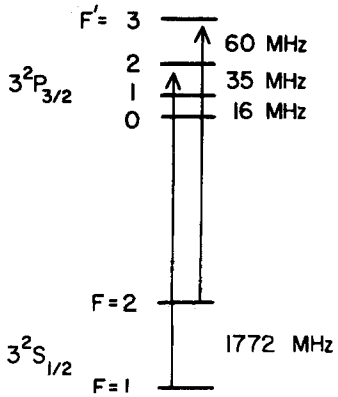

Fig. 2. Excitation of sodium atoms by two-frequency laser radiation

The four-level scheme excitation of sodium atoms by laser radiation was used in the experiment (Fig. 2). The two-mode radiation was tuned to the D_2 line of the sodium atoms. The frequency difference was 1712 MHz. One frequency excited the atoms from the level $F=1(3S_{1/2})$ to $F'=2(3P_{3/2})$, the other frequency excited them from $F=2(3S_{1/2})$ to $F'=3(3P_{3/2})$.

The excitation of the atoms from both sublevels of the ground state excluded optical pumping and thus provided cyclic interaction between the atoms and the radiation. Their excitation to two different sublevels of the hyperfine structure of the excited state made it possible to avoid coherent trapping of the population of the sublevels of the ground state [8].

The atomic-beam profile was measured by recording the fluorescence excited by an additional single-mode dye laser. For this purpose the radiation focused by a long-focus lens crossed the atomic-beam in the plane of Fig. 1 at an angle of 10°. In the perpendicular plane the laser beam moved parallel to itself within several diameters of the atomic beam. The probing transition frequency was tuned to the frequency of the transition $3S_{1/2}$ ($F=1$ or $F=2$) $-3P_{3/2}$ and was set within the atomic-beam Doppler contour. The use of single-mode laser radiation and an almost longitudinal intersection of the atomic-beam with the laser beam allowed recording the atomic-beam profile with a definite longitudinal velocity. The atomic-beam profile was measured on the sublevels $F=2$ and $F=1$. The real distribution was determined by summing the both profiles.

The measurement of the atomic-beam profile with a definite spatial transverse (rectangular) distribution gives an effective value for the probing beam diameter which is equal to 1.4 mm.

It should be noted that in this experiment we measured the transverse coordinate distribution of the atomic-beam. It was impossible to determine the transverse velocity distribution because even at the initial collimation of the beam the transverse Doppler broadening of the absorption line is comparable to its homogeneous width.

3. Experimental Results

Figure 3 presents the profiles of the atomic-beam before and after its interaction with the laser radiation. The two-frequency radiation power is 60 mW. The laser radiation frequency is red-shifted from the atomic transition frequency ($\omega-\omega_0\simeq-3\gamma$). The results are given for the atoms whose longitudinal velocity is 7.3×10^4 cm/s. The intensity at the center of the beam increases considerably, by 5 times. At the same time the atomic-beam becomes narrowed (collimated). The measurement of the beam diameters before and after interaction with the radiation, with allowance made for the final diameter of the probing beam, makes it possible to calculate the change of the maximum transverse velocity of the atoms in the process of collimation. For the case illustrated in Fig. 3 the maximum transverse velocity changes from 11.7×10^2 to 3.5×10^2 cm/s. This corresponds to the decrease of transverse motion temperature from 190 to 17 mK. The angular divergence of the atomic-beam decreased from 3.2×10^{-2} to 0.9×10^{-2}. It must be said that the degree of collimation greatly depends on, first, the coincidence of the atomic-beam axis with the axicone axis and, secondly, the uniformity of illumination of the axicone by laser radiation.

We have studied the atomic-beam profile changes with the value and sign of the laser detuning around the transition frequency (Fig. 4). The laser power in this case was 60 mW, the initial atomic-beam divergence was 2.2×10^{-2}.

There is an optimum negative detuning when the atomic-beam collimation is maximum. As the detuning is decreased, the degree of collimation drops essentially. Near zero detunings the broadening of the atomic-beam is clearly seen, and its intensity is decreased. This beam broadening seems to be caused by the velocity diffusion of atoms.

At positive detunings the atomic-beam becomes essentially spread (decollimated). The strongest decollimation is observed when the detuning is +13 MHz, that is, when its value is the same but the sign is opposite to the detuning for the maximum collimation. The atomic-beam profile becomes ring-shaped. The atomic intensity at the centre of the beam is 0.6% relative to the original intensity. The atomic-beam divergence increases up to $\Delta\varphi=6\times10^{-2}$. It should be noted that the atomic-beam exceeds its initial dimensions in cross section.

It is clearly seen from Fig. 4 that collimation can be observed when the detuning ranges from −30 to −8 MHz and decollimation occurs with the detuning between 0 and +25 MHz. Thus, the entire phenomenon takes place in the frequency range of 55 MHz. The atomic intensity at the centre of the beam changes

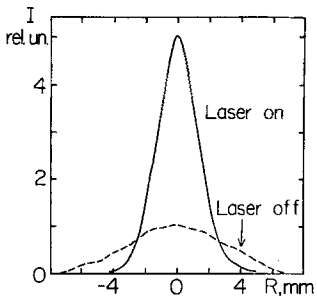

Fig. 3. Collimation of an atomic-beam by laser radiation ($P_L=60$ mW)

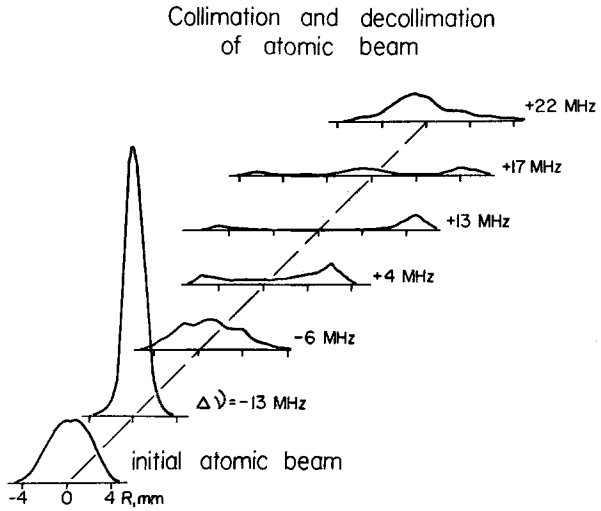

Fig. 4. Series of atomic-beam profiles using different tuning of the laser frequency ($\Delta\nu=\nu_L-\nu_0$, $P_L=60$ mW)

by more than factor 800. The total atomic-beam intensity in the experiment was determined from $I_\Sigma=\int I(\varrho)\varrho d\varrho$. Its value in the process of collimation (decollimation) remained constant within the experimental error.

4. Potential Applications of Atomic-Beam Collimation (Decollimation)

Finally, we discuss some possible applications of the collimation and decollimation of the atomic-beam. First, the method makes it possible to change the atomic-beam intensity ($I_{\text{coll}}/I_{\text{decoll}}\simeq10^3$), second, to act on the velocity and spatial characteristics of the atomic-beam with a frequency selectivity of $\Delta\nu\simeq\gamma$, third, to increase greatly the selectivity of action for atomic-beams with hyperfine splitting of the ground state and, finally, to change the parameters of the beams with a high initial divergence (and intensity, respectively) $\Delta\varphi_0\sim10^{-1}\div1$ rad.

All these features of the method open up strong possibilities of manipulating atomic beams. Among

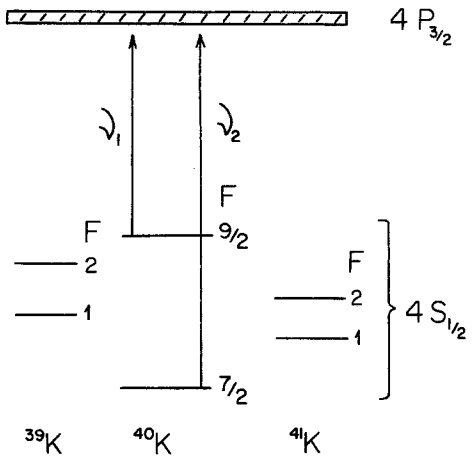

Fig. 5. The scheme of energy levels for the ground and first excited states of potassium isotopes and the position of laser frequencies for isotope-selective spatial separation of the beam

them are: a) isotope-selective spatial separation of beams; b) highly selective detection; c) spatial scanning of beams. Here we shall consider the first possibility taking potassium isotopes as an example. In the natural mixture there are three potassium isotopes – ^{39}K, ^{40}K, ^{41}K – with the following percentages, respectively: 93.10%, 0.012%, 6.89%. The isotope ^{40}K has a comparatively small isotope shift relative to the other isotopes ($\Delta\nu_{is}\simeq 120$ MHz). The effect of collimation and decollimation can be used to separate ^{40}K from the natural mixture.

One of the optical schemes suitable for this task is similar to the one considered in the present paper (Fig. 1). Figure 5 schematically shows how to excite the mixture of potassium isotopes at the D_2-line by two-frequency laser radiation. It can be seen that the excitation levels of ^{39}K and ^{41}K are separated from the levels of ^{40}K by a frequency interval ~ 300 MHz [9]. When the radiation is in resonance with ^{40}K and the radiation intensity $I\simeq 10\, I_{sat}$, the probability of excitation of ^{39}K, ^{41}K due to the Lorentzian wing of absorption line will be $P\lesssim 10^{-3}$. To separate a beam of any desired isotope, it is necessary that the atoms should go beyond the original atomic-beam. When the angular divergence of the atomic-beam is similar, for example, to the divergence used in our experiment, this can occur when an atom reradiates $N\sim 300$ photons. The selectivity of isotope beam separation is obviously determined by the ratio of the probabilities of deviation of the resonant atom to the nonresonant atom which in our case is $S\sim(P_{res}/P_{nonres})^N\simeq P_{nonres}^{-N}$ [10]. It is evident that the value of S is so high that it is actually restricted by other factors (for example, by the collisions between the atoms in the beam).

Here we shall estimate what parameters the laser radiation must have to separate the ^{40}K atoms out of the initial atomic beam. In a plane standing wave a two-level atom is acted upon by a spontaneous light pressure force [5]

$$F_{sp}=\hbar k\gamma G(\mathscr{L}_- - \mathscr{L}_+)/[1+G(\mathscr{L}_- + \mathscr{L}_+)]. \tag{3}$$

Here $\mathscr{L}_\pm$ denotes Lorentzian functions of transverse velocity v

$$\mathscr{L}_\pm=\gamma^2/[(\Omega\pm k\vartheta)^2+\gamma^2]. \tag{4}$$

The equation of atomic motion in the field of a standing light wave is

$$F_{sp}(\vartheta)=m\frac{d\vartheta}{dt}. \tag{5}$$

It can be integrated and then we shall find the implicit function between the initial (v_0), the final (v_f) transverse atomic velocities and their interaction time t_{inter}

$$t_{inter}=f(\vartheta_f, v_0, \Omega, G). \tag{6}$$

The solution of the last equation enables us to find the conditions under which the beam of ^{40}K can be effectively separated from the beam of natural isotope mixture.

Suppose we have an atomic beam of potassium isotope mixture with a high initial divergence, $\Delta\varphi_0=8\times 10^{-2}$, and an average longitudinal velocity of 7×10^4 cm/s. The interaction length inside the axicone equals $l=10$ cm, the radiation parameters $\Omega=7\gamma$ and $G=50$. Then more than 90% of the ^{40}K atoms will acquire the velocity of the original atomic beam, that is, they will go beyond the atomic-beam.

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