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Focusing of an Atomic Beam by a Two-Dimensional Magneto-Optical Trap

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A method for focusing neutral atoms based on the light-pressure force in a nonuniform magnetic field is proposed and analyzed. Its particular scheme is realized by means of a two-dimensional magneto-optical trap using a thermal beam of Rb atoms. A feature of this focusing method is the linear dependence of the focal length on the longitudinal velocity of atoms in contrast to the quadratic dependence in the known methods of focusing material-particle beams. The minimum size of the waist of the focused atomic beam is equal to 270 μm. Owing to focusing by means of the two-dimensional magneto-optical trap, the velocity monochromatization of a thermal atomic beam is realized: the width of the distribution of the longitudinal atomic velocities in the beam is reduced from 350 to 60 m/s.

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Recent investigations in atomic optics provide a deeper understanding of the fundamental processes of transferring momentum between an atom and electromagnetic field, as well as the creation of atomic optical elements such as mirrors, lenses, interferometers, and various atomic traps [1–3]. Despite advances in atomic optics, the problem of focusing atoms is still poorly studied. The main cause is the difficulty of creating an appropriate configuration of the electromagnetic field ensuring the focusing of an atomic beam. It is well known that a field whose potential has a quadratic dependence of the interaction energy on the transverse coordinate of atoms in the beam is ideal for focusing.

There are numerous proposals for the realization of schemes of an atomic lens based on using the electric field [4], magnetic field [5], laser light [6], atomic diffraction on Fresnel zone plates [7], and the quantum reflection effect [8]. An ideal atomic lens has not yet been designed as a field configuration with an interaction potential that ensures both the focusing of atoms into an area whose size is close to the diffraction limit and the construction of an image of an atomic source similar to the construction of an image of a light source by an ordinary lens.

The problem of the realization of the interaction of atoms with a certain field that leads to the convergence of atoms to a point is simpler but no less important. The most impressive results in this area have been obtained using a quasiresonant standing light wave that forms a one- or two-dimensional set of potential wells. Atoms are concentrated along the bottoms of such potential wells; i.e., channeling of atoms occurs [9, 10]. Periodic one- and two-dimensional nanostructures on a plane surface are created by means of this method [11, 12]. This method of the concentration of atoms is also called focusing, although the interaction potential is not the ideal-lens potential and the construction of an image is absent in such a system.

Another example of the concentration of atoms along a line is the compression of an atomic beam by means of the dissipative force of light pressure in a nonuniform magnetic field [13, 14]. In this case, atoms are not focused but concentrated along the propagation line of the atomic beam. This configuration is called a two-dimensional magneto-optical trap (2D MOT).

In this work, we analyze another approach to the focusing of neutral atoms. It is based on using the light-pressure force acting on atoms in a nonuniform magnetic field that was proposed for increasing the phase density of atom ensembles in [15]. Its particular scheme is realized using a 2D MOT, which is shown in Fig. 1a. In this scheme, the 2D MOT is formed by two mutually perpendicular circularly polarized (σ^+–σ^-) standing laser waves propagating along the $\bar{e}_1$ and $\bar{e}_2$ axes and a spatially nonuniform magnetic field of the quadrupole form

$$B(\bar{r}) = B_0[\bar{e}_1(x/a) + \bar{e}_2(y/a)], \tag{1}$$

where B_0 is the magnetic field amplitude and a is the characteristic spatial size of the magnetic field. Atoms intersecting the laser field of the 2D MOT are subjected to the light-pressure force. When atoms move along the

x axis and an atomic transition is weakly saturated, this force is given by the expression

$$F_x/m = -\beta_x V_x - \omega_{0x}^2 x, \qquad (2)$$

where

$$\beta_x = \frac{4V_r k(\Omega_{xR}^2/\gamma)(\delta/\gamma)}{[1+(\delta/\gamma)^2]^2}, \qquad (3)$$

$$\omega_{0x}^2 = \frac{4V_r b(\Omega_{xR}^2/\gamma)(\delta/\gamma)}{[1+(\delta/\gamma)^2]^2}, \qquad (4)$$

$$b = (\mu_B/\hbar)(dB/dx). \qquad (5)$$

Here, Ω_{xR} is the Rabi frequency, 2γ is the homogeneous linewidth of the atomic transition, $\delta = \omega - \omega_0$ is the detuning of the laser field frequency ω from the atomic-transition frequency ω_0, k is the wavenumber, V_x is the velocity of the atom along the x axis, μ is the atomic magnetic moment, μ_B is the Bohr magneton, and V_r is the atomic recoil velocity. According to Eqs. (2)–(5), the behavior of the atom in a laser–magnetic field is well described by the damped-oscillator model with the damping coefficient β_x and oscillation frequency ω_{0x}. If the time of interaction between the atom and laser field is $t_{\text{int}} \cong (5\text{–}10)\beta^{-1}$, the change in the transverse coordinate of the atom after the interaction with the 2D MOT is insignificant and the velocity of the atom along the x axis acquires the value

$$V_x = -(\omega_{0x}^2/\beta_x)x_0 + [(\omega_{0x}^2/\beta_x)x_0 + V_{0x}]e^{-2\beta_x t}, \qquad (6)$$

where x_0 and V_{0x} are, respectively, the coordinate and velocity of the atom at the entry to the 2D MOT. It follows from Eq. (6) that, if the time of the interaction between the atom and laser radiation is much longer than the inverse damping constant, i.e., $t \geq \beta^{-1}$, the atomic velocity is damped to the value

$$V_B = -(\omega_{0x}^2/\beta_x)x_0 = -(b/k)x_0, \qquad (7)$$

which is determined only by the magnetic field gradient and the atomic coordinate in the laser field of the 2D MOT. A surprising result follows immediately from Eq. (7): the time necessary for atoms leaving the 2D MOT to intersect the x axis,

$$t_{\text{cross}} = x_0/V_B = k/b, \qquad (8)$$

is the same for all atoms. Owing to this circumstance and under the condition of the equality of the longitudinal velocities of atoms, all atoms are focused at a certain distance from the 2D MOT; i.e., the atom completely forgets its initial transverse velocity and coordinate.

Figure 1b shows the results of the computer simulation of the trajectories of atoms focused by means of the 2D MOT. The vertical x axis is the transverse coordinate of the atom and the horizontal z axis shows the direction of the atomic beam motion. The curves in Fig. 1b show the free flight of atoms from the source to the left from the region of the 2D MOT, sharp change in the velocity of atoms subjected to the laser field of the 2D MOT, and their further convergence to a point, i.e., focusing.

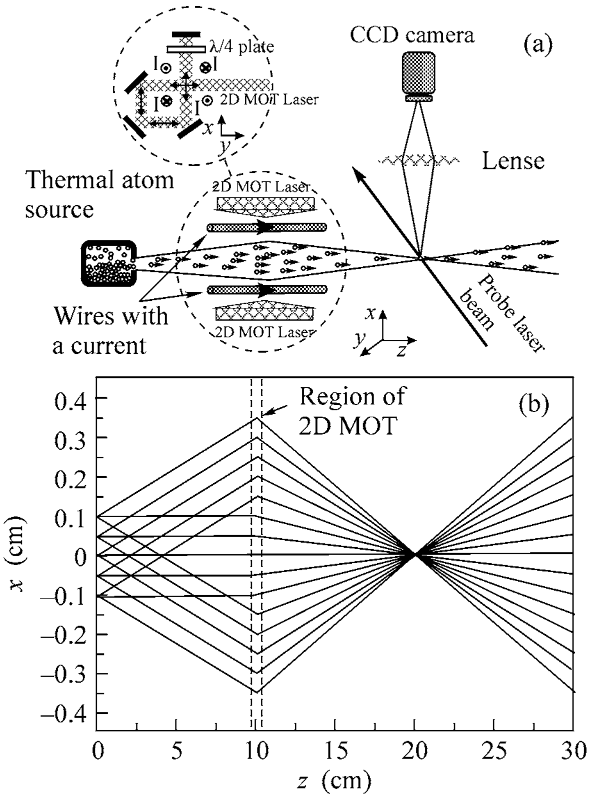

Fig. 1. (a) Layout of the experimental setup for the investigation of focusing of the ^{85}Rb atomic beam by means of the 2D MOT. (b) Results of the computer simulation of the trajectories of atoms focused by means of the 2D MOT. The x axis is the transverse coordinate of the atom in the beam and the z axis is the distance along the atomic beam propagation.

A feature of the focusing of the atomic beam by means of the 2D MOT is its dissipative character, arising due to a decrease in the kinetic energy of atoms by reemitted photons. In view of this circumstance, the transverse velocity of atoms leaving the 2D MOT in the focusing mode is a function of only the transverse coordinate of the atom and the parameters of the trap field [15]. The focal length, defined as the distance from the 2D MOT to the intersection point of the beam axis by atoms, depends only on the longitudinal velocity $V_{\parallel}$ of the atom and the trap parameters and is equal to

$$f = \frac{k}{b}V_{\parallel}. \qquad (9)$$

Here, the gradient b of the magnetic field is given by Eq. (5) and k is the wavenumber of the laser radiation of the 2D MOT. This focusing method provides a linear

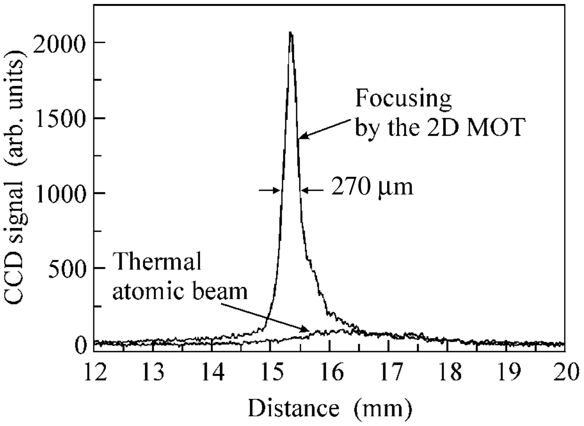

Fig. 2. Profiles of the transverse spatial distribution of the atoms in the initial thermal beam before and after its interaction with the 2D MOT. The longitudinal velocity of the atoms is equal to 100 m/s.

dependence of the focal length on the longitudinal velocity of atoms, whereas such dependences are quadratic for atomic and ion magnetic lenses. This circumstance reduces the chromatic aberration when focusing atoms.

Another important feature of the above focusing method is the absence of the focal plane characteristic of traditional lenses: the spatial position of the beam focusing point is independent of both the transverse velocity of atoms and their transverse coordinate. For this reason, for an arbitrary spread of transverse velocities and coordinates (bounded by the capture region of the 2D MOT), atoms that have identical values of the longitudinal component of the velocity before the interaction with the field of the 2D MOT converge at one spatial point after passing the 2D MOT. Such a feature makes it possible to increase the phase density of the atomic beam when focusing by means of the 2D MOT, which is a direct consequence of the dissipative character of the trap under consideration.

The waist size of the atomic beam at the focus is determined primarily by momentum diffusion and by the difference of the spatial distribution of the magnetic field of the 2D MOT from the linear dependence. For the typical parameters of the 2D MOT, the waist size due to momentum-diffusion is equal to about 10 μm. It is worth noting that the atomic beam size at the waist when focusing atoms by means of the 2D MOT is less than the value for the case of the compression of atoms by means of the 2D MOT due to a much shorter time of the interaction of atoms with laser radiation in their focusing mode.

For the typical parameters of the 2D MOT, the damping time is $\beta^{-1} \sim 0.02$ ms. For a 2D MOT with a longitudinal size of 2 cm, the "compression" mode is realized for atoms of the beam with velocities $V <$ 30 m/s, whereas the "focusing" mode is observed for atoms with velocities up to $V \sim$ (100–200) m/s. Thus, the 2D MOT in the focusing mode makes it possible to deal with thermal beams.

The focusing of a thermal beam of ^{85}Rb atoms by means of the 2D MOT was investigated on the experimental setup schematically shown in Fig. 1a. Sources of thermal atoms and the 2D MOT are placed in a vacuum chamber with a residual-gas pressure of 3×10^{-7} Torr. The 2D MOT consists of four parallel conductors with current and two pairs of mutually perpendicular, circularly polarized laser beams with transverse spatial sizes 6 × 25 mm. In order to compensate for the Earth's magnetic field, three pairs of Helmholtz coils were used.

The profile of the atomic beam was detected by means of a 2D CCD camera using the signal of the resonance fluorescence of atoms from the laser beam that intersects the atomic beam at an angle of 17° and a distance of 8 cm from the end of the 2D MOT. Varying the detuning of the probing laser beam, we detect the profiles of the spatial distribution of atoms in various velocity groups of the thermal atomic beam.

To probe the spatial distribution of atoms in the beam, we used a laser system based on a 10-mW external-cavity semiconductor laser. Focusing laser radiation for the 2D MOT was formed by another laser system with an output-radiation power of 80 mW. In this system, the radiation of the generator laser (low-power laser system) was injected into the amplifier laser (high-power semiconductor laser) in the frequency-locking mode [16]. The detuning of the laser radiation of the 2D MOT from the exact frequency of the $F = 3 \longrightarrow F' = 4$ transition was on the order of two natural linewidths of the ^{85}Rb atoms (natural linewidth is $\gamma = 5.9$ MHz). The radiation spectra of the probing and focusing laser systems were two-frequency in order to eliminate the effects of the optical pumping of the ^{85}Rb atoms between the sublevels of the hyperfine structure of their atomic ground state. The radiation wavelength of the laser systems was equal to 780 nm. The laser frequencies were controlled by means of systems of active frequency stabilization based on the absorption resonances of the ^{85}Rb atoms.

Figure 2 shows the experimental profiles of the transverse spatial distribution of the atoms in the beam with a longitudinal velocity of 100 m/s when the 2D MOT is switched off and on. The profiles were obtained with the magnetic field gradient $dB/dx = 10$ G/cm, which corresponds to the focusing of the atomic beam in the detection region. As is seen in this figure, the action of the 2D MOT on the atomic beam reduces its transverse size in the detection region from 2.5 mm to 270 μm. The size of the atomic beam waist at the focus is primarily determined by the imperfection of the spatial distribution of the magnetic field of the 2D MOT.

When the gradient of the magnetic field of the 2D MOT was decreased or increased in the experiments, we observed an increase or a decrease in the focal length in agreement with dependence (9) of the focal length on the magnetic field gradient. The linear dependence of focal length (9) on the atomic velocity was also experimentally corroborated: atoms of different velocity groups of the thermal atomic beam are focused at different spatial points at distances from the 2D MOT that depend linearly on the longitudinal atomic velocity.

The last circumstance enables one to use the focusing mode of the 2D MOT for the velocity selection of the atoms of the thermal beam: if a screen with a hole equal to the beam waist in the focus is placed in the focusing region for a given velocity group of the beam atoms, atoms of only this velocity group pass behind the screen.

Figure 3 shows the velocity distribution of the atoms of the thermal beam probed by a laser beam 0.4 mm in diameter at a distance of 8 cm from the 2D MOT. Such probing is equivalent to the measurement of the velocity distribution of atoms in the beam that pass through a diaphragm 0.4 mm in diameter that is placed at a distance of 8 cm from the 2D MOT. It is seen in the plots that the velocity distribution of atoms when the 2D MOT is switched off is a broad Maxwellian distribution. When the 2D MOT is switched on, the distribution changes strongly: a peak arises at a velocity of 90 m/s. This peak corresponds to the thermal-beam atoms focused into the probing region. As is seen in Fig. 3, the number of atoms passing through the probing region with a velocity of 90 m/s increases by more than 40 times when the 2D MOT is switched on. In the experiment, the peak position can be changed by varying the gradient of the magnetic field of the 2D MOT. In this case, the condition for focusing atoms into the probing region was valid for the atoms with a longitudinal velocity determined both by the distance from the 2D MOT to the probing region and by the gradient of the trap magnetic field according to Eq. (9).

In order to increase the efficiency of the velocity selection of the atoms, we inclined the 2D MOT by 2° to the atomic beam axis. The probing region of the velocity distribution was located on the axis of the 2D MOT at the same distance from the trap and had the same characteristic sizes. In this case, atoms are focused at a spatial point outside the atomic beam. For this reason, atoms are absent in the detection region when the 2D MOT is switched off. Figure 4 shows the velocity selection of atoms in this case. The solid line is the initial distribution and the points show the distribution after the focusing of the atomic beam. The velocity distributions shown in this figure indicate that fast atoms are efficiently blocked in this configuration so that the most probable atomic velocity in the beam decreases from 340 to 100 m/s. The FWHM of the distribution is equal to 60 m/s, which is much less than the corresponding value for the thermal distribution of the atoms (~350 m/s).

The experimental results obtained in this work have several potential application areas. The velocity monochromatization of the thermal atomic beam can be applied in experiments on atomic nanolithography, where the spread of the longitudinal velocity of the atoms of the thermal beam limits the resolution of the method. The production of high concentrations of atoms that are limited by the reabsorption of laser-radiation photons from the 2D MOT by atoms is another possible application of the focusing of an atomic beam by means of the 2D MOT [14]. This concentration limit can be exceeded due to the focusing of atoms into a region free of the magnetic and laser fields of the 2D MOT.

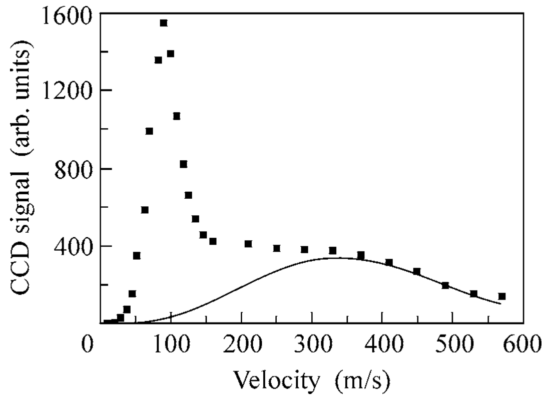

Fig. 3. Velocity monochromatization of the atoms that are focused by the 2D MOT and are spatially selected in the focal region. The solid line is the initial velocity distribution of atoms in the beam. The points show the velocity distribution of atoms in the beam after the 2D MOT is switched on.

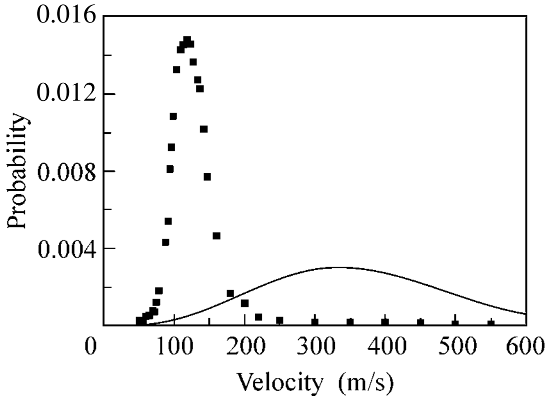

Fig. 4. Same as in Fig. 3, but when the axis of the 2D MOT deviates by 2° from the axis of the atomic beam.

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