Cooling and heating of atoms colliding in an optical field

N. I. Zhukova and A. P. Kazantsev

L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences
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It is shown that the rate of cooling or heating of atoms colliding in a resonant field, under radiation-dragging conditions, can reach 10^5–10^7 deg/sec.

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In a resonant optical field, the atoms can become cooled or heated, depending on the detuning $\Delta = \omega - \omega_0$. This effect is due to Raman scattering: the atom absorbes a field quantum $\hbar\omega$, and emits a resonant quantum $\hbar\omega_0$. The question is how the excess energy $\hbar\Delta$ is transferred from the atom to the field (or from the field to the atom). The case when the work is performed by the light-pressure forces was investigated in[1–3]. In the present paper we discuss another energy-transfer mechanism, connected with the forces that arise when the atoms collide.

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As shown by estimates, the rates of colliding can reach 10^5–10^7 deg/sec. This cooling is three-dimensional and can lead to a phase transition. In addition, in the field of a high-power light pulse, the deviation of the velocity-distribution function of the atoms from equilibrium can be large enough to be able to use this effect to obtain the differential cross section of the collisions. We note that this question is closely connected with the problem of radiative collisions.[4-6]

1. We consider first the simplest case of scattering of atoms by heavy impurities. Let $V_1(\mathbf{r})$ and $V_2(\mathbf{r})$ be the potentials of the interaction with the impurity atoms in the ground and excited states. We write down the kinetic equations for the concentrations $n_{\mathbf{p}}^{+}$ of atoms with momentum $\mathbf{p}$ in mixed states (in "atom + field" states). When the field is turned off, $n_{\mathbf{p}}^{+}$ is the density of excited atoms, and $n_{\mathbf{p}}^{-}$ is the density of the atoms in the ground state. Leaving out the elastic part of the collision integral (it vanishes from isotropic distributions), we have

$$\frac{\partial n_{\mathbf{p}}^{(\pm)}}{\partial t} \pm (\gamma_+ n_{\mathbf{p}}^{(+)} - \gamma_- n_{\mathbf{p}}^{-}) = n_c \int \frac{\partial \mathbf{p}'}{(2\pi\hbar)^3} W(\mathbf{p}, \mathbf{p}') \delta(\epsilon(\mathbf{p}) - \epsilon(\mathbf{p}') \pm 2\epsilon_0)$$

$$\times (n_{\mathbf{p}}^{(-)} - n_{\mathbf{p}}^{(\pm)}); \quad \epsilon_0 = \frac{\hbar \Delta \chi}{2}, \qquad \gamma_\pm = \frac{\gamma}{4\chi^2}(\chi \pm 1)^2, \tag{1}$$

where n_c is the impurity density, $\chi = [1 + (2dE/\hbar\Delta)^2]^{1/2}$, d is the dipole moment, and E is the field intensity. In the Born approximation, the transition probability $W(\mathbf{p}-\mathbf{p}')$ is determined by the Fourier transform of the effective potential $V(\mathbf{r}) = dE[v_1(\mathbf{r}) - v_2(\mathbf{r})]/2\epsilon_0$. This approximation is suitable strictly speaking, in fields that are not too strong, when the characteristic impact parameters exceed the Weisskopf radius. In a strong field, an important role is played by small distances and $W(\mathbf{p},\mathbf{p}')$ is determined by the square of the scattering amplitude in the potential $V(\mathbf{r})$. At low energy transfer $\epsilon_0 \ll \epsilon(p)$ the equations (1) for the isotropic case can be written in the form

$$\frac{\partial}{\partial t}(n^+(\epsilon) + n^{(-)}(\epsilon)) = \frac{\epsilon_0}{\sqrt{\epsilon}} \frac{\partial}{\partial \epsilon}(\sqrt{\epsilon}\, j(\epsilon)), \tag{2}$$

$$j(\epsilon) = \Gamma(\epsilon)\left[n^{(-)}(\epsilon) - n^{(+)}(\epsilon) + \frac{1}{2}\epsilon_0 \frac{\partial}{\partial \epsilon} n^+(\epsilon) + n^{(-)}(\epsilon)\right),$$

$$\frac{\partial}{\partial t}(n^+(\epsilon) - n^{(-)}(\epsilon)) + 2(\gamma_+ n^{(+)}(\epsilon) - \gamma_- n^{(-)}(\epsilon)) = 2j(\epsilon). \tag{3}$$

Here $\Gamma(\epsilon)$ is the collision frequency corresponding to the transition probability W and to the density n_c. The integral with respect to energy of the left-hand side of (2) (the total number of particles) is conserved. From this equation we can easily estimate the rate of change of the temperature

$$dT/dt \sim \frac{\epsilon_0}{2} \frac{\Gamma(\gamma_+ - \gamma_-)}{(\gamma_+ + \gamma_- + \Gamma)}. \tag{4}$$

At small Γ the effect is proportional to the impurity concentration, and at $\Gamma > \gamma_{\pm}$ it is independent of the density. From the condition $j=0$ we obtain the minimum cooling temperature $T_{\min} = 1/2\,|\epsilon_0|(\gamma_+ + \gamma_-)(\gamma_+ - \gamma_-)^{-1}$ at $\Delta < 0$. In collisions of light atoms we can use as an estimate $\Gamma \sim (nd^2/\hbar)(dE/2\epsilon_0)^2$.

2. For cooling, we can use the concrete structure of the levels, for example doublet splitting in alkali-metal atoms. Let a light field resonant to the transition $3S_{1/2} - 3P_{1/2}$ transfer the sodium atom into the state $3P_{1/2}$. The collisions cause the atoms to "flow over" into the state $3P_{3/2}$.[1)] In each such transition, the kinetic energy of the atoms increases by $\epsilon_0 = \epsilon_{3/2} - \epsilon_{1/2} \sim 25°$. In strong collisions $\Gamma > \gamma$ the cooling rate is of the order $\epsilon_0\gamma$. Under radiation-dragging conditions, γ can be estimated from the Holstein relation $\gamma \sim \gamma_0/qL$, where γ_0 is the rate of spontaneous emission of a free atom, q is the absorption coefficient at the line center, and L is the vessel dimension. At $qL \sim 10^4$ we have $\gamma \gtrsim 10^4$ sec^{-1}. If the light-pulse repetition frequency is 10^4 sec^{-1}, then we have a cooling rate of the order of 10^5 deg/sec.

Under conditions of strong saturation on the $3S_{1/2} - 3P_{1/2}$ transition, the population difference on the $3S_{1/2} - 3P_{3/2}$ transition is also small, of the order of γ/Γ. In other words, $q \sim q_0\gamma/\Gamma$, where q_0 is the absorption coefficient in the absence of saturation. This yields $\gamma \sim (\gamma_0\Gamma)^{1/2}\,(q_0L)^{-1/2}$. At $\Gamma \sim \gamma_0$ and $q_0L \sim 10^4$ we have $\gamma \sim 10^6$ sec^{-1}, and accordingly the cooling rate is $\sim 10^7$ deg/sec. Thus, in strong saturation, the role of the reabsorption of the radiation can decrease significantly.

3. At low pressures (molecular flow) the energy of the atoms in the light field can change in collisions with the wall. We consider a monoenergetic atom beam incident on the surface at a small angle θ. A light beam propagates along the z axis at the point of incidence (see Fig. 1). The atom in the field has a two-component wave function

$$\Psi_- = (1 + a^2)^{-1/2}\begin{pmatrix} a \\ 1 \end{pmatrix},$$

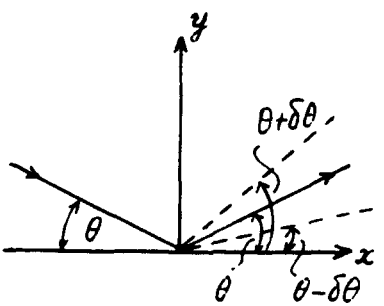

FIG. 1.

where $a = 2\,dE/\hbar\Delta\,(1+\chi)^{-1}$. If α_1 and α_2 are the probability amplitudes of specular reflection of the atoms in the ground and excited states, then after the collision with the wall we have

$$\psi' = (1 + a^2)^{-1/2}\begin{pmatrix} a\alpha_2 \\ \alpha_1 a \end{pmatrix}.$$

At $\alpha_1 \neq \alpha_2$ there appears an admixture of states

$$\psi_+ = (1 + a^2)^{-1/2}\begin{pmatrix} 1 \\ -a \end{pmatrix}.$$

The momentum P_y' of the inelastic component is obtained from the energy conservation law $p_y'^2/2M+\epsilon_0=p_y'^2/2M-\epsilon_0$. The atom in it decreases after collision at $\Delta<0$ and increases at $\Delta>0$. The intensities of the elastic and inelastic components are determined by the expressions $(\alpha_1+a^2\alpha_2)^2(1+a^2)^{-2}$ and $(\alpha_1-\alpha_2)^2a^2(1+a^2)^{-2}$, respectively. The splitting angle is $\delta\theta=2\epsilon_0M/\theta v^2$. If a laser beam of 25 mW power is focused into a spot of 10^{-2} cm diameter, then at $\theta=10^{-2}$ rad we obtain $\delta\theta\sim\pm\theta$.

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[1)]Cooling in collision of molecules of two sorts with close vibrational frequencies was considered in[7]. Observation of a slight lowering of the temperature ($\sim 0.2°$) in a CO_2-N_2 gas mixture under the influence of laser radiation is reported in[8].

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