COOLING AND TRAPPING OF ATOMS AND MOLECULES BY A RESONANT LASER FIELD

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Received 17 June 1976

A method is suggested for simultaneous cooling and trapping of atoms and molecules in a low-pressure gas under forces caused by recoil during spontaneous or induced transitions of the particles in the resonance field of a three-dimensional standing light wave. It is shown that at light field intensities ~0.01–0.1 W/cm^2 it is possible to cool atoms and molecules to the resonance field photon momentum and to hold the particles in the light field volume during a long period of time. The proposed approach opens the way for high-resolution Doppler-free spectroscopy of a small number of atoms and molecules.

1. It is well known that the widths of narrow atomic or molecular resonances produced by up-to-date methods of non-linear laser spectroscopy are limited by broadening caused by the finite transit time of particles across the light beam and by the second-order Doppler effect [1]. These limitations are of principal importance both in the methods of saturation and two-photon Doppler-free spectroscopy because both these methods are based essentially on the interaction of light waves with free-moving atoms or molecules.

Complete or partial elimination of transit broadening and broadening due to the second-order Doppler effect, and observation of narrow resonances whose widths are conditioned only by the properties of atomic or molecular quantum transitions, are possible, of course, only in the case when the particle motion in a low-pressure gas is either fully impeded or considerably limited.

At present there are two effects predicted which in principle may form the basis for laser Doppler-free spectroscopy with extremely high resolution ($> 10^{12}$) and with a very small number of atoms or molecules. One of them (the effect of radiative trapping of atoms or molecules [2]) is based on using the strong field of a three-dimensional standing light wave beyond resonance transitions of an atom or a molecule for particle trapping by non-resonance forces of recoil in the nodes or loops of the light field. The practical realization of this technique has proved rather complicated because the effect appears for very slow atoms, the number of which in a low-pressure gas at 300 K is extremely small [1]. Besides, the required field intensity is rather high (for particles with velocity 0.1 to 1 cm/sec it should be 10^3 W/cm^2).

The second effect (radiative cooling of atoms [3]) is based on atom moderation by the spontaneous light pressure force as the low-frequency part of a Doppler-broadened line of an optical transition is isotropically irradiated by an intense resonance light field. For this effect a sufficiently intense field is required too. In particular, it takes a power of 10^3 W/cm^2 to cool atoms to velocities which would correspond to the homogeneous width from 10 to 100 MHz. Besides, cooled particles quickly fly out from the region of the laser field (for instance, because of recoil effects at the probe laser field), and for long experimentation it is necessary that new particles should be cooled periodically.

It is easy to imagine a method of spectroscopy

based on a combination of these effects: radiative precooling of particles by a resonance field and subsequent capture of the cooled low-speed particles by a nonresonance intense light field. This technique offers strong possibilities of realizing the spectroscopy of slow trapped particles discussed in refs. [1,4]. The topic of our Letter however is much wider. The idea of our next suggestion is that a considerable decrease of required field intensities and a substantial widening of the trapped particle velocity range can be achieved if we use both for cooling and trapping atoms and molecules the forces caused by recoil during spontaneous and (or) induced transitions of an atom or molecule in the resonance field of a standing light wave with the frequency scanned by a certain law.

In this work we shall demonstrate that *in the resonance field of a three-dimensional standing light wave it is possible to cool particles* to velocities corresponding to the resonant photon momentum and, *simultaneously, to capture a considerable part of the cooled particles*, hence to eliminate transit broadening, and the broadening induced by the second-order Doppler effect for a considerable part of atomic or molecular transitions.

2. In the resonance field of a one-dimensional standing light wave

$$E = 2E_0 \cos \omega t \cos kz \qquad (1)$$

two recoil forces act upon an atom or a molecule. One of them – the spontaneous light pressure force – is conditioned by recoil during spontaneous transitions of a particle in the field, the other one – the induced light pressure force – is conditioned by recoil during induced transitions of a particle in the field. When the lower level of the resonance transition is the ground one and the upper level width is conditioned by spontaneous decay at the rate 2Γ only to the ground level, these forces have the form:

$$F_{sp} = 2\hbar k\Gamma \times \frac{G[\mathcal{L}(\Omega - kv) - \mathcal{L}(\Omega + kv)]}{1 + G[\mathcal{L}(\Omega - kv) + \mathcal{L}(\Omega + kv)]} \sin^2 kz , \qquad (2)$$

$$F_{ind} = \hbar k\Omega \times \frac{G[(1 - kv/\Omega)\mathcal{L}(\Omega - kv) + (1 + kv/\Omega)\mathcal{L}(\Omega + kv)]}{1 + G[\mathcal{L}(\Omega - kv) + \mathcal{L}(\Omega + kv)]} \times \sin 2kz , \qquad (3)$$

where $k = \omega/c$ is the wave vector of the light wave, v is the particle velocity projection onto the wave direction, $\Omega = \omega - \omega_0$ is the detuning of the field frequency about the center frequency of the resonance transition, d is the matrix element of the resonance transition dipole moment, and the following notations are introduced

$$G = \frac{1}{2}\left(\frac{dE_0}{\hbar\Gamma}\right)^2 , \quad \mathcal{L}(x) = \frac{\Gamma^2}{x^2 + \Gamma^2} . \qquad (4)$$

Forces (2) and (3) act on the particles in a low-pressure gas in different ways (fig. 1). The force F_{sp} conducts directed acceleration of particles: with $\Omega > 0$ the particles are accelerated by the field, with $\Omega < 0$ they are moderated. The force F_{ind} conducts

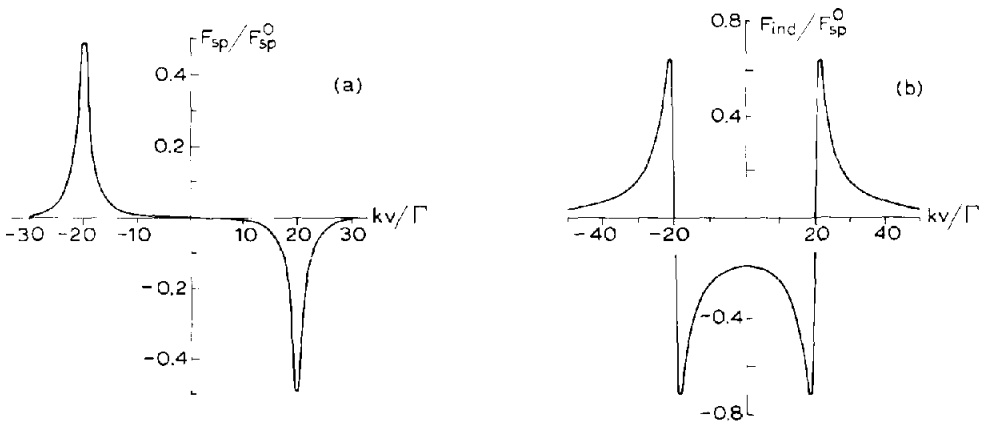

Fig. 1. Dependence of spontaneous light pressure force (a) and induced light pressure force (b), normalized to $F_s^0 = 2\hbar k\Gamma$, on particle velocity for $G = 1$, $\Omega/\Gamma = -20$. Both forces are calculated at spatial points corresponding to the maxima of F_{sp} and F_{ind}.

either a finite motion (trapping) of particles [the average force (3) with respect to the light wavelength is equal to zero] or, if the particle velocity is high enough, conducts trebly periodic modulations of the particle velocity.

3. When the detuning $|\Omega| \gtrsim \Gamma$, the induced light field force brings about only a modulation of the resonant particle velocity $v = \pm\Omega/k$:

$$\left|\frac{\Delta v}{v}\right| \sim \frac{R_{\mathrm{rec}}}{\hbar|\Omega|}\left(\frac{\Gamma}{\Omega}\right)^2 \frac{G}{1+G} , \qquad (5)$$

where $R_{\mathrm{rec}} = (\hbar\omega)^2/2mc^2$ is the recoil energy. In the important case $R_{\mathrm{rec}}/\hbar \ll \Gamma$ this velocity modulation corresponds to the resonant frequency modulation of the atom or molecule

$$|\omega - \omega_0| \sim \Gamma \frac{R_{\mathrm{rec}}}{\hbar|\Omega|} \frac{\Gamma}{|\Omega|} \frac{G}{1+G} \ll \Gamma . \qquad (6)$$

Such relations will be apparently true for a three-dimensional standing light wave.

As the action of the induced light pressure force on particle motion with $|\Omega| \gtrsim \Gamma$ may be neglected, the spontaneous light pressure force can be used to cool the particles to velocities corresponding to the homogeneous line width by adiabatic scanning of the field frequency from $\omega \approx \omega_0 - \Delta\omega_{\mathrm{D}}$ to $\omega \approx \omega_0 \quad \Gamma$, where $\Delta\omega_{\mathrm{D}}$ is the Doppler half-width of resonance transition. The equation for particle motion in any coordinate system

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = F_{\mathrm{sp}} = \hbar k\Gamma \frac{G\Gamma^2}{[\Omega(t) \pm kv]^2 + \Gamma^2(1+G)} , \qquad (7)$$

shows that the rate of gas cooling will be maximum at time-linear scanning of field frequency, with the time required to cool the particles from the velocity $|v| \approx \Delta\omega_{\mathrm{D}}/k$ to $|v| \approx \Gamma/k$ being

$$\tau_{\mathrm{col}} = \frac{1}{2\Gamma} \frac{\Delta\omega_{\mathrm{D}}}{R_{\mathrm{rec}}/\hbar} \frac{1+G}{G} . \qquad (8)$$

It should be noted that the time of particle cooling to velocities corresponding to the homogeneous line width of the resonance transition is practically the same both during isotropic saturation of the whole Doppler contour [3] and during saturation of its part only within the limits of the homogeneous line width by tunable radiation. In the latter case, however, much smaller field intensities are needed. For example, for the resonance transition $3^1S_0 \quad 3^1P_1$ of ^{24}Mg atoms ($\Delta\omega_{\mathrm{D}} = 1600$ MHz, $R_{\mathrm{rec}}/\hbar = 0.1$ MHz) with $I = 0.4$ W/cm^2 ($G = 1$) the cooling time $\tau'_{\mathrm{col}} = 6 \times 10^{-5}$ sec which is much smaller than the time between collisions at pressures $\lesssim 10^{-3}$ torr.

It is clear that rapid gas cooling during adiabatic scanning of the light field frequency is of use only down to velocities $|v| \approx \Gamma/k$, that is when the field frequency changes up to the detuning $|\Omega| \approx \Gamma$. With a further decrease of detuning the force of spontaneous light pressure tends to zero and the cooling time rises drastically.

But at constant detuning $|\Omega| \approx \Gamma$ the particles will continue to be cooled by the force of the spontaneous light pressure down to velocities corresponding to the resonance photon momentum. Indeed, with $|\Omega| \approx \Gamma$ the particles with their velocities $|v| \lesssim \Gamma/k$ are acted upon by the average force

$$F_{\mathrm{sp}} = \hbar k\Gamma \frac{G(kv/\Gamma)}{\frac{1}{4}(kv/\Gamma)^4 + \frac{1}{2}G(kv/\Gamma)^2 + G + 1} , \qquad (9)$$

which moderates the particles according to the exponential law

$$v(t) = v(0)\exp\left(-\frac{R_{\mathrm{rec}}}{\hbar} t\right) . \qquad (10)$$

For particles whose velocities are adiabatically moderated down to $|v| \approx \Gamma/k$ the time of cooling to the minimum velocity $|v| \approx hk/m$ with $G = 1$ is given by the expression

$$\tau''_{\mathrm{col}} = \frac{1}{2\Gamma} \frac{\hbar\Gamma}{R_{\mathrm{rec}}} \ln \frac{\hbar\Gamma}{R_{\mathrm{rec}}} . \qquad (11)$$

For the transition of ^{24}Mg atoms being considered $\tau''_{\mathrm{col}} = 5 \times 10^{-6}$ sec. Note that the cooling of ^{24}Mg atoms to resonance photon momentum corresponds to the gas temperature $T = R_{\mathrm{rec}}/k = 4.9 \times 10^{-6}$ K.

Thus, the maximum cooling of particles to the limit conditioned by quantum fluctuations can be done in a very short time, and almost all the atoms in the area of the light field can be cooled to the photon momentum.

4. An important feature of cooling atoms or molecules by the resonance field of a three-dimensional standing light wave is that it is possible to trap particles by the force of induced light pressure. When $|\Omega| \simeq \Gamma$, the force of induced light pressure not affecting, on the average, particle cooling to photon momentum forms for slow particles a potential barrier which

limits the spatial movement of particles. The equation for the particle motion under force (3) shows that when the particle velocity v is smaller than a certain trapping rate v_{tr}

$$|v| < v_{tr} , \tag{12}$$

the particles are trapped in the loops of light field (with $\Omega < 0$). The critical velocity of trapped particles, v_{tr}, is given by the equation:

$$\frac{1}{2}\left(\frac{kv}{\Omega}\right)^4 + \left[(3+2G)\frac{\Gamma^2}{\Omega^2} - 1\right]\left(\frac{kv}{\Omega}\right)^2 + 4(1+G)\frac{\Gamma^2}{\Omega^2}\left(1+\frac{\Gamma^2}{\Omega^2}\right)\ln\left[1 - \frac{(kv/\Omega)^2}{1+(\Gamma^2/\Omega^2)}\right] + 8G\frac{R_{rec}}{\hbar\Omega}\frac{\Gamma^2}{\Omega^2} = 0 . \tag{13}$$

When $R_{rec}/\hbar \ll \Gamma$ and $G \simeq 1$, the maximum of the critical velocity of particle capture will be

$$v_{tr} \approx (\Gamma/k)\sqrt{R_{rec}/\hbar\Gamma} . \tag{14}$$

It is reached with $|\Omega| \approx \Gamma$, i.e. with detuning being optimal for fast cooling of particles to photon momentum. For example, for the transition 3^1S_0–3^1P_1 of ^{24}Mg atoms with $I = 0.4$ W/cm^2 and $|\Omega| \approx \Gamma$: $v_{tr} \approx 60$ cm/sec.

The holding time of cooled particles will depend, of course, on the actual vacuum in the cell illuminated by the light field. With a typical full cross-section of atomic or molecular scattering $\sigma \approx 10^{-14}$ cm^2, an average thermal velocity of added particles $u \simeq 10^4$ cm/sec and an actual vacuum pressure $\sim 10^{-10}$ torr ($n = 3.6 \times 10^6$ cm^{-3}) this time equals

$$\tau = 1/n\sigma u \simeq 1 \text{ hour} . \tag{15}$$

Thus, simultaneous cooling and trapping of particles in the resonance field of a three-dimensional standing light wave makes it possible both to hold the atoms and molecules during a long period of time in the area limited by the volume of the resonance light field and to carry out spectroscopic studies of absorption (emission) lines with their width determined by natural broadening only [4]. The probe light field used to detect narrow lines must also form a three-dimensional standing light wave because only with such a field configuration the particles will not escape from the region of the resonance field when acted upon by the recoil effect due to the probe field.

Finally, we think that cooling and keeping the cooled particles in a limited spatial region for a long time, open the way for monoatomic high-resolution spectroscopy of isolated atoms and molecules.

References

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