Velocity selection of atoms from beams by a Raman method

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Ultracold atoms with an effective temperature $T \simeq 10^{-12}$ K can be obtained through velocity selection of atoms from a beam by a method involving a stimulated Raman transition.

1. In some recent experiments, Kasevich *et al.*[1] used a velocity selection technique to obtain a sample of sodium atoms with a velocity distribution of width $\Delta v \simeq 3 \times 10^{-2}$ cm/s. This figure is two orders of magnitude below the recoil velocity of an atom ($v_R \simeq 3$ cm/s). The effective temperature of these atoms was only 24 pK. The selection technique which Kasevich *et al.*[1] used involved stimulated Raman transitions, which were excited by two, oppositely directed light waves.

In the present letter we show that this technique can be utilized to form narrow structures in the velocity distribution of any atoms which have a Λ configuration of levels. We show that the process depends only weakly on the magnitude and direction of the wave vectors of the exciting fields. These structures can be observed in the case of copropagating waves and also in the case of counterpropagating waves (as in Ref. 1). In fact, they can be observed in the case of an rf-optical double resonance.

This velocity selection technique can be outlined qualitatively as follows. Initially, all the atoms are optically pumped into a common low-lying state, e.g., $|1\rangle$ (Fig. 1). After these atoms interact with two coherent fields, whose properties are chosen to correspond to a π pulse which couples the long-lived $|1\rangle$ and $|2\rangle$ levels, the atoms go into state $|2\rangle$ by means of a stimulated Raman transition. Since the conditions for a resonance between the waves and the transitions depend on the velocity of the atom, only some of the atoms from the initial distribution reach the $|2\rangle$ level. As a result, a velocity peak forms in the second level. The width of this peak is determined, in general, by the Rabi frequencies of the applied fields and by the duration of the interaction of the atoms with the fields. For certain properties of the exciting waves, the

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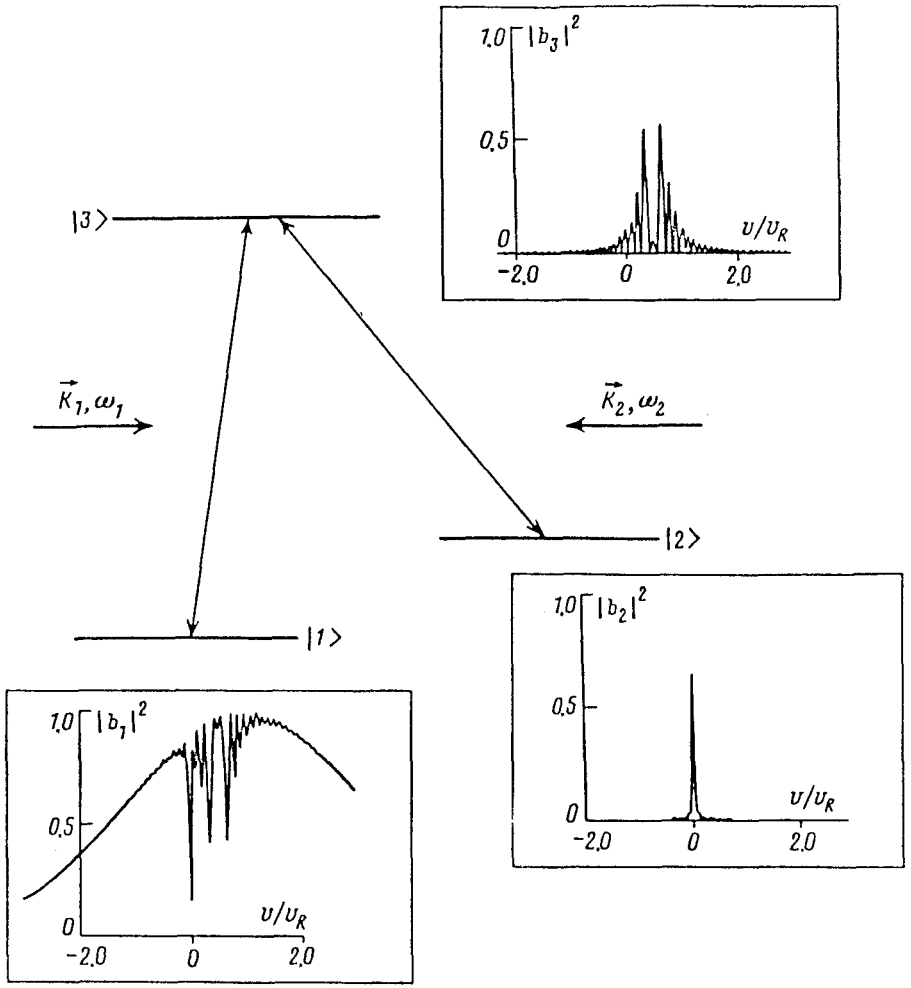

FIG. 1. A Λ atom which is interacting with two electromagnetic waves. The insets show the velocity distributions of the populations of the corresponding levels at a time $\tau = 60.5(\omega_R)^{-1}$ after the fields are applied, for the case of counterpropagating waves. Initially, the entire population is in the $|1\rangle$ level and has a Gaussian velocity distribution. This distribution is centered at $v_0 = v_R$ and has a width $\Delta v(t=0) = 3v_R$. Here $g_1 = g_2 = 0.1\omega_R$.

width (Δv) of the velocity peak in the $|2\rangle$ level can be much smaller than the atomic recoil velocity v_R.

2. Let us examine a realization of this method in the particular case of a Λ atom (Fig. 1) which is interacting with two electromagnetic waves, with frequencies ω_m and wave vectors $\vec{k}_m$ ($m = 1,2$):

$$\vec{E}(z,\ t) = \vec{e}_1 E_1 \cos(\omega_1 t \mp k_1 z) + \vec{e}_2 E_2 \cos(\omega_2 t - k_2 z), \qquad (1)$$

where E_m are the wave amplitudes, $\vec{e}_m$ are unit polarization vectors, the minus sign corresponds to the case of copropagating waves, and the plus sign corresponds to the case of counterpropagating waves. We assume that no spontaneous relaxation occurs in this system. The coherent interaction of the atom with field (1) can then be described by the wave function

$$\Psi(z,\zeta,t) = \sum_{m=1,2,3} \Psi_m(z,t)\psi_m(\zeta)\exp(-\frac{i}{\hbar}\epsilon_m t), \tag{2}$$

where z is the coordinate of the center of mass of the atom (we are considering the motion along the z axis exclusively), ζ is the set of coordinates of internal motions, and ϵ_m are the energies of the levels in the Λ atom.

The dynamics of the atomic states is governed by the Hamiltonian

$$\hat{H} = \hat{H}_0 - \frac{\hbar^2}{2M}\frac{\partial^2}{\partial z^2} + \hat{V}, \tag{3}$$

where $\hat{H}_0$ corresponds to internal states of the atom, with the eigenfunctions $|k\rangle$ ($k = 1,2,3$), the operator $\hat{V}$ represents the interaction of the atom with field (1), and M is the mass of an atom.

Substituting (2) into a Schrödinger equation with Hamiltonian (3), and adopting the resonance approximation, we obtain a system of equations describing the spatial motion of a Λ atom in field (1). When we go over to the momentum representation of the wave functions, we obtain equations for the probability amplitudes b_m (v,t) for quantum states in momentum space:

$$\begin{aligned} i\dot{b}_1 &= (\Omega_1 - y_1)b_1 - g_1 b_3, \\ i\dot{b}_2 &= (\Omega_2 - y_2)b_2 - g_2 b_3, \\ i\dot{b}_3 &= -g_1 b_1 - g_2 b_2. \end{aligned} \tag{4}$$

Here $y_1 = \pm k_1 v - \omega_{R1}$; $y_2 = k_2 v - \omega_{R2}$; $\omega_{Rm} = \hbar k_m^2/2M$ is the recoil frequency; v is the velocity of an atom; $g_m = 2(\hbar)^{-1}\langle m|\hat{V}|3\rangle$ is the Rabi frequency; and Ω_m ($m = 1,2$) is the detuning.

3. As an example, we will go through an analytic solution of Eqs. (4) for the case in which a Λ atom is interacting with two copropagating light waves. The probability for observing an atom in state $|2\rangle$ with a velocity v is thus

$$|b_2(v - v_R, T)|^2 = \frac{1}{2}|b_1(v,0)|^2 \left\{1 - \frac{4g^2}{\Delta_0^2}\sin^2\left(\frac{1}{2}\Delta_0 t\right)\right.$$
$$\left. - \frac{\Delta_0 + \Delta}{2\Delta_0}\cos\left(\frac{\Delta_0 - \Delta}{2}t\right) - \frac{\Delta_0 - \Delta}{2\Delta_0}\cos\left(\frac{\Delta_0 + \Delta}{2}t\right)\right\}, \tag{5}$$

where we have assumed for simplicity that the detunings are equal ($\Omega_m \equiv \Omega$), that the Rabi frequencies are equal ($g_m \equiv g$), and that the wave numbers of the fields are equal

($k_m \equiv k$). Here $\Delta = \Omega + \omega_R - kv$, and $\Delta_0^2 = \Delta^2 + 8g^2$. We are also assuming that the entire population is initially in the $|1\rangle$ level.

It follows from (5) that the populations of the various states of the atom depend directly on the velocity of the atom. This circumstance makes the velocity selection possible. After the atoms interact with field (1) for a time

$$\tau = (n - 1/2)^{1/2}\pi g^{-1}, \qquad n = 1, 2, ..., \tag{6}$$

which corresponds to a π pulse coupling the $|1\rangle$ and $|2\rangle$ levels, velocity peaks appear in the $|2\rangle$ level. These peaks have a width

$$\Delta v = v_R g \omega_R^{-1} \frac{(2m-1)}{(2n-\frac{1}{2})^{1/2}}, \qquad m \leq n = 1, 2, ..., \tag{7}$$

and are centered at the velocity

$$v_n^m = \left(\Omega - \omega_R \pm 2g \frac{(2m-1)}{(2n-\frac{1}{2})^{1/2}}\right) k^{-1}, \qquad m \leq n = 1, 2, ... \tag{8}$$

From (7) we see that for Rabi frequencies g, which are much smaller than the recoil frequencies ω_R ($\omega_R \simeq 30$ kHz for Na^{23} atoms on the $3S_{1/2} \rightarrow 3P_{3/2}$ transition), the width (Δv) of the velocity peak in the $|2\rangle$ level is much smaller than the recoil velocity v_R of an atom.

The expressions for the probability amplitudes b_m (v,t) in the case of counterpropagating light waves and in the case of an rf-optical double resonance are similar to (5) in form. The insets in Figs. 1 and 2 show the populations of the levels of the atom versus its velocity for the case of counterpropagating light waves and for the case of the double resonance, respectively. Here again, after a time τ corresponding to a π pulse in the Raman transition scheme, a narrow velocity peak with a width $\Delta v \ll v_R$ forms in level $|2\rangle$. In the case of counterpropagating waves, for example, we would have $\Delta v = 10^{-2} v_R$ at $g = 0.1\omega_R$. This figure corresponds to an effective temperature $T_{\text{eff}} \simeq 10^{-12}$ K (for Na atoms).

Velocity selection by the Raman technique in the case of an rf-optical double resonance can be implemented easily for Zn, Ca, Mg, Cd, and Hg atoms (for example). In these cases, the frequency of the $|1\rangle$–$|3\rangle$ optical transition falls in the blue part of the visible spectrum, and the frequency of the rf transition is a few terahertz. This case is particularly interesting in that beams of Ca and Mg atoms prepared by the velocity selection technique might find important applications in beam frequency standards.[2]

4. The technique of Raman velocity selection imposes some extremely severe requirements on corresponding experiments. Here we will mention simply the most important of them.

If the interaction with the field is to be coherent, the contribution of spontaneous relaxation to the dynamics of the system must be small. This condition usually means that the interaction times must be short: $t \ll \gamma^{-1}$, where γ is the rate of spontaneous relaxation. Practical realization of this selection technique, on the other hand, would

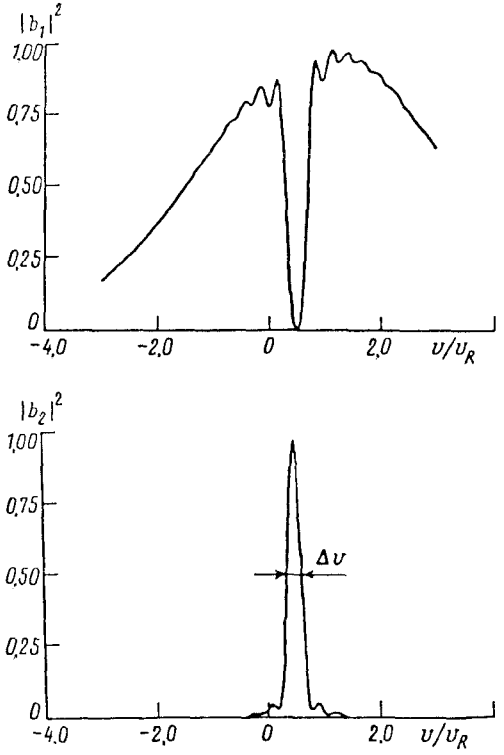

FIG. 2. Velocity selection of atoms in the case of an rf-optical double resonance. The interaction time is $\tau = 23(\omega_R)^{-1}$. The parameters are otherwise the same as in Fig. 1.

require substantial times, $\simeq 10^{-3}$ s. In order to achieve a significant reduction of the spontaneous-relaxation component, it would be necessary to populate the $|3\rangle$ excited level slightly, either by virtue of a large detuning from resonance (as in Ref. 1) or by virtue of low Rabi frequencies.

In real experiments of this sort, the minimum width of the Raman transition and thus the minimum width of the final velocity distribution are determined by the rate (Γ) of transverse relaxation between the $|1\rangle$ and $|2\rangle$ levels. Physically, a transverse relaxation might be caused by several factors: a finite spectral width of the laser light fields, transit-time broadening, collisions of atoms with each other, etc. It would therefore be necessary to use well-correlated light sources, e.g., sources correlated by acoustooptic modulation.[3] Precooled atomic beams could be used to reduce the transit-time broadening.

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