Velocity-Selective Resonances and Sub-Doppler Laser Cooling

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We describe several one-dimensional sub-Doppler laser-cooling experiments that cool Rb to finite and zero velocities in a magnetic field and polarization gradients. We then present a physical picture that unifies these measurements in terms of coherent two-photon velocity-selective resonances (VSR) between atomic ground-state sublevels (including Raman resonances). We propose several sub-Doppler cooling schemes without fields or without polarization gradients, based on VSR between nondegenerate ground states.

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Laser cooling to temperatures well below the Doppler limit $T_D = \hbar\gamma/2k_B$ has been demonstrated experimentally for several atoms and different experimental configurations [1-8]. The first theoretical models [9,10] attributed the lower temperatures to the nonadiabatic response of a multilevel atom moving through the optical polarization gradients that are always present in a three-dimensional optical molasses. It has also been shown that sub-Doppler laser cooling (SDLC) can be achieved in a one-dimensional optical molasses of constant polarization by adding a small magnetic field [3-7]. In both cases the cooling arises from the nonadiabatic response of moving atoms lagging behind the changes of the optical field. A recent more general theory presents an extended description of SDLC [11,12].

Recently, we reported SDLC to a nonzero resonance velocity v_r proportional to an applied magnetic field [5,6]. We attribute this to momentum transfer by coherent two-photon transitions that induce velocity-selective resonances (VSR) between two ground-state (g.s.) sublevels. Such VSR are similar to magnetic resonances induced by modulated light [13]. Such coherent two-photon Raman processes produce many interesting phenomena in laser spectroscopy such as pressure-induced resonances [14], narrow (subnatural width) resonances [15], and coherent population trapping [16]. Recently, Berman has shown that narrow resonances and SDLC are related [17].

In this Letter we show that the VSR picture can be generalized and extended to include most other SDLC experiments. First we present our data from several one-dimensional experiments in an applied uniform magnetic field **B**, with and without polarization gradients, that support this point of view, then we generalize the VSR picture to describe most other SDLC experiments, and finally we suggest extensions to other atoms and applications.

The VSR occur when the difference of the Doppler-shifted frequencies of two light beams seen by a moving atom, $(\mathbf{k}_1-\mathbf{k}_2)\cdot\mathbf{v}\equiv\Delta\mathbf{k}\cdot\mathbf{v}$, equals the frequency splitting between a pair of g.s. sublevels. In the VSR picture the laser polarization and the direction of **B** can be used to predict the velocity to which atoms are cooled. We emphasize that VSR alone is not sufficient for SDLC; there must also be dissipation, such as the nonadiabatic response of moving atoms to optical pumping by the changing light field.

Our experimental apparatus was described in Refs. [4-6]. There is a retroreflection mirror that forms a 1D optical molasses to transversely cool a Rb atomic beam. In front of it there is an additional quarter-wave plate so that two kinds of polarization gradient schemes, σ^+-σ^- and linear ⊥ linear, can be used. We excite the $5S \rightarrow 5P$ transition at $\lambda = 780$ nm whose natural width is 6 MHz and whose saturation intensity is 1.6 mW/cm^2. The atomic beam profile is measured by a scanning hot wire 1.3 m from the interaction region. Three Helmholtz coil pairs provide a controlled field **B**.

In various experimental configurations, the atomic beam is deflected to a nonzero transverse velocity v_r but still may be cooled to below the Doppler limit [5,6]. However, atoms with same v_r but different longitudinal velocities arrive at different positions in the detector plane, thus broadening the signal. To solve this problem we make a velocity-selected ^{85}Rb beam by optical pumping with two diode lasers. The first one crosses the atomic beam perpendicularly and is tuned to optically pump all the atoms into the $F=2$ hyperfine level of the g.s. The second crosses the atomic beam at an angle ~16°, and is frequency locked 65 MHz below the $F=2 \rightarrow F'=3$ transition using the saturated absorption signal from an auxiliary Rb cell. This laser excites a particular velocity class ($v \cong 200$ m/s), chosen by the Doppler shift, thus populating the $F=3$ g.s. by spontaneous emission. The optical molasses (formed by a third diode laser) is tuned for the $F=3$ to $F'=4$ transition. Therefore those atoms participating in the cooling and deflecting process are longitudinally velocity selected with resolution of ~50 m/s, determined by the angle and the power-broadened width of the transition. With mechanical shutters we sequen-

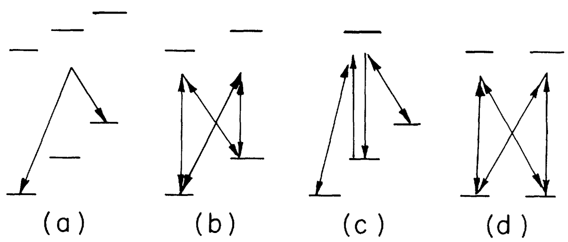

FIG. 1. Schematic diagram of atomic transitions at the resonance condition in VSR. (a) The σ^+-σ^- case where the g.s. energies are split by a magnetic field. VSR between them requires the light frequencies to be different, and in the rest frame of a moving atom this is provided by the Doppler shift. The energy splitting could be much larger (e.g., hyperfine structure) and the light have different laboratory-frame frequencies. (b) The scheme for the linear $\perp$ linear case. (c) The case for $v_r=0$ when a magnetic field is applied that splits the sublevels by more than γ_p'. Different polarizations at different places cause either $\Delta M_F=\pm 1$ or $\Delta M_F=0$ VSR. (d) The degenerate case where cooling is to $v=0$.

tially record the atomic beam profile with and without velocity selection.

One of the simplest examples of VSR is the σ^+-σ^- polarization gradient scheme with an applied magnetic field **B** along the laser beam direction. Since the σ^+ (σ^-) laser beams drive $\Delta M_F=+1$ (-1) transitions, a coherent two-photon process couples g.s. sublevels whose M_F values differ by ± 2 [see Fig. 1(a)]. The condition for VSR is then $2kv_r'=2\omega_z$, where $\omega_z=g_F\mu_B B/\hbar$ is the Larmor frequency. Obviously this scheme can only work for $J_{\text{g.s.}}\geq 1$.

Figure 2 shows a typical set of cooling and deflection data using the velocity-selected ^{85}Rb beam for various

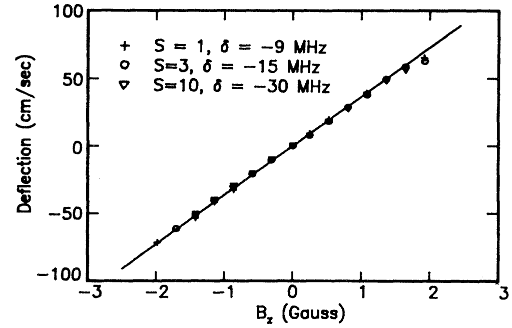

FIG. 3. The deflection of the peaks in Fig. 2 vs **B**. Note that the deflection reverses when **B** is reversed. The straight line is $v=\omega_z/k$.

values of **B**. The undisturbed atomic beam has a flat profile spanning ± 4 mm. Figure 3 shows the displacement of the peaks of Fig. 2 versus B. Deflection of the cooled atoms out of the main atomic beam is easily detected. For $B<2$ G our data show a velocity spread of ~ 5 cm/s, well below the 1D Doppler limit $v_D=10$ cm/s for Rb. For larger B the beam profile broadening by the residual longitudinal velocity spread becomes important. At $B=3$ G, $v_r'\sim 1$ m/s and the longitudinal velocity spread of 50 m/s predicts a peak 1.6 mm wide. This deflection can be alternatively interpreted by applying Larmor's theorem, which implies that a **B** field along a σ^+ (σ^-) light beam has the same effect on the evolution of an atom as lowering (raising) the optical frequency by ω_z [11]. The connection between atomic motion in a **B** field and the Larmor theorem has already been described [9].

VSR can also be created using optical molasses formed

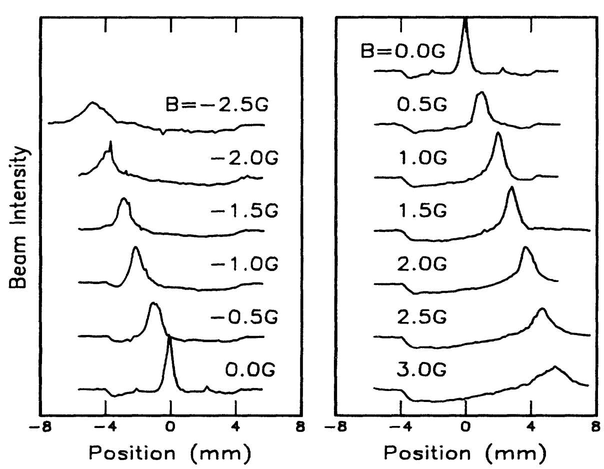

FIG. 2. Change in the velocity-selected beam profile of ^{85}Rb 1.3 m away from a σ^+-σ^- optical molasses with a magnetic field along the laser axis. The laser parameters are saturation parameter $s=3$ and detuning $\delta=-12$ MHz.

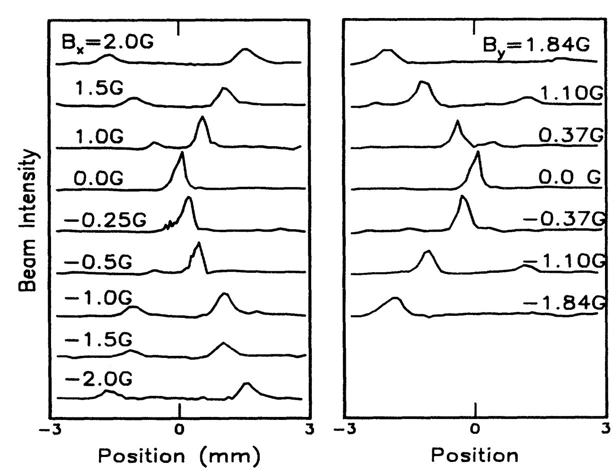

FIG. 4. Change in the velocity-selected beam profile of ^{85}Rb 1.3 m away from a linear $\perp$ linear optical molasses with **B** along one of the laser polarizations. The laser parameters are $s=3$ and $\delta=-12$ MHz.

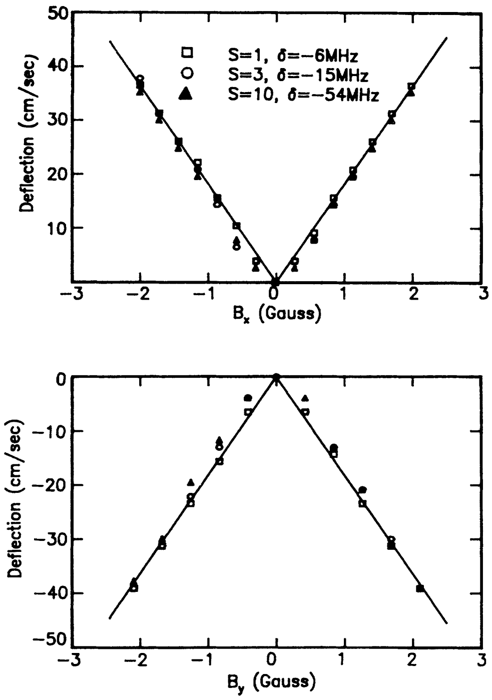

FIG. 5. The deflection of the peaks in Fig. 4 vs **B**. The straight line is $v=\omega_z/2k$.

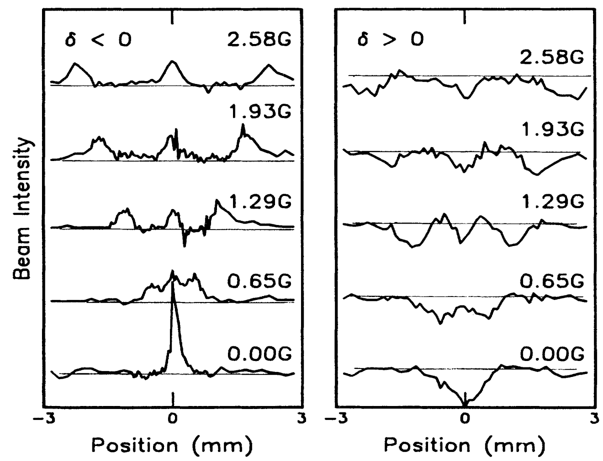

FIG. 6. Change in the velocity-selected beam profile of ^{85}Rb 1.3 m away from a linear ⊥ linear optical molasses with **B** at 45° to both laser polarizations. The laser parameters are $s=3$ and (a) $\delta=-18$ MHz, (b) $\delta=+18$ MHz. Note that for $v=v_r$, $\delta<0$ produces cooling and $\delta>0$ produces heating.

by two laser beams with orthogonal linear polarizations and **B** perpendicular to their **k** vectors. With **B** and the quantization axis parallel to the polarization of one laser beam it induces $\Delta M_F=0$ transitions, while the other beam induces $\Delta M_F=\pm 1$ transitions [Fig. 1(b)]. Therefore VSR can couple g.s. sublevels with M_F differing by ± 1 so the VSR condition becomes $v_r=\omega_z/2k$, one-half of v_r' as in the σ^+-σ^- case.

In Fig. 4 we show the measured beam profile for various values of B. The data show two asymmetric peaks of unequal height. This asymmetry is to be expected [12] because the conditions for which the force is an odd function of velocity no longer hold in this case. The asymmetry is determined by the direction of **B**; rotation of **B** by 90° about the laser axis reverses it. This is clear since reversing the atomic velocity and rotating **B** by 90° leaves the geometry unchanged. Figure 5 shows the position of one of the deflected peaks versus B. We emphasize that the atoms are not simply deflected, but are always *cooled* to v_r with a width well below the Doppler limit.

The VSR discussed so far involve Raman transitions that couple two different g.s. sublevels [see Figs. 1(a) and 1(b)]. In a polarization gradient and strong **B** field it is also possible to have VSR that return an atom to its original g.s. sublevel, and transfer a photon from one beam to another [Fig. 1(c)]. This leads to the resonant condition $v_r=0$. As before, the state of a moving atom will lag behind the changing optical field as the polarization varies in space. We have observed this by applying **B** at 45° to both laser polarizations in the linear ⊥ linear configuration. Figure 6 shows our data using the velocity-selected ^{85}Rb beam. There are three cold peaks with sub-Doppler spread for $B\neq 0$. The two side peaks correspond to the type of VSR shown in Fig. 1(b) and the center one, which does not shift with B, corresponds to the type shown in 1(c), and satisfies $v_r=0$.

Our numerical calculations [12] corroborate all the results discussed above. When ω_z is much larger than the optical pumping rate, we can even find analytical results by transforming the evolution equations for the density matrix and the force operator to a frame rotating about **B** at ω_z. The resulting expression for the force shows a $v_r=0$ resonance only if alignment over the g.s. sublevels can exist and if the polarization of the laser beams are different and not along **B**. A detailed analysis is forthcoming.

When the VSR condition is satisfied, the velocity-dependent force on moving atoms has a dispersion-shaped resonant enhancement [12,17] whose width γ'/k is determined by the damping rate of the coherence γ', namely, the rate of excitation followed by spontaneous emission. Since γ' can be very small, the narrow resonance can produce a strong velocity damping. Heating by momentum diffusion decreases with γ' so that sub-Doppler temperatures may be obtained. As long as $\Delta\mathbf{k}\cdot\mathbf{v}_r$ is considerably larger (smaller) than γ', atoms are cooled toward v_r ($v=0$). When $\Delta\mathbf{k}\cdot\mathbf{v}_r\cong\gamma'$, only numerical solutions can predict the velocity distribution.

The role of the polarization gradient in previously studied cases of SDLC with $\mathbf{B}=0$ [1-3,8-10] can now be discussed in terms of the VSR picture. With $B=0$ the g.s. sublevels are nearly degenerate, mixed polarizations permit coherent two-photon transitions to be driven by photons from different beams, and $v_r=0$ as in Fig. 1(d).

We point out that coherent population trapping in a three-level Λ system that cools below the recoil limit [16] is the limiting case of VSR with vanishing width. At resonance, atoms are in a coherent superposition of atomic g.s. that cannot absorb light. The VSR model may thus be viewed as a generalization of coherent population trapping.

The VSR picture not only applies to the known SDLC processes, but also suggests extensions to more complicated systems. For example, SDLC in Na can be realized by VSR between two g.s. hyperfine sublevels induced by two lasers tuned to $F=1 \rightarrow F'=2$ and $F=2 \rightarrow F'=2$ transitions, respectively [see Figs. 1(a) and 1(b)]. Similarly, in Tl we could use two lasers at 378 and 535 nm to create VSR between two g.s. fine-structure levels $6^2P_{3/2}$ and $6^2P_{1/2}$. Experimentally we could exploit technological progress to produce such light by frequency doubling both a 756-nm diode laser and a diode-pumped Nd^{+3} laser. Thus it makes a very attractive way to prepare high-density, cold Tl atoms for precision measurement of an electric dipole moment. For two-frequency laser cooling, the atoms will be cooled to the resonance velocity satisfying $\Delta\mathbf{k}\cdot\mathbf{v}=\omega_1-\omega_2-\Delta$, where the ω_i are the laser frequencies and $\hbar\Delta$ is the separation between the two g.s. A recent calculation showed the feasibility of SDLC in a nondegenerate three-level scheme [18], consistent with our VSR model.

Finally, we propose some applications of cooling to nonzero velocity. If the deflection is applied to a decelerated beam, it is a superb method for extracting or steering a well-defined cold beam. Also, one could imagine building an atomic storage ring based on this deflecting and cooling technique that could provide a beam that is ideal for precision spectroscopy, the study of cold collisions, and collective effects of cold atoms.

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