Laser cooling of a sodium atomic beam using the Stark effect

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A method of slowing and cooling a thermal sodium atomic beam using the Stark effect to hold the atoms in resonance during the slowing is described. A deceleration of the atoms down to 17 m/s could be experimentally achieved.

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Up to now, four techniques for slowing down the velocity of the atoms in thermal beams have mainly been used: the chirped-laser-method [1–3], Zeeman-tuned slowing [4–6], cooling with broadband lasers [7–9], and the angle-tuned method [10]. In all techniques two main problems have to be solved: (a) to hold the frequency of the cooling laser in resonance with the absorption frequency of the atoms to be decelerated and (b) to avoid undesired optical-pumping processes which trap atoms in ground states that cannot be excited by the cooling-laser light.

In our experiment we use an electric field, slowly varying along the deceleration path (about 65 cm long), in order to hold the atoms in resonance with the cooling-laser light whose frequency is fixed (Fig. 1). The changing Doppler shift during slowing is compensated for by an equal but opposite stark shift of the cooling transition. Suggestions concerning a similar method for the cooling of cesium atoms were discussed by Knize and Yeh [11].

In contrast to a magnetic field (where we have a symmetric splitting of the sublevels), the direction of the frequency shift due to the electric field is given by properties of the atom (the signs of scalar and tensor polarizabilities). In the case of sodium, one observes a shift of the D lines to lower frequencies [12,13]. Therefore, we have to start slowing (high atomic velocities, $\sim$1000 m/s) in zero field and to end (small velocities, $\sim$10 m/s) in a high electric field ($\sim$260 kV/cm).

For sodium atoms in an electric field it is not possible to create a two-level system that avoids optical pumping during the cooling cycles. So we have to repump atoms from the second hyperfine ground state by shining in a second laser frequency. One of the properties of the Stark effect is that the sodium ground state $3\,^2S_{1/2}$ is shifted in energy but its hyperfine splitting ($F=1$-$F=2$) is independent of the field strength. We can excite the atoms from both ground states in the whole cooling region by means of two laser frequencies with fixed frequency spacing easily produced using an electro-optical modulator [14,15].

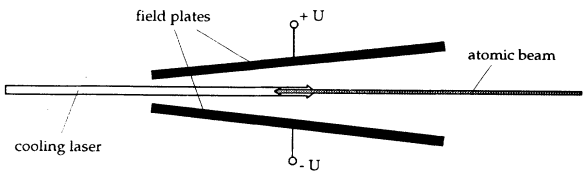

FIG. 1. Principal setup.

The Stark shift $\Delta\nu_E$ of the cooling transition can be written as

$$\Delta\nu_E=\frac{\alpha}{2}E^2\ , \tag{1}$$

where E is the electric-field strength and

$$\alpha=\left[\alpha_0+\alpha_2\frac{M_J^2-J(J+1)}{J(2J-1)}\right]-\alpha_{0,g}\ . \tag{2}$$

The scalar polarizability of the $3\,^2P_{3/2}$ atomic state is

$$\alpha_0=88.98\ \text{kHz/(kV/cm)}^2$$

(Ref. [13]). The tensor polarizability of the $3\,^2P_{3/2}$ state is

$$\alpha_2=-21.97\ \text{kHz/(kV/cm)}^2$$

(Ref. [13]). The ground-state polarizability ($3\,^2S_{1/2}$) for sodium is

$$\alpha_{0,g}=39.7\ \text{kHz/(kV/cm)}^2$$

(Ref. [16]). Earlier measured values for α_0 and α_2 can be found in [17,18]. J is the total angular momentum quantum number; M_J is the magnetic quantum number. In our experiment we use laser light polarized parallel (π) to the direction of the electric field; therefore, we excite the transitions $3\,^2P_{3/2}(|M_J|=\frac{1}{2})$–$3\,^2S_{1/2}$ for cooling (the transition probabilities for the components with $|M_J|=\frac{3}{2}$ and π polarization of the exciting laser light vanish in high electric fields [13]) so that we get for α:

$$\alpha=71.75\ \text{kHz/(kV/cm)}^2$$

(in comparison: for cesium the value of α for the equivalent transition is about three times higher [19]).

The varying Doppler shift $\Delta\nu_D$ along the deceleration path s reads

$$\Delta\nu_D = \frac{1}{\lambda}\sqrt{v_0^2 + 2as} \quad . \tag{3}$$

λ is the wavelength of the cooling transition, v_0 is the initial velocity of the fastest velocity group to be cooled, and $a < 0$ is the deceleration.

The laser detuning $\Delta\nu_L$ from the atomic resonance can be written in relative units b of the maximum Doppler shift:

$$\Delta\nu_L = b\frac{v_0}{\lambda} \tag{4}$$

($b < 0$: laser detuning opposite to the Doppler shift).

To hold the atoms in resonance during the whole cooling process, the sum of the Stark shift, the Doppler shift, and the laser detuning has to be zero. Assuming constant deceleration, this condition leads to an expression for the variation of the electric field along path s

$$E(s) = \left[\frac{2v_0}{|\alpha|\lambda}\right]^{1/2}\left[-b - \left[1 + \frac{2as}{v_0^2}\right]^{1/2}\right]^{1/2}$$

$$b \leq -1, \; a < 0 \; . \tag{5}$$

A value of $b = -1$ means that the atoms with a velocity v_0 start deceleration at zero field at the entrance of the cooling zone; for $b < -1$ (laser detuning larger than the Doppler shift of atoms with the velocity v_0), a field strength $E(s=0) > 0$ has to be applied at the entrance of the deceleration zone to get the atoms in resonance with the laser field. In our case, $b = -1.04$ was chosen.

The shape of the field plates was approximately determined by

$$d(s) = \frac{U}{E(s)} \; , \tag{6}$$

where U is the voltage between the field plates and d the distance between them.

The deceleration a appearing in Eq. (5) was chosen somewhat smaller than the maximum deceleration a_{sat} corresponding to a fully saturated cooling transition (see [2]) so that small divergences between the calculated field distribution and the real one (due to the above approximation and inaccuracies in manufacturing the field plates) cannot make the atoms drop out of resonance.

The scheme of our experimental setup can be seen in Fig. 2. It consists of a thermal sodium beam, a counterpropagating cooling-laser beam (L1), the field plates (FP) connected to two high-voltage supplies (HV), and a diagnostic laser beam (L2) to probe the velocity distribution of the atoms in the beam.

The atomic beam emerges from an oven (O) at a temperature of 350 °C through a 1-mm hole and is collimated before entering the deceleration section by a 1-mm aperture. Oven and aperture are made adjustable using vacuum bellows and micrometer mountings. The oven and the cooling zone are separated by a 4-mm aperture to limit the gas load from the relatively poor vacuum in the oven chamber to the cooling chamber.

The field plates to generate the Stark field were milled from blocks of stainless steel; their distance was made adjustable by two micrometer screws. They were connected

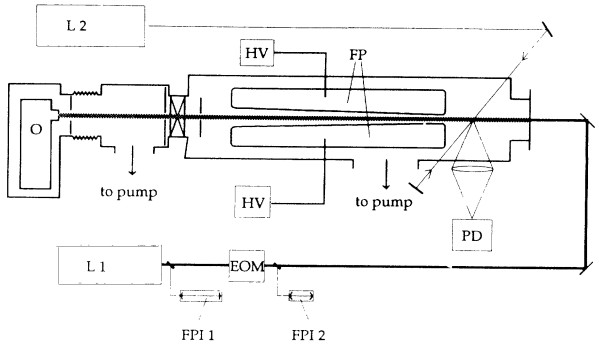

FIG. 2. Experimental arrangement: L1; slowing laser; EOM, electro-optical modulator; FPI1 and FPI2, scanning étalons; FP, field plates; HV, high-voltage supplies; O, sodium oven; L2, probe laser; and PD, photodetection.

to two stabilized high-voltage supplies that were able to produce voltages up to ±20 kV.

The cooling-laser beam was produced by a commercial actively stabilized dye ring laser (Coherent Model 899) tuned to the D_2 line. Usually about 500 mW of linear po-

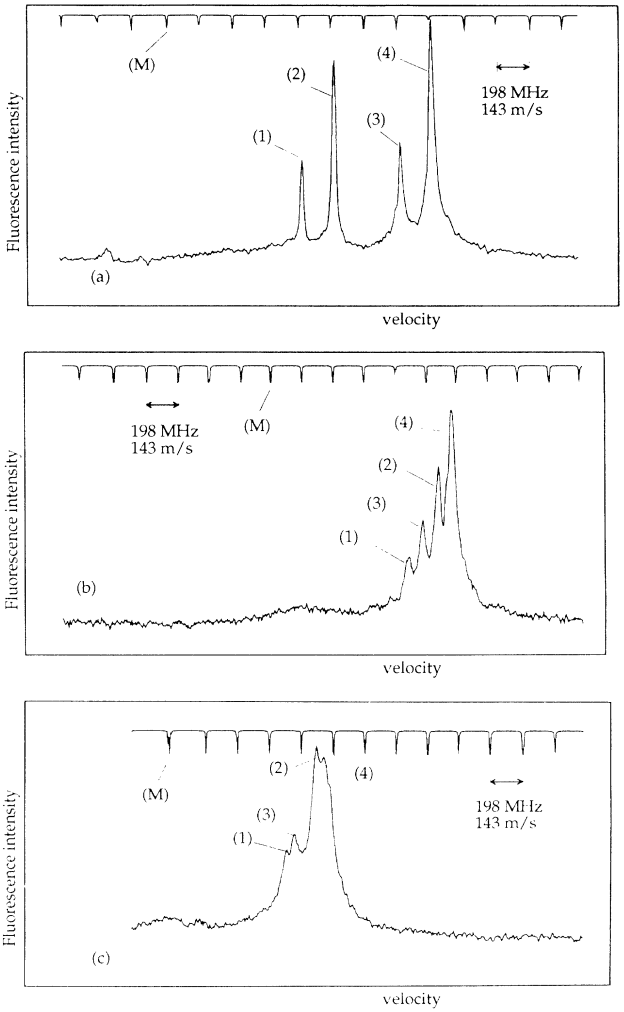

FIG. 3. Velocity distribution in the atomic beam for different cooling-laser detunings ($\Delta\nu_L$). Mean velocity of the slowed atoms: (a) 210, (b) 28 and (c) 17 m/s. For the meaning of the figures, see the text.

larized light were available. To generate the two laser frequencies, we built an electro-optical modulator (EOM) using a $LiTaO_3$ crystal in a microwave cavity[14,15]. The two first-order sidebands have a frequency spacing equal to the hyperfine splitting of the ground state and were used to slow down the atoms. The modulation of the laser frequency was controlled by a spectrum analyzer (FPI2). To determine the detuning $\Delta\nu_L$ of the cooling laser, its beam was first sent in orthogonally to the atomic beam and tuned in resonance with a known transition (with the electro-optical modulator switched off). Then, by monitoring the laser spectrum on a scanning étalon (FPI1) with a free spectral range of 150 MHz, the laser detuning could be set with an accuracy of about 20 MHz.

A second tunable dye ring laser tuned to the D_1 line (Coherent Model 699) was used to probe the velocity distribution in the atomic beam. The laser beam crossed the atomic beam under an angle of 35° and is reflected into itself. The velocity distribution was observed by measuring the Doppler shift of the velocity groups in the beam (compressed by a factor of cos35°). The measurement of the fluorescence light has to be done by means of a lock-in technique because of a high fluorescence noise in the detection region that is produced from fast velocity groups interacting with second-order sidebands in the cooling-laser frequency spectrum.

In Fig. 3 the flux of atoms in different velocity groups for varying detunings of the cooling laser can be seen. Peaks (1) and (2) belong to the fluorescence generated by the counterpropagating probe beam, peaks (3) and (4) to that generated by the copropagating one. The frequency difference between copropagating and counterpropagating signals gives us via Doppler shift two times the velocity of the atoms in the beam. Signal (M) gives us a frequency scale—and via Doppler shift, a velocity scale—and is generated by the transmission signal of a marker étalon with a free spectral range of 198 MHz linked to the probe-laser beam. As one can see in Fig. 3, there is only a very low fluorescence signal coming from uncooled atoms, so we emphasize that almost all atoms in the beam are slowed. Furthermore, it can be seen that the cold atoms are polarized in the $3\,^2S_{1/2}$ $(F=1)$ ground state [the fluorescence signal from the $3\,^2S_{1/2}$ $(F=2)$–$3\,^2P_{1/2}$ transition that should appear 1772 MHz shifted to the left side of the peaks described above is missing]. This is due to the fact that an optical-pumping process at the exit of the cooling zone occurs. At the end of the field plates, the electric field declines rapidly and due to the decreasing Stark shift, the transitions $3\,^2S_{1/2}(F=2)$–$3\,^2P_{1/2}$, comes into resonance with the central laser frequency that pumps the atoms into the $3\,^2S_{1/2}$ $(F=1)$ state.

Using an electric field to hold the atoms in resonance could offer some advantages in contrast to other cooling methods. Due to the high conductivity of some metals compared with the limited permeability of μ metals, an electric field can be shielded much more effectively from an experimental zone following the cooling region than a magnetic field can.

Another property is the simplicity of the generation of a static electric field; there are no high-current magnetic coils to fabricate, and a change of the field geometry can simply be obtained by changing the field plates or adjusting their relative spacing and angle by two micrometer holders.

In conclusion, we have applied an electric field in order to hold the atoms in resonance with the laser field during cooling of an atomic beam. Further, we were able to produce a steady, highly polarized beam of slow atoms at velocities that are low enough for direct filling of a magneto-optical trap.

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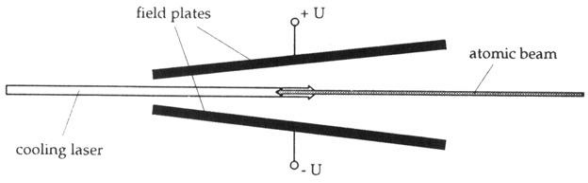

FIG. 1. Principal setup.