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Preparation of a single-state atomic beam by optical pumping and radiative deflection

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A simple technique for producing a single-state sodium atomic beam is described. A single laser both optically pumps the $F=2$ ground-state atoms into $m_F=+2$ and deflects the pumped atoms away from residual $F=1$ atoms. Data demonstrating the technique are presented, and a practical design for an apparatus based on these principles is described.

The two-state system is the foundation for many basic problems in atomic physics. In addition to allowing relatively simple analysis of experiments involving the interaction of atoms with radiation, a closed two-state system does not suffer from population losses by undesirable optical-pumping processes. The preparation of atoms in a single quantum state also finds many applications in atomic collision studies[1] and in the production of spin-polarized nuclei.[2]

Unfortunately, the experimental realization of a two-state system often requires considerable effort. In alkali-metal atoms, for instance, hyperfine structure introduces a myriad of states. Optical pumping can be used to transfer the population of a given hyperfine level (labeled by F) into a particular magnetic sublevel (labeled by m_F). With sodium, for example, the usual approach[3–5] is to drive the $F=2 \rightarrow F'=3$ transition (primed quantum numbers refer to the excited state) of the D_2 line with circularly polarized light ($\Delta m=+1$ selection rule), causing accumulation of the $F=2$ atoms in the $m_F=+2$ state after ~ 15 absorption–spontaneous-decay cycles.[5–7] The selection rules for this process leave the $F=1$ population essentially unchanged,[5] unless the intensity of the pumping light is large enough to cause unwanted (off-resonant) transitions to the $F'=2$ level, which can decay to $F=1$.

Several authors have described techniques for preparing atomic beams in a single quantum state (i.e., completely polarized beams). These relatively complicated procedures make use of two dye lasers,[8] two frequency-shifted beams from a single laser,[9] several Doppler-tuned beams from a single laser,[10] a multimode laser,[9] optical-rf double resonance,[11] or state-selecting magnets.[8,12] Recently, Watts *et al.*[13] have prepared a single-state cesium beam using a rapidly switched, single-mode diode laser.

We suggest a simple single-state-selection technique which uses a single laser resonant with the $F=2 \rightarrow F'=3$ transition of the sodium D_2 line not only to optically pump the $F=2$ level into $m_F=+2$, but also to deflect[14] (via resonant radiation pressure) these pumped atoms away from the unaffected $F=1$ atoms. Appropriate placement of collimators allows selection of only the $F=2$, $m_F=+2$ atoms. We present data demonstrating the technique and offer a practical design for an apparatus based on these principles.

A basic schematic of the technique is shown in Fig. 1. An atomic beam from a source aperture (diameter D) in plane S is collimated by two slits (width w) located at distances L_1 and L_2 from S. Just before entering slit 1, the atomic beam passes through the optical-pumping (OP) laser beam, which is located a distance L_0 from S and oriented perpendicular to the axis defined by the source aperture and slit 2. The first slit is displaced by a distance d_1 from the axis, so that undeflected $F=1$ atoms which pass through both slits must have left the source plane from a strip of width $w_0=[(L_2+L_1)/(L_2-L_1)]w$ centered at an off-axis displacement $d_0=(L_2/L_2-L_1)d_1$. If this strip has no overlap with the actual source (i.e., if $d_0-w_0/2>D/2$), then no $F=1$ atoms will be present in the collimated beam, provided no $F=2 \rightarrow F'=2$ transitions occur in the optical-pumping region. However, atoms originally in $F=2$ (and pumped into $m_F=+2$ by the laser) will be deflected by an angle θ and pass through both slits.

We have used the arrangement described above to produce a highly collimated, single-state atomic beam for light-deflection experiments reported elsewhere.[15] In those experiments, the atoms emerging from slit 2 passes through a second laser beam, and the transverse momentum they received from this "deflection laser" was measured. To permit resolution of momentum transfers corresponding to single-photon absorption, we used slits with $w=10$ μm (3 mm high) separated by 87 cm. The effective source aperture was the 500-μm-diameter orifice of the skimmer used to extract the supersonic beam. The

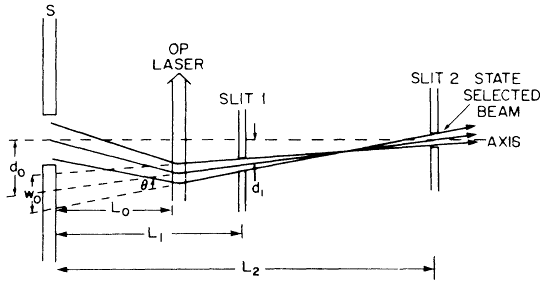

FIG. 1. Schematic of state-selection technique. Atoms from the source plane S are optically pumped and deflected (by an angle θ) by the optical pumping (OP) laser before passing through the two collimating slits.

remaining geometry was designed to optimize final beam flux rather than to eliminate $F=1$ atoms. Nevertheless, our apparatus clearly discriminates against these atoms.

In our apparatus, radiation from a Coherent model No. 699-21 single-mode ring dye laser is transported to the atomic beam via a single-mode polarization-preserving optical fiber. The collimated and circularly polarized Gaussian beam has a full width at half maximum (FWHM) of 3 mm and a total power of 1.25 mW resulting in a peak intensity approximately equal to the saturation intensity for the transition. This optical-pumping laser has its frequency locked to the $F=2 \rightarrow F'=3$ transition by feeding back the difference signal from a split photodiode which monitors the optical-pumping fluorescence.[5,16] A small magnetic field (~ 4 G) along the laser beam provides a quantization axis and serves as a "guiding" field to maintain the atomic polarization. This field does not significantly lift the m_F degeneracies for a given value of F.

The laser crosses the atomic beam at a point 19 cm from the source ($L_0=19$ cm) and 2.8 cm from slit 1 ($L_1=22$ cm). Our supersonic sodium beam (~ 10 torr of sodium seeded in 1800 torr of argon emerging from a 70-μm-diameter nozzle) has a mean velocity of 10^5 cm/s and a velocity spread of 11% FWHM. Under these conditions the average number of optical-pumping cycles, with deflection-induced Doppler detuning taken into account, is about 90. This is roughly six times the number needed to produce essentially stable m_F populations.

Our state-selection technique relies on a combination of the two process: (1) elimination of $F=1$ atoms by state-selective radiative deflection, and (2) accumulation of $F=2$ atoms in $m_F=+2$ by optical pumping. The effectiveness of each of these processes was measured independently to yield the overall effectiveness of the technique.

Suppression of $F=1$ atoms was determined by observing the collimated beam with a scanning hot-wire ionizer and channel electron multiplier located ~ 1.4 m downstream from slit 2. For a fixed displacement d_1, of slit 1 from the axis, the ratio, R, of beam intensities with optical pumping off and on may be interpreted to yield the fraction of atoms in the optically pumped beam which are in the $F=1$ state. Assuming that the optical pumping does not alter the $F=1$ population and that $\frac{3}{8}$ of the atoms in the unpumped beam are in $F=1$, we see that the $F=1$ fraction in the pumped beam is $f=\frac{3}{8}R$. Measured values of f are plotted in Fig. 2 as a function of the displacement, d_1, of slit 1. The smallest value of f (2%) was obtained with a 54% loss in total intensity (only 27% loss of $F=2$ atoms) relative to the situation where $d_1=0$ and the OP laser is off.

The method described above for measuring f, the fraction of the beam in $F=1$, was checked by deflecting[14] the collimated and optically pumped beam (upon emerging from slit 2) with the deflection laser (low-power traveling wave) tuned to the $F=2 \rightarrow F'=3$ transition. With an average deflection of $\sim 4\hbar k$, where $\hbar k$ is the photon momentum, atoms in the $F=2$, $m_F=+2$ state were deflected well away from the undeflected profile. The undeflected peak consisted of $F=1$ atoms and gave a direct measure of f in agreement with the value inferred by the method just described.

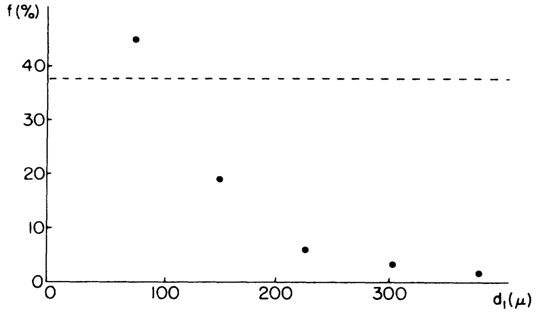

FIG. 2. Fraction of beam in $F=1$ as a function of the displacement of slit 1 from the axis. Experimental parameters are described in the text. The dashed line represents the naturally occurring statistical fraction ($\frac{3}{8}$).

To analyze the effectiveness of the optical pumping to $m_F=+2$, we use our deflection laser to induce fluorescence in the atomic beam at a point just downstream from the second slit. The power of this laser is greatly reduced to avoid perturbing the m_F populations, and one or the other of the collimating slits is removed to allow observation of the induced fluorescence with good signal-to-noise ratio. (This degrades f but should have no significant effect on the polarization of the $F=2$ atoms.) We use a circularly polarized ($\Delta m=+1$) probe beam tuned to the $F=2 \rightarrow F'=1$ and $F=2 \rightarrow F'=2$ transitions of the D_1 line as an indicator or the optical-pumping effectiveness. For perfect pumping there should be no signal at all in these transitions (due to the $\Delta m=+1$ selection rule). A nonzero $F=2 \rightarrow F'=2$ signal indicates residual population in the $m_F=+1$ sublevel, and a nonzero $F=2 \rightarrow F'=1$ signal is primarily a measure of polarization contamination in the probe beam. If we denote by f_1 and f_p, respectively, the small fractional $F=2$, $m_F=+1$ population and the small fractional $\Delta m=-1$ polarization contamination, examination of the relative transition strengths of the individual hyperfine transitions leads to the following ratios of probe fluorescence ($I_{\text{on}}/I_{\text{off}}$) for optical pumping on and off:

D_1 transition	$I_{\text{on}}/I_{\text{off}}$
$F=2 \rightarrow F'=1$	$3f_p$
$F=2 \rightarrow F'=2$	f_1+f_p

Our measured fluorescence ratios yield the values $f_1=4.6\%$ and $f_p=1.4\%$.

In probing with the D_1 line, we must ensure that the signal reduction is not caused by loss of atoms to $F=1$. This is checked by measuring fluorescence induced by transitions from the $F=1$ sublevel. We observe a 10% increase in these signals when the optical pumping is turned on, implying that 6% of the atoms initially in $F=2$ are lost to $F=1$. Since transitions to $F=1$ during optical pumping cannot occur from the $F'=3$ level, it is clear that in the absence of polarization contamination, any transition to $F=1$ must occur early in the optical-pumping process, with the result that atoms transferred to $F=1$ absorb only a few photons from the optical-pumping beam. This suggests that the 10% fluorescence increase we observe would not be seen if both slits were present.

Although our technique is ideally suited for state selection in a highly collimated beam, it is practical to construct an apparatus which discriminates completely against $F=1$ atoms without resorting to collimator slits as narrow as ours. As shown in Fig. 1, the key geometrical consideration is that the deflection angle be large enough to remove the source aperture from the collimation penumbra of slits 1 and 2. In principle, this can always be achieved, by sufficiently increasing the deflection angle, θ, and/or the distance between the source and the optical-pumping region.

We should point out that processes which cause a spread in the deflection, such as the recoil distribution of the spontaneously emitted photons, the photon statistics, and a finite beam-velocity distribution, do not lead to $F=1$ atoms in the collimated beam. These mechanisms result only in a decrease in the intensity of the final beam and this only occurs in cases where the spread removes the origin of a trajectory outside the actual source aperture.

As an illustration, consider a 2.0-mW optical-pumping laser beam of 3-mm FWHM Gaussian beam profile. This gives 1.5 times the saturation intensity at the center of the profile and ensures that only a small fraction of $F=2$ atoms will be transferred to $F=1$ during optical pumping. The mean number, N, of photon absorptions is maximized at $N=110$ if the incident and deflected atoms make equal angles with the laser beam. Given a mean atomic velocity $v=10^5$ cm/s and a 10% velocity spread, the mean deflection angle (and rms deviation) is approximately $\theta=3.2(5)$ mrad. Referring to Fig. 1, we see that the final beam flux is maximized if slit 1 is located immediately following the optical-pumping region, making $L_0=L_1=L_2/2$ and $d_1=L_1\theta/2$. Assuming equal slit widths, w, we find that the source strip for undeflected $F=1$ atoms has a geometric width $w_0=3w$, and a displacement $d_0=2d_1$ from the axis.

For a source-aperture diameter D, the condition for complete elimination of $F=1$ atoms is that this aperture not overlap the $F=1$ source strip, i.e., that

$$D<4d_1-3w\ .$$

For $D=500$ μm, this is achieved for $w=D$ (slit height $=3$ mm) and $\theta=3.2$ mrad if $L_0=L_1=L_2/2=32.2$ cm. The final beam flux emerging from slit 2 for this system would be approximately 60 times greater than that used in our deflection experiments.

Finally, our technique not only provides selection of quantum state, but is also effective in selecting against undesired species (e.g., dimers or different isotopes).

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