

## Spin-Polarized Spontaneous-Force Atom Trap

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We present observations of a spontaneous-force optical trap in which rubidium atoms are spin polarized by optical pumping. Stable trapping is achieved in two dimensions by the same force as in the Zeeman-shift optical trap, and in the third dimension by a macroscopic vortex force that is insensitive to light polarizations and magnetic fields. When the light along this third direction is circularly polarized and a parallel magnetic field is applied, the atoms become spin polarized.

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The techniques of optical pumping have been used for many years to manipulate the internal (spin) degrees of freedom of atoms by controlled absorption and emission of polarized light. Recently, precise manipulation of the external (momentum, position) degrees of freedom of atoms has also become possible using laser cooling and trapping techniques. In this Letter, we describe our observations of an atomic vapor in which both external and internal degrees of freedom are simultaneously controlled: An optically pumped spontaneous-force atom trap. In addition to observing spin polarization of atoms in this trap, we find that, in contrast to conventional optically pumped vapors, small magnetic fields of a few gauss dramatically affect the optical pumping process. The use of appropriate polarizations and magnetic fields is necessary for efficient optical pumping of these samples.

Optical pumping of atoms [1] is a tremendously useful technique for atomic spectroscopy. Lately, optical pumping with lasers has also been successful in producing dense spin-polarized vapors for applications such as spin-polarized targets for high-energy and nuclear physics [2], production of spin-polarized proton beams [3], and sensitive surface probes [4,5]. Independently, much progress has been made in optical cooling and trapping of atoms. Recent simplification of the apparatus required to load atoms into traps [6] and increased numbers of trapped atoms [7] make atom traps attractive for many applications. In particular, the robust Zeeman-shift optical trap (ZOT) [8] can trap over  $10^{10}$  unpolarized atoms at microkelvin temperatures in a vapor cell [7]. It is clear that many new experiments may be feasible with a trap of spin-polarized atoms.

While the ZOT is efficient for trapping and cooling atoms, the atoms in such a trap experience light fields whose polarizations change over a  $\lambda/2$  spatial dimension, so while the atoms may be locally optically pumped, the ensemble is necessarily unpolarized. This difficulty in achieving a net spin polarization is overcome in the present work by using a vortex trap that allows considerable freedom in the choices of light polarization and magnetic field along one dimension. This allows us to spin polarize the sample as described below.

The vortex trap uses the ZOT trapping mechanism

along two directions and a vortex force along the third to achieve three-dimensional trapping [9]. The operation of this trap can be understood from Fig. 1. The laser beams are derived from a single laser tuned 1-2 linewidths below resonance. The opposite polarizations of the laser beams coming from the  $\pm \hat{y}$  directions and the magnetic field gradient  $\partial B_y/\partial y$  produce a ZOT restoring force  $F_y = -ky$ . Along the  $z$  direction, there is no ZOT restoring force since  $\partial B_z/\partial z = 0$  and the  $\pm \hat{z}$  beams have the same polarization. However, atoms that begin to leave the trap along the  $z$  direction are pushed in a counter-

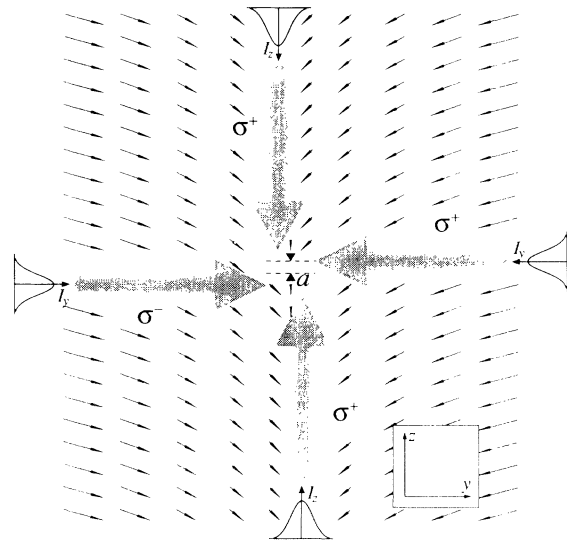


FIG. 1. Configuration (in the  $y$ - $z$  plane) of laser beams and magnetic fields to make a spin-polarized atom trap. The Gaussian spatial profiles of the laser beams are indicated by the shaded arrows and the small graphs. The thin arrows show the magnetic field intensities and directions. Opposing  $\sigma^+$  and  $\sigma^-$  polarizations of the  $y$ -axis beams coupled with the magnetic field gradient produce a restoring force along the  $\pm \hat{y}$  direction. The offsets of the four beams by the distance  $a$  produce a vortex force that provides for stable trapping along the  $\pm \hat{z}$  directions as well. Since the  $\sigma^+$ -polarized  $\pm \hat{z}$  beams are intense compared to the others, the atoms absorb an excess of  $\sigma^+$  photons and become spin polarized. The negative magnetic field along the  $z$  direction is necessary for efficient pumping.

clockwise direction by the intensity imbalances due to the offset Gaussian laser beams. Thus the  $z$  motion is coupled by this vortex force to the  $y$  motion, which is subject to the ZOT restoring force. To approximately describe atomic motion in this trap, we must include a strong viscous damping force  $-\alpha\mathbf{v}$ , where  $\mathbf{v}$  is the velocity, and a ZOT force along the  $x$  direction. Then the equations of motion for the atoms in the vortex trap [9] are  $\alpha v_z = k'y$ ,  $\alpha v_y = -k'z - ky$ , and  $\alpha v_x = -kx$ . The resulting trajectories spiral in toward  $x=y=z=0$ . Thus it is the combination of the vortex and ZOT forces that is responsible for the stability of the trap. (Note that the macroscopic vortex force used here is to be distinguished from previous work on microscopic vortex forces that result from standing-wave fields [10,11] and have a rapid spatial variation.)

The trap of Fig. 1 produces spin-polarized atoms by taking advantage of the insensitivity of the trapping force both to the polarization of the  $\pm\hat{z}$  beams and to  $B_z$ . Since the  $\pm\hat{z}$  beams are both  $\sigma^+$  polarized, on the average the atoms will tend to become spin polarized by depopulation pumping. Increasing the intensity of the  $\pm\hat{z}$  beams relative to the others will enhance the pumping. The inclusion of a uniform, negative  $B_z$  should reduce unwanted precession of the atomic spins about the transverse fields and enhance the depopulation pumping since in a negative magnetic field the transition frequencies for absorption of  $\sigma^+$  light are shifted closer to resonance with the negatively detuned light fields.

We have constructed the trap of Fig. 1, and have achieved a spin polarization of 75% as estimated from the circular dichroism of a probe beam. The trapping apparatus [9] is similar to other vapor-cell traps [6,7], consisting of an ion-pumped stainless-steel vacuum chamber (a six-way cross constructed from  $1\frac{1}{2}$ -in. tubing, with uncoated Pyrex windows) in which a rubidium vapor pressure of  $1 \times 10^{-10}$  Torr is maintained. Two pairs of orthogonal anti-Helmholtz coils ( $1\frac{1}{2}$ -in. diameter,  $1\frac{1}{2}$ -in. separation) with equal currents produce a field which, to lowest order, is  $\mathbf{B} = B'(x\hat{x} - y\hat{y})$  with  $B' = 16$  G/cm, and no gradient along the  $\hat{z}$  direction. A similar pair of Helmholtz coils produces a uniform field along the  $z$  direction. The laser used for trapping is an 8-mW grating-stabilized diode laser [12] locked near the 780-nm  $^{85}\text{Rb}$   $5S_{1/2}(F=3) - 5P_{3/2}(F'=4)$  resonance of a Doppler-free saturated-absorption spectrometer. The laser is spatially filtered to provide a Gaussian profile (beam waist 1.8 cm) and is split into the various trapping beams by polarizing and nonpolarizing beam splitters, which allows the relative intensities of the beams to be adjusted. The mean intensity of the trapping beams was typically  $6.9$  mW/cm<sup>2</sup>. Before the beams enter the vacuum chamber,  $\lambda/4$  plates circularly polarize the beams as needed. A second laser, which overlaps the  $x$ - and  $y$ -trapping beams, is locked near the  $5S_{1/2}(F=2) - 5P_{3/2}(F'=3)$  resonance and therefore depletes any popu-

lation of the trapped atoms in the  $5S_{1/2}(F=2)$  level. A weak probe beam from a third laser is polarized by a  $\lambda/4$  plate and focused through the cloud of trapped atoms nearly parallel to the  $z$  direction for absorption measurements.

The trap was operated first as a conventional ZOT, using only one of the two pairs of anti-Helmholtz coils. Then the trapping lasers were offset in the  $y$ - $z$  plane, as shown in Fig. 1. The current in the orthogonal anti-Helmholtz coils was gradually turned up, while the beam alignments were adjusted to keep the trap working. When the currents in the two pairs of coils were the same (giving  $\partial B_z/\partial z = 0$ ), the trap operated as a vortex trap; accordingly, the trap remained working when the  $\pm\hat{z}$   $\lambda/4$  plates were removed. The offsets of the beams ( $a$  in Fig. 1) were typically 2.5 mm. Next the Helmholtz coils were turned on to add a constant magnetic field along the  $z$  direction, and the  $z$  beams were circularly polarized for optical pumping. We found it necessary to adjust the frequency of the trapping laser to optimize the number of trapped atoms. In general, for our beam intensities and alignments the vortex trap worked better with smaller detunings than the ZOT. Since the vortex trap is sensitive to intensity imbalances of the antiparallel beams [9], the equilibrium position was different from the ZOT. We also observed that the number of trapped atoms is about a factor of 3 larger for antiparallel magnetic field as opposed to parallel to the angular momentum of the light.

To estimate the polarization of the trapped-atom sample, we used a circular dichroism technique. The absorption of a circularly polarized, weak probe laser along  $\hat{z}$  was measured as the laser frequency was swept across the  $5S_{1/2}(F=3) - 5P_{3/2}(F'=4)$  transition. The difference in the maximum absorptions for  $\sigma^+$  and  $\sigma^-$  polarizations of the probe laser is dependent principally on the spin polarization of the sample, although higher multipoles of the atomic density matrix can contribute in a nonzero magnetic field [1,13]. Note that a circular dichroism measurement using a fixed-frequency laser near resonance yields ambiguous information about the spin polarization since circular dichroism is present even for an unpolarized vapor in a magnetic field.

Typical absorption spectra are shown in Fig. 2 for  $\sigma^+$  and  $\sigma^-$  probe polarizations. The data were taken for a spatially averaged photon polarization of 54% (i.e., each of the  $\sigma^+$  polarized  $\pm\hat{z}$  beams had about twice the intensity of each of the  $\pm\hat{x}$  and  $\pm\hat{y}$  beams). The bias magnetic field was  $-6$  G. Assuming the peak absorption is sensitive principally to  $\langle F_z \rangle$ , we deduce a spin polarization of 65% (for this sample data) from the maxima of the absorptions. The number of trapped atoms was  $4.3 \times 10^6$ , the column density was  $6.4 \times 10^8$  cm<sup>-2</sup>, and the absorption path length was about 0.23 cm.

In Fig. 3 we present the dependence of the observed circular dichroism on the bias magnetic field  $B_z$ . When the magnetic field is antiparallel to the light angular

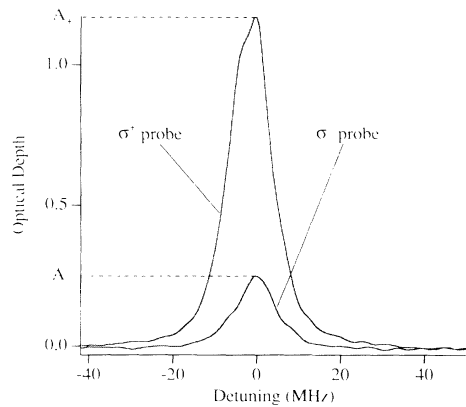


FIG. 2. Probe absorption spectra used for estimating the spin polarization of the sample. The circular dichroism  $(A_+ - A_-)/(A_+ + A_-)$  is approximately the atomic spin polarization. The data were taken with  $\sigma^+$  polarization of the  $\pm \hat{z}$  beams, a bias field of  $-5.6$  G,  $B' = 14.2$  G/cm, a detuning of  $-8.1$  MHz, and a total light intensity of  $6.9$  mW/cm<sup>2</sup>.

momentum we achieve the highest spin polarizations. Since our laser frequency is always less than the atomic resonance frequency (as necessary for cooling), in a negative magnetic field the Zeeman shift tunes the transition frequencies for absorption of  $\sigma^+$  light toward resonance with the laser, while the  $\sigma^-$  transition frequencies are tuned away from resonance. Likewise the optical pumping efficiency should be increased in a positive magnetic field for  $\sigma^-$  polarization of the  $\pm \hat{z}$  beams, and decreased for  $\sigma^+$  polarization. The role of the magnetic field is more complex than this simple argument would indicate, since the observed circular dichroism goes to zero when  $B_z = 0$  even though the photon polarization is high. This may be a result of precession of the atomic spins around the necessary transverse magnetic field. Also, we observe large atomic polarizations for positive magnetic fields, where the depopulation pumping should be degraded for  $\sigma^+$  light. We note that optical pumping has not been studied in detail for the case where Zeeman shifts are comparable to atomic linewidths, as in this experiment. It is known that in high fields, the magnetic field can be treated just like an additional angular momentum [13]. An example of this is the recent suggestion that the efficiency of optical pumping of certain polarized targets can be improved by using linearly polarized light and large magnetic fields [14]. In fact, we have observed a circular dichroism of 40% in our trap with the  $\pm \hat{z}$  beams linearly polarized along the  $x$  direction and a  $-6$  G bias field along  $\hat{z}$ .

Another issue of importance to this trap is the spatial dependence of the light polarization. Since the trap is a three-dimensional standing wave, the light polarization will be different at different points in the standing wave. If we assume the internal states of the atoms adiabatically follow the local light polarization, this implies that

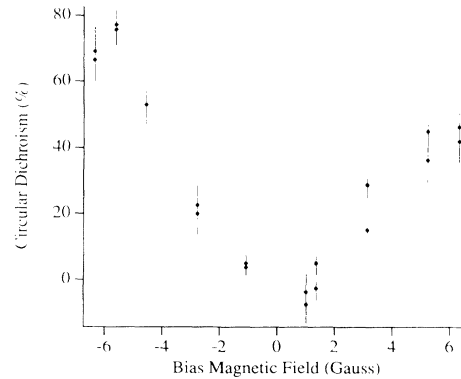


FIG. 3. Observed circular dichroism as a function of the uniform bias magnetic field along  $\hat{z}$ , for  $\sigma^+$  polarization of the  $\pm \hat{z}$  beams. The magnetic field clearly plays an essential role in the optical pumping process.

complete optical pumping of the atoms cannot occur. The magnetic field may reduce this spatial modulation of the atomic spin polarization. Also, we note that if the atoms are moving at speeds of 20 cm/s or more, as typical in a ZOT, the optical pumping will not adiabatically follow the local light field, but will depend on an averaged field, which can be highly polarized. Thus we believe that polarizations higher than the 75% we have achieved are possible.

There are a number of ways the performance of the trap could be improved. The spin polarization is currently limited by the photon polarization, and the number of atoms trapped is limited by the available laser power. More powerful lasers would increase the number of spin-polarized trapped atoms because the intensity ratios and the sizes of the laser beams could be increased. In addition, optical pumping could be enhanced by adding another laser beam whose diameter is just slightly larger than the diameter of the spin-polarized atom cloud. This laser beam would not contribute to the trapping but would improve the optical pumping. Note that this cannot be done with a ZOT, because the direction of the magnetic field varies rapidly in space. Although this experiment was done at low laser intensity, we expect that the optical pumping efficiency will not degrade at high intensities. Based on the largest [7] numbers and column densities attained so far for a ZOT [7], more than  $10^{10}$  atoms and column densities exceeding  $10^{10}$  cm<sup>-2</sup> should be attainable with a few watts of laser power in a vapor cell, with possibly more using loading from an intense slowed atomic beam. For experiments where the optically pumped vapor would be used as a target, the trapped-atom cloud could be elongated along one direction to maximize the column density.

The circular dichroism technique used here to measure the spin polarization suffers from some ambiguity due to possible contributions from higher multipoles of the atomic density matrix. There are other ways to measure

the polarization that may be more accurate. Faraday rotation of off-resonant light has the advantage that it is sensitive only to the spin polarization, and to no other multipoles [1]. The rotation angles can be large due to the substantial optical thickness of the vapor. Another possibility which may be useful for some experiments is to use a magnetic trap that traps only the  $m_F = F$  sublevel of the ground state as a polarimeter. However, for experiments that are concerned with only the dipole moment of the ensemble this still has the disadvantage of being sensitive to moments of the distribution greater than one.

There are two other techniques that produce spin-polarized trapped atoms. The dipole-force trap can be spin polarized [15] but is limited to very small numbers of atoms. Magnetic traps [6,16] are spin polarized also but are more complex than the trap described here due to the need to pre-cool the atoms with an optical trap or to use a cryogenic apparatus with high magnetic fields.

A number of experiments should benefit from a spin-polarized atom trap. Many collisional processes, such as hyperfine-state-changing collisions [17] or Penning ionization of metastable He [18], are suppressed for spin-polarized atoms. Other collisional processes may have spin dependences as well. The optically pumped trap will allow more detailed studies of these collisions. A practical benefit will be reduced collisional loss arising from these effects. Loading of magnetic traps [6] will be more efficient with spin-polarized atoms. As mentioned before, a spin-polarized trapped vapor may be an interesting target for polarized scattering experiments. Such a trap would be an ideal internal target, since there are no material walls required to confine the atoms, greatly reducing background scattering. Finally, studies of beta decay should benefit from these developments.

In summary, optically trapped atoms can be highly spin polarized by optical pumping in a trap that uses both spontaneous and vortex forces. This simple and effective technique affords the experimenter control over both the internal and external degrees of freedom of neutral

atoms.

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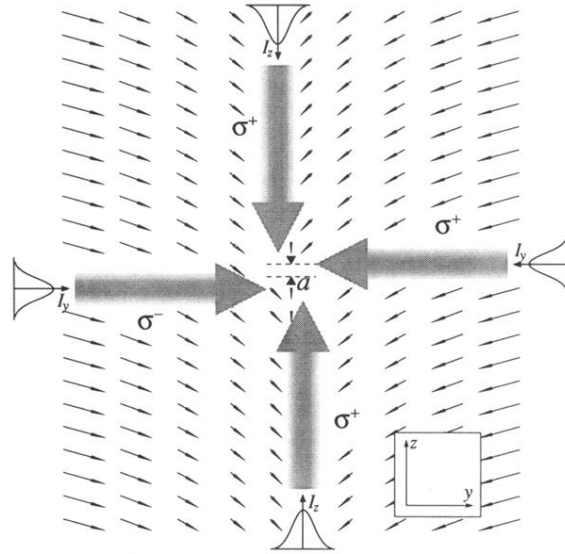


FIG. 1. Configuration (in the  $y$ - $z$  plane) of laser beams and magnetic fields to make a spin-polarized atom trap. The Gaussian spatial profiles of the laser beams are indicated by the shaded arrows and the small graphs. The thin arrows show the magnetic field intensities and directions. Opposing  $\sigma^+$  and  $\sigma^-$  polarizations of the  $y$ -axis beams coupled with the magnetic field gradient produce a restoring force along the  $\pm \hat{y}$  direction. The offsets of the four beams by the distance  $a$  produce a vortex force that provides for stable trapping along the  $\pm \hat{z}$  directions as well. Since the  $\sigma^+$ -polarized  $\pm \hat{z}$  beams are intense compared to the others, the atoms absorb an excess of  $\sigma^+$  photons and become spin polarized. The negative magnetic field along the  $z$  direction is necessary for efficient pumping.