High-brightness, high-purity spin-polarized cesium beam

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We describe a cesium atomic beam (10^{14} atoms s^{-1}, 6×10^{16} atoms $sr^{-1}s^{-1}$) spin polarized using light from two diode lasers. Of the atoms, 95% may be placed into either the $6S_{1/2}(F,m_F)=(3,3)$ or (4,4) state, with less than 2×10^{-4} of the atoms left in the depleted hyperfine level. The latter fraction rises linearly with atomic beam intensity because of reabsorption of light scattered during the optical pumping process. This and other effects limiting complete hyperfine pumping are discussed.

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I. INTRODUCTION

Spin-polarized atomic beams are useful in a number of studies. The use of atoms in specific quantum states allows more information to be extracted from atomic collision studies [1], and polarized heavy-ion beams likewise allow cleaner nuclear physics experiments [2]. Polarized atomic beams are also employed in microwave frequency standards [3,4] and in spectroscopic studies [5].

This paper describes a polarized cesium source developed for a third-generation parity-nonconservation (PNC) experiment using a shelving approach [6–8]: $6S\rightarrow7S$ transitions are detected not in the interaction region through observation of the $7S\rightarrow6P\rightarrow6S$ cascade fluorescence but instead by detecting those atoms which return to the depleted hyperfine level after a $6S\rightarrow7S$ transition. Since more than 100 $6S\rightarrow6P$ transitions may be detected for each atom that returns to the depleted hyperfine level when exciting on the cycling $6S$ $F=4\rightarrow6P_{3/2}F'=5$ and $F=3\rightarrow F'=2$ transitions, the signal size is vastly increased, and photodetector and scattered light noise become negligible by comparison. The removal of the photodetector from the interaction region also allows better control of stray electric and magnetic fields in this region. This approach requires, however, that the fraction of atoms left in the depleted hyperfine state after optical pumping be small compared to the fraction ($\sim10^{-3}$) of atoms undergoing $6S\rightarrow7S$ transitions. Moreover, a good signal-to-noise ratio requires that the polarized beam be as intense as possible. High beam intensity (above 3×10^{13} s^{-1}) [9] and thorough depletion of one hyperfine state (to the 10^{-4} level) are not entirely compatible because of reabsorption of optical pumping fluorescence [1,10]. This problem and others associated with complete hyperfine pumping are discussed below.

Approaches to obtain nearly complete (>90%) population of a single F,m_F ground state in an alkali-metal atom involve two processes: transfer of angular momentum to the atomic beam to put atoms into specific magnetic substates, and transfer of atoms out of the unwanted hyperfine level. To do this, Hils, Jitschin, and Kleinpoppen [11] used a hyperfine-level selecting hexapole magnet followed by circularly polarized dye-laser excitation to populate the $3S_{1/2}(F,m_F)=(2,2)$ level in sodium. Bechtel and Fick [2] employed laser-rf double resonance to put 95% of all sodium atoms into the (2,2) level. Schinn, Han, and Gallagher [1] obtained similar results using an electro-optic modulator to excite atoms out of both hyperfine ground levels at once. Our approach has grown out of the work of Watts and Wieman [6]. Like Avila *et al.* [3], we use two diode lasers to excite atoms out of both ground-state hyperfine levels. Appropriate choice of the lasers' polarizations can then put nearly all atoms into a single (F,m_F) state.

To populate fully a single ground level, atoms are excited out of all (F,m_F) ground levels but the desired one; eventually, all atoms decay into the desired level and stop absorbing light. The cesium D_2 transitions used are indicated in Fig. 1. One laser (the "hyperfine pump") is linearly polarized and excites the

$$6S_{1/2}F=4\rightarrow6P_{3/2}F'=3$$

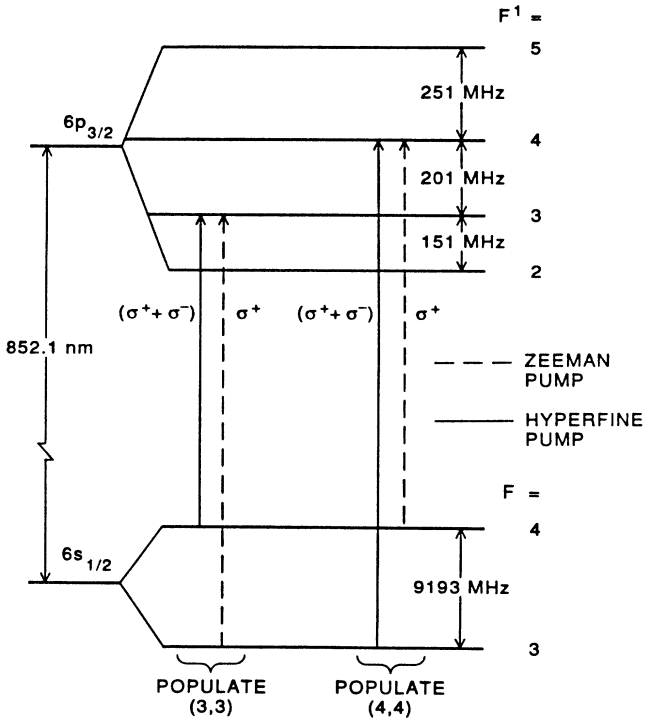

FIG. 1. Optical pumping transitions.

transition to drive atoms out of the $F=4$ level, while the second (the "Zeeman pump") is tuned to the

$$6S_{1/2}F=3\rightarrow 6P_{3/2}F'=3$$

transition and is circularly polarized to transfer all atoms into the (3,3) state. By tuning the hyperfine pump laser to the $3\rightarrow 4$ transition and the Zeeman pump to the $4\rightarrow 4$ transition, all atoms are put into the (4,4) state.

The choice of optical pumping transitions is dictated by two requirements: Atoms must be excited out of all (F,m_F) levels but the desired one and the fluorescence from the optical pumping region must be minimized in order to preserve spin polarization downstream. For pumping into the (3,3) level, then, the hyperfine pump laser cannot drive the $6S\ F=4\rightarrow 6P\ F'=5$ transition because the $\Delta F=\pm 1,0$ selection rule prevents depletion of the $F=4$ level, while the $4\rightarrow 3$ transition is preferred over the $4\rightarrow 4$ transition because fluorescence from the optical pumping region is twice as large with $4\rightarrow 4$ pumping. Similarly, the $3\rightarrow 2$ transition is unsuitable for Zeeman pumping since atoms are excited out of neither the (3,2) nor the (3,3) ground levels, while $3\rightarrow 4$ excitation leads to ten times the fluorescence of $3\rightarrow 3$ pumping since atoms in the desired (3,3) state continue to be excited. Analogous considerations lead to the transitions chosen for (4,4) pumping.

II. EXPERIMENT

The experimental setup is depicted in Fig. 2. A cesium beam of cross section 0.5×2.5 cm^2 effuses out of a two-stage oven through a glass microchannel plate [12]. This ribbon-shaped beam has a divergence [full width at half maximum (FWHM)] near 5° and a flux of 7×10^{14} cm^{-2}s^{-1}. After passing through a liquid-nitrogen-cooled aperture, the beam passes through a collimator composed of a set of vertical vanes 2.5 cm long and spaced 0.05 cm apart and then through another cooled aperture. This results in an atomic beam flux of 10^{14} cm^{-2}s^{-1} at the optical pumping region with a horizontal divergence of 25 mrad and a vertical divergence of 70 mrad. The cross section of the cesium beam allows for a long laser-beam interaction length, necessary for studies of weak transitions.

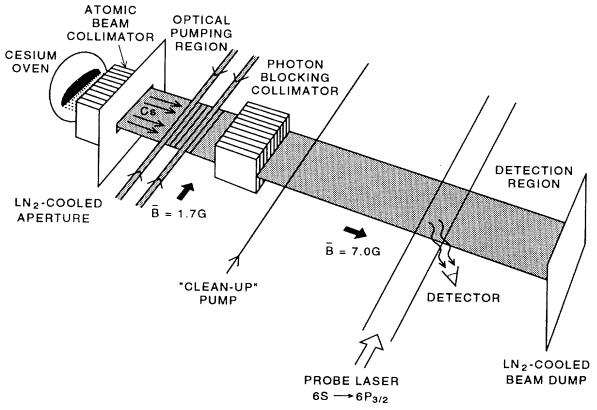

FIG. 2. Experimental arrangement.

In the optical pumping region, the hyperfine pump and Zeeman pump lasers overlap and make two double passes through the atomic beam, each 0.5 cm wide (yielding a 20-μs interaction time) and separated by 1 cm. Two separate passes through the atom beam are necessary to achieve complete polarization in spite of atomic fluorescence [1]. Atoms which enter the desired (F,m_F) level and stop absorbing laser light may still absorb the unpolarized fluorescent light emitted by other atoms during the optical pumping process and subsequently decay into other states. In the first pass, then, most of the optical pumping occurs but is not complete because of this reabsorption of fluorescence light. In the second pass 1 cm downstream, the intensity of fluorescent light is much reduced, and the atoms need absorb only one or two photons each to enter the desired nonabsorbing level. The magnetic field in the optical pumping region is 1.7 G and within 10 mrad of being parallel to the pumping laser beams. The hyperfine pump laser power is 3 mW. These laser powers provide far greater than the ten photons required to polarize each atom and suffice to saturate the pumping process (see Fig. 3). This is important since the 1.7-G field produces some splitting of $(F,m_F)\rightarrow(F',m_F')$ transitions (8 MHz for the outmost magnetic sublevels). Moreover, an atomic beam whose populations do not fluctuate as the pump lasers' frequencies and amplitudes change is essential for the parity experiment.

The diode lasers are Sharp Model No. LT015 lasers with high-reflection coatings on the rear surfaces and antireflection coatings on the front surfaces, selected for lasing near 840 nm at room temperature. With heating to 35 °C and optical feedback from blazed diffraction gratings, the wavelengths are pulled to the cesium D_2 transitions at 852 nm and the laser linewidths narrowed to <0.5 MHz. The lasers are ditherlocked to the appropriate transition peaks in saturated absorption spectrometers [13] and will remain locked to within 0.1 MHz for many hours under favorable conditions. These lasers oscillate in a single external cavity mode at the 10^{-3} level but have a non-negligible amount of power in a pedestal which extends several hundred megahertz out from the lasing frequency.

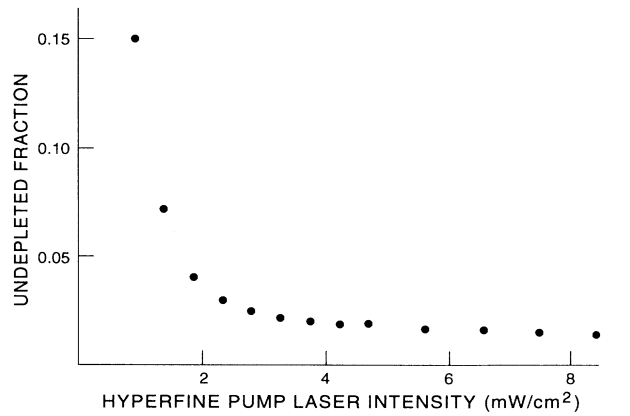

FIG. 3. Fraction in wrong hyperfine level vs hyperfine pump laser intensity (no cleanup optical pumping).

After the optical pumping region, the atoms pass through a set of soot-coated vertical vanes which stop some of the optical pumping fluorescence from passing downstream. In this region the polarized atoms adiabatically follow the magnetic field as it rotates by 90° and increases to 7 G in the interaction and detection regions. Before entering the interaction and detection regions, the atoms pass through a final hyperfine pump laser beam to deplete the unwanted hyperfine level of atoms put there by absorption of optical pumping fluorescence downstream. At the interaction region the density is 1×10^{9} cm^{-3} and the intensity is 2×10^{13} s^{-1}.

In the detection region the atoms pass through a 2.5-cm wide probe laser beam usually tuned to either the $4\rightarrow5$ or the $3\rightarrow2$ transition. Fluorescence from the detection region is collected by a large-area silicon photodiode (collection efficiency 30%) and allows sensitive detection of atoms in either hyperfine level.

III. PROBING THE POPULATIONS

The degree of spin polarization and the depletion of the unwanted hyperfine level are tested separately. We consider here population of the (3,3) state but comparable results are obtained when pumping into the (4,4) state.

To test the depletion of the $F=4$ hyperfine level, the probe laser light is horizontally polarized (parallel to the magnetic field) so that it can excite only $\Delta m=0$ transitions and is tuned to the cycling $4\rightarrow5$ transition, where more than 200 photons may be detected for each atom in the $F=4$ level. The fluorescence of the atomic beam is then measured with and without optical pumping. Since approximately 30% of the probe laser light is absorbed by the atomic beam in the absence of optical pumping, the fluorescence value is multiplied by 1.2 ± 0.05 to obtain a modified fluorescence which remains proportional to atomic beam density. No such correction is required in the optically pumped case since the relevant beam density is then four orders of magnitude smaller. With this correction, the ratio of fluorescence with and without optical pumping is equal to the ratio of the $F=4$ populations.

Optical pumping by the probe laser occurs in two ways and it is important to know how this optical pumping affects the measured population ratio. First, m_F-state redistribution by the probe laser occurs in ten excitations. Since more than 500 absorption cycles take place in the probe region, this redistribution occurs rapidly and the measured fluorescence should be independent of the initial m_F-state populations. Hence our population ratio should not be strongly affected by the fact that the atoms are uniformly distributed among the $F=4$ Zeeman substates in the absence of optical pumping but are nearly all in the $m_F=4$ substate with optical pumping. To test this assumption, the magnetic field in the probe region was cancelled to give an average field of less than 0.5 G but with nonuniformities of up to 2 G. With the m_F states thus scrambled, the fluorescence ratio was remeasured and found to agree with the ratio obtained with a uniform 5-G field in the probe region.

A second source of optical pumping by the probe laser occurs because of leakage out of the $F=4$ level due to off-resonant $4\rightarrow4$ transitions. At our probe intensity (slightly above the saturation intensity 1 mW/cm^2), the radiative width of the $4\rightarrow4$ transition leads to one $4\rightarrow4$ transition and decay to the $F=3$ level in 10^4 $4\rightarrow5$ excitations and is therefore negligible. The diode laser power spectrum contains large wings, however, and is the primary cause of these off-resonant transitions. Fortunately, such leakage has the same effect on the monitored fluorescence no matter how many atoms occupy the $F=4$ level so that the fluorescence ratio is unaffected.

A more serious problem occurs because of off-resonant excitation of $F=3$ atoms and subsequent repopulation of the $F=4$ level due to the probe laser's spectral impurity, as discussed in Sec. IV. If the probe laser intensity increases above the saturation intensity, then the rate of $F=4$ repopulation proceeds more rapidly than the rate of $F=4$ depopulation (since the transitions leading to this process are saturated) and the measured hyperfine pumping will deteriorate. It is observed experimentally that the unpumped fraction increases slowly with probe laser intensity above 1 mW/cm^2, which is chosen as our operating point.

To determine the relative populations of the various m_F substates, microwave excitation on the cesium clock transition at 9.19 GHz is used to drive atoms out of specific m_F states in a "flop-in" experiment. With the microwave cavity situated so that the microwave magnetic field is parallel to the 7-G dc magnetic field in the interaction region, only $\Delta m_F=0$ magnetic dipole transitions can occur. When the microwave frequency comes into resonance with a given $(3,m_F)\rightarrow(4,m_F)$ transition, some of the atoms in the $(3,m_F)$ state are transferred to the depleted $(4,m_F)$ state where they are efficiently detected by the probe diode laser 10 cm downstream.

The 7-G magnetic field completely resolves the microwave spectrum (see Fig. 4) and allows simple determination of the relative populations by comparing microwave spectra with full optical pumping with spectra with hyperfine pumping alone. If one assumes a uniform

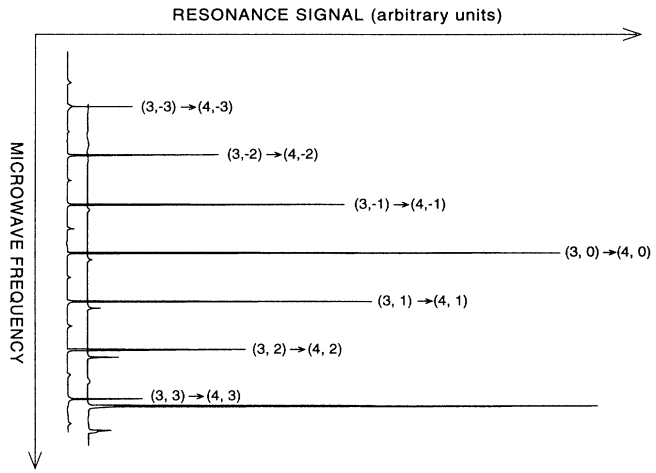

FIG. 4. Microwave spectrum in 7-G magnetic field. Lower: hyperfine pumping only. Upper: full optical pumping.

TABLE I. Populations of the $6S_{1/2}F,m_F$ level with optical pumping.

State (F,m_F)	Fraction of beam
(4,4) pumping: $3\rightarrow4$ $(\sigma^+ + \sigma^-)$ hyperfine pump, $4\rightarrow4$ σ^+ Zeeman pump.	
4,4	0.978
4,3	0.018
4,2	0.0034
4,1	0.0003
4,0	0.000 08
All others	<0.0005
(3,3) pumping: $4\rightarrow3$ $(\sigma^+ + \sigma^-)$ hyperfine pump, $3\rightarrow3$ σ^+ Zeeman pump.	
3,3	0.965
3,2	0.026
3,1	0.007
3,0	0.0015
All others	<0.0005

distribution of atoms among magnetic substates with hyperfine pumping alone, then the relative populations of the m_F states with full optical pumping are equal to the ratios of the line intensities with full optical pumping to the intensities with hyperfine pumping alone. The populations in Table I were derived in this way.

The assumption of uniform distribution among the magnetic substates with hyperfine pumping alone requires justification. Symmetry forbids an orientation (the number in the $+m$ state different from the number in the $-m$ state) of the atoms by the hyperfine pump laser but not an alignment. Such an alignment is miniscule, however, since on average only two absorption cycles occur before the atoms enter the desired hyperfine level and become transparent to the hyperfine pumping light. Moreover, one expects a somewhat different alignment to occur when pumping on the $3\rightarrow4$ transition to deplete the $F=3$ level compared with $4\rightarrow3$ pumping for $F=4$ depletion [4], while no difference is seen in the $4\rightarrow3$ and $3\rightarrow4$ microwave spectra.

The relative intensities in the microwave spectra differ significantly from theoretical expectations. Transitions between large $-|m_F|$ states are small compared to $0\rightarrow0$ transitions. This may be explained by magnetic-field inhomogeneity in the microwave excitation region. A 10-mG inhomogeneity would lead to a 7-kHz broadening of the $1\rightarrow1$ transition, a 14-kHz broadening of the $2\rightarrow2$ transition, etc. Since we measure only peak intensities of microwave lines rather than line strengths integrated over the entire resonances, the broadened lines look smaller. The small asymmetry in the spectrum between the $m_F\rightarrow m_F$ and the $-m_F\rightarrow -m_F$ transitions is due to a detuning of the cavity resonance from the $0\rightarrow0$ transition and a subsequent difference in microwave power on different transitions. Since we determine the relative m_F populations by measuring only the ratios of microwave line strengths with and without spin polarization, these effects do not influence our results.

IV. LIMITS TO HYPERFINE-LEVEL DEPLETION

A high-density atomic cesium beam with less than 10^{-4} of the atoms in one hyperfine level is difficult to achieve. If an atomic beam could be produced with no atoms in one level, processes such as reabsorption of fluorescent light and collisional depolarization are likely to put atoms back into the depleted level. In this section we consider these processes and ways to minimize them.

The reabsorption of fluorescent light from the optical pumping region is the dominant source of atoms in the wrong hyperfine level in our atomic beam. Starting with a perfectly polarized cesium beam, we may estimate the effect of fluorescence reabsorption as follows. The number of atoms excited out of the desired $F=3$ level per second in a slice dz of the atom beam a distance z downstream from the optical pumping region is

$$D=\frac{K\langle\sigma_r\rangle F^2}{4\pi\langle v\rangle}\frac{dz}{z^2}\ , \tag{1}$$

where F is the total beam intensity, K is the number of fluorescent photons emitted per optically pumped atom (roughly ten), $\langle v\rangle$ is the thermal velocity of 2.7×10^4 cm s^{-1}, and $\langle\sigma_r\rangle$ is the effective cross section for absorption of a fluorescent photon followed by a decay into the wrong hyperfine level. We may crudely estimate $\langle\sigma_r\rangle$ from σ_0, the $6S\rightarrow6P$ absorption cross section on resonance. Since the longitudinal Doppler broadening in the cesium beam is 300 MHz while the natural width is 5 MHz, we expect a factor of 5 MHz/300 MHz$=\frac{1}{60}$ to account roughly for the Doppler detuning of the reabsorbed photons. Another factor of $\frac{1}{4}$ arises since there is a 25% probability that an atom excited out of the (3,3) state will decay into the $F=4$ manifold. Hence, $\langle\sigma_r\rangle=\sigma_0/240$.

What is measured is not D but the total fraction of atoms excited into the depleted hyperfine level by the time the atoms reach the detection region:

$$f=\int_{z_{\min}}^{z_{\text{detect}}}\frac{D}{F}=\frac{K\langle\sigma_r\rangle F}{4\pi\langle v\rangle}\left[\frac{1}{z_{\min}}-\frac{1}{z_{\text{detect}}}\right], \tag{2}$$

where $z_{\min}=0.5$ cm is on the order of the size of the optical pumping region. The fraction in the wrong hyperfine level is seen to be proportional to the beam density in accordance with the trend in the top curve in Fig. 5. At an intensity of 10^{14} s^{-1} at the optical pumping region (or a

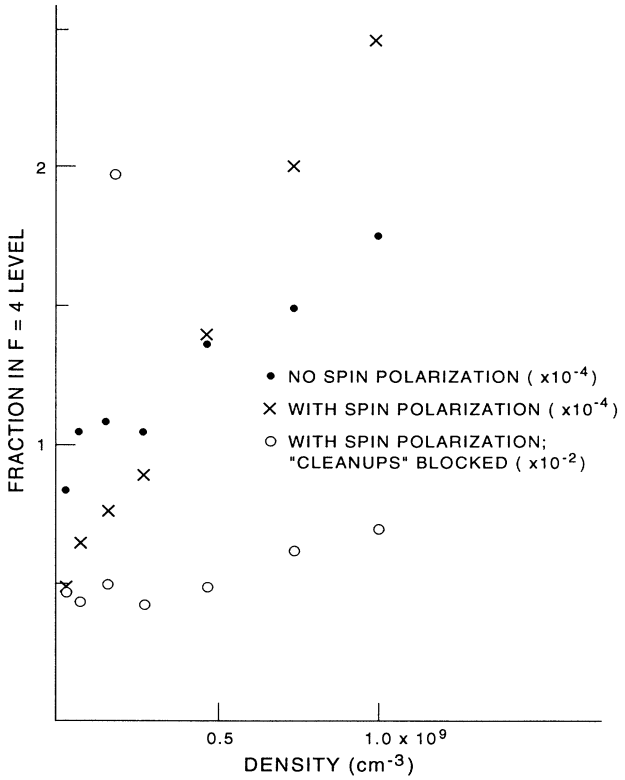

FIG. 5. Depletion of $F=4$ ground level vs beam density at the detection region.

density of 10^9 cm^{-3} at the detection region), the fraction left in the $F=4$ state is 0.025. Inserting this into Eq. (2) along with the 20-cm distance between optical pumping and detection regions gives

$$\langle \sigma_r \rangle = 4.4 \times 10^{-12} \text{ cm}^2 ,$$

which is $\frac{1}{260}$ times the resonant cross section 10^{-9} cm^2. This is reasonable because of the relevant Doppler shifts.

The fraction of atoms excited into the depleted level by optical pumping fluorescence as a function of distance downstream was tested by sending in a second hyperfine pump laser beam at various positions downstream of the optical pumping region. This "cleanup" pump could deplete all atoms put into the wrong hyperfine level upstream of itself. As expected, the fraction of atoms in the depleted level at the detection region was inversely proportional to the distance from the optical pumping region to the cleanup pump.

To overcome the problem of fluorescence reabsorption, we take four steps. The first and most effective is to send in the cleanup hyperfine pump laser beam as far downstream as is practical. This depletes the unwanted level of all atoms except those excited between the cleanup pump and the detection region and reduces by a factor of 140 the number of atoms in the wrong level, as Fig. 5 indicates.

The second step is to improve the cesium-beam collimation. This allows a reduction of the beam flux without a loss in signal on resonance, which is the important quantity for the parity experiment. In our case, only those atoms whose Doppler shifts are less than the $6S \rightarrow 7S$ natural width (3 MHz) contribute significantly to the $6S \rightarrow 7S$ signal size. The vertical-vane collimator described in Sec. II, by rejecting those atoms with large transverse velocities (>8 m s^{-1}), reduces the beam flux by a factor of 3.5 but reduces the residual Doppler width by nearly the same factor (from 31 to 9 MHz) so that the signal size is unchanged. Since the residual Doppler width remains larger than the natural width, further collimation is desirable but is difficult to obtain without a reduction in signal.

The rather tight atom beam collimation allows us to take a third step since now the atoms moving downstream are collimated to within 25 mrad, while the offending fluorescent light emerges isotropically from the optical pumping region. By installing a second, soot-coated vertical-vane collimator between the optical pumping region and the detection region, we can stop some of the optical pumping fluorescence from coming downstream. This reduces the fraction of atoms in the unwanted hyperfine level by a factor of 2 for a given beam flux in the detection region.

The final step taken is to choose those optical pumping transitions which minimize the amount of fluorescent light, as discussed in Sec. I. Comparison of the atomic beam flux at the optical pumping region with the total fluorescence from this region implies that less than ten photons are scattered for each polarized atom.

Other sources of light capable of exciting atoms into the depleted hyperfine level must be considered. The hyperfine pump and probe lasers are both tuned to excite atoms in the depleted hyperfine level. Because of spectral impurity due to relaxation oscillation sidebands, however, there may be a small amount of power 9.2 GHz away from the nominal laser wavelength to excite atoms out of the populated level and into the depleted level. This unwanted optical pumping will proceed until the fraction of atoms in the depleted level is equal to the fraction of laser power available to excite atoms out of the populated level. This problem can be magnified in external cavity lasers which may oscillate in several external cavity modes. To avoid this problem, we shorten the external cavities to 2.5 cm. This forces the lasers to run mainly single mode [14] and puts the mode spacing at 6 GHz so that any residual sidemodes cannot excite the hyperfine transition 9.2 GHz away. As a final precaution, flat Fabry-Pérot filter cavities with 1-GHz linewidths and 20-GHz free spectral ranges are placed in the hyperfine pump and probe laser beams to minimize power at the unwanted hyperfine transition.

Finally, absorption of Zeeman pumping laser light scattered off windows and other optics also degrades the hyperfine depletion. The intensity required to limit depletion to the 10^{-4} level is less than 10 nW/cm^2. Scattered light is the most likely reason the depletions with and without spin polarization do not agree in the limit of low atom beam density. Extensive baffling of stray light both inside and outside the vacuum chamber reduces this source of background atoms to less than 10% of that due to photon reabsorption at the densities of interest to us.

Collisions are the last potential source of atomic beam depolarization. Cs-Cs, Cs-surface and Cs-background gas collisions need to be considered. The largest Cs-Cs collisional depolarization mechanism is spin exchange in elastic collisions. The spin-exchange cross section for cesium is [15]

$$\sigma_{\text{Cs-Cs}}=2\times10^{-14}\ \text{cm}^2$$

and leads to a spin-exchange rate:

$$\frac{1}{T}=n\sigma_{\text{Cs-Cs}}\langle v\rangle\approx0.6\ \text{s}^{-1}\ . \tag{3}$$

This leads to a thermalization of hyperfine populations:

$$\frac{n_F}{n}-\left[\frac{g_F n_{F'}}{g_{F'}n}\right]=e^{-t/T}\approx1-n\sigma_{\text{Cs-Cs}}\langle v\rangle t\ , \tag{4}$$

where g_F is the degeneracy of the F level. If we start with a fully polarized beam in the F state and assume a low depolarization rate, so that $n_F/n\approx1$, then

$$\frac{g_F n_{F'}}{g_{F'}n}=n\sigma_{\text{Cs-Cs}}\langle v\rangle t=n\sigma_{\text{Cs-Cs}}d_{\text{OP-det}}\ , \tag{5}$$

where $d_{\text{OP-det}}$ is the distance between the optical pumping and detection regions. When this is 20 cm, we therefore expect

$$\frac{n_{F'}}{n_F}\approx4\times10^{-4}\ . \tag{6}$$

This assumes, however, that all atoms put into the depleted hyperfine level by spin-exchange collisions are detected downstream. Since atoms undergoing these collisions may have their trajectories significantly altered, only a small fraction of them contribute to the residue detected downstream. In fact, only about 0.01 of the depolarized atoms enter the detection region with small enough Doppler shifts to be detected as part of the atomic beam. [Spin-exchange depopulation is, moreover, easy to detect: Since electron spin polarization is preserved in these collisions, depolarizing collisions cannot occur between two atoms in the (4,4) state. Hence, spin-exchange depolarization would show up unequivocally as a difference between (3,3) pumping and (4,4) pumping, which is not observed experimentally.]

Collisions with surfaces lead to complete depolarization and need to be avoided. In our case, the use of liquid-nitrogen-cooled apertures and a cooled beam stop downstream of the detection region prevents atoms from striking surfaces and then wandering into the detection region. Finally, collisions with background gases must be considered. Nitrogen is fairly innocuous, with a depolarizing cross section of 5×10^{-22} cm^2 [16], but molecular oxygen has a much larger cross section and since oxygen is much lighter than cesium, O_2-Cs collisions may result in depolarization without significantly changing the Cs atoms' directions. We find that a pressure less than 1.0×10^{-6} Torr makes this background source small relative to other sources.

V. RESULTS

Figure 5 plots the hyperfine depletion as a function of atomic beam density at the interaction region. Without spin polarization, all but fewer than 7×10^{-5} of the atoms are removed from the $F=4$ level. Contributions to this residue of unpumped atoms have been discussed above. With spin polarization the residue is much larger and rises with atom beam density, indicating that reabsorption of fluorescent light from the optical pumping remains the dominant source of atoms in the wrong hyperfine level.

Since both the hyperfine pump and Zeeman pump intensities in the optical pumping region are greater than the saturation intensity and the laser linewidths are much less than the radiative linewidth of the $6S\rightarrow6P$ transition, Zeeman coherences are possible which leave atoms in nonabsorbing states before they reach the desired (F,m_F) level [17]. Since the optical pumping takes place in a 1.7-G magnetic field, however, $\Delta m_F=2$ coherences oscillate at more than 3 Mrad s^{-1} and higher-order coherences oscillate more rapidly. With an optical pumping time on the order of a few microseconds, then, such coherences are destroyed before atoms evolve into nonabsorbing states. Figure 6 plots hyperfine depletion as a function of magnetic field, showing the destruction of coherence effects by fields greater than 0.4 G.

The ramifications of this spin-polarized cesium beam for the atomic parity-nonconservation experiment are threefold. First, since all atoms in the atomic beam are placed into the correct spin state to undergo $6S$-$7S$ transitions, there is a sixteenfold increase in useable beam density for a given total density. Because the overall den-

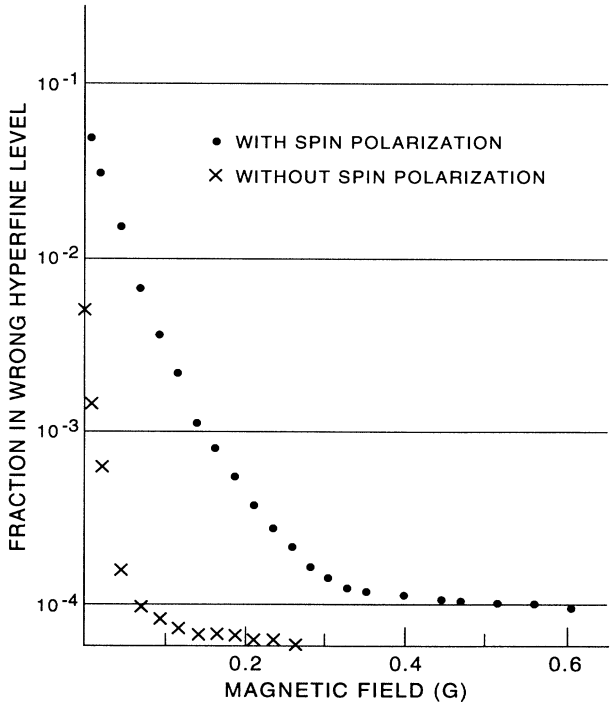

FIG. 6. Hyperfine depletion vs magnetic field: ●, with spin polarization; ×, without spin polarization.

sity is reduced by the extra collimation required for spin polarization, the useable beam density is only increased by a factor of 2.3. Second, the elimination of neighboring transitions out of different spin states removes dilutions due to neighboring lines and allows the resolving magnetic field to be reduced from 70 to 7 G, thereby making hyperfine mixing effects negligible. Third, the use of the shelving approach allows the detection efficiency to be increased from 25% to 70% and simplifies the design of a $6S$-$7S$ excitation region free of stray fields. Since the background fluorescence due to unpumped atoms is shot-noise limited over the range of densities explored here, the PNC signal-to-noise ratio does not change as the density changes, so the largest practical density is used in the PNC experiment in spite of the increase in the size of the background.

To summarize, a spin-polarized cesium beam with thorough depletion of one of the two ground-state hyperfine levels has been demonstrated. It will prove useful in a parity-nonconservation experiment and is of interest for other possible shelving experiments.

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