

Sensitive dependence of hydrogen Balmer-alpha laser-induced fluorescence signal from hydrogen neutral beam on background magnetic field

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A previously unreported result for the dependence of a laser-induced fluorescence (LIF) signal from the H-alpha (Balmer-alpha) transition in a hydrogen neutral beam passing through a background of neutral hydrogen gas is presented. The LIF signal from a 30 kV beam is found to be enhanced and the fine-structure line amplitudes in the H-alpha spectrum are seen to vary significantly with an applied perpendicular magnetic field over the range of 0–0.01 T. The phenomenon has also been observed and investigated in a background electric field of ~ 0 –300 V/cm, and in the presence of crossed perpendicular magnetic and electric fields, demonstrating that the magnetic-field effect is due to the motional Stark electric field perceived in the beam reference frame as it passes through the magnetic field. The effect has been studied with variations of background neutral gas pressure, laser power, and polarization direction and at different locations along the neutral beamline. The phenomenon could be exploited as a low-field diagnostic technique in environments that are not appropriate for magnetic probes. © 2005 American Institute of Physics. [DOI: [10.1063/1.2121935](https://doi.org/10.1063/1.2121935)]

I. INTRODUCTION

Very sensitive dependence on magnetic fields in the region of 0–100 G has been observed in a laser-induced fluorescence (LIF) signal from the H-alpha transition in a hydrogen neutral beam. The total magnitude of the signal as well as the individual fine-structure lines observed from the beam were found to vary significantly. The phenomenon is understood to be due to the mixing of the atomic sublevels in the $\mathbf{v} \times \mathbf{B}$ Lorentz electric field that is perceived in the beam atom's frame as it moves at the beam velocity $\mathbf{v}$ through the background magnetic field $\mathbf{B}$. It has the potential to be exploited as a low-magnetic-field diagnostic in experiments which are hostile to magnetic probes and have neutral gas backgrounds or limited charged particle interactions. The possibilities include measuring the self-generated magnetic fields of ion¹ or electron² beams or measuring magnetic fields in vacuum or low-density plasma devices with hostile environments.

The experiment in which this phenomenon has been observed is primarily a test bed for the development of the motional Stark effect with laser-induced fluorescence (MSE-LIF) diagnostic. The motional Stark effect (MSE) diagnostic has been widely applied to measure magnetic-field pitch angle in high-field toroidal plasma devices^{3–5} since its development.⁶ The technique of this measurement is to observe the polarization of the Stark manifold of spectral lines emitted by a hydrogen neutral beam passing through a $\mathbf{v} \times \mathbf{B}$ electric field in a magnetized plasma. It was originally employed in 1989 to achieve a measurement of the central rotational transform, $q(0)$, in a tokamak and has since be-

come the standard technique for q -profile measurement in tokamaks worldwide^{7–9} due to its high spatial and temporal resolution, accuracy, and nonperturbing nature.

While the motional Stark effect diagnostic has been very successful as it has been previously applied, the technique has limitations that prevent it from being extended to the measurement of magnetic-field magnitude and pitch angle in devices with magnetic fields under ~ 0.75 T, many of which have recently been built.^{10–15} The MSE-LIF technique¹⁶ is being developed to extend the low-field limit of MSE. It is also designed to allow the determination of the magnitude of the magnetic field and allow MSE measurements to be taken on machines without heating beams or at times when the heating beams are not operating or desired on the machines that have them. More details on the MSE-LIF technique and the apparatus discussed in this paper can be found elsewhere.^{16,17}

Previous work on laser-induced fluorescence on the Balmer-alpha line has been done in various contexts, but the enhanced LIF phenomenon in low magnetic fields has not been reported. Some other work has focused on using LIF on neutral hydrogen atoms in plasmas as a density and/or temperature diagnostic.^{18–20} A series of experiments was performed using LIF on the Balmer-alpha line of hydrogen atoms in a neutral beam in background electric field with the aim of producing a hydrogen beam with a significant population in selected sublevels of the $n=3$ state for atomic physics studies.^{21–24}

II. EXPERIMENTAL APPARATUS

Figure 1 shows a diagram of the experiment. A 30–40 kV neutral hydrogen beam is created by charge-exchange neutralization of a proton beam extracted from a

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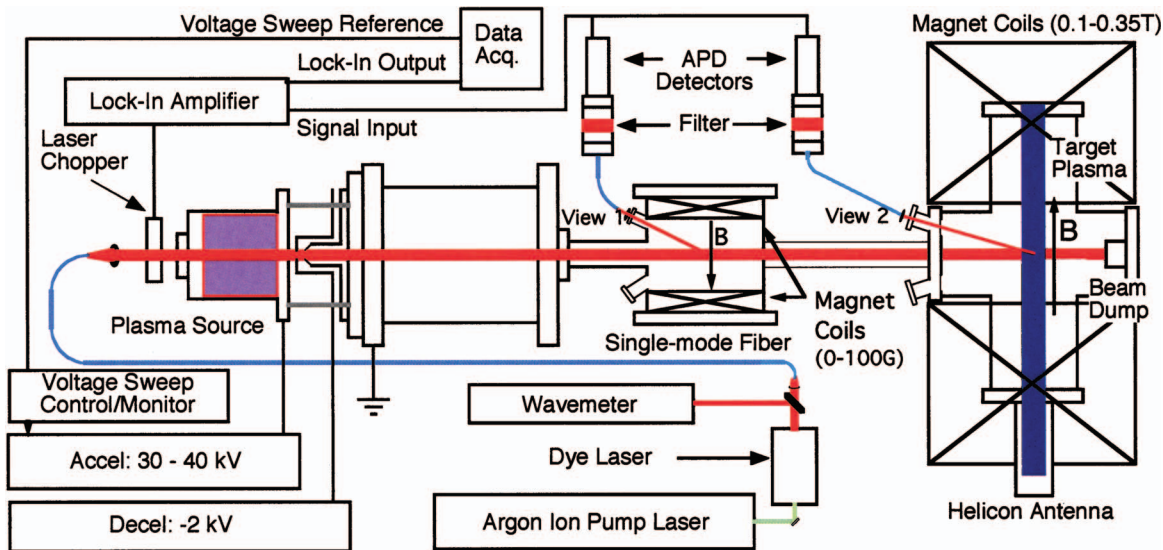


FIG. 1. (Color) Schematic diagram of experimental system.

multicusp rf source through a three-grid electrode system. The source has been carefully designed and constructed to minimize the axial energy spread of the beam. This includes floating the rf generator at the extraction potential with fully shielded leads and installing a magnetic filter which limits the spread in plasma potential in the source over the region where the beam ions are born.^{25,26} The acceleration power supply and rf generator were designed to apply minimal oscillation to the extraction voltage to keep the axial energy spread of the beam as low as possible for a maximally precise spectroscopic measurement. The linewidth of the LIF measurement is presently limited by collisional processes within the neutralization cell and beamline which cause the energy spread in the beam. The beam travels through a partially evacuated beamline with a background neutral hydrogen pressure of 0.1–0.5 mT. Two sets of magnetic coils are positioned along the beamline to apply transverse magnetic fields to the beam. At 1 m from the acceleration region, the magnetic coils and associated power supply can create an applied field of 0–0.01 T and at 2 m, a field of 0.1–0.35 T can be attained.

A Coherent 899-21 dye laser, pumped by a Coherent Sabre argon-ion laser at 7.5 W and 514 nm, is used with DCM dye in EPH solvent to excite the Doppler-shifted H-alpha transition from $n=2$ to $n=3$ in the hydrogen beam near 650 nm. The laser interacts with the neutral beam axially, passing through a window in the rear of the neutral beam source. The laser is coupled to a single-mode fiber at the output and recollimated at the location of the neutral beam source to be ~ 1 cm in diameter to match the size of the neutral beam. A lens is set up to collect light from the beam at the center of the magnetic coils. The light is focused on a bundle of optical fibers and transmitted through a thermally tuned narrowband (8 Å) filter, which selects only the Doppler-shifted H-alpha emission from the beam and blocks both the background H-alpha from stationary atoms and stray laser light signals. The transmitted light is focused onto an avalanche photodiode (APD) with a 1 cm diameter active area. The APD, from Advanced Photonix, is cooled to

-20°C to reduce dark current noise. Its intrinsic gain is variable and on the order of ~ 300 . It employs a high-gain transimpedance amplifier which gives 10^6 V/A followed by a $10\times$ voltage amplifier. The APD output is the input to the lock-in amplifier.

III. LIF SIGNAL IN APPLIED MAGNETIC FIELD

Experimental data for the LIF signal with no applied field are shown in Fig. 2. Data with magnetic fields of 20, 45, 60, and 105 G applied perpendicular to the beam are shown in Fig. 3. In these spectra, the laser was tuned close to the Doppler-shifted H-alpha line and the neutral beam voltage was swept over 400 V, centered at 30 kV, to cover all of the possible resonant transitions. The vertical axis is the lock-in signal magnitude output and the horizontal axis is the sweep voltage. The conversion factors between sweep voltage, frequency, and wavelength are approximately $100\text{ V} \sim 6\text{ GHz} \sim 0.09\text{ Å}$.

The H-alpha transition, even in the absence of applied fields, consists of a series of lines due to the fine structure of the $n=2$ and $n=3$ levels. Figure 4 displays the levels, to scale within each n , including the spin-orbit interaction and the Lamb shift, but neglects the hyperfine structure. The energy

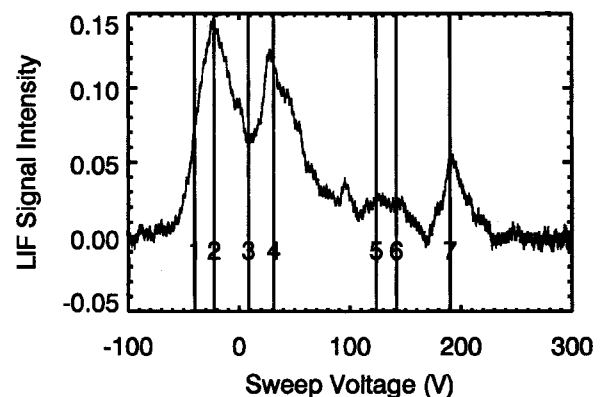


FIG. 2. LIF data with no applied fields.

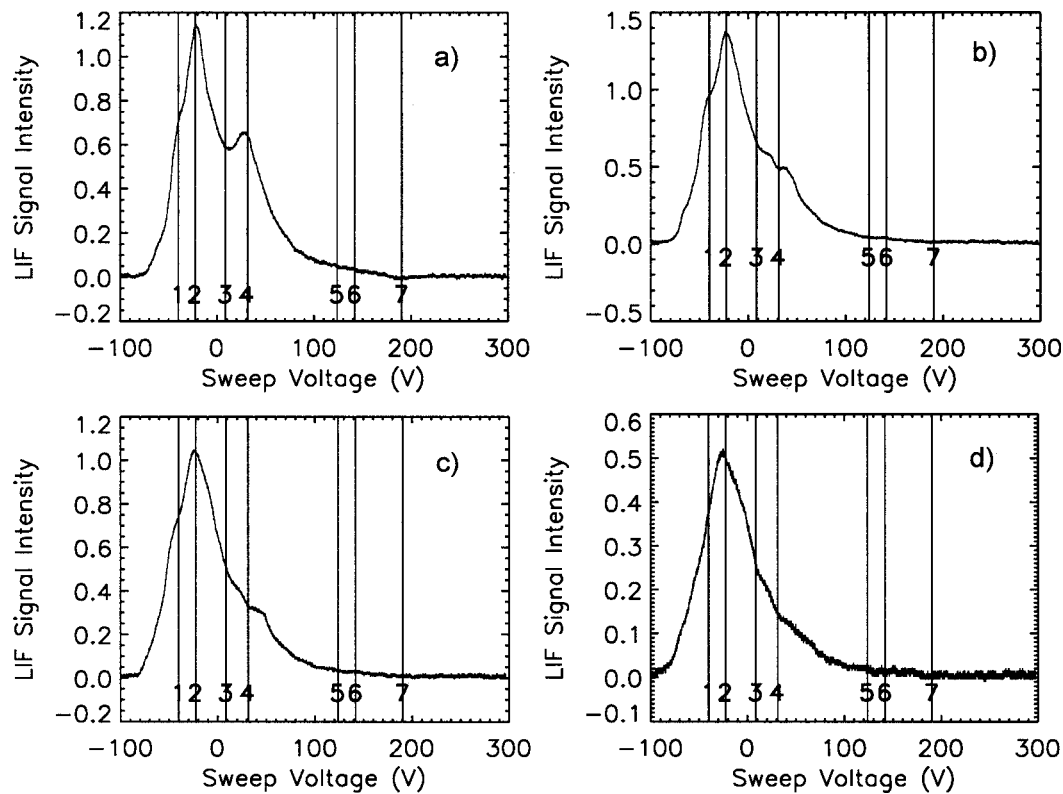


FIG. 3. LIF data with perpendicular magnetic field applied: (a) 20, (b) 45, (c) 60, and (d) 105 G.

differences are given in cm^{-1} and the levels are identified in spectroscopic notation l_j , where s , p , and d refer to the l or orbital angular momentum quantum number of 0, 1, and 2, respectively, and j is the total angular momentum quantum number, which in the case of hydrogen with a single electron of spin $\frac{1}{2}$ is given by $j=l\pm\frac{1}{2}$.

Also shown in Fig. 4 are the allowed transitions in the absence of applied fields. Their relative locations in frequency or wavelength space are shown on the bottom of the figure, and the seven lines are numbered, in order of increasing wavelength, for ease of comparison to the experimental data. These lines are overlaid on the experimental data plots for reference.

An examination of the zero-field spectrum shown in Fig.

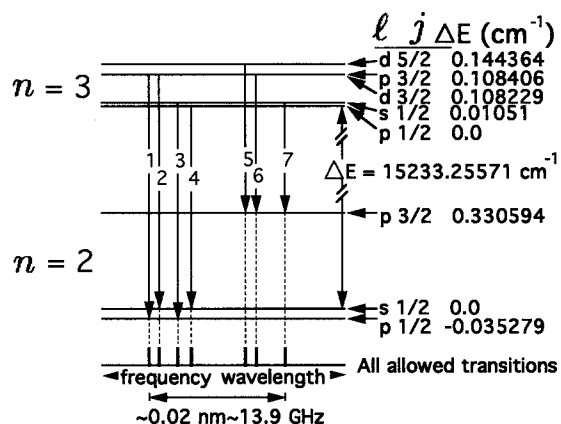


FIG. 4. Diagram showing fine structure and allowed transitions for H-alpha line.

2 reveals that some of the possible fine-structure transitions are seen, while others are not. In this figure, lines 2, 4, and 7 are all present, while lines 1, 3, 5, and 6 are either significantly smaller in amplitude or not present at all. In the zero-field spectrum, it is important to note that the phase of line 7 is opposite to that of the other lines; that is, while lines 2 and 4 represent an increase in the observed fluorescence due to laser tuning at those wavelengths, the negative phase of the lock-in output for line 7 means that the total fluorescence actually decreased when the laser was tuned to this transition. When a magnetic field is applied perpendicular to the beam in the observation region, the LIF spectrum changes dramatically and continues to change with fields up to 100 G. Figure 5 gives a summary of the background collisionally induced fluorescence (CIF) signal and the integrated LIF signal versus applied magnetic field. Here, the integrated LIF signal is calculated by summing the total area under the curves such as those in Figs. 2 and 3. From Fig. 5, it is clear that the LIF signal magnitude increases dramatically as the applied field rises from zero to about 40 G and then begins to decrease. Over this same range of applied field, the background collisionally induced fluorescence signal decreases and then flattens out.

The detailed spectra of Fig. 3 show that the individual lines observed are also varying over this range of applied field. Line 1 appears, and line 7 disappears at low field, the gap between lines 2 and 4 grows, and line 4 appears to split in two and then returns to a single line. All of the lines begin to stray from their original field-free line locations.

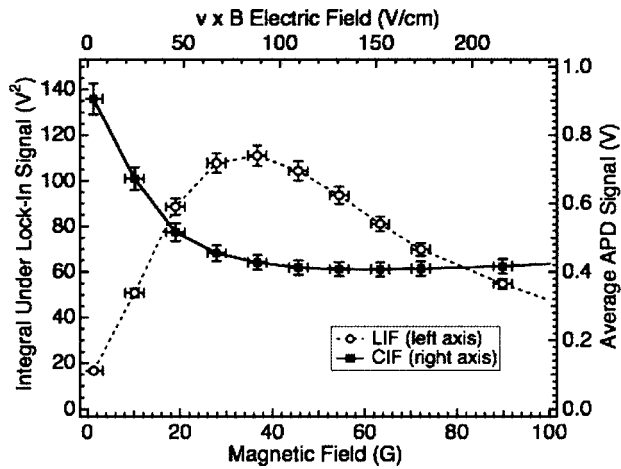


FIG. 5. Background collisionally induced fluorescence (CIF) signal and integrated laser-induced fluorescence (LIF) signal vs applied magnetic field.

IV. LIF SIGNAL IN APPLIED ELECTRIC FIELD

In order to investigate the effects of an electric field applied directly to the neutral beam, parallel water-cooled copper plates were positioned on either side of the beamline a few centimeters from the beam and a voltage of 0–5 kV was applied across the plates. Scans of the LIF signal with applied electric field reveal behavior that is very similar to the applied magnetic-field case. Figure 6 shows the LIF data with applied voltages of 75, 150, 230, and 325 V/cm. Figure 7 shows the background CIF signal, and the integrated LIF signal, for a scan of applied voltage on the parallel plates. The horizontal axis displays the applied voltage divided by the distance between the plates, in units of V/cm. This quantity is not exactly the same as the actual applied electric field between the plates, as there are charged particles between the plates which can create a sheath and shield the center from the applied voltage. In fact, the first few data points in Fig. 7 are nearly unchanged from the zero-applied-voltage case because a sheath is created between the plates and there is no applied electric field at the beam location at this low voltage. As the voltage rises, the influence of the sheath is overcome

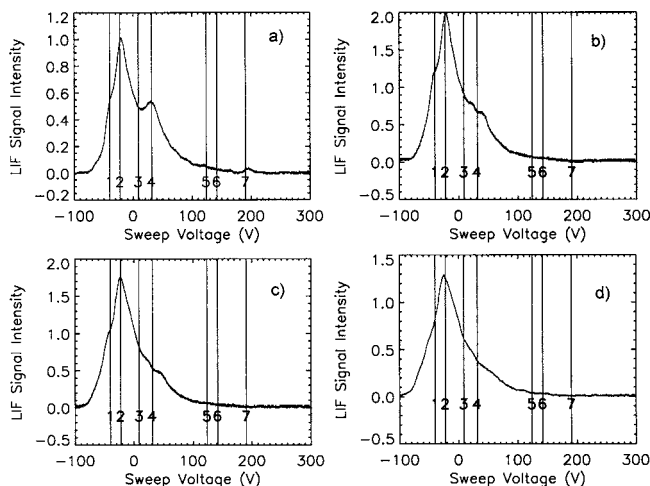


FIG. 6. LIF data with electric field applied, given as volts applied divided by capacitor plate spacing: (a) 75, (b) 150, (c) 230, and (d) 325 V/cm. Actual electric field in the beam line varies due to nonlinear sheath effect.

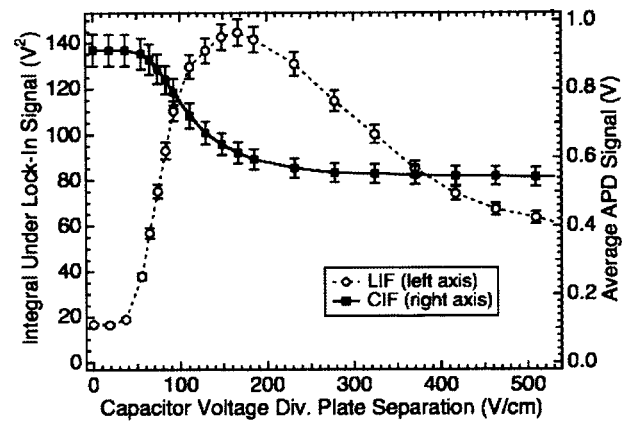


FIG. 7. Integral under signal and background CIF signal for applied electric field.

and the changing LIF and CIF behavior is seen. Applied voltage scans with a background magnetic field were done as well. In some cases, the background magnetic field was directed to create a Lorentz electric field in the beam frame which was parallel to the electric field from the applied voltage, and in other cases the magnetic field was in the opposite direction, creating a Lorentz electric field in the beam's frame which is opposite to the electric field created by the applied voltage.

A series of scans such as those in Fig. 7 was taken with varying applied magnetic fields in order to verify that the effect was due to the perceived electric field in the beam frame. By combining applied magnetic fields with applied voltage, it was seen that the location of the LIF peak in each case was consistent with it being approximately constant with the total perceived electric field. This can be seen in Fig. 8, which displays the applied electric field at the peak of the LIF enhancement versus the applied magnetic field. The “turn-on” field, due to sheath effects, was subtracted from the peak location as an estimate of the sheath effect, though this simplification clearly becomes increasingly inaccurate at higher applied electric fields as the slope of the data deviates from the lower field values.

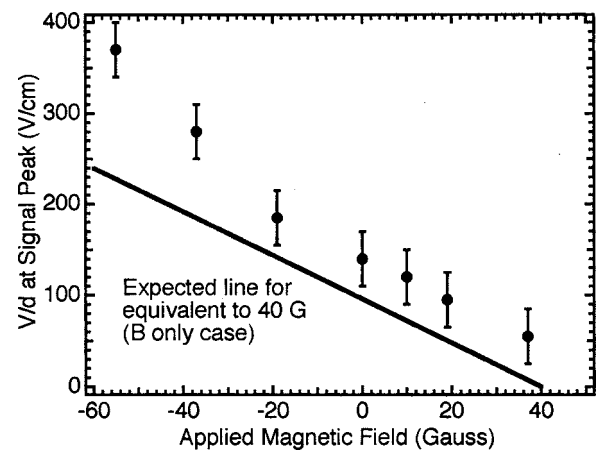


FIG. 8. Applied electric field at the peak of LIF enhancement vs applied magnetic field.

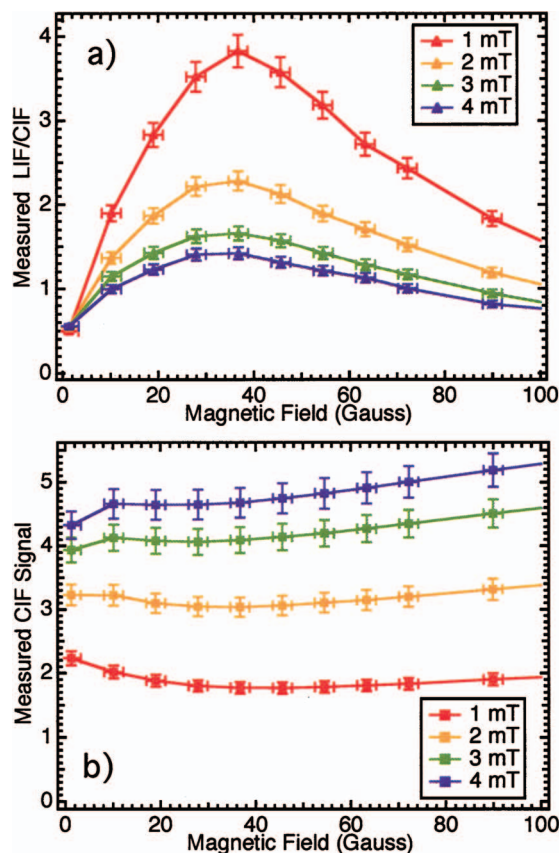


FIG. 9. (Color) Experimental results for pressure scan. Laser-induced fluorescence data shown in (a), collisionally induced fluorescence data shown in (b).

V. EFFECTS OF VARIATION OF EXPERIMENTAL PARAMETERS

Magnetic-field scans were taken under various conditions of background gas pressure in the beamline. The data are shown in Fig. 9. For these scans, hydrogen gas was added through a gas inlet located in the viewing region. All of the pressures indicated are measured in this location, and are higher than for usual operating conditions, where the pressure there is typically measured to be ~ 0.2 mT. As the pressure rises, it is seen that the enhancement phenomenon is less pronounced and the background CIF signal is increased.

The results of a scan of input laser power, attenuated with neutral density filters, is shown in Fig. 10. It shows that the transition is not being fully saturated under the usual operating conditions, as the LIF signal decreases as the input laser power decreases. It also shows that the enhancement phenomenon is present even as the laser power is reduced.

Scans were repeated with the laser polarization parallel to the perceived electric field as well as with the laser polarization perpendicular to the perceived electric field; in both cases the laser beam itself is parallel to the beam and the polarization is therefore perpendicular to the neutral beam propagation direction. The enhancement phenomenon was seen in both polarization cases, with no observed differences in the enhancement behavior. Differences were observed in the individual spectra, as shown in Fig. 11. Most notably, the

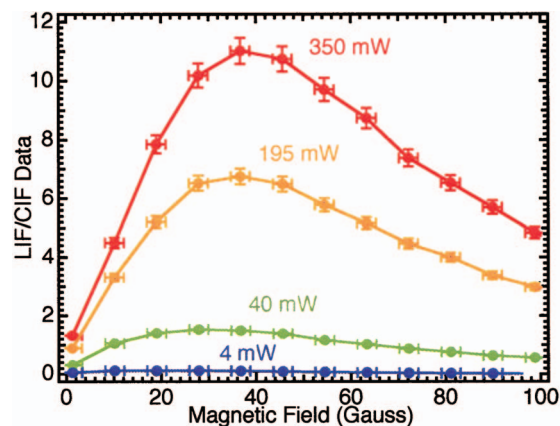


FIG. 10. (Color) Experimental results for neutral density filter scan.

horizontal polarization case, where the laser is perpendicular to the perceived/applied electric field, includes a peak which is absent in the vertical polarization case.

VI. DISCUSSION

An understanding of this enhanced laser-induced fluorescence phenomenon can be gained through consideration of the variation in atomic sublevel parameters with the applied electric field. In the absence of field, the $2s$ state is

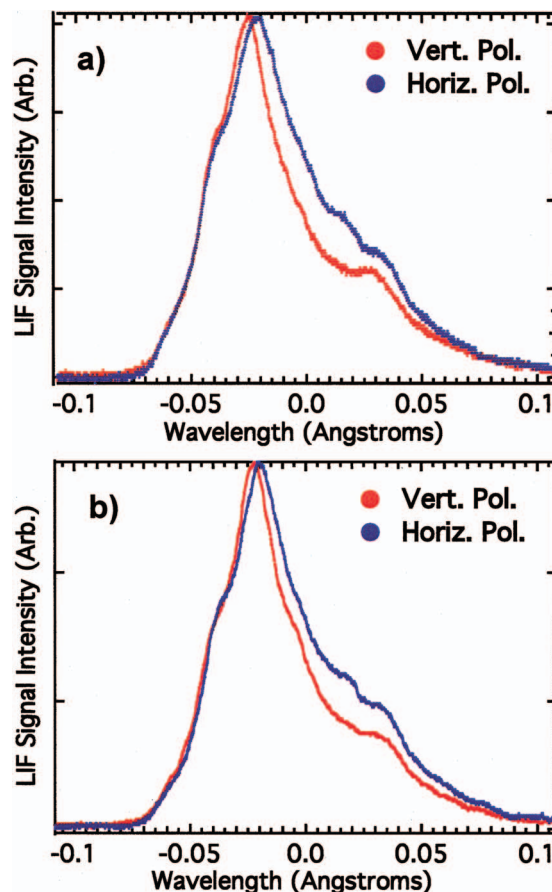
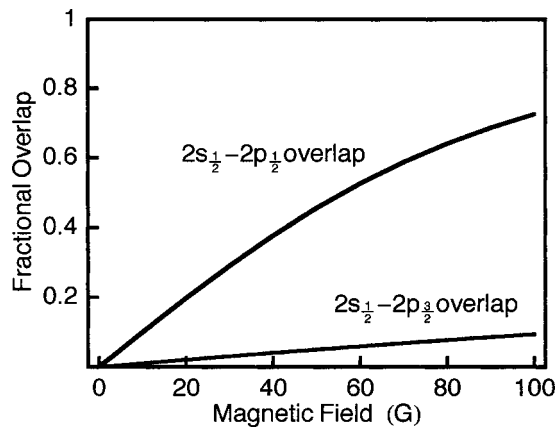


FIG. 11. (Color) LIF data taken with varying laser polarization in a magnetic field of 45 G (a) and with an applied voltage of 150 V/cm (b). Here, vertical polarization is parallel to the perceived/applied electric field and horizontal polarization is perpendicular to it.

FIG. 12. Overlap of $2s$ and $2p$ wave functions vs applied magnetic field.

metastable and, due to its long lifetime, is likely to have a significantly higher population than the $2p$ states. In the zero-field spectrum of Fig. 2, the dominance of lines 2 and 4, which represent the allowed transitions from the $2s$ state as shown in Fig. 4, is due to the excess of electrons in the $2s$ state. In the absence of fields, the $3s$ lifetime is significantly longer than the $3p$, $3d$, and $2p$ states. The negative-going line 7 can be understood as a sign that the $3s$ state has a higher population than the $2p_{3/2}$ state and that stimulated emission occurs when the laser is tuned to resonance with that transition. The change in the shape of the gap between lines 2 and 4 as field is applied and line 7 disappears is an indication that stimulated emission is also occurring at line 3 with no applied field, showing that the $3s$ population is higher than the $2p_{1/2}$ population.

As field is applied, the $2s$ state begins to mix with the $2p$ states and transitions that were previously forbidden become allowed. Figure 12 shows the result of a calculation of the overlap of the states which the zero-field $2s$ and $2p$ states evolve into as the field is turned on. These forbidden transitions can be seen as the additional lines that appear in the spectra of Figs. 3 and 6 when a field is applied. Calculations of the expected wavelengths of these transitions were performed and fits were made to the data for these calculated wavelengths at different field values. Examples are shown in Fig. 13. Here the individual colored peaks represent the average locations of the lines from the $3d_{5/2}$, $3d_{3/2}$, $3p_{3/2}$, $3p_{1/2}$, and $3s_{1/2}$ states. The line amplitudes are obtained from a least-squares fitting routine and the line shapes were defined as exponentially modified Gaussians to match the line shapes produced through a combination of symmetric broadening mechanisms and the asymmetry caused by nuclear straggling and neutralization of beam protons before the full acceleration potential gradient is traversed.

The total LIF signal increases for a combination of reasons. The greater number of allowed transitions results in a larger overall signal. Also the branching ratios for the $3p_{3/2}$ state to all of the $n=2$ states increase with field, accounting for some of the total signal increase. Additionally, it is not possible in this apparatus to discern between the wavelength of a $2s-3d_{5/2}$ transition and the $2p_{1/2}-3d_{3/2}$ transition. Both would appear nearly at the location marked as line 1. The fluorescence observed there may be a combination of previ-

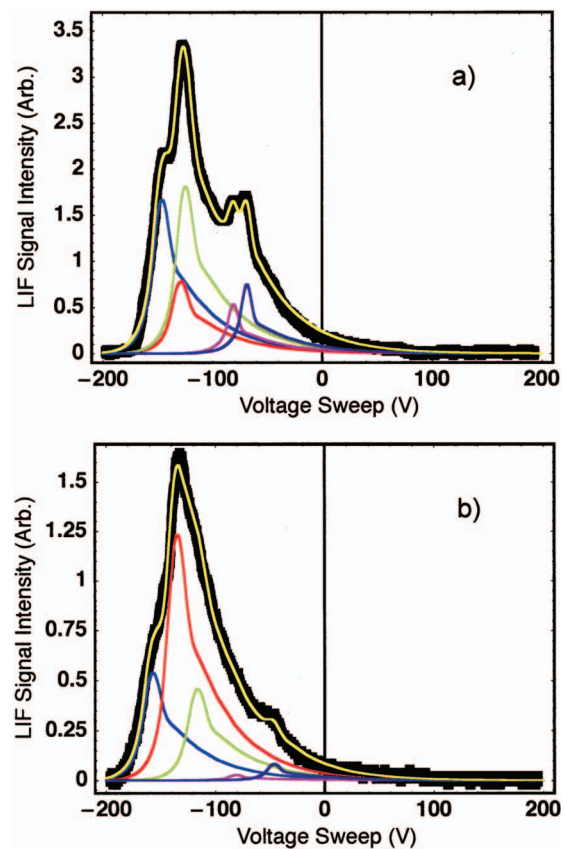
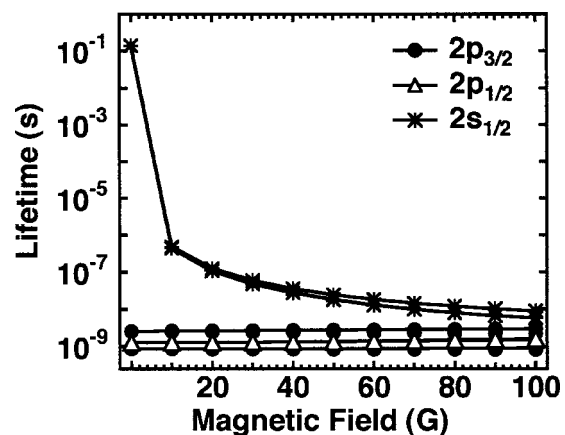
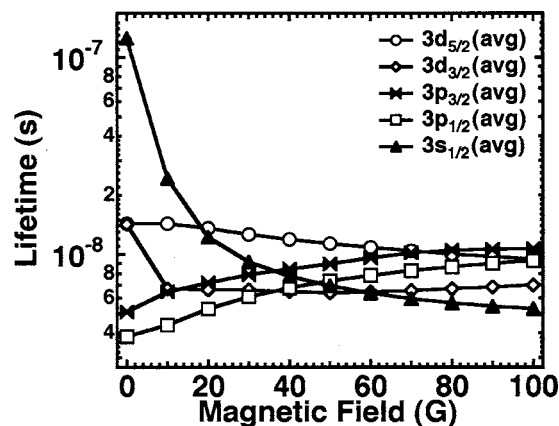


FIG. 13. (Color) Example of peak fitting to data at 27 (a) and 97 G (b).

ously forbidden transitions from $2s$ to $3d_{5/2}$, and some contribution from the $2p_{1/2}$ state, to which $2s$ electrons may transition²⁷ as they experience the time-changing field upon entering the viewing region.

As the field continues to increase, the LIF signal decreases because the population in the $2s$ state drops as transitions to ground become allowed. The lifetime of the $2s$ state decreases significantly over the course of the measurement and it approaches the $2p$ state lifetime by 100 G, as shown in Fig. 14. The variation in the total enhancement factor and peak field value at maximum enhancement between the applied magnetic field case of Fig. 5 and the applied electric field case of Fig. 7 may be due to the difference

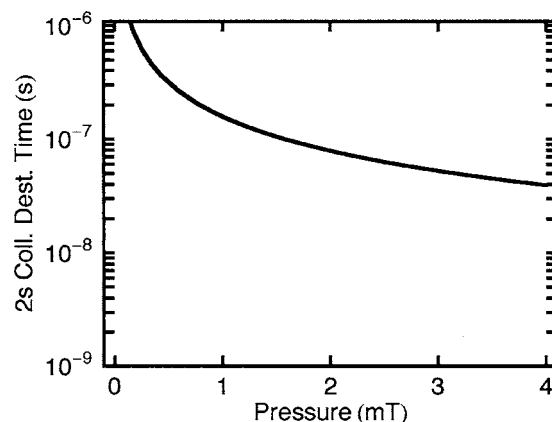
FIG. 14. Variation in lifetimes of $n=2$ states with applied magnetic field.

FIG. 15. Variation in lifetimes of $n=3$ states with applied magnetic field.

in the fringing field distribution along the beamline as the atoms approach the viewing region in the two geometries. The electric field is applied with a steeper gradient and lesser penetration of field into the beamline than the magnetic field, thus this case allows a greater signal enhancement before the competing effect of $2s$ -state loss through quenching during the approach to the viewing region comes to dominate. The difference in the fringing field extent and sheath effects are responsible for the line representing the equivalent electric field expected to match the 40 G magnetic-field peak being lower than the data in Fig. 8.

The reduced penetration of field into the beamline in the applied electric field case similarly accounts for the smaller decrease of CIF signal with field in the applied electric field case as opposed to the applied magnetic field case. The CIF signal decreases with applied field as the $3s$ lifetime decreases and the excess population in $3s$ diminishes. The disappearance of the stimulated emission at lines 3 and 7 is supporting evidence that the $3s$ population significantly decreases with the applied field. The variation of the $n=3$ lifetimes with applied field was calculated and is shown in Fig. 15.

As pressure in the viewing region is increased, Fig. 9 shows that the collisionally induced fluorescence signal increases and the effect of the applied field changes from causing a drop in the CIF signal with field at low background pressure to causing an increase in the CIF signal with field at high background pressure. This, too, can be understood in terms of the competing effects populating each level and the variation of the sublevel parameters. At low pressures, the relatively long lifetime of the $3s$ state as compared to the $3p$ and $3d$ states is likely to cause an excess of electrons in the $3s$ state, and these transitions contribute significantly to the total CIF signal. Thus, as a field is applied, and the $3s$ lifetime drops, this enhancement is reduced and the signal goes down. At higher pressures, even without an applied field the total CIF signal goes up because of enhanced collisional excitation from ground and $n=2$ states. The effect of collisional depopulation of the $3s$ state may come to dominate over radiative decay, and so the sublevels of the $n=3$ level are expected to be more evenly distributed. As field is applied, many previously unseen radiative transitions from $n=3$ sublevels to $n=2$ sublevels become allowed and the net effect

FIG. 16. Collisional destruction time for $2s$ metastable beam vs background gas pressure.

could be an increase in the overall branching ratio from $n=3$ to $n=2$, and thus an increase in the CIF signal. The LIF signal enhancement phenomenon relies heavily on the excess of electrons in the $2s$ state due to that state's long lifetime with no field. Figure 16 shows the collisional destruction time for the metastable $2s$ versus gas pressure, where the cross section for collisional destruction is taken from Gilbody *et al.*²⁸ As the background gas pressure rises, the effective lifetime of the $2s$ state, always dominated by collisions rather than radiation in the absence of external fields, drops. As the $2s$ effective lifetime drops, so does the excess electron population in that level and thus also the enhancement.

The decrease in the total LIF signal with decreasing laser power is an indication that the transition is not saturated. An accurate calculation of the saturation parameter in this case would need to include the effect of collisions on the lifetimes of the upper and lower states.

VII. DIAGNOSTIC APPLICATIONS

The polarization effect shown in the data of Fig. 11 can also be seen in a model of the system, shown in Fig. 17. This calculation solves for the eigenvalues and eigenvectors of the $n=1$, $n=2$, and $n=3$ states in hydrogen neutrals in an energetic beam, including the Stark, motional Stark, and Zeeman effects, as well as the fine structure from the spin-orbit coupling and the Lamb shift. The calculated intensities at each wavelength for all possible transitions to $n=2$, shown as bars in Fig. 17, are calculated as the square of the appropriate dipole moments. The aggregate peaks shown in Fig. 17 are the result of individual Gaussian curves assigned to each intensity component and summed to represent a more physical spectrum. The actual spectral line shape in this experiment is very asymmetric and is better represented by the exponentially modified Gaussians of Fig. 13. The peaks in Fig. 17 serve to demonstrate the difference between the orthogonal polarization cases. The horizontal polarization case has additional transitions in the center of the spectrum, leading to a shallower decay on the right side of the main peak (in Fig. 11) and an additional small peak being observed. This line could be exploited for a measurement of the magnetic-field direction. With the laser wavelength fixed to excite this wavelength, the polarization of the laser could be

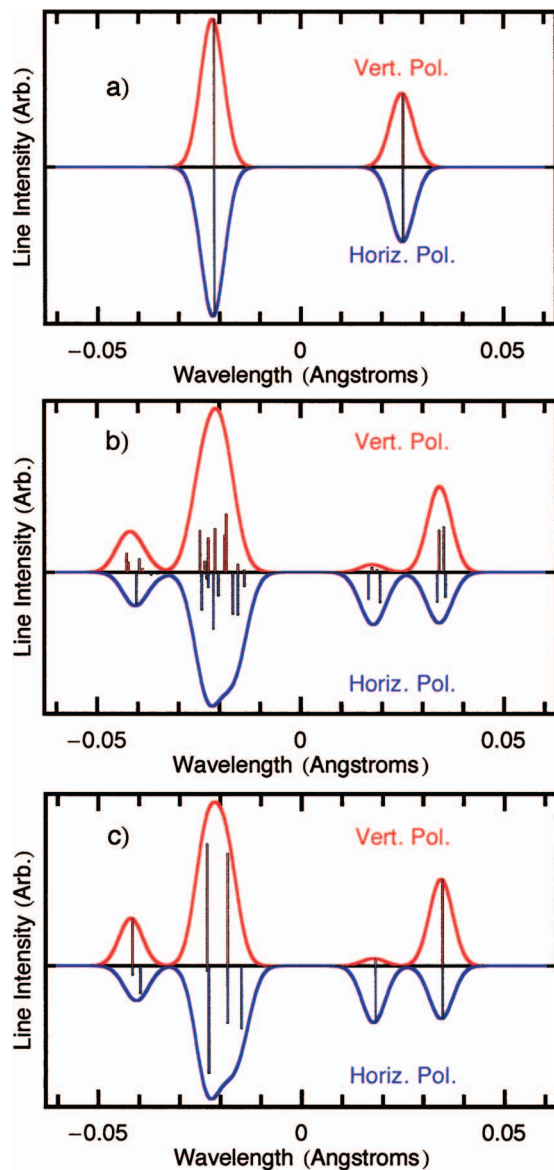


FIG. 17. (Color) Result of simulation showing asymmetry in polarization direction: (a) no applied fields, (b) magnetic field of 45 G, and (c) electric field of 110 V/cm.

rotated in time and the LIF signal observed. The alignment-dependent resonance would result in a sinusoidal LIF signal of the same frequency as the input polarization rotation, but with shifted phase. This phase shift could be used to extract the direction of the observed magnetic field.

For the measurement of the magnetic-field magnitude, two techniques are possible. The sensitive dependence of the integrated LIF signal on the background field would allow a measurement based on the total LIF signal, whereas the enhanced signal also allows resolution of the fine-structure components, and the field magnitude can be determined by fitting these to a comprehensive model such as the one shown in Fig. 17. Based on the variation of the total signal with field as shown in Fig. 5, measurement resolution on the order of a few Gauss should be possible with the integrated signal technique. The line location measurement is very dependent on the energy spread of the beam used, but even with the tens of volts seen in the present experiment, fitting can distinguish at least on the order of 5 G.

VIII. CONCLUSIONS

The LIF enhancement phenomenon described in this paper displays a very sensitive dependence on magnetic field in the range of 0–100 G. A conceptual understanding is given in terms of the variation of the sublevel lifetimes and transition probabilities in electric field. For a more complete understanding of the phenomenon, and in order to use the enhancement to diagnose the magnetic field in a given system, a detailed computer simulation of the neutral beam system, including the calculation of the sublevel parameters, consideration of the effects of laser pumping, and collisions with background particles on the populations, is necessary. Such a calculation for the parameters given in this experiment is in progress and will be reported in a future paper.

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