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Electric-field-vector measurement in a glow discharge

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The magnetic quantum number selection rule implies that radiation that is linearly polarized perpendicular to the electric field will not excite $\Delta m = 0$ transitions. This phenomenon in Stark spectra has been used to determine the electric field vector in a positive column dc discharge in helium. The technique is applicable to both linear and nonlinear Stark effects.

The Stark effects of atomic and molecular spectra have been very successfully used for electric field measurements in weakly ionized plasmas.[1,2] The demonstrated experimental techniques rely on either the electric-field-induced breakdown of optical transition selection rules or the Stark splitting or line broadening of high Rydberg states. In all of the aforementioned methods with the exception of Stark splitting, the measurement provides the value of F^2 or $|F|$, where F is the electric field vector and therefore only the magnitude of the net field is measured.

In plasma discharge modeling not only the magnitude of the net electric field is a useful parameter but the electric field vector is probably the most useful parameter for modeling the cathodic regions and positive column discharge characteristics. However, until now it has not been accessible by direct measurement.

In optical Stark spectra, the orbital and total angular momentum selection rules break down but the magnetic quantum number selection rule is preserved. In this work, we have relied on the magnetic quantum number selection rule to measure the electric field vector in a positive column dc discharge. The net electric field at any given radial location of the positive column is the vector sum of the axial, radial (ambipolar), and the isotropic microfield. Therefore, the electric field vector in a positive column changes from essentially radial at the sheath boundary to axial in the center of the discharge column. Using polarized laser pumping and the optogalvanic response, the Stark spectra measured along the radial profile thus provide an opportunity to measure the continuously variable electric field vectors.

In this experiment, we have measured the Rydberg spectra of ^3S and ^3P states of atomic helium from $n = 25$ and above, photoexcited from the metastable state $2s\,^3S$, in a 6-mm diameter (effective diameter at the measurement location is 8 mm due to uv windows) positive column dc discharge with 1.2-torr gas pressure at 0.8-mA discharge current. The optogalvanic spectroscopic technique has been used to measure linewidths and other characteristics of the high-lying triplet states. The experimental details have been described earlier.[3] In this measurement, the uv laser polarization has been set at a 50° angle with respect to the axial field direction (as shown in the inset of Fig. 1). Figure 1 shows the ^3S and ^3P spectra for three different (representative) radial locations. The spectra labeled A and C are at the radial locations 2 mm away from the center of the discharge tube and the spectrum B is at about the center of the tube. Most of the spectral features are quite easy to understand and have been observed before in singlet high Rydberg spectra of helium.[3] Since the metastable helium population is maximum at the axis of the discharge tube, the spectral intensity is highest at the center of the tube as compared to the radial locations away from the center. Also the net field is lowest at the center, where the electric field is purely axial. The microfield at the chosen current density is negligible and does not contribute to the linewidths.

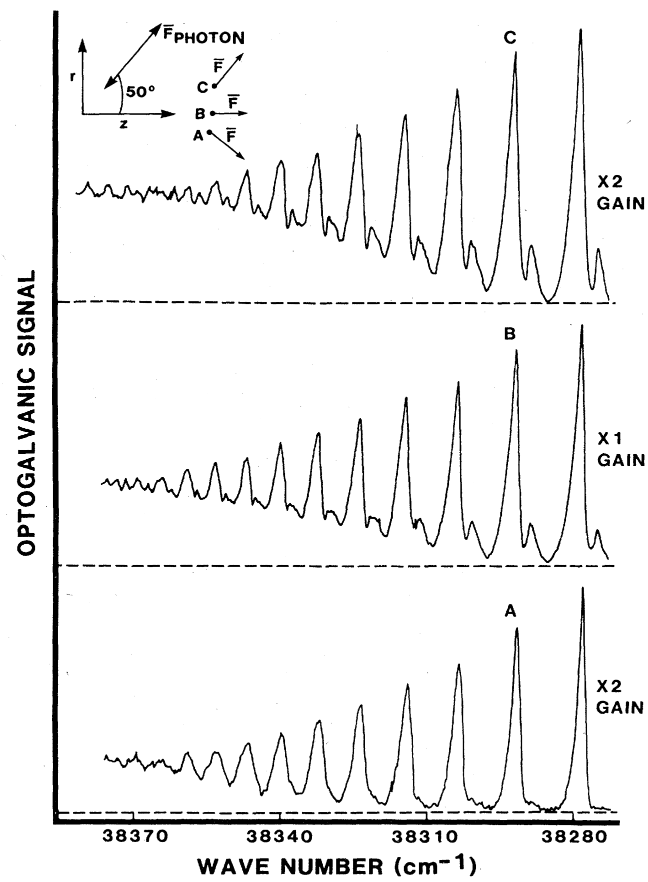

FIG. 1. Rydberg spectra of ^3P and ^3S atomic helium from $n = 25$ and above for three different radial locations in the positive column, as shown in the insert. The spectrum labeled B is on the radial axis. The spectra labeled A and C are 2 mm away from the axis. The spectrum B is at two-times reduced gain as compared to spectra A and C. The extrapolated background signal levels are represented by the dashed lines.

Therefore, the Stark line broadening for the on-axis spectrum is a minimum as shown in the spectrum labeled B in Fig. 1. Also note that the onset of the continuum[4] in spectrum B occurs at relatively high principal quantum numbers ($n > 35$). Since the net field increases with increased radial distance, we expect that the line broadening and the ratio of the forbidden to allowed transition intensities will increase,[5] along with the onset of continuum occurring at lower principal quantum numbers. As shown in Fig. 1, the linewidths of corresponding transitions are greater for the spectra A and C as compared to B. The Stark line broadening permits the calculation of the magnitude of net electric field. The linear Stark line broadening, using the quasistatic approximation, is given by[3]

$$|\Delta\omega| = \frac{3\hbar}{2emz}(n_f^2 - n_i^2)F,$$

where $\Delta\omega$ is the half-width at half maximum (HWHM), n_i and n_f are the initial- and final-state effective principal quantum numbers, $z=1$ for the neutral atoms, and F is the net electric field in atomic units. The measurement accuracy of FWHM is 0.15 cm^{-1} which corresponds to 1-V/cm resolution of the electric field for the $n=29$ transition. The FWHM of $29p\,^3P$ transition in spectrum B is 1.85 cm^{-1}, whereas in A and C it is 2.8 cm^{-1} which corresponds to 12 ± 1- and 17 ± 1-V/cm net electric fields, respectively. Also, the ratios of the forbidden to the allowed intensities are higher for spectrum C as compared to spectrum B. In contrast however, in spectrum A only ^3P transitions are observed and the forbidden ^3S transitions are not observed. Even though the net electric field at this radial position is higher than the axial field, the electric field vector at this location is orthogonal to the laser polarization and therefore $\Delta m = 0$ transitions are not allowed; consequently, the $2s\,^3S$ to $ns\,^3S$ transitions are forbidden even in Stark spectra. For this line of sight measurement, the $\Delta m = 1$ condition is satisfied over the entire interaction volume due to the cylindrical symmetry of the electric field in the positive column. In this measurement, the angular resolution of the field vector is measured to be about $\pm 5°$. The angular resolution is primarily determined by the laser-discharge interaction cross section and (for a given signal to noise) the intensity ratio of the allowed to forbidden transitions. At high currents the method loses angular resolution due to the contribution of the isotropic microfield.

The optogalvanic signal magnitudes, in the continuum overshoot region (above 38 370 cm^{-1}), for $\Delta m = 0$ transitions are approximately three times greater than the $|\Delta m| = 1$ transitions. Similar differences have been observed in the Stark ionization spectrum of hydrogen[6] and other alkali atoms.[7,8]

In conclusion, this measurement clearly demonstrates a means by which the Stark effect can be used to measure not only the magnitude of the electric field, but with the use of a rotatable linearly polarized laser beam, the electric field vector as well. In principle, a two-polarization-dependent ($m_J = 0$ and ± 1) Stark splitting measurement also could determine the electric field vector. However, the forbidden transition-intensity change technique described above is easier to use. Similar methods should be applicable to the electric-field-vector measurement in discharges in other atoms and molecules.

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