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Polarization of Lyman-α Radiation Emitted in Electron Collisions with Hydrogen Atoms and Molecules*

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The polarizations of Lyman-α radiation produced (i) by electron impact on atomic and molecular hydrogen and (ii) by electric field quenching of metastable 2S hydrogen atoms have been measured. The polarization analyzer was a LiF crystal set at the Brewster angle, with reflected radiation being detected by an iodine-vapor photon counter. Generally good agreement between the measured polarization fractions and recent theoretical predictions was found. The radiation produced by quenching metastable atoms in an electric field was found to be polarized with a polarization fraction of -0.30 ± 0.02, which compares with the theoretical value -0.323.

I. INTRODUCTION

Lyman-α radiation emitted from hydrogen atoms excited by electron impact will be partially polarized since the excited magnetic substances are in general not equally populated. The polarization is characterized in terms of an experiment in which a beam of electrons moves in the z direction and the radiation is observed at 90° with respect to the electron beam. If $I_{\|}$ is defined as the intensity of radiation observed with the electric vector parallel to the direction of the electron beam and $I_{\perp}$ as the intensity with the electric vector perpendicular to the electron beam's direction, the polarization fraction P is given by

$$P = \frac{I_{\|} - I_{\perp}}{I_{\|} + I_{\perp}} = \frac{I_{\|}/I_{\perp} - 1}{I_{\|}/I_{\perp} + 1} \quad . \tag{1}$$

The same definition can apply to the case of quenching of metastable 2S hydrogen atoms in an electric field, where the direction of the quench field replaces the direction of the electron beam.

This paper describes three related experiments designed to measure the polarization fraction of Lyman-α radiation produced by the following mechanisms: (i) electron-impact excitation of hydrogen atoms, (ii) electron-impact dissociative excitation of hydrogen molecules, (iii) quenching of metastable H(2S) atoms in a weak electric field. Some of the data have been reported previously.[1,2] The present results represent the completed research effort.

Fite and Brackmann[3] have previously attempted to measure the polarization fraction for Lyman-α impact radiation in e + H collisions by observing the intensity of radiation per unit solid angle $I(\theta)$ emitted at an angle θ with respect to the electron beam and relating it to the total intensity I_T of emitted radiation,

$$I(\theta) = (3/4\pi)\, I_T\, (1 - P\cos^2\theta)/(3-P)\,. \tag{2}$$

The polarization fraction was determined from measurements of $I(45°)$, $I(90°)$, and $I(135°)$, where the criterion for acceptability of data was that $I(45°) = I(135°)$, as required by symmetry of electric dipole radiation. Cumulative uncertainties were large in general, and additional problems were encountered at very low energies, where it was found that $I(45°)$ exceeded $I(135°)$. At energies above 25 eV, however, Fite and Brackmann used their experimental values of P to relate the total cross section Q_T for Lyman-α excitation to a cross section Q_{90} by

$$Q_T/Q_{90} = I_T\,/\,I(90°) = 1 - \tfrac{1}{3}P\ . \tag{3}$$

Q_{90} is a fictitious cross section that would be deduced from intensity measurements made at $\theta = 90°$, on the assumption that the radiation is isotropically distributed at all electron energies.

Subsequent experiments using similar techniques have concentrated on measurements of Q_{90}.[4-6] A reliable experimental determination of the polarization fraction, therefore, not only provides additional information concerning the details of the excitation cross section by determining the relative populations of the degenerate magnetic substates, but also enables the available Q_{90} experimental data to be compared with calculations of the total cross section.

Fite and Brackmann[3] have also measured the Q_{90} cross section for uv radiation excited in e + H_2 collisions and transmitted through the transmission windows of an oxygen filter. In extending these results, Vroom and de Heer[7] have spectroscopically identified the "countable uv radiation" measured by Fite and Brackmann as predominantly Lyman-α. Polarization measurements of the emitted radiation enable a determination of the total cross section for dissociative excitation to the H(2P) states, using Eq. (3) and the available Q_{90} data. Additionally, they are necessary to understanding the details of the dissociative excitation process.[7,8]

The polarization of the Lyman-α radiation emitted by metastable H(2S) atoms in a weak electric field has been previously discussed theoretically by Lichten,[9] and is of practical importance, since electric field quenching of H(2S) atoms is often used to determine Q_{90} cross sections for the production of the H(2S) metastables.[10–12] The following paper discusses the significance of this measurement in more detail.

II. LYMAN-α IMPACT RADIATION IN e+H COLLISIONS

A. Experimental Approach

A schematic of the experimental apparatus is shown in Fig. 1. Hydrogen was thermally dissociated in a tungsten furnace maintained at $T = 2600$ °K in the first of three differentially pumped chambers. The atomic beam was mechanically interrupted at 270 Hz by a chopper wheel in chamber two and was crossed by an electron beam in chamber three. The gold-plated electron gun was a modified version of a source described by Simpson and Kuyatt[13] and produced currents of about 3 μA at the lowest energies. Magnetic fields were not used to collimate the electron beam since a field component perpendicular to the electron beam may be sufficient to remove the degeneracy among the magnetic sublevels of the excited state and thus decrease the polarization.[14,15] Even a pure axial field may introduce depolarization due to the helical trajectories of the electrons about the z direction. A gaussmeter revealed the presence only of the earth's magnetic field in the interaction region which was electrostatically shielded by high-transmission gold-mesh screen. Other surfaces surrounding this region were made from OFHC copper and gold-plated in the same bath to minimize contact potential differences; they were also heated to about 200 °C during the experiments to hinder the buildup of insulating layers.

Ions formed in the interaction region drifted downstream and were focused into a quadrupole mass filter where they were analyzed in order to determine the electron-gun characteristics and

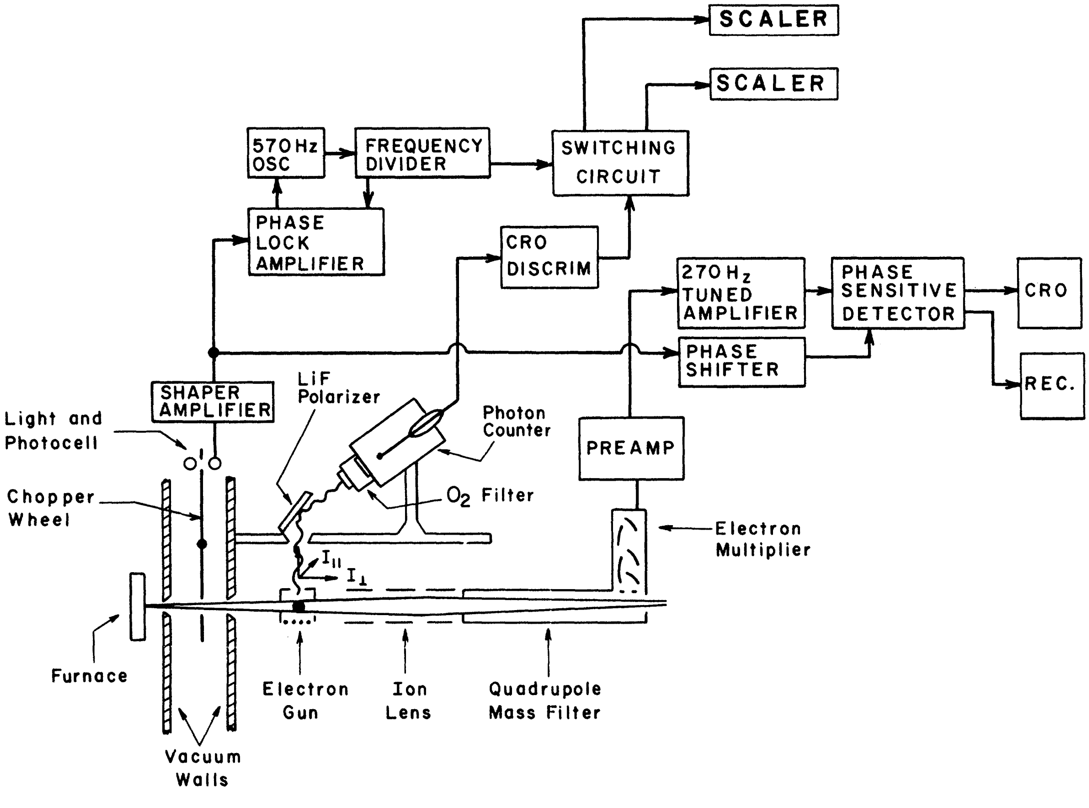

FIG. 1. Schematic of apparatus and detection electronics.

the dissociation of the hydrogen beam. The dissociation fraction D is defined in terms of the current of particles N_A of atomic mass A leaving the furnace:

$$D(T) = N_1(T)/[N_1(T)+2N_2(T)], \tag{4}$$

and was determined by mass spectrometric sampling of the H_1^+ and H_2^+ beam densities. In terms of the measured ion currents S_1 and S_2 and the known ionization cross sections $Q_1(E)$ and $Q_2(E)$,[16] the dissociation fraction was obtained from the expression[3]

$$D(T) = \{\sqrt{2}\,[S_2T/S_1T]/[Q_1(E)/Q_2(E)] + 1\}^{-1}. \tag{5}$$

Dissociation fractions of about 0.8 were normally used except near threshold, where a very low $e + H_2$ cross section for emission of countable uv radiation relieved the need for beam homogeneity and made practical the use of greater furnace pressures for increased beam densities. Dissociation fractions as small as 0.5 were used at the lowest energies.

The absolute energy and the energy distribution of electrons in the beam were determined from curves of ionization of H as a function of electron energy in the immediate vicinity of threshold. On the assumption that the ionization cross-section curve is linear with excess energy, $y = E - E_0$, where E_0 is the known threshold for ionization, it can be shown that the second derivative of the curve of ion signal versus y yields the energy distribution and that the energy axis intercept of the extrapolated signal curve for the first 2 or 3 eV above threshold occurs when the average electron energy equals E_0. Although recent data of McGowan and Clarke[17] indicate that linearity of the ionization cross section with excess energy is not strictly true, the procedure can evidently be used with errors in the absolute energy of substantially less than 0.1 eV and with negligible error in the energy distribution. For our electron gun this procedure gave an energy distribution described by the expression

$$f(y) = Ay^{1.05}e^{-5.25y}, \tag{6}$$

where A is a constant and y is given in eV.

The Lyman-α radiation was detected by an iodine-vapor-filled uv photon counter[18] preceded by a dry oxygen filter. Phase-sensitive detection was employed in all measurements of photon or ion intensities. The data could be displayed either in integrated form on a pen recorder or in digital form on a set of synchronous scalers. In the case of photon measurements, the gate output of an oscilloscope acted as a pulse amplifier for the 0.1-V pulse from the photon counter. The count was then registered on either of two scalers which were being switched at the modulation frequency by an oscillator whose phase was synchronized with a signal provided by a light bulb and photocell attachment mounted near the chopper wheel. The phase of the reference signal could be varied in a phase-lock amplifier unit. When the phase was properly adjusted, one of the scalers would record the signal due to the beam plus background, and the other would record only the background signal. The difference in the two readings would be the signal due to the beam interactions alone. At the same time, the pulses from the oscilloscope could be amplified on a tuned amplifier and phase-sensitive detection carried out with a conventional phase demodulator, as described by Fite and Brackmann.[16] In the case of ion-current measurements, the same versatility was available. The output of the electron multiplier and preamplifier could either be connected directly to the switching circuit or to the tuned amplifier and phase demodulator.

The polarization fraction was measured directly with a Brewster angle analyzer (a crystal of LiF 1.5 mm thick and 2.5 cm in diam) mounted so that radiation emitted at 90° with respect to both atom and electron-beam strikes the plane-faced crystal at an angle of 60° with respect to the normal. Radiation reflecting from the crystal was plane-polarized and was detected by the photon counter located at the mirror angle. Both the analyzer and photon counter were mounted on a platform which rotates about the x axis. With the platform in the 90° position, as shown in Fig. 2, radiation with the electric-field vector perpendicular to the electron-beam's direction was completely transmitted by the crystal; the only signal

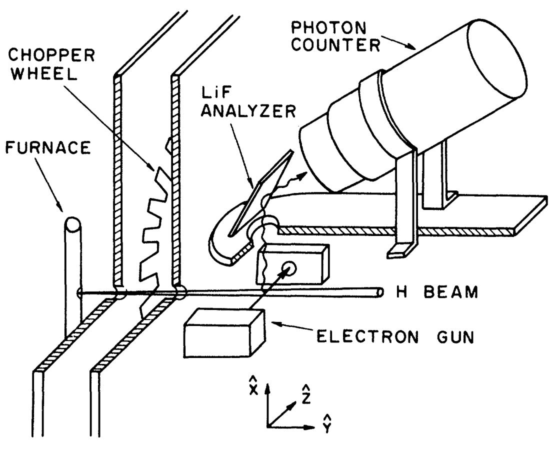

FIG. 2. Experimental arrangement for measurements of the polarization fraction of Lyman-α impact radiation using a Brewster angle analyzer.

registered by the photon counter should be proportional to $I_{\parallel}$. Upon rotating the platform $\frac{1}{4}$ revolution about the x axis to the 0° or 180° position, radiation with the electric field vector was parallel to the electron-beam's direction was transmitted by the crystal; and the counter should respond only to $I_{\perp}$. The polarization fraction was then determined directly from the definition given in Eq. (1).

The experimental procedure was first to measure $I_{\parallel}$ or I_{90°, rotate the platform counterclockwise and measure I_{0°, rotate and remeasure I_{90°, rotate clockwise and measure I_{180°. The measurements of $I_{\perp}$ in the two opposite positions should be equal and serve as a check on possible asymmetries due to misalignment. The cycle was then repeated to accumulate more data and obtain better statistics. The effect of slow drifts caused by heating or cooling of the photon counter and by changes in vacuum and furnace conditions tended therefore to average out. Counting times for each measurement ranged 1–5 min. The H_1^+ and H_2^+ ion currents S_1 and S_2 could be monitored throughout on the recorder, and were required to remain constant to within 2%. In the threshold range 10–14 eV, the electron energy calibration was checked before and after each data run at a given energy.

The observed count rates were subject to two corrections. The first was a correction for the loss of counts due to saturation effects of the photon counter, which had a measured dead time of 500 μsec. However, the observed count rates were kept sufficiently low, so that the correction for the loss of counts would be much smaller than the statistical error in counting.

Next, the observed count rates were corrected for the photon signal due to the presence of molecular hydrogen in the beam. The furnace was lowered to a temperature T_0 near 1200 °K, where the dissociation fraction $D(T_0)$ was zero and the photon signal $I^{(2)}(T_0)$ due to H_2 alone was measured. The signal $I^{(1)}(T)$ attributed to H at temperature T is then given by[3]

$$I^{(1)}(T) = I(T) - I^{(2)}(T_0)(T_0/T)^{1/2}[1 - D(T)] \ , \qquad (7)$$

where $I(T)$ is the actual measured photon signal. Since the polarization fraction for the radiation emitted in $e + H_2$ collisions was known (see Sec. III), this procedure had to be carried out only in one platform position at each energy. The correction term in Eq. (7) was about 3% of $I(T)$.

The final step in the analysis was to correct all polarization fractions for the analyzer polarization efficiency ε, which relates the true polarization P to the apparent polarization P_A:

$$P_A = \varepsilon P \ , \qquad (8)$$

if all of the radiation were incident at the Brewster angle $\epsilon = 1$. However, not all of the radiation strikes the LiF crystal at the Brewster angle. Since the radiation source is a small volume at a short distance rather than a plane-wave source, and since the diameter of the counter window was of finite size rather than a pinhole, there was a range of angles of incidence of the detected radiation on the LiF surface. In practice in this experiment, some radiation striking the LiF surface as much as 4° from the Brewster angle could be detected. The degradation caused by the spread of angles is not a serious problem, however, as can be seen from Fig. 3, which shows the reflection coefficients for the parallel (P) and perpendicular (S) components of radiation as a function of angle and which indicates the very low reflectivity R_P over a wide range in the vicinity of the Brewster angle and its very slow variation. Rather than independently measuring the Brewster angle and calculating the integral over the angles of incidence to determine ε, we determined the polarization efficiency experimentally by using an identical crystal to polarize an unpolarized photon beam which had been excited in high-energy $e + H$ collisions and which was incident at the assumed Brewster angle. The reflected radiation was then analyzed, and the apparent polarization was assumed to be

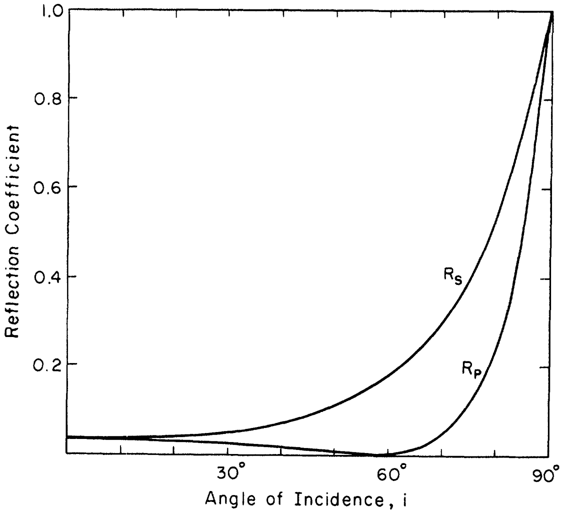

FIG. 3. Calculated reflection coefficients for the two polarization components of radiation at a dielectric medium with an index of refraction of $n = 1.6$ plotted as a function of the angle of incidence. R_P and R_S are the reflection coefficients of the components of radiation which have their electric vector in the plane of, and perpendicular to the plane of incidence, respectively. The plane of incidence contains the normal to the surface and the incident radiation propagation vector. LiF has an index of refraction of $n = 1.6$ for Lyman-α radiation.

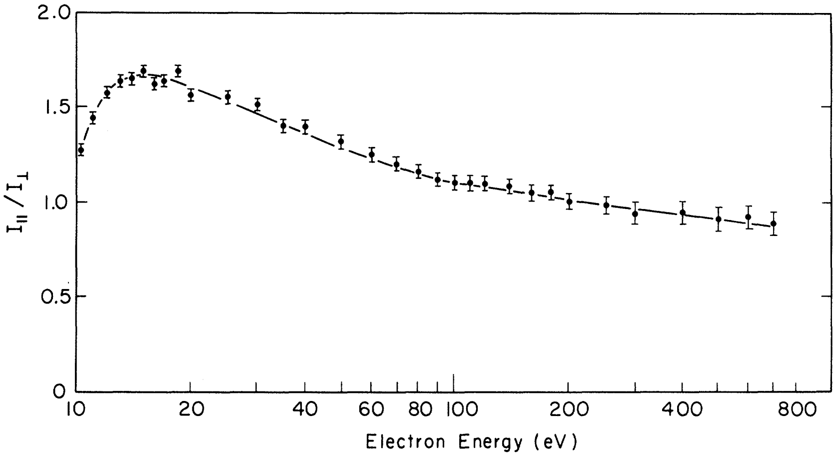

FIG. 4. Ratio of intensities $I_{\parallel}$ and $I_{\perp}$ in the energy range 10–700 eV.

given by $P = \varepsilon^2$. For an assumed Brewster angle of 60° and for a radiation source with 4° half-angle cone of incidence, ε was measured to be 0.94. All polarization measurements were therefore corrected by increasing the apparent fractions according to Eq. (8).

B. Discussion of Results

The basic experimental results (the ratio $I_{\parallel}/I_{\perp}$ as a function of electron energy) are plotted in Fig. 4. Figures 5 and 6 show the polarization fraction P obtained by applying the data of Fig. 4 to Eq. (1). Available theoretical results for P are also shown in Figs. 5 and 6. All but one of the calculations consider only direct excitation of the $2P$ state and the polarization of the subsequent emitted radiation; the calculation of Morrison and Rudge[20] also accounts for cascade effects. The error bars on all the figures represent standard deviations based on the accumulated data at each energy.

It can be seen in Fig. 5 that the Born approximation[19] is in reasonable agreement with the experimental data above 20 eV and that most of the other approximations[20–23] do not differ significantly from the Born. The Born-Oppenheimer and first-order exchange approximations yield very nearly the same polarization fractions as the Born approximation at high energies, and therefore only a single low-energy value is plotted for each. The experimental polarizations are slightly greater than the high-energy approximations throughout the range 20–250 eV. Long *et al.*[24] have estimated that 2% of the photon signal measured at $\theta = 90°$ $(I_{\parallel} + I_{\perp})$ is due to the population of the $2P$ states by

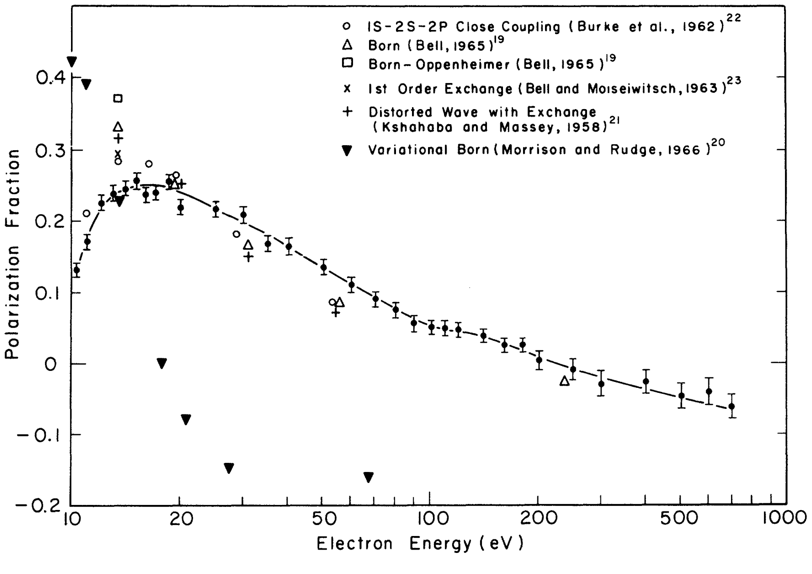

FIG. 5. Comparison of experimental values of the Lyman-α polarization fraction with theory in the energy range 10–700 eV.

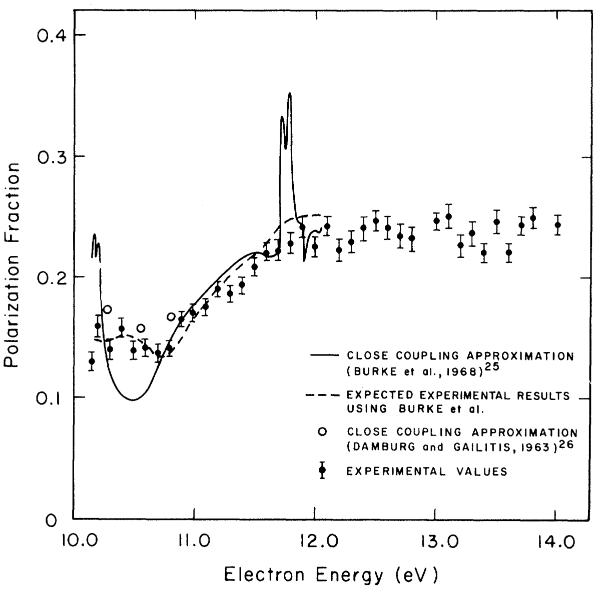

FIG. 6. Comparison of experimental values of the Lyman-α polarization fraction with theory in the vicinity of threshold.

cascade processes and not by direct excitation. Assuming that the magnetic substates are equally populated by cascade transitions, the experimental polarization fractions would have to be increased by about 2% at the higher energies.

The variational Born calculation by Morrison and Rudge[20] can be compared directly with the experimental data. It can be seen that the calculation is in disagreement with experiment and the approximation does not accurately predict the relative populations of the degenerate magnetic substates as a function of electron energy. This indicates that the close agreement with experiment which is obtained in the calculation by this approximation of the Q_{90} cross section for Lyman-α excitation may indeed be fortuitous.

The 1S-2S-2P 3-state close-coupling approximation appears to give the best agreement in the shape of the polarization function. It overestimates the polarization fraction by about 15% at the peak value, and underestimates at higher energies in close agreement with the Born approximation.

Figure 6 illustrates the near-threshold dependence of the polarization fraction. The theoretical calculations represented are the 1S-2S-2P close-coupling approximations both with (CCW)[25] and without (CCWO)[26] correlation terms included to account for electron-electron interactions. The former is sufficiently detailed to allow the experimental electron energy distribution to be folded into the theoretical curve resulting in a predicted experimental energy dependence. It can be seen that, to within the limits of resolution of the electron gun, the polarization data do not tend to the Percival and Seaton limit of 0.42 at threshold.[27] The shape and absolute magnitude of the polarization data appear to be in excellent agreement with the CCW calculations as well as the three CCWO points. However, because of the broad energy distribution of the electron gun used and the scatter in the data obtained, it is not possible unequivocally to verify the existence of the predicted resonances at the $n=2$ threshold and just below the $n=3$ threshold.

Figure 7 shows curves of the relative signals observed for each component of polarization as a function of energy in the near-threshold region. The observations were made at an angle of 90° with respect to the electron-beam direction. Figure 7 also shows the total cross section Q_T for production of Lyman-α radiation. This was obtained from the easily derivable relationship

$$Q_T/Q_{90} = \tfrac{2}{3}(I_\parallel + 2I_\perp)/(I_\parallel + I_\perp) \ . \qquad (9)$$

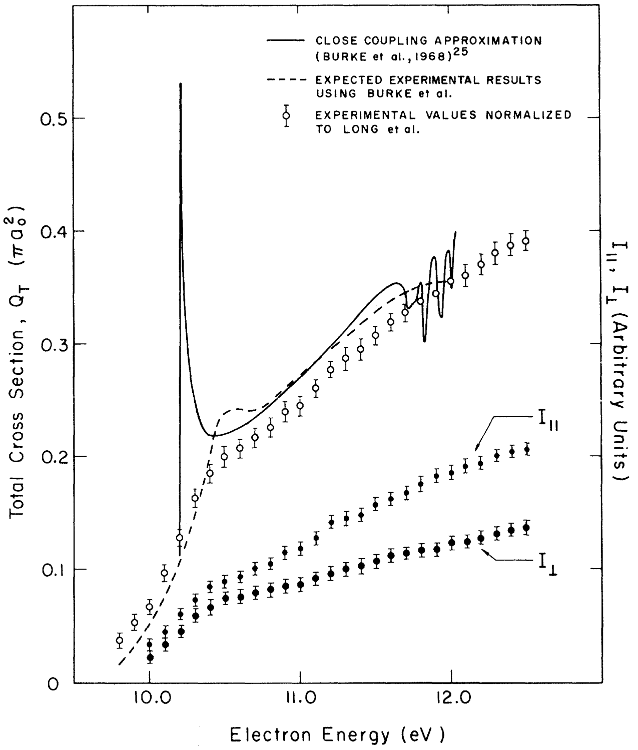

FIG. 7. Comparison of experimental values of the total cross section Q_T with the close-coupling theory of Burke *et al.* (Ref. 25). $I_\parallel$ and $I_\perp$ are the relative signals of each component of polarization observed at an angle of 90° with respect to the electron-beam direction as a function of energy.

Assignments of absolute values were made by taking the value of Q_{90} at 11 eV to be $0.259\pi a_0^2$, the value given by Long *et al.*[24] The knee in the three curves is similar to that observed by Chamberlain *et al.*[5] in their threshold studies of Q_{90}. The theoretical curve of Burke *et al.*[25] is shown for comparison.

III. LYMAN - α IMPACT RADIATION IN $e + H_2$ COLLISION

The polarization of the countable impact radiation emitted in electron collisions with room-temperature molecular hydrogen was measured using the identical apparatus and procedure as previously described in Sec. II, and these results are illustrated in Figs. 8 and 9. As the electron energy decreases, the polarization fraction increases to a maximum of 0.09 ± 0.015 at about 30 eV, decreases rapidly to a minimum at about 17 eV, and increases once again to a peak of 0.13 ± 0.015 at about 14 eV. The relative Q_{90} cross section for excitation of countable uv radiation from molecular hydrogen was determined in the energy range 12–22 eV from the sum of the experimental intensities $I_{\parallel}$ and $I_{\perp}$ and is also illustrated in Fig. 9. Since the threshold for dissociative excitation of molecular hydrogen is about 14.6 eV, Figs. 8 and 9 suggest that the radiation detected above about 15 eV is mainly Lyman-α, in agreement with the observations of Vroom and de Heer.[7] The partially polarized radiation below 15 eV can be attributed to excitation to the *B* or *C* electronic states of the molecule, which have respective onset energies of 11.5 and 12.6 eV.

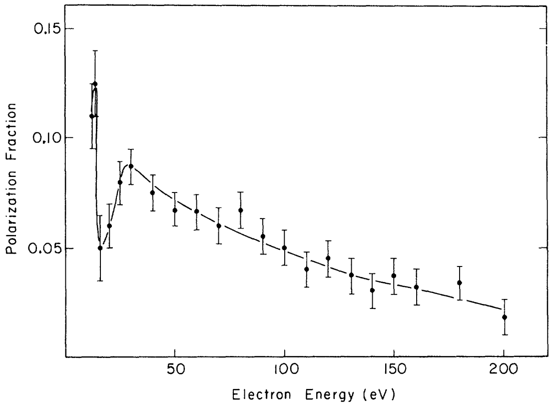

FIG. 8. Polarization fraction of countable uv radiation emitted in $e - H_2$ collisions in the energy range 12–200 eV.

IV. LYMAN - α QUENCH RADIATION

A. Experimental Approach

In order to measure the polarization of Lyman-α radiation emitted by metastable H(2*S*) atoms quenched in electric fields of about 10 V/cm, the atoms excited in $e + H$ collisions were allowed to travel downstream along the atom beam to a region where there was little background signal from the electron-atom interaction region. A uniform electric field was established in this region with a pair of 10-cm-square gold-plated copper plates biased at opposite potentials $+V$ and $-V$ with respect to ground. The distance between these inner plates was 7.6 cm, so that it was not

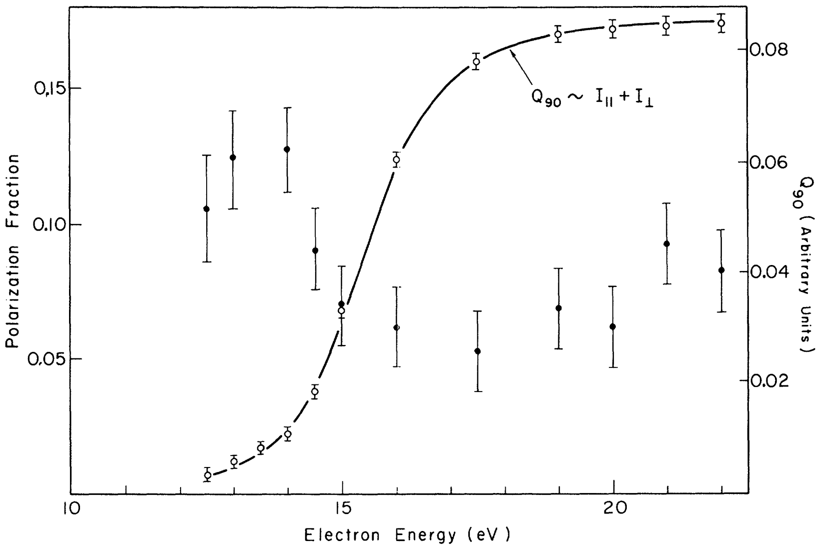

FIG. 9. Polarization fraction of countable uv radiation emitted in $e - H_2$ collisions in the range 12–22 eV.

possible for radiation emitted in the quench region to be reflected from the quench plates and up into the Brewster angle analyzer located above the center of the quench region, as illustrated in Fig. 10. A set of potential image plates, a distance of 1.3 cm from the inner plates, was used to reduce the magnitude of the fringe fields. Electrolytic tank field plots of the quench region bounded by the grounded analyzer platform and electron-gun apparatus demonstrated that the electric field was uniform within the plates for a length of about 7.6 cm along the hydrogen-beam axis. An aperture located in the analyzer platform 6 cm above the hydrogen beam and the diameter of the photon-counter end-window limited the radiation entering the counter to a half-angle cone of 15° emitted from a 3.8-cm length along the beam axis. This effective radiation source represents a worst-case situation since photon counters of this type are less sensitive to radiation incident off-axis.[28]

Measured photon signals had to distinguish between the modulated signal due to the presence of the dc electric field and the modulated signal due to natural or collision-induced decay. The latter contribution was measured with the electric field removed. Care was taken to be certain that these measurements actually corresponded to the background conditions when the field was on. In particular the effect of possible stray electrons entering the quench region was investigated. Instead of being symmetrically biased about the grounded electron-impact region, the quench plates were referred to a variable circuit common. The field strength and the downstream location of the quench plates were also varied and the gold-plated enclosure for the electron-gun elements was removed in order to enhance the possibility for stray electrons. No changes in the polarization fraction were observed. In addition the polarization fraction tracked the direction of the electric field when the quench plates were rotated 90°. In this case transparent gold-plated grids instead of solid plates were used so that the beam might pass through the quench region. Care was taken so that the counter did not observe the nonuniform field region near the grids.

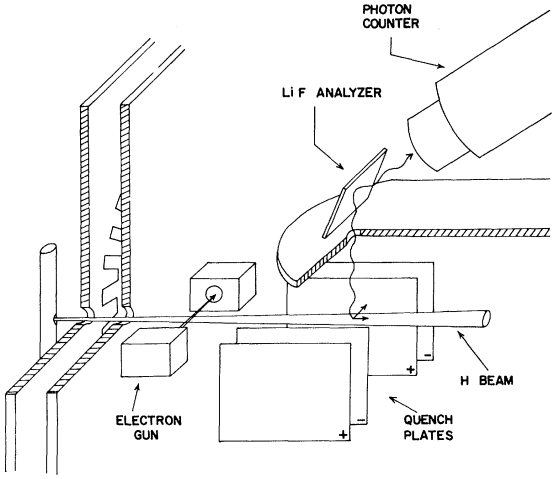

FIG. 10. Experimental arrangement for measurement of the polarization fraction of Lyman-α radiation emitted by H(2S) atoms in weak electric fields.

B. Discussion of Results

The observed polarization of Lyman-α radiation emitted by H(2S) atoms in fields of about 10 V/cm was -0.30 ± 0.02 and appeared to be independent of electron energy in the range 12–200 eV. The data were corrected for the dead time of the photon counter, the presence of H_2 in the incompletely dissociated beam, and an estimated polarizing efficiency $\varepsilon = 0.94$. The subtraction of radiation due to the presence of H_2 would not be necessary if its effect were only to produce H(2S) atoms through dissociative excitation. However, the polarization fraction of the quench radiation resulting from $e + H_2$ collisions, although the statistics were rather poor, was measured to be on the order of -0.1 at 100 eV, suggesting that perhaps some of the radiation was arising from the quenching of metastable molecular states.

The experimental value of -0.30 disagrees with the prediction by Lichten[9] of zero polarization. However, this discrepancy can be understood by reconsidering the theoretical treatment. If a thermal beam of atoms initially prepared in the metastable $2S_{1/2}$ state interacts with an electric field F, the perturbed wave functions, calculated in first-order, stationary-state perturbation theory while neglecting hyperfine structure, are given by

$$\psi_m = u(2S_{1/2,\,m}) + a u(2P_{1/2,\,m}) + b u(2P_{3/2,\,m}) \quad , \tag{10}$$

where the azimuthal quantum number m takes on the values $\pm\frac{1}{2}$ according to the Stark-effect selection rule $\Delta m = 0$, and where

$$a = 8a_0\, eF \,/\, E_{11}\, \sqrt{3} \quad , \tag{11}$$

$$b = -\, 8a_0\, eF \,/\, E_{31}\, \sqrt{\tfrac{3}{2}} \quad , \tag{12}$$

using the notation of Schiff.[29] E_{11} and E_{31} are the fine-structure energy separations between the $2S_{1/2}$ state and the $2P_{1/2}$ and $2P_{3/2}$ states, respectively. The eigenvectors in Eq. (10) are the usual well-known L-S coupled hydrogen wave functions. The transition probability per unit time w is proportional to the sum of the squares of the matrix elements of the vector $\vec{r}$ between the doublet ground state and the perturbed wave functions

$$w \propto \langle \psi_m | \vec{\mathrm{r}} | u(1S_{1/2,\,1/2}) \rangle^2 + \langle \psi_m | \vec{\mathrm{r}} | u(1S_{1/2,\,-1/2}) \rangle^2 . \qquad (13)$$

If the matrix element connects states such that $\Delta m = 0$, only the z component of the dipole moment is nonvanishing. The radiation corresponding to this transition has its electric field vector in the z direction of the applied Stark field and has an intensity proportional to the transition probability for this process. If the matrix element connects states with $\Delta m = \pm 1$, the z component vanishes and the x and y components of the dipole moment are equal to within a phase factor. For example, with $m = \frac{1}{2}$, the matrix elements to the ground state are

$$\langle \psi_{1/2} | \vec{\mathrm{r}} | u(1S_{1/2,\,1/2}) \rangle = (2^8 a_0 / 3^5 \sqrt{6})(a + b\sqrt{2})\hat{z}, \qquad \Delta m = 0, \qquad (14)$$

$$\langle \psi_{1/2} | \vec{\mathrm{r}} | u(1S_{1/2,\,-1/2}) \rangle = (2^8 a_0 / 3^5 \sqrt{6})(a - b/\sqrt{2})(i\hat{y} - \hat{x}), \quad \Delta m = -1. \qquad (15)$$

Identical expressions are obtained for $m = \frac{1}{2}$ except that the second equation corresponds to a $\Delta m = +1$ transition. Since the polarization is measured from a direction perpendicular to the electron beam, the intensity corresponding to the component of the dipole moment along the x axis, the direction of observation, is not observed and $I_\perp$ is a measure only of the y component of the dipole moment. The ratio of $I_\parallel$ to $I_\perp$ is obtained, therefore, from the square of the z and y components of the dipole matrix elements in Eqs. (14) and (15):

$$I_\parallel / I_\perp = (a^2 + 2b^2 + 2\sqrt{2}ab)/(a^2 + 0.5b^2 - \sqrt{2}ab). \qquad (16)$$

It can be seen that, if mixing to the $2P_{3/2}$ state were considered negligible and were assumed to be zero, the ratio would be equal to unity and the polarization would be zero. This was essentially the calculation described by Lichten. However, although $b^2 \ll a^2$, the interference term ab can not be neglected. Using $E_{31}/E_{11} = 9.4$,[30] the polarization is calculated to be -0.329.

Casalese and Gerjuoy[30] have included the effects of hyperfine structure in a similar calculation and have obtained a theoretical polarization fraction of -0.323. While this is still barely outside the standard deviation uncertainty of the measurements of -0.30 ± 0.02, we believe the theoretical value is preferable. The experimental conditions under which the polarizer efficiency ε was measured to be 0.94 were not identical to the conditions of the quench radiation polarization measurement. In particular, in the latter experiment, the volume source of the radiation to be detected was larger and the analyzer could accept radiation entering over a cone of 15° half-angle. Under these conditions ε could have been somewhat lower than 0.94, in which event the corrected polarization would have a value in better agreement with the theoretical value of Casalese and Gerjuoy.

V. CONCLUSION

The polarization of Lyman-α radiation emitted in e + H collisions has been measured in the energy range 10–700 eV. With these data it is now possible to determine total cross sections for Lyman-α excitation using previously measured Q_{90} cross-section measurements. The near-threshold behavior of the polarization fraction seems to be rather accurately described by the $1S$ - $2S$ - $2P$ close-coupling approximation including 20 correlation terms. It was expected from the folding procedure that perhaps the effect of the predicted resonance at 11.7 eV could be observed. However, the data do not seem to support the existence of such a large and broad resonance. The experiment will have to be performed with an electron gun capable of better resolution before any further conclusions concerning the resonant structure can be made.

The polarization of countable uv radiation emitted in $e + \mathrm{H}_2$ collisions was seen to have a definite energy dependence in the energy range 12–200 eV. Relative Q_{90} cross-section measurements in the energy range 12–22 eV suggest that the radiation detected above about 15 eV is Lyman α, emitted in the dissociative excitation of H_2 in agreement with the results of Vroom and deHeer.[7]

The polarization of Lyman-α radiation emitted by H($2S$) atoms in weak electric fields was measured to be -0.30 ± 0.02, in close agreement with the theoretically expected value of -0.323. This affects, in particular, total cross-section measurements of Stebbings *et al.*[10] for excitation of H atoms to the metastable $2S$ state by increasing their results. A remeasurement of this cross section utilizing the ratio method of Stebbings *et al.* has been performed and is discussed in the following paper.

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[1] W. R. Ott, W. E. Kauppila, and W. L. Fite, Phys. Rev. Letters 19, 1361 (1967).

[2] W. L. Fite, W. E. Kauppila, and W. R. Ott, Phys. Rev. Letters 20, 409 (1968).

[3] W. L. Fite and R. T. Brackmann, Phys. Rev. 112, 1151 (1958).

[4] W. L. Fite, R. F. Stebbings, and R. T. Brackmann, Phys. Rev. 116, 356 (1959).

[5] G. E. Chamberlain, S. J. Smith, and D. W. O. Heddle, Phys. Rev. Letters 12, 647 (1964).

[6] J. W. McGowan and E. M. Clarke, Phys. Rev. Letters 21, 719 (1968).

[7] D. A. Vroom and F. J. de Heer, J. Chem. Phys. 50, 580 (1969).

[8] R. J. Van Brunt and R. N. Zare, J. Chem. Phys. 48, 4304 (1968).

[9] W. Lichten, Phys. Rev. Letters 6, 12 (1961).

[10] R. F. Stebbings, W. L. Fite, D. G. Hummer, and R. T. Brackmann, Phys. Rev. 119, 1939 (1960).

[11] I. A. Sellin, Phys. Rev. 136, A1245 (1964).

[12] J. E. Bayfield, Bull. Am. Phys. Soc. 13, 66 (1968).

[13] J. A. Simpson and C. E. Kuyatt, Rev. Sci. Instr. 34, 265 (1963).

[14] G. Breit, Rev. Mod. Phys. 5, 117 (1933).

[15] L. C. Chiu, Phys. Rev. 168, 32 (1968).

[16] W. L. Fite and R. T. Brackmann, Phys. Rev. 112, 1141 (1958).

[17] J. W. McGowan and E. M. Clarke, Phys. Rev. 167, 43 (1968).

[18] W. E. Kauppila, W. R. Ott, and W. L. Fite, Rev. Sci. Instr. 38, 811 (1967).

[19] K. L. Bell, Proc. Phys. Soc. (London) 86, 246 (1965).

[20] D. J. T. Morrison and M. R. H. Rudge, Proc. Phys. Soc. (London) 89, 45 (1966).

[21] S. Khashaba and H. S. W. Massey, Proc. Phys. Soc. (London) 71, 574 (1958).

[22] P. G. Burke, H. M. Schey, and K. Smith, Phys. Rev. 129, 1258 (1962).

[23] K. L. Bell and B. L. Moiseiwitsch, Proc. Roy. Soc. (London) 276A, 346 (1963).

[24] R. L. Long, D. M. Cox, and S. J. Smith, J. Res. Natl. Bur. Std. 72A, 521 (1968).

[25] P. G. Burke, A. J. Taylor, and S. Ormonde, J. Phys. B 1, 325 (1968).

[26] M. Gailitis and R. Damburg, Proc. Phys. Soc. (London) 82, 192 (1963).

[27] I. C. Percival and M. J. Seaton, Phil. Trans. Roy. Soc. (London) 251A, 113 (1958).

[28] R. T. Brackmann, W. L. Fite, and K. E. Hagen, Rev. Sci. Instr. 29, 125 (1958).

[29] S. J. Brodsky and R. G. Parsons, Phys. Rev. 163, 134 (1967).

[30] J. S. Casalese and E. Gerjuoy, Phys. Rev. 180, 327 (1969).