## POLARIZATION OF LYMAN-ALPHA RADIATION PRODUCED IN COLLISIONS
## OF ELECTRONS AND HYDROGEN ATOMS*

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The polarization of Lyman-alpha radiation emitted when electrons excite free hydrogen atoms has been studied in a modulated crossed-beam experiment, in which the polarization was measured directly using a Brewster's-angle reflection analyzer. Preliminary data presented by the authors at the Fifth International Conference on the Physics of Electronic and Atomic Collisions in Leningrad last July have been supplemented and extended to the threshold region.

The experiment is shown in Fig. 1. Lyman-alpha radiation which was emitted perpendicular to the plane of the intersecting electron and atom beams was reflected from a lithium fluoride crystal set at the Brewster's angle (59°) and entered an oxygen-gas-filtered, iodine-vapor-filled, uv-photon counter.[1] The counter output was recorded in two phase-locked scalers whose difference gave the signal desired.

In the position shown in Fig. 1, designated as the 90° position, radiation whose electric vector is perpendicular to the electron beam direction should be transmitted by the LiF, so that the signal registered by the counter should be proportional to the intensity $(I_\parallel)$ of radiation whose electric vector is parallel to the electron beam. When the assembly containing the LiF crystal and the photon counter is rotated about the $Z$ axis of Fig. 1 to either the

0° or 180° position, radiation of the opposite polarization reaches the counter and the signal should be proportional to $I_\perp$. The polarization fraction is defined as $P = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$ and under ideal circumstances $P$ would therefore be determined by

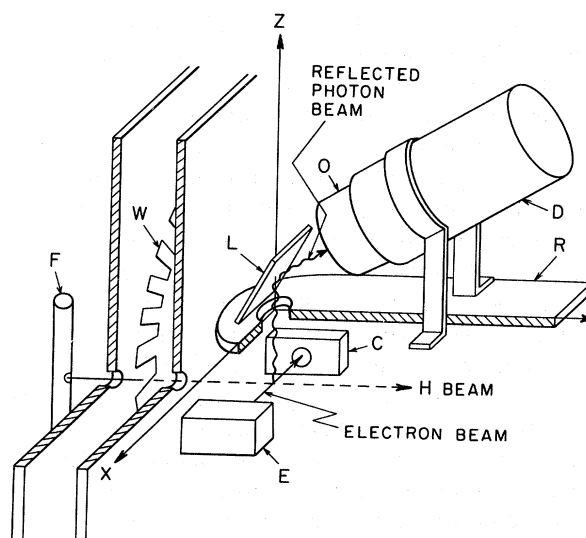$$P = \frac{S_{90} - S_0}{S_{90} + S_0}, \qquad (1)$$



FIG. 1. Experimental arrangement. F, atomic hydrogen furnace; W, chopper wheel; E, electron gun; C, electron collector; L, LiF Brewster's-angle reflector; O oxygen gas filter; D, photon counter; R, mounting which rotates about the Z axis.

where $S_{90}$ and $S_0$ are the signals at the 90° and 0° positions, respectively.

The value so obtained is in fact less than the true polarization because of two effects. First, the volume of interaction of the two beams was not infinitely small and the angular aperture subtended by the LiF and the counter entrance was finite. The radiation entering the counter actually was reflected from a small range of angles around the Brewster's angle. Second, photons could be reflected from the back as well as the front surface of the LiF crystal and multiple internal reflections could occur. From the known geometry and electromagnetic theory it is estimated that the values obtained from Eq. (1) should be increased by about 5%.

The degradation of the polarization analyzer due to these combined effects was also checked experimentally by measuring the apparent polarization of a beam of Lyman-alpha radiation which had been reflected from another LiF crystal at the Brewster's angle. The source of the original Lyman-alpha was the intersection volume of the two beams with the electrons at high energy. An apparent polarization of 0.88 was found. Since the angular apertures associated with the two LiF crystals were similar and since multiple reflections would occur similarly in both, it was concluded that the analyzer would record an apparent polarization of about 0.94 for a beam which was fully polarized, i.e., the apparent polarization is about 6% less than the true polarization. The 6% figure has been used to correct the direct experiment results.

Care was taken to keep stray fields in the interaction region sufficiently low that photons produced by the quenching of atoms excited to the 2S state could be neglected. Measurements were also made on the polarization of radiation detected when electrons struck $H_2$ molecules. From the latter measurements and mass-spectrometric sampling of the H and $H_2$ in the modulated beam, corrections were made for the contribution of small amounts of residual $H_2$ in the beam. Ionization for the mass-spectrometric sampling was done with the same electron gun used to excite the radiation, and therefore the absolute energy scale for the excitation measurements could be set from the appearance potential for ionization of H. Additionally, the curve of ionization signal versus electron energy was used to determine the energy distribution of the electrons

through taking the second derivative of the curve in the vicinity of threshold. The electron source was a tungsten filament.

Figure 2 shows the measured polarization fraction $P$ as a function of electron energy up to 250 eV, and two theoretical predictions. It is to be noted that the calculations relate to Lyman-alpha resulting from excitation to the $2P$ state, whereas the experiment necessarily includes Lyman alpha produced as the final step of cascade processes. It is seen that the $1s$-$2s$-$2p$ close-coupling calculation of Burke and Smith[2] is preferable to the Born calculations of Wu and Ohmura,[3] the values of which are similar to those of Khashaba and Massey[4] who used the distorted-wave approximation.

Figure 3 shows the experimental results over the energy range 10 to 14 eV. The figure also shows two theroetical predictions, the $1s$-$2s$-$2p$ close-coupling approximation results of Damburg and Gailitis[5] and the more recent results of Burke, Taylor, and Ormonde,[6] who added to the $1s$-$2s$-$2p$ approximation a set of correlation terms to account for effects of higher states not considered explicitly in the wave functions. The dashed curve of Fig. 3 is what should be expected in the experiment on the basis of the calculations of Burke, Taylor, and Ormonde. To obtain this curve, their calculations of the polarization and the total cross section were used to obtain the separate inten-
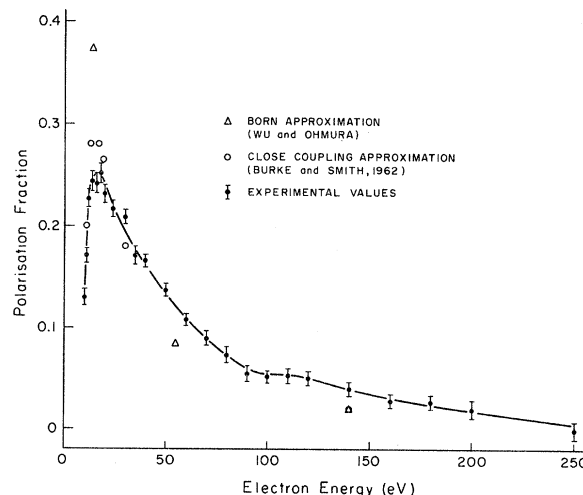


FIG. 2. Polarization fraction versus electron energy. The flags indicate the rms deviations. The theoretical results are those of P. G. Burke and K. Smith, Rev. Mod. Phys. **34**, 458, 499 (1962), and T.-Y. Wu and T. Ohmura, Quantum Theory of Scattering (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1962), p. 195.
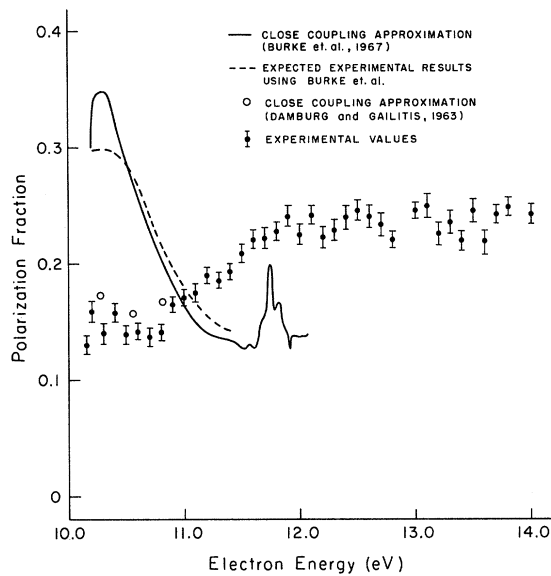
FIG. 3. Polarization fraction versus electron energy in the vicinity of threshold, compared with the predictions of R. Ya. Damburg and M. K. Gailitis, Proc. Roy. Soc. (London) 82, 1068 (1963), and P. G. Burke, A. J. Taylor, and S. Ormonde, United Kingdom Atomic Energy Authority Report No. T.P. 279, Atomic Energy Research Establishment, Harwell, England, May, 1967 (unpublished), Pt. III. The experimental uncertainties shown are rms deviations.

the electron energy distribution in the experiment. The absence of sufficient detail in the results of Damburg and Gailitis precluded applying the same procedure there.

The close agreement between the simpler calculations of Ref. 5 and experiment is quite striking. Equally striking is the disagreement with the predictions of the more complex calculations of Burke, Taylor, and Ormonde, suggesting that the technique of including correlation terms does not, in its present form, lead to improved predictions, at least for the relative population of magnetic substates.

[1]R. T. Brackmann, W. L. Fite, and K. E. Hagen, Rev. Sci. Instr. 29, 125 (1958); W. L. Fite and R. T. Brackman, Phys. Rev. 112, 1151 (1958).
[2]P. G. Burke and K. Smith, Rev. Mod. Phys. 34, 458 (1962); see especially p. 499.
[3]T.-Y. Nu and T. Ohmura, Quantum Theory of Scattering (Prentice-Hall, Inc., Englewood Cliffs, N. J., 1962), p. 195.
[4]S. Khashaba and H. S. W. Massey, Proc. Phys. Soc. (London) 71, 574 (1958).
[5]R. Ya. Damburg and M. K. Gailitis, Proc. Phys. Soc. (London) 82, 1068 (1963).
[6]P. G. Burke, A. J. Taylor, and S. Ormonde, United Kingdom Atomic Energy Authority Report No. T. P. 279, Atomic Energy Research Establishment, Harwell, England, May, 1967 (unpublished), Pt. III.

sities of $I_{\parallel}$ and $I_{\perp}$ at each electron energy, and then numerical integration was performed over

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# ATOMIC DIFFERENTIAL SPIN-EXCHANGE SCATTERING*

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Differential spin-exchange scattering of sodium from cesium has been observed by the crossed-atomic-beam scattering technique. The angular dependence of the exchange probability yields details of the singlet-triplet potential differences, including the depth and position of the triplet potential minimum. Results are also reported for potassium scattering from molecular oxygen.

Electron spin exchange can occur in any collision between atoms with unpaired electrons. Spin exchange plays a vital role in establishing the spin temperature of interstellar hydrogen,[1] and it can serve as a damping or polarization-transfer mechanism in resonance experiments.[2] In the latter role it has proven to be a powerful tool in radio-frequency spectroscopy, particularly in optical pumping experiments. In principle, spin exchange should also be a powerful tool for studying interatom-

ic potentials. However, up to the present, all investigations have involved total cross sections which are generally averaged over wide ranges of momentum and scattering angle. We wish to report what we believe are the first observations of differential spin-exchange scattering between atoms.[3] The experiments were carried out with a crossed-atomic-beam apparatus in which the scattering angle, collision energy, and atomic spin states were all well defined. Our first results include direct deter-