Polarization of Lyman-β radiation from atomic hydrogen excited by electron impact from near-threshold energy to 1000 eV

G. K. James
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

D. Dziczek
Institute of Physics, Nicholas Copernicus University, Toruń, Poland

J. A. Slevin*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

I. Bray
Physics and Energy Studies, School of Mathematical and Physical Sciences, Murdoch University, Perth, Western Australia 6150
(Received 12 April 2002; published 17 October 2002)

The polarization of Lyman-β radiation, produced by electron-impact excitation of atomic hydrogen, has been measured over the extended energy range from near threshold to 1000 eV. Measurements were obtained in a crossed-beams experiment using a silica-reflection linear polarization analyzer in tandem with a vacuum ultraviolet monochromator to isolate the emitted line radiation. Our data are in excellent agreement with convergent close-coupling calculations over the entire energy range. The data are broadly similar to the earlier measurements of H Lyman-α polarization reported from the Jet Propulsion Laboratory.

DOI: 10.1103/PhysRevA.66.042710 PACS number(s): 34.80.Dp, 39.10.+j, 33.20.Ni, 31.15.Ar

I. INTRODUCTION

Polarization of atomic line radiation has been of general interest since its early discovery in the Zeeman effect, and there is now a relatively large body of data available on polarization of electron-impact-induced radiation (McConkey, Hammond, and Khakoo [1], Heddle and Gallagher [2]). Polarization measurements in the vacuum ultraviolet (VUV) present particular difficulties for experimentalists. Much of the available experimental VUV polarization data have been obtained by the Windsor group and refer to the excitation of the rare gases and various molecules (see, for example, Westerveld *et al.* [3], Malcolm, Dassen, and McConkey [4], Huschilt, Dassen, and McConkey [5], Dassen and McConkey [6], and Noren *et al.* [7–9]). As part of a systematic study of VUV optical emissions from electron-impact excited atomic hydrogen, the Jet Propulsion Laboratory recently reported detailed measurements of the polarization of H Lyman-α radiation at electron energies from near threshold to 1800 eV (James *et al.* [10]). We present here the results of a similar study for the next resonance line in the $1s$-np Lyman series, Lyman β.

The motivation for this program is straightforward. Accurate experimental values for the polarization of radiation produced by electron-impact excitation provide a sensitive test for theory by determining the relative populations of the degenerate magnetic sublevels in the excitation process. In addition, since electron-impact excitation cross sections are typically measured in a crossed-beams configuration, with the emitted photons detected at 90° to the electron-beam axis, polarization measurements are required to correct data to obtain values for the integral cross section.

In this paper, we report polarization measurements of H Lyman-β radiation, produced by electron-impact excitation of atomic hydrogen in the extended energy range from near-threshold to 1000 eV. These data are for the $1s$-$3p$ transition. Our data are compared with convergent close-coupling (CCC) calculations over the entire energy range, and with the Bethe approximation in the high-energy regime.

The present experimental approach is identical to that of our previous polarization measurements for the H Lyman-α line. Our technique utilizes a radio-frequency (RF) atomic hydrogen discharge source (Slevin and Sterling [11]) and a reflection VUV polarization analyzer (Chwirot *et al.* [12]). We also employ a 0.2-m VUV monochromator to unambiguously select the Lyman-β radiation. This is essential for an accurate determination of the molecular contribution to the observed signal.

II. POLARIZATION OF LINE RADIATION

Our previous paper on H Lyman-α polarization (James *et al.* [10]) details the relationships between excitation cross sections and the polarization of line radiation. We summarize here the general principles. Dipole radiation emitted in the relaxation of an atom excited by electron impact will, in general, be polarized due to the anisotropy of the collision process. The present experiment has a crossed-beams geometry, with the incident electron beam defining an axis of symmetry and therefore an excitation process satisfying conditions of cylindrical symmetry. The radiation can be completely characterized by a single integrated Stokes parameter S_1 which is defined by

$$S_1 = \frac{I(0°) - I(90°)}{I(0°) + I(90°)}, \tag{1}$$

*Present address: 56 Waterloo Road, Dublin 4, Ireland.

where $I(0°)$ (also referred to as $I_{\parallel}$) and $I(90°)$ (or $I_{\perp}$) are the photon intensities observed at 90° to the electron beam axis with electric vector parallel or perpendicular to the electron beam, respectively. This parameter is often given the symbol $P(=S_1)$, and is usually referred to as the *polarization* of the radiation.

The relationship between the cross sections for populating the different degenerate magnetic sublevels of the excited state and the resulting polarization is characterized by a set of constants that depend on the relative magnitudes of these interactions. For the Lyman series the polarization takes the following form:

$$P(nP)=\frac{3(Q_0-Q_1)}{7Q_0+11Q_1}, \tag{2}$$

where Q_m is the cross section for excitation of the magnetic sublevel m related to the orbital angular momentum and it is assumed that hyperfine interactions and radiation damping can be neglected.

At high energies, the polarization P of electron-impact-induced radiation from an atomic state j can be calculated from an expression derived by McFarlane [13] and Heddle [14], assuming the validity the Bethe approximation. The parameter P can be represented in this approximation by the expression

$$P=P_0\left[3-\ln\left(4c_j\frac{E}{R}\right)\right]\left[(2-P_0)\ln\left(4c_j\frac{E}{R}\right)+P_0\right]^{-1}, \tag{3}$$

where P_0 is the polarization at threshold produced by electron impact of monoenergetic electrons of energy E_j, c_j is a parameter that describes the angular distribution of the scattered electrons, and R is the Rydberg constant. The parameter P_0 can be calculated exactly from angular momentum conservation considerations and has a value of 0.42 for nP excitations in atomic hydrogen (Percival and Seaton [15]). Using a Bethe approach to the excitation, Inokuti [16] has obtained a value of 0.408 for c_j. With these values for the constants P_0 and c_j, Eq. (3) determines the high-energy Bethe limit for the polarization.

One consequence of the above formulation is that the polarization has a value of zero at an energy given by $E=e^3R/4c_j$. Using the above value for c_j, the polarization of Lyman β is zero at an impact energy of 167 eV. An experimental determination of this quantity is therefore of interest.

For an optically allowed excitation process, Heddle [14] shows that if the polarization P is plotted against $\ln E$ then the gradient (G) of this curve at the energy (E_P) where the polarization passes through zero is given by

$$G(1+\beta)=-\frac{P_0}{(6-2P_0)}, \tag{4}$$

where β is the fractional cascade component of the observed radiation at energy E_P. A determination of the slope G from the experimental data thus allows an measurement of P_0 to be made well away from the threshold energy region.

III. EXPERIMENTAL APPROACH

A. Experimental apparatus

The experimental apparatus has been described in detail by James *et al.* [10]. It consists of an electron-impact collision chamber equipped with an atomic hydrogen source, in tandem with a 0.2-m VUV monochromator (resolving power 250). A silica-reflection linear polarization analyzer (Chwirot *et al.* [12]) is positioned after the exit slit of the monochromator. Since magnetically confined electron beams may be subject to systematic errors due to spiraling and other effects associated with magnetic fields (Ott, Kauppila, and Fite [17]), an electrostatic electron gun is used to produce the electron beam over the entire energy range from near threshold to 1000 eV.

A Faraday cup designed to eliminate backscattered secondary electrons is used to monitor the electron-beam current (typically 5 μA). The energy spread of the electron beam is approximately 0.4 eV, with an uncertainty in the beam energy of ± 0.1 eV, as measured from the appearance potential for excitation of the Lyman-β transition.

The atomic hydrogen source has been described in detail by Slevin and Sterling [11]. Hydrogen molecules are dissociated in a discharge, excited within an RF cavity, resonant at 36 MHz. Hydrogen atoms effuse from a water-cooled Pyrex discharge tube, past a quartz photon trap and through a 1 mm capillary into a field-free interaction region where they are crossfired by the electron beam. Photons emitted from the interaction region are dispersed by the VUV monochromator, with slit widths chosen to ensure adequate separation of atomic line emissions. The VUV monochromator provides precise wavelength selection, a factor that is critical in quantifying the molecular contribution to the observed Lyman-β signal.

The polarization analyzer has been described in detail by Chwirot *et al.* [12] who also compare its performance to other analyzer designs. The optical constants of the silica mirror require an angle of incidence of 70° to reflect a single plane of polarization only. On the basis of the optical data, the calculated polarizance ε (or extinction ratio for the two orthogonal polarizations) of the analyzer used in the present measurements for Lyman-β radiation is 0.63 ± 0.03. A channeltron, with a CsI-coated entrance cone to enhance the quantum efficiency at Lyman β and positioned at the reflector angle, is used to detect the photons.

In order to eliminate any polarization effects that may be induced by the monochromator and detector systems, the grating is rotated such that the plane defined by the monochromator entrance slit and optic axis is at 45° to the electron-beam axis (James *et al.* [10]). Clout and Heddle [18] and Donaldson, Hender, and McConkey [19] describe the theoretical basis for this orientation in detail).

Polarization measurements are made in the conventional manner by aligning the analyzer axis such that signals proportional to $I_{\parallel}$ and $I_{\perp}$ reach the detector. This is achieved by rotating the analyzer mirror and detector assembly using a stepper motor.

The entire experimental system is interfaced to a PC that controls the electron-beam energy and the stepper motor

used to change the polarization analyzer orientation. Measured signals are normalized to the electron-beam current and hydrogen source pressure. Data are accumulated in a multiple scanning mode to reduce the effects of any drifting in other experimental parameters.

B. Correction procedure for molecular contribution

Since the hydrogen beam is not fully dissociated, the observed Lyman-β photon signal at 102.56 nm contains a (small, but not negligible) contribution from molecular emission, which must be quantified. The molecular component results from Lyman-β radiation produced by dissociative excitation of H_2, as well as radiation from molecular bands transmitted within the bandpass of the monochromator (operated at a full width at half maximum of 2.4 nm at typical slit widths of 600 μm). In order to correct the measured polarization data for this molecular contribution, the dissociation fraction must be measured, together with the polarization of a pure molecular hydrogen target produced with the RF discharge off.

The dissociation fraction is established in the manner described by James *et al.* [10] by tuning the monochromator to an H_2 molecular band at 110 nm (with the bandpass adjusted to exclude any atomic component from Lyman β) and measuring the molecular emission with the discharge on and off at the same hydrogen source driving pressure and electron beam current. The dissociation fraction D is then related to these two signals S_1 (on) and S_2 (off) by the relationship

$$1-D=\sqrt{\frac{T_2}{T_1}}\frac{S_1}{S_2}, \tag{5}$$

where T_1 and T_2 are the effective kinetic temperatures in the gas beam with the discharge on and off, respectively. Using this value for the dissociation fraction, the polarization of the atomic line radiation can then be obtained in the manner described by James *et al.* [10], from separate measurements of the polarization with the RF discharge on (where the beam contains a mixture of atomic and molecular hydrogen) and with the RF discharge off (where the beam is purely molecular). The true polarization of the atomic radiation is finally obtained by correcting the measured data for the analyzer polarizance ε. The present data are corrected using a polarizance value of 0.63 for Lyman β, calculated using the optical constants for fused silica.

C. Resonance trapping

Since trapping of resonance Lyman-β radiation by ambient atomic hydrogen generally leads to a reduction in the polarization, it is essential to ensure that the column density of atomic hydrogen is such that the probability of absorption of a Lyman-β photon en route to the detector is negligibly small. To ensure the absence of resonance trapping effects in the present experiment, measurements are made under conditions where the detected photon signal is proportional to the hydrogen source pressure. Operating under Knudsen conditions at the beam source preserves a linear relationship between the source pressure and the number density in the interaction region. Previous measurements with this source described by James *et al.* [10] verify the absence of resonance trapping and associated depolarization effects for source pressures less than 46 mTorr. The present experiment was carried out at a source pressure of ~40 mTorr.

TABLE I. Experimental and theoretical Bethe values for the polarization of Lyman-β radiation from atomic hydrogen excited by electron impact from near-threshold energy to 1000 eV.

Energy (eV)	Experiment	Error	Bethe
15	0.256	0.021	
20	0.297	0.015	
25	0.267	0.016	
30	0.240	0.012	
35	0.205	0.015	
40	0.169	0.015	0.208
50	0.137	0.015	0.156
60	0.112	0.016	0.122
70	0.114	0.013	0.097
80	0.067	0.011	0.078
100	0.045	0.017	0.050
150	0.008	0.017	0.009
200	−0.019	0.014	−0.014
300	−0.023	0.019	−0.040
400	−0.071	0.021	−0.056
500	−0.064	0.020	−0.067
600	−0.059	0.018	−0.075
800	−0.067	0.018	−0.086
1000	−0.078	0.023	−0.094

IV. THEORETICAL APPROACH

The CCC method for e-H scattering calculations has been described in detail by Bray and Stelbovics [20]. The scattering amplitudes for the $3P$ excitation are calculated after partial wave T-matrix elements are evaluated. The spin-averaged magnetic-sublevel-dependent integrated cross sections Q_m are then obtained and used to define the polarization fraction P via

$$P=\frac{Q_0-Q_1}{2.375Q_0+3.749Q_1}. \tag{6}$$

This formulation takes into account the (very small) effects of hyperfine structure [15], and differs slightly from Eq. (2) because of this.

V. RESULTS AND DISCUSSION

The experimental H Lyman-β polarization data measured in the present work over the electron-impact energy range from near-threshold to 1000 eV are listed in Table I, together with the results of Bethe calculations at the higher energies where this approximation is expected to be valid. The Bethe values were calculated from the formula of McFarlane [13]. (CCC results are not included in the table because the energy

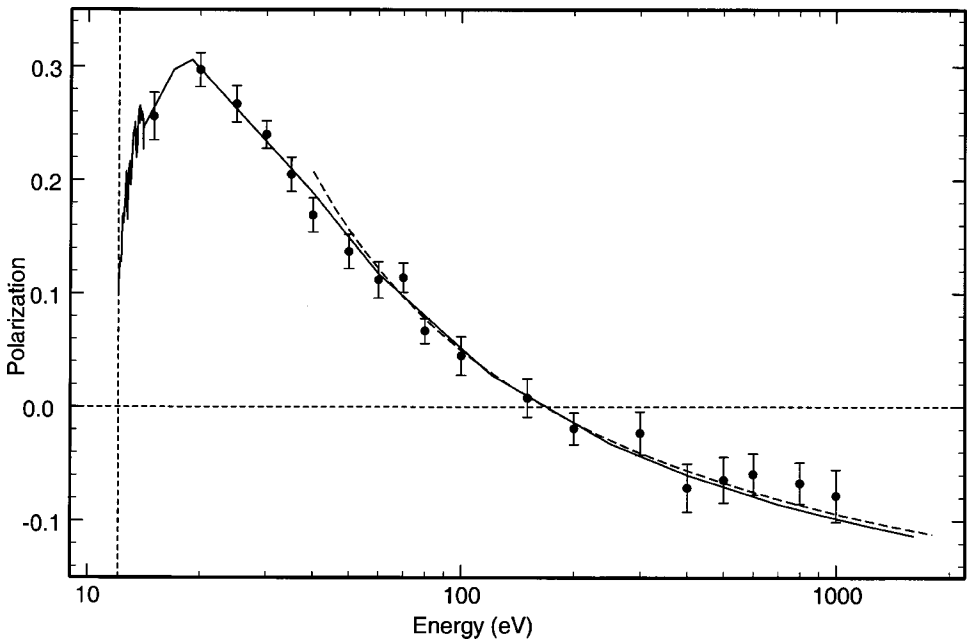

FIG. 1. Experimental (solid circles) and theoretical CCC (solid line) and Bethe (dashed line) values for the polarization of Lyman-β radiation from atomic hydrogen excited by electron impact over the energy range from threshold ($\sim$12.1 eV) to 1600 eV. For clarity, only a few representative values of the present CCC calculations are shown for energies $\leqslant$14 eV; the detailed near-threshold behavior of our CCC calculations is shown in Fig. 2. The dashed horizontal line representing zero polarization is added for clarity. The position of the H($1s$-$3p$) excitation threshold is indicated by the vertical dashed line.

basis for these calculations had only limited overlap with the experimental energies.)

Our data are illustrated in Figs. 1 and 2, together with the CCC calculations. There are no previous experimental measurements. The stated experimental errors in our data correspond to one standard deviation in the signal statistics, combined with an additional contribution from identifiable sources of systematic error, estimated on the same basis as described by James *et al.* [10].

The data also show the polarization passing through zero at a value of $E_P = 175 \pm 20$ eV, in excellent agreement with the predicted value of 167 eV. Clearly, the agreement between the present experimental H Lyman-β polarization data and the CCC calculations is excellent over the entire energy range of these measurements. Overall excellent agreement with CCC theory was also found in our previous measurement of the polarization of H Lyman-α radiation (James *et al.* [10]) as well as for the optical excitation function of H($2P$) (James *et al.* [21]). CCC calculations of the H($2P$) cross section were in excellent agreement with the experimental cross section data over the entire electron-impact energy range from near threshold to 1800 eV, providing further confirmation of the validity of the CCC methodology.

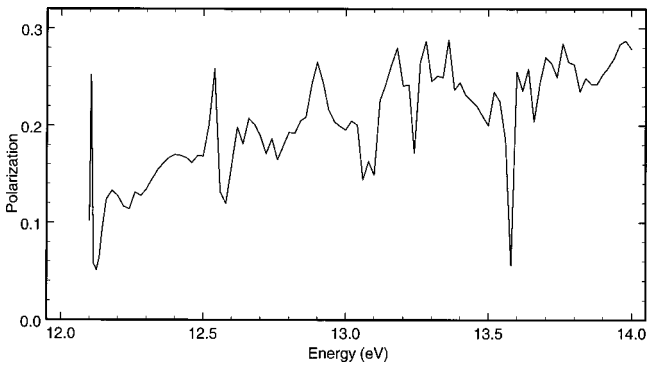

FIG. 2. Theoretical CCC calculations for the polarization of Lyman-β radiation from atomic hydrogen excited by electron impact over the energy range from threshold ($\sim$12.1 eV) to 14 eV.

At energies greater than 100 eV the convergence of the present experimental data to Bethe values for the polarization can be seen in Fig. 1. This convergence of experiment and Bethe theory at high energies provides further evidence that the present experimental method is free from any significant unknown systematic effects (for example, in the polarizance of the analyzer, or the presence of low-energy secondary electrons).

It is worth noting that, like our Lyman-α data, the present experimental Lyman-β polarization data do not tend to the Percival and Seaton [15] limit of 0.42 at threshold. However, the behavior of the polarization in the near-threshold region will necessarily be masked by the electron-beam energy resolution of $\sim$0.4 eV obtained in the present experiment. Any resonance structure present will therefore not be observable in the present experiment. The low-energy CCC calculations (Fig. 2) show considerable structure in the polarization function in the near-threshold region. It should also be noted that the lack of convergence to the Percival and Seaton limit cannot be attributed to the effect of cascade since the $n=4$ cascade threshold is at $\sim$12.8 eV.

The existence of resonances is well known to have a profound effect on polarization functions (see, for example,

Heddle, Keesing, and Watkins [22], Noren and McConkey [8]). Thus the energy resolution of the electron gun is crucial. If this is larger than the resonance widths, or if multiple overlapping resonances are contributing to the observed signal, significant distortion of the measured polarization function results. In $2\,^1P$ excitation in helium, where no resonance contribution occurs until $\sim$1 eV above threshold, the predicted threshold value of P is clearly observed (Noren *et al.* [7]). It is not unreasonable to argue that the low near-threshold value of P measured in the present experiment is an indication of the presence of the strong perturbing effects of the resonances in the near-threshold energy region.

Based on Eq. (4), the gradient of the P versus $\ln E$ curve at the energy ($E_P = 175 \pm 20$ eV) at which the measured polarization function passes through zero yields an experimental value for P_0 of 0.38 ± 0.06, using a value of $\beta = 0.05$ (James *et al.* [10]). This is consistent with the theoretical value of 0.42 within the (rather large) error bars.

CONCLUSIONS

The polarization of Lyman-β radiation, produced by electron-impact excitation of atomic hydrogen in the extended energy range from near threshold to 1000 eV, has been measured in a crossed-beams experiment using a silica-reflection linear polarization analyzer. The present experimental values have been compared with CCC calculations and are in excellent agreement over the entire energy range of the measurements, and also converge to Bethe values at high energies. The present data are broadly similar to the earlier measurements of H Lyman-α polarization reported from the Jet Propulsion Laboratory.

ACKNOWLEDGMENTS

This work is based upon activities carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was supported by the National Science Foundation under Agreement No. PHY-9722748, the Astrophysics and Planetary Atmospheres programs of the National Aeronautics and Space Administration, and by the Air Force Office of Scientific Research. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors wish to thank J. W. McConkey for many useful discussions. The authors also acknowledge Stanislaw Chwirot of the Nicholas Copernicus University, Poland for many valuable suggestions in the design of the experiment and analysis algorithms. The authors also wish to acknowledge Bill Lanigan of the National University of Ireland at Maynooth for his significant contribution to the design and implementation of the computer control of the experimental apparatus.

[1] J. W. McConkey, P. Hammond, and M. A. Khakoo, *Electronic and Atomic Collisions* edited by H. B. Gilbody, W. R. Newell, F. H. Read, and A. C. H. Smith (Elsevier, New York, 1988), p. 105.
[2] D. W. O. Heddle and J. W. Gallagher, Rev. Mod. Phys. **61**, 221 (1989).
[3] W. B. Westerveld, K. Becker, P. Zetner, J. Corr, and J. W. McConkey, Appl. Opt. **24**, 2256 (1985).
[4] I. C. Malcolm, H. W. Dassen, and J. W. McConkey, J. Phys. B **12**, 1003 (1979).
[5] J. C. Huschilt, H. W. Dassen, and J. W. McConkey, Can. J. Phys. **59**, 1893 (1981).
[6] H. W. Dassen and J. W. McConkey, J. Phys. B **14**, 3777 (1981).
[7] C. Noren, J. W. McConkey, P. Hammond, and K. Bartschat, Phys. Rev. A **53**, 1559 (1996).
[8] C. Noren and J. W. McConkey, Phys. Rev. A **53**, 3253 (1996).
[9] C. Noren, W. L. Karras, J. W. McConkey, and P. Hammond, Phys. Rev. A **54**, 510 (1996).
[10] G. K. James, J. A. Slevin, D. Dziczek, J. W. McConkey, and I. Bray, Phys. Rev. A **57**, 1787 (1998).
[11] J. A. Slevin and W. Sterling, Rev. Sci. Instrum. **52**, 1780 (1981).
[12] S. Chwirot, S. Nic Chormaic, D. Dziczek, and J. Slevin, Appl. Opt. **32**, 1583 (1993).
[13] S. C. McFarlane, J. Phys. B **7**, 1756 (1974).
[14] D. W. O. Heddle, J. Phys. B **16**, 275 (1983).
[15] I. C. Percival and M. J. Seaton, Proc. R. Soc. London, Ser. A **251**, 113 (1958).
[16] M. Inokuti, Rev. Mod. Phys. **43**, 297 (1971).
[17] W. R. Ott, W. E. Kauppila, and W. L. Fite, Phys. Rev. A **1**, 1089 (1970).
[18] P. N. Clout and D. W. O. Heddle, J. Opt. Soc. Am. **59**, 715 (1969).
[19] F. G. Donaldson, M. A. Hender, and J. W. McConkey, J. Phys. B **5**, 1192 (1972).
[20] I. Bray and A. T. Stelbovics, Phys. Rev. A **46**, 6995 (1992).
[21] G. K. James, J. A. Slevin, D. E. Shemansky, J. W. McConkey, I. Bray, D. Dziczek, I. Kanik, and J. M. Ajello, Phys. Rev. A **55**, 1069 (1997).
[22] D. W. O. Heddle, R. G. W. Keesing, and R. D. Watkins, Proc. R. Soc. London, Ser. A **337**, 443 (1974).