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Polarizations of the Balmer-α and -β lines produced by dissociative collisions of $H_2{}^+$ with the rare gases

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The polarizations of the Balmer-α and -β lines produced by dissociative collisions of H_2^+ have been measured at energies from 0.1 to 10 keV for a helium target and from 0.1 to 3 keV for argon and krypton targets. The Balmer-α line exhibits almost zero polarization in all these experiments. The Balmer-β line, however, has a maximum polarization near 13% for the helium target and lower maxima, 6.0% and 2.5%, for argon and krypton targets. The relationship of these results to selective excitation of the H_2^+ molecule and to the angular distributions of the dissociation products is discussed.

I. INTRODUCTION

During the past two decades extensive studies have been made of dissociation in heavy-particle collisions.[1] Ideally, such investigations could be performed by preparing both the beam and the target in single states, then determining the separate cross sections for each set of final states which are produced. However, experimental limitations usually prevent the achievement of such well-defined conditions. For example, direct detection of the products is the most important technique used for determining cross sections and angular distributions, but it is often impossible from such measurements to isolate, for separate study, the dissociation through a given channel of the several that are possible. In some cases, though, the process may lead to excited fragments which radiate spectral lines, and for these situations measurements of the emission can provide added details about the total cross sections for the individual channels through which the dissociation takes place.

Van Brunt and Zare[2] have suggested that optical studies might also be used to reveal the dependence of a dissociative cross section upon the relative orientation of the internuclear molecular axis and the direction of the beam used for excitation. If the magnetic substates of the upper level of a spectral line are unequally populated, then the magnitude of any polarization present is related to the angular distribution of the dissociation axes. When collisions take place by exciting a molecule to a state from which it breaks up before any appreciable rotation occurs, then such distributions are identical to those for the probability of excitation.

The application of this suggestion was explored in a recent study of the polarization of the Balmer lines[3,4] produced by dissociative charge exchange of the $He^+ + H_2$ system. In this reaction the polarization of the Balmer-α line was maximum at low collision energies, being 12% at 40 eV and declining to zero at about 90 eV. A secondary maximum of about 2% also appeared at 150 eV. The data for the Balmer-α line at low energies was interpreted as showing the dissociation peaked at right angles to the beam direction. This result was the same as that obtained by McKnight[5] from direct measurements of metastable fragments at energies from 1 to 5 keV. The lack of significant polarization above 90 eV was ascribed to the populations of the magnetic sublevels being more uniform at the higher energies than they were near threshold. The small polarization of the Balmer-β line throughout the energy range studied was also believed to be caused by populating several magnetic substates almost equally. This analysis indicated that even though the excitation might be highly anisotropic in many collisions, the polarization would be very small.

In the present paper we discuss measurements of the polarization of Balmer-α and -β lines which arise from dissociative collisions of $H_2{}^+$ with He, Ar, and Kr at energies between 0.1 and 10.0 keV. Although the polarization is almost zero for some of the reactions, its magnitude is several percent over most of the energy range for others, in contrast to the data obtained for the $He^+ + H_2$ collisions. These results are discussed for the high-energy portion of the collision range in terms of the orientation-dependent selection rules proposed by Dunn[6] and the calculations of Green and Peek which utilize the Born approximation.[7]

II. APPARATUS AND EXPERIMENTAL TECHNIQUE

A schematic diagram of the apparatus used for the present experiments is shown in Fig. 1. It consists of three main sections: (i) a chamber in which ions are produced by electron bombardment, (ii) a collision chamber which contains the target gas, and (iii) an intermediate section which incorporates a series of electrostatic lenses and a low-resolution Wien filter. Modular construction that is compatable with the High Voltage Engineering Corporation's 4-in. beam line components and coupling flanges has been used in the fabrication of the system. All electrical feedthroughs, leak valves, and observation windows are mounted on conflat flanges and sealed into the various modules with oxygen-free high-conductivity copper gaskets. The ion and lens chambers are evacuated by 2-in. mercury-pumping systems and achieve ultimate pressures of 10^{-7} Torr, but the collision chamber, which reaches 10^{-6} Torr, is evacuated only through the entrance hole in the bulkhead that separates it from the lens section and through the slit of the vacuum monochrometer which is coupled to an observation port directly opposite the window shown in Fig. 1.

Ions are made by bombardment of H_2 with 100-eV electrons in a source that is similar to the one described previously by Isler and Nathan.[3] A Wien filter which is 2 in. long and has a magnetic field of 500 G is used to eliminate H^+ and H_3^+ from the beam. The currents of H_2^+ ions entering the collision chamber vary from 0.2 to 8.0 μA depending upon the beam energy and the extraction voltage. When making polarization measurements the current is stabilized within 0.5% over the counting period. Details of the construction and method of current stabilization are contained in a separate note.[8]

Spectral scans are performed with two monochromators: a McPherson model No. 225 which is useful from 500 to 6000 Å and a Jarrell-Ash model No. 82-410 which can be employed for studies between 2800 and 10 000 Å. Several detectors are employed depending upon the spectral range being investigated. A Bendix model No. 306 electron multiplier is used below 1300 Å, an EMR 542 G tube between 1200 and 1700 Å, and an EMI 9558Q or 6256S above 1700 Å. The EMI tubes are cooled if necessary to reduce their dark current.

The optical system for measuring polarizations consists of a limiting aperture, lens, rotatable polarizer, interference filters, and photomultiplier tubes. The aperture, which is placed just beyond the window to the collision chamber, prevents light that is emitted outside a 4° cone from entering the detector. Filters with 30-Å bandpasses are used to isolate the Balmer lines. There are no intense spectral lines of helium that lie within the bandpass of either filter; however, lines of argon and krypton do lie close enough to the hydrogen lines to be transmitted, and at energies above 3 keV these lines are intense enough to prevent meaningful polarization measurements from being made. A bench test of the optical system shows the intrinsic polarization to be less than 0.5%.

The polarizations of collisionally excited lines are investigated by alternately orienting the polarizer so that the axis of transmission is perpendicular, then parallel, to the beam and counting the number of photons detected for each direction. The polarization is defined in the usual manner by

$$P = I_{\parallel} - I_{\perp}/I_{\parallel} + I_{\perp} . \tag{1}$$

Four or more sets of measurements are obtained at each collision energy for counting periods that are usually 100 sec long. Attempts are made to record a sufficient number of photons that the counting statistics have uncertainties of 0.5% or less, although, it is not feasible to obtain this

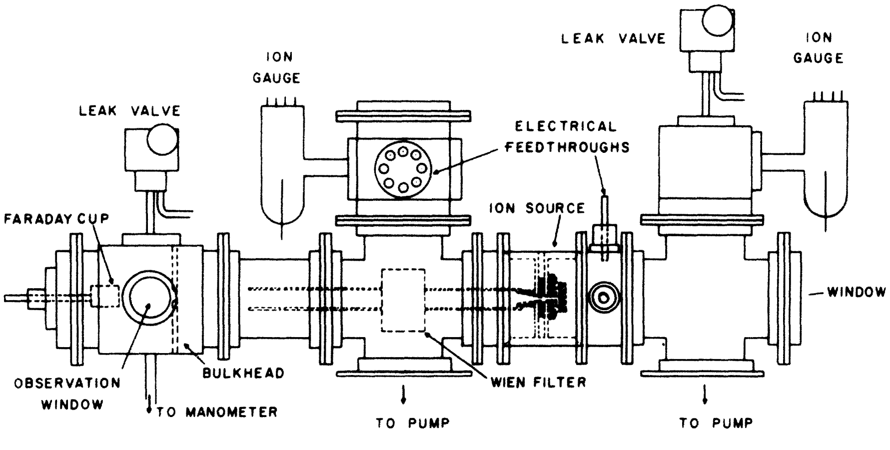

FIG. 1. Schematic diagram of the apparatus.

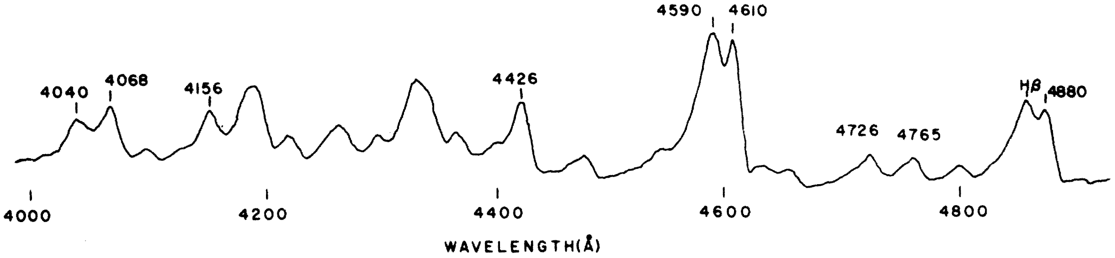

FIG. 2. Visible spectrum produced by H_2^+ + Ar collisions at 7.5 keV. All features except the Balmer-β line can be attributed to Ar II.

accuracy at the lowest energies because both the excitation cross sections and the beam intensities are small enough to make the required time prohibitive.

III. EXCITATION SPECTRA

Before attempting any polarization measurements several spectral scans were taken using various target gases primarily for determining whether any lines were excited which would interfere with studies of the Balmer series. The spectra were recorded over a much wider range than required for this purpose in order to see if any lines of H_2 could be observed which would directly indicate charge exchange taking place into excited states of the neutral molecule, and also to obtain some estimates of the probability of exciting the target gases.

Experiments show that only the hydrogen lines are excited strongly in collisions with helium. At a collision energy of 10 keV the 584-Å resonance line produces a signal which is less than 0.5% of the one produced by the Lyman-α line. The combination of monochromator and detector is not calibrated in the vacuum ultraviolet region so that these numbers cannot be translated into relative intensities. However, the decreased reflectivity of the grating at the shorter wavelength tends to be compensated by the higher quantum efficiency of the detector (15% at 600 Å vs 3% at 1216 Å according to manufacturers specifications) so that the intensity of the 584-Å HeI line is estimated to be no more than a few percent of that of the Lyman-α line at collision energies below 10 keV.

In contrast to the small probability for excitation of the helium lines, relatively intense spectra of argon and krypton are produced. Figures 2 and 3 show portions of these spectra for collisions of H_2^+ with Ar at 7.5 keV. The visible region is completely dominated by ArII lines. Several of these are noted in Fig. 2, and all of the prominant features with unspecified wavelengths are groups of lines which can be attributed to this species. The intensity of the radiated light is insufficient for obtaining spectra at resolution high enough to identify all of the individual lines in this region, and any lines of H_2 which might be excited would be obscured by the argon radiation. The Balmer-β line is clearly discernible, but nearby argon lines are produced with comparable intensity at this energy. At energies below 3 keV the argon lines are still very much in evidence, but most of the radiation around 4861 Å comes from the Balmer-β line. Similar results are observed in collisions with krypton and the polarization measurements have been limited to energies below 3 keV for these two gases.

The far-ultraviolet spectrum produced by collisions with argon is shown in Fig. 3. The Lyman-α line produces the strongest signal, but both ArI and ArII lines are prominent. Again, there are no strong features that can definitely be identified with lines of molecular hydrogen.

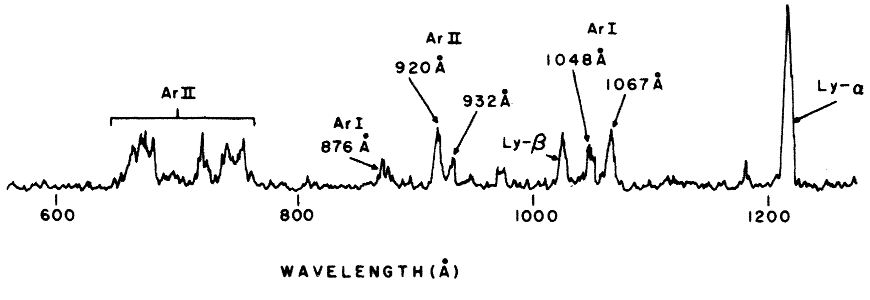

FIG. 3. Vacuum ultraviolet spectrum produced by H_2^+ + Ar collisions at 7.5 keV.

IV. DISCUSSION

Before proceeding to the results of the polarization measurements, a discussion of the relationship of the spectral observations to other experimental and theoretical results will prove useful. The calculations of Green and Peek[7] are of particular interest. They employ the Born approximation to compute angular distributions of the products from dissociative collisions of H_2^+ with helium and argon. It is assumed that the process takes place through excitation to an unbound state of H_2^+ which then breaks up into two fragments. Calculations have been performed for transitions from the $1s\sigma_g$ ground state to a limited number of final states ($2p\sigma_u$, $2p\pi_u$, $2s\sigma_g$, $4f\sigma_u$) as a function of the internuclear separation of the molecule. Cases of simultaneous target excitation have also been investigated. Tabulated results that apply to the current experimental energy range are at 3 and 10 keV. Several general features of these computations are worth noting. First, excitation appears to take place predominately to the $2p\sigma_u$ state which dissociates into a proton and a hydrogen atom in the ground state. Second, the angular distribution for these dissociation products from the $2p\sigma_u$ state depends strongly upon the internuclear separation of the H_2^+ at the time the transition occurs; at 10 keV, the dissociation is calculated to take place mainly in the direction of the beam for small internuclear separations and perpendicular to the beam for large internuclear separations. However, products which are produced subsequent to excitation to the $2p\pi_u$, $2s\sigma_g$, and $4f\sigma_u$ states at this collision energy are not strongly dependent upon the internuclear separation. The angular distribution of products from the first two of these highly excited states is peaked at 90° with respect to the beam direction and the distribution from the third state is peaked parallel to this direction. These computed angular distributions are consistent with the orientation-dependent selection rules that are applicable where the Born approximation holds[6]; they require the internal symmetries of the initial and final systems to be conserved with respect to the momentum transfer axis.

Several experimental results are available to test these computations. Measurements of the absolute cross section for exciting the Lyman-α line through collisions of H_2^+ with the rare gases have been made by Van Zyl *et al.*[9] and imply disagreement with the theoretical prediction that only the $2p\sigma_u$ state is highly populated. The cross section for producing this line at 10 keV is about 30% and at 3 keV, almost 100% of the total dissociation cross section determined by Williams and Dunbar.[10] Because the hydrogen lines can be produced either by collision-induced dissociation,

$$(A):\ H_2^+ + T \rightarrow (H_2^+)^* + T \rightarrow H^* + H + T,$$

or by dissociative charge exchange,

$$(B):\ H_2^+ + T \rightarrow H_2^* + T \rightarrow H^* + H + T,$$

it is necessary to ascertain whether mechanism (A) is dominant before trying to determine what fraction of the dissociation proceeds through unbound states of H_2^+. Van Zyl *et al.* have deduced that process (A) is indeed responsible for the excitation of the Lyman-α line if the target is helium, since the magnitude of the emission cross section is larger than that for total charge exchange,[11] and the energy dependences of the two reactions are quite different. The charge-transfer cross sections are much larger for the heavier gases, and at 10 keV the Lyman-α radiation is probably produced by both reactions (A) and (B). Below 3 keV, though, Van Zyl *et al.* conclude that reaction (B) is dominant.

Gibson, Los, and Schopman[12] have taken a different approach to substantiating the theoretical work. They have measured the angular distribution of the emitted protons with respect to the center of mass of the H_2^+. By assuming that the dissociation proceeds via the $2p\sigma_u$ state and by measuring the dissociation energy of a detected proton, they associate it with a particular internuclear separation at the time of excitation. In general, the angular dependences found by this technique agree qualitatively with those calculated by Green and Peek for dissociation from the $2p\sigma_u$ state except for narrow superimposed peaks around 90°. This anomaly is barely discernible with a helium target but becomes quite pronounced for the heavier gases. Gibson *et al.* have taken these results as substantiating the calculations in the Born approximation, with dissociation occurring primarily through the $2p\sigma_u$ state, but with the added feature that the superimposed peaks result from simultaneous excitation of $m = \pm 1$ states of the target. However, the Born approximation also indicates simultaneous excitation of target and projectile to be very unlikely, so that if such a process does occur readily its theoretical treatment lies outside the framework of this theory. Thus the experimental evidence seems to support some aspects of the available calculations and to contradict others.

Some insight into the possibility of simultaneous excitation of the target and the H_2^+ ion can be gained from the spectral studies. The relative response of the system is known at 1200 and 1000 Å so that the intensity of the Ar I lines at 1048 and 1067 Å can be compared to the intensity of the Lyman-α line in a first approximation by using a linear interpolation between the calibration points. The resonance lines of Kr I lie close enough to the Lyman-α line that a direct comparison is possible. At 10 keV the intensities of the Ar I and Kr I resonance lines are 0.4 and 0.15 of the Lyman-α line, so that the cross sections for excitation of these states are 0.12 and 0.05 of the total cross section for collision-induced dissociation.[9,10] Most of the excitation of the neutral species is revealed by the intensity of the resonance lines, and it would appear, particularly for krypton, that simultaneous direct excitation is not probable enough to account for the observed deviations from the theoretical results. Ions of the target gases are excited strongly, however, and it might be argued that these excitations occur simultaneously with excitation of the projectile. But, the spectra of Figs. 3 and 4 are similar to those produced by collisions of He^+ with the rare gases in that the ionic lines dominate. Such excitations are understood to occur by charge exchange through the potential curve-crossing mechanism. There is no way of actually determining if such a mechanism is operating in these collisions of H_2^+, but it does appear probable that the Ar II lines are produced by charge exchange through an excited state. It is of interest to note that Gibson *et al.* also found structures in their total cross sections which do not appear in the calculated results. Such structures may well be indicative of surface crossings being important in some of the inelastic processes considered here.

V. POLARIZATION MEASUREMENTS

The observed polarizations of the Balmer-α and -β lines are shown in Figs. 4 and 5 where the error bars represent one standard deviation in the statistical uncertainties. These polarizations are very small for the Balmer-α line over the entire energy range, (1–2)% for a helium target and essentially zero for the argon and krypton targets. They are much larger for the Balmer-β line, although the magnitudes depend markedly on the target gas, and they vary significantly as a function of collision energy. It is obvious that even at energies of a few hundred electron volts that the probability of excitation must be highly dependent upon the orientation of the molecular axis with respect to the beam.

The relationships between the spectral polarizations and the angular distributions of the dissociation products have been computed in Ref. 3 for excitation of individual angular momentum substates, $|Lm\rangle$. The computations assume that the quantum number Λ of the excited molecule is conserved when the particles separate so that σ states go to levels with $m=0$ in the atom; π states go to levels with $m=\pm 1$; etc. After accounting for electronic and nuclear spins the expressions shown in Table I are obtained for the various transitions which comprise the Balmer lines, ${}^2S\rightarrow{}^2P$, ${}^2P\rightarrow{}^2S$, and ${}^2D\rightarrow{}^2P$. The quantities $\beta_{L,m}$ are the second-order coefficients of the angular distribution of the dissociation products expanded in Legendre polynomials,

$$\sigma(\theta)=1+\alpha_{L,m}P_1(\cos\theta)+\beta_{L,m}P_2(\cos\theta)+\cdots, \quad (2)$$

where L and m are the orbital and magnetic quantum number of the upper state of the transition. The polarization results can provide a measurement only of the second-order term in Eq. (2), but in many studies of dissociation the zeroth-

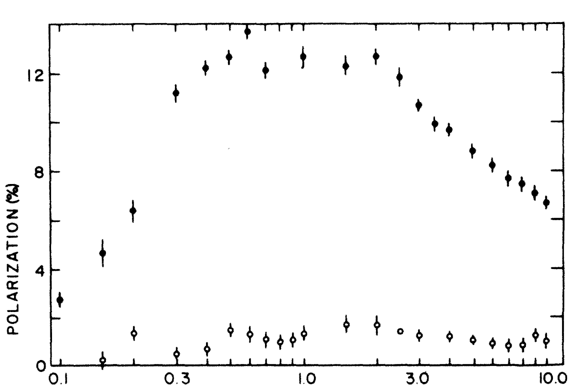

FIG. 4. Polarization measurements as a function of energy for H_2^+ + He collisions; open circles, Balmer-α; solid circles, Balmer-β. The error bars represent one standard deviation in the statistical uncertainty.

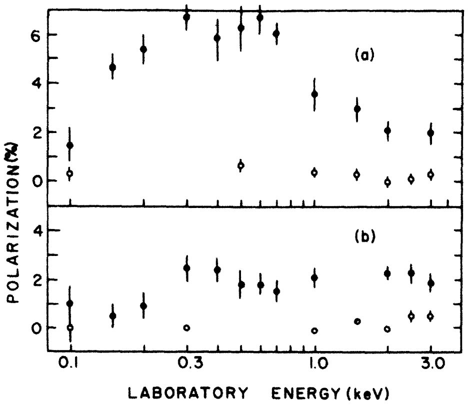

FIG. 5. Polarization measurements as a function of energy for (a) H_2^+ + Ar collisions and (b) H_2^+ + Kr collisions; open circles, Balmer-α; solid circles, Balmer-β. The error bars represent one standard deviation in the statistical uncertainties.

and second-order terms appear to dominate the angular distribution. If such is indeed the case, positive values of $\beta_{L,m}$ imply a distribution which is peaked parallel to the beam and negative values indicate that the maximum is perpendicular to the beam. There is no polarization produced by $^2S \rightarrow {}^2P$ transitions. It should be noted that even for large anisotropies of $\sigma(\theta)$ the polarization of atomic fluorescence is expected to be small if the $\beta_{L,m}$'s are all about the same and if the magnetic sublevels are nearly equally populated.

A Hanle-effect[13] experiment (depolarization in a magnetic field) was performed on the Balmer-β line at 1500-eV collision energy with helium to determine whether the polarization was coming mainly from the $^2D \rightarrow {}^2P$ component or the $^2P \rightarrow {}^2S$ component. The polarization as a function of magnetic field is shown in Fig. 6. The polarization should be zero at the high fields but appears to have a residual value of about 2.2%. It has been noted in Sec. II that the systematic polarization of the optical system was measured in a bench test to be less than 0.5%, so it appeared at first that the residual must have come about from internal reflections within the collision chamber. However, substitution of argon for the helium produced the expected result that the polarization was indeed zero in a 20-G field; the apparent residual with the helium target is not understood.

If the base line of the depolarization curve is taken to be 2.2% then its half-width is 1.8 ±0.15 G. For $^2D \rightarrow {}^2P$ transitions the computed widths lie between 1.37 and 1.58 G but for $^2P \rightarrow {}^2S$ lines the widths should be 3.9 G. Therefore, the measured polarizations of the Balmer-β line mainly reflect the populations of the $4\,^2D$ substates. This is not surprising since only 12% of the transition probability of the $4\,^2P$ terms branch to the $2\,^2S$ terms but 74% of the transitions from the $4\,^2D$ terms branch to the $2\,^2P$ terms.

VI. DISCUSSION

The results presented in Sec. III demonstrate that atomic fluorescence lines which arise from dissociative reactions may exhibit polarization over a wide range of collision energies. Arguments have sometimes been made that the isotropic orientation of internuclear axes of the molecules would preclude the existence of any polarization. The experimental evidence shows that this assumption is not generally valid and, in view of the theoretical work on the angular dependences of the excitation cross sections, should not be expected. Also the differences in the results for the Balmer-α and Balmer-β lines show that the lack of polarization in any one line cannot be used to infer that the other lines are unpolarized.

TABLE I. Expressions for the polarization expected in Balmer transitions if a single molecular state is excited.

Transition	Molecular state	Polarization
$^2S \rightarrow {}^2P$	σ_g , σ_u	0
$^2P \rightarrow {}^2S$	σ_g , σ_u	$3\beta_{1,0}/(40+\beta_{1,0})$
	π_g , π_u	$-3\beta_{1,1}/(40-\beta_{1,1})$
$^2D \rightarrow {}^2P$	σ_g , σ_u	$105\beta_{2,0}/(1600+35\beta_{2,1})$
	π_g , π_u	$138\beta_{2,1}/(3200+46\beta_{2,1})$
	δ_g , δ_u	$-243\beta_{2,2}/(3200-81\beta_{2,2})$

A theoretical calculation of the polarization of a given Balmer line would require computations of the excitation cross sections and angular distributions for all the molecular states of H_2^+ which are correlated to a given level in the separated hydrogen atom. Such computations have not been performed so a detailed comparison of the experimental results to a theoretical prediction is not possible; however, some general conclusions of the present work can be drawn from a consideration of the calculations which are currently available.

In relating the polarization measurements to theoretical calculations the most attention will be concentrated on the results for which helium was employed as the target gas. The fact that collision-induced dissociation seems to dominate the excitation of the hydrogen lines in reactions of H_2^+ with helium means that it is possible to make comparisons without considering complications owing to charge exchange into highly excited states of H_2. Also, the Born approximation is more likely to be valid at higher energies and, as discussed in Sec. II, polarization measurements using argon

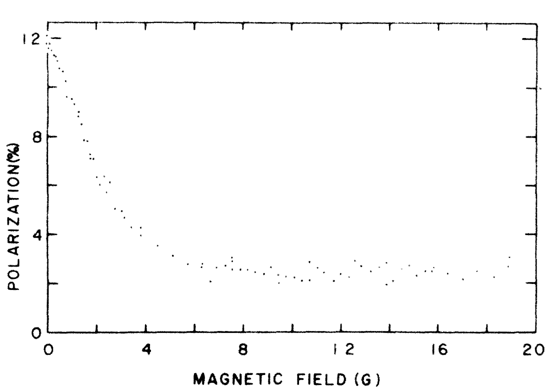

FIG. 6. Depolarization curve for the Balmer-β line produced by collisions of $H_2^+ + He$ at 1500 eV. Statistical uncertainties in the polarizations at each point are less than 0.5%.

and krypton targets were not pursued above 3 keV.

In Table I, it is seen that positive polarizations are expected for $^2D \rightarrow {^2P}$ transitions if β is positive and the excitation proceeds through σ and π states, or if β is negative and the excitation takes place through δ states. The sign of β depends upon the angular distribution of the dissociation products, and comparison between experiment and theory is accomplished by considering the calculated distribution for molecular states of various symmetries. Although these distributions have not been computed for states of H_2^+ which are correlated to the $n = 3$ and 4 levels of hydrogen the qualitative behavior for all molecular states of a given symmetry (other than $2p\sigma_u$) should be similar, particularly in view of the orientation-dependent selection rules which arise only from considerations of the symmetries and are independent of the details of the interaction.[6] These selection rules indicate that if the Born approximation is valid that excitation of H_2^+ to π_u and δ_g states takes place perferentially for perpendicular alignment of the internuclear axis and the direction of the momentum transfer and to σ_u states for parallel alignment. There is no preferred orientation for excitation to σ_g states, and π_g and δ_u are forbidden for either alignment. The momentum transfer axis tends, on the average, to be aligned in the beam direction at energies of 10 keV but not so strongly aligned in this direction at 3 keV.[12] When the Born approximation is employed at these two energies the results show agreement with the selection rules for the $4f\sigma_u$ and $2p\pi_u$ states. In addition, the results for the $2s\sigma_g$ state shows that excitation is most probable for a perpendicular orientation of the beam and the internuclear axis at 10 keV, but that it is strongly dependent upon the internuclear separation at an energy of 3 keV, being most probable for perpendicular alignment at large separations and most likely to occur for parallel alignment at small separations.

Considering the present results for the Balmer-β lines, first at 10 keV, the implications of the calculations and the fact that the measured polarization is positive indicate that the σ_u or the δ_g states must be excited in preference to the others because the σ_g and π_u states would give a negative contribution to the polarization. The implications are similar at lower energies (provided the Born approximation is valid) except that the negative contributions from the σ_g and π_u states should be smaller according to the calculated distributions, so the net polarizations are expected to be larger than at 10 keV. The experimental observations show that this is indeed the case.

The energy region over which the Born approximation may be valid is not known. It most likely is not an accurate description for the collision process over the range in which the polarization of the Balmer-β line is increasing and maintaining a maximum, 0.1–1.5 keV, so that the experimental results cannot be correlated to calculations for the angular distribution of emitted particles.

In an experiment quite pertinent to the present one Sauers *et al.* have measured the angular distribution of metastable hydrogen atoms produced by dissociative collisions of $H_2^+ + He$ from 4 to 10 keV.[14] They find this distribution to be very close to a $\cos^2\theta$ dependence, where θ is the angle between the beam direction and the internuclear axis. Only the $2s\sigma_g$ and $3p\sigma_u$ states dissociate into metastable hydrogen atoms so that in accordance with the preceeding discussion it would appear that the $3p\sigma_u$ state is preferentially populated, a result analogous to that inferred from the polarization measurements.[15]

The distribution varies significantly from $\cos^2\theta$ for other target gases (Ar, H_2, N_2) which they employed. It is interesting to note that the value of β which implies a pure $\cos^2\theta$ distribution [$\beta = 2$, all other coefficients being zero in Eq. (2)] leads to a polarization of 12.6% for $^2D \rightarrow {^2P}$ transitions in which only the σ states of the upper level are populated. This value is very close to the peak value observed over the broad plateau (0.4–1.5 keV) in the Balmer-β data and may indicate that only the σ states are populated appreciably in this energy range.

The differences in polarizations of the Balmer-α and -β lines is quite striking since both arise from the same type of transitions. If the angular dependence of the differential cross sections are indeed similar for states of the same symmetry, then large differences in the polarization must be caused by a strong dependence of the relative excitation cross sections for substates, $|Lm\rangle$, upon the total quantum number n. In a two-step process these variations may occur from differences in the primary excitation cross sections for H_2^+, but they may also occur if the excitation can be transferred from one state to another as a result of potential curve crossings during the subsequent separation of the proton and the hydrogen atom. Any *a priori* calculations of the relative populations of the $n = 2$ sublevels would have to take this latter process into account.

The inclusion of charge exchange to explain both the excitation and polarization of spectral lines is undoubtedly important for argon and krypton targets. Even though no spectral lines of H_2 have been observed to provide direct confirmation of the importance of charge transfer into excited states it does not follow that dissociative charge exchange is unimportant in the excitation of the hydrogen lines. As noted previously, the experiments of Van Zyl *et al.* have indicated this process to be comparable in magnitude to the collision-induced dissociation. It is possible that the fraction of the intensity of the Balmer-β line, which is produced by charge exchange, increases with the atomic number of the target gas and that this fraction is unpolarized. If so, the observed polarizations (Fig. 5) may be due entirely to collision-induced dissociation but are smaller in magnitude because of the additional mechanism for excitation of the line.

ACKNOWLEDGMENTS

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[15] Ref. 14 indicates that the $\cos^2\theta$ distribution for H(2s) agrees with calculations for dissociation from the $2s\sigma_g$ state of H_2^+ (Ref. 7). However, the $2s\sigma_g$ state most probably dissociates perpendicular to the beam, and excitation to the $3p\sigma_u$ state would seem more likely to dominate the metastable production.