Lyman-α Production and Polarization in He^+ Collisions with H and H_2*

ROBIN A. YOUNG,† R. F. STEBBINGS,‡ AND J. WILLIAM MCGOWAN
Gulf General Atomic Incorporated, John Jay Hopkins Laboratory for Pure and Applied Science, San Diego, California 92112
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The total cross section for Lyman-α production from He^+-H(1s) collisions has been measured over the energy range from 0.5 to 30 keV. At the lower ion energies the cross section remains large. This probably reflects rotational interaction between certain states of the collision complex HeH^+. A similar result had been reported by Stebbings *et al.* for the H^+-H(1s) collision system. Also presented are measurements of the total cross section for Lyman-α production from He^+-H_2 collisions. Some polarization values have been obtained for emission of Lyman-α from collisions of He^+, Ne^+, and Ar^+ with atomic hydrogen.

I. INTRODUCTION

WITHIN the last few years, both experimental measurements[1] and theoretical calculations[2,3] of the Lyman-α production in H^+-H(1s) collisions have been reported. Although theory and experiment do not as yet agree in detail, the results appear to demonstrate the influence of coupling between states of the HH^+ quasimolecule.[4]

In this paper we report measurements on the reaction

$$\begin{aligned} He^+(1s)+H(1s) &\rightarrow \\ & He^+(1s)+H(2p) \\ & \searrow \\ & \qquad H(1s)+\text{Lyman-}\alpha, \end{aligned} \quad (1)$$

in which coupling between states of the HeH^+ quasimolecule[5] might also be important at low ion energies. These reactions are of particular significance because the states of all reactants and measured products are known.

As an integral part of this work, it was necessary to measure the total cross section for the production of Lyman-α in He^+-H_2 collisions over the same energy range since the signal from this reaction is unavoidably mixed with the signal from the reaction with atomic hydrogen. Cross sections for the above reactions are normalized by direct signal comparison with the $e^-+H \rightarrow L_\alpha$ and $e^-+H_2 \rightarrow$ cuv (countable ultraviolet) cross sections, which have been reported previously.[6]

The polarization of the emitted Lyman-α radiation has been determined over limited energy ranges, for collisions between H atoms and He^+, Ne^+, and Ar^+, and these measurements are discussed in the light of available theory.

II. EXPERIMENTAL TECHNIQUE

The basic apparatus for the production of the ion and H-atom beams is similar to that described in detail previously,[1] and the pertinent features are shown in Figs. 1 and 2.

Ground-state hydrogen atoms issuing from a tungsten furnace, heated to about 2700°K in the first of three

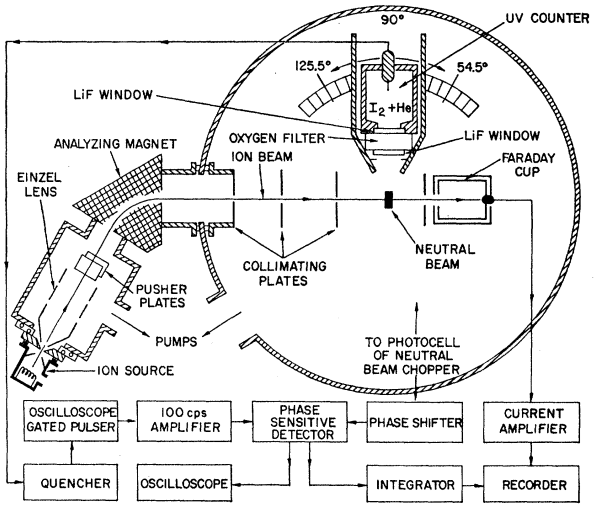

FIG. 1. Diagram of the apparatus sectioned through the ion beam axis with the "magic" angles marked on the scale for the rotatable ultraviolet counter.

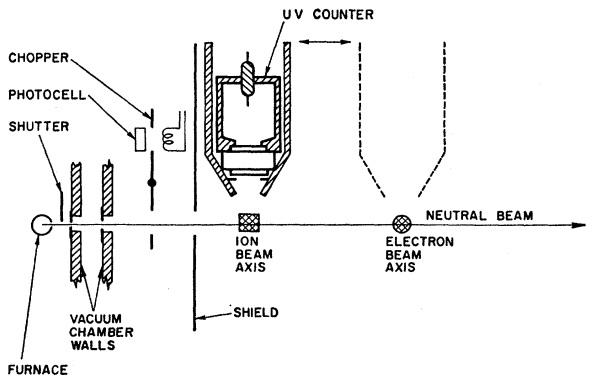

FIG. 2. Section of the apparatus through the H-atom beam axis.

* Research supported by NASA under Contract No. NAS 5-9321.
† Present address: Douglas Advanced Research Laboratories, Huntington Beach, Calif. 92646.
‡ Present address: University College, London, England.
[1] R. F. Stebbings, R. A. Young, C. L. Oxley, and H. Ehrhardt, Phys. Rev. 138, A1312 (1965).
[2] D. R. Bates and D. A. Williams, Proc. Phys. Soc. (London) 83, 425 (1964).
[3] L. Wilets and D. F. Gallaher, Phys. Rev. 147, 146 (1966).
[4] W. Lichten, Phys. Rev. 131, 229 (1963).
[5] H. H. Michels, J. Chem. Phys. 44, 3834 (1966).
[6] W. L. Fite and R. T. Brackmann, Phys. Rev. 112, 1151 (1958).

separately pumped vacuum chambers, are collimated as they pass through the intermediate chamber, which acts as a vacuum buffer. Upon entering the third chamber, in which the experiment is performed, the atom beam is modulated at 100 cps by a rotating toothed chopper wheel.

Ions extracted from a duoplasmatron source are focused with an Einzel lens, and then enter an analyzing magnetic field which selects the proper ion component for transmission through a series of collimating apertures before passage through the umbra of the neutral beam and collection in a Faraday cup. The ion beam is collected in a shielded Faraday cup which is biased at +23 to +46 V with respect to the grounded guard shield placed between it and the interaction region.

The region of interaction of the H-atom beam with the charged beam is viewed by an ultraviolet photon counter[7] which can be rotated about the neutral beam axis in a plane containing the ion beam. The output of the counter is fed through a quenching circuit to a pulse shaper and then through a 100-cps amplifier and phase-sensitive detector.

The counter itself is sensitive to radiation within the wavelength range 1080 to 1260 Å. However, in transit to the counter, the radiation passes through a cell containing dry molecular oxygen which is opaque in this wavelength region except at seven extremely narrow transmission windows,[8,9] one of which corresponds precisely with Lyman-α radiation (1215.7 Å).[10]

In the interaction region, excitation to the metastable $2s$ state of atomic hydrogen occurs. However, the unperturbed lifetimes of these atoms is greater than a few milliseconds[11]; thus, because of their translational velocity, they decay outside the counter field of view in the absence of perturbations. In the presence of a weak electric field F, the lifetime[11] is $\tau=3.6\times10^{-4}F^{-2}$ sec, where F is in V cm^{-1}. To prevent field quenching of $2s$ atoms with consequent emission of Lyman-α radiation, considerable care was taken to minimize the residual electric field at the interaction region. Gas quenching[11] gives an average H($2s$) lifetime of 50 to 100 msec in this experiment and is therefore negligible.

Surfaces can give off large amounts of countable ultraviolet (cuv) when struck by charged particles[6]; therefore, care is taken to prevent the counter from seeing any such surfaces. The surfaces within the field of view of the counter are cadmium-plated steel and aged aluminum which have Lyman-α reflectivities of 0.5% and ~20%, respectively.[12] The nearest surface the counter sees is 1 ft away; consequently, effects due to multiple reflection of Lyman-α or cuv are negligible. In addition, the counter collimation system acts as an antireflection baffle.

As a general rule, when a gas is excited by a particle beam, the emitted radiation has a nonuniform angular distribution with an associated fractional polarization P. For dipole radiation, the angular distribution of the radiation intensity is given by[13]

$$I(\theta)=\frac{3I_0(1-P\cos^2\theta)}{4\pi(3-P)}, \tag{2}$$

where $I(\theta)$ is the intensity per unit solid angle emitted in the direction θ with respect to the charged particle beam, and I_0 is the total intensity. For observation at the "magic angles" (54.5° or 125.5°), $I(\theta)$ is independent of the polarization and is given by

$$I(\theta)=I_0/4\pi. \tag{3}$$

Therefore, in the present investigation the magnetic angle has been used exclusively when measuring Lyman-α cross sections. The Lyman-α intensity was measured as a function of energy yielding relative cross section data which were then normalized with the aid of measurements of Lyman-α production in electron–hydrogen-atom collisions. For this purpose, the photon counter was moved to view the region of interaction of the same neutral H-atom beam with an electron beam as shown in Fig. 2. Measurements at the two counter positions, with allowance for the neutral beam divergence, enabled the ratio of the cross sections for Lyman-α production in e^--H and He^+-H collisions to be determined. Knowing the absolute e^--H cross section for Lyman-α production (taken[6] to be $0.37\pi a_0^2$ at 300 eV), the absolute He^+-H cross section for Lyman-α production was determined at 10 keV (the calibration point). The total cross sections at other He^+ energies were then determined relative to this value.

The apparatus for the polarization experiments was the same as for the cross section measurements. Equation (2) gives the angular distribution of the radiation for a given polarization P. Therefore, at each ion energy, the absolute value of P was determinable from measurements of the relative intensity at two angles. In this experiment, 90° and 50° were used since these were the two angles where the maximum difference in signal intensity was obtainable. This procedure was repeated at several energies for each ion species.

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

[8] K. Watanabe, Advan. Geophys. **5**, 153 (1958).

[9] These seven wavelength regions contain all countable ultraviolet (cuv) observable in these experiments.

[10] There are several transitions between the fourth and second level of He^+ that radiate at about the same wavelength as Lyman-α; for instance, $He^+(4s)\rightarrow He^+(2p)$ radiates at 1215.2 and 1215.1 Å. These wavelengths are absorbed only 36% more and 80% more, respectively, than Lyman-α by the oxygen filter. However, Dunn *et al.* have found that no measurable amount of signal was received when He^+ was incident on He indicating that there are no helium ion or atomic states that radiate enough in the O_2 windows to provide interfering signals for the present experiment.

[11] H. A. Bethe and E. E. Salpeter [*Quantum Mechanics of One- and Two-Electron Atoms* (Academic Press Inc., New York, 1957), p. 287] have theoretically demonstrated that the two-photon-decay natural lifetime of the H($2s$) atom is 1/7 sec.

[12] L. R. Koller, in *Ultraviolet Radiation* (John Wiley & Sons, Inc., New York, 1952), p. 209.

[13] L. C. Percival and M. J. Seaton, Phil. Trans. Roy. Soc. London **A251**, 113 (1958).

III. DATA ANALYSIS

In the present experiments it was necessary to work with hydrogen beams which were incompletely dissociated; consequently a significant fraction of the Lyman-α radiation observed was due to the molecular hydrogen residual in the beam.

Under ion impact, the Lyman-α signal per unit ion current may be expressed as

$$S=(K/r)[\sqrt{2}D\sigma_1+\sigma_2(1-D)], \tag{4}$$

where σ_1 and σ_2 are the cross sections for L_α production from ion bombardment of H and H_2, respectively. D is the fraction of the neutral beam that is dissociated, r is the distance between the H source slit and the ion beam, and K is a proportionality constant for ion beam strength, counter geometry, etc. An analogous expression is obtained for the case of electron impact:

$$S_e=(K/r_e)[\sqrt{2}D\sigma_{1e}+\sigma_{2e}(1-D)]. \tag{5}$$

The appearance of r rather than r^2 in the denominator of Eqs. (4) and (5) is due to the fact that although the number density in the neutral beam falls off as $1/r^2$, the length of the collision path increases proportionately with r.

Combining these expressions to eliminate K gives

$$\sigma_{1R}=\frac{S_R r}{S_e r_e}\left[\sigma_{1e}+\sigma_{2e}\left(\frac{1-D}{\sqrt{2}-D}\right)\right]-\sigma_{2R}\left(\frac{1-D}{\sqrt{2}D}\right), \tag{6}$$

where σ_{1R}, σ_{2R}, and S_R refer to σ_1, σ_2, and S at the reference energy R. σ_{1e} and σ_{2e} are the cross sections for $e^-+H\rightarrow L_\alpha$ and $e^-+H_2\rightarrow$ cuv, respectively. Knowing D, σ_{1R} may be found as a function of σ_{1e}, σ_{2e}, and σ_{2R}.

At any other energy X, the cross section can then be written

$$\sigma_{1X}=\frac{S_X}{S_R}\left[\sigma_{1R}+\sigma_{2R}\left(\frac{1-D}{\sqrt{2}D}\right)\right]-\sigma_{2X}\left(\frac{1-D}{\sqrt{2}D}\right). \tag{7}$$

In this study it was convenient to make use of the previously determined values of σ_{1e} and σ_{2e}[6] while σ_{2R} was obtained with reference to σ_{2e}. A minor correction was necessary because in the determination of σ_{2e} the length of the oxygen filter was 2 cm, while here a 1-cm filter was used. The correction arises from the fact that different spectral distributions of the detected radiation result from e-H_2 and He^+-H_2 collisions.[14] This correction has been discussed by Dunn,[15,16] who showed that a correction factor is given by

$$\frac{N_1}{N_2}\frac{N_{20}}{N_{10}}\exp[-K_{L_\alpha}(x_2-x_1)], \tag{8}$$

where N_1/N_{10} is the ratio of counts received when a 1-cm filter is filled with 1 atm of oxygen to counts received when the filter is evacuated. N_2/N_{20} is the same except for a 2-cm filter. K_{L_α} is the absorption coefficient of oxygen for Lyman-α at 1-atm pressure. x_2-x_1 represents the difference in path length between filters, which in this case equals 1 cm. Dunn determined that this correction factor amounts to 0.86.

Coupling this with Eq. (6), one obtains

$$\sigma_{1R}=\frac{S_R r}{S_e r_e}\left[\sigma_{1e}+0.86\sigma_{2e}\left(\frac{1-D}{\sqrt{2}D}\right)\right]-\sigma_{2R}\left(\frac{1-D}{\sqrt{2}D}\right). \tag{9}$$

Two methods were used to obtain the total excitation cross section σ_1. In the first method above, the energy profile of the $He^++H\rightarrow L_\alpha$ cross section was obtained and then normalized at the reference energy 10 keV. In the second method, S was measured both when the furnace was at a high temperature T_h and at room temperature T_c. For the latter method,

$$\sigma_1=\frac{\sigma_2}{\sqrt{2}D}\left[\frac{S_h}{S_c}\left(\frac{T_h}{T_c}\right)^{1/2}+D-1\right], \tag{10}$$

where

$$\sigma_2=\frac{S}{S_e}\frac{r}{r_e}\sigma_{2e}(0.86). \tag{11}$$

Each method has specific advantages. Together they afford a good check on the validity of the measurements.

A. Incomplete Dissociation

The fractional dissociation of the neutral hydrogen beam effusing from the furnace was determined as a function of temperature and pressure using a mass spectrometer. The hydrogen pressure and the furnace temperature were also recorded with all data. With this information the appropriate fractional dissociation was obtained and inserted into the calculations. The contribution to the Lyman-α production from undissociated H_2 in the beam was small over most of the energy range, where the cross sections σ_1 and σ_2 were comparable, but below 2 keV where σ_2 becomes considerably larger than σ_1, the presence of small amounts of H_2 becomes quite serious. In fact, below 0.5 keV the signal from H was completely buried in the signal from H_2, thus setting the experimental lower-energy limit. In the He^+-H collisions incomplete dissociation represents the largest source of error.

B. Modulated Background

Another source of interfering signal from H_2 comes from the collisionless flow of background H_2 through the

[14] The detected radiation from e^--H_2 collisions consists partly of wavelengths other than Lyman-α and with evidently different absorption coefficients; thus the percentage of Lyman-α in the detected cuv will vary with filter length. The percentage of the total signal penetrating the filter therefore varies with both wavelength composition and filter length.

[15] G. H. Dunn, thesis, University of Washington, Seattle, Washington, 1962 (unpublished).

[16] H. Dunn, R. Geballe, and D. Pretzer, Phys. Rev. **128**, 2200 (1962).

chopper wheel and on to the interaction region. This modulated gas flow was such that over most of the energy range it contributes about 5–10% of the observed Lyman-α radiation, but in an analogous manner to the case of incomplete dissociation, this effect became large below 2 keV. A correction is made for this effect so that the error in the data is much less.

C. Lost Counts

The signal was corrected for counts lost due to the dead time of the counter-quench system; this correction was small since high counting rates were not used.

D. Other Corrections

There are a few other small corrections applied to the data such as the variation of the counter sensitivity with the point of origin of the radiation, escape of secondary electrons, variation of the current, and linear and nonlinear drifts.

IV. RESULTS AND DISCUSSION

A. Total Lyman-α Production in (He^+-H) Collisions

In Fig. 3, the cross section for $He^+ + H(1s) \rightarrow He^+ + H(2p)$ is plotted as a function of the energy in both the laboratory frame and the center-of-mass frame. A possible interpretation other than the drawn curve would be that there are three minor peaks instead of a broad hump below 10 keV, but the data are insufficient for this conclusion. The error bars represent the probable error in the relative cross section. No error is shown at 10 keV because this is the reference energy. (The estimated probable error in the calibration procedure is 20%. In this case, the e-H cross section is quite accurate since the Born approximation is good at 300 eV.) Above 1 keV ion energy, the total probable error is 25–30%.

The cross section for He^+ excitation of $H(2p)$ is again plotted in Fig. 4 along with that for H^+ impact excitation. As in the case of H^+ impact excitation, the cross section for He^+ excitation remains surprisingly large at ion energies below several keV.

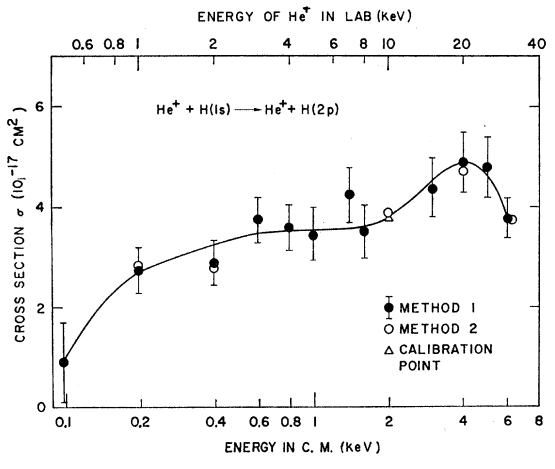

FIG. 3. Cross section for Lyman-α production in He^+-H collisions.

In the case of $H(2p)$ excitation under proton impact, it was pointed out by Bates and Williams[2] that rotational coupling of two or more states of the HH^+ quasimolecule[17] may be important under circumstances of tangential approach. A parallel case occurs with He^+ excitation of $H(2p)$. The coupling most likely to produce the unexpectedly large cross section in the lower energy region, is rotational coupling between the $A\ ^1\Sigma$ and $C\ ^1\Pi$ states of the HeH^+ quasimolecule. In Fig. 5 the pertinent portion of the correlation diagram in the $(He\text{-}H^+)\text{-}Li^+$ system is shown.[5,18]

Bates and Griffing[19] calculated cross sections for excitation to higher states of the H atom upon proton impact, based on the Born approximation. Assuming that

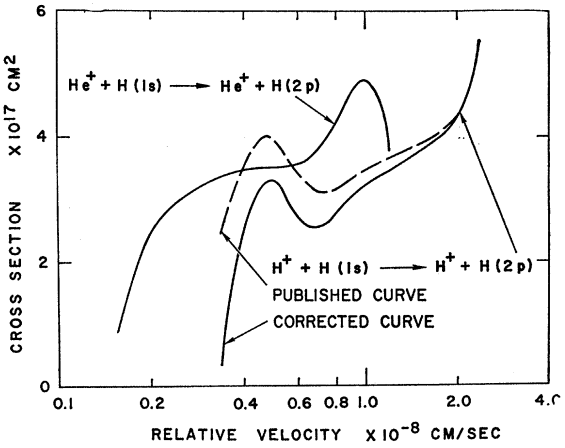

FIG. 4. A comparison of He^+-H and H^+-H Lyman-α production cross sections. The difference between the two H^+-H curves comes from the use of different O_2 absorption coefficient data. The previously published curve (Ref. 1) used data of Watanabe (Ref. 8) and the assumption that the absorption coefficients are uniformly proportional to the pressure within a few angstroms below Lyman-α. Recently, D. Gailey, University of Washington (private communication), measured the pressure variation over the same wavelength interval. He found that the above assumption was incorrect. The corrected excitation curve uses his pressure dependence. Metzger and Cook, Ogawa, and Watanabe (private communication with Metzger) have also shown that the deviation of the absorption coefficient with pressure is in the same sense as that found by Gailey. The curve for charge transfer excitation to $H(2p)$ has a similar correction which will be discussed in a separate publication.

a similar cascade proportion holds for He^+ impact above 5 keV, and using the selection rules, the cascade contribution to the cross section is 10% at 10 keV and 16% at 30 keV. The contribution is $<4\%$ at 1 keV if the additional assumption is made that the low-energy increase in the cross section over the Born approximation

[17] L. Wilets and D. F. Gallaher (Ref. 3) have used hydrogenic wave functions, and more recently they have used the Sturmian representation in their description of the coupling of states in the (H^+-H) scattering problem. Both calculations give cross sections which exhibit structures similar to that found by Stebbings *et al.*; however, neither has been able to generate the principal features and at the same time the magnitude of the cross section from the (H^+-H) measurements.

[18] Discussions with T. A. Greene are greatly appreciated.

[19] D. R. Bates and G. Griffing, Proc. Phys. Soc. (London) **A66**, 961 (1953).

is due to direct excitation to the H(2p) state, and making also the substitutive assumption that the cross section for excitation to higher states is no greater for He^+ impact than for H^+ impact. {*Note added in manuscript.* Through energy-level crossing or near crossing higher states may possibly be important [W. Lichen (private communication)].}

B. Lyman-α from (He^+-H_2) Collisions

The results[20] for $He^+ + H_2 \rightarrow L_\alpha$ are shown in Fig. 6 along with the 90° data of Dunn *et al.*[16] and Van Zyl *et al.*[21] Again the error bars represent the probable error in the relative cross section. The probable error in the calibration process is about 15%, while the error in Fite's data is about 30%.[22] The total probable error then is 35–40%.

In comparing the experimental results shown in Fig. 6, it is worthwhile to note the most significant possible causes for these differences. The following three differences exist:

(1) Polarization of the emitted Lyman-α does not affect the present results because measurements are made at the "magic angle," whereas Dunn *et al.*[16] and Van Zyl *et al.*[21] measured the radiation perpendicular to the charged beam, thus being affected by whatever polarization was present. If both sets of data could be taken at their face value, it would follow directly that at low ion energies the polarization would be markedly negative. However, there is some reason to think that the University of Washington data may be in error, especially at low energies.

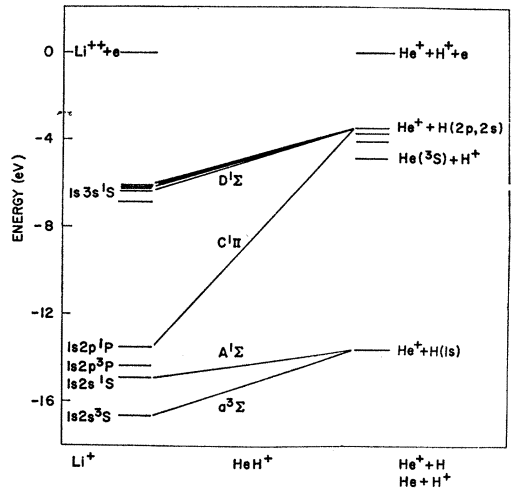

FIG. 5. Correlation diagram showing states of the (HeH^+) quasimolecule pertinent to our discussion.

(2) The ion beam shape was far more critical in Dunn's experimental geometry because of the tremendous sensitivity of the counter to the position of the radiation origin[7] combined with his much greater solid angle subtended at the counter by the area of radiation. Dunn tested for this,[15] but only at the higher energies of his data. Even so, a deviation can be seen in the baffled counter data going toward lower energies, which indicates just what one would expect; namely, that the ion beam is more divergent at lower energies. By extrapolating his, baffled counter data, relative to the unbaffled counter data, down to 0.5 keV, a cross section 39% higher than the unbaffled data line can be seen in Fig. 15, and 47% higher in Fig. 20 of Dunn's thesis. These extrapolated percentages are quite rough due to the scatter in the data, but if this correction, of

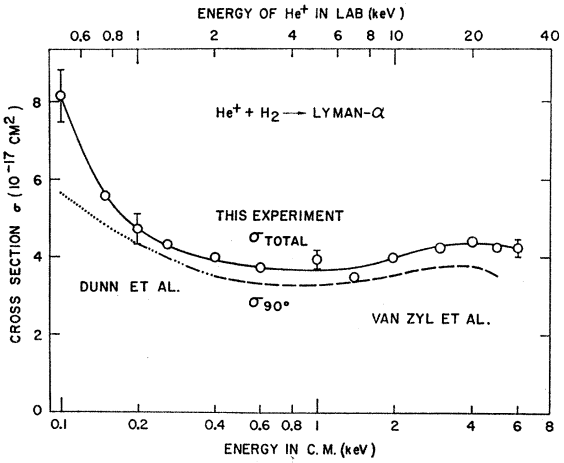

FIG. 6. Cross section for Lyman-α production in He^+-H_2 collisions.

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[20] Dunn *et al.* (Ref. 16) point out in their paper that, although there are a number of detectable lines from allowed transitions in H_2 repulsive states and H_2^+ bound states, the majority of transitions that would be seen by the detector with the filter evacuated would not be seen by the detector with oxygen in the filter. Their experiment on count rate change with evacuation of the filter shows the result that would be expected if it were assumed that the only radiation emitted in the 1080–1260 Å range were Lyman-α; thus, they concluded that the cuv is all L_α for He^+-H_2 collisions. However, some doubt can be shed on this conclusion by the following reasoning: Watanabe's (Ref. 8) Lyman-α absorption coefficient oxygen pressure dependence curve yields 0.7 cm^{-1} when extrapolated to 760 Torr. Consequently $\exp(-K_{L_\alpha}X)=0.5$ for a 1-cm path length and 0.25 for a 2-cm filter. In other words $N_1N_{20}/N_2N_{10}=2$ if all radiation is Lyman-α in the counter sensitivity range, assuming the correctness of Watanabe's curve and its extrapolation. Now, for electrons on H_2,

$$\frac{N_1}{N_2}\frac{N_{20}}{N_{10}}\exp[-K_{L_\alpha}(x_2-x_1)]=0.86,$$

as mentioned above, and $\exp[-K_{L_\alpha}(x_2-x_1)]=0.5$. Therefore, $N_1N_{20}/N_2N_{10}=1.7$. The fact that this number is measured to be less than 2 indicates that the absorption of detected spectral lines (resulting from e^-+H_2), other than L_α, is less than for L_α. This is a surprising result since the oxygen absorption cross section for radiation is greater than that for Lyman-α over nearly the entire wavelength range acceptable by the uv counter. If the pressure dependences of the absorption coefficients for most wavelengths near windows between 1080 and 1260 Å are considerably less than for Lyman-α, then the result would be less surprising. At any rate the e^-+H_2 experiment shows that there is a significant amount of radiation at wavelengths with less absorption in oxygen than Lyman-α. There could be a similar amount excited in $He^+ + H_2$ collisions plus a compensating amount from excitation of states that are more absorbed by oxygen than Lyman-α, thus yielding the experimental factor of 2. If this is true, then one would need to write $H^+ + He \rightarrow$ cuv instead of $H^+ + He \rightarrow L_\alpha$.

[21] B. Van Zyl, D. Jaecks, D. Pretzer, and R. Geballe, Phys. Rev. **158**, 29 (1967).

[22] W. L. Fite (private communication).

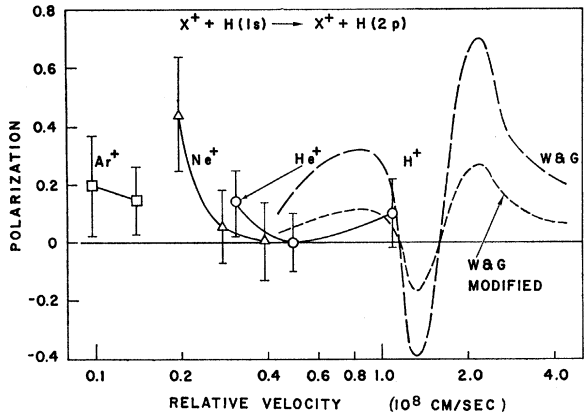

FIG. 7. Experimental values for the polarization of Lyman-α from He^+, Ne^+, and Ar^+ collisions with atomic hydrogen, together with calculations for the polarization of Lyman-α radiation from H^+-H collisions.

approximately 40%, where applied to Dunn's cross section data, then his data would be in excellent agreement with the data of the present experiment.

(3) No magnetic field (<1 G) existed in the interaction region for the experiments reported here, whereas in Dunn's work there was a field of 70 G during calibration runs. This magnetic field sensitizes the H(2s) such that any stray electric field would cause the H(2s)-$m_{-1/2}$ state to mix with the H(2p)-$m_{+1/2}$ state.[11] The close proximity of the gas chamber walls floating at the potential of the ion energy relative to the grounded counter and other elements could have presented complications with respect to H(2s) quenching. If the above factors did indeed quench some H(2s) atoms, the signal which was measured for electron collisions with H_2 would have been too large and therefore the cross section for $He^+ + H_2 \rightarrow L_\alpha$ would appear too small at all energies.

Provided the implications of (2) and (3) above are correct, the polarization derived from the two sets of data and Eq. (2) would be very small over the entire energy range. This might be expected for molecules since experimentally there is no way of preferentially fixing the molecular axis.

C. Polarization of Lyman-α from (X^+-H) Collisions

Since it is nearly impossible with the present state of art to measure the polarization of Lyman-α from the H^+-H collision system, an attempt was made to determine a mass dependence of the polarization for the sequence He^+, Ne^+, and Ar^+ impinging upon H(1s). If a mass dependence had been found, it might have been possible to extrapolate back to the proton case. These experiments were partially prompted by calculations of Fennema,[23] who, by using a Born approximation, observed a slight mass dependence and a structureless decrease with energy in polarization of Lyman-α from the H^+-H collision system. After these calculations were reported, those of Wilets and Gallaher[3,17] of both the polarization and cross section for excitation (see Fig. 7) have theoretically demonstrated that neither the cross section nor the polarization are monotonic functions of the primary ion energy. Instead, they both changed rapidly through our experimental interval. As a consequence, it is difficult to draw any significant conclusion regarding the mass dependence of Lyman-α polarization. Furthermore, signal and mass spectrometer magnetic field limitations did not allow sufficient overlap of the data in the relative velocity system to permit this comparison. However, the data do serve as an indication of the magnitude of the polarization, which for the most part is slightly positive and increasing with decreasing energy. In Fig. 7 the data are plotted as a function of relative velocity of the colliding particles. Shown for comparison are the calculated values of Wilets and Gallaher[3] (WG) for Lyman-α excitation in H^+-H collisions. The modified WG curve results from inserting the H(1s-2p) multiplet distribution which takes into account fine structure, hyperfine structure, and linewidth.[13]

[23] J. W. R. Fennema, in *Proceedings of the Third International Conference on the Physics of Electronic and Atomic Collisions, University College, London, 1963*, edited by M. R. C. McDowell (North-Holland Publishing Co., Amsterdam, 1964), p. 779.

V. CONCLUSIONS

As in the case of proton–H-atom collisions, our experimental data appear to demonstrate the influence of the rotation-inversion coupling between noncrossing states of the molecular ion formed during the collision. In the case of the HeH^+ quasimolecule, it is likely that the coupling occurs between the $A\ ^1\Sigma$ and the $C\ ^1\Pi$ states, which at the Li^+ united-atom limit are separated by $\sim$1.4 eV. Unfortunately, there are no calculations yet available with which to compare our results.

The present measurements of the total cross section for Lyman-α excitation in He^+-H_2 collisions are in close agreement with measurements of the 90° cross section, above 2 keV implying that the polarization of the emitted radiation is small at these energies.

Finally, the measurements of the polarization from He^+, Ne^+, and Ar^+ collisions with H atoms all give positive values of polarization. Although these measurements were taken to determine a mass dependence of the polarization, none can be drawn because of the possible complexity of the polarization functions and the limited extent of the data.

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