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Formation of H(2*p*) and H(2*s*) in Collisions of 1-25-keV Hydrogen Atoms with the Rare Gases*

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Cross sections have been measured for the emission of Lyman-α radiation in collisions of 1–25-keV hydrogen atoms with He, Ne, Ar, Kr, and Xe owing to excitation of the fast atom to the $2p$ and $2s$ states. The intensity of Lyman-α emitted spontaneously from collisionally excited H($2p$) was measured at 54.7 or 125.3° with respect to the H beam in an essentially field-free collision chamber with an oxygen-filtered photometer calibrated by reference to previous results for H^+ on Ar. After a small correction for cascade effects, the data yield the cross sections for population of the $2p$ state in these collisions. An electric field, oriented in the direction of the beam, was applied within the collision chamber to quench collisionally excited H($2s$), and the resulting increase in Lyman-α radiation has been used to derive the cross sections for formation of the $2s$ state. The viewing geometry and the electric field orientation were designed to minimize the effects of polarization of the light emitted from H($2p$) and H($2s$), and of changes in polarization when the quenching electric field was applied that might otherwise lead to large errors in the $2s$ cross section. The cross sections increase in magnitude and degree of structure with increasing atomic number of the target. Except for collisions with Ne, excitation of H($2p$) is always more probable than excitation of H($2s$). A relationship between the emission and stripping cross sections is presented, the relative probabilities of excitation and stripping being rather independent of target. Our results are compared with previous measurements made at higher energies and with theoretical estimates of these cross sections. The present extension of previous results to lower energy has revealed new structure in the energy dependence of the cross sections for the heavier targets. Existing theoretical treatments of these collisions fail to yield either the magnitude or energy dependence of the cross sections at energies below 5 keV.

I. INTRODUCTION

The experiments reported in this paper have been carried out as part of a laboratory measurements program with the goal of obtaining cross sections for excitation and ionization of atmospheric and other common gases by 1–25-keV protons and hydrogen atoms. This energy range is of particular interest in space physics because of the precipitation of significant fluxes of protons with these energies during breakup auroras and in quiet proton-induced auroral arcs.[1–3] At these rather low energies, a primary proton flux is readily converted by electron-capture collisions to an equilibrium mixture of H^+, H, and H^-, with H being the major constituent.[4] Hydrogen-atom collisions therefore will be of major importance in any process involving low-energy proton bombardment. While several groups of investigators have reported H^+ impact excitation cross sections in this energy range,[5,6] there have been very few studies made of excitation in H collision processes, particularly below 10 keV.[6] This is surprising not only in view of the importance of such processes in many applications but also because of the fundamental role the processes play in heavy-particle collision physics.

In previous publications we have reported cross sections for positive-ion and electron production in collisions of 1–25-keV H with a variety of target gases[7–9] and for emission of Lyman-α radiation from H atoms excited by collisions of 1–25-keV H with N_2 (Refs. 6 and 10) and O_2.[10] In this paper cross sections are reported for emission of Lyman-α from H($2p$) and H($2s$) produced in the processes

$$H + M \rightarrow H(2p) + M, \qquad (1)$$

$$H + M \rightarrow H(2s) + M, \qquad (2)$$

where M = He, Ne, Ar, Kr, or Xe and the range of impact energies is 1–25 keV. Processes (1) and (2) are only illustrative of many detailed processes involving all energetically accessible excited and ionized states of the target gas. The collisional excitation cross section that we obtain is the sum of the cross section for all of these individual processes that result in excitation of the H to the specified state. Brief accounts of this work have been given elsewhere.[11,12]

Excitation of Lyman-α radiation in electron-capture collisions of protons with rare gases has been studied by a number of groups.[13–23] Collisional excitation of fast hydrogen atoms has received much less attention. Dose and co-workers have measured[24,25] the cross section $\sigma(2p)$ for emission of Lyman-α radiation from $2p$ hydrogen atoms produced in collisions of 3–55-keV H with He, Ne, and Ar. Cross sections for emission of Lyman-α from $2s$ [$\sigma(2s)$] and $2p$ hydrogen atoms formed in bombardment of these targets plus Kr and Xe by 5–40-keV H atoms have been reported by Orbeli *et al.*[26] Our work was motivated by the need to extend the rare-gas data to lower energies and to resolve significant discrepancies between the previously reported results for $\sigma(2p)$. In the earlier work, it was assumed that the angular distribution of quench-induced Lyman-α radiation from H(2s) was isotropic. It has recently been shown[27–31] that substantial apparatus-dependent anisotropies in this radiation can exist and must be taken into account in the measurements of $\sigma(2s)$. Our measurements were carried out with an experimental configuration designed to minimize these effects.

The five rare gases together represent a series of targets having a wide range of polarizabilities and internal excitation energies. Especially in the case of the lighter atoms, they are simple enough in electronic structure to permit the development of meaningful models of collisional excitation and ionization processes by comparison of approximate theoretical calculations[32–35] for the H + rare-gas collision system with experimentally measured cross sections. The results reported here are compared to the available calculations and some systematic trends in the cross sections for the various targets are identified.

II. EXPERIMENTAL PROCEDURE

The apparatus used to prepare and detect H^+ and H beams and bring them into collision with thin gas targets has been described in detail elsewhere[7–9] and only the improvements will be discussed here.

In this work Lyman-α emitted during bombardment of the rare gases by H^+ and H was viewed at 54.7, 90, or 125.3° with respect to the beam direction by a photometer which is a modified version[10] of an instrument developed by Clark and Metzger[36] for satellite studies of auroral Lyman-α. It consists of an EMR 542J solar-blind photomultiplier with a MgF_2 end window preceded by an O_2 filter with MgF_2 windows and a retractable SrF_2 filter. The effective path length through the O_2 was 10 mm. Except at several narrow transmission windows[37,38] the oxygen effectively absorbs all light with wavelengths shorter than 175.0 nm and the photomultiplier is insensitive to longer-wavelength radiation. The MgF_2 windows provide a short-wavelength cutoff at approximately 112.0 nm when the O_2 filter is evacuated. With the SrF_2 filter retracted, the transmission function[36] for the photometer at the most transparent O_2 window, centered at 121.6 nm, has a full width at half-maximum transmission of approximately 0.3 nm and is nearly a maximum at 121.567 nm, the Lyman-α wavelength. For the gases studied in this work, the only significant spectral features located near the oxygen windows are a He II line at 121.52 nm (Ref. 39) and a Kr I resonance line at 116.49 nm (Ref. 40) near the O_2 window[37] at 116.7 nm; however, the Kr resonance line at 123.58 nm and the Xe resonance lines at 129.56 and 146.96 nm (Ref. 40) fall within the range of sensitivity of the photomultiplier. In order to rule out these lines as a source of contamination of the Lyman-α results, an auxiliary set of experiments was carried out in which the oxygen-pressure dependence of the photometer signal for 1–25-keV H atom impact on Kr and Xe was compared with that for Ne and Ar at all three viewing angles. These experiments established that with the filter evacuated, about 80–95% of the countable photons from Kr and Xe targets were Lyman-α, but that for Kr, the contamination could be eliminated effectively by the addition of 150-torr O_2. For Xe, however, the contamination could be successfully eliminated only at 90°. Apparently the reduced transmission of the O_2 filter for Doppler-shifted Lyman-α at 54.7 or 125.3° precluded successful elimination of the Xe contaminant radiation. The values of $\sigma(2p)$ for He, Ne, and Ar reported in this paper were measured at 54.7 and 125.3° with the O_2 filter evacuated. The $\sigma(2p)$ measurements for Kr were also carried out at 54.7 and 125.3°, but with enough O_2 added to eliminate the contamination. For Xe, $\sigma(2p)$ was measured at 90° with 700-torr O_2 in the filter.

With the SrF_2 filter inserted, only radiation with wavelengths $\gtrsim 128$ nm is transmitted and this signal is a measure of the long-wavelength contamination of the observed signal. This background signal in these measurements was found to be insignificant when sufficient O_2 was added to block the Kr and Xe resonance lines.

The region viewed by the photometer was defined by a pair of narrow rectangular collimating slits oriented with their long dimension perpendicular to the axis of the beam. The maximum acceptance angle of the photometer was 1.2° in the umbra and 1.8° in the penumbra of the viewing zone.

The output pulses from the photomultiplier were fed into a preamplifier, amplifier, and discriminator, and were counted with a scaler. Beam currents were measured with a digital charge integrator, and a differential capacitance manometer was used for target-pressure measurements. Matheson UHP He and Ar and research grade Ne, Kr, and Xe were used without further purification.

The photometer was calibrated by normalization of our Lyman-α emission cross sections for 1–25-keV H^+ impact on Ar, made at 54.7 and 125.3° with the oxygen filter evacuated and in the absence of a quenching electric field, to two previous absolute determinations of this cross section[13,15] carried out at 90°. Subsidiary calibration points at these angles and at 90° were measured with O_2 in the filter to make the $\sigma(2p)$ measurements for Kr and

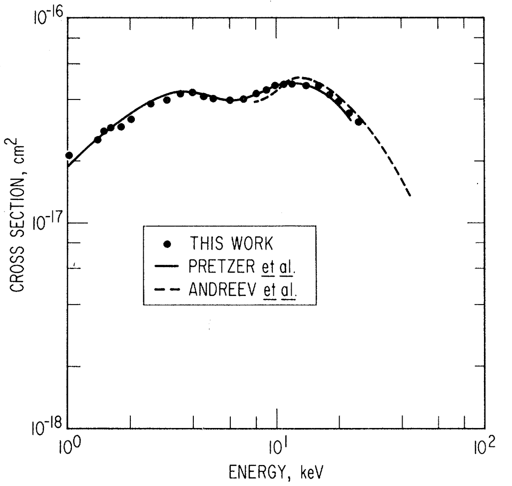

FIG. 1. Cross section for emission of Lyman-α radiation in collisions of 1–45-keV H^+ with argon in the absence of an applied electric field. The Lyman-α photometer used in this work was calibrated by normalizing the present data to the absolute measurements of Pretzer *et al.* and Andreev *et al.* as described in the text: See Pretzer *et al.*, Ref. 13; see Andreev *et al.*, Ref. 15.

Xe absolute. In order to compare data obtained at different viewing angles, one must take account of the angular distribution of the radiation, which is given by

$$I(\theta)=\frac{3I_T}{4\pi}\left(\frac{1-P\cos^2\theta}{3-P}\right), \qquad (3)$$

where θ is the viewing angle, I_T is the total intensity, and $P=(I_\parallel - I_\perp)/(I_\parallel + I_\perp)$ is the polarization. The components $I_\parallel$ and $I_\perp$ are the intensities of radiation measured at 90° with respect to the reference axis with polarization parallel or perpendicular to that axis. The intensity measured at 54.7 or 125.3° is related to the total intensity in a manner independent of polarization. The desired cross section σ deduced from intensity measurements at either of these two angles is related to cross sections $\sigma_{90°}$ obtained from measurements at 90° by

$$\sigma=(1-\tfrac{1}{3}P)\,\sigma_{90°}. \qquad (4)$$

Previous measurements[17,21] of the polarization of Lyman-α radiation from H^+ on Ar in our energy range indicate that this correction is $\lesssim 3\%$ at energies ≥ 8 keV, no more than 5% at energies as low as 3 keV, and hence can be ignored. Polarization effects have, therefore, no significant effect on the photometer calibration. Viewing at 54.7 or 125.3° then ensures that there are no polarization effects on the cross sections for the other gases relative to Ar.

The normalizing factor was determined graphically by the superposition of our relative data on the absolute measurements so that the best overlap was obtained in the 3–25-keV range as shown in Fig. 1. The excellent agreement of our energy dependence for this cross section with that of the earlier measurements, which were carried out with different Lyman-α detection techniques, is a useful verification of the reliability of our experimental procedure. Frequent checks of the normalization were made during the measurements of cross sections for H impact on the rare gases to account for the effects of small drifts in photometer sensitivity.

For studies of H(2s) formation in (2) an electric field was applied within the collision chamber in a direction parallel or antiparallel to that of the beam. The field was generated by application of a voltage of the same magnitude, but of different sign, to a pair of parallel plates oriented perpendicular to the beam direction. The plates were coated with cadmium to minimize reflection of Lyman-α and each had a 0.375-in.-diam hole to allow the beam to pass through without striking any surfaces. Lyman-α emitted from a portion of the beam track midway between the plates was viewed at 54.7 or 125.3° with respect to the beam and the electric field direction using the photometer with its oxygen cell evacuated. This experimental configuration minimizes the effects of the polarization of quench-induced radiation from H(2s) for which the reference axis in Eq. (3) is the direction of the applied electric field. In this configuration, both quenching plates were completely blocked from the viewing zone of the photometer. The field needed to quench H(2s) was determined by increasing the applied voltage until no further enhancement of the Lyman-α signal could be detected with further increases in voltage. Care was taken to demonstrate that the magnitude of the saturation voltage and the enhancement of the signal owing to electric quenching were unchanged when the direction of the field was switched from parallel to antiparallel with respect to the beam direction. The experimentally determined differences between the Lyman-α count rate with the field on and with the field off was used to calculate $\sigma(2s)$, the cross section for emission of Lyman-α from H(2s). Because the intensity observed at 54.7 or 125.3° with the field on and off is related to the total intensity in a polarization-independent manner, the anisotropies in the radiation from H(2p) and the changes in anisotropy as the field is switched on cannot affect determinations of $\sigma(2s)$ from the differences in intensities with the field on and off.

We believe that from gas to gas the relative H(2p) Lyman-α emission cross sections $\sigma(2p)$ for H-atom impact are accurate to within 15%. This estimate is based on contributions of < 5% from measurements of the secondary electron emission current and photometer counts as well as < 2% from nonlinearity in the pressure measurements for each

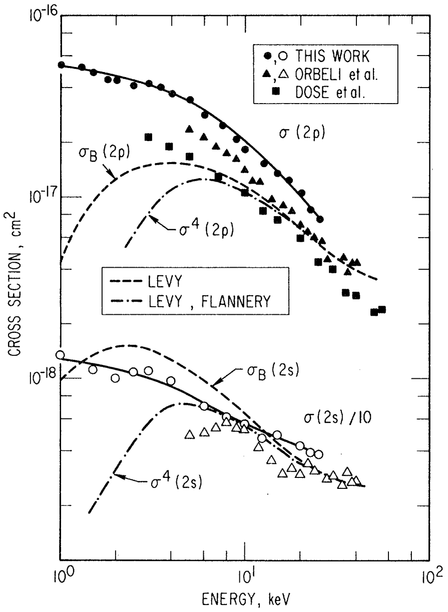

FIG. 2. Cross sections for emission of Lyman-α radiation in collisions of 1–55-keV H atoms with He. The broken curves labelled σ_B and σ^4 give the results of Born-wave and four-state impact-parameter calculations. The results for H(2*s*) are divided by 10: See Orbeli *et al.*, Ref. 26; see Dose *et al.*, Ref. 25; see Levy, Ref. 33(a); see Flannery, Ref. 34.

target gas. The required subtraction of photometer counts leads to an additional fractional error in $\sigma(2s)$. If the ratio of photometer counts with the quenching field on to the number of counts observed with the field off is Y, the subtraction process causes a fractional error in $\sigma(2s)$ of $\approx [(Y+1)^{1/2}/(Y-1)]$ times the fractional error in the number of counts with the field off. The reproducibility of the experimental measurements was always well within these estimates. The absolute cross sections have an additional uncertainty of about ± 10% owing to errors in the neutral beam detection technique[7–9] and there are uncertainties of about ± 25% in the previous determinations of the Lyman-α emission cross section for $H^+ + Ar$ to which our results were normalized.

III. EXPERIMENTAL RESULTS

The cross sections $\sigma(2p)$ and $\sigma(2s)$ for emission of Lyman-α radiation from H(2*s*) and H(2*p*) formed in 1–25-keV H bombardment of the rare gases are shown in Figs. 2–7 and compared with previous results, where available.

In Fig. 2 our results for a helium target obtained at 54.7 and 125.3° are compared with the 90° measurements of Orbeli *et al.*,[26] who employed a thermoelectric hydrogen-atom detector. Their method of pressure measurement was not given. Metastable H(2*s*) was quenched by an electric field applied within the collision chamber. A Seya-Namioka vacuum monochromator and a scintillation photoelectron counter were used to analyze and detect the Lyman-α radiation, and the relative measurements were normalized to the value of $\sigma(2p)$ for $H^+ + Ne$ determined by Andreev *et al.*[15] with an earlier version of the same apparatus.

Also shown on Fig. 2 are the 90° measurements of Dose *et al.*[25] This group used a classical Rutherford-scattering calculation to relate the total H beam flux to the secondary-electron emission owing to H atoms elastically scattered at 2.2°. The pressure of the scattering gas was monitored with an ion gauge, but no details were given concerning the calibration or corrections for the relative sensitivity of this device for different gases. Lyman-α radiation was detected with a He-I_2 counter, calibrated by normalization to the determination of $\sigma(2p)$ for H^+ on He of Andreev *et al.*[15] Thus all three sets of H-atom data shown in Figs. 2–7 are tied to the same set of absolute determinations.

The cross section for emission of Lyman-α from H(2*p*) drops off rapidly with increasing energy. While the agreement in energy dependence between the three determinations of $\sigma(2p)$ is satisfactory, our results are systematically larger by about 35% and 80%, respectively, than those reported by Orbeli *et al.* and Dose *et al.* Contamination of the Lyman-α signal by the He-II line at 121.52 nm can probably be excluded both as a potential systematic error in the measurement of $\sigma(2p)$ for a helium target and as the source of the discrepancy. Neither a He-I_2 counter nor a Seya-Namioka monochromator as employed by Orbeli *et al.* would have discriminated against this line if it had been present. The total cross section for slow positive-ion production (σ_+) for impact of H on He is about an order of magnitude lower than our value of $\sigma(2p)$ at 3 keV.[8] Furthermore, since the He-II line arises from a state of He^+ with principal quantum number equal to four, the cross section for excitation of the He-II line must be considerably smaller than σ_+. Therefore, even at 10 keV, where $\sigma_+ \approx \sigma(2p)$, and at 25 keV, where $\sigma_+ \simeq 10\ \sigma(2p)$, contamination by the He-II line is not expected to be a serious source of difficulty.

The cross section $\sigma(2s)$ also decreases monotonically for a He target as the impact energy is increased from 1 to 25 keV. As is emphasized by the plot of the $\sigma(2s)/\sigma(2p)$ ratio in Fig. 3, $\sigma(2s)$ for He is considerably smaller than $\sigma(2p)$. At impact energies $\geq$ 8 keV, the comparison between our H(2*s*) results and those of Orbeli *et al.* is quite favorable; however, our results for $\sigma(2s)$ do not show the plateau at lower energies indicated by the previous work.

The present results are in somewhat better agree-

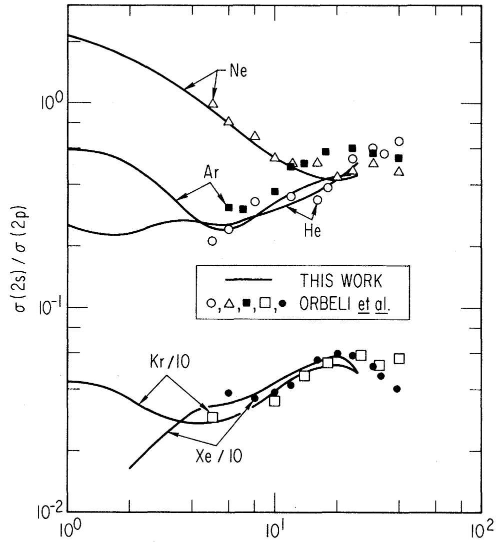

FIG. 3. Ratio of emission cross sections for H(2s) and H(2p) formed in collisions of 1–40-keV H with the rare gases. The ratios for Kr and Xe have been divided by 10: See Orbeli *et al.*, Ref. 26.

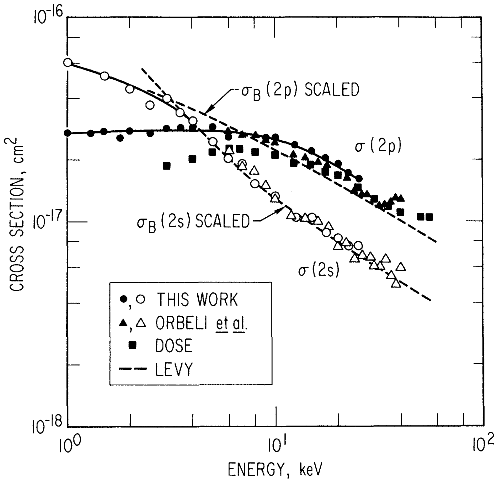

FIG. 4. Cross sections for emission of Lyman-α radiation in collisions of 1–55-keV H atoms with Ne: See Orbeli *et al.*, Ref. 26; see Dose, Ref. 25; see Levy, Ref. 32.

ment with Levy's[32] Born-wave values σ_B than with the four-state impact-parameter cross sections σ^4 calculated by Levy[33(a)] and Flannery[34]; however, the low-energy maxima predicted by these theoretical treatments were not observed.

Lyman-α emission cross sections for a neon target are given in Fig. 4. Levy calculated his theoretical curves[32] by multiplication of the Born-wave cross sections by experimentally determined velocity-dependent scaling factors. The H(2p) cross section is nearly energy independent from 1 to 10 keV, and drops off more gradually than for a He target in the 10–25-keV range. Inspection of Fig. 3 shows that neon is the only rare-gas target for which $\sigma(2s)/\sigma(2p)$ is greater than ~ 0.6 in the 1–40-keV energy range. At energies $\lesssim 4$ keV, we have $\sigma(2s) > \sigma(2p)$. The agreement between our cross sections and those of Orbeli *et al.* for both 2s and 2p excitation is very good, as is the agreement between our work and that of Dose *et al.* at energies $\gtrsim 10$ keV; however, we did not observe the maximum in the curve at $E \sim 6$ keV reported by the latter workers. The agreement between our measurements and the scaled Born calculations for Ne is the best for any of the rare-gas targets for which a comparison can be made.

Figure 5 shows our results for an argon target. The cross section $\sigma(2p)$ is quite similar in shape to that for Ne, but is larger in magnitude by about a factor of 2. Extension of the $\sigma(2s)$ measurements to 1 keV reveals structure in the emission cross section which had not been previously observed. The cross section drops off quite rapidly with increasing energy in the 1–7-keV energy range and then rises to a plateau at ~ 20 keV.

As for Ne, the agreement between our $\sigma(2p)$ results and those of Orbeli *et al.* in the region of overlap is quite good; however, the large disparity between the work of Dose *et al.* and other workers is apparent. The cross sections of Dose *et al.* are similar in energy dependence, but lower in magnitude, than other measurements by a factor of 2–3. Our H(2s) emission cross sections for an argon target appear to be systematically lower than those of Orbeli *et al.* by about 20%.

There is fairly good agreement between the scaled Born calculation of $\sigma(2p)$ and our measurements;

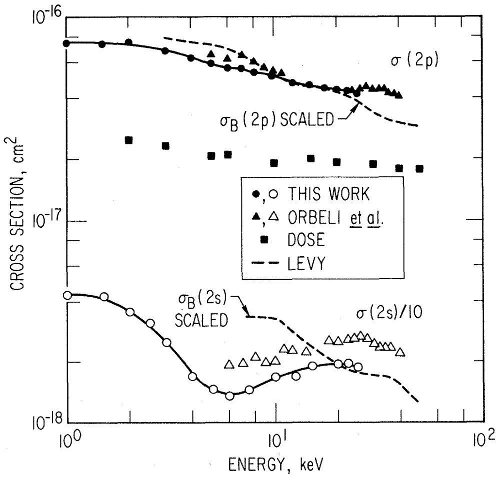

FIG. 5. Cross sections for emission of Lyman-α radiation in collisions of 1–50-keV H atoms with Ar. The results for H(2s) are divided by 10: See Orbeli *et al.*, Ref. 26; see Dose, Ref. 25; see Levy, Ref. 32.

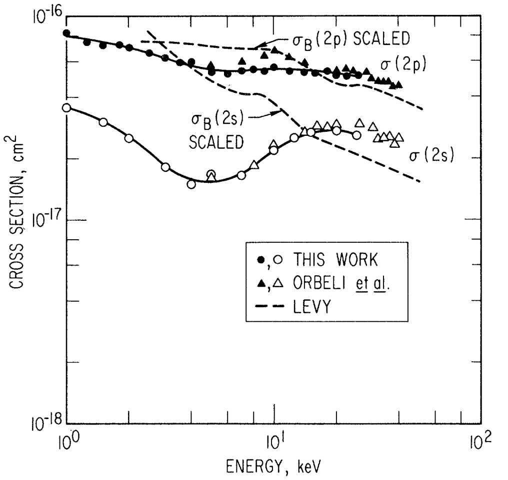

FIG. 6. Cross sections for emission of Lyman-α radiation in collisions of 1–40-keV H atoms with Kr: See Orbeli *et al.*, Ref. 26; see Levy, Ref. 32.

however, the theoretical curve for $\sigma(2s)$ decreases monotonically in the same range where our measurements show the cross section rising to a plateau.

The Lyman-α emission cross sections for H atoms incident on Kr shown on Fig. 6 are quite similar in energy dependence and, especially for $\sigma(2p)$, in magnitude to those for Ar. Our results for $\sigma(2s)$ and $\sigma(2p)$ are in satisfactory agreement with those of Orbeli *et al.* over the range in which they overlap, although the two maxima reported in their $\sigma(2p)$ work could not be resolved. Extension of the measurements to 1 keV in the present work reveals the existence of substantial new structure in the energy dependence of cross section.

Levy's scaled Born calculations for Ar and Kr also show a remarkable similarity. Hence, the agreement between theory and experiment for $\sigma(2p)$ is quite good, but, for $\sigma(2s)$, the scaled Born calculation fails to predict the observed energy dependence.

Figure 7 gives our results for hydrogen-atom collisions with xenon. The structure in $\sigma(2p)$ is more pronounced than that we have observed for H-atom impact on any other target gas. On the other hand, $\sigma(2s)$ rises monotonically with increasing energy. In the common energy range, the energy dependence of our $\sigma(2p)$ results agrees well with the previous work, although our values are smaller by 15% at energies below 15 keV.

IV. DISCUSSION

The over-all comparison of our work with the results of Orbeli *et al.* in the common energy range is quite favorable. Only in the case of a He target does the difference between their values and ours exceed the sum of the relative errors in the two cross sections. A general trend exists as the mass of the rare-gas target atom increases. Our $\sigma(2p)$ values are greater than those of Orbeli *et al.* by ~ 20–40% for He and by ≈ 10% for Ne. For Ar, the results of the two studies are of comparable magnitude, whereas our curves for Kr and Xe fall ≈ 15% below those given previously. The same general trend is displayed in the $\sigma(2s)$ results. Although the direction of the trend is consistent with what one would expect if Orbeli and co-workers had used a liquid-N_2 trapped McLeod gauge to measure scattering gas pressure and had not corrected for the pumping effect of mercury streaming to the cold trap,[41] the magnitude of the trend is greater than one would expect from this effect. Differences in beam-detection methods would not lead to this kind of systematic difference.

Other possible sources of the difference include polarization effects in the measurements. According to Eq. (4), the $\sigma(2p)$ measurements made at 90° would be in better agreement with ours if in the 1–25-keV energy range the polarization of the $2p$ Lyman-α radiation were negative and fairly large for He and Ne, nearly zero for Ar, and positive and fairly large for Kr. Theoretical estimates[32–34,42] and existing results[25(a)] on the polarization of Lyman-α radiation from H($2p$), obtained by observing the ratio of measurements at different angles, both indicate a large positive value of the polarization for He, Ne, and Ar. The errors attendant to this experimental determination of the polarization are quite large, and, especially for a Ne target, the results are of questionable validity.[42,43] Polarization cannot be invoked in the case of Xe, as both sets of $\sigma(2p)$ measurements were performed at 90°.

When $\sigma(2s)$ is measured at 90° by observing the

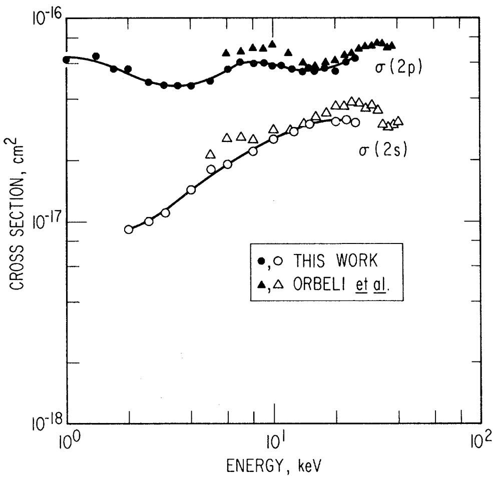

FIG. 7. Cross sections for emission of Lyman-α radiation in collisions of 1–40-keV H atoms with Xe: See Orbeli *et al.*, Ref. 26.

difference in the signal with the quenching field on and off, it is assumed that the Stark-induced Lyman-α radiation is isotropic and that the polarization of the $2p$-$1s$ radiation is unaffected by the field. While the latter assumption has not been examined in detail,[30] the effect of the former for the geometry and strength of the quenching field employed by Orbeli *et al.* probably requires a rather small correction and can be ignored.

Finally, since a Seya-Namioka spectrometer can have substantially different transmission for the components $I_{\parallel}$ and $I_{\perp}$,[44,45] systematic errors could have been induced in the work of Orbeli *et al.* if the polarization of the Lyman-α radiation in any of the H-atom impact experiments were markedly different from that in the $H^+ + Ne$ $\sigma(2p)$ measurements which they used for detector calibration.

The discrepancy between the $\sigma(2p)$ measurements for H + Ar of Dose *et al.* and the results of either our experiments or those of Orbeli *et al.* is much larger than the sum of the relative errors in the values being compared. The most probable cause of this discrepancy lies in the large uncertainties in the method used by Dose *et al.* to calculate the H-atom flux. As these authors pointed out,[24,25] the method is extremely sensitive to the values of the parameters used to make the large screening corrections in the classical H-atom Rutherford-scattering calculations.

In order to convert the phenomenological emission cross sections reported here to H(2s) and H(2p) population cross sections, small corrections should be subtracted to account for cascade effects. Based on considerations of the lifetimes and probability of collisional excitation of states of the H atom with higher principal quantum numbers, one can ignore cascade effects other than the formation of H(n = 2) via Balmer-α (H_α) transitions. In the absence of an applied electric field, the 3s and 3d levels are connected to H(2p) and the 3p level is connected to H(2s) by an allowed transition. There are very few data on excitation of H(n = 3) in H-atom bombardment. Lyman-β measurements for H-atom impact on the rare gases[26] imply that 3p-2s transitions are responsible for only 3–5% of the 2s H atoms which are formed. Recent H_α measurements[46] show that $\sigma(3s) \lesssim 0.1\ \sigma(2p)$ and $\sigma(3d) \lesssim 0.1\ \sigma(2p)$ for impact of 10–35-keV hydrogen atoms on He, Ne, and Ar. Owing to the relatively long H(3s) radiative lifetime of 1.6×10^{-7} sec in field-free space, only ~ 50% of 1-keV H atoms, 20% of those with 10-keV kinetic energy, or ≈ 12% of the 25-keV H atoms formed under our experimental conditions, could radiate H_α followed by Lyman-α before moving downstream from the field of view of the photometer. On the other hand, ≈ 100% of 1-keV H(3d), ~ 90% with 10 keV, and 75% with E = 25 keV could yield H_α followed by Lyman-α in the photometric viewing zone. We conclude, therefore, that corrections of − 10 to − 15% would be required for the field-free $\sigma(2p)$ measurements in order to obtain the H(2p) population cross section. Application of an electric field shortens the H(3s) lifetime and may enhance other cascade transitions, but it also will enhance the transitions to the 1s level from potential cascade states since it has been observed[47] that Lyman-β intensity is enhanced by application of an electric field. It is not expected that application of an electric field leads to a significantly larger cascade contribution than that occurring under field-free conditions.

Consideration of recently reported cross sections for destruction of H(2s) in collisions with rare-gas atoms in our energy range[48,49] shows that, under our experimental conditions, collisional quenching of metastable 2s H atoms would not affect our values of $\sigma(2p)$ and $\sigma(2s)$.

The results of our work can be summarized by noting the following general properties of the cross sections for Lyman-α emission in impact of 1–25-keV H atoms on the rare gases.

(i) At fixed impact energy, there is a trend toward increasing cross section with increasing number of electrons in the target atom. This correlation holds exactly for either $\sigma(2s)$ or $\sigma(2p)$ at $E \gtrsim 10$ keV and for $\sigma(2s+2p)$ at $E \gtrsim 6$ keV.

(ii) For the lighter targets He and Ne, the cross sections decrease monotonically with increasing energy. Pronounced structure appears in the energy dependence of $\sigma(2s)$ for Ar and Kr and in $\sigma(2p)$ for Xe. It is the appearance of this structure which invalidates the correlation in property (i) at lower impact energies.

(iii) For all of the rare gases except neon, the probability of excitation of the H projectile to the 2s level is no more than ≈ 0.6 times the probability of 2p excitation. At the high end of our energy range, the $\sigma(2s)/\sigma(2p)$ ratio is ≈ 0.5 for all five rare gases. There is no indication of a "statistical" value of $\frac{1}{3}$ for this ratio anywhere within our energy range.

(iv) The relationship between the emission cross sections and the stripping cross section σ_{01} for the process

$$H^0 + X \rightarrow H^+ + X + e^- \tag{5}$$

is quite similar for the different target atoms studied here. Figure 8 gives the ratio of $\sigma(2s)$, $\sigma(2p)$, and $\sigma(n=2)$ to σ_{01} (Ref. 50) for the rare gases. It is important to note that, as these ratios are not constant, the energy dependence of the excitation cross section differs from that for σ_{01}; however, especially for $\sigma(2p)$ and $\sigma(n=2)$ with He, Ne, and Ar targets, the magnitude and energy dependence of the relative probability of promotion and removal of an electron is rather insensitive to

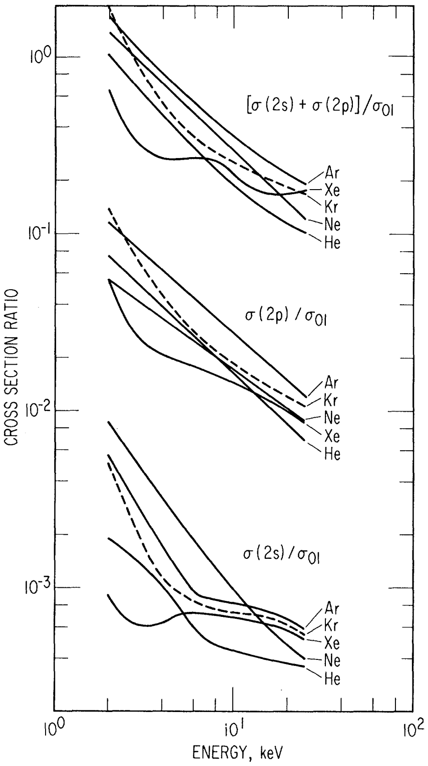

FIG. 8. Ratio of $\sigma(2s)$, $\sigma(2p)$, and the sum $\sigma(2s)+\sigma(2p)$ to the stripping cross section σ_{01} of Williams (Ref. 50) for impact of 2–25-keV hydrogen atoms on the rare gases. The ratios involving $\sigma(2p)$ and $\sigma(2s)$ have been divided by 10 and 100, respectively.

the identity of the target. A similar correlation between the excitation and stripping cross sections has also been observed for a number of diatomic and polyatomic target molecules.[51]

There are some interesting similarities and differences between the systematics of Lyman-α excitation processes in hydrogen-atom and proton impact on the rare gases in our energy range. The correlation of the magnitude of both $\sigma(2s)$ and $\sigma(2p)$ is quite clear cut for proton impact.[13–23] In comparison with the magnitude of $\sigma(2p)$ for H^+ bombardment,[13,15,23] the H impact cross section is larger for a He or Ne target, comparable for Ar and Kr, and smaller for Xe. In the case of 2s excitation,[14,18,22,23,28] the H-atom cross section exceeds the H^+ value at $E \lesssim 25$ keV for He and at $E \lesssim 15$ keV for Ne and Ar. For Kr and Xe, the values of $\sigma(2s)$ are smaller for H than for H^+ impact.

In contrast to property (iii) for hydrogen-atom impact, there are two well-resolved maxima [such as those in $\sigma(2p)$ for $H^+ + Ar$ in Fig. 1] in the 2p emission cross section for collisions of protons with all of the rare gases except He. This structure becomes more pronounced as the complexity of the target atom increases. On the other hand, only for an Ar target have two maxima been observed in $\sigma(2s)$. (The 2s measurements for Kr do not extend below 10 keV.)

Distinctly different behavior in the $\sigma(2s)/\sigma(2p)$ ratio is displayed in H and H^+ impact. For all of the rare-gas targets, the ratio increases with increasing H^+ impact energy, with the probability of electron capture into the 2s state becoming comparable to or exceeding the probability of 2p capture at energies $\gtrsim$ 20–25 keV.

The ratio of the 2s, 2p, and the total $n=2$ emission cross section to σ_{10}, the electron-capture cross section into all states of H for proton impact, is nearly independent of energy and relatively insensitive to the identity of the target for the rare gases.[23] Similar behavior has also been observed in electron capture collisions with a number of other target molecules.[51]

There are a number of significant deficiencies in existing theoretical treatments of hydrogen-atom excitation collisions. As Levy has previously pointed out,[33] the agreement between the shape of the measured and calculated cross section curves is considerably better for $\sigma(2p)$ than for $\sigma(2s)$; and, for targets more complicated than He, the unscaled Born and four-state treatments seriously overestimate the magnitude of these cross sections. Extension of the measurements to lower energies has shown that neither the four-state nor the Born calculation predicts the correct energy dependence of either $\sigma(2s)$ or $\sigma(2p)$ for a He target at $E \lesssim 5$ keV, and has revealed new structure in the cross sections which will provide an interesting test of future theoretical approaches. Further experiments in which the polarization of Lyman-α radiation from H(2p) is measured with a reflection-type analyzer[21] would also be helpful in gaining a more detailed understanding of these collision processes.

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