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Production of Lyman-Alpha Radiation by 20- to 120-keV Hydrogen-Atom Impact on He, Ne, Ar, and N_2 †

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Absolute cross sections have been determined for the production of Lyman-α radiation by 20–120-keV ground-state hydrogen atoms impacting on He, Ne, Ar, and N_2. Atom impact on He follows the predicted energy dependence of Levy's Born wave calculation of $2p$ excitation beyond 30 keV. Although the experimental value remains about 25% higher than the theoretical value in this region, the agreement is well within experimental error. For Ne, Levy's scaled Born calculation for $2p$ excitation agrees reasonably well with experiment. However, it is particularly apparent for impact on Ar that the scaled Born calculation underestimates the excitation at the higher energies. All cross sections decrease more rapidly with energy initially than at the higher energies, where a characteristic flattening of the cross-section–vs–energy curve occurs, suggesting the importance of simultaneous excitation of the target and projectile atoms at these energies.

I. INTRODUCTION

Production of Lyman-α radiation by hydrogen atom impact on N_2 has been measured by Dahlberg *et al.*[1] for 20–130-keV impact, and by Birely and McNeal[2] below 30 keV. Similar measurements have been carried out on He, Ne, and Ar by Birely and McNeal[3] to 25 keV, by Dose *et al.*[4] to 55 keV, and by Orbeli *et al.*[5] to 40 keV. We extend the energy range in this investigation of these rare gases.

Levy has calculated the excitation of these rare gases using the Born wave method by describing the target atoms by elastic and inelastic x-ray form factors.[6] In the case of helium[6,7] he found excellent agreement with the experimental work of Orbeli *et al.*[5] when the experimental values for $2s$ and $2p$ cross sections were summed over the entire experimental range of 5–40 keV. Some discrepancies became apparent when the two cross sections were treated separately. Levy also found that he could reasonably reproduce the $n=2$ measurement of Ref. 5 for Ne, Ar, and Kr by scaling his Born calculation by a velocity-dependent factor obtained by a comparison of the theoretical ionization cross sections with the experimental values.[6,8]

Birely and McNeal[3] made $n=2$ measurements for impact on the rare gases and discovered an apparent discrepancy in the helium work of Ref. 5. Both experiments used the same optical calibration, which is based on the charge-transfer work of

Andreev *et al.*[9] Birely and McNeal[3] reproduced the work of Ref. 5 reasonably well, within experimental error, for impact on Ne, Ar, Kr, and Xe, but produced cross sections for impact on helium that were systematically larger. Discrepancies with the work of Dose *et al.*[5] were noted.

II. APPARATUS

The apparatus used in a study of the production of Lyman-α radiation by proton impact on gases[10] was modified to produce a beam of fast hydrogen atoms. The mass-analyzed proton beam passed through a differentially pumped neutralizing chamber into an evacuated chamber where a strong transverse electric field was applied to sweep the remaining protons from the partially neutralized beam. The electric field also served to quench H(2*s*) atoms produced in the neutralizer. The prepared beam then passed into the collision chamber, where the Lyman-α radiation from excitation of ground-state hydrogen atoms to the 2*p* state was detected by a helium- and iodine-filled Geiger counter. The counter was fitted with an oxygen filter for spectral isolation of the Lyman-α radiation.

The atom beam density was measured using a secondary electron detector which was calibrated using protons of the same energy, and was corrected for the difference in secondary emission coefficients between the two species.[11]

The counter was used in two different positions. It could view the collision region at 90° to the beam direction or it could view the collision region at 75° to the beam direction. The Lyman-α radiation from the fast hydrogen atom was passed by the oxygen filter in the 90° position, and hence this position was used in obtaining the data. There was a possibility that there were background emissions from slow target atoms which were also passed by the filter. Particular examples of such emissions are the Balmer-β line of He^+ and the Lyman-Birge-Hopfield bands of N_2.[10] This slow-atom background could easily be determined when the counter-filter system was placed in the 75° position. In this position the Lyman-α radiation from the fast hydrogen atoms was Doppler shifted away from the oxygen transmission window, leaving the slow-atom emissions from target-gas excitation as the countable radiation.

The oxygen-filter transmission window is sufficiently narrow that a Doppler correction must be applied at the higher energies. (The Doppler correction is required because the counter views a finite cone of light, which means some of the fast atom emitters will have a component of velocity parallel to the line of sight.) A velocity-dependent correction factor was determined by comparing the velocity response of the counter without the filter and with the filter when viewing Lyman-α radiation produced by proton impact on Ne.[10] (There are no Ne emissions within the spectral sensitivity of the counter, and hence the response of the counter without the filter will give a Doppler-free indication of the Lyman-α radiation.)

III. RESULTS AND DISCUSSION

The Lyman-α counter was calibrated by pumping out the neutralizing chamber, allowing a 60-keV proton beam to enter the collision chamber, and normalizing to the 2*p* measurements of Ref. 10 for each gas. An internal consistency check, independent of Ref. 10, was made by determining the excitation by 60-keV atom impact on three of the gases relative to the other target gas. These gas-to-gas ratios were consistent with the corresponding ratios of the absolute cross sections at 60 keV.

The absolute calibration procedure of Ref. 10 involved normalizing to an average of the determinations of Lyman-α production by Pretzer *et al.*[12] for 20-keV proton impact on He, Ne, and Ar. Birely and McNeal[2,3] calibrated their apparatus by normalizing to both Pretzer *et al.* and Andreev *et al.*[9] for proton impact on Ar, since both these independent calibrations gave the same result for proton impact on Ar. It is evident from Figs. 1–4 that our calibration and that of Birely and McNeal are identical, within experimental error. The similarity between our calibration and that of Birely and McNeal was also established in Ref. 10 for proton impact on N_2 and O_2. The calibration of our apparatus is nominally based on the measurements of Pretzer *et al.*, who quote an uncertainty of ±45%. However, Andreev *et al.*[9] quote a much smaller uncertainty on their absolute calibrations. Birely and McNeal, who use both Pretzer and Andreev for their calibration, add a basic absolute calibration uncertainty of ±30% to the uncertainties inherent in their own apparatus.[2] The total absolute uncertainty in the present measurements is estimated to be about ±50%.

Cascade to the 2*p* states can be estimated for 20-keV impact from preliminary $n = 3$ excitation measurements.[13] The largest single contribution will be from the $n = 3$ level, because all of the 3*s* and 3*d* decay will go to the 2*p* state, while only a fraction of the *ns* and *nd* decays, $n > 3$, go to the 2*p* state. (These $n > 3$ states also decay to $n > 2$ *p* levels.) The *ns* and *nd* ($n > 3$) states contribute less also because of an expected inverse relationship between principal quantum number and cross section. We estimate that the cascade contribution to the 2*p* state from $n = 3$ cascade was from 5 to 7% for all gases at 20 keV. In our experiment, the fraction of the total 2*p* excitation by cascade decreased as the energy increased, because the cascading states are much longer lived than the 2*p*

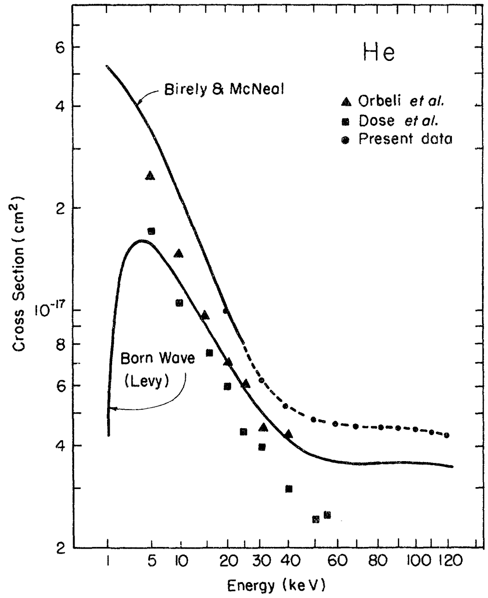

FIG. 1. Comparison of the production of Lyman-α radiation with the Born wave calculation of the excitation of the $2p$ state by hydrogen-atom impact on He. Energy is on a square-root scale.

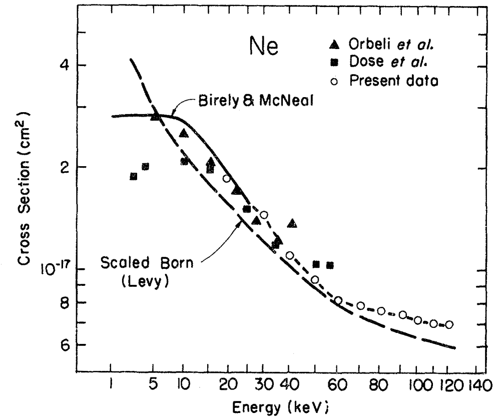

FIG. 2. Comparison of the production of Lyman-α radiation with a scaled Born calculation of the excitation of the $2p$ state by impact on Ne.

state, and the time of flight from the entrance aperture of the collision chamber to the observation point was generally not sufficient to produce an equilibrium population in these states. The buildup in the population of excited states in the beam was proportional to a factor $f = 1 - e^{-x/v\tau}$, where $x \approx 4.5$ cm is the distance between the observation point and the entrance aperture, v is the velocity, and τ is the radiative lifetime of the state. The factor $f \approx 1$ at all energies for the short-lived $2p$ state, while f was about 0.06 and 0.5 for the $3s$ and $3d$ states, respectively, for 100-keV impact. Also, the fraction of $2p$ excitation by cascade should have been reduced at the higher energies, because the excitation cross section of the optically allowed $2p$ state should increase relative to the cascading s and d states as the energy increases.

The cross sections are not corrected for polarization. However, any polarization corrections for the $2p$ cross section will be within the generous limits of -14% and $+9\%$ which are associated with the maximum positive polarization fraction and the maximum negative polarization fraction, respectively.[14] Dose *et al.*[15] have made polarization measurements for impact on the rare gases. They obtained positive polarization fractions which indicate that a small correction factor, generally less than 10%, is needed which will reduce the apparent cross sections for energies up to 55 keV. The polarization fractions are energy dependent and will decrease to zero as the energy increases, and go negative as the energy is further increased.[7,14]

No appreciable background emanating from any of the target gases was detected by the counter-filter system in the 75° viewing position.

A. Helium

Figure 1 displays the results for impact on He. Also displayed are the results of Birely and McNeal,[3] Orbeli *et al.*,[5] and Dose *et al.*[4] The agreement with Birely and McNeal is excellent. The measurements of Orbeli and Dose are considerably lower. Birely and McNeal[3] discuss the surprising discrepancy between their work and the work of Orbeli for impact on He. Presumably the optical calibration between the two groups (and also our group) should be the same, since the calibration of Orbeli is also based on the measurements of Andreev *et al.*[9]

Also shown is the Born wave calculation of Levy. The experimental curve reproduces the Born curve

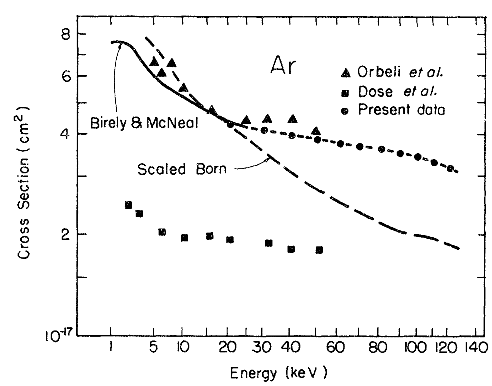

FIG. 3. Comparison of the production of Lyman-α radiation with a scaled Born calculation of the excitation of the $2p$ state by impact on Ar.

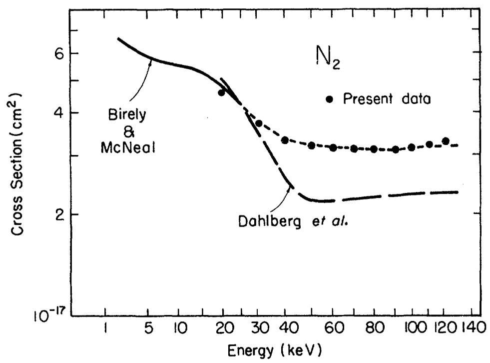

FIG. 4. Plot of the cross sections for the production of Lyman-α radiation by impact on N_2. The Birely-McNeal curve to 20 keV is taken from Ref. 2. The curve segment from 20 to 25 keV is based on newer data [Dr. John Birely (private communication)].

in shape beyond 30 keV, but remains about 25% higher. However, this is well within the experimental uncertainty of ± 50%. The leveling of the theory curve at the higher energies is brought about by the interplay of the excitation process where the target atom is left in the ground state, which is the dominant process at the lower energies, and the excitation process where the target atom is left excited, which is dominant at the higher energies. This effect has been also observed in H-H collision calculations by Bates and Griffing.[16] (The Born cross section for excitation to the 2*p* state leaving helium in the ground state has been separately calculated by Levy.[8] From his calculations we find that this process represents less than 40% of the excitation at 100 keV, while it represents more than 90% at 25 keV.) The leveling of the experimental curve then represents a verification of the importance of the rolе of simultaneous excitation of the target atom and the projectile.

B. Neon

Figure 2 shows the results for impact on Ne. The agreement with Birely and McNeal,[3] Orbeli *et al.*,[5] and Dose *et al.*[4] is generally good in the overlapping energy regions.

Levy's Born calculation has been scaled to include the entire energy range of this experiment by using Levy's scaling method. While the scaled Born fits the curve resonable well, a change in slope appears in the experimental curve at the higher energies, similar to impact on He, that suggests the effect of simultaneous excitation.

C. Argon

The agreement with Birely and McNeal[3] and Orbeli *et al.*[5] is good. However, there is a marked disagreement with the scaled Born calculation. The disagreement is in the direction of an underestimate of simultaneous excitation by the scaled Born calculation.

D. Nitrogen

The agreement with Birely and McNeal[2] to 25 keV is good. However, the agreement with Dahlberg *et al.*[1] is poor. The reason for this disagreement is not known. Dahlberg *et al.* used a fast vacuum monochromator for spectral isolation, while we used the oxygen filter. The oxygen filter did allow some Lyman-Birge-Hopfield emission to pass in the study of proton impact of N_2.[10] However, no significant background was detected in this experiment. It should be noted that both experiments show a change in slope in the curve at the higher energies, again indicative of the simultaneous excitation process becoming prominent.

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