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Electron Capture into the $n=2$ States of Hydrogen by Fast Proton Impact on Gases*

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Cross sections for electron capture into the $2s$ and $2p$ states of atomic hydrogen have been measured for proton impact on He, Ne, Ar, N_2, and O_2. In addition, capture into the $2s$ state has been measured for proton impact on H_2. Generally, these measurements have been carried out in the energy range from 20 to 130 keV. Absolute calibration of the helium-filled iodine Lyman-alpha counter was obtained by a normalization procedure involving previous $2p$ capture measurements for impact on He, Ne, and Ar, after an investigation of the detector response for electron impact on H_2. Calibration for the $2s$ capture was established by determining the $2s$ cross section relative to the $2p$ cross section for 20- and 30-keV impact on Ne. The polarization effect in the Stark-quenched $2s$ radiation was minimized by observing the Stark-induced radiation at 54.7° to the electric field direction. The $2s$ cross sections relative to the previously measured $3s$ cross section show a remarkable (about 10%) agreement with the n^{-3} law (predicted at high energies) above 20 keV for all gases, excluding He. It appears that the n^{-3} behavior sets in at about 100 keV for He. In general the $2s$ cross section tends to be somewhat higher than predicted by the n^{-3} law for impact on He in the range from 25 to 100 keV. It appears that the $2s$ cross sections will agree with the coupled-state calculation of Sin Fai Lam for impact on He above 100 keV. The $2p$ cross sections are lower than those predicted by theory for impact on He in this energy range. The $2p$ cross sections relative to the previously measured $3p$ cross sections appear to roughly follow an n^{-3} behavior at the higher energies, again with the possible exception of helium. Comparisons are made with the results of other experimental investigations.

I. INTRODUCTION

Electron capture into the $n=2$ states of hydrogen by fast proton impact on gases has been the subject of several experimental investigations within this energy range.[1–10] This investigation generally extends the energy range of the incident protons.

Pretzer *et al.*[1] and Jaecks *et al.*[2] calibrated their detector by normalizing its response to the cross-section determination of Fite and Brackmann[11] for the reaction $e^- + H_2 \rightarrow L_\alpha$. Fite's calibration in turn was obtained by normalizing to the Born approximation for the reaction $e^- + H \rightarrow L_\alpha$. The calibration of Bayfield[4] was based on the photoelectric efficiency of the tungsten surface of his detector. The calibration of Andreev *et al.*[3] was based on the calculated sensitivity of an ionization chamber filled with NO. (All others calibrated either by normalizing to one of these works or by normalizing to the Born approximation for either protons on helium or atomic hydrogen. However, Gaily[12] has indicated that the Born approximation fails to describe the charge-capture process into excited states.) There is some uncertainty in the absolute calibration of these investigato [1–4] because polarization of radiation was not taken into account. In particular, the $2s$ cross-section measurements have been performed by monitoring Lyman-alpha emission from Stark-quenched $2s$ atoms, assuming the radiation to be isotropic. This radiation, however, can be strongly polarized, as first observed by Fite *et al.*[13] Sellin *et al.*[14] has observed highly polarized radiation at quench-field strengths used by Bayfield, by Jaecks, and by Andreev. Such large polarization fractions can appreciably affect the apparent cross section. Further, the polarization fraction can be dependent on the experimental apparatus.

Polarization corrections to the data of Bayfield,[4] Jaecks,[2] and Andreev[3] are difficult to assess, each for a different reason. Jaecks and Andreev observed the induced $2s$ radiation from $2s$ atoms born in the quenching field. Crandall[15] has calculated the polarization of this radiation in the sudden approximation which applies to the work of Jaecks and Andreev. At 600 V/cm the polarization is about about − 18%. Jaecks used a quench configuration where the electric field was perpendicular to the beam direction but reversed directions as the beam passed through the field. The direction of the field was generally either parallel or antiparallel to the viewing direction. These field uncertainties contribute to the difficulty in applying a correction factor to this work. Andreev viewed the quench radiation perpendicular to a constant electric field of 600 V/cm which also was perpendicular to the beam direction. However, he used a monochromator with reflecting optics which treat the polarization components differently. Further, both Jaecks and Andreev obtained their $2s$ cross section by subtracting the $2p$ radiation obtained with the field-off mode from field-on mode. The polarization calcula-

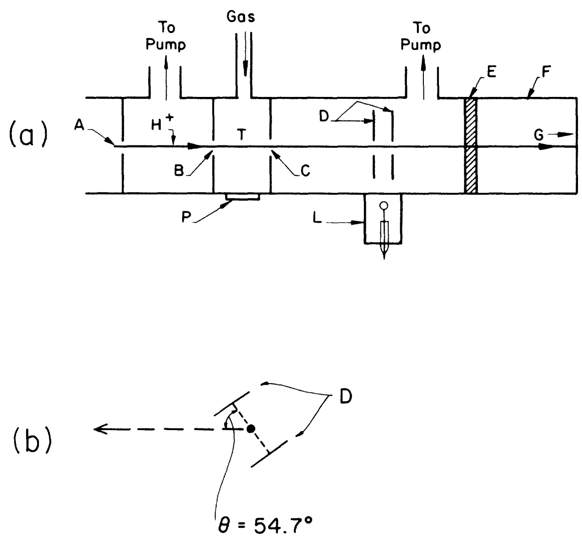

FIG. 1. (a) Apparatus configuration used in making the relative 2*s* measurements. A: beam collimating aperture; B: entrance aperture to the collision chamber; C: exit aperture of the collision chamber; D: electric quench assembly (see text); E: nylon insulator; F: Faraday cup; G: liquid air-cooled surface; L: Lyman-alpha counter; and P: aperture port to accept counter L for the 2*p* measurements. (b) End-on view of quench configuration used in making 2*s* measurements relative to 2*p* measurements for calibration purposes (see text). D: quench electrodes θ: angle between observation direction and electric field direction.

tion of Crandall treats only 2*s* atoms radiating in the presence of the electric field. It is not obvious what the added perturbation of radiating 2*p* states does to the radiation pattern.

Bayfield, on the other hand, measured Stark-induced 2*s* radiation outside the collision chamber after all the 2*p* states had decayed off. Here the 2*s* atoms are formed outside the quench field and enter the field through the fringe field. How quickly the atoms make the no-field–to–field transition is not known, but they probably approach the adiabatic approximation of Sellin which shows a −56% at 600 V/cm. Bayfield's field was not uniform, so the application of a polarization correction is impossible.

II. APPARATUS

The apparatus used for measurements of the 2*s* capture cross sections is shown schematically in Fig. 1. The mass-analyzed beam of protons was highly collimated and produced no evidence of striking any of the apertures after entering the collision region. The collision chamber was 9.5 cm long and was differentially pumped through circular apertures 0.79 and 1.59 mm in diam on the beam entrance and exit sides, respectively. The quench-field assembly was 30 cm from the collision-chamber exit aperture, and consisted of two parallel plates 4.45 cm in diam separated by a distance of 1 cm. Apertures 0.37 cm in diam allowed free passage of the beam through the quench-field region. A deep Faraday cup following the quench assembly collected the beam for current measurements.

The Lyman-alpha photons emitted in a direction perpendicular to the beam axis from a beam segment located in the center of the quench region were counted with a He and iodine-filled Geiger tube similar to the design described by Brackmann *et al.*[16] The beam segment viewed by the counter was defined by two 0.8×10.0-mm slits placed 2.4 and 4.6 cm from the beam axis. Since the photons counted were primarily from the fast hydrogen beam, the discriminatory action of the counter alone[16] was sufficient to select the Lyman-alpha component.

Differential pumping reduced the contributions from collisions with residual gas molecules outside of the collision region to less than 10% of the total signal, except in the case of both low- and high-energy impact on He where it approached 15%. The data were corrected for the residual gas contribution by removing the target gas from the collision region, introducing target gas into the region containing the detection apparatus to duplicate the pressure found there when the collision cell was filled, and subtracting the count rate obtained under these "background" conditions from the previous data.

Data were taken of quench-field versus Lyman-alpha intensity. These data were compared to curves drawn using the theoretical lifetime of the metastable hydrogen atom[17] in an electric field in order to find the expected variation of Lyman-alpha intensity with field strength. Fields up to 1000 V/cm were used with beam energies that spanned the entire energy range used. A good fit was found in all cases indicating that prequenching of the metastables was not a problem.

The apparatus was modified for the 2*p* capture cross-section measurement by removing the exit aperture of the collision region and the chamber containing the quench region, detection apparatus, and pumping ports. The Faraday cup was then attached directly to the collision cell with no intervening aperture. An O_2 filtered[18,19] detector was positioned so that it viewed a beam segment 4.3 cm from the beam entrance aperture. The beam segment was defined by two (1.6- and 10.0-mm) slits positioned 4.5 and 6.7 cm from the beam axis. The O_2 filter absorption path was 1.5 cm at a pressure of 1 atm. The narrow pass of the filter and the finite width of the beam segment viewed required Doppler corrections to the data. Andreev *et al.*[3] have shown that when viewing the region of interaction of H^+ and Ne gas, one finds that the only spectral line in the region of sensitivity of the counter is the Lyman-alpha line. Since neither Ne, nor any of its ions, has emission lines in this region,[20] one can assume all of the counted photons are emitted from fast hydrogen atoms. Data were taken with the O_2 filter filled and then evacuated with Ne as the target gas. The difference in the shape of the two excitation curves was attributed to the Doppler broadening of the emission as the beam velocity increased. An empirically determined correction factor was applied to the curve for the filtered data to make it agree with the unfiltered data. The filtered data was multiplied by a factor of the form $(1-\beta v^2)^{-1}$, where v is the beam particle velocity and β is an empirical constant. This correction superimposed the two curves within experimental error. The correction factor indicated that there was a 30% reduction in the signal at 120 keV due to the Doppler effect.

Data were taken to determine the variation of Lyman-alpha intensity with current and pressure for all gases except O_2. (Pressure measurements for O_2 were difficult at best and caused rapid deterioration of the ion gauge.) All of the reported cross-section data were taken in the range where the Lyman-alpha intensity was a linear function of current and pressure.

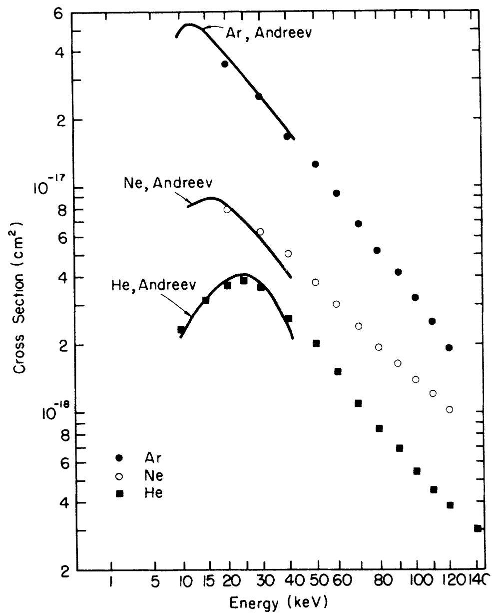

FIG. 2. Cross sections for the production of Lyman-alpha radiation by proton impact on Ar, Ne, and He. Also plotted are the results of Andreev *et al.* (Ref. 3). The abcissa is a square-root scale in energy; hence, is a linear scale in velocity.

III. CALIBRATION PROCEDURE

A calibration procedure was used which was the basis of the calibration of Pretzer and Jaecks. The filter chamber was filled with O_2 at atmospheric pressure. The count rate was determined for 200-eV electron impact on H_2 at a given electron current and collision-chamber pressure, and the apparent cross section was normalized to the results of Fite *et al.*[11] This procedure yielded a cross section which was the same as Pretzer's, within experimental error.

The final procedure was to normalize our relative $2p$ cross sections to Pretzer's values for $2p$ production for 20-keV impact on He, Ne, and Ar by weighting each gas equally. This produced $2p$ cross-section values that have a discrepancy with Pretzer of $\pm 7\%$ for Ne and Ar, respectively, and about $+3\%$ for He. Figure 2 shows the results of the calibration when compared with Andreev's results for these gases. The agreement is quite good.

The $2s$ calibration was established by determining the ratio of $2s$ capture to the absolute $2p$ cross section for 20- and 30-keV impact on Ne inside the collision chamber. The collision chamber was modified to accept interior quench plates. The quench arrangement in this case consisted of two $0.16 \times 1.5 \times 7.0$-cm parallel electrode plates spaced 2.0 cm apart. The ion beam passed between the plates of this electrode assembly, which was placed with one end about 1 cm from the beam entrance aperture and with the long dimension parallel to the ion beam direction. The electric field was applied in a direction perpendicular to the ion beam axis but 54.7° to the observation direction [Fig. 1(b)].

The question of the polarization of quench radiation was avoided by tipping the quench plates so that the observation was made at the "magic angle" of 54.7° to the electric field direction. Quench fields used were about 400 and 500 V/cm, respectively, for 20- and 30-keV impact. According to Sellin,[21] the $2s$ lifetime at these field strengths is about 6 nsec or less. In this calibration configuration, our observation point was about 5 cm from the beam entrance into the electric field, which means that the $2s$ atom density was built up through about 4 lifetimes or had a build-up of better than 98%. The build-up was checked as a function of field strength to make certain a saturation signal was obtained. Possible effects produced by deflecting the ion beam as it passed through the quench field were checked by observing the radiation with different polarities on quench plates. No change was detected with the unfiltered detector. The $2s$ calibration points were then determined by subtracting the field-off signal from the field-on signal as done by Jaecks and Andreev. There was an obvious difference as a function of the polarity of the field with the filtered detector. This was probably

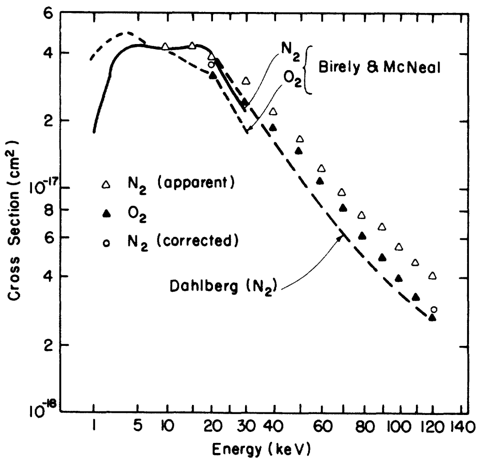

FIG. 3. Cross sections for the production of Lyman-alpha radiation by proton impact on N_2 and O_2. Plotted also are the results of Birely and McNeal (Ref. 10) and Dahlberg *et al.* (Ref. 8). Open triangles are apparent cross sections for impact on N_2 which include some N_2 background radiation passed by the O_2 filter. This background has been removed at 20 and 120 keV (circles).

caused by the Doppler shift of the radiation as a function of the polarity, coupled with the fact that the Lyman-alpha frequency is not quite centered on the O_2 absorption minimum. A shift to the shorter wavelengths reduces the signal more than a shift to the long wavelengths. (The Doppler shift is produced by the tilted electric field which imparts a component of motion along the line of sight.)

Polarization corrections to the apparent 2*s* and 2*p* cross sections for H^+ impact on Ne at 20 keV are negligible in the calibration configuration. The "true" cross section Q is given by

$$Q = Q_a(1 - \tfrac{1}{3}P)/(1 - P\cos^2\theta) ,$$

where Q_a is the apparent cross section when the radiation is viewed at an angle θ to the axis of quantization; P, the polarization fraction, is given by $(I_\parallel - I_\perp)(I_\parallel - I_\perp)^{-1}$, where $I_\parallel$, $I_\perp$ are the intensities with the electric vector parallel and perpendicular, respectively, to the axis of quantization when $\theta = 90°$. For the 2*p* measurements the axis of quantization is the beam direction and $\theta = 90°$. For the 2*s* measurements, the quenching electric field direction is the axis of quantization and $\theta = 54.7°$. For 20-keV impact on Ne, $P \simeq -0.02$ for radiation from the 2*p* state.[22] The polarization is so small that, to within experimental accuracy, the radiation is isotropic and $Q = Q_a$. The problem of polarization effects when the electric field is the axis of quantization is avoided when $\cos^2\theta = \frac{1}{3}$. At this angle $Q = Q_a$. Simply twisting the quench plates to give $\theta = 54.7°$ fulfills this condition. Since the radiation is essentially isotropic in both the field-off and field-on modes, the procedure of subtracting signals should give the contribution from the *s* state with no polarization correction. A calibration 2*s* point was also established at 30 keV, assuming that the 2*p* radiation was also isotropic.

The largest polarization fractions found by Teubner *et al.*[22] in the energy range of this study were in the case of H^+ impact on He. They observed the field-free Lyman alpha to be about +0.15 from the 20- to 24-keV impact. This implies that the 2*p* cross section should be reduced by 5%. The correction is ignored since it is no larger than the reproducibility of the relative data.

IV. RESULTS AND DISCUSSION

A. Lyman-Alpha Cross Sections

Figure 2 shows the cross sections for the emission of Lyman-alpha radiation induced by proton impact on He, Ne, and Ar. The energy range was extended to 10 keV for impact on He. The He curve at the lower energies agrees well with Andreev in both magnitude and shape.

Figure 3 shows the cross sections for emission of Lyman-alpha radiation induced by proton impact of O_2 and N_2. Also shown are the corresponding cross sections measured by Birely and McNeal.[10] These investigators calibrated their O_2 filtered detector by normalizing to the Lyman-alpha cross sections measured by Pretzer and Andreev. In order to better compare our results with theirs, our energy range was extended to 10 keV for proton impact on N_2. Their curve shapes from 20 to 30 keV do not agree well with ours in the region from 20 to 30 keV; however, there is excellent agreement below 25 keV. (In a private communication, Dr. John Birely indicated that new data suggest that the cross-section curve from 20 to 30 keV does not decrease as rapidly with energy as indicated in Ref. 10.) Van Zyl *et al.*[7] have made measurements below 25 keV also using the O_2 filter. They obtained values about 25% higher than Birely and McNeal.[10] Dahlberg *et al.*[8] have made measurements for impact on N_2 from 20 to 130 keV. They used a fast spectrometer with a narrow spectral slit width.

Figure 3 displays our "apparent" Lyman-alpha cross sections for impact on N_2. This curve is entirely different from Dahlberg in shape. The "apparent" curve is obtained from measurements with the O_2 filtered detector oriented to detect the radiation emanating at 90° to the proton beam. Unfortunately the filter also passes a significant amount of Lyman-Birge-Hopfield radiation from N_2. The N_2 background was measured by mounting our filtered detector to detect the radiation emanating at 75° to the proton beam. In this mounting arrangement the Lyman-alpha radiation was Doppler-

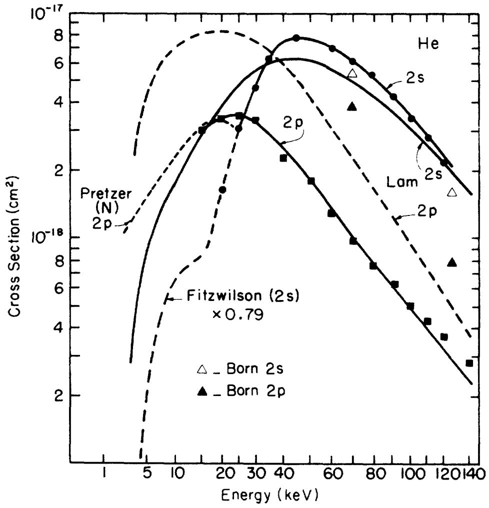

FIG. 4. Cross sections for capture into the $2s$ and $2p$ states by proton impact on He. The experimental results of Pretzer *et al.* (Ref. 1) and Fitzwilson and Thomas (Ref. 9) have been normalized to the present measurements (see text). The (N) symbol means normalized (see text). Also plotted are calculations from Refs. 23 and 24.

shifted to the low-wavelength side of the 1216-Å O_2 filter window leaving only the unshifted N_2 radiation passing through the filter. This background was subtracted from the 90° measurements at 20 and 120 keV. The N_2 background contributed about 10% and 30% to the 90° signal at 20 and 120 keV, respectively. Taking the background into account puts our data in much better agreement with Dahlberg *et al.* (It is possible that a small Doppler correction should be applied to the data of Ref. 8 at the highest energies.)

B. $n = 2$ Capture Cross Sections

Estimates of cascade population of the $2s$ state were made from the known $3p$ cross section and by scaling higher np cross sections according to an n^{-3} behavior. The cascade was summed to $n=6$. The cascade contribution was negligible at the higher energies and was generally less than 5% at 20 keV. Since the cascade contribution is at most of the order of the reproducibility, the $2s$ data are presented without a cascade correction. Cascade to the $2p$ state could not be generally ignored. The cascade correction to the $2p$ radiation includes cascade from the $3s$ and $3d$ states along with other ns and nd states up to $n=6$, using an n^{-3} behavior to estimate the higher n capture.

Figure 4 includes the $2s$ capture cross sections for impact on He. Also shown are the $2s$ cross sections calculated by Sin Fai Lam[23] using a two-state approximation. The experimental and theoretical curves may reach agreement above 100 keV. Also shown are points taken from Mapleton's Born calculation.[24] Ryding *et al.*[5] have made $2s$ relative measurements from 40 to 200 keV. Normalizing their curve with ours at 100 keV produces a curve that reproduces Sin Fai Lam's curve to 200 keV to within the reading error of the graphical displays in Refs. 5 and 23.

Fitzwilson and Thomas[9] measured relative $2s$ capture cross sections for He, Ar, N_2, and O_2 up to 26-keV impact. They normalized to Andreev's $2s$ cross section for 20-keV impact on Ar. A very consistent fit to our data for all four gases can be obtained by simply multiplying their normalized data by 0.79. Both the $2s$ experiments are based on measurements taken outside the collision chamber which are inherently more accurate, in a relative sense, than those measurements performed inside the chamber which required subtracting the $2p \rightarrow 1s$ radiation as a background from the total quench radiation. (However, one must be careful at lower energies that scattering to the cell walls before leaving the exit chamber does not affect the result.)

Also shown in Fig. 4 are the $2p$ cross sections for impact on He. These cross sections have been corrected for cascade. For helium the cascade correction is quite small. It is less than 10% for helium at all energies. (The cascade correction is larger for the other gases although the correction systematically becomes negligible at the highest energies.) The $2p$ measurements of Pretzer have been normalized to our cascade-corrected low-energy points. (The normalization is required to account for our smaller cross sections brought about by the cascade correction.) Sin Fai Lam's calculation for the $2p$ cross sections overestimate the experimental points at all energies. It has been shown that the Born approximation overestimates the capture in the $3p$ state.[25,26]

Care must be exercised in making Lyman-alpha measurements for impact on He. The $4\rightarrow 2$ transition in He^+ lies within about $\frac{1}{2}$ Å on the short-wavelength side of Lyman alpha. One can reasonably expect that this He^+ emission will bother all Lyman-alpha measurements done inside the chamber without some attempt at spectral isolation. Dose's measurements[6] undoubtedly suffered at higher energies where the He^+ emission becomes a large fraction of the total light. An estimate of the total contribution can be made using the cross-section measurements of Dodd and Hughes[27] for producing $4\rightarrow 3$ He^+ emissions by H^+ impact. Without knowledge of how $n=4$ fine-structure states are populated, we can only place limits on the branching of $4\rightarrow 2$ relative to $4\rightarrow 3$. The $4\rightarrow 2$ emission will be between 1.4 and 2.9 times the $4\rightarrow 3$ emission. Scaling Mapleton's Born approximations for charge transfer[24] and simultaneous ionization and excita-

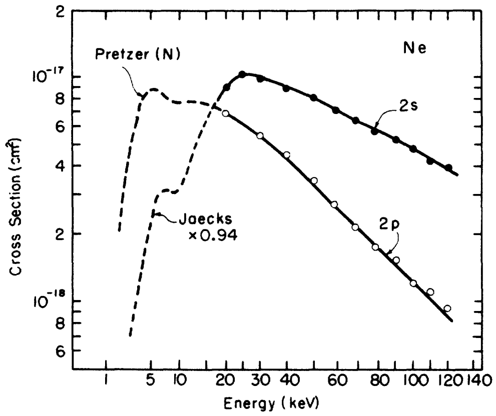

FIG. 5. Cross sections for capture into the 2*s* and 2*p* states by proton impact on Ne. Also plotted are the normalized results of Ref. 1 and Ref. 2.

tion calculations[28] to the $n = 4$ level, we estimate that the $4 \rightarrow 2$ emission should be about twice the $4 \rightarrow 3$ emission. This indicates that the He^+ emission contributes about 25% of the apparent Lyman-alpha signal for an unfiltered detector at 120-keV impact. The O_2 filter absorption is a sharp function of the wavelength on the short-wavelength side of Lyman alpha; thus it was expected that the O_2 filter will discriminate against the He^+ emission, even though it is only $\frac{1}{2}$ Å away. To check this the detector mount was changed from 90° to the beam to 75° to the beam, so that the Doppler shift was to the short-wavelength side of Lyman alpha. The intensity was determined as a function of the O_2 filter pressure for H^+ on Ne at 120-keV impact. The emissions produced by impact on Ne were all Doppler-shifted Lyman alpha. The intensity dropped off exponentially with the pressure indicating a high absorption coefficient. The target was changed to He. The intensity dropped exponentially with O_2 pressure with the same absorption coefficient as with the Ne target, indicating that the absorption coefficient for the Doppler-shifted line and that for the $4 \rightarrow 2$ He^+ emission were about the same (about eight times the coefficient at unshifted Lyman alpha). A comparison was taken for impact on He at 90° to the beam with the O_2 filter filled (atmospheric pressure) and unfilled. Since we estimate that the He^+ emission is less than 3% of the total emission at 20 keV, we simply normalized the two sets of data at 20 keV. The data obtained with no O_2 was about 25% higher at 120 keV than the filtered data, as expected. We estimate that the He^+ emission contributes less than 1% to the O_2 filtered data at 120 keV.

Figure 5 shows the results for impact of Ne. Again the 2*p* data has been corrected for cascade, and Pretzer's data has been normalized to the cascade-corrected values about 20 keV. Jaecks's values for the 2*s* cross sections must be multiplied by 0.94 to agree with our data. This close agreement is to be expected since the calibration basis to both sets of data is the same. Only a minor discrepancy with Jaecks's values should be expected, which is brought about by the different polarization effects in the two sets of data.

Figure 6 displays the cross sections for impact on Ar. Pretzer's 2*p* data is normalized to the cascade-corrected values about 20 keV. Fitzwilson's curve, multiplied by 0.79 to account for the normalization discrepancy, is also shown, showing an apparent agreement in curve shape at the overlapping energies. Bayfield's results are also shown. There is a systematic difference between Bayfield's work and the present work that shows up particularly at the higher energies. Since Bayfield's work does not agree well with either our curve shape or with Fitzwilson's work, we conclude there may be a velocity-dependent systematic effect in Bayfield's work. (We later show that there is excellent agreement with the 3*s* curve shape which tends to support the present 2*s* shape.) A discrepancy in curve shape with Jaecks's work below 20 keV has already been noted by Bayfield.[4] Bayfield's curve is multiplied by 0.72 in order to normalize at 20 keV.

We conclude, like Fitzwilson and Thomas,[7] that the apparent agreement of Bayfield, Jaecks, and Andreev at 20 keV for Ar is fortuitous. The cross-section versus energy curve shapes are considerably different for these investigators. The curves simply come close to intersection at 20 keV. In general, Jaecks's values are considerably lower than Bayfield's between 7 and 20 keV.

Figure 7 displays the cross sections for capture into the 2*s* state by impact on H_2. Bayfield has also

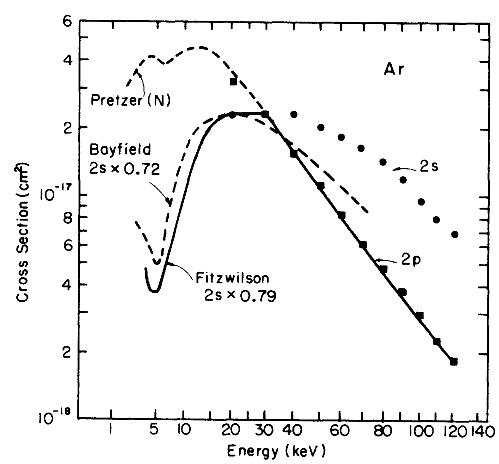

FIG. 6. Cross sections for capture into the 2*s* and 2*p* states by proton impact on Ar. Also plotted are the normalized results of Ref. 4.

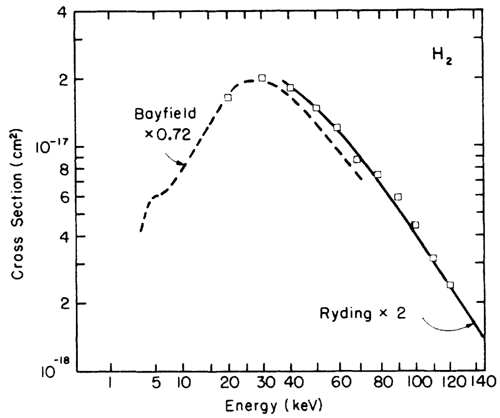

FIG. 7. Cross sections for capture into the $2s$ states by proton impact on H_2 along with normalized results of Ref. 4.

measured this reaction. Multiplying by 0.72, the same factor required for Ar, normalizes his data against ours at 20 keV. The velocity-dependent discrepancy is not quite as apparent as in the case of the Ar target but may still be there.

Figures 8 and 9 show the results for capture from N_2 and O_2 targets. Also shown are Fitzwilson's $2s$ data renormalized by the factor of 0.79. We extend the $2p$ curves below 20 keV with the Lyman-alpha work of Birely and McNeal normalized to our cascade- and background-corrected value at 20 keV. Our $2s$ data for 20-keV impact are in good agreement with Birely and McNeal. Our cross sections are lower, but the difference is less than 10% for both gases. Their cross-section curve shapes agree with Fitzwilson and Thomas below 20 keV.

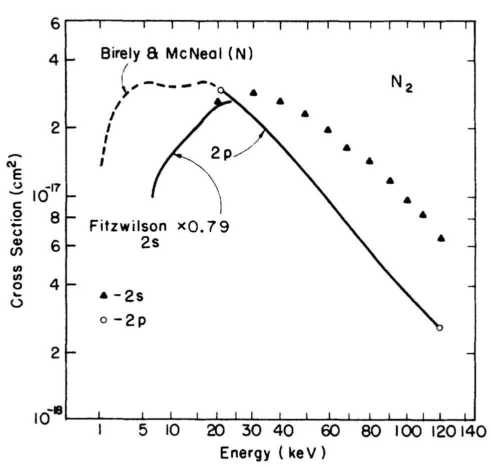

FIG. 8. Cross sections for capture into the $2s$ and $2p$ states by proton impact on N_2 along with the normalized results of Refs. 9 and 10. The $2p$ curve is obtained by subtracting the estimated N_2 background in the apparent Lyman-alpha cross sections in Fig. 3 as well as correcting for cascade.

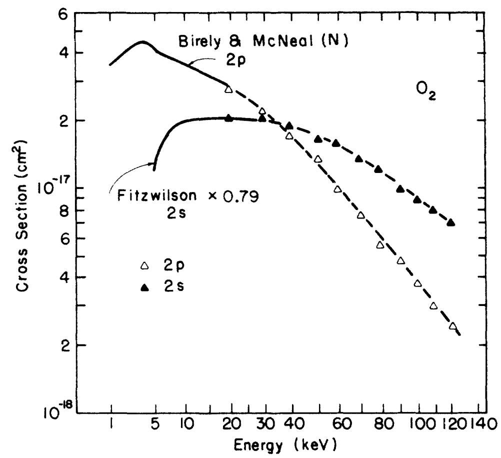

FIG. 9. Cross section for capture into the $2s$ and $2p$ states by proton impact on O_2 along with the normalized results of Ref. 9 and 10.

High-velocity approximations[29,30] for charge transfer indicate capture into the s states should follow an n^{-3} law. Figure 9 compares the $2s$ cross sections with previously measured $3s$ cross sections. The n^{-3} law would predict that the $2s$ cross section would be 3.4 times the $3s$ cross sections. We find that multiplying the published $3s$ cross sections by 3.6 essentially reproduces the $2s$ cross sections for all gases above 30-keV impact with the possible exception of helium where the law appears to be setting in above 100 keV. The agreement is quite striking. We choose to interpret this agreement as strong evidence for the validity of the n^{-3} rule ($n \geq 2$). Further support for this rule comes from the $4s$ capture results relative to the $3s$ results.[31] If this rule has any validity, then it is expected that the $3s$ relative to the $4s$ measurements would confirm the rule since these absolute measurements were based on an optical calibration using a common absolute-standard lamp in the same laboratory. However, here we compare the $2s$ absolute cross section obtained by normalizing to entirely different standards than those used in the $3s$ measurements, which again bears out the n^{-3} rule. This implies that the two calibration methods must be consistent with one another.

The agreement with the n^{-3} rule is not quite as striking for impact on He below 100 keV. The $2s$ points lie consistently higher than expected by the n^{-3} scaling from the $3s$ curve. However, this should not be interpreted as a violation of the n^{-3} rule since the rule was derived as a high-velocity rule. High velocity is a relative term which generally means that the impact velocity is large compared with the orbital velocity of the electron being captured. This condition will be satisfied at a higher energy in He than in any of the other gases.

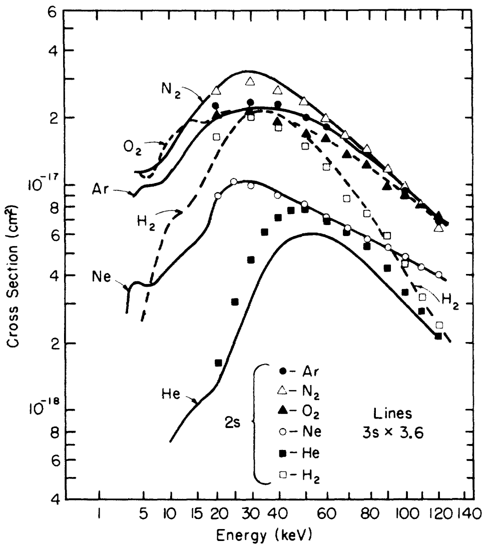

FIG. 10. Comparison of the capture into the $2s$ state with the capture into the $3s$ state (Ref. 25).

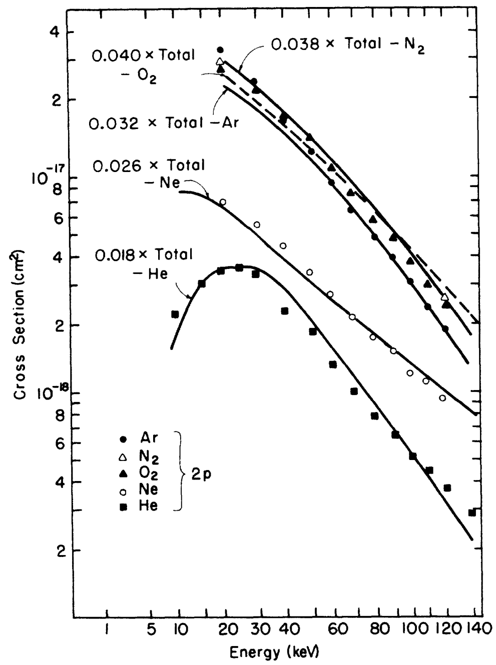

FIG. 12. Comparison of the $2p$ capture cross sections with the total capture cross section.

Certainly no discrepancy can be claimed above 100 keV in Fig. 10. Even at 60 keV, which is near the maximum, the discrepancy appears to be no more than 20%.

Figure 11 compares the $2p$ cross sections with the $3p$ cross sections,[28] multiplied again by 3.6 which is the "n^{-3}" scaling obtained from the $2s$, $3s$ comparison in Fig. 10. The relative error in the $3p$ cross sections is quite large. The $3p$ reproducibility quoted by Ref. 25 is about ± 25% in this energy range. However, the relative error may be somewhat larger. For Ne, the n^{-3} scaling of the $3p$ curve gives a good reproduction of the $2s$ curve. In the case of the remaining four gases, the n^{-3} scaling of the $3p$ curve generally falls below the corresponding $2p$ curve, perhaps suggesting a higher-power law. However, with the exception of He, the n^{-3} scaling of the $3p$ curve gives a fit to within 50% of the $2p$ curves at the higher energies. Considering the experimental uncertainties, these data seem to indicate that an n^{-3} dependency may be used as a rough approximation for capture into p states, again with the possible exception of helium.

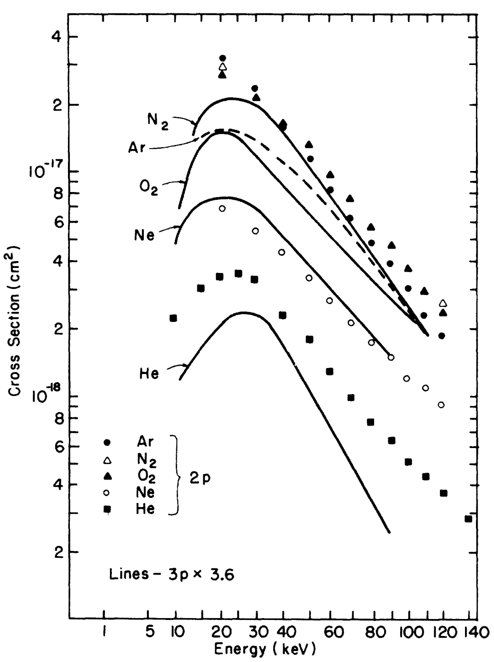

FIG. 11. Comparison of the capture into the $2p$ state with the capture into the $3p$ state (Ref. 25).

It is of interest to compare the capture into excited states with the total capture.[32] We find that capture into the excited s states is less important at the lower energies than at the higher energies. At 120 keV, the $2s$ capture represents about 13%, 11%, 12%, 17%, and 10% of the total for impact on He, Ne, Ar, H_2, and O_2, respectively. The n^{-3} law predicts that at high energies capture into the $2s$ state should be about 12.5% of the capture into the $1s$ state.

Unlike the $2s$ capture, the $2p$ capture is a fairly constant fraction of the total capture in this energy range. This fact is brought out in Fig. 12 which shows a comparison of the $2p$ capture relative to the total capture.

It is of further interest to estimate the capture into the 1*s* state. This can be done easily. We have seen that capture into excited *ns* states follows an n^{-3} behavior for $n=2$, 3, 4 and that an n^{-3} dependence for capture into *p* states for $n=2$, 3 may be used as a rough approximation. Hence, we can estimate the total capture σ_c by using the relationship[30]

$$\sigma_c = Q_{1s} + 1.62\,(Q_{2s} + Q_{2p}),$$

which used the n^{-3} law to estimate capture into the $n \geq 3$ states. (Capture into the higher orbital-angular-momentum states is neglected. Capture into the 3*d* states has been measured.[28] Using the 3*d* measurements and using an n^{-3} law for $n > 3$, it becomes apparent that capture into the *d* states can be ignored as an important capture process relative to capture into the *s* and *p* states.)

Using the above relationship we find that capture into excited states is less important at the lower energies than at the higher energies. Capture into the 1*s* state is about 89% of the total capture for Ar, Ne, O_2, and N_2 at 20 keV, while capture into the 1*s* state is about 96% in the case of He. At 120 keV, capture into the 1*s* state is 75%, 79%, 75%, 80%, and 77% for impact on He, Ne, Ar, O_2, and N_2, respectively. Estimating the 2*p* cross section for impact on H_2, we conclude that capture in excited states may be about 30% for 120-keV impact on H_2. Impact on H_2 appears to produce the highest fraction of capture into excited states in this energy range. The fraction, however, is not a particularly strong function of the target gas at the highest energies.

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