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# Angular Distribution of Metastable Hydrogen Formed by Electron Capture in a Helium Target

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A study has been made of the angular distribution of scattered particles induced by proton impact on a target of helium. Cross sections are presented for scattering of protons, of neutral hydrogen atoms, and of metastable hydrogen atoms. Impact energies range from 4 to 20 keV; scattering angles are from 0° to 2.0°. Measurements of the fractional metastable content of the scattered neutral flux rise from 1% or less at 0° to as much as 8% at angles of 1°. Theoretical predictions of the cross sections for scattering of all particles, neutrals and protons, show reasonable agreement with experiments. Theoretical predictions, by Colegrave and Stevens, of the probability for forming a neutral atom disagree with the experimental values by a constant phase factor. Measurements of the probability for forming a metastable atom do not agree with available theoretical predictions.

## I. INTRODUCTION

A study has been made of metastable hydrogen formation resulting from proton impact on a helium target. The process can be described by the following equation:

$$H^+ + He \rightarrow H(2s) + [He^+] . \quad (1)$$

Here the square brackets indicate that there is no information about the state of ionization or excitation of the target after the collision. Measurements of the cross section for the process are made as a function of scattering angle (0°–2°) and impact energy (4–20 keV). Also presented are measurements on the scattering of protons and the scattering of all neutral particles.

A differential scattering cross section may be operationally defined in the following manner. A projectile beam of flux $N_B$ (particles/sec) is incident on a gaseous target of density $N_T$ (molecule/cm$^3$). The detection system is arranged to have its axis at some angle $\theta$ to the original direction of the projectiles; it selects and detects those projectiles scattered into a small range of angles about $\theta$. Suppose that the detector subtends a solid angle $\omega(x)$ at some point $x$ on the path of the projectile beam. The integral $\int \omega(x)\,dx$ is the effective value of the product between collection angle and observed length of beam path. The detector will receive a flux of projectiles $N_s$ (particles/sec) scattered into its effective aperture. Combining these factors the differential cross section is given by

$$\frac{d\sigma}{d\omega} = \frac{N_s}{N_T N_B \int \omega(x)\,dx} . \quad (2)$$

In measurements of the differential cross section for the formation of H(2$s$) by the mechanism of Eq. (1), the flux $N_s$ is of scattered metastables.

The most direct form of data presentation is the differential cross section. However, use also will be made of another quantity that will be called the probability for forming the metastable state. Suppose that the detector can respond to scattered ions, scattered neutrals (irrespective of excited state), as well as scattered metastables. Let the flux of scattered ions be $N_s^+$, let the flux of all scattered neutrals be $N_s^0$, and let the flux of scattered metastables be $N_s^*$. We define the probability $P_{2s}$ that the scattered projectile is in the metastable state by the following relationship:

$$P_{2s} = N_s^* / (N_s^+ + N_s^0) . \quad (3)$$

Obviously $P_{2s}$ is the ratio of the cross section for scattering metastables to the cross section for scattering all projectiles. This probability may be measured directly as a ratio of fluxes and is not dependent on the other parameters found in the definition of cross section; as a result the accuracy with which $P_{2s}$ is determined may be greater than that with which the corresponding cross section may be determined.

In a previous publication[1] we have discussed in some detail the various features that should be incorporated into the design of an experiment of this type. The previous paper[1] was concerned with the study of the angular distribution of neutral hydrogen and protons which result from proton impact on various target gases; in that work there was no attempt to study the excited state content of the scattered neutrals. The present experiments utilize the same apparatus as that which we have previously described[1]; the only change is that we have now incorporated a metastable-particle detector that permits a study of the metastable content in the scattered neutral flux.

Previous studies of this collision reaction have been primarily concerned with the measurement of probability that the scattered particle is neutral, and of the probability that the scattered particle is metastable. Helbig and Everhart[2] have made an extensive study of the probability for forming neutrals. Crandall and Jaecks[3] and also Dose[4] have studied the probabilities of forming metastables. In all previous work the objective was a measurement at a restricted range of scattering angles. The objective of the present work was the direct measurement of cross sections as a function of scattering angles, rather than the cross section ratios of the existing publications.[2-4] Probabilities for forming different states represent a ratio of cross sections; the direct measurement of a cross section should be a more sensitive test of a theoretical prediction.

## II. EXPERIMENTAL ARRANGEMENTS

In Fig. 1 is shown a diagrammatic representation of the apparatus. It may be considered as being composed of five basic parts: First there is an accelerator that produces a mass analyzed beam of projectiles. Second there is a pair of apertures that collimate the primary beam into a narrow pencil. Third, we have the cell containing the gas. The final three sections are to define the scattered flux; a collimator selecting a range of scattering angles is followed by a metastable-atom detector and a Faraday cup that is used to measure particle fluxes. The metastable-particle detector has been discussed in a previous publication on the measurement of total cross sections for the projection of metastable particles.[5] All other segments of the apparatus as well as detailed constructional features have also been discussed previously.[1] In light of these previous publications[1,5] we will give here only a summary of the important features.

The source of primary projectiles is a 30-kV accelerator fitted with an rf ion source. A magnetic momentum analyzer is used to eliminate contaminants in the projectile beam. The projectile beam was collimated by two collinear circular apertures; the apertures were 0.102 cm in diameter and were situated at 7.40 and 41.40 cm from the center line of the target cell.

The helium target gas was contained in a cylindrical cell which was traversed by the projectile beam along a diameter. Target pressures were monitored using a capacitance manometer type of pressure gauge; the calibration of this device had previously been checked against a McCleod gauge. Target pressures were typically 1 or $2\times10^{-4}$ torr; residual background pressure in the apparatus was $5\times10^{-8}$ torr.

The purpose of the scattered flux collimator is to define the geometrical parameter $\int\omega(x)\,dx$ of Eq. (2). In the present experiments this collimator was provided by two rectangular slits; the first slit was 0.0324 cm wide; 0.31 cm high, and 4.17 cm from the center of the target cell, while the second was 0.1085 cm wide, 0.31 cm high, and 14.33 cm from the center of the cell. All scattered particles that traverse this slit system were analyzed to determine the metastable-, neutral-, and charged-particle fluxes. The evaluation of the geometrical parameter $\int\omega(x)\,dx$ has been discussed in our previous paper.[1] The procedure utilized Skalskaya's[6] formulation of the integral in terms of geometrical parameters of the apparatus; at very small angles the approximations made by Skalskaya break down and a direct point by point integration over the scattering volume was utilized.[1]

The angular resolution of the detector system (defined as the half-width of the transmission function through the scattered particle collimator) was approximately 0.5°.[1] This figure should not, however, be used for any detailed assessment of how the apparatus resolution distorts the true form of a cross section. We have previously suggested[1] that a comparison of a theoretical prediction with experiment should be made by taking the theoretically predicted values and the known geometrical parameters to provide a predicted value of $d\sigma/d\omega$ as defined by Eq. (2).

The metastable detector was of conventional

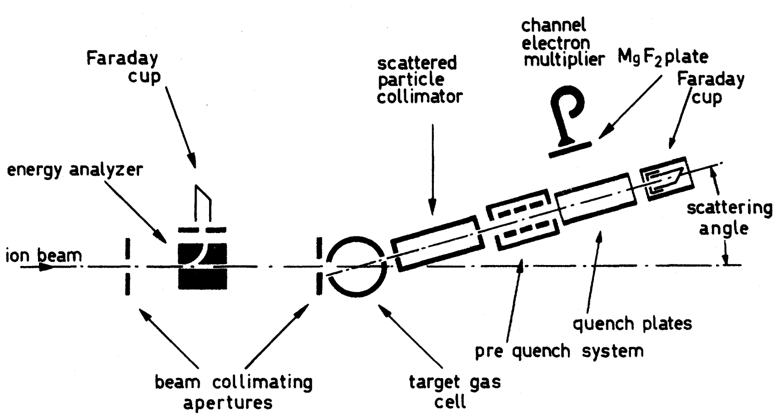


FIG. 1. Schematic diagram of the apparatus.

design; full details including dimension, are given in an earlier paper.[5] An electric field was used to mix the metastable $2s$ state with the $2p$ level; subsequently the $2p$ level decays with the emission of a Lyman-$\alpha$ photon. The field was provided by voltages on two parallel plates placed on opposite sides of the particle beam emerging from the scattered particle collimator. A funneled channel electron multiplier was used to detect the Lyman-$\alpha$ photons. In principle the true metastable signal is the difference between the multiplier count rate with the field turned off and with the field on. However, there was concern that spurious background signals observed with the field turned on might be different from those observed with the field turned off. To ensure that such spurious signals did not cause error, an alternative method of operation was adopted. Immediately in front of the quench region was a so-called prequench region; this was an electric field parallel to the direction of motion of the scattered particles. This field could be used to quench the metastables without altering the trajectory of any scattered ions. The quench field was maintained continuously and the prequench field turned alternately on and off; the difference between photon detector signals at these two settings was taken as proportional to the H($2s$) flux.

Figure 2 gives a diagrammatic view of the metastable detector. The prequench region consists of three cylinders placed coaxial with the trajectory of the scattered particles. The outer cylinders were at ground potential while a voltage could be applied to the central cylinder to cause quenching. The quench unit was designed to have an accurate field configuration so that it was possible to assess the influence on detection sensitivity of both field distortion and fringing. The quench plates, across which the voltage is applied were shielded by two U-shaped pieces to prevent field distortion. The photon detector viewed the whole of the region between the plates as well as a small segment between the grounded shields.

Beyond the metastable detector was located a Faraday cup for the detection of ions. This device was designed so that it could also be used for the detection of neutrals by means of secondary electrons ejected from the base of the cup. Charged-particle flux was measured simply as the total current to the cup; when measuring neutrals the ions are deflected away by an electric field over the quench plates and the neutral flux entering the cup is monitored by the ejection of secondary electrons from its base. Our previous paper[1] gives a complete description of this device and includes a discussion of the method used to determine the detection efficiency for neutrals.

The metastable detector, Faraday cup, and scat-

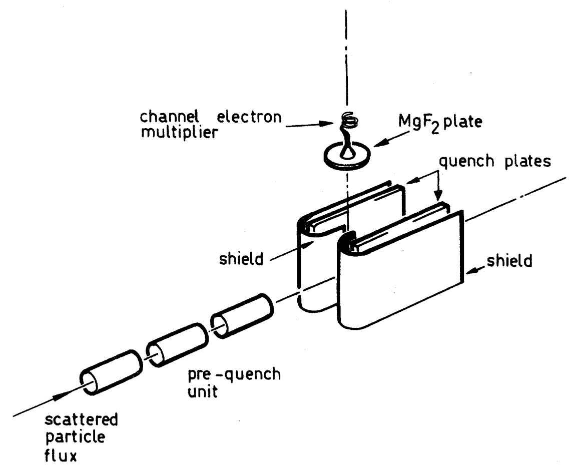


FIG. 2. Schematic diagram of the metastable detector.

tered particle defining apertures were all mounted on a rigid arm; this arm could be rotated about the center of the scattering cell. Although an angular range of $-5°$ to $+45°$ was available, the rapid fall off of signal with angle caused measurements to be restricted to a range of $\pm 2°$ about the primary beam direction.

The primary beam current was measured in the following manner. When the detection systems were rotated to 0.6° or more the ion beam fell on the inner surface of the target gas cell. The walls of the cell were isolated and the current to them could be measured directly. The construction of the cell was such that it formed a deep Faraday cup from which secondary emitted particles could not readily escape. A small potential (+10 V) applied to the target cell was sufficient to suppress secondary electrons and cause a saturation of the current measured on the cell wall. Thus the beam current could be measured by the current of the gas cell wall. Tests were made to show that the small electric field at the exit of the cell did not significantly quench the flux of scattered metastables; the metastable signal was independent of suppression field employed.

A test of the beam monitoring method was made in the following manner. With the scattered particle collimator removed, and the scattering angle set to 0°, the primary projectile beam falls directly on the Faraday cup. With this configuration the following comparison was made: First the scattering angle was set to 0° and the current measured on the Faraday cup; second the scattering angle was set to 0.6° (or more) and the current measured on the target chamber wall. These two configurations gave the same result (within $\pm 1\%$) and it was therefore concluded that the measurement of current on the target cell wall was an accurate procedure.

The detailed construction of the target cell has been described in our previous work.[1] The diameter of the cell was 6.7 cm. Entrance and exit aperture were made larger than other apertures in the apparatus so that they do not limit the size of the primary beam nor intercept the scattered particles.[1,5] At low scattering angles (less than 1°) the length of beam path observed by the scattered particle detection system was limited by the finite length of the gas cell. The method of allowing for this in the evaluation of the integral in Eq. (2) has been previously described.[1]

Studies were made of the dependence of metastable signals on the various potentials applied in the quenching and prequenching regions. These tests were carried out at various scattering angles and also at 0° scattering angles. The tests, and the conclusions, were essentially the same as those described in our previous paper on measurements of total cross sections for metastable formation.[5] In our previous work[5] it was concluded that the various fields caused at least 97% of the metastable atoms to be quenched within the region viewed by the photon detector.

Particular care was directed to the elimination of spurious background signals. All measurements of scattered flux were shown to vary linearly with the target pressure and beam intensity. Under some circumstances appreciable signals were observed at zero target pressure; these signals presumably came from scattering on residual gas in the chamber as they demonstrated a rapid decrease with increasing scattering angle. Corrections were made for all such spurious signals. The circumstances under which corrections were appreciable were a function of the nature of the collision combination and the energy of the projectiles. Under no circumstance did this type of background exceed the true signal and for most measurements, the background corrections were less than 10% of the true signal.

All measurements were repeated on both sides of the primary beam direction. Asymmetry of the distributions about the center line indicated improper alignment of the ion beam with the defining apertures. An example of the symmetry that was obtained is given in our previous paper.[1]

### III. ESTABLISHMENT OF ABSOLUTE CROSS SECTIONS

The cross section for scattering ions was measured directly as an absolute value. The scattered ion flux was measured as a current and all the other factors in Eq. (2) were determined by the techniques described above.

The cross section for scattering neutrals was also measured directly as an absolute value. Scattered neutral flux was measured with the secondary electron emission detector; the efficiency of that device was calibrated directly by the techniques described previously.[1]

The cross sections for formation of metastables are, in fact, only relative values. In a previous paper[5] we have described techniques by which the efficiency of the metastable detector was shown to be independent of projectile energy. Thus the variation of metastable signal with energy and angle does in fact provide directly the relative variation of cross section. Rather than presenting these relative values we consider that it is more useful to assign an absolute value to the data by normalization of the whole data set to some previous measurements by other workers.

In a previous article we have described how the present apparatus can be used to measure total cross sections for formation of metastables by charge transfer.[5] The same apparatus was used as for differential measurements but the detectors were set to receive particles scattered at 0° and the collimating apertures that define the scattered flux were removed; with this arrangement all metastables formed with scattering in the range ±5° were detected simultaneously. In this manner the apparatus may be used for measurement of total cross sections for charge transfer; if one assumes a value for such a cross section from some previous experiments then a metastable detection efficiency may be evaluated.

It was decided to utilize for the normalization a previous determination of H(2*s*) formation by neutralization in argon. Three independent and reasonably accurate absolute measurements of this case have been made; the work is done by Jaecks *et al.*,[7] Andreev *et al.*,[8] and by Bayfield.[9] These three determinations appear to be in good agreement in both magnitude and energy dependence. The agreement in magnitude is, however, illusory. All three experiments neglect to correct for the polarization of the field-induced emission[10–12]; this polarization will cause an anisotropic distribution of the emission about the direction of the electric field. It is not possible to carry out a retrospective assessment of the resulting error. The published calculations of polarization[10,12] show that the magnitude of the necessary correction for polarization effects depends on the specific quench field configuration and the time required for the metastable atom to enter the field. It is not clear what situation is appropriate to any of the previous experiments. Moreover the field configuration in some of the previous experiments was not completely specified. It was decided to normalize to the work of Andreev *et al.*[8]; this experiment is a direct absolute measurement for which a small uncertainty (±20%) is claimed. If the polarization predictions of Sellin *et al.*[10] are valid for the experiment of Andreev *et al.* then the data will be too low by an amount of 18%.

Specifically the normalization was carried out on the assumption that the cross section for H(2*s*) formation by neutralization of 20 keV $H^+$ in Ar was $3.0\times10^{-17}$ $cm^2$. The absolute accuracy of the present measurements cannot exceed that of the data to which they are normalized; that limitation of accuracy cannot readily be assessed.

## IV. ACCURACY OF DATA

From Eq. (2) it is seen that three factors are common to all cross section determinations; these are the target density, primary beam current, and geometrical factor. The measurement of target density was assigned an absolute accuracy of ±5%; this represents the accuracy of the McLeod gauge against which the instrumental calibration was checked. Random errors in pressure measurements due to zero drift and reading error did not exceed ±2%. The electrometer that was used to measure primary beam current was calibrated with a standard current source; systematic errors were essentially zero. Reading errors and zero drift in current measurement caused a random uncertainty of less than ±2%. The uncertainty in the geometrical factor arises from the limitations of accuracy with which the sizes and positions of the various slits were determined; that uncertainty was estimated to be less than ±6%.

The measurement of scattered $H^+$ and $H^0$ again used a calibrated electrometer for which the systematic error was essentially zero. The random uncertainty arises from reading errors and zero drifts; for $H^0$ measurement there is additional uncertainty in the measurement of secondary emission coefficient. The random errors in measurement of scattered $H^+$ and $H^0$ currents are, respectively, ±5 and ±7%.

Measurement of H(2*s*) flux was not carried out absolutely; the objective was to provide relative values of cross sections. Tests[5] showed that the detection efficiency varied by less than 10% between extremes of particle energy used here. Thus relative values of cross sections at different energies should be accurate to better than 10% under all conditions. The random errors in this measurement are a strong function of angle. At large scattering angles the signals were very small and the statistical errors in the count was sometimes as high as 10%. Furthermore, appreciable corrections for background were necessary. The estimated limits of accuracy are summarized briefly as follows. For all data at angles of less than 1° the limits are ±6%; for data at angles greater than 1° for 4-keV impact the limits are ±20%; for all other data the limits are ±15% or less.

The limits of absolute accuracy of the metastable data cannot be properly estimated since the values are assigned by normalization.

We choose to estimate the net uncertainty in a cross section by taking the square root of the sum of the squares of the various contributing factors. In this manner the absolute values of cross sections for formation of $H^+$ and $H^0$ should be accurate to within ±8%; random errors for $H^+$ and $H^0$ production are, respectively, less than ±6 and ±8%. Maximum random errors in H(2*s*) cross sections for angles less than 1° are ±7%; for angles greater than 1° at an energy of 4 keV the limit is ±20%; for all other conditions this limit is ±15%. Relative values of H(2*s*) cross sections at different

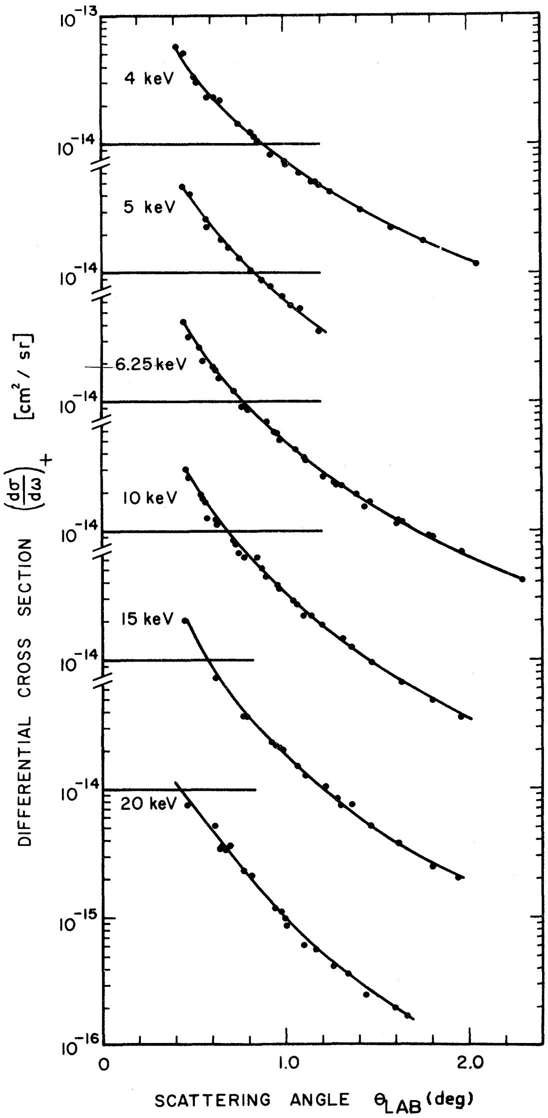


FIG. 3. Differential cross section for scattering of $H^+$ induced by $H^+$ impact on He. Note broken cross-section scale; intersection of horizontal line with data points indicates a cross section of $10^{-14}$ $cm^2/sr$.

angles and energies should not exhibit systematic errors in excess of 10%.

The measurement of scattering angle was carried out with a mechanical scale. The error in angle did not exceed ±0.034° at any point. The energy of the primary projectiles was determined periodically with an electrostatic analyser that was placed in the beam line. The precision of this determination was ±3%.

There is one additional source of uncertainty in the measurements. The cross section in any differential scattering experiment is an average over the range of scattering angles accepted by the detector. Thus there may be a systematic difference between the measured cross section and the true

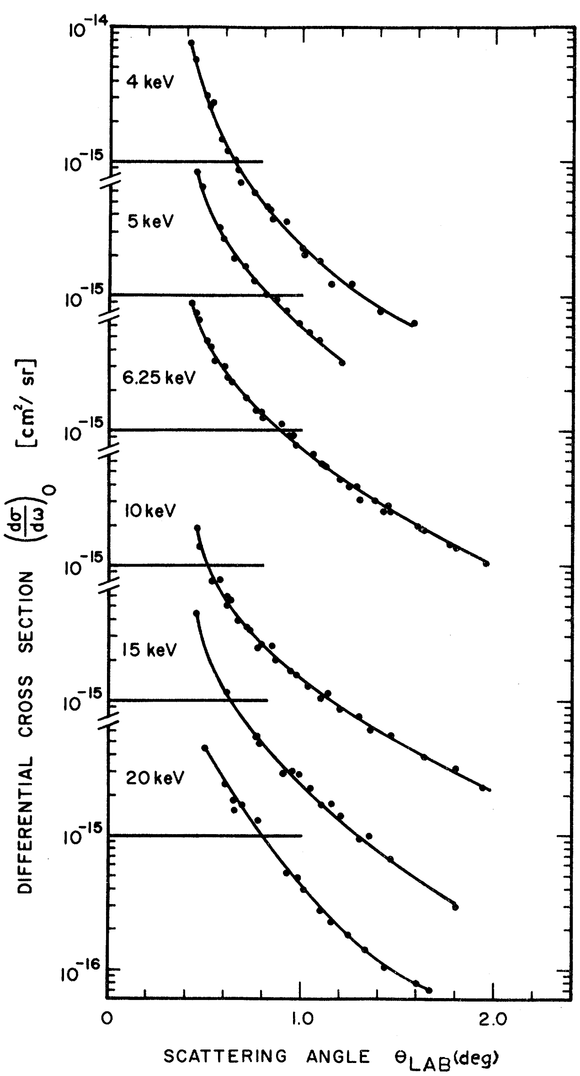


FIG. 4. Differential cross section for scattering $H^0$ induced by $H^+$ impact on He. Note broken cross section scale; intersection of horizontal line with data points indicates a cross section of $10^{-15}$ $cm^2/sr$.

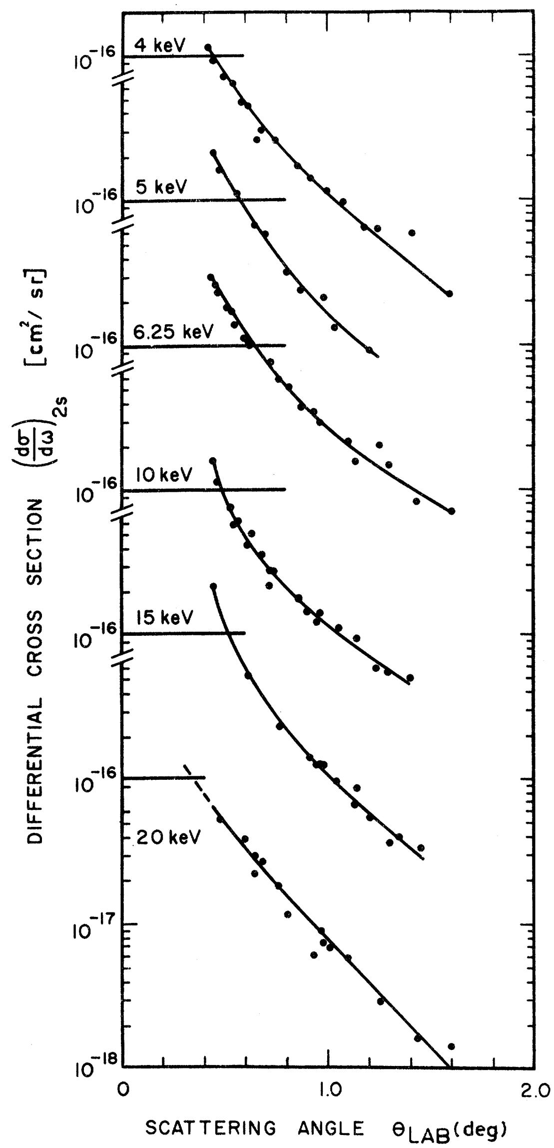


FIG. 5. Differential cross section for scattering H(2*s*) induced by $H^+$ impact on He. Note broken cross section scale; intersection of horizontal line with data points indicates a cross section of $10^{-16}$ $cm^2/sr$.

microscopic cross section. We do not attempt to unfold the true cross section from the measured data nor to estimate the resulting error. It is suggested that the most satisfactory method of comparing a theoretical prediction of cross section with this data is to fold the theoretical values into the apparatus geometry (given in Ref. 1), and thereby arrive at a predicted value of the experimentally measured quantity. This problem of resolution is of course inherent in any differential scattering experiment.

At angular settings below 0.5° the collimator that defines the scattered particle flux permits un-

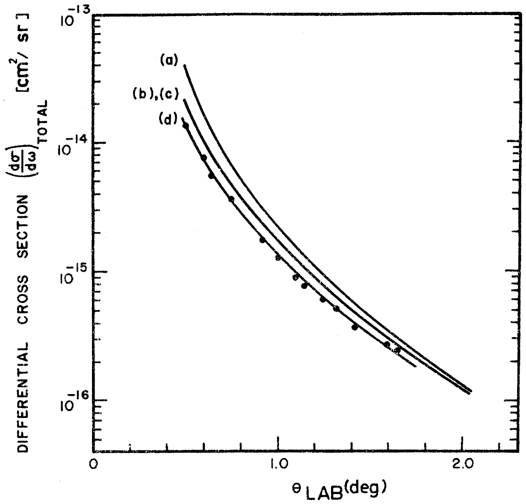


FIG. 6. Differential cross section for scattering of all projectiles; $H^+$ impact on He at 20-keV impact energy. Lines (a), (b), and (c) are theoretical calculations using potentials proposed by Smith (Ref. 14), Bingham (Ref. 13), and Bingham (Ref. 15), respectively. Line (d) is the experimental data.

deviated projectiles to reach the detection region. At these angles the scattering cross section decreases very rapidly with increasing angle and the flux entering the detector will be heavily weighted by undeviated particles. It is likely that the cross sections for $H^0$ and H(2$s$) production measured at angles below 0.5° will be unrepresentative of the true behavior; we therefore present no data for these angles. In the case of $H^+$ scattering it is clearly impossible to make any measurements with this apparatus at angles less than 0.5° since there is no way of resolving scattered projectiles from unscattered primary projectiles.

## V. RESULTS

In Figs. 3–5, we show the differential cross sections for scattering of $H^+$, $H^0$, and H(2$s$) resulting from $H^+$ impact on He. All cross sections are smoothly varying functions of scattering angle $\theta$, showing no undulations or extraordinary behavior. In general, most data sets fit curves of the form $K\theta^{-n}$ with $n$ ranging from 2.5 to 3.2 depending on the energy and reaction. Smooth curves have been drawn through the data points. There are no direct comparisons that may be made with theory; however, from these data one may derive some quantities that do permit comparisons.

There have been a number of predictions of cross sections for scattering of all particles. In Fig. 6, we show that cross section at 20 keV impact obtained by the addition of data in Figs. 3 and 4. Also shown in that figure are a number of theoretical predictions[13–15] that differ only in the potential utilized. The recent work of Bingman,[15] used a "static potential" that takes into account all interactions between electrons and nuclei at all points during the collision process. The earlier work of Bingham[13] used a screened potential and the work of Smith[14] uses a similar potential but with allowance for shell structure. At 20 keV energy the two predictions by Bingham[13,15] are in agreement; they agree with experiment when account is taken of possible experimental errors in determination of cross section and angle. At lower energies the predictions of Bingham[15] lie slightly below those of Smith[14] and the data of Bingham[15] correspond most closely to experiment.

In Figs. 7 and 8, we show the probability of forming neutrals $P_0$ and the probability of forming metastables $P_{2s}$. The data are presented at a fixed scattering angle of one degree; probabilities at larger angles remain essentially unchanged. The probabilities are shown as a function of reciprocal velocity. Also included are a number of previous experimental[2–4] and theoretical re-

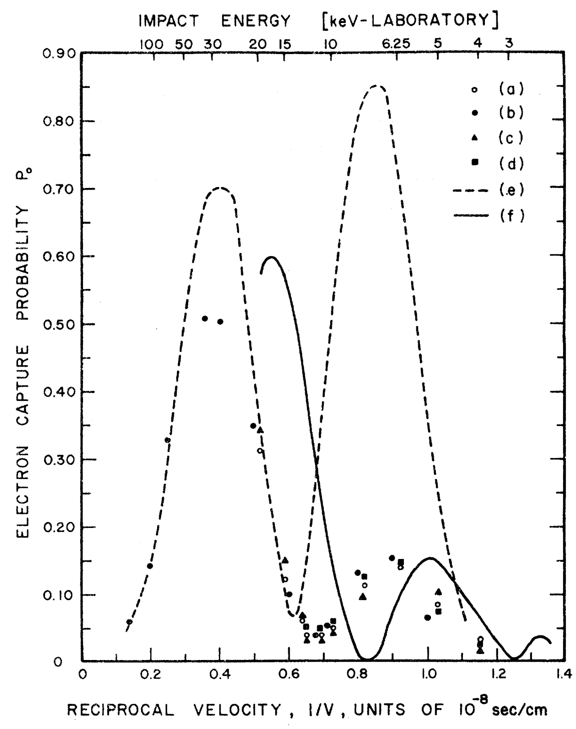


FIG. 7. Probability of transfer to all states of hydrogen from protons on helium. (a) Present experimental results at a fixed scattering angle Θ of 1°. (b) Data of Helbig and Everhart (Ref. 2) for a fixed value of Θ$E$ of 20 keV deg. (c) and (d) Data of Helbig and Everhart (Ref. 2) for fixed angles Θ of 1.5 and 0.7°, respectively. (e) Theoretical results of Sin Fai Lam (Ref. 16) for transfer to 1$s$, 2$s$, and 2$p$ states at Θ$E$ of 20 keV deg. (f) Theoretical results of Colegrave and Stevens (Ref. 17) for transfer to 1$s$ state at 1.5°.

sults.[16,17]

The angles $\theta$ and energies $E$ at which the various data were obtained are specified in the figure captions. The theoretical values used for $P_0$ differ from the experimental data in that they take into account only the formation of a few excited states (see caption, Fig. 7). The experimental values of $P_0$ are all in excellent agreement with each other; they disagree substantially with theory. The absolute values of $P_{2s}$ from the work by Dose[4] were established by normalization to theory; this is not likely to be accurate[2] and we have arbitrarily renormalized the data to the results of the present experiment. The three experimental determinations are in fair agreement with each other. Again there is little correlation of theory with experiment. Crandall and Jaecks[3] have provided a detailed discussion of the $P_0$ and $P_{2s}$ data as well as the theoretical results. In particular, it is notable that the theoretical prediction of $P_0$ from the work of Colegrave and Stevens[17] differs from the experimental data only by a constant phase factor; magnitude and relative position of the peaks is in good agreement with experiment.

## VI. FRACTIONAL METASTABLE CONTENT OF NEUTRAL FLUX

A further quantity of interest is the fraction of the scattered neutral flux that is in the metastable state; we shall refer to this by the symbol $F(2s)$. This quantity is of course equal to the ratio of the cross section for formation of metastables to the cross section for formation of all neutrals. The fraction $F(2s)$ can be operationally defined in a

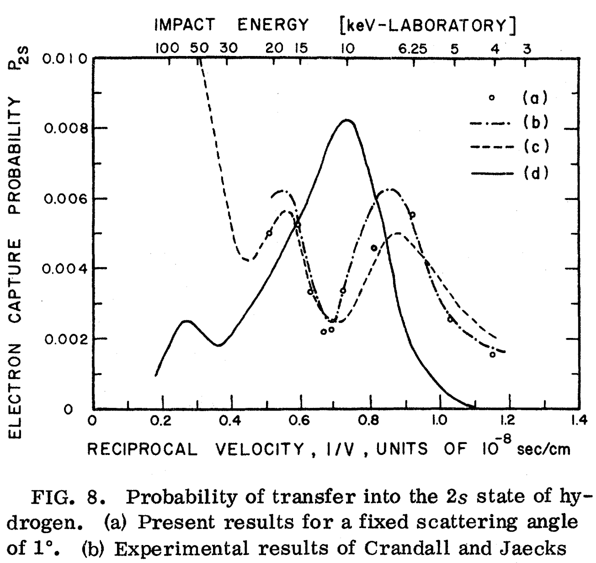


FIG. 8. Probability of transfer into the $2s$ state of hydrogen. (a) Present results for a fixed scattering angle of 1°. (b) Experimental results of Crandall and Jaecks (Ref. 3) for a fixed value of $\Theta E$ of 20 keV deg. (c) Experimental results by Dose (Ref. 4) at $\Theta$ of 2.2°, normalized to curve (a) at 20 keV. (d) Theoretical calculations of Sin Fai Lam (Ref. 16) for a $\Theta E$ of 20 keV deg.

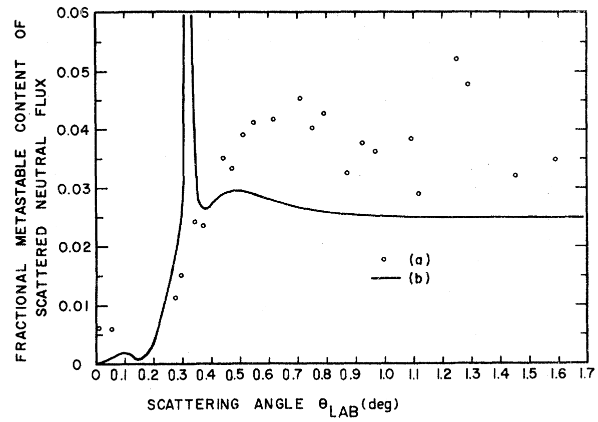


FIG. 9. Fractional metastable content of the scattered neutral flux, $F(2s)$. (a) Present data. (b) Theoretical data by Sin Fai Lam (Ref. 16) for ratio of $2s$ cross section to sum of $1s$, $2s$, and $2p$ cross sections.

very simple manner; it is just the ratio of the metastable flux to the total neutral flux.

From the data of this experiment we can generate $F(2s)$ curves. The measurements of $F(2s)$ encompass the full range of angles for which cross-section measurements were carried out. In addition the quantity has been evaluated for scattering angles below $\frac{1}{2}$° where no cross-section data are presented. Data on $F(2s)$ at such low angles will of course be severely distorted by the limited angular resolution of the detection systems; nevertheless they do show some interesting features.

Figure 9 shows such a measurement of $F(2s)$ at an energy of 6.25 keV; the raw data points are shown. There is an appreciable scatter of data points at large angles due to the poor statistical accuracy of the data. For small scattering angles the fraction is small, approximately 0.005. The fraction rises and apparently reaches a constant value of about 0.035 at angles from 0.7° to 1.7°. Thus at large scattering angles some 3.5% of the neutral flux is metastable compared with 0.5% at 0° scattering. These general features are repeated at all scattering angles; the highest metastable content we have measured is 7.5% at an energy of 10 keV and angles greater than 0.6°. In a previous experiment with an atomic hydrogen target, Bayfield[18] has also observed a rapid rise in $F(2s)$ at small scattering angles; that is very similar in all respects to the behavior exhibited in the present work.

Figure 9 also includes a theoretical value of $F(2s)$ evaluated from the theoretical predictions of Sin Fai Lam.[16] The theory predicts $P_{1s}$, $P_{2s}$, and $P_{2p}$. We have here estimated the theoretical value of $F(2s)$ by the quantity $P_{2s}/(P_{1s}+P_{2s}+P_{2p})$; this should be a reasonable estimate if the probability for excitation of higher states may be neglected. There is good qualitative agreement between the theory and experiment; the sharp peak shown by the theory would be smoothed out by the limited angular resolution of the apparatus and would therefore be absent from the experimental data. The agreement is particularly surprising because the individual predictions of $P_{2s}$ and $P_0$ do not agree particularly well with experiment.

In Fig. 10, we show some further data on $F(2s)$ at various energies; here for clarity we omit individual data points and show a smoothed curve. Figure 10 includes data for energies of 5, 6.25, and 10 keV. There must be some concern about the distortion of these curves at low angles due to the limited angular resolution of the apparatus. In particular at angles less than 0.5° the detector system accepts some projectiles that have not been deflected by a collision. This is particularly worrying since the rapid decrease of $F(2s)$ occurs at just this angle. To assess the influence of the finite beam size the primary beam collimation was improved by reducing the collimator slit widths by a factor of 3.3; the measurements were then repeated. These new data with reduced beam diameter are shown on the figures as a dotted line. At the energy of 4 keV the data at the improved resolution are in complete agreement with the original measurements; for this case the dotted line coincides with the solid line and it has been omitted for clarity. At the two higher energies the effect of improved collimation is to slightly shift the curve to lower angles; however, the major features remain unchanged. From this test we conclude that the general features of the $F(2s)$ curves are not severely distorted by the finite size of the primary beam.

It is well known that the impact parameter in a collision is a function of the product between scattering angle $\theta$ and impact energy, Bingham[13] has calculated the relationship between $E\theta$ and impact parameter for a Bohr potential. From Bingham's[13] calculations we have evaluated values of impact parameter and have included such a scale in Fig. 10. It is observed that rapid rise of the metastable fraction occurs in a very limited range of impact parameters from about 0.5 to 0.25 Å. This behavior appears to be independent of the projectile energy.

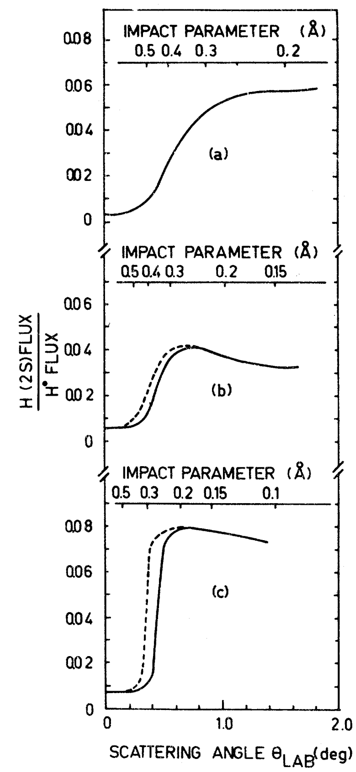


FIG. 10. Fractional metastable content of the scattered neutral flux $F(2s)$. At impact energies of (a) 4.0 keV; (b) 6.25 keV; (c) 10 keV. Solid lines represent data with a 0.10-cm-diam beam; the dashed lines are for a 0.03-cm-diam beam.

## VII. CONCLUSIONS

The various cross-section values exhibit the expected rapid decrease with scattering angle. There are theoretical predictions of the scattering of all particles, irrespective of charge and state of excitation. Such predictions by Bingham[13,15] are in reasonable agreement with experiment. Attempts to predict the proportion of scattered flux in the neutral charge state or the metastable excited state are not successful. The fractional metastable content of the neutral flux rises rapidly with increasing angle; this behavior appears to be related to the impact parameter in the collision.

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# Cross Sections for Single-Electron Capture in Collisions of Protons and Deuterons with Atoms

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Electron-capture cross sections by protons (into 1*s*, 2*s*, and 3*s* states) resulting from collisions with the atomic systems have been calculated using simple classical formula of Gryzinski. Results obtained have been compared with the other theoretical calculations and experimental results. Comparison has been made between the capture and ionization cross sections from collisions of heavy singly charged particles with atoms.

## INTRODUCTION

The collision of positively charged particles with atomic and molecular systems differs in one important respect from the electron-impact phenomena. In the former situation the particle may capture one or more electrons from the target system and thereby become neutral. The target atom or molecule is reduced to an ionized state. Under suitable conditions (impact velocity, etc.) this capture process may make a substantial contribution to the cross section for ionization of atoms and molecules by positively charged heavy-particle impact. This circumstance makes the evaluation of capture cross sections an important aspect of studies in atomic collisions.

It is very difficult to study the capture process in quantum mechanics and, therefore, theoretical calculations of capture cross sections have been restricted almost exclusively to classical methods. The initial approach due to Thomas[1] has been modified recently by Bates and Mapleton[2] and by Mapleton.[3] Another calculation using classical methods has been given by Abrines and Percival.[4] Gryzinski[5–7] in his pioneering work on the classical description of the collision process has also studied the capture process. Making simplifying assumptions and approximations, he has succeeded in deriving analytical expressions for the capture cross sections. In view of the relative simplicity of the calculational procedure, it was thought worthwhile to study the applicability of Gryzinski's[7] expressions for capture from several atoms. This was hoped to be especially useful for comparison with expressions for the capture cross sections as given by Garcia *et al.*[8] These latter authors use for $\sigma_{\Delta E}$ the exact expression derived by Gerjuoy[9] and have pointed out the limitations of Gryzinski's[7] formulation in some examples.

In this paper we have calculated the cross sections for electron capture from various systems by protons and deutrons into their ground as well as excited states using the simple classical formula formula of Gryzinski.[7] Calculated results are compared with earlier calculations[8,10,11] and available experimental[12–17] results.

## METHOD OF CALCULATION

Gryzinski's[7] classical expression for the cross section of capture process can be written as

$$\sigma_c = (\sigma_0/U_i^{A2})(2U_i^B/U_i^A)G_c(U_i^B/U_i^A;\ v_B^+/v_i^A)\ ,$$

where

$$G_c(U_i^B/U_i^A;\ v_B^+/v_i^A) = \frac{f_{\bar{v}}(v_B^+/v_i^A)}{[1+(v_B^+/v_i^A)^2]^2-(U_i^B/U_i^A)^2}$$

and

$$f_{\bar{v}}(v_B^+/v_i^A) = (v_i^A/v_B^+)^2\{v_B^{+2}/(v_B^{+2}+v_i^{A2})\}^{3/2}\ ,$$

where

$U_i^A$ is the binding energy of the electron in the target system, $U_i^B$ is the binding energy of the electron in the incident particle, $\sigma_0 = \pi e^4 = 6.56\times10^{-14}$ $eV^2\,cm^2$, $v_i^A$ is the velocity of the electron corre-