SURVEY ON ELECTRON-ATOM COLLISION EXPERIMENTS

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The field of electron-atom collision experiments is a formidable topic for a forty minute survey paper. This field has a long proud history studded with the names of distinguished experimentalists. In our host country alone one thinks immediately of the early work of Ramsauer and Kollath in low energy electron scattering, Hanle in electron impact excitation of optical transitions, and Maier-Liebnitz in the study of metastable production by electron impact. In the wake of such leaders there has appeared an outpouring of important work by students and colleagues, which continues to the present day. Any comprehensive up-to-date survey of electron-atom collision work would necessarily include a discussion of the very exciting work on electron polarization underway at Mainz under the leadership of Dr. Deichsel, and at Karlsruhe with Dr. Kessler. One would also include the beautiful high resolution electron beam scattering work of Dr. Ehrhardt at Freiburg, and the major contributions by Dr. Kleinpoppen and his students in electron scattering from atomic hydrogen and the alkalis.

Then, when one also considers the large amount of work which has come out of other European countries, the USSR, and the United States it becomes clear that this paper cannot do justice to the field of electron-atom collisions in all its breadth and historical depth.

Taking refuge in the second part of the title of this International Symposium, I will confine most of my remarks to electron collisions with "one- and two-electron atoms". Also, taking note of the papers to be read later in this meeting, by Dr. Reichert on "Polarization of Scattered Electrons" and by Dr. Ehrhardt on "Resonance Scattering Experiments" I will, with considerable regret, avoid any serious intrusion into these fascinating and very active areas.

First I will undertake a review of the experimental results available for electron scattering from atomic hydrogen. Recently this has been the subject of the most intensive theoretical effort, and hence this is where valid experimental results are in the greatest demand for comparison with calculated cross sections. Unfortunately the experiments are extremely difficult, so that the available data have been rather limited. However, within the past year or two there have been some very significant experimental

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accomplishments, several to be reported at this meeting. A recapitulation of the experimental situation may be useful.

The modern era of electron-hydrogen atom collision measurements rests on the development of techniques for producing hydrogen atom beams. The initial breakthrough was the application of a tungsten oven to the production of a dissociated hydrogen beam by Lamb and Retherford [1] in connection with their famous measurement of the fine structure constant. By 1955, we were receiving enthusiastic letters from our colleague Wade Fite about his collaboration with R. L. F. Boyd and G. R. Green at London on the application of hydrogen beam techniques to electron-atom scattering problems. From that start Fite and his coworkers carried out the series of measurements which were published in late 1958 on electron-impact ionization of atomic hydrogen (Fite and Brackmann [2]), on excitation of the 2p state of atomic hydrogen (Fite and Brackmann [3]), and on elastic scattering of electrons from atomic hydrogen (Brackmann, Fite and Neynaber [4]). In 1959 Lichten and Schultz [5] reported the first direct measurement of excitation of the 2s state of atomic hydrogen by electron impact. More recently additional measurements have become available and an intercomparison of results becomes possible and profitable.

![Fig. 1. Schematic diagram of the crossed-beam apparatus used by Fite and Brackmann [3] to study the excitation of Lyman-α radiation.](image)

The crossed beam method is illustrated schematically in fig. 1, taken from [3]. A hydrogen atom beam, produced from a tungsten furnace, is crossed by a beam of electrons. The products of the electron-atom interaction can be studied by use of appropriate detectors. In this figure a photon counter is illustrated as appropriate for measurement of the probability for exciting Lyman-α photons.

For most measurements it is necessary to separate the signal originating in the crossed beams from that originating from the electron interaction with the background gas. Typically, a mechanical chopper is used to modulate the atom beam. The products of the electron-atom beam interaction are then modulated and can be separated from background effects by standard demodulation techniques.
Fig. 2. Relative measurements of the cross section for excitation of the 2p→1s transition in atomic hydrogen: (Fite and Brackmann [3], O; Fite, Stebbings and Brackmann [12], △; and Long, Cox and Smith [6], +) compared with the Born approximation result for Q, without cascading (curve 1) and with cascading (curve 2), and compared with the result of a 1s-2s-2p close coupling calculation for Q (Burke, Schey and Smith [7]) (curve 3) without cascading. Error bars shown for Fite et al., [12] are confidence limits. Fite and Brackmann [3] give ±12½% confidence limits; Long et al. [6] results are limited by systematic errors of about 3%.

In fig. 2 are displayed the results of several measurements of the relative cross section for excitation of the 2p state of atomic hydrogen. The method is based on the use of a photon detector to view the region of interaction of the electron and atom beams. For all of these measurements the angle of observation was at 90° to the axis of the electron beam. The interaction region is shielded from external fields; and other sources of fields, such as space charge, have to be reduced to a fraction of a volt per centimeter to avoid quenching the metastables, which have a field-free lifetime of 1/7 sec. The lifetime of the 2p state is so short (≈1.6×10⁻⁹ sec) that the displacement of the atoms during the radiation time, at ≈10⁹ cm/sec, can be neglected.

The measurements obtained by Fite and collaborators and those carried out more recently with improved accuracy (±3%) by Long, Cox and Smith [6], appear to be entirely consistent. They are shown here normalized to the Born approximation at 200 eV, to permit comparison with the shapes obtained from the Born approximation and from a 1s-2s-2p close coupling calculation by Burke, Schey and Smith [7]. Although the validity of this normalization to Born may be in some question, there is a most significant disagreement between the theoretical and experimental results in the energy range below 40 eV. Burke [8] showed that inclusion of the 3s and 3p states in the close-coupling scheme produced a 10% reduction at 16.5 eV,
but this still leaves a large discrepancy, and apparently a large number of states will have to be included to obtain good agreement.

Fig. 3 shows the situation very near to threshold, where there are only a few open channels and where all can be incorporated in the close-coupling scheme. The experimental results shown here are the work of Chamberlain, Smith and Heddle [9]. These authors compared their results to a quadratic trial function of form similar to that obtained by Damburg and Galitsis [10] by folding the measured electron energy distribution into the trial function. The same folding procedure has been applied here to the 3-state plus 20 correlation terms result obtained by Burke, Taylor and Ormonde [11], and is shown here as a dashed line. The excellent agreement verifies the existence of structure at threshold.

The circles represent points obtained by Fite, Stebbings and Brackmann [12] with the energy scale shifted slightly and the amplitude adjusted to improve the fit to the theoretical result.

Fig. 4 shows the most recent experimental study of the 2p excitation threshold region by McGowan, Williams and Curley (private communication 1968) and carried out with much higher energy resolution than the preceding work. This figure is dramatic confirmation of the reality of the \(^1\)P resonance at threshold. It also shows some structure just above the \(^1\)P resonance not yet predicted by theory, and exhibits for the first time the structure in the vicinity of the \(n = 3\) threshold predicted by Burke, Taylor and Ormonde. McGowan, Williams and Curley have used a 127° electrostatic
Fig. 4. H(2p) excitation cross section in the vicinity of threshold (McGowan, Willliams and Curley, private communication, 1968).

analyzer to obtain a 0.07 eV electron energy distribution. This is about one-fifth the width used by Chamberlain et al. They also carried out their observations at the "magic angle" of $\theta = 54.5^\circ$ to the axis of the electron beam. At this angle the cross section has the same energy dependence as the integrated cross section. That observed at $\theta = 90^\circ$ does not, and must be corrected for angular anisotropy. This is most easily accomplished using the polarization.

The polarization of radiation excited by electron impact can be expressed in terms of the intensities of the components having electric vectors parallel ($I_{||}$) and perpendicular ($I_{\perp}$) to the electron beam axis, as observed in a direction at $90^\circ$ to the electron beam:

$$P = \frac{I_{||} - I_{\perp}}{I_{||} + I_{\perp}},$$

(1)

For electric dipole radiation the percentage polarization $P$ and angular distribution $I(\theta)$ are uniquely related through the expression

$$I(\theta) = \frac{3I}{(1 - P \cos \theta) (300 - P)}.$$

(2)

The polarization or the angular distribution must be known in order to complete the characterization of the excitation process. Several attempts have been made to measure the angular distribution of Lyman-$\alpha$ emission, but these have not yielded useful results. Ott, Kauppila and File [13] recently succeeded with a direct measurement of the polarization at 1216 Å.
using the Brewster angle analyzer shown in fig. 5. At the Brewster angle only the electric vector lying parallel to the reflecting surface is reflected into the detector. In the position shown, the detector receives only $I_\perp$. Rotated 90° about the Z-axis, only $I_\parallel$ is transmitted. With this simple configuration Ott et al. obtained the polarization shown in fig. 6.

![Polarization](image)

Fig. 6. Polarization of Lyman-α radiation excited to the 2p state by electron impact (Ott, Kauppila and Fite [13]).
Fig. 7. Polarization, near threshold, of Lyman-\(\alpha\) radiation excited to the 2p state by electron impact (Ott, Kauppila and Fite [13]).

At high energies the polarization behaves qualitatively as expected from the theory of Percival and Seaton [14], falling from positive values in the low-energy range through zero at medium energies, and presumably going negative as the momentum change vector becomes more nearly perpendicular to the direction of propagation. At the low-energy limit, the excitation threshold, where the momentum change vector is exactly along the electron trajectory, momentum conservation would require that the polarization should be 42\%, but for the 2s-2p near degeneracy. In fig. 7 are shown the results obtained in a detailed study of the threshold region. Here, too, the results are indifferent to the requirement of angular momentum conservation, which Damburg and Gaillitis have shown to hold only at threshold within an energy band comparable with the fine structure splitting.

A demonstration that there is a gratifying degree of consistency among the results coming out of the various laboratories is given in fig. 8. Here the \(\theta = 90^\circ\) measurements of Long, Cox and Smith [6] have been corrected for angular anisotropy, using the polarization measurements of Ott, Kauppila and Fite [13]. They are compared with the \(\theta = 54.5^\circ\) data of McGowan and Williams (private communication 1968), and the agreement is seen to be most satisfactory.

The atomic hydrogen 2p state excitation cross section now appears to be in a very satisfactory state on the experimental side, and the pronounced discrepancies between theory and experiment in the energy range below 50 eV are conclusively demonstrated to lie in the deficiencies of the theory.

The next set of results to be discussed are those presently available for excitation of the 2s state of atomic hydrogen. In fig. 9 are displayed the results obtained by Lichten and Schultz [5], Stebbings, Fite, Hummer and Brackmann [15], and Hils, Kleinpoppen and Koschnieder [16]. This most
Fig. 8. Relative measurements of the cross section for excitation of the 2p → 1s transition in atomic hydrogen by McGowan, Williams and Curley (private communication, 1968) taken at 54.3°, are compared with results by Long, Cox and Smith [6] corrected for angular anisotropy using the polarization data of Ott, Kauppila and Fite [13]. Normalization was based on the Born approximation at 200 eV.

Fig. 9. Interecomparison of relative measurements for excitation of hydrogen atoms into the metastable 2s state, including cascade contributions (Hils, Kleipapen and Kuschmiedler [16], □; Lichten and Schultz [5], solid line; Stebbings, Fite, Hummer and Brackman [15], △). Hils et al. show error bars equal to twice rms errors plus 15% systematic errors. Stebbings et al. show confidence limits. Lichten and Schultz quoted a 15% error for the total cross section, the rms sum of all systematic errors and three times the probable statistical error. The dashed curve is the exchange cross section obtained by Lichten and Schultz, shown in the ratio to the total cross section determined by them to within 5%.
interesting comparison shows that the results of the three measurements are really in as good agreement as one would expect from a consideration of the assigned errors. The disturbing features are the different slopes exhibited at the highest energies for which Lichten and Schultz obtained results, and the structure which is quite pronounced in the results obtained by Hils et al. This structure, which is not inconsistent with the results of Stebbings et al., has no theoretical explanation. It has the effect of introducing considerable uncertainty into any attempt to establish an absolute basis through normalization to the Born approximation result. Because of the size of the error bars and the relative size of the structure, any fit to the Born approximation must be subject to a large percentage error, if indeed such a fit is appropriate at all.

The question of normalization of the 2s excitation cross section is of considerable importance. On the one hand a valid normalization at high energies would obviously establish the cross section at low energies where applications are most likely to occur and where the Born approximation is most likely to fail. On the other hand, the recent theoretical results of Burke, Taylor, and Ormonde seem to offer the possibility of normalizing near threshold, and, at the least, require an attempt to reconcile the high and low energy behaviors of theoretical and experimental results.

In fig. 10 are shown the results for excitation near threshold of the 2s state of atomic hydrogen by electron impact, obtained by Burke et al. The point of interest here is the extent to which the theoretically obtained shape is consistent with the experimental results. Of the several measurements, those obtained by Lichten and Schultz best define the shape near threshold, and these results are presented here. A Gaussian electron energy distribution has been folded into the theoretical curve to yield a line for comparison with the experimentally determined shape. The quality of the agreement obtained seems to support the suggestion that normalization of experimental results to the theoretical threshold results may be useful. However, normalization on this basis, applied to the results shown in fig. 9, lifts the high energy results (at 300 eV, for example) to values that are 50% to 100% larger than predicted by the Born approximation (including cascading).

Stebbing's et al. provided an alternative basis for normalization. Their method involved quenching the metastable 2s atoms within the field of view of their photon detector. This same detector could be translated to a position over the electron beam in order to observe the 2p excitation. The ratio thus obtained could be used in a normalization of the 2s excitation cross section based on the Born approximation result for 2p excitation at high energies.

The interpretation of this result depends on a knowledge of the angular distributions of both the 2p and the 2s excitation since the photon detectors accepted a limited solid angle in a direction perpendicular to the electron beam and to the electrostatic quenching field, respectively. The original assumption used by Stebbings et al. about the angular distribution of the radiation resulting from quenching was challenged by Lichten [17], who asserted that emission resulted from a perturbation of the $2^2S_{1/2}$ state by the
Fig. 10. Measurements of the relative cross section for excitation of hydrogen atoms to the metastable 2s state by Lichten and Schultz [5], shown as circles, are compared with the results of close coupling calculations by Burke, Taylor and Ormonde [11]. A Gaussian electron-energy distribution 0.2 eV wide has been folded into the theoretical results in order to permit direct comparison. The lower set of curves are the corresponding results for the exchange cross section, and the calculated relative height is consistent with the ratio determined by Lichten and Schultz.

nearby $2^2\text{P}_j$ levels only, the $2^2\text{P}_j$ levels being too far away to have an effect. On this assumption, the radiation must be isotropic and unpolarized.

More recently Fite, Kauppila and Ott [18] had occasion to measure the polarization of radiation emitted due to electrostatic quenching of 2s atoms. They used their newly developed Brewster angle reflector which was rotated about the direction of propagation of incident radiation to analyze the polarization. To their astonishment, the Lyman-α radiation from metastable atoms was observed to have a -30% polarization, instead of the anticipated zero polarization. The explanation rests on the realization that the $\text{P}_j$ state does, in fact, play a role in an interference term with the $\text{P}_j$ state, and Fite et al. calculated a -32.9% polarization on the basis of the linear Stark effect.

For electric dipole radiation the intensity $I(90^\circ)$ observed at $90^\circ$ to the axis of polarization, and the observed percentage polarization $P$ are related to the intensity $I$ averaged over 4π solid angle by the expression

$$\bar{I} = I(90^\circ) \left[ 1 - \frac{P}{300} \right].$$

Therefore the -30% polarization requires that the observed intensity be increased by 10% for purposes of comparison with calculated values of the total 2s excitation cross section.
Fig. 11. New measurements of the 2s excitation cross section (Fite, private communication, 1968) are compared with the results of other workers.

Taking these effects into account, one obtains from the Stebbings et al. experimental comparison of 2s and 2p excitation, and on the basis of normalization to the Born result for 2p excitation, values of the 2s cross section which are roughly 50% higher at energies above 200 eV and 10% lower at threshold than the theoretical results.

It appears, therefore, that the theoretical and experimental results for 2s excitation in atomic hydrogen are in substantial disagreement, and one or the other must be shown to be incorrect. Remeasurements are underway in several laboratories. Fig. 11 shows recent results obtained by Fite and his collaborators (private communication 1968) which differ from the earlier results shown in fig. 9, by Stebbings, Fite, Hummer and Brackmann, and by Hils, Kleinpoppen and Koschwieder. When normalized to the Born approximation at higher energies the new results appear to be more nearly consistent with the threshold behavior predicted by Burke et al. than are the old results.

For the excitation of the \( n = 2 \) level of atomic hydrogen a separation of the 2s and 2p excitation functions is possible because of the extraordinarily long life of the 2s state. For the \( n = 3 \) level the lifetimes of the 3s, 3p and 3d states are 16, 0.54 and 1.56 \( \times 10^{-8} \) sec, not suitable for spatial separation of the components. However, Kleinpoppen and Kraiss [19] have obtained an excitation function for the total intensity of the Balmer-\( \alpha \) line excited by electron impact. This measurement, which also uses a crossed beam technique, is especially difficult because it must be done against a strong background of radiation from the hydrogen dissociator. This background is chopped by the atom beam chopper, so that this means of tagging the desired signal does not discriminate against the major source of back-
Fig. 12. Excitation function of the hydrogen Balmer-\( \alpha \) line corrected for cascading. The errors are three times rms errors. (Kleinpoppen and Kraiss [19].)

Fig. 13. Measured polarization of the hydrogen Balmer-\( \alpha \) line as a function of electron energy. The errors are three times the rms errors plus 2% systematic errors (Kleinpoppen and Kraiss [19]).

ground. Kleinpoppen and Kraiss were able to alleviate this problem somewhat by using a glass chopper wheel. This reduces the chopped background to a manageable level, and the excitation was observed as the component controlled by the electron beam. In effect, it was a double modulation experiment. The results are shown in fig. 12. Kleinpoppen and Kraiss were able to measure the polarization of the radiation using a simple polaroid filter, and obtained the result shown in fig. 13.

The recent study of the threshold shape by McGowan and Clarke [20] is the only very new addition to experimental information on ionization of atomic hydrogen by electron impact. They enter the complex ionization
threshold law controversy with a 1.13 power dependence on excess electron energy, over a 0.4 eV range near threshold, not conformance to any of the theoretically derived power laws.

The existing experimental data on the electron impact ionization, over a large energy range, of atomic hydrogen are shown in fig. 14. In every case, the crossed beam method is used, adapted to permit collection of the positive ions produced. Normalization for two of the curves is based on a fit to the Born approximation result, and two are based on a comparison with ionization produced in a beam of H₂, using the early absolute measurements of Tate and Smith [21].

Finally, to complete this survey of crossed beam electron-hydrogen atom collision studies, the two measurements of the total scattering cross sections are shown in fig. 15. The region of greatest interest in these measurements is the very low energy range, where all scattering is elastic. In particular, at the very low energies, approaching thermal energies, the elastic scattering cross section apparently becomes very large. The measurements are very difficult here, because of the finite energy spreads of electron beams, because of space charge limitations on available electron current, and because of the difficulty of controlling small stray field effects. In the work shown here two and three volts seem to be the lower limits of the useful energy range.
The measurement by Brackmann, Fite and Neynaber [4] involved collection of electrons scattered at 90° to the axis of the electron beam, within a 45° half-angle. The results are presented in the figure, as total cross section using the angular distribution calculated by Bransden, Dalgarno, John and Seaton [22]. The absolute scale was established by measuring the ratio of the atomic and molecular scattering cross sections, and referring to the absolute measurements of Ramsauer and Kollath [23] in molecular hydrogen.

The apparatus used by Neynaber, Rothe, Marino and Trujillo [24] was designed to collect a large fraction of the scattered electrons so that essentially the integrated cross section was measured directly. The normalization was based on the measurements in molecular hydrogen by Brüche [25] and by Normand [26]. The results are shown as a line fitted to the points, the bars representing the scatter.

In the Neynaber paper it was pointed out that the use of a more nearly isotropic scattering cross section, as later indicated by the differential cross section measurements of Gilbody, Sebbling and Fite [27], and by more recent theoretical work, would lower the Brackmann results and lead to rather good agreement with those by Neynaber et al.

These are the major results of ten years of work with crossed beams of hydrogen atoms and electrons. They are relatively few in number, each being something of an experimental tour-de-force, but they have had enormous influence in electron-atom collision physics. To the extent that they have withstood the test of time and competition, they constitute the bounds of reality for the outpouring of theoretical work on electron-hydrogen atom interactions which continues year after year.

Helium is a much more difficult subject than atomic hydrogen. Because
Fig. 16. Measured values of the total scattering (elastic below 19.8 eV) of electrons from helium atoms by Golden and Bandel [28], compared with results by Ramsauer [44], Ramsauer and Kollath [23], Brode [45], and Normand [26]. Also shown are the results of a calculation by Morse and Allis [29].

of the apparent relative simplicity of the experimental technique there are great numbers of electron-helium atom experiments described in the literature. One of the areas of greatest current interest is that of resonances, and I leave this subject to another author.

Some notable attempts at precise absolute scattering measurements have been carried out in helium, in recent years. One good example is the measurement of total scattering of electrons in helium from 0.3 eV to 28 eV by Golden and Bandel [28], using a Ramsauer type of apparatus. The results they obtained, shown in fig. 16, were in excellent agreement with the calculated total elastic scattering cross section of Morse and Allis [29] at higher energies. At the very low energies their results contain none of the structure which appeared in the early work by Normand [26] and by Ramsauer and Kollath [30].

Another cross section which has been measured with considerable care is that for ionization, and the results, shown in fig. 17, are reasonably consistent considering the difficulties of measuring gas densities absolutely.

However, the greatest effort in electron-helium atom collisions has gone into the study of excitation functions. Kieffer's bibliography [31] lists 95 experimental papers purporting to contain data on some aspect of electron impact excitation in helium. The techniques involved appear to be quite simple. One passes an electron beam through helium gas. The path of
the electron beam is delineated by the visible radiation in the helium lines excited by electron impact. A particular helium line is isolated with a conventional spectrometer and the intensity of the line measured as a function of electron energy.

In principle, this kind of work can be done with great accuracy using the techniques and physical understanding now available. Certainly, accurately measured excitation functions would be of great value to the theoretician. Unfortunately, the great bulk of the available data does not stand up under close scrutiny.

Fig. 18, from a study by Heddle and Lucas [32] of the pressure sensitivity of several of the helium excitation functions, serves to emphasize the most common and serious failure. At pressures high enough to produce a comfortable flux of photons, secondary effects cause gross distortions in the apparent cross sections.

The n^1P - 2^1S transitions are significantly enhanced, through trapping of resonance radiation, to pressures below 10^-3 Torr, according to a theoretical study by Phelps [33]. This leads to distortion of the n^1S - 2^1P excitation functions by a drastic increase in the cascading fraction. Another contributor, the dominant effect for the other lines, results from transfer of excitation in collisions with ground state atoms.

Other important sources of error arise out of polarization of the radiation with respect to the electron beam axis, and the corresponding angular anisotropy. Fig. 19 compares the polarization measurements available for four of the important helium lines. It is clear that the difficulties involved
Fig. 18. Pressure dependence of excitation functions for several helium lines. Electron energies used are indicated on the figure (Hedde and Lucas [32]).
Fig. 19. The results of measurements of polarization of four helium lines excited by electron impact are intercompared (Hedde and Lucas [32], curves 1 and □; McFarland and Soltysik [52], curves 2 and △, except 4^1D which is McFarland [53]; Mous-tafa Moussa [54], curves 3 and ○; and Dolgov [53], curves 4).

Fig. 20. Pressure dependence of measured polarizations for several helium lines (Hedde and Lucas [32]).
Fig. 21. Depolarization of radiation excited by electron impact, due to Larmor precession, shown for several states of helium as a function of the magnetic field component perpendicular to the electron beam. Observation is along the perpendicular magnetic field component. The mean natural lifetime $\tau$ for each of the $^1D$ states is indicated on the figures. (Meiselwitzsch and Smith [56].)

in the polarization measurements have not been surmounted, and that corresponding errors in the excitation functions will be significant. Some of the sources of difficulty can be identified as due to pressure depolarization (as indicated in fig. 20, from Heddle and Lucas), depolarization resulting from Larmor precession in residual magnetic fields (illustrated in fig. 21, which shows that the longer lived helium $^1D$ states are particularly subject to this effect), and the effects of instrumental polarization (illustrated in fig. 22) which can interact with the natural polarization of a line to produce serious distortions of an excitation function.

As a result of a widespread failure to recognize and deal effectively with these problems, the available optical excitation function results are more qualitative than quantitative. The situation is illustrated in fig. 23 for the helium 5048 Å line. One would be hard pressed to justify a detailed critique of a theoretical result on the basis of these experimental results.

Direct comparison between theory and experiment is of limited value in any case where a large component of the excitation is due to cascading. Another type of experiment circumvents this cascading problem as well as all the difficulties due to excitation transfer and polarization. This technique is based on direct measurement of that component of the scattered electron current which has suffered a loss of energy corresponding to the transition of interest. All the desired information is available in the scattered electrons at any pressure for which multiple scattering is negligible. The other secondary processes which have been cited affect only the residual atom and the radiation produced when it decays. The energy loss technique has been widely used in the study of resonance structure, as in the zero angle scattering study by Chamberlain and Heideman [34] shown in fig. 24. However, this is at one angle. In order to obtain the equivalent of an absolute excitation function it would be necessary to obtain absolute
measurements and angular distribution measurements adequate to support an integration over all angles. This procedure has its own difficulties as we shall see. However, a step in this direction has been taken recently by Chamberlain, Mielczarek and Kuyatt [35]. They have made an absolute measurement of the 20.61 eV energy loss component, corresponding to $2^1S$ excitation, at a scattering angle of 5° and over the energy range from 50 to 400 eV. The work was carried out with great care, and the error limits are conservatively estimated as $+6.4\%$ and $-8.7\%$. Since the question of normalization to the Born approximation arises repeatedly in electron-atom collision work, it is of particular interest that Chamberlain et al. obtain an absolute value of the differential cross section at 400 eV that is still 10\% below the Born calculation of Kim and Inokuti [36], for which 1/2\% accuracy is claimed.

A similar absolute measurement is underway, also for $2^1S$ excitation, by Bromberg, working in Lassettre's laboratory at the Carnegie-Mellon Institute, but the results are not yet available.

The absolute measurements, combined with precision, high-resolution angular measurements such as those which have been carried out by Lassettre and his collaborators (Lassettre and Jones [37]; Silverman and Lassettre [38]), would lead to unambiguous level excitation cross sections. However, Lassettre's work has been confined to a few fixed energies and to a relatively small angular range, being particularly intended for extrapolation to zero momentum for determination of optical oscillator strengths. New high resolution differential cross section measurements from 0 to 180° and over a wide range of energies would be required to provide accurate total cross sections. These measurements would be much more difficult on energy loss components corresponding to levels other than the $2^1S$, which has a large cross section. It appears, therefore, that the inelastic electron scattering method is likely to be applied to only a few of the helium levels, and that we will have to rely on improved measurements of optical excitation functions for most of the data on inelastic collisions in helium, and in other elements.
Finally, I would like to show the excitation function obtained by Dance, Harrison and Smith [39] for the positive ion of helium He⁺(2s). The experimental points are shown in fig. 25, except in the threshold region, where they are too dense to show in the figure. Curve 1 is a trial cross section which gives a good fit to the experimental points when folded with the electron energy distribution. Curve 2 is the cross section corrected for cascading. Curve 3 is the theoretical result of Burke, McVicar and Smith [40].

The experimental technique involved here was especially difficult and especially significant. It is a modulated crossed charged beam measurement, and the difficulties arise from mutual interaction of the two beams due to space charge fields. However, there have now been several such measurements and the techniques are better understood. This type of measurement, through careful determination of beam overlap factors, and through accurate measurement of beam current, can be used to obtain accurate absolute values. It is the only type of crossed beam experiment for which this is true. This is then an important technique to exploit.

The greatest need in experimental electron-atom collision work is for accurate absolute measurements. Such measurements still seem to be in the distant future for the atomic hydrogen experiments. In helium, although density measurements still offer some difficulty, the techniques now available seem to open the possibility for reliable and very accurate cross sections of all types. However, much more work on electron-helium collisions
Fig. 24. Energy dependences of the components of forward inelastically scattered electron current in helium corresponding to excitation to the 2^5S, 2^1S, 2^3P, and 2^1P states. The curves are smoothed tracings of the original data, and the width of the noise is indicated by the error bars. (Chamberlain and Heideman [34].)

Fig. 25. Measured excitation function for He^+(2S) from the He^+(1s) ground state (Dance, Harrison and Smith [34]) compared with the result of a close coupling calculation by Burke, MoVicar and Smith [40] to which has been added an estimated cascade contribution (curve 3). Curve 1 is a trial cross section chosen to give a good fit to the experimental points when folded with the electron energy distribution. Threshold points have been omitted from this figure. Curve 2 is derived by subtraction from curve 1 of estimated cascading. The error bars represent 90% confidence limits.
is needed. The prospects for improvement of inelastic cross sections are evident, both through the optical excitation technique with due regard for the physical environment, through the energy loss technique now opening up as a result of the development of high resolution electron energy analysis, and, for special cases, through application of the crossed charged beam technique.

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