Electron detachment of H^- in collisions with argon at 0.5 and 1.0 MeV

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H^- ions with energies of 0.5 and 1.0 MeV were passed through a crossed beam of Ar atoms. Secondary electron energy spectra in the energy region of $v_e \approx v_i$ were measured in the forward direction. These spectra seemed to manifest characteristics of two types of ionization processes. The results are discussed within the framework of theories of electron loss. A group of electrons was tentatively identified as being produced by the single-electron-loss process. Another group of electrons was interpreted as respresenting only a small portion of the electrons from double-electron-loss collisions.

I. INTRODUCTION

The mechanisms by which H^- loses electrons are of practical as well as theoretical interest. As will be discussed below, the doubly differential cross section (DDCS) near 0° for electrons ejected with energies in the region where $v_e \approx v_i$ are of significance since they may represent a signature of the ionization mechanism. Here and throughout this paper v_e is the laboratory electron velocity and v_i is the laboratory velocity of the projectile.

Recent collision experiments using H^- as the projectile have been concerned with total electron detachment cross sections,[1,2] with collisionally excited autoionizing states of H^-,[3] and with DDCS measured at angles greater than or equal to 10° in the ion energy range from 0.2 to 10 keV.[4] (These references are not intended to represent a survey of the literature. However, earlier work is cited in these papers.) Since the details of the secondary electron spectra in the forward direction were not available, a program to measure the electron detachment DDCS near 0° from H^- collisions with Ar was initiated at projectile energies of 0.5 and 1.0 MeV. These energies proved advantageous because of the relative ease of accelerator operation and because the $v_e \approx v_i$ electrons were well separated in energy from any appreciable background.

Experiments measuring secondary electron spectra from fast positive-ion collisions with gas targets[5] have shown a prominent group of electrons in the forward direction whose velocities were near the ion velocity, $v_e \approx v_i$. These DDCS were largest at 0°. When fully stripped ions were used as projectiles the process producing those electrons (from target ionization) was called "charge transfer to the continuum," and such a group of electrons has been predicted theoretically.[6] Other experiments, using partially stripped ions,[7,8] measured electron spectra for angles no smaller than 20° and also found a group of electrons near $v_e \approx v_i$. The electrons were attributed to electron loss from the projectile on the basis of an electron elastic-scattering model (ESM).[7] This model treats the projectile electrons as being elastically scattered by the screened Coulomb field of the target.

Experiments near 0° with partially stripped projectiles[9] showed that, in agreement with a recent theoretical description of electron loss,[10] the DDCS from projectile ionization look similar to those from target ionization via charge transfer to the continuum. The fact that target and projectile ionization look similar in the forward direction for electrons with $v_e \approx v_i$ is a consequence of the dominant Coulomb interaction in the final state between the fast ion and the electron moving slowly with respect to it. This interaction is the same in both target and projectile ionization. On the other hand, projectile electrons emitted with larger velocities relative to the ion, and which may therefore appear at larger angles, are not as strongly influenced by the Coulomb field of the ion. In this case the electron-target interaction becomes important and the predicted results agree with the ESM.

Projectile ionization of H^- provides an opportunity for testing theoretical predictions as well as providing new experimental data on secondary electron production. The two important general ionization processes are single electron loss (SEL) and double electron loss (DEL)

$$H^- + X \nearrow H + X + e\,,$$
$$H^- + X \searrow H^+ + X + 2e\,.$$

Near 0° in the $v_e \approx v_i$ region one does not expect to see many electrons from the target since H^- is not expected to participate in charge transfer to the continuum and since electrons ejected from the target by head-on binary collisions with the proton will be found with velocities near $v_e \approx 2v_i$. When H^- undergoes SEL, the final-state interaction between the fast neutral atom and the electron does not contain a "bare" Coulomb interaction. Therefore, for SEL, the approximation of Drepper and Briggs which neglects the effects of the Coulomb field of the projectile in the final state may be applicable. This means that the DDCS resulting from SEL near 0° may have the ESM characteristics, which heretofore have been seen only at large angles, rather than the characteristics of projectile ionization where a final-state Coulomb interaction is present. On the other hand, the DEL process may have some of the characteristics of projectile ionization with a final-state Coulomb interaction. However, the effects of the second electron have not been investigated theoretically specifically for experiments of the type reported here.

In an attempt to provide quantitative data on these matters a series of measurements of secondary electron spectra in the $v_e \approx v_i$ region resulting from collisions of H^- with Ar were initiated. Argon proved to be a convenient target since it provided a reasonable number of Rutherford-scattered ions which were used for monitoring purposes. Also, Ar has previously been used as a target for positive ions as well as H^-.

II. EXPERIMENTAL PROCEDURE

H^- ions were extracted from the duoplasmatron ion source of The University of Georgia 5-MV Van de Graaff accelerator equipped with an auxiliary control circuit for negative-ion acceleration. Although satisfactory, the accelerator stability during negative operation was not as good as during positive operation. Direct energy calibration of the accelerator under negative operation was not available, however, our results confirmed that the positive-ion calibration was sufficiently accurate for use in these experiments.

Details of the scattering chamber, beam monitoring procedure, crossed beam parameters and methods of identifying backgrounds have been presented elsewhere.[9] For the present work the electron suppressor was maintained at all times at twice the potential necessary to stop $v_e = v_i$ electrons and the energy resolution of the analyzer was $\Delta E/E = 0.01$ full width at half-maximum (FWHM).

In order to determine the neutral fraction of the incident beam the charged components were magnetically deflected before they could enter the scattering chamber. The small magnetic field necessary to accomplish this deflection produced no effect in the region of the analyzer and crossed beam. The neutral beam which entered the chamber was passed through a carbon foil which was located at the center of the chamber in place of the crossed beam and the resulting H^+ beam was measured in the Faraday cup. The neutral fraction was found to be less than 0.03 of the total beam. This neutral beam was then passed through the crossed beam of Ar and the secondary electrons were measured. The number of secondary electrons after normalization to the number of monitor counts was sufficiently small that no correction to the data was necessary.

In an attempt to obtain an estimate of the H^+ fraction of the beam, the normal negative beam current was compared to the positive current resulting from the passage of the total beam thru a carbon foil. No difference in the magnitude of the current was observed suggesting that the H^+ fraction was extremely small, as one would expect from a comparison of the SEL cross section, σ_{-10}, and the DEL cross section, σ_{-11}, at these energies.[2] Accordingly, no correction due to the H^+ fraction was deemed necessary.

III. DATA ANALYSIS

As before, the raw data were corrected for the variable energy resolution of the analyzer. The electron-energy spectra near 0° showed a large peak near $v_e \approx v_i$ whose wings decreased smoothly to a uniform background within about 90 eV of the peak. This uniform background, due to random counts and electrons produced by processes other than those of interest here, was between one and two orders of magnitude smaller than the peak maximum. All data presented have had this small background subtracted.

Typical electron-energy spectra produced by 0.5 MeV H^- ions are shown in Fig. 1. The spectra near 0° exhibited two characteristic features, namely, a sharp peak around $v_e \approx v_i$ and a prominent shoulder on the low-energy side. For angles greater than 2.5° the sharp peak disappeared leaving a broader group whose maximum was at an energy slightly less than that corresponding to $v_e = v_i$. A comparison of spectra observed previously, i.e., He^+/Ar (projectile ionization) and He^{++}/Ar (target ionization), with the H^-/Ar spectra indicated that both the sharp and the broad groups were different from the cusp-shaped peak characteristic of a strong final-state Coulomb interaction. Further examination of the data indicated that the shape of the broad peak was essentially unchanged in the angular range from 2.5° to 7° and changed only slightly at larger angles. For angles less than 2.5°, where the sharp peak appeared, the shape of the DDCS for low electron energies, up to approximately the position of the shoulder, seemed similar to each other as well as similar to the low-energy portion of the broad peak. These similarities suggested the possibility

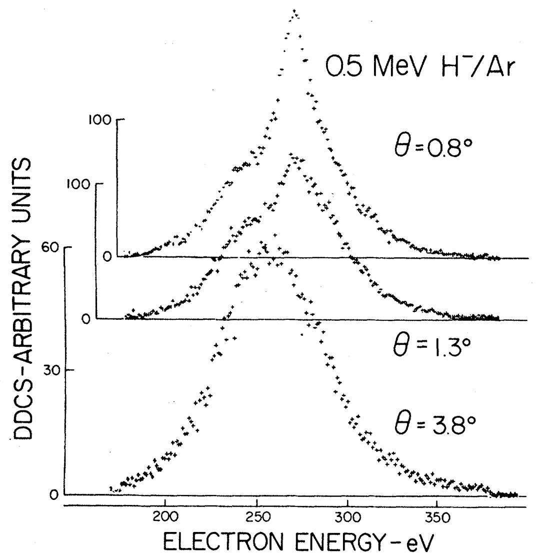

FIG. 1. Energy spectra observed for 0.5 MeV H^-/Ar at three angles. The group seen at 3.8° is referred to as the broad group and the sharp peak appearing at smaller angles with a slightly higher energy is referred to as the sharp group.

that the DDCS tentatively be considered as a superposition of two different groups of electrons, namely, a rather sharply peaked group around $v_e \approx v_i$ and a broad group centered about a smaller energy.

In order to verify the supposition that these similarities were real, detailed comparisons between different spectra were made. These comparisons were effected by dividing the DDCS obtained at one angle, channel by channel, by the DDCS obtained at another angle. These comparisons were made using individual runs as well as averaged runs where data at one angle had been repeated. In the angular range from 2.5° to 5°, where only the broad group was present, the divisions produced ratios which, when plotted as a function of electron energy, were approximately constant. The scatter of the ratios was greatest at the low and high energies since there the statistical fluctuations due to the small number of counts were largest. The fact that the ratios were essentially constant indicated that the shapes were approximately independent of angle. When a run for $\theta < 2.5°$ was divided by a run for $\theta > 2.5°$ the appearance of the sharp peak was always seen. However, for electron energies less than the energy at which the shoulder appeared the ratios again were essentially constant. When two runs, both of which were for angles less than 2.5°, were divided it was found that again the ratios at low energies were constant. These results confirmed the idea that the shape of the low-energy portion of the spectra was at

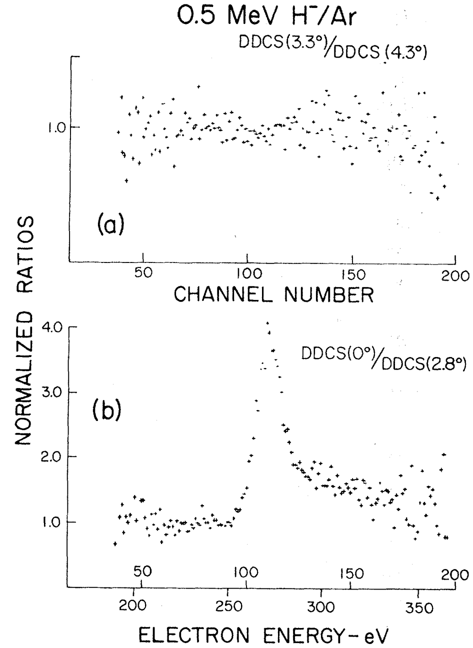

FIG. 2. (a) Channel by channel division of the corrected energy spectra at 3.3° by the spectra at 4.3° showing the similarity in shape of the broad group at these angles. (b) Results of a similar division using energy spectra at 0° and 2.8°. The presence of the sharp group is clearly seen. Note that below an energy of about 250 eV the ratio is approximately constant.

least approximately the same at all angles and, furthermore, suggested a technique for stripping the broad peak from the small angle spectra. Two typical examples of these ratios are shown in Fig. 2.

If one makes the assumptions that the broad peak

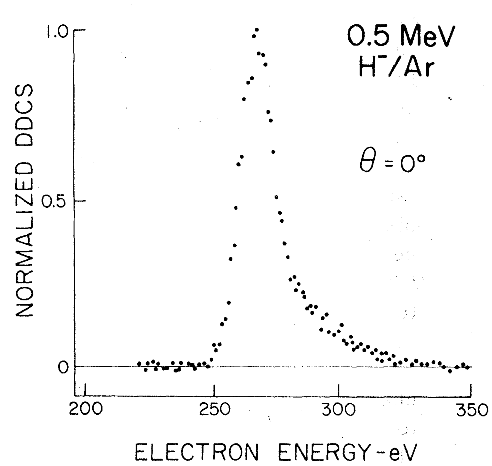

FIG. 3. Shown is the result of stripping out the broad group, as described in the text, from the total spectrum at 0° leaving the DDCS of the sharp group which has its peak value at $v_e \approx v_i$.

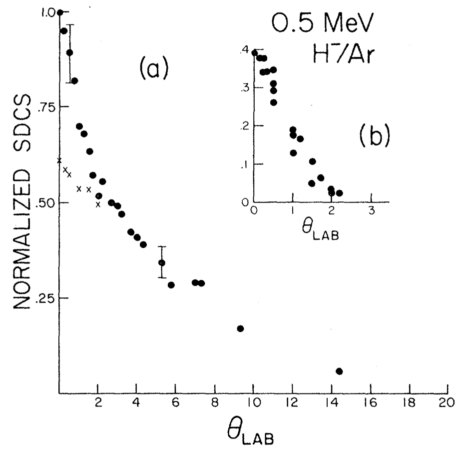

FIG. 4. (a) ●, SDCS obtained by integration of the total DDCS obtained at 0.5 MeV. X, SDCS of the broad group obtained by subtracting the contribution of the sharp group from the total. All data points shown for angles less than 2° represent average data, where at least two runs have been averaged together. Estimated errors are shown. (b) The SDCS of the sharp group.

is present at all angles and that its shape does not change in the first three degrees, the data for $\theta > 2.5°$ can be used to establish its shape. For some angle less than 2.5° the DDCS was divided by the DDCS for the broad peak in the angular range 2.5°–4° and the low-energy ratio was used to determine a scaling factor. The data for the broad peak were then scaled until the low-energy data was on the average the same in both the DDCS of interest and the broad peak. Then, channel by channel, the scaled broad peak was subtracted from the DDCS measured at the small angle. The difference after subtraction was the sharp peak. By repeating this operation for angles $0° \leq \theta \leq 2.5°$ the DDCS and the angular distributions of the sharp peak were extracted. It should be noted that the ratio method was also used for runs both of which were at angles less than 2.5°. This enabled one to compare the sharp peak extracted using small-angle data alone to the sharp peak extracted in the usual way by comparison of small- with large-angle data. The methods gave similar results. Figure 3 shows the results of a subtraction of a scaled run at 2.8° from a run at 0°.

The singly differential cross section (SDCS) which were obtained by integrating the DDCS are shown in Figs. 4 and 5. Also shown are the SDCS for the separate groups. The SDCS are peaked in the forward direction although not as sharply as observed for target ionization and projectile ionization. The sharp group was found to have an extremely narrow angular distribution whereas the broad group was found to have a much wider angular distribution.

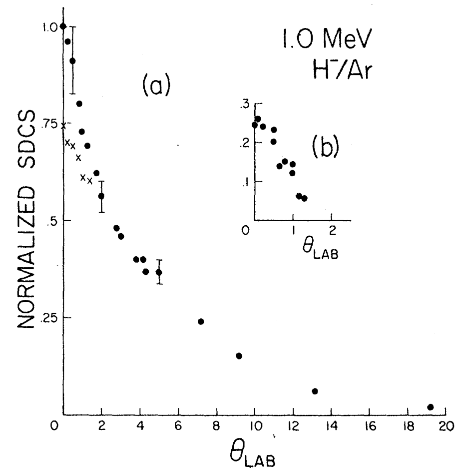

FIG. 5. Same caption as for Fig. 4 except the bombarding energy is 1.0 MeV.

IV. DISCUSSION

In view of the apparent success of the peak stripping procedure an identification of the sources of the two groups was attempted. The shape of the broad group changed little with angle and was not similar to the DDCS resulting from a slowly moving electron in the Coulomb field of a positive ion.

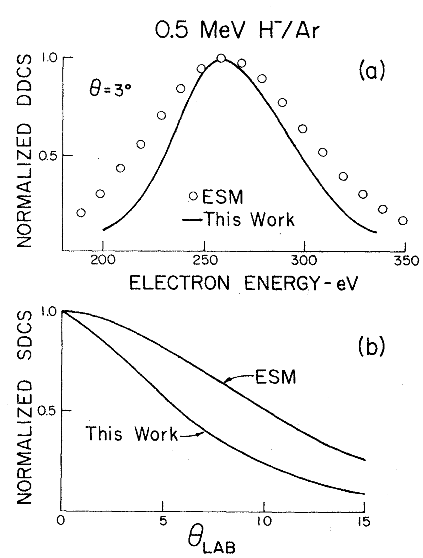

FIG. 6. Comparison of the ESM predictions and the experimental results at 0.5 MeV. (a) The DDCS are compared at 3°. For ease of comparison of shapes the peak of the calculated distributions has been shifted down 13 eV to coincide with the maximum of the broad peak. The data are represented by a smooth curve drawn through a typical spectrum. (b) Comparison of the SDCS at 0.5 MeV. The data are represented by a smooth curve which has been drawn through points taken from Fig. 4(a).

In fact, the broad group displayed the general characteristics of the ESM. Since this model has been shown to be equivalent to a Born calculation where the Coulomb interaction between the projectile and the electron was neglected, and since the single ionization of H^- does not produce a bare Coulomb interaction in the final state it seemed reasonable to tentatively identify the broad group with the SEL process.

As a first step in attempting to confirm this association several ESM calculations were made for 0.5 and 1 MeV H^-/Ar collisions. The screened potential of the Ar atom in these calculations was taken from the work of Abrahamson on the Fermi-Thomas-Dirac model.[11] The initial-state velocity distribution of the electron was calculated from the two-particle wave function

$$\psi = N[\exp(-\alpha r_1)\exp(-\alpha' r_2) + \exp(-\alpha r_2)\exp(-\alpha' r_1)],$$

with $\alpha = 1.04$ and $\alpha' = 0.28$ in atomic units. Partial results of these calculations are shown in Fig. 6.

Qualitative agreement between the experimental results and the calculations was seen. The shapes of the calculated DDCS, although wider than the measured spectra, were similar to them. The calculated angular distributions, although not quite as peaked as the experimental SDCS, were similar in shape. The calculations predicted that at 1.0 MeV the DDCS were broader than at 0.5 MeV while the SDCS at 1.0 MeV were more sharply peaked than at 0.5 MeV. Although not shown, the measured DDCS at 1.0 MeV were wider than at 0.5 MeV and were again narrower than the calculations. A comparison of Figs. 4 and 5 shows that, as predicted, the angular distributions were more sharply peaked at 1.0 MeV than at 0.5 MeV.

A persistent difference between the data and the calculations was that the broad group peaked at an energy 13 ± 1.5 eV less than that for $v_e = v_i$. A similar effect has been seen previously.[4] The formalism of Drepper and Briggs did predict a small energy shift associated with the initial binding energy of the electron but this was not incorporated in the ESM. However, preliminary data for other targets have indicated that the measured energy shift seems to be target dependent. Further investigations of these details are planned. In spite of these discrepancies the assumption that the source of the electrons found in the broad group was due to the SEL process seemed to be at least qualitatively reasonable.

The natural assumption was then made that the sharp $v_e \approx v_i$ group was associated with the double-electron-loss process even though no theoretical guidance was available on what features of the DDCS might be expected due to the presence of the other electron.[12] This sharp group which was extracted using the stripping procedure had a shape which was different from any seen previously for projectile ionization. Although the DDCS were peaked at $v_e \approx v_i$ they were asymmetric, were not cusp-shaped, and had prominent high-energy tails. Since the peak stripping procedure was based on the assumption that the shape of the broad group was unchanging from 3° to 0°, there existed the possibility that the true shape of the $v_e \approx v_i$ group was not correctly determined. For example, it was possible that the asymmetry or the high-energy tail or both were artifacts due to the handling of the data. In particular, putting ESM predictions aside, one can raise the question of whether or not it would be reasonable to expect that the broad group would become even broader on the high-energy side near 0° and therefore reduce the high-energy tail of the sharp group. A supposition was considered where, in the frame of the fast projectile, the single electron ejection probability had a maximum at a small but finite velocity. Such a circumstance would produce a broad double humped peak near 0°. This double peak would smoothly coalesce into a single peak at some small angle. However, this single supposition is not sufficient since any broadening near 0° would occur on both the low- and high-energy sides of the distribution. Since no broadening on the low-energy side was observed this possibility received no further consideration.

Under the assumption that the source of the electrons in the broad group was the single-electron-loss process a comparison with other data was possible. The SDCS for this group was integrated over the solid angle associated with polar angles between 0° and 15° where most of the yield was located. From these calculations an estimate of $\sigma_{-10}(0.5\text{ MeV})/\sigma_{-10}(1.0\text{ MeV})$ was found to be approximately 1.2. This value is in good agreement with ratios of total cross sections at these energies.[2] Furthermore, the same ratio, calculated using ESM DDCS which were integrated from 0° to 90°, was found to be 1.8. It seemed, therefore, that the assignment of the SEL process to the broad group was reasonable.

Assuming that the sharp group contained only electrons from double electron loss, the SDCS of this group was integrated over the solid angle where it was nonzero. This allowed an experimental estimate of $\sigma_{-10}/\sigma_{-11}$ at both 0.5 and 1.0 MeV. The experimental ratios were approximately 125 at 0.5 MeV and 250 at 1.0 MeV. These values were in sharp conflict with the experimental total cross section ratio which was approximately 14 at 0.5 MeV.[2] On the basis of this comparison it is clear that the sharp group contained only a small fraction of the DEL electrons.

The fact that the shape of the $v_e \approx v_i$ group was different from that seen previously for projectile ionization was not considered to be a serious problem with respect to the interpretation of the source of the electrons found in this group. The group was sharply peaked near $v_e \approx v_i$ which could be associated with a final-state attractive Coulomb interaction. Also, since the initial state is highly correlated and the final state contains an additional repulsive interaction it was not unreasonable to expect these factors to manifest themselves in the spectra of electrons found moving slowly relative to the proton.[12]

The question of the angular and energy distributions of most of the electrons produced in double electron loss collisions immediately arose. In an attempt to understand why these electrons were not observed in the present experiments two possibilities were given consideration. They were (i) The other DEL electrons were scattered with all allowed energies resulting in a relatively small yield over a large energy range. Unfortunately, electrons distributed in this manner would be indistinguishable from the normal flat background as measured, for example, in the energy range from a few eV to the onset of the broad group. Accordingly, these experiments were unable to either confirm or deny this conjecture; (ii) The other DEL electrons acquired a large velocity in the projectile frame due to binary encounters with the target. This possibility is amenable to verification by observing electrons for which $v_e \approx v_i$ in the backward laboratory direction where they are most likely to be found.

A search for the electrons mentioned in the second possibility above is planned. The present apparatus will be modified to facilitate measurements in the backward direction.

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[12]No specific theoretical calculations are available for two-electron loss from H^- due to collisions with atomic targets. However, the three-body problem with two continuum electrons in the Coulomb field of an ion has received attention recently. See, for example, A. R. P. Rau, Phys. Rev. A 4, 207 (1971); T. N. Chang, and R. T. Poe, *ibid*. 12, 1432 (1975); U. Fano and C. D. Lin, *Atomic Physics* (Plenum, New York, 1975), Vol. 4, p. 47; U. Fano, in *Photoionization and Other Probes of Many-Electron Interactions* (Plenum, New York, 1976), p. 11. Included in these references are discussions of electron-atom ionization near threshold, double photoionization, and correlations of excited electrons. A prediction arising from these studies is that as the energy absorbed by the atom increases well beyond threshold, one electron tends to carry away most of the available energy, thereby leaving the other electron moving slowly in the field of the ion. Although slow electrons were found in this work, the connection between the above prediction and our experiment is not clear since we do not know how much energy has been transferred and, moreover, this type of collision may more appropriately be considered a four-body problem.