Collisional electron detachment of H^- by He: A target effect

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Detailed measurements of the collisionally induced electron detachment of H^- during collisions with He at an ion energy of 0.5 MeV are reported for $\theta = 0$–173°. These data are compared to similar measurements using Ar as the target and to electron elastic scattering from He. These comparisons reveal that, while some characteristics of the electron energy spectra are similar for both targets, one feature shows a marked target dependence. Further experiments, in the forward direction only, using other H^- energies in the range 0.35–1.35 MeV, as well as D^- at 1.0 MeV, indicate that the results have no simple interpretation in the rest frame of the projectile.

I. INTRODUCTION

Measurements of the double differential cross sections (DDCS) for electron detachment of H^- during collisions with Ar at 0.5 MeV have been recently reported.[1,2] Very near 0° the electron energy spectra exhibited a sharp, cusplike peak with a prominent shoulder on the low-energy side. The energy of the maximum of the sharp peak was at $E_e = \frac{1}{2}m_e v_e^2 = \frac{1}{2}m_e v_t^2$, where v_t is the ion laboratory velocity. The yield of the sharp group declined rapidly with angle and this peak was no longer visible for angles greater than about 3°. A broad lower-energy group, presumably associated with the shoulder seen near 0°, remained for angles greater than 3°, and its character changed slowly throughout the rest of the angular range. Under the assumption that the structure seen near 0° was, in fact, due to two distinct but unresolved groups, these groups were tentatively interpreted as resulting from two different processes; single and double electron loss (SEL and DEL, respectively). However, in no other angular region did any feature of the DDCS appear which could be interpreted as being the signature of either SEL or DEL. Of course, since the SEL cross section is known to be about ten times the DEL cross section, the spectrum at any angle was probably dominated by SEL electrons.

Furthermore, it was shown that the angular distribution obtained by integrating the DDCS over the group of electrons from H^- was rather similar in shape to the measured single differential cross section (SDCS) resulting from the elastic scattering by argon of electrons moving with the same velocity as the H^- ions. A more elaborate calculation which takes into account the velocity distribution of the electrons on the projectile[3] and uses realistic scattering cross sections,[2] the electron scattering model (ESM), did not predict a shape much different than that from e-Ar scattering for the angular distribution. The most prominent dissimilarities between the H^--Ar SDCS and the ESM calculations were at the forward angles and in the back hemisphere for angles greater than about 130°.

If one considers the fact that H^- is a very weakly bound system it may not be surprising that the SDCS for electron loss from H^- shows some similarity to the elastic scattering SDCS. In fact, a theoretical description of electron loss[4] predicts that at large angles the electron-loss SDCS should look like those predicted by the ESM. Differences in the shapes between the measured and calculated SDCS at large angles might be interpreted as being associated with some details of projectile and/or target structure.

Hydrogen is a more strongly bound projectile and its electron-loss SDCS is somewhat different from that from H^--Ar and less like e-Ar. Nevertheless, the general features of the angular distribution[5] are similar to H^--Ar. One might wish to interpret the similarities of the measured electron-loss angular distributions with electron elastic scattering as lending support for the ESM. However, in both experiments, H^--Ar and H-Ar, the DDCS predicted by the ESM did not compare well to the measured spectra, and in both cases, the SDCS in the back direction were rising more rapidly than the calculated ones. Thus although the details of the shapes of both the DDCS and SDCS did change when the projectile was changed, which clearly established the expected importance of projectile structure, both projectiles produced angular distributions which seemed to be somewhat characteristic of e-Ar elastic scattering.

These results raise two questions: (i) Does the target, in first approximation, determine the gross features of the shape of the electron-loss SDCS? The results of the H^--Ar experiments, the present experiment, and a preliminary investigation of H^--Ne would suggest that the answer is yes. However, further investigation of this point is

needed and the SDCS for Ne as well as other targets will be the issue examined in a future publication. In this paper we concentrate on the second question which had an unexpected answer. (ii) Are there any details of the DDCS which show a marked dependence on the target? Preliminary data taken near 0° for the targets N_2, H_2, and Ne gave spectra which were similar to those seen previously in the H^--Ar work (a sharp peak at E_s with a low-energy shoulder) and thus do not provide a positive response. However, the DDCS for the H^--He system were substantially different from the other cases and provide a positive response to the question.

The H^--He DDCS in the forward direction showed for the first time, two separate maxima at different electron energies. One maxima was found at $E_s = 272$ eV and the other about 30 eV lower, thus providing reasonable support for the previous assumption that two groups were present at small angles when Ar was used as a target. Accordingly, a series of measurements of the DDCS was made as a function of angle and projectile velocity to examine the manner in which the group at the lower energy depended on these variables. Clearly, the experiments with He as a target demonstrated that some features of the DDCS for electron loss of H^- were sensitive to the target electrons.

At this time the single calculation of projectile ionization that takes into account the presence of target electrons,[6] investigates the ionization of He^+ by He in only the forward direction. Since single-electron loss producing neutral atoms is the dominant process in the collisional detachment of H^-, the above calculation with a bare Coulomb interaction in the final state is not directly applicable. Furthermore, the measured DDCS are strongly angular dependent. Thus these data are presented in the hope that they will provide guidance for the theoretical investigation of electron loss of H^-.

II. RESULTS AND DISCUSSION

Energy spectra of electrons ejected during collisional electron detachment of 0.5-MeV H^- by He are shown in Figs. 1 and 2. At $\theta \approx 0.3°$ the sharp, cusplike peak is centered about E_s, while a broader group has its maximum about 30 eV below E_s. The sharp peak decreases in magnitude so rapidly that it is no longer apparent for observation angles greater than about 4°. The variation of the energy of the maximum of the broad group is shown in Fig. 3 where the error bars show our estimate of the accuracy with which the peak can be located. Comparison of these data with analogous data obtained with Ar as the target[1,2] reveal some similarities and what appears to be a significant difference: (i) the DDCS for both targets exhibit a sharp, cusplike peak whose magnitude decreases rapidly with angle; (ii) the trend toward higher energies of the maximum of the broad group with increasing angle is similar for both targets; and (iii) the position of the broad group is at a substantially lower energy for He than it is for Ar.

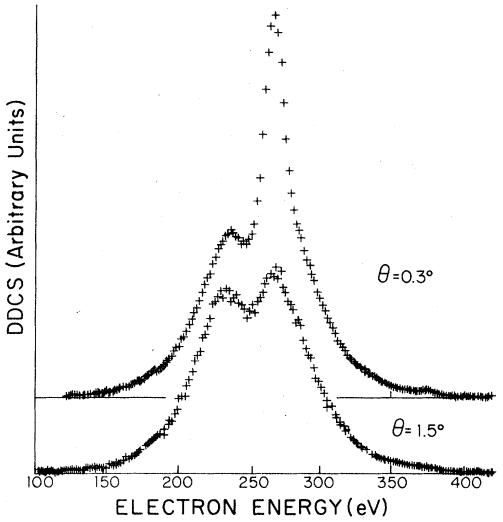

FIG. 1. DDCS in the forward direction for electrons from H^- He collision at 0.5 MeV. Vertical scales have been adjusted to give similar peak heights. The uncertainty in the angle is estimated to be less than ±0.15.

The character of the broad group changes smoothly from a relatively symmetric group

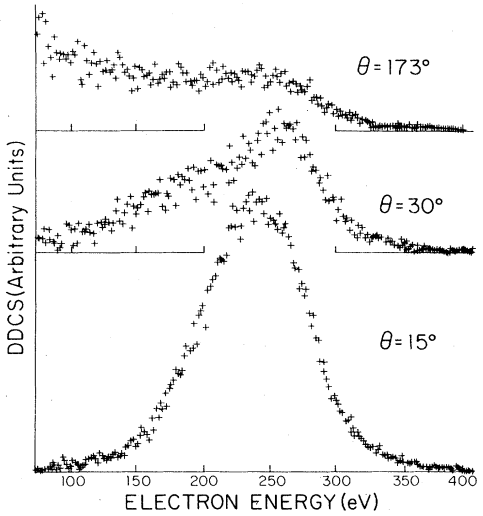

FIG. 2. DDCS for larger angles. Vertical scales have been adjusted.

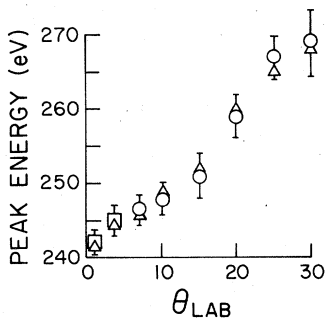

FIG. 3. Variation of the energy of the peak of the low-energy group as a function of detection angle. ○: 0.5-MeV H^- He. □: average of data taken with 0.35-, 0.5-, 0.7-, 1.0-, and 1.35-MeV H^-. △: 1.0-MeV D^-–He. Errors for D^- data are the same size as shown for the H^- data.

around 5° to an asymmetric group with a low-energy tail as the angle increases. Beyond 30° the small yield makes a determination of the position of the maximum of the group quite uncertain. At 173° one sees a smooth background at low energies. This background is due to electrons from target ionization, stray electrons, and electron-multiplier dark current.

The yield of electrons above background is shown in Fig. 4. Except at the large angles the uncertainty in the points is no more than 25%. The points for $\theta < 15°$ were taken from a smooth curve drawn through many data points including a 4° interval on the other side of the beam. Both sides of the beam were used to insure that there were no asymmetries. Usually several runs were made at each angle. At large angles the error bars represent the maximum spread of the integrated yields from the average point which is shown. The absolute cross section was obtained by a straightforward normalization procedure. The experimental relative SDCS was integrated over solid angle and normalized to the known electron-yield cross section,[7] $\sigma_{-10} + 2\sigma_{-11}$.

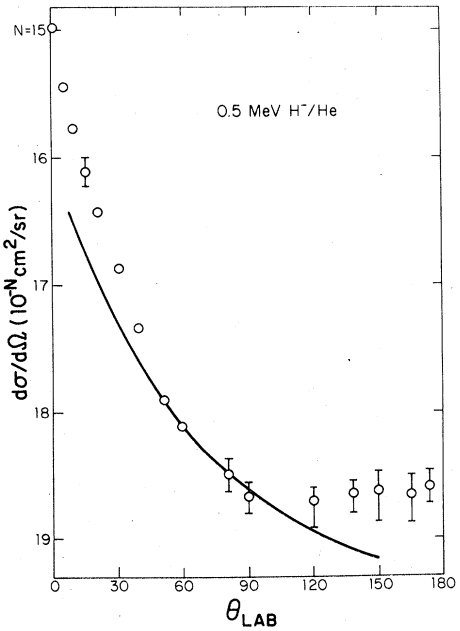

FIG. 4. Comparison of absolute SCDS. ○: H^--He data; —: 300-eV e-He elastic scattering calculations.

Also shown in Fig. 4 is the differential electron elastic scattering cross section from He at an incident energy[8] of 300 eV. The ESM produces a SDCS essentially the same as that shown for e-He scattering. As in the case of Ar, the general shape of the measured SDCS is in qualitative agreement with electron elastic scattering; differences occurring in the forward and backward directions. However, the significance of this remains an open question since the DDCS predicted by the ESM do not agree well with the measured ones. For example, the ESM calculation at 15° for the H^--He system is not only peaked 20 eV higher than the measured DDCS but has a full width at half maximum which is approximately one-half that of the measured DDCS. This calculated DDCS is almost identical in shape to the calculation shown in Fig. 2a of Ref. 2 for the H^--Ar system. This result is not surprising since the shapes of the calculated ESM DDCS change very little with angle and are determined primarily by the initial state of the projectile electron and not by the target.

As previously mentioned, a comparison of Fig. 1 with a spectrum for H^--Ar in the forward direction (see Fig. 1 of Ref. 5) reveals a distinct similarity. The sharp peak at E_e is common to both targets. If, in fact, the sharp peak is due to the double electron-loss process one would expect similar sharp peaks for both targets since the shape of the peak is governed by the presence of a "bare" Coulomb interaction between the electrons and the projectile in the final state. The same two figures reveal a marked target effect, whereas, for H^--Ar the low-energy group appears as a shoulder on the sharp peak for H^--He this group is at a lower energy sufficient to resolve it from the sharp peak. At angles greater than about 4° the sharp group disappears leaving the low-energy group which has been attributed to SEL. However, the details of the mechanism which gives rise to this group is uncertain. Nevertheless, it appears that two possibilities can be discarded.

First, consider the possibility that the low-energy group may be the result of isotropic electron emission from autoionizing states of 0.5-MeV

H^- that give rise to approximately 1-eV electrons in the rest frame of the projectile.[9] Electrons with an energy of 1 eV in the projectile frame would appear at a laboratory angle of 0° at 309 and 242 eV for the case of forward and backward ejection in the projectile frame, respectively. Autoionizing peaks have been observed in H^--Ar collisions,[2] collisions of H^- with several targets[9] and collisions of C, O, and Si ions with Ar and have been observed,[10] as expected, both above and below E_e. Peaks similar to A and B in Fig. 1 of Ref. 2 are seen in the H^--He case but they are less prominent. The low-energy group near 0° appears at 242 eV for H^--He collisions, however, it is not accompanied by its high-energy partner. Furthermore, electrons from autoionizing states have a strong kinematic energy dependence on the laboratory angle. In this case the autoionizing peaks in question should disappear at 3.5° and it is noteworthy that the broad group does not show a change in any characteristic near this angle. Thus it is unlikely that the broad group is due to autoionizing transitions. A similar analysis of the H^--Ar spectra leads to the same conclusion.

Second, it is unlikely that the low-energy group corresponds to an energy-loss peak produced by some inelastic interaction of one of the electrons previously detached since the experiments are conducted under single-collision conditions. Furthermore, the increase in the peak energy with angle as seen in Fig. 3 is in the opposite direction to that predicted by such an energy-loss process.

A third possibility is not as easily discarded although it must be considered highly speculative. Restricting our attention to the spectrum near 0°, shown in Fig. 1, the maximum of the low-energy group corresponds to an energy of about 1 eV in the projectile frame and could result from a differential cross section which peaks at this energy in the projectile frame. Although the incident energy is much higher here, for energies up to 10 keV there is no evidence, experimental or theoretical, that the electron-loss cross section has a maximum anywhere other than 0 eV in the projectile frame.[9,11] Nevertheless, for the sake of argument let us suppose that the differential cross section does peak at 1 eV instead of 0 eV. Then the absence of a similar peak on the high-energy side of E_e requires that the angular distribution be highly anisotropic in the projectile frame. This view suggests the possibility of some perturbation due to a postcollisional interaction between the free electron and the target. Presumably, this interaction would be target dependent. However, since there is no information available on the final state of the target it is difficult to lend solid support to this view. The notion of a postcollisional interaction leading to an anisotropic angular distribution could also be applied to the case of electrons from autoionizing transitions of the projectile. However, in this case it is still impossible to circumvent the expected kinematic behavior.

If the SEL cross section in the projectile frame is not a strong function of the projectile energy the supposition that this cross section has a maximum at an electron energy other than zero may be tested by measuring DDCS in the forward direction at different projectile energies. As mentioned above, the cross section must have a maximum at approximately 1 eV to shift the low-energy group 30 eV in the laboratory for 0.5-MeV H^-. If the position of the maximum of the projectile frame cross section remains the same for 1-MeV H^- the energy shift in the laboratory will be about 42 eV. In order to investigate this possibility, the H^- energy was changed from 0.5 MeV to 0.35, 0.7, 1.0, and 1.35 MeV and relative DDCS were measured in the forward direction. The positions of the peaks were measured at $\theta \approx 1°$ where both peaks are clearly visible and at $\theta \approx 3.5°$ where the low-energy group dominates the spectra. These spectra showed that at 1° the peak separation was, within the uncertainty of locating the peak, 30 eV at all ion energies. Also, at 3.5° the broad group was centered about 26.5 eV below E_e for the energy range investigated. Furthermore, data taken for $\theta < 30°$ using 1.0-MeV D^- ions, produced peak energies which agree with the H^- results as can be seen in Fig. 3. Therefore, unless the position of the maximum of the electron-loss cross section in the frame of the projectile has a dependence on the ion energy which is just that necessary to compensate for a changing laboratory ion velocity, which seems unlikely, we must conclude that the supposition that the cross section peaks at 1 eV is also incorrect.

Thus the details of the interactions producing the low-energy group of electrons from H^- seem to be independent of the ion velocity in the energy range examined here, but do depend on the electronic structure of the target.

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[1]M. M. Duncan and M. G. Menendez, Phys. Rev. A 16, 1799 (1977).
[2]M. G. Menendez and M. M. Duncan, Phys. Rev. Lett. 40, 1642 (1978).
[3]D. Burch, H. Wieman, and W. B. Ingalls, Phys. Rev. Lett. 30, 1823 (1973).
[4]F. Drepper and J. S. Briggs, J. Phys. B 9, 2063 (1976).
[5]M. M. Duncan and M. G. Menendez, Phys. Rev. A 19, 49 (1979).
[6]J. S. Briggs and F. Drepper, J. Phys. B 11, 4033 (1978).
[7]J. Heinemeier, P. Hvelplund, and F. R. Simpson, J. Phys. B 9, 2669 (1976).
[8]I. E. McCarthy, C. J. Noble, B. A. Phillips, and A. D. Turnbull, Phys. Rev. A 15, 2173 (1977).
[9]J. S. Risley, Ph.D. thesis, University of Washington, 1973 (unpublished).
[10]M. Suter, C. R. Vane, S. B. Elston, G. D. Alton, P. M. McGriffin, R. S. Thoe, L. Williams, and I. A. Sellin, Z. Phys. A 289, 433 (1979).
[11]M. R. C. McDowell and G. Peach, Proc. Phys. Soc. London 74, 463 (1959).