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Absolute cross-section measurements of the direct charge transfer of He$^+$ in neon in the energy range 0.5–5 keV

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Measurement of the differential cross sections of the electron capture of He$^+$ in Ne in the energy range 0.5–5 keV has been made. From these the total cross sections were calculated by integration. The present values are compared with those from previous measurements and with a recent diabatic calculation, with which good agreement has been found.

The absolute cross section for the direct charge transfer process of He$^+$ on a Ne target has been measured over the energy range 0.5–5 keV. On the experimental side, the pioneering measurements of Stedeford and Hasted[1] were followed by Fedorenko,[2] Barnett and Stier,[3] and by Eisele and Nagy,[4] who measured the total cross section. Jones *et al.*[5] integrated the angular distributions to obtain the total cross section. In addition to this, de Heer *et al.*[6] and Gilbody *et al.*[7] focused their research on the formation of metastable He. Altogether, these investigations covered a wide range, from 0.4 to 100 keV.

The electron-capture process of He$^+$ impact on Ne has been the subject of several theoretical approaches. Rapp and Francis[8] applied their charge-transfer model to this process. Coffey, Lorentz, and Smith[9] explained the results of Stedeford and Hasted below 2 keV, based on the available crossings of the potential-energy curves of the HeNe$^+$ states. Recently, Zygelman and Dalgarno,[10] using a diabatic formulation, found that their cross-section values were dependent on the choice of the origin of coordinates (He, Ne, or center of mass). They also found that at 0.9 keV the cross-section value was independent of the choice of origin.

From the above, it appears that there is already a good set of data on this process. Then, why are we reporting additional cross-section measurements? First, to the best of our knowledge, there are only two sets of measurements covering the range 0.5–5 keV, with substantial discrepancies between them as regards the measured values, and also with respect to the trends of the data below 2 keV. Thus we find this study justifiable. Second, these measurements provide further support to Zygelman and Dalgarno's calculations, and confirm the theoretically predicted value for the cross section of this process at 0.9 keV. Furthermore, it would have been desirable to assess the origin of coordinates by comparing our data with those of these authors. However, because of the limitations of the experiment and of the closeness of the cross sections based on either the Ne-atom or the center-of-mass origin of coordinates, it was not possible to establish a clear distinction.

The experimental apparatus and technique needed to generate the fast ion beam are essentially the same as that reported recently,[11] with some modifications and refinements in accordance with this experiment (Fig. 1). He ions were formed in a Colutron-type ion source, accelerated to the desired energy, focused and velocity-analyzed by a Wien filter, and passed through a series of collimators before entering the gas target cell, consisting of a cylinder of 2.5 mm in length and diameter, with a 2-mm-wide, 6-mm-long exit aperture. All other apertures and slits had knife edges. The target cell was located at the center of a rotatable, computer-controlled vacuum chamber that moved the whole detector assembly 47 cm away from the target cell. A precision stepping motor ensured a high repeatability in the positioning of the chamber over a large series of measurements. The detector chamber housed a parallel-plate electrostatic analyzer, located at 45° with respect to the incoming beam direction, with two funnel-type channel electron multipliers (CEM) for particle detection. The He^0 atoms formed by electron capture passed straight the analyzer through a 1-cm-diam hole on its rear plate, and impinged on a CEM so that the neutral counting rate could be measured. Separation of charged particles occurred in-

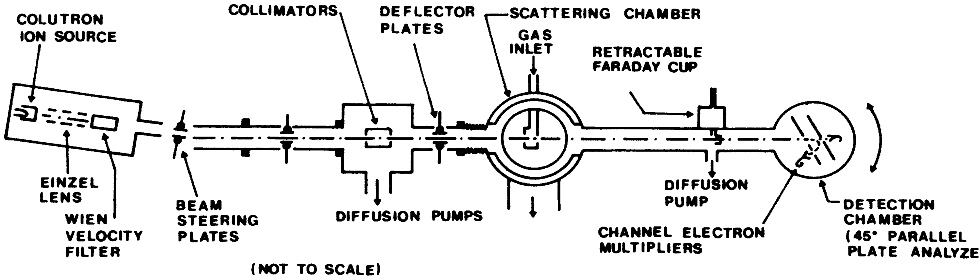

FIG. 1. Schematic diagram of the apparatus.

side the analyzer, which was set to detect the He$^+$ species with a second CEM. This flux was used as a measure of the stability of the beam during the experiment. Care was taken in handling the He$^+$ beam intensity in order to assure that the CEM operated in the charged-saturated mode. Corrections for the multiplier counting efficiency e were allowed for as described in Ref. 12. The total beam current I_0 was measured by a retractable Faraday cup.

The measurement technique was as follows. With the He$^+$ beam accelerated at the desired energy, the total current I_0 was measured by the Faraday cup. The number of He^0 particles, $[N(\theta,\phi)]$, scattered through a solid angle $d\Omega$ was determined by the CEM as the assembly was rotated about the Ne cell. The 0° angle was set by scanning the beam sideways until symmetry could be ensured. The differential cross section per unit time was determined by the relation

$$\frac{d\sigma}{d\Omega}=\frac{N(\theta,\phi)}{I_0 nled\Omega} ,$$

where n is the target density corrected to standard temperature (273 K) and l is the effective path length. The total cross section was derived by integrating the differential cross section over θ and ϕ:

$$\sigma=2\pi\int\frac{d\sigma}{d\Omega}\sin\theta\, d\theta .$$

The actual value of the differential cross section (DCS) was obtained by measuring the DCS at two different pressures in the range $(1-4)\times10^{-4}$ Torr with the same steady beam. Then a point-to-point subtraction of both DCS's was carried out to eliminate the counting rate due

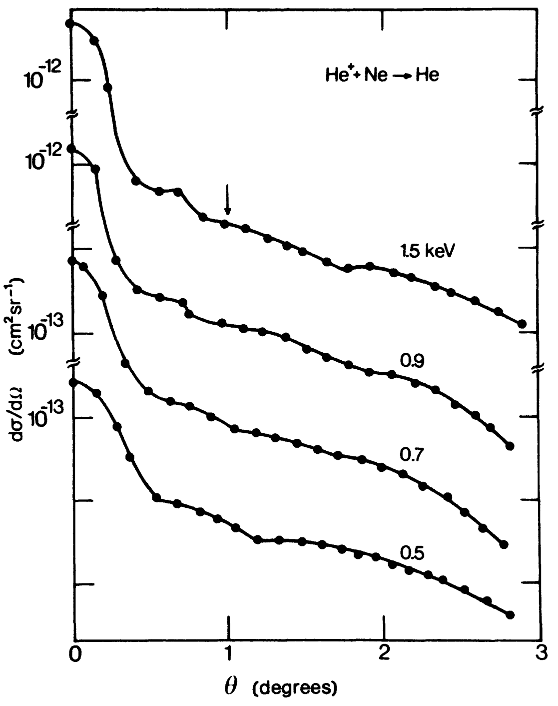

FIG. 2. Differential scattering cross sections for He^0 formation as a function of the scattering angle at several energies. The arrow at 1.5 keV indicates the integration limit up to $\theta=1°$ for comparison of our cross section value with that of Ref. 13.

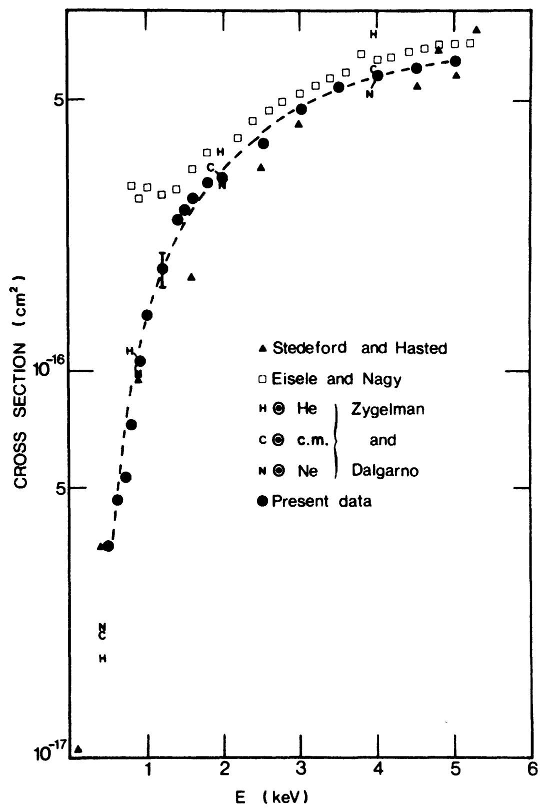

FIG. 3. Present absolute cross sections for the direct charge transfer of He$^+$ in Ne from 0.5 to 5 keV.

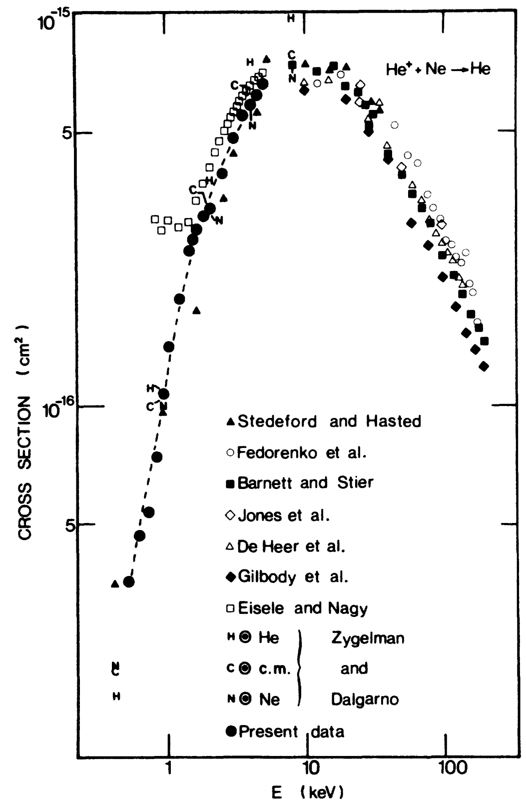

FIG. 4. Full set of data for the direct charge transfer of He$^+$ in Ne.

to neutralization of the He^+ beam on the slits and that arising from background distributions. This procedure had to be followed for energies below 1.5 keV. Above this value, the beam dispersion became so small that the effect was negligible. The He^+ beam flux was measured before and after each angular scan. Path lengths and apertures were chosen such that the angular resolution of the system was 1.7 mrad or $\sim 0.1^\circ$. The operating pressures were always less than 4×10^{-4} Torr in order to ensure a single-collision regime, and were measured by a capacitance manometer. Figure 2 shows typical angular distributions from 1.5 keV down. These distributions show some structure that has been studied previously,[13,14] and has been successfully explained in terms of the interference of two scattering amplitudes arising from two scattering channels. Measurements not agreeing to within 5% were discarded.

At 1.5 keV of He^+ the differential cross section was integrated from 0° to 1° to compare it with a recent measurement that covers this angular range.[13] The measured cross section from this reference was $\sigma=1.77\times10^{-16}$ cm^2, which compares well with a value of 2.1×10^{-16} cm^2, as derived from integration of our distributions.

The differential scattering cross sections have been integrated and the total electron-capture cross sections are shown in Figs. 3 and 4. Figure 3 displays the present data and those due to Stedeford and Hasted[1] and to Eisele and Nagy,[4] over the energy range 0.5–5 keV, together with the theoretical data from Zygelman and Dalgarno.[10] Above 2 keV the present cross sections agree well with those measured by Stedeford and Hasted and by Eisele and Nagy. Below this value, agreement with Stedeford-Hasted data remains, but a strong discrepancy was found with the data of Eisele and Nagy. The predicted cross section value by Zygelman and Dalgarno, using a diabatic formulation at 0.9 keV of 1×10^{-16} cm^2 has been confirmed by this experiment. Moreover, the present data follow the trend of these calculations based on either the Ne atom or the center of mass in the origin of coordinates. Figure 4 shows the experimental data with the calculations of Ref. 10 in the energy range 0.4–100 keV. Notice that above the present range of measurement the cross-section value due to Barnett also lies between the calculated cross sections for center of mass and for Ne. As it was stated above, due to experimental uncertainties it was not possible to make a distinction between these two possibilities.

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