Ionization of Helium Near Threshold by Electron Impact

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The ionization threshold of helium has been studied experimentally using the retarding potential difference technique. The cross section for the formation of He^+ is nonlinear for at least the first 2 eV above threshold, in agreement with recent results obtained by Brion and Thomas using a 127° electrostatic energy selector.

The threshold law for the cross section for ionization of simple monatomic gases by electron impact has recently been the subject of renewed interest [1, 2]. To date, studies of He^+, using the retarding potential difference (RPD) technique [3–6] have been taken as support for, or interpreted with the aid of, a linear threshold law [7, 8]. Recent studies with a 127° electrostatic energy selector have, however, suggested that the ionization cross section for He^+ [2], and also for H^+ [1], are consistent with a nonlinear threshold law [9, 10].

In this paper we present the results of a study of He^+, undertaken in an attempt to resolve the discrepancy. Using the RPD technique, we find that the ionization efficiency curve for He^+ is nonlinear for at least 2 eV above threshold, and that over this region it is in essential agreement with that reported by Brion and Thomas [2], who used a selector. Data reported by other workers for He^+ over the same energy range [3–6] are shown to be consistent with the above result. At present no definite conclusion can be drawn regarding the situation prevailing at higher energies, which will be more difficult to resolve.

Experiments were performed with a 5-electrode RPD gun, similar to that used by Fox et al. [11], mounted on the ion stack of a Nuclide 12-inch 90-degree mass spectrometer. Slit widths were 0.5 mm for the draw out and two shields, 0.2 mm for the retard and 1.65 mm for the entrance to the ionization chamber. A magnetic field of 70 gauss was used to collimate the electron beam which was usually not pulsed. The maximum energy distribution of the electrons was about 0.3 eV, which would correspond to a full width at half peak height of about 0.15 eV. Perturbation of the electron beam by fields penetrating into the ionization chamber was prevented by keeping the electron collector and ion repeller at chamber potential, and by using a low ion draw-out field. The variation of the electron current with electron energy over the range of interest was less than 4%, as was the variation of ion current with sample pressure ($\sim 5 \times 10^{-6}$ mm Hg) and with ionizing electron current ($\sim 5 \times 10^{-8}$ A).

The ionization efficiency curve obtained for He^+ formation over a range of roughly 2 eV above threshold is shown in Fig. 1 (a), along with the curve for CO^+. Whereas the points comprising the latter clearly fall on a straight line, the curve for He^+, by comparison, is seen to be decidedly nonlinear.

We believe that instrumental factors cannot explain the shape of the He^+ ionization efficiency curve. The RPD gun has consistently yielded the same result over a period of a few months under markedly differing conditions, chosen to show up possible spurious effects. For example, the source magnetic field was increased by a factor of ten, its spatial alignment was changed arbitrarily, the slit potentials were varied between wide limits, the repeller and trap potentials were changed, the electron beam and repeller electrode were sequentially puls-

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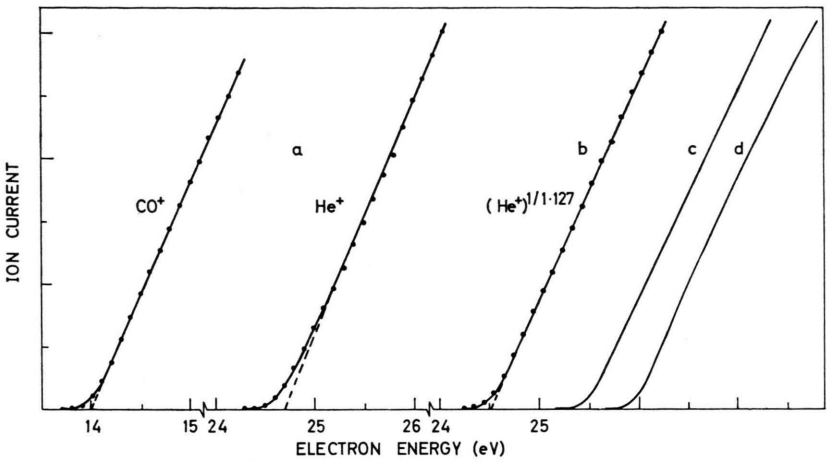

Fig. 1. (a) Experimental ionization efficiency curves for CO^+ and He^+ obtained by the RPD technique. (b) The experimental ionization efficiency curve for He^+ raised to the power 1/1.127. (c) Calculated 1.127 power law curve; and (d) linear power law curve, both raised to the power 1/1.127, with the experimental electron energy distribution folded in.

ed, and the ionization efficiency curve for He^+ was determined in mixtures of CO and He. These results, in conjunction with the consistency checks noted above, would seem to indicate that the only remaining instrumental factor which could account for the nonlinearity of the curve for He^+ would be an excessive spread in electron energy.

The difference between the onsets of the CO^+ and He^+ curves in Fig. 1(a) agree to within 0.13 eV with the spectroscopic difference (10.57 eV). Consequently, a broad electron energy distribution would imply the presence, in the ionization chamber, of a large number of electrons with kinetic energy about 0.5 eV less than the kinetic energy corresponding to the potential difference between the ionization chamber and the retard electrode. Such electrons could be produced in the region immediately beyond the ionization chamber if electrons in the primary beam with, say, 25 eV kinetic energy were to lose about 0.5 eV kinetic energy on hitting the collector, and were then reflected back into the chamber. To investigate this possibility, SF_6, which resonantly captures ~ 0.03 eV electrons to form SF_6^- [12], was used as a detector molecule. The electron collector was fixed at about $+20$ volts with respect to the ionization chamber. Electrons losing V eV of kinetic energy in the vicinity of the collector would then be observed as SF_6^- ions, when the chamber is at about $+V$ volts with respect to the retard electrode. Although this voltage was varied continuously from 0 to $+10$ volts, no low-energy electrons were observed. In a second experiment, we investigated the possibility that low-energy electrons were being formed in the region immediately preceding the ionization chamber. The potential on the shield located between the retard electrode and the chamber was increased considerably, so that electrons were first accelerated up to the shield, and then decelerated into the chamber. Again no low-energy electrons were observed.

The above evidence has led us to believe that the ionization process is responsible for the nonlinear shape of the He^+ ionization efficiency curve. According to Wannier [9], the energy dependence of the ionization cross section, I, near threshold should be of the form

$$I^{(1/1.127)} = C(E - E_0)$$

where E is the electron energy, E_0 is the ionization potential and C is a proportionality constant. Using this relation as a convenient basis for the comparison of different sets of experimental data, we have plotted in Fig. 1(b) our experimental values raised to the power 1/1.127. We have also folded the experimental electron energy distribution into data calculated from 1.127 and linear power laws, and have treated the resultant curves in the same way [Figs. 1(c) and 1(d)]. Fig. 2 shows the experimental results of Brion and Thomas [2] and others [3–6] raised to the power 1/1.127.

It is clear that our curve for He^+ in Fig. 1(b), obtained with the RPD technique, closely resembles that of Brion and Thomas, determined with the aid of an electron selector (Fig. 2). Both sets of data yield essentially straight lines when plotted in the above way, in contrast to the shape that a linear power law yields [Fig. 1(d)].

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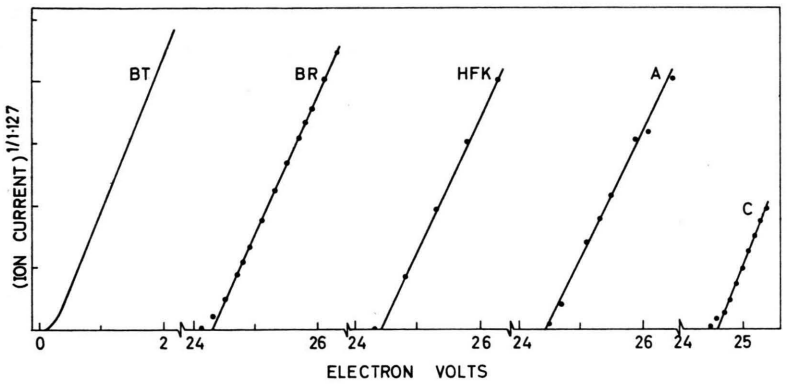

Fig. 2. Ionization efficiency curves for He^+ near threshold, raised to the power 1/1.127, obtained from the data of BRION and THOMAS (BT), BRIGLIA and RAPP (BR), HICKAM, FOX and KJELDAAS (HFK), ASUNDI (A) and CURRAN (C). The energy scale for (BT) refers to electron volts above threshold. The other energy scales denote electron energy.

None of the remaining curves in Fig. 2 differs significantly from those in Figs. 1(b) and 2(BT), when due allowance is made for experimental scatter shown in the data. In fact, the curve obtained by Briglia and Rapp [Fig. 2(BR)] compares favourably with those in Figs. 1(b) and 2(BT), and would be explicable in terms of a linear threshold law only if the electron energy distribution were considerably greater than their estimated value.

The agreement regarding the shape of the ionization efficiency curve for He^+ below 2 eV does not persist to higher energies. If straight lines are extrapolated from Figs. 2(BT), (BR) and (HFK) to 6 eV above threshold, they respectively lie about 10% below, 4% above and 10% above the experimental curves given by the authors, i. e. the experimental curves differ markedly when a 6 eV energy range is considered. Results obtained by us indicated that the error in the ion current at 6 eV above threshold, relative to that at 1 eV above threshold, can be as high as 10% when the RPD technique is used in conjunction with a mass spectrometer. A possible explanation for this is that the path followed by the electron beam may vary with electron energy, and that the ion collection efficiency for light ions may change significantly when a different region is traversed by the electron beam. Although the above 10% change is significant over 6 eV, it corresponds to a change of about 3% over 2 eV, which would not affect our previous conclusions.

BRION and THOMAS have suggested that their data obey a power law in excess of 1.127 near threshold [2]. This is reflected in the curve in Fig. 2(BT), from which it is seen that, even though one gets a straight line when the ion current is raised to the power 1/1.127, the intercept of the straight line is about 0.25 eV above the experimental threshold. The experimentally measured width of their electron energy distribution at half height was 0.054 eV – considerably less than the above difference.

The intercept of the straight line in Fig. 1(b), determined by us, is 0.08 eV below the spectroscopic ionization potential (IP), and our results are thus represented by the 1.127 power law within the experimental error. The energy scale for this curve was determined by making the CO^+ intercept in Fig. 1(a) agree with its spectroscopic IP. The rather large difference in IP's between CO^+ and He^+ admittedly introduces some uncertainty into the energy calibration. Further studies of the ionization of He^+ over the first 0.4 eV above threshold, with special emphasis on the exact position of the threshold, would seem desirable.

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