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[19]The theoretical curve given in Ref. 4 shows less detail than Fig. 2 here because calculations quoted there were carried out at fewer energy points, as shown. Note that Fig. 2 includes also ^3S, ^3P, and ^3D contributions not shown in Fig. 1.

[20]P. G. Burke, private communication.

ELECTRON-IMPACT EXCITATION OF THE 2S STATE AND AUTOIONIZATION BELOW THE $n=3$ LEVEL OF He^+ (EXPERIMENTAL)

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Madden and Codling[1] have reported observing autoionizing neutral-atom energy states in helium. Cooper, Fano, and Prats[2] have interpreted the energy states theoretically. These high-energy states require the simultaneous excitation of two electrons and the states interact with the adjacent continuum and decay by autoionization in times of 10^{-13}-10^{-14} sec. The interaction leads to resonances in the photoionization continuum of helium.

Madden and Codling[3] have recently shown that autoionizing states, excited by photon absorption, exist below the $n=3$ threshold of He^+. Numerous theoretical studies have been made of the electron-impact excitation of He^+. The excitation cross section for He^+ $1S \rightarrow 2S$ has been calculated by Burgess,[4] Hummer,[5] and Burke, McVicar, and Smith.[6] Ormonde, Whitaker, and Lipsky,[7] using close-coupling calculations, have shown the effect of autoionizing levels in helium below the $n=3$ level on the cross section for He^+ $1S \rightarrow 2S$. An experimental measurement has been made by Dance, Harrison, and Smith[8] of this cross section, using the crossed-beam technique. Ormonde, Whitaker, and Lipsky[7] and Burke and Taylor[9] predict that this cross section should peak at threshold and decrease at higher energies. The experimental work showed that the cross section reached a maximum just below the $n=3$ threshold at about 48 eV. Ormonde, Whitaker, and Lipsky[7] suggest that the position of this peak can be explained in terms of autoionizing levels below the $n=3$ level of He^+.

The object of this work was to study (1) the shape of the excitation function for

$$He^+ + e \rightarrow He^+(2S)$$

very close to threshold; (2) to look for resonant effects in excitation in the preceding reaction.

An experimental technique different from the crossed-beam method used by Dance, Harrison, and Smith[8] has been used in this work to observe the excitation function for the He^+ $2S$ state. Also, in contrast to the crossed-beam method, the signal-to-noise ratio is very good. The method described by Baker and Hasted,[10] in which ions are trapped for considerable times by the space charge of a magnetically confined electron beam, has been used. The ion source used is based on the design described by Redhead.[11] Ions formed in the source were magnetically analyzed by a 12-in. radius, 90°-sector mass spectrometer. Ions were detected by the ion detector shown in Fig. 1. The reason for the use of this type of ion detector can be explained if we consider the reactions that can take place in the ion source. These, with their appearance potentials, are as follows:

$$He + e \rightarrow He^+(1S) + 2e, \quad 24.6 \text{ V}; \tag{1}$$

$$He^+(1S) + e \rightarrow He^+(2S) + e, \quad 40.8 \text{ V}; \tag{2}$$

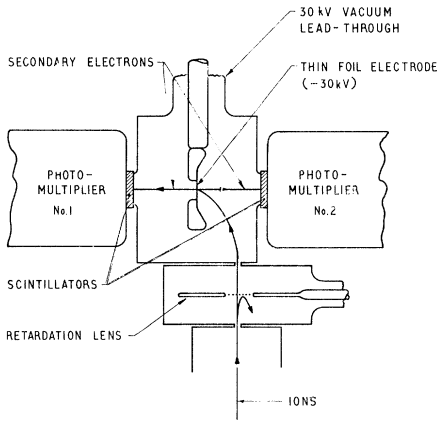

FIG. 1. Ion detector showing retardation lens and thin-foil arrangement.

$$He^+(2S)+e \rightarrow He^{++}+2e, \quad 13.6\ V; \tag{3}$$

$$He^+ + e \rightarrow He^{++}+2e, \quad 54.4\ V; \tag{4}$$

$$He + e \rightarrow He^{++}+3e, \quad 79\ V. \tag{5}$$

It can be seen that He^{++} can be formed by three electrons colliding successively with the same helium atom, and that the appearance potential for He^{++} should be that of Reaction (2) at 40.8 V. It should be possible to study the excitation function for Reaction (2) between 40.8 and 54.4 V, at which point Reaction (4) becomes dominant since these He^{++} ions can be formed by a two-collision process. Thus, the triple-collision process forms the basis for our study of the excitation function for $He^+(2S)$.

This method results in having to detect He^{++}-ion currents in the range 10^{-17}-10^{-19} A. Also, at $m/e=2$ there is a large ion current from H_2^+ arising from background hydrogen in the mass spectrometer. The background pressure in the ion source is about 5×10^{-7} mm Hg. This results in H_2^+ ion currents of 10^{-11}-10^{-12} A. A resolution of about 150 is required to separate H_2^+ from He^{++} and the mass spectrometer resolution was set at 400. However, because of ion scatter caused by collisions of ions with residual gas atoms along the flight path of the instrument, an H_2^+ ion current of 10^{-15}-10^{-16} A scattered into the He^{++} mass position. To reduce this "noise" at the He^{++} mass position to less than 10^{-19} A, two methods were used. The first was the use of a retardation lens described by Freeman, Daly, and Powell.[12] This rejects most ions that have made collisions, and it reduced H_2^+ scatter currents by a factor of about 50. A further reduction of 100 was obtained by the use of a thin-foil scintillation detector described by Daly.[13] Figure 1 shows the foil through which He^{++} ions can penetrate and release electrons off the back of the foil. These electrons are detected by the phosphor-photomultiplier combination. H_2^+ ions do not have sufficient range to penetrate the foil and hence are not detected. The combination of these two devices reduced the H_2^+ "noise" to below 10^{-19} A.

Spectroscopically pure helium was admitted to the ion source. Helium pressure in the ion-source region was 10^{-6} mm Hg and the electron trap current was 2×10^{-4} A. The electron energy was scanned linearly with time. Figure 2, curve A, shows the variation of He^{++} ion current between 40- and 55-eV electron energy. This run took 20 min with a 5-sec time constant on the recorder, and the maximum ion intensity was about 200 ions/sec.

It can be seen that the initial break is at 41 eV and this is followed by a sharp rise to a maximum at 42 eV, followed by a slow fall. Between 42 eV and 54 eV there is structure in the curve. A sharp rise occurs beyond 54 eV. Over the energy range 40 to 54 eV it was found that the ion intensity varies linearly with helium pressure in the ion source, and that it varies as I^3 where I is the electron beam current. Thus it appears that Reactions (1), (2), and (3) are producing He^{++} in the ion source, and that above 54 eV Reaction (4) is dominant.

As a check on whether the structure appearing on the curve was instrumental, the following reaction was examined:

$$Ne^+ + e \rightarrow Ne^{++}, \quad 41.1\ V. \tag{6}$$

It can be seen in Fig. 2, curve B, that this reaction, examined under the same experimental conditions as for helium, produces no structure over this energy region.

Curve A of Fig. 2 rises from threshold to a maximum over about 1 eV and then proceeds to fall as predicted by theory. However, the shape of the curve is controlled by Reactions (1), (2), and (3), and the fall-off must be considered in relation to the behavior of the cross sections for these three reactions. Reaction (1) has a positive slope in the region of 40 eV energy. Burke and Taylor,[14] using close-coupling calculations, have investigated the ionization cross sections for Reaction (3) and have shown that the cross-section gradient is negative in the region of 40 eV energy. A comparison of the gradients at this energy shows that for Reaction (1), $(1/\sigma)(d\sigma/dE)\simeq0.04$, and for

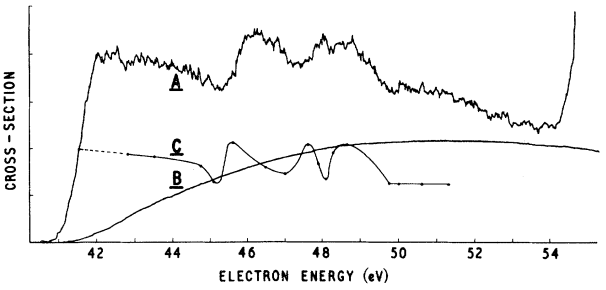

FIG. 2. Curve A is experimental excitation function for $He^+(1S)+e \rightarrow He^+(2S)+e$; curve B is excitation function for $Ne^+ + e \rightarrow Ne^{++}+2e$; and curve C is calculated excitation function for $He^+(1S)+e \rightarrow He^+(2S)+e$. The relative magnitudes of the cross sections in Fig. 2 and Fig. 3 bear no relationship to each other.

Reaction (3), $(1/\sigma)(d\sigma/dE) = -0.013$. Therefore, the fall-off shown in curve A would be even more rapid if allowance were made for the effects of the cross-sectional variations for Reactions (1) and (3).

Ormonde, Whitaker, and Lipsky[7] have calculated $\sigma(1S\text{-}2S)$ and this is reproduced as curve C of Fig. 2. For the purpose of matching these curves, the $n = 2$ level at 40.8 eV of He^+ for the experimental curve A has been taken as the midpoint of the nearly linear rise from threshold to its maximum value. The first dip in the region of 45 eV for curve C corresponds to the ^1S partial-wave contribution to $\sigma(1S\text{-}2S)$, and it matches well in position and shape that recorded experimentally on curve A. Two further resonances on curve C are not reproduced in the experimental curve, but there is evidence of structure in the latter curve over the broad peak.

An attempt was made to remove the smearing effect of the electron energy distribution on the structure. The deconvolution method described by Winters, Collins, and Courchene[15] was used. It was applied to a curve similar to curve A of Fig. 2 but drawn with a larger time constant to reduce statistical noise. The result is shown in Fig. 3, curve A. Curve B shows the experimentally observed $\sigma(1S\text{-}2S)$ obtained by Dance, Harrison, and Smith.[8] Curve C again reproduces the results of Ormonde, Whitaker, and Lipsky.[7]

It can be seen that three distinct resonances appear. Madden and Codling[3] have shown that the resonances corresponding to levels $(sp, 3n^+)^1P$ with $n = 3$, 4, and 5 occur at 45.37 $\pm$ 0.04, 47.09 $\pm$ 0.01, and 47.63 $\pm$ 0.01 eV, respectively.

One cannot compare our structure too directly with the results of Madden and Codling[3] as they can only observe ^1P resonances, whereas in this experiment we see the effects of resonances in all partial waves. From the calculations of Ormonde, Whitaker, and Lipsky,[7] the first dip coreesponds to a ^1S resonance and the second to a combination of the second ^1S and a ^1P and ^1D resonance.

No absolute cross section for the He^+ $2S$ excitation can be obtained from this work. However, the very strong effect of resonance on this cross section has been observed. Also, the threshold behavior of the excitation function has been shown to agree with theoretical predictions.

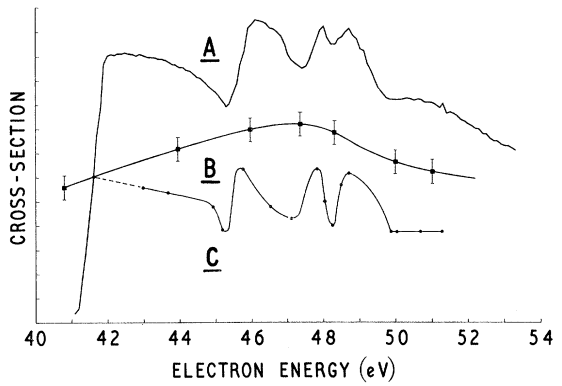

FIG. 3. Curve A is a deconvoluted excitation function for $He^+(1S) + e \rightarrow He^+(2S) + e$; curve B is the same excitation function measured by the crossed-beam technique; and curve C is the calculated excitation function.

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