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Measured Cross Sections for Photoionization of Ground-State He to $He^+(n=2)$

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Cross sections for simultaneous photoionization of He and excitation to $He^+(n=2)$ have been measured from threshold to 160 eV. The data show clear evidence of autoionization from levels converging on $He^+(n=3)$. Away from such structure, they are in good agreement with previous experimental values. None of the theoretical predictions gives the correct magnitude at low energies.

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Helium is the simplest atom in which electron correlation effects can occur. Hence, a comparison between experiment and theory for the simultaneous photoionization and excitation of helium is a good test of the theoretical understanding of correlation effects. In particular, the measurement affords an opportunity to study the interaction with the excited state of the autoionizing series converging to the $n=3$ threshold. A single, weak series has been seen in the total absorption cross section,[1] although in theory five series can be expected. The measurement is also of importance in correcting the measured total absorption cross section in order to compare it with theoretical calculations for ionization to ground state He^+.[2]

The main transition of interest is $He(1s^2)+h\nu \rightarrow He^+(n=2)+e^-$ which has a threshold at 65.4 eV. Existing theoretical calculations[3-5] disagree with each other at low energies by up to 40%. The disagreement is even greater for the ratio of ions formed in the $2s$ and $2p$ levels, with only the close coupling calculations of Jacobs and Burke[5] predicting a substantial contribution from the $2p$ level. Previous experimental data[6-8] have come from photoelectron experiments giving the ratio of ions formed in the $He^+(n=2)$ state to those formed in the $He^+(n=1)$ state. These experiments could not distinguish between the $2s$ and $2p$ levels because of the very small energy difference between them. However, the angular distribution for the $n=2$ continuum electrons found by Krause and Wuilleumier[7] indicates that there is an appreciable contribution from the $2p$ state. The ratios $He^+(n=2)/He^+(n=1)$ found in this work agree with those predicted by Jacobs and Burke,[5] but the later data of Wuilleumier[8] are somewhat lower.

In the present experiment, the relative cross section was measured by utilizing the subsequent decay of the $n=2$ level to the ground state with the emission of a 40.8-eV photon. The source of incident radiation was the University of Wisconsin storage ring, Tantalus. The experiment was mounted on the 2.2-m grazing incidence monochromator which has been described by Carlson *et al.*[9] The fluorescence was detected by a proportional counter[10] mounted perpendicularly to the incident photon beam. The proportional counter was operated with methane at a pressure of about 80 Torr, and was separated from the experimental chamber by a VYNS window (a copolymer of vinyl acetate and vinyl chloride). The combined transmission of the window and the nickel mesh used as support was 8%. Research grade helium was admitted to the experimental chamber via a needle valve. The chamber was separated from the monochromator by a further VYNS window which, as well as confining the gas, served to eliminate stray light with a photon energy below about 35 eV.

The $2p$ level of He^+ decays to the ground state by an electric dipole transition with a lifetime of 10^{-10} s. The $2s$ level is metastable, and its natural decay mode is by a two-photon $E1$ transition with a lifetime of 1.9 ms.[11] However, the collisional deexcitation cross section[12] is sufficiently large to ensure that the $2s$ level decays by a single-photon transition at the pressure used (0.2 Torr).

Collisions between helium metastable ions and neutral atoms can also result in Penning ionization of the neutral with no photon emission. This is most likely to be important at smaller impact parameters than those for which mixing can occur.[13] For the thermal-energy He^+ ions formed in the present experiment, the impact parameter of the collision will be large, and so Penning ionization should have a limited effect on the total deexcitation rate.

For photon energies from threshold up to 90 eV, the data were taken with the monochromator bandpass set at ~0.5 Å. At higher photon energies the bandpass was increased to ~3 Å in order to obtain reasonable counting statistics. The signal rate varied from 20 to 2 s^{-1}, while the background counts were 2–3 s^{-1}. The fluorescent signal was normalized to constant photon flux by use of the monochromator output measured with no gas present, with a sodium salicylate–covered window and a photomultiplier.

The variation with photon energy of the simultaneous ionization and excitation cross section for the region just above threshold is shown in Fig. 1. For clarity, error bars are not shown, but random errors are typically 5%. The structure clearly visible in the cross section is a result of autoionization from excited levels leading to the $He^+(n=3)$ threshold. This structure, first seen by Madden and Codling,[1] is very weak in the total absorption cross section. The strong effect in the $n=2$ cross section confirms the prediction of Fano and Cooper[14] and the calculations of Senashenko and Wague[15] that the main interaction is with the $n=2$ continuum. As in the analogous experiment on the negative hydrogen ion,[16] only one series is seen.

Figure 2 shows the variation of the fluorescence signal at higher photon energies. Above the $n=3$ threshold at 73 eV, there is the possibility of additional fluorescence from the higher excited states. The efficiency with which it is detected will depend on whether the decay is directly to the ground state, or whether it cascades through the $n=2$ level. This, in turn, depends on the probability for the excitation of the different angular momentum states. From the dipole selection rules, only the p states can decay directly. A comparison of lifetimes for similar transitions in hydrogen shows that this mode of decay is more probable than a cascade. Because of the transmission characteristics of the VYNS window, the higher-energy photon emitted in the direct decay of the $n=3$ level will be detected twice

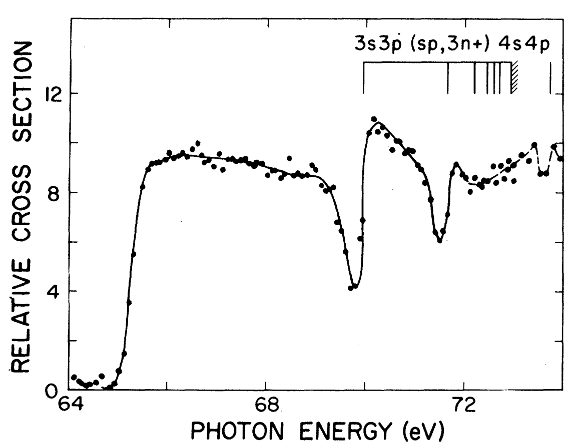

FIG. 1. The near-threshold variation of the $He^+(n=2)$ cross section. The positions of the autoionizing lines are taken from Ref. 1.

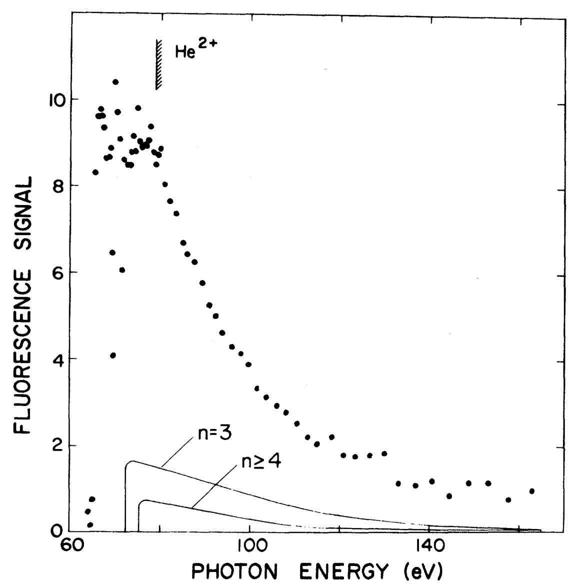

FIG. 2. The variation of the total fluorescent signal with photon energy. The contributions from levels $n \geq 3$ have been estimated from the data of Ref. 17.

as efficiently as that from decay of the $n = 2$ level. However, no significant increase in signal is seen at the $n = 3$ threshold and, in the absence of evidence to the contrary, it will be assumed that decay from higher excited levels proceeds via the $n = 2$ level. The relative cross section for excitation of the $n = 3$ level and the combined cross sections for the higher levels have been measured at several energies between 77 and 151 eV.[17] Values for other energies have been estimated from these data assuming a smooth behavior of the cross sections with photon energy. This assumption is most likely to break down close to threshold. The contribution of the higher levels, which is shown in Fig. 2, was subtracted from the total in order to give the signal due to the $n = 2$ level only. The correction introduces a systematic error of about 5%.

Figure 3 shows the corrected cross section for the $n = 2$ level. For clarity, a smooth line has been drawn through the data. It has been placed on an absolute scale by normalizing to the data of Wuilleumier[8] at 82.5 eV. The ratios measured by Wuilleumier were made absolute by normalizing to the total-absorption cross-section data of Marr and West[18] with corrections for double ionization taken from an average of the data of Wight and Van der Wiel[17] and Holland *et al.*[20] The agreement between the present data and the previous experimental values is good over the whole energy range. The agreement with theoretical calculations is less good. The cross section calculated by Salpeter and Zaidi,[3] using the Hartree approximation, lies some 30% below the data at low energies. The cross section calculated by Brown[4] is almost identical to that of Salpeter and Zaidi and is not shown. The close-coupling calculation of Jacobs and Burke[5] is 10–15% high at low energies. All the calculated cross sections come into better agreement at high energies.

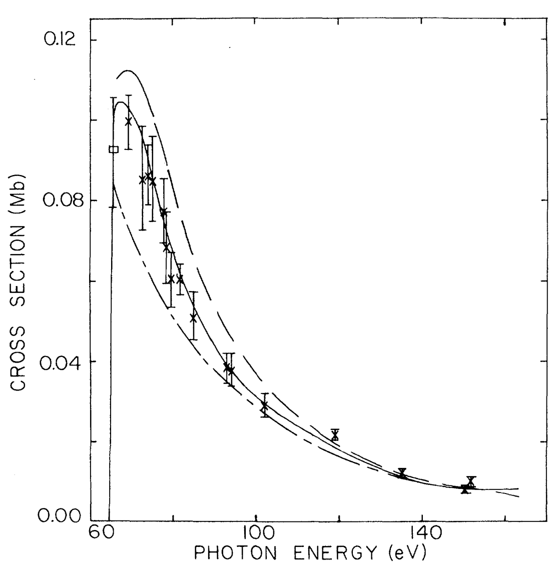

FIG. 3. The cross section for $He(1s^2) + h\nu \rightarrow He^+(n = 2) + e^-$. Experimental: solid lines, present data; squares, Ref. 5; crosses, Refs. 7 and 8. Theory: dot-dashed lines, Ref. 3; dashed lines, Ref. 5.

These measurements have shown the dominance of interactions with the $n = 2$ channel in the autoionizing region below the $n = 3$ threshold, and the inadequacy of present calculations at low energies. Measurements with both better resolution and better statistics are required in order to search for the remaining autoionizing series. In addition, by eliminating the pressure effects that cause the $2s$ level to decay in the present experiment, it will be possible to measure the separate contributions of the $2s$ and $2p$ states. Modifications to the apparatus are in hand to accomplish this.

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