Double Excitation of Helium by Fast Electrons, Protons, and $C^{(4-6)+}$ Ions

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The electron emission yield from the doubly excited $\{(2p^2)^1D+(2s2p)^1P\}$ states in He excited by impact of fast equivelocity electrons, protons, and carbon ions (charge state 4–6) has been measured at the reduced energy of 1.84 MeV/u. The data constitute a challenge to the recently proposed models that incorporate electron-correlation effects in atomic collisions.

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Electron-correlation effects in atomic collisions are currently receiving a great deal of interest. These effects have, e.g., been studied in the double ionization of helium, where Haugen *et al.*[1] observed that in a broad range of velocities around $10v_0$ the cross sections for double ionization by electrons was almost twice as large as those seen with equivelocity protons. Andersen *et al.*[2,3] recently found that antiprotons in the same velocity range gave results similar to electrons, thus showing that double ionization depends on the sign of the projectile charge. The results have been interpreted in theoretical studies by Andersen *et al.*,[3] Reading and Ford,[4] Olson,[5] McGuire,[6] and Vegh,[7] and predictions have also been made[8,9] about the ejected-electron spectra for ionizing collisions between helium and protons and antiprotons.

New experiments by Giese and Horsdal[10] and Kamber *et al.*[11] have revealed structures in the cross section for double ionization of helium differential in projectile scattering angle, and an explanation of the observed structure has been published by Reading, Ford, and Fang.[12]

The object of the present work is to study a different two-electron process. Following a proposal by McGuire and Deb[13] we present data on double excitation of helium by electron and proton impact at a velocity in the range where the charge effect in double ionization was observed. The measurements have been extended to include also carbon-ion projectiles.

Some of the theoretical models[3,6] explained the observed charge effect in double ionization as due to interference between different double-ionization mechanisms. The shakeoff mechanism involves a single interaction between the projectile and a target electron and the second electron is then ejected in the subsequent rearrangement of the target. The other mechanisms, called two step, involve interaction of the projectile with each of the two target electrons (TS-2) or interaction with one electron and a subsequent collision between the recoiling electron and the other electron (TS-1). Since the ejected electrons from ion-atom collisions leave the atom rather slowly, one might expect that the same mechanisms which are thought to be responsible for double ionization will also be important for double excitation.

All doubly excited states in helium lie above the first ionization limit and because of the low nuclear charge, autoionization dominates for many levels. This has led us to study the double-excitation process by measuring the yield of autoionizing electrons from the doubly excited state, differential in energy and emission angle.

The electron spectrometer used is an apparatus described earlier by Dahl *et al.*[14] and only slightly modified. The projectiles traverse a target gas cell containing about 2 mTorr helium. The electrons emitted from the collisions pass through an exit in the top part of the gas cell, and this part, together with the electron spectrometer, can be rotated continuously to give angles θ of observation from 20° to 160°. θ is the angle between the direction of the incoming projectile beam and the direction of the ejected electrons.

The spectrometer is a cylindrical analyzer with a sector angle of 60° and a mean radius of 50 mm. A set of electrodes before and after the analyzer constitutes an acceleration-deceleration system. A spectrum of electron energies is obtained by scanning the acceleration voltage at a constant analyzer potential, normalizing the counting time in each channel to the current of the projectile beam. The resolution is 1.0 eV. The magnetic field in the collision region is reduced to below 5 mG with three pairs of Helmholtz coils. Background spectra were also taken and subtracted from the primary spectra.

The projectiles used were protons, electrons, and C^{q+} ions ($q=4$, 5, and 6) at the reduced energy of 1.84 MeV/u, corresponding to a velocity of $8.6v_0$. Energy spectra of ejected electrons with energies between 26 and 44 eV were recorded at seven angles (θ) between 20° and 160°. The data thus allow comparison of the effect of different charged-particle impact in a wide range of emission angles. Autoionizing electron emission from helium following electron impact has been reported before at both high and low collision velocities.[15] Experimental results using heavy particle beams have usually been obtained at lower velocities,[16] whereas measurements using heavy particles in our velocity region are scarce,[17] and do not allow a direct comparison between equivelocity positive and negative projectiles.

Figure 1 shows a collection of spectra taken at θ equal to 20° and 160°. The prominent peak which is present in all the spectra at about 35.4 eV can originate from both the $(2p^2)^1D$ and the $(2s2p)^1P$ states. The resolu-

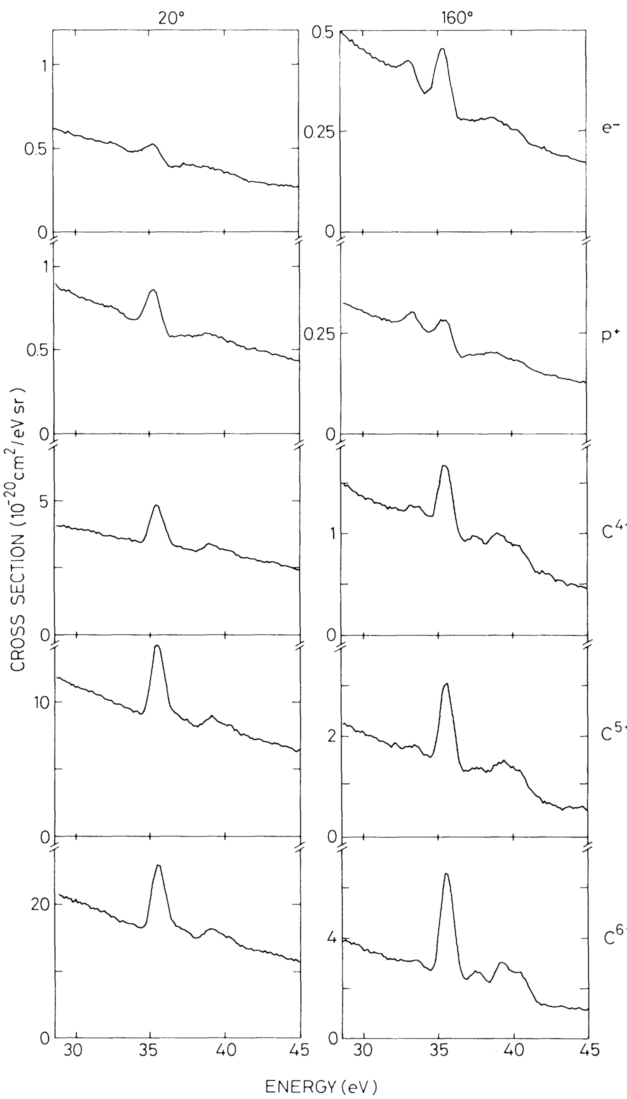

FIG. 1. Energy spectra of electrons emitted at 20° and 160° with respect to the direction of the incoming beam, in collisions of 1-keV e^-, 1.84-MeV p^+, and 22.0-MeV $C^{(4-6)+}$ with He.

tion is not sufficient to resolve these states which are separated by only 0.24 eV.

In some of the spectra at 160° another peak [due to $(2s^2)\,^1S$ and/or $(2s2p)\,^3P$] can be seen on the left-hand side of the prominent peak and in other spectra several peaks can be seen on the right-hand side. The first of the peaks to the right originates from $(2p^2)\,^1S$, whereas the higher-lying states approaching the series limit fall close together and overlap.

The continuum background in the spectra originates from electrons emitted in direct ionization. This background has been used to calibrate the measured electron intensities in absolute units. For the electron-induced ionization of helium we have used the recommended double-differential cross sections given by Kim.[18] The cross sections for the proton and carbon projectiles have been obtained by normalizing to experimentally measured cross sections for ionization by 1-MeV protons and using the data for this projectile energy from Rudd, Toburen, and Stolterfoht.[19]

Using the Born approximation Balashov, Lipovetskii, and Senashenko[20] have shown that the angular and energy distribution of the emitted electrons in the region of an autoionizing resonance can be written in the form

$$\frac{d^2}{d\theta dE}=C(\theta,E)+\frac{A_j(\theta)\epsilon_j J+B_j(\theta)}{1+\epsilon_j^2}\,, \qquad (1)$$

where $C(\theta,E)$ is the contribution to the differential cross section from direct ionization, $B_j(\theta)$ describes the angular distribution of electrons from the autoionizing state, and $A_j(\theta)$ characterizes the profile of the resonance. The profile may become asymmetric due to interference between electrons from the direct and resonance ionizations. $\epsilon_j=2(E-E_{rj})/\Gamma_j$, where E_{rj} is the energy of the resonance and Γ_j is its natural width.

Since all of the above-mentioned states have $\Gamma_j<0.15$ eV, we have not tried to extract the $A_j(\theta)$ parameters. To enable a comparison of our data with theoretical predictions, we have instead obtained the intensity of the resonances (emission yields) from the spectra. From Eq. (1) one can show that the area under the peak corresponding to resonance j is given by

$$\frac{d\sigma}{d\theta}=\int C(\theta,E)dE+\tfrac{1}{2}\pi\Gamma_j B_j(\theta)\,. \qquad (2)$$

Our spectra are broadened by the apparatus function, but by assuming that this function has a Gaussian shape and a width which is much larger than that of the natural line profile, it can be shown (using the results of Ref. 21) that this equation also holds for the convoluted spectra. These conditions are to a good approximation fulfilled in the experiment.

From Eq. (2) it is seen that the emission yield from a resonance can be obtained if the continuum background can be subtracted from the experimental spectra. It is reasonable to assume that the continuum background is a slowly varying function, and we have therefore tried to interpolate it from the regions outside the resonances.

In this Letter we will concentrate on the $\{(2p^2)\,^1D+(2s2p)\,^1P\}$ peak only, for which we have shown the extracted emission yields in Fig. 2. The problem of interpolating the continuum introduces an unknown uncertainty in the emission yields, and the representative error bars in the figure originate mainly from uncertainties in the normalization data.

From Fig. 2 it is seen that the differential electron emission yield is very different for excitation by electrons and protons. At small emission angles the yield is larger for proton impact than for electron impact; at larger emission angles this is just the opposite. Because of the high velocity of the projectiles an explanation of this difference in terms of a post-collision effect due to the

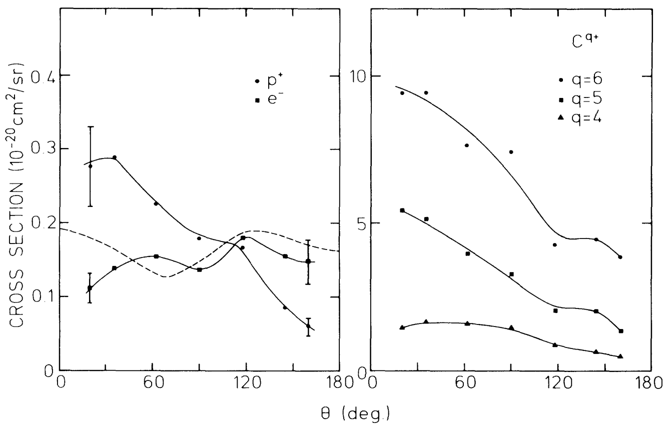

FIG. 2. The differential emission yield from the $\{(2p^2)^1D+(2s2p)^1P\}$ states after excitation by electrons, protons, and carbon ions. The broken line is a calculation by Balashov, Lipovetskii, and Senashenko (Ref. 20) for the $(2s2p)^1P$ level excited by 1-keV electron impact. The other lines are drawn to guide the eye.

field from the projectile when the excited state decays can be excluded. Instead we believe it should be explained by a difference in the excitation of the doubly excited states and the effect of interference between the amplitudes for ionization through these states and for the direct ionization. We note that in the absence of such effects, the excited states would decay symmetrically around $\theta=90°$.

The differential yields for carbon projectiles (Fig. 2) are seen to increase with charge state, but the general behavior of the angular dependence of the emission yield is similar to the one obtained using proton projectiles. Theoretical calculations of the differential emission yield at our projectile velocity are scarce, but in Fig. 2 is shown a calculation by Balashov, Lipovetskii, and Senashenko[20] of the emission yield for excitation to the $(2s2P)^1P$ level by 1-keV electrons [their scale has been transformed according to Eq. (2), using $\Gamma=0.041$ eV [22]]. Their result is close to our measured curve, which seems to indicate that mainly the $(2s2p)^1P$ level is populated by electron impact at this energy. This is in agreement with a calculation by Lipovetskii and Senashenko[23] showing that for 1-keV electrons the total excitation cross section of the $(2p^2)^1D$ state is almost an order of magnitude lower than for the $(2s2p)^1P$ state. This is probably different for the carbon projectiles since Burch, Bolger, and Moore[17] using 1.88-MeV/u O^{5+} projectiles have found that for 90° emission the $(2p^2)^1D$ line is more intense than the $(2s2p)^1P$ line.

In order to allow a comparison with theory where experimental artifacts or errors in the normalization can be excluded, we have also formed the relative resonance yield $R(\theta)$, defined as the ratio between the emission yield and the continuum contribution in an interval of

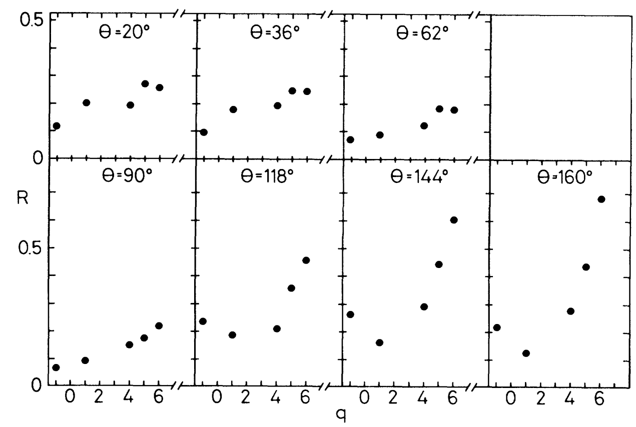

FIG. 3. Relative resonance yield $R(\theta)$ (see text).

width 2.25 eV around the peak energy. The result is shown in Fig. 3. The ratio can of course change due to changes in both the numerator and denominator, and the result is seen to be a drastic dependence on the projectile charge for emission in the backward direction, whereas

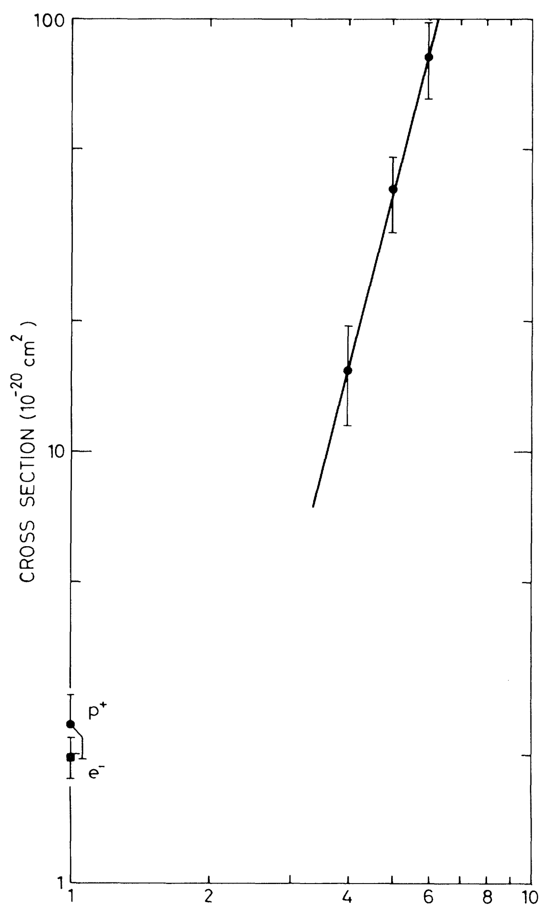

FIG. 4. Total emission yield from the $\{(2p^2)^1D+(2s2p)^1P\}$ states after excitation by electrons, protons, and carbon ions.

the charge dependence is weak for 90° and forward emission.

The total excitation cross section for a doubly excited state is in principle proportional to the total electron emission yield from the state. If interference effects are present, however, the intensity will be redistributed both in emission angle and energy. We have nevertheless tried to obtain the total emission yield for the $\{(2p^2)\,^1D + (2s2p)\,^1P\}$ states by integrating the differential yields from Fig. 2 over all angles. The integration has been performed by interpolation between the data points. For the end points the extrapolation has obvious uncertainties, but this contributes little to the total yield. The result is shown in Fig. 4, and corresponds to integrating Eq. (2) over all angles:

$$\sigma = \pi^2 \Gamma_j \int B_j(\theta) \sin\theta \, d\theta \,. \qquad (3)$$

The cross section obtained for excitation by protons is seen to be larger than for electrons, but the difference is within the estimated uncertainty. The cross section for excitation by the multiply charged carbon ions is seen to scale as q^4. This high-q charge dependence seems to indicate that the double excitation for these ions at this velocity, contrary to singly charged projectiles, is dominated by a two-step process, in agreement with the suggestion of Burch, Bolger, and Moore[17] on the basis of the favored $(2p^2)\,^1D$ excitation.

In summary, we have measured the electron emission yield from the doubly excited $\{(2p^2)\,^1D + (2s2p)\,^1P\}$ states in He excited by impact of electrons, protons, and $C^{(4-6)+}$ ions. The data are presented with the intention to challenge and stimulate the further development of the models which have been used to explain the proton-antiproton difference for the double ionization of helium.

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