Ionization plus Excitation of Helium by Fast Electron and Proton Impact

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We report the first experimental results on the state selective cross-section ratio σ^{+*}/σ^{*} of helium for electron and proton impact. Our results show consistently higher yields for electrons than for protons at higher velocities. A comparison is made between the cross-section ratios σ^{2+}/σ^{+} of helium for electron and proton impact.

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Recently there has been much interest in theoretical investigations [1-14] and in atomic collision experiments involving many-electron transitions, in particular, double ionization [15-20], double excitation [21,22], and ionization plus excitation [23-29] of helium. The emphasis of this paper is to present for the first time extensive experimental absolute cross sections for the ionization excitation of He by electron and proton impact. The primary reason for this interest is the need to understand the simplest dynamical few-electron effects. At high collision velocities the dominant mechanisms for two-electron transitions require few-electron dynamics. Correlation, produced in the interaction between two or more electrons, occurs when the full scattering wave function cannot be described by the independent particle model (IPM) (corresponding to the time-independent Hartree-Fock approximation). In this model, the electrons move in an effective potential which represents the attraction of the nucleus and the average effect of repulsive interactions between the electrons. Helium is the simplest many-electron atom, and therefore ideally suited for achieving a better theoretical understanding of many-electron processes.

Although much work has been conducted in this field, the basic physical mechanisms producing two-electron transitions at high collision velocities are currently not well understood. One important process reported in the literature which requires electron-electron interaction is double ionization. A comparison of atomic collision experiments with electrons, positrons, protons, and antiprotons as projectiles [15,16] revealed that negatively charged particles (electrons or antiprotons) give consistently higher yields in the cross sections for double ionization σ^{2+} than positively charged particles (positrons or protons).

Reading and Ford [4-6] using the forced impulse model (FIM) have obtained good agreement with the experimental results for σ^{2+}/σ^{+} for He, while Olson [11] using the classical trajectory Monte Carlo method was also able to predict a significant difference in the cross sections for positive and negative projectiles. In contrast, the IPM fails to explain such a charge-state dependence for σ^{2+}/σ^{+} of He. To our knowledge, there has been no theoretical calculation applied to ionization excitation of He.

More recently, cross sections for double excitation (σ^{**}) to $n=2$ levels of helium have been measured for impact by protons and electrons at velocities of about 8 a.u. [21]. Unlike double excitation to the continuum (i.e., ionization), cross sections for double excitation by positive and negative projectiles appear to differ by much less than a factor of 2. It is not well understood why double excitation to the continuum differs so dramatically in this regard from double excitation to lower-lying autoionizing states.

Ionization excitation is an intermediate-energy process when compared to double ionization and double excitation (Fig. 1). In this figure we present the apparent threshold processes characterized by σ^{**} (double excitation), σ^{+*} (ionization plus excitation), and σ^{2+} (double ionization). We note that for σ^{**} we have well defined initial and final states, whereas in the case of σ^{+*} and σ^{2+} we have one or two electrons in the continuum, respectively. To shed more light on this interesting process we have performed an extensive series of scattering experiments to study simultaneous ionization and excitation of He using various atomic and molecular projectiles, i.e., e^-, H^+, H_2^+, H_3^+, Li^{3+}, Be^{5+}, and C^{q+} ($q=1,\ldots,6$) over a large energy range. In the present work we report absolute extreme ultraviolet (EUV) cross-section measurements for $He^+(np)$ Rydberg states ($n=2$ to 4) decaying to the $He^+(1s)$ ground state.

The experimental setup has been described in detail by Fülling [30]. In brief H^+ ions have been accelerated, focused, mass and charge analyzed, and passed after tight collimation into a differentially pumped gas cell and final-

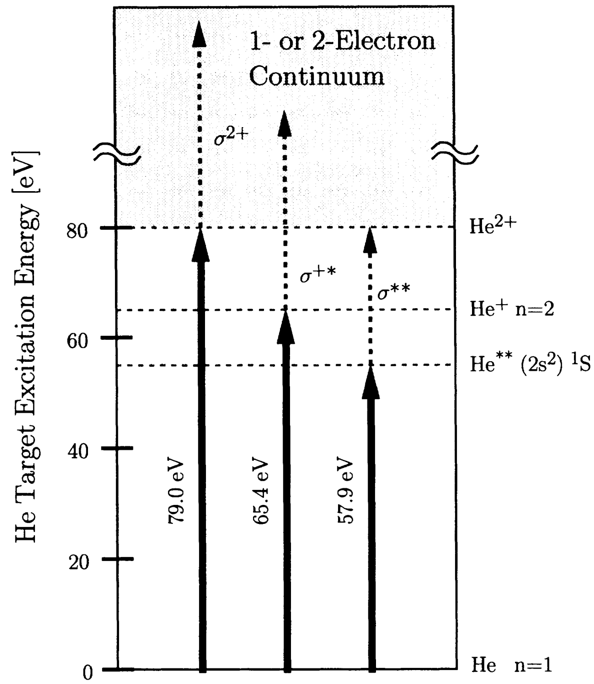

FIG. 1. Schematic diagram of different two-electron processes significant for σ^{**}, σ^{+*}, and σ^{2+} cross sections. Note that the ionization processes include some ejected electron energies above threshold.

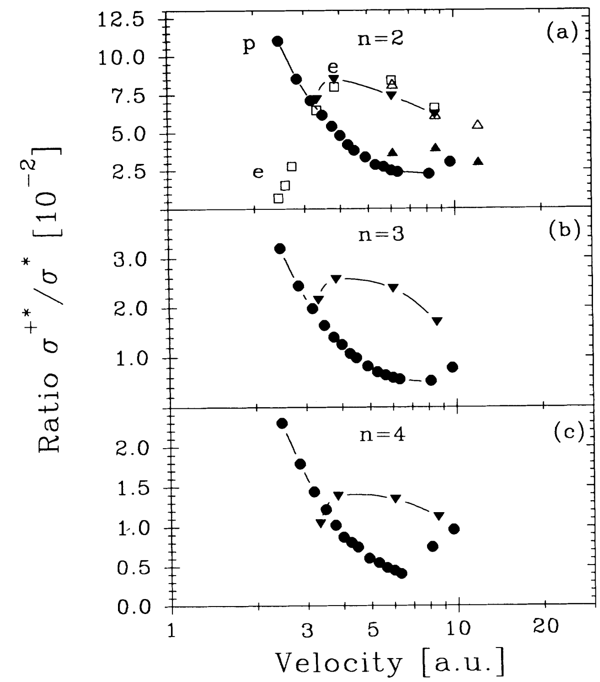

FIG. 2. Ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ for (a) $n=2$, (b) $n=3$, and (c) $n=4$. ●, protons and ▼, electrons (this work); □, electrons (Forand, Becker, and McConkey [26]); ▲, protons and △, electrons (Pedersen and Folkmann [23]).

ly collected in a Faraday cup for charge normalization. Typical ion beam currents in the target area are 3-25 μA in the energy range of 50 keV to 1.8 MeV. A 1.5-m grazing incidence monochromator (Acton Research) equipped with a 600-groove/mm grating has been used for wavelength dispersion. All measurements have been performed under single collision conditions. The gas pressure in the cell has been accurately monitored with a capacitance manometer and kept constant with a feedback control system. The observed Lyman transitions of He II up to $n=5$ are completely resolved. Data acquisition and control of the experiment have been accomplished by a versatile CAMAC-PC/AT system [31]. The relative detection efficiency of the monochromator has been determined to high accuracy over a large wavelength range. The present data have been placed on an absolute scale by additional electron impact measurements using identical excitation and detection geometries for electron and proton impact [32].

Absolute EUV emission cross sections for ionization plus excitation (σ^{+*}) of helium atoms have been measured for both electrons and protons. We are the first to report the ratio σ^{+*}/σ^{*} for electrons and protons. These ratios give a similar velocity dependence as obtained for σ^{2+}/σ^{+} but are larger by about 1 order of magnitude for $2p$ states. In the case of electrons as projectiles, our data also show that the trend of the cross section ratio for σ^{+*}/σ^{*} is shifted towards the lower energies when compared to the σ^{2+}/σ^{+} ratio. This effect may be due to the smaller momentum transfer involved.

These results clearly show a strong dependence on the charge state of the projectile, suggesting that a Z_P^3 term may be of great importance in this two-electron transition. We are specifically interested in a comparison of our results with those obtained for double ionization, since in the limit $n\rightarrow\infty$ ionization excitation should approach the double ionization threshold. This procedure gives us for the first time not only a comparison of ionization-excitation cross sections with those for double ionization, but also the ability to compare these cross sections for specific n values up to $n=4$.

In order to determine the ratio σ^{+*}/σ^{*} we used our data for the ionization excitation of He II($1s\rightarrow np$) and the most recent cross-section values on the excitation of He I($1s^2\rightarrow 1snp$) for $n=2,\ldots,4$ by electron impact from Shemansky *et al.* [28], and the data from Hippler and Schartner [33] for excitation by protons. For additional comparison, the ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ for $n=2$ has been compiled from data for electron impact ionization excitation of He by Forand, Becker, and McConkey [26] using the same data for excitation of He as Shemansky *et al.* [28]. We consider first the ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ as a function of the impact energy. These ratios are displayed in Figs. 2(a)-2(c) for $n=2$, 3, and 4 and versus velocity. An interesting result is that these ratios have a characteristic shape similar to σ^{2+}/σ^{+} at

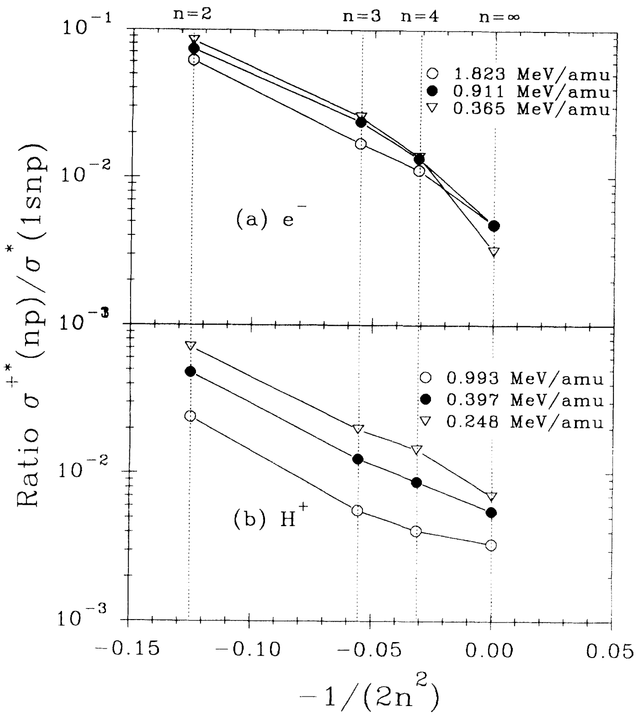

FIG. 3. Ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ for $n=2,3,4$ and σ^{2+}/σ^{+} plotted against $-1/2n^2$ in a.u. (a) for electron and (b) for protons at three different impact energies. Electron data from Adamcsky *et al.* [35]; proton data from Shah and Gilbody [36]. Note that the change in the slope in the electron data for lower energies is due to threshold effects.

higher velocities [30].

We expect the ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ to approach σ^{2+}/σ^{+} in the limit of large n values. In order to demonstrate this effect for both electron and proton projectiles, we have plotted in Fig. 3 $\sigma^{+*}(np)/\sigma^{*}(1snp)$ for specific projectile velocities versus $-1/2n^2$ in a.u. The direct comparison of excitation ionization to double ionization is a little problematic since ionization is summed over all final electron energies, $\epsilon_k=k^2/2$, while ionization excitation is taken for specific n values with $\epsilon_n=-Z_{T\mathrm{eff}}^2/2n^2$, where the $Z_{T\mathrm{eff}}$ term contains electron screening for the He state, for example, $Z_{T\mathrm{eff}}=1.69$ appears to be a good approximation [34]. Direct comparison of $\sigma^{+*}(np)$ to σ^{2+} is difficult since the final electron(s) state wave functions are represented by continuum electron states which are currently unknown. From Fig. 3 it appears that the ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ does indeed approach σ^{2+}/σ^{+} for higher np Rydberg levels. The double ionization threshold is reached for $n\rightarrow\infty$ corresponding to $-1/2n^2\rightarrow 0$. According to Fig. 1 the double ionization process can excite states in the two-electron continuum associated with small positive ϵ_k values. Since the detailed target electron correlation effects are not well known for double ionization processes, we have shifted the σ^{2+}/σ^{+} ratios symbolically to $\epsilon_k=0$. In addition to EUV emission, we need to measure the velocity of the emitted electrons.

In conclusion, we have demonstrated that our experimental results show similarity to the double ionization process of He using projectiles with different charge signs and magnitudes but not to double excitation of $2l2l'$ levels. The importance of Z_P^3 terms in the cross sections for both double ionization and ionization excitation reflects the presence of dynamical few-electron interactions in these two-electron transitions. Based on our experimental results for the cross-section ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ obtained for $n=2$ to 4, it has been demonstrated that the ratio $\sigma^{+*}(np)/\sigma^{*}(1snp)$ approaches σ^{2+}/σ^{+} in the limit for large n. Both mechanisms show a factor of 2 difference from electron cross sections when the sign of the projectile is reversed at higher impact velocities. These experimental data may not only be helpful in further discussions of two-electron transitions in He but may also provide theoretical groups with a larger variety of data for testing various theoretical models and scattering calculations including dynamical few-electron effects. In particular calculations, as well as observations of differential double electron transition, cross sections and velocity distributions of the emitted electrons could promote a deeper understanding of the dynamics of few-electron phenomena in ion-atom, ion-molecule, and ion-surface collisions.

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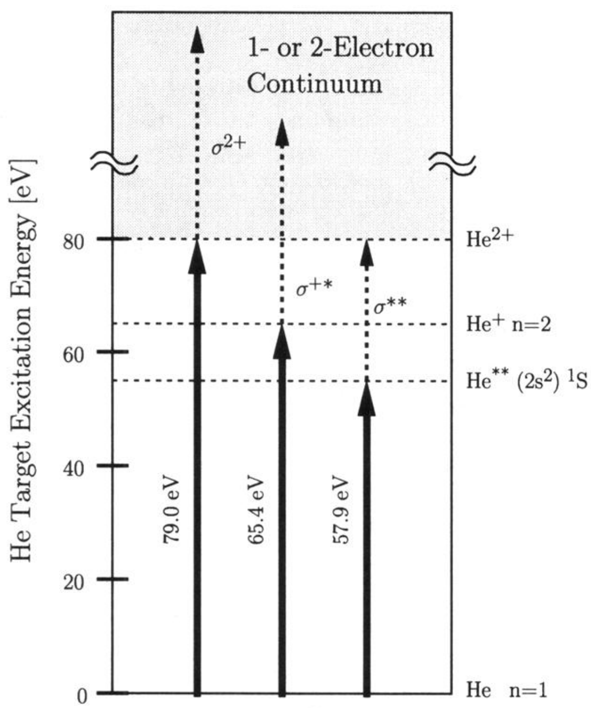

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