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Single and double ionization of helium by neutral-particle to fully stripped ion impact

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New measurements of direct single and double ionization of helium by hydrogen, helium, carbon, nitrogen, and oxygen ions are presented for projectile charge states ranging from 0 to 3+. These data are combined with previously published values to provide a detailed description of direct double ionization of helium for a wide range of experimental parameters, i.e., projectile ions include protons through oxygen, impact energies from 25 to 5000 keV/u, and projectile charge states ranging from neutral to fully stripped. The charge-state and impact-velocity dependencies of the measured cross sections are compared with the dependencies predicted by an independent electron multiple-ionization model. It is found that a multistep mechanism (i.e., the independent ionization of both target electrons) is the dominant direct double-ionization mechanism for charged-particle impact energies above 100 keV/u. This mechanism dominates until some maximum impact velocity, which depends on the projectile charge, is reached. For higher velocities a single-step ionization mechanism becomes important. The limited neutral-particle impact data indicate that the single-step mechanism becomes dominant at much lower impact velocities and there is no evidence of the multistep mechanism in the neutral-particle impact energy range investigated.

I. INTRODUCTION

Target ionization is one of the basic processes that can occur in ion-atom collisions. It order to obtain information about the interaction mechanism, absolute cross sections for single and multiple target ionization and the ratios of these cross sections have been studied as a function of impact velocity and projectile charge state. In this paper we investigate the direct ionization of one or more electrons from helium. By direct ionization we mean that the projectile does not change its charge state during the collision. A helium target is studied as this is the simplest case where multiple ionization can occur and interpretation of the data is not complicated by contributions from inner shell ionization followed by Auger relaxation. Data are included for projectile ions ranging from protons to oxygen and for projectile charge states ranging from neutral to fully stripped.

Specifically we are interested in determining the velocity region where direct double ionization is the result of an independent interaction of the projectile with each target electron. This is investigated by studying the velocity dependence of the single- and double-ionization cross sections and also by studying how the cross sections scale as a function of the projectile charge. This investigation includes clothed as well as fully stripped projectiles.

In order to provide information about direct single and double ionization of helium by low charge-state ions, new measurements for hydrogen, helium, carbon, nitrogen, and oxygen ions with incident charge states ranging from 0 to 3+ are presented. These data are combined with data obtained from the literature in order to investigate the impact velocity and projectile charge dependencies of the cross sections over a large velocity and charge-state range.

II. BACKGROUND

It is known that single ionization of atoms by fast fully stripped ion impact ($Z/v \ll 1$) can generally be well described within the framework of the first Born approximation. Here Z is the projectile nuclear charge and v is the impact velocity. However multiple ionization of atoms is less well understood theoretically. McGuire[1] has shown that direct double ionization of helium (as opposed to double ionization resulting from charge transfer) may occur either via a single-step or via a two-step projectile-target interaction.

In the single-step mechanism, the projectile interacts with a single target electron in order to eject it. The ejection of this electron then induces ionization of the second target electron thus resulting in double ionization. As a result, the double-ionization cross section σ_2 is proportional to the single-ionization cross section σ_1. This also means that σ_2 is proportional to the total electron production cross section σ_T since, by definition, $\sigma_T = \sigma_1 + 2\sigma_2$. Thus σ_T, σ_1, and σ_2 all result from a single projectile-target interaction and hence they all should demonstrate the same projectile charge and impact-velocity dependencies. As a consequence, the ratios σ_2/σ_1 and σ_2/σ_T should be independent of projectile charge and velocity.

The other mechanism that can lead to direct-multiple ionization is the multistep (two-step in the case of a helium target) interaction. Here the projectile is considered to interact independently with each target electron in order to ionize them and an independent electron model is thus appropriate for determining the cross sections. For proton impact this model predicts that the direct ionization of q targets electrons from a shell containing N electrons is given by

$$\sigma_q = 2\pi \int_0^\infty \binom{N}{q} P(b)^q [1-P(b)]^{N-q} b\, db \; . \qquad (1)$$

In this expression $P(b)$ is the proton impact single-electron ionization probability as a function of the impact parameter b. Cross sections for other fast, fully stripped projectiles can be obtained[2] by multiplying $P(b)$ by Z^2. This scaling is valid whenever the collision can be considered as perturbative, i.e., whenever $Z/v \ll 1$. For collisions in which Z/v is not small, the total ionization cross sections have been shown[3] to scale at a slower rate which can be represented by Z^2 times a function of Z and v. To allow for this possibility, we shall assume that $P(b)$ scales as $Z^2 f(Z,v)$ where the function $f(Z,v)$ can be unity or have a smaller value depending on the magnitude of Z/v.

With this assumption, the helium single- and double-ionization cross sections for any fully stripped projectile are given by

$$\sigma_1 = 4\pi \int_0^\infty Z^2 f(Z,v) P(b) b\, db - 4\pi \int_0^\infty [Z^2 f(Z,v) P(b)]^2 b\, db \; , \qquad (2a)$$

$$\sigma_2 = 2\pi \int_0^\infty [Z^2 f(Z,v) P(b)]^2 b\, db \; . \qquad (2b)$$

Also the total ionization cross section ($\sigma_T \equiv \sigma_1 + 2\sigma_2$) is given by

$$\sigma_T = 4\pi \int_0^\infty Z^2 f(Z,v) P(b) b\, db \; . \qquad (2c)$$

Note that for fully stripped ion impact, the quantity $Z^2 f(Z,v)$ can be removed from the integrand since it has no impact-parameter dependence. Thus these equations indicate that, if the two-step interaction applies, we should expect to find the *same* projectile charge state dependencies for σ_T, $\sqrt{\sigma_2}$, and, whenever the second term in Eq. (2a) is negligible, also for σ_1. These dependencies are different from those expected in the case of a single-step projectile-target interaction where σ_2, not $\sqrt{\sigma_2}$, has the same Z dependence as does σ_T and σ_1. Thus by studying how the cross sections scale as a function of projectile charge Z, it is possible to determine whether a two-step or a one-step interaction picture is appropriate for describing double ionization of helium.

The velocity dependencies of the cross sections can also indicate whether the two-step picture is the dominant double-ionization interaction mechanism. To demonstrate this, a specific form for the ionization probability $P(b)$ must be selected and Eqs. (2) must be integrated. For example, in the high-energy Bethe approximation where $P(b) \sim v^{-2} b^{-2} e^{-kb}$ with k being a constant, the velocity dependencies have been shown[1] to be $v^{-2}\ln(v)$ for σ_1 (or σ_T) and v^{-4} for σ_2. Thus, using this approximation and the two-step interaction picture, the ratio $\sigma_T/\sqrt{\sigma_2}$ should behave as $\ln(v)$ for large v. This is different than the $v^{-1}[\ln(v)]^{1/2}$ dependence expected if the single-step interaction picture is valid since then σ_T, σ_1, and σ_2 should all have a $v^{-2}\ln(v)$ dependence. It is important to remember, however, that this discussion is limited to direct ionization of the target induced by *fully stripped* ion impact; hence all charge transfer contributions to the cross sections must be excluded from the cross sections that are used.

In the case of partially stripped ion impact, the projectile nuclear charge Z is partially screened by the projectile electron cloud. Hence the projectile interacts with an effective charge $Z_{\text{eff}}(b)$ that is a function of the impact parameter[4,5] b. Here we explicitly designate that we are dealing with an effective charge as opposed to the nuclear charge Z. In this case, the projectile charge dependence cannot be removed from under the integration signs in Eqs. (2) as was done for fully stripped ion impact. Rather, knowledge of $Z_{\text{eff}}(b)$ is required in order to integrate over impact parameters and predict the projectile charge and impact-velocity dependencies of the cross sections.

Thus, the following procedure will be used to determine when double ionization of helium results from a two-step interaction mechanism. First the projectile charge and impact-velocity dependencies of σ_T, σ_2, and $\sigma_T/\sqrt{\sigma_2}$ are studied for fully stripped ion impact. Then, information about the average effective projectile charge as a function of impact velocity and degree of target ionization is obtained for various partially stripped projectiles. This is done by comparing cross sections obtained for various partially stripped projectiles with those obtained for fully stripped ion impact. Next the velocity dependencies of $\sigma_T/\sqrt{\sigma_2}$ are studied to determine the validity of the two-step interaction in the case of partially stripped ion impact. Finally, it will be shown that available theoretical models for $Z_{\text{eff}}(b)$ used in conjunction with Eqs. (2) can provide a qualitative understanding of our observations as to how bound projectile electrons influence the cross sections and their ratios.

III. RESULTS

Absolute cross sections for direct single and double ionization of helium by H^0, He^{i+}, ($i=0,1$), C^{i+} ($i=0,1,2$), N^{i+} ($i=0,1,2,3$), and O^{i+} ($i=0,1,2$) were obtained by measuring coincidences between the fast projectile ions which have not changed their charge during the collision and the slow recoil target ions. Time-of-flight techniques were used to determine the charge state of the target ions. A detailed description of the experimental technique and apparatus can be found in Ref. 6. The present study required a slight modification in order to study neutral-particle impact. The neutral beams were generated via charge capturing collisions with the background gases along the incoming beam path. Then the charged components of the beam were removed immediately before the target cell by an electrostatic deflection plate system positioned between the beam collimating apertures. The electric fields used were typically several hundred volts per centimeter or larger and were applied over a 20-cm length of beam trajectory. Thus, the resulting H^0 and He^0 beams should consist primarily of ground-state atoms although the C^0, N^0, and O^0 beams may contain some long-lived metastable contamination.

The cross sections, in units of 10^{-16} cm^2, are given in Table I for several low charged and neutral ions. Experimental uncertainties for these cross sections are typically $\pm 15\%$ but can be as large as 25–30 % in a few cases.

TABLE I. Absolute cross sections for direct single and double ionization of helium by neutral and charged hydrogen, helium, carbon, nitrogen, and oxygen impact. The cross sections are in units of 10^{-16} cm^{-2}. Typical experimental uncertainties are ±15% except for those cases indicated by the asterisks where the uncertainties are 25–30%.

	E/M (keV/u)													
	25		33.3		37.5		50		75		100		150	
Ion	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2
H^0													0.361	0.00 302
He^0					1.11	0.0378	0.985	0.0476*	0.922	0.0534	0.844	0.0494		
He^+			0.647	0.0129	0.882	0.0268*	0.975	0.0481*	1.08	0.0553	1.07	0.0545		
C^0			1.74	0.0331					1.65	0.139			1.42	0.143
C^+			1.99	0.0767					2.42	0.268			2.27	0.252
C^{2+}			1.78	0.0767					3.07	0.322			3.26	0.419
N^0	1.94	0.0233					1.90	0.0952			1.56	0.147		
N^+	1.35	0.0460					1.66	0.138			2.18	0.266		
N^{2+}	0.848	0.0301					2.40	0.216			3.15	0.360		
N^{3+}	1.01	0.0440					2.13	0.160			4.14	0.439		
O^0	1.74	0.0176					2.00	0.0951			1.69	0.169		
O^+	1.23	0.0118					2.85	0.140			3.64	0.398		
O^{2+}											2.81	0.356		

IV. DISCUSSION

The present measurements are combined with previously published data[7–11] in order to present a detailed picture of ionization of helium by partially and fully stripped projectiles ranging from hydrogen to oxygen. The projectile charge state and impact-velocity dependencies of these data are studied in order to determine the range where a two-step interaction is the dominant direct double-ionization mechanism.

V. FULLY STRIPPED ION IMPACT

A. Projectile charge-state dependence

As presented in the Introduction, a pure two-step mechanism implies that σ_T and $\sqrt{\sigma_2}$ should have the same projectile charge-state dependencies. In Fig. 1, these cross sections are plotted versus the projectile charge for several impact energies between 0.1 and 2.3 MeV/u. In addition, the ratios $\sigma_T/\sqrt{\sigma_2}$ are shown. From these curves is is clear that σ_T and $\sqrt{\sigma_2}$ have the same projectile charge scaling dependencies except for 1.44- and 2.3-MeV/u H^+ impact and possibly for 2.3-MeV/u He^{2+} impact. Also shown in Fig. 1 are pure Z^2 dependencies which demonstrate that the measured cross sections behave approximately as Z^2 for small Z/v but with a somewhat slower dependence otherwise. This is in agreement with the scaling dependencies discussed in the Introduction. However, the major point to be derived from Fig. 1 is that $\sqrt{\sigma_2}$ has the *same* Z dependence as σ_T. This is a strong implication that for the particular projectiles and impact velocities shown, direct double

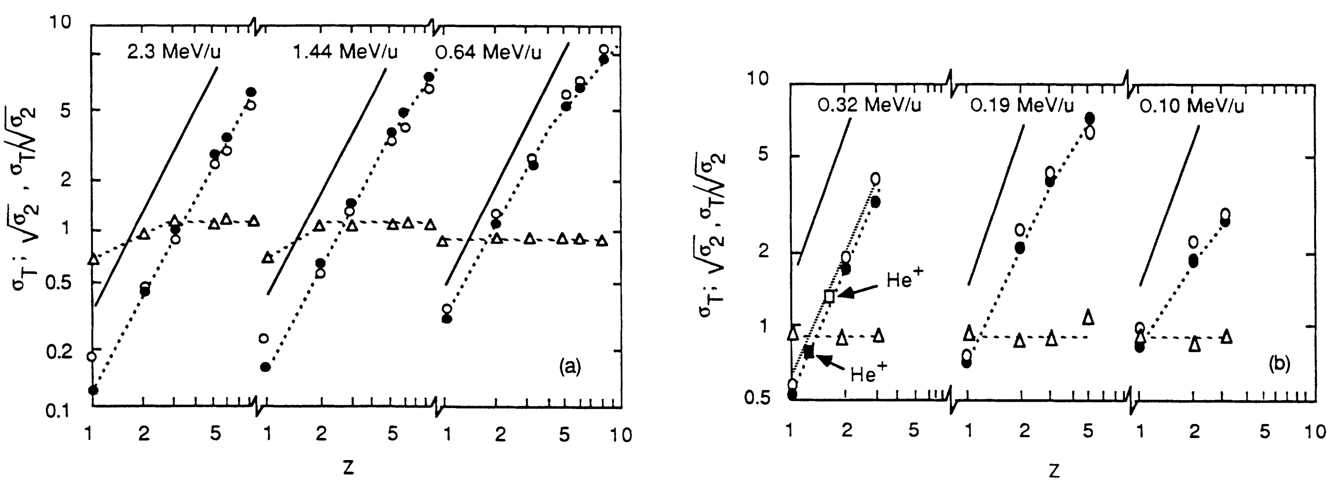

FIG. 1. Measured cross sections [σ_T (closed circles), $\sqrt{\sigma_2}$ (open circles), and the ratio $\sigma_T/\sqrt{\sigma_2}$ (triangles)] for direct ionization of helium as a function of projectile charge Z. The curves drawn through the data points are only meant to guide the eye. The data, obtained from Refs. 6–11, are in units of 10^{-16} cm^2 for σ_T, 10^{-9} cm for $\sqrt{\sigma_2}$, and 10^{-7} cm for $\sigma_T/\sqrt{\sigma_2}$. Note that total ionization scales as Z^2 (solid curve) but double ionization (σ_2) scales as Z^4 for small Z/v. This scaling implies that double ionization occurs via an independent interaction between the projectile ion and each target electron. The two He^+ impact points shown on the 0.32-MeV/u curve indicate that for partially stripped ion impact the average effective projectile charge depends on the degree of target ionization. See text for details.

TABLE I. (*Continued*).

	E/M (keV/u)													
	175		200		250		300		375		400		500	
Ion	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2
H^0			0.295	0.002 69			0.216	0.002 34			0.160	0.001 71		
He^0	0.575	0.0256*			0.488	0.0212			0.325	0.0108*			0.189	0.0210*
He^+	1.00	0.0386*			0.879	0.0248*			0.628	0.0127*			0.560	0.0087
C^0														
C^+														
C^{2+}														
N^0														
N^+														
N^{2+}														
N^{3+}														
O^0														
O^+														
O^{2+}														

ioinization of helium results predominantly from a multiple projectile-target interaction. The only exceptions are for H^+ and possibly for He^{2+} impact at high energies. These are attributed to the emergence of the one-step mechanism which has previously been demonstrated[6,9] for proton impact energies above 1 MeV.

B. Projectile velocity dependence

In order to provide more information about the interaction mechanism, the velocity dependence of $\sigma_T/\sqrt{\sigma_2}$ is now investigated. Results for several fully stripped ions are shown in Fig. 2. Also shown are results for some singly charged and neutral projectiles; these will be discussed in a later section. For comparison, we show by solid lines the expected high-velocity dependencies for a single-step and a two-step interaction, i.e., $v^{-1}[\ln(v)]^{1/2}$ and $\ln(v)$, respectively. All the bare ion data demonstrate that, between 100 keV/u and 2 MeV/u (0.5 MeV for H^+), the velocity dependence is either approximately constant or is slowly increasing. In fact, at the higher impact velocities, the velocity dependence is approximately

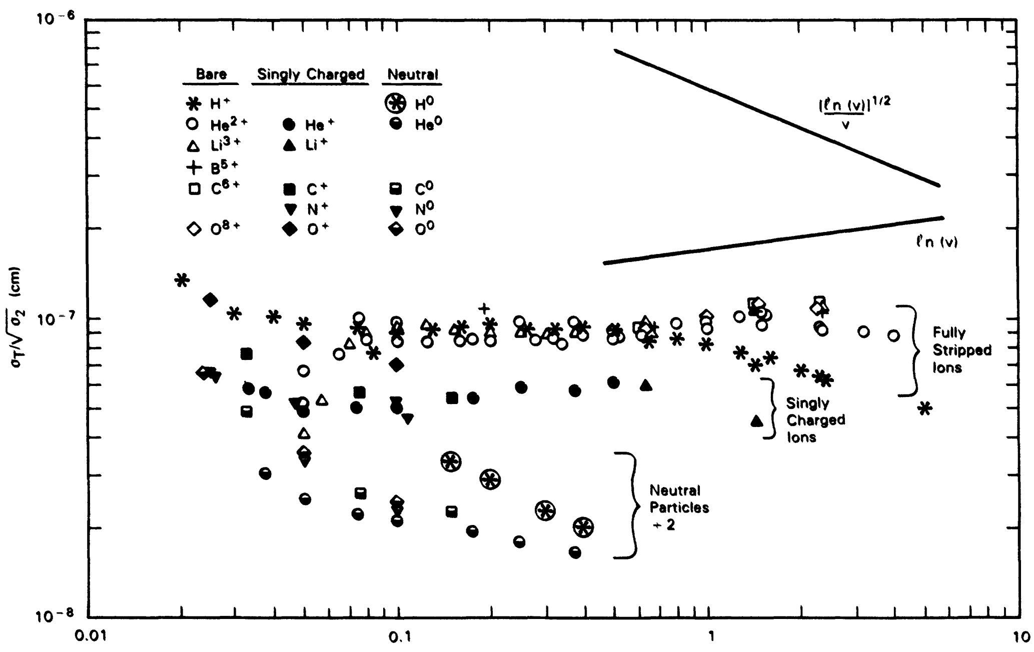

FIG. 2. $\sigma_T/\sqrt{\sigma_2}$ as a function of impact energy for direct ionization of helium. Data shown are for fully stripped ion impact (open symbols), singly charged ion impact (filled symbols), and neutral-particle impact (half-filled symbols). The data include the present measurements and previously measured values obtained from Refs. 6–11. The solid curves give the expected high-velocity dependence of this ratio of cross sections depending on whether the double-ionization interaction is a one-step $\{v^{-1}[\ln(v)]^{1/2}\}$ or a two-step $[\ln(v)]$ mechanism.

$\ln(v)$ as predicted by the Bethe approximation and the independent electron model discussed above. In addition, all the fully stripped ion data tend to fall on a single curve in accordance with the projectile charge scaling predictions of Eqs. (2). Thus these observations are interpreted to mean that above 100 keV/u the two-step mechanism is the predominant double-ionization mechanism.

One obvious exception to this trend for bare ions is that shown for proton impact above approximately 500 keV. Here, instead of a slowly increasing function, $\sigma_T/\sqrt{\sigma_2}$ decreases and this decrease is approximately what one would expect if the double ionization is induced via a one-step interaction mechanism. A similar decrease is indicated for high-velocity He^{2+} impact. This decrease occurs because the one-step interaction mechanism begins to dominate the double-ionization cross section at sufficiently large impact velocities since it scales[1] as $(Z/v)^2\ln(v)$ whereas the two-step mechanism scales as $(Z/v)^4$. This scaling also implies that the velocity v where the one-step mechanism becomes important is directly proportional to the projectile charge Z. Hence, in Fig. 2 the emergence of the one-step mechanism (i.e., where the ratio $\sigma_T/\sqrt{\sigma_2}$ beings to decrease) occurs at 500 keV for proton impact, at 2 MeV/u for He^{2+} impact, and is not seen for any of the heavier ions since it should occur at correspondingly higher velocities.

This is consistent with the work of Knudsen *et al.*[7] who showed that the measured σ_2/σ_1 ratios could be expressed as the sum of two terms where the first term was a constant attributable to a single-step projectile-target interaction and the second was a variable attributable to a two-step interaction. According to their work, the two-step term is proportional to Z^2/E and hence dominates only for large values of Z^2/E.

Thus the projectile charge and impact velocity dependencies shown in Figs. 1 and 2 are consistent with the interpretation that above approximately 0.1 MeV/u, double ionization of helium induced by fully stripped ion impact occurs predominantly via a two-step interaction mechanism and this mechanism dominates until the projectile charge and impact-velocity combination is such that $(E/Z^2)=0.5$ MeV/u.

VI. PARTIALLY STRIPPED ION IMPACT

As discussed in the Introduction, partially stripped ions interact with effective charges $Z_{\text{eff}}(b)$ that are a function of the impact parameter b. Information about how this influences the cross sections, and their ratios, is essential in interpreting the data to determine whether such projectiles interact via a one-step or a two-step mechanism. To provide such information, we now analyze total and double-ionization cross sections measured for a variety of partially stripped projectiles. First we will determine average effective charges for the ions and note how these average charges depend on the degree of target ionization and impact velocity. This information will then be used to interpret the velocity dependence of the ratio $\sigma_T/\sqrt{\sigma_2}$ obtained for partially stripped projectile impact.

A. Projectile charge-state dependence

Average values for the effective projectile charges were obtained by comparing partially stripped ion impact cross sections to those obtained for fully stripped ion impact. This was done for a range of impact energies using total as well as double target ionization cross sections. The procedure used was to draw curves through the fully stripped ion impact data as shown in Fig. 1. Then the partially stripped ion impact cross sections were placed on the curves according to the magnitude of the cross sections. At this point, values for average effective charges were obtained by referring to the abscissa.

For example, cross sections for σ_T and σ_2 for 0.32-MeV/u He^+ impact were obtained by interpolating the data in Table I to the proper energy. These values were placed on the 0.32-MeV/u curves in Fig. 1 as shown. By referring to the abscissa, it is concluded that He^+ interacts with an average charge of 1.25 if one considers total (mostly single in this case) ionization of the target. But a larger average charge (1.6) is indicated if one considers only double target ionization. The accuracy of the average effective projectile charges that we obtain in this fashion depends on the accuracy of the individual cross sections as well as on how well a curve through the fully stripped ion data can be defined. In general, the uncertainties in Z_{eff} are estimated to be 10%. We note that the average charges we obtain for single and double ionization of He by He^+ impact are in complete agreement with the results of Edwards, Wood, and Ezell[12] who studied ionization of H_2 by He^+.

The same procedure was used for other projectiles and impact energies with the results recorded in Table II. In all cases where the projectile charge state was small, the average effective charge obtained using double target ionization cross sections was larger than the average charge obtained using total ionization cross sections. Again we point out that the data being discussed here, total ionization is predominantly due to single ionization of the target and thus the average effective projectile charge is larger when multiple, rather than single, ionization of the target occurs *if* the projectile is only slightly stripped. For nearly fully stripped projectile ions, the average effective projectile charges were found to be approximately the same whether total or double target ionization occurred.

The results in Table II also indicate that, as a function of impact velocity, the average effective projectile charges are approximately constant. A possible exception may occur for helium ion impact although this could be due to the lower impact velocities investigated rather than from the particular ion species.

B. Projectile velocity dependence

Although we have not definitively demonstrated that $Z_{\text{eff}}(b)$ is independent of impact velocity and therefore does not influence the velocity dependence of $\sigma_T/\sqrt{\sigma_2}$, it should still be possible to determine the type of double-ionization interaction mechanism since the velocity dependencies of the one-step and the two-step mecha-

TABLE II. Average effective charges for electron bearing projectiles that were obtained from the measured total and double ionization cross sections as described in the text. Note that for projectiles where the charge state is small, the average effective charge is smaller if total (mostly single) ionization occurs than if double target ionization occurs.

E/M (MeV/u)	0.10		0.19		0.32		0.64		1.44		2.3	
	Effective projectile charge obtained from											
Ion	σ_T	σ_2	σ_T	σ_2	σ_T	σ_2	σ_T	σ_2	σ_T	σ_2	σ_T	σ_2
H^0			0.59	0.8	0.6	0.95						
He^0	1.1	2.0	0.92	1.5	0.88	1.5	0.68	1.5				
He^+	1.3	2.1	1.3	1.6	1.25	1.6	1.3	1.2	1.3		1.2	
Li^+							1.75	2.15	1.55	2.45		
Li^{2+}							2.1	2.35	2.15	2.55	2.1	2.35
B^{2+}							2.5	3.1	2.7	3.4		
B^{3+}							3.2	3.4	3.1	3.6	3.2	3.5
B^{4+}			4.0	4.2			3.7	4.0	4.0	4.15	4.0	3.9
C^0	1.95	~3.5										
C^+	3.0											
C^{2+}	3.8											
C^{3+}							3.1	3.5	3.4	4.0	3.4	3.8
C^{4+}							3.9	4.3	4.0	4.25	4.2	4.3
C^{5+}							4.9	4.5	4.9	5.1	4.8	4.8
N^0	1.95	3.7										
N^+	2.8											
N^{2+}	~4.2											
O^0	2.1											
O^+	4.4											
O^{4+}							4.2	4.6	4.3	5.2		
O^{5+}							5.1	5.5	5.1	5.9	5.4	5.8
O^{6+}							6.1	6.4	5.8	6.4	5.8	6.2
O^{7+}									6.9	7.4	7.2	7.1

nisms are radically different. Thus, the velocity dependence of $\sigma_T/\sqrt{\sigma_2}$ is plotted in Fig. 2 for singly charged ions and neutral-particle impact. We immediately observe that the ratios are approximately a factor of 2 smaller than those shown for fully stripped ion impact. Although not shown we also found that the ratios for "nearly fully stripped" ions have approximately the same magnitude as those for bare ion impact; but, as the projectile electronic structure becomes more complex, the ratios decrease in magnitude toward the values for singly charged and neutral-particle impact.

If we now concentrate on the velocity dependence of $\sigma_T/\sqrt{\sigma_2}$, we see that for impact energies below approximately 0.1 MeV/u this ratio of cross sections increases. Although again not shown, the available data indicate that, for any given projectile, the onset of this increase occurs at increasingly lower impact velocities as the charge state increases.

At higher velocities, the He^+ data exhibit a slow increase as predicted by the Bethe approximation and a two-step interaction picture. At still higher velocities, the two Li^+ data points indicate a decreasing ratio indicative of an emerging one-step interaction mechanism. However, additional data are required to confirm this.

For neutral-particle impact the higher velocity data indicate that, in the same velocity range where the He^+ ratios are increasing in accordance with a two-step picture, the He^0 and the H^0 ratios are decreasing as would be expected for an emerging one-step mechanism. In fact, the velocity dependence for H^0 impact is approximately that expected for a one-step interaction mechanism. A possible explanation for the one-step mechanism dominating at such low velocities for these projectiles could be as follows. In the case of fully stripped ion impact, we showed that the one-step interaction picture becomes important when the impact energy is roughly equal to 0.5 MeV/u times the projectile charge squared. According to Table II, the average effective projectile charge for total ionization of He by H^0 impact is approximately 0.6 which implies that the one-step mechanism should become important above 180 keV for H^0 impact. Likewise, since Table II indicates that $Z_{\text{eff}} \sim 0.8$ for He^0 impact and ~ 1.6 for Li^+ impact, the one-step mechanism would become important as slightly higher impact velocities 320 and 1280 keV/u for He^0 and Li^+ impact, respectively. Although this qualitatively explains our observations, definitive answers require additional data.

C. Modeling the influence of $Z_{\text{eff}}(b)$

As noted above, for partially stripped ion impact the average effective projectile charge was found to be smaller when total (mostly single) target ionization than when double target ionization occurred. Only for small projectile charges, however, was this difference significant; for nearly fully stripped projectiles, the average effective charges were found to be nearly the same regardless of the degree of target ionization. In addition, the ratio $\sigma_T/\sqrt{\sigma_2}$ was seen to decrease as the projectile charge state varied from fully stripped to fully clothed.

In order to better understand these observations we have used Eqs. (2) to calculate cross sections for single and double ionization of helium for various partially and fully stripped ion impact. For partially stripped ion impact, an impact-parameter-dependent screened nuclear charge $Z_{\text{eff}}(b)$ was used instead of the full nuclear charge shown in Eqs. (2). For these calculations the variable $Z_{\text{eff}}(b)$ was determined according to the formulas presented by Toburen *et al.*[4] and by McGuire, Stolterfoht, and Simony[5] According to their models, $Z_{\text{eff}}(b)$ has a limiting value of $Z-n$ for large impact parameters since the nuclear charge is screened by the entire electron cloud. Here n is the number of bound electrons and Z is the full nuclear charge. For intermediate impact parameters, the screening decreases and $Z_{\text{eff}}(b)$ becomes larger. For very small impact-parameter collisions, the collision takes place inside the bound electron cloud. Here, according to Toburen *et al.*,[4] the target electrons are subject to a force due to the full nuclear charge Z and thus $Z_{\text{eff}}(0)=Z$. McGuire *et al.*,[5] on the other hand, also include ionization induced by the bound projectile electrons which must be added incoherently to the ionization induced by the nuclear charge. Hence the effective charge at small impact parameters in the formulation of McGuire *et al.* is given by $(Z^2+n)^{1/2}$.

Examples of $Z_{\text{eff}}(b)$ are shown in Fig. 3 where we have used hydrogenic wave functions and the two screening

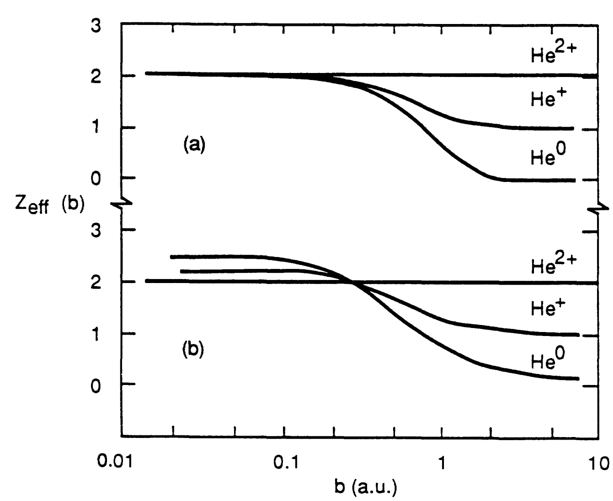

FIG. 3. Effective charge of helium ions as a function of distance from the nucleus calculated using the procedures presented in Refs. 11 and 12. Hydrogenic wave functions were used to determine the screening by the bound electrons. (a) $Z_{\text{eff}}(b)$ according to Toburen *et al.* (Ref. 4). (b) $Z_{\text{eff}}(b)$ according to McGuire *et al.* (Ref. 5).

models to determine the effective charge that would be seen by an electron at a distance b from various charge states of helium projectiles. Note that only for very distant collisions will a partially stripped He^{i+} projectile interact with an effective charge equal to its net charge i. From smaller impact parameters, $Z_{\text{eff}}(b)$ is larger than i, but only at very small impact parameters will the incident particle interact with at least its full nuclear charge.

The cross-section calculations using Eqs. (2) also require specific forms for the ionization probabilities $P(b)$. We have used three different forms for $P(b)$ in our calculations. First of all, we chose an exponential form, $P(b)=P(0)e^{-b/R}$ where $P(0)$ and R were obtained by fitting to the experimental data for fully stripped ion impact. For example, substituting this form of $P(b)$ into Eqs. (2), performing the integrations, and fitting the ratio $\sigma_T/\sqrt{\sigma_2}$ to the experimental data yielded $P(0)=0.012$ and $R=2$ a.u. at 1.44-MeV/u. A second form for $P(b)$ was determined by taking the $P(b)$ values given by Salin[13] for 1.44 MeV/u P^{15+} impact and scaling to H^+ impact according to the $Z^2f(Z,v)$ rules discussed previously. A third form for $P(b)$ was determined according to the procedures outlined by Hansteen, Johnsen, and Kocbach[14] for 1.44-MeV H^+ impact.

Using these three different forms for $P(b)$ and the two forms for $Z_{\text{eff}}(b)$, σ_1 and σ_2 were determined at 1.44 MeV/u using Eqs. (2). To simplify matters, $f(Z,v)$ was set equal to unity, which according to Fig. 1 is reasonably valid for $Z<5$. σ_T was then determined from σ_1 and σ_2. Comparing our calculated values with experimental results for bare ion impact indicated that all three forms for $P(b)$ were equally appropriate for determining σ_T. However the Hansteen, Johnsen, and Kocbach formulation severely overestimated the amount of double with respect to single ionization; so it was rejected. Also since our scaling of Salin's $P(b)$ may not be permissible, we chose to concentrate on the exponential form for our comparison of calculated and measured cross sections.

Thus, using the exponential form for $P(b)$, the calculated and measured cross sections for fully stripped ion impact were found to agree within 10% for $Z<5$ at 1.44 MeV/u. This agreement of course excludes σ_2 for H^+ impact where the two-step mechanism has been shown to be inappropriate. For large values of Z the calculated values increasingly (35% at $Z=8$) overestimated the experimental values since $f(Z,V)$ is no longer unity.

To calculate cross sections for partially stripped ion impact, $Z_{\text{eff}}(b)$ was allowed to vary according to the formulations of Toburen *et al.*[4] or McGuire *et al.*[5] Average effective projectile charges were determined in the same manner as before but this time using calculated values for σ_T and σ_2. Selected results for 1.44-MeV/u impact are given in Table III. Comparing the results in Table III with the experimentally determined values in Table II shows that our simple calculation is in qualitative agreement. Namely, the average effective projectile charge is larger for double target ionization than for total (primarily single) target ionization. This is true whenever the projectile charge state is small. For nearly fully stripped projectiles, the average effective projectile

TABLE III. Average effective projectile charges and $\sigma_T/\sqrt{\sigma_2}$ ratios obtained using calculated values for σ_T and σ_2 at 1.44 MeV/u. The calculations assumed an exponential ionization probability $[P(b)=0.012e^{-b/2}]$ for proton impact and a pure Z^2 scaling for heavier ions. For partially stripped projectile impact, a variable $Z_{\text{eff}}(b)$ according to the formulations of Toburen *et al.* (Ref. 4) and McGuire *et al.* (Ref. 5) was used in Eq. (2) to determine σ_T and σ_2, which, in turn, were used to determine Z_{eff}.

	Toburen *et al.* formalism			McGuire *et al.* formalism		
	Z_{eff} Obtained from		$\sigma_T/\sqrt{\sigma_t}$	Z_{eff} Obtained from		$\sigma_T/\sqrt{\sigma_2}$
Ion	σ_T	σ_2	(10^{-7} cm)	σ_T	σ_2	(10^{-7} cm)
H^0	0.31	0.65	0.26	0.48	0.85	0.33
He^0	0.44	0.58	0.17	0.46	1.1	0.19
He^+	1.05	1.3	0.75	1.1	1.3	0.76
Li^+	1.1	1.5	0.56	1.15	1.45	0.62
Li^{2+}	2.0	2.1	0.96	2.1	2.15	0.98
B^{2+}	2.3	2.8	0.71			
B^{3+}	3.0	3.15	0.98	3.1	3.2	1.01
B^{4+}	4.0	4.0	1.04	4.1	4.1	1.04
C^0	1.6	3.1	0.27			
C^+	1.9	3.2	0.37			
C^{2+}	2.4	3.3	0.59			
C^{3+}	3.2	3.6	0.84			
C^{4+}	3.9	4.1	1.02	4.1	4.15	1.03
C^{5+}	4.8	5.0	1.05	4.8	5.0	1.05
N^0	1.65	3.5	0.23			
N^+	1.9	3.6	0.31			
N^{2+}	2.6	3.7	0.50			
O^0	1.7	4.0	0.20			
O^+	2.0	4.0	0.27			
O^{4+}	4.2	4.8	0.83			
O^{5+}	4.9	5.4	0.96			
O^{6+}	5.6	6.0	1.05	5.6	6.0	1.05
O^{7+}	6.5	7.0	1.06	6.5	7.0	1.06

charge is the same whether total or double target ionization occurs.

Table III also gives the ratio $\sigma_T/\sqrt{\sigma_2}$ which can be compared with the experimental results shown in Fig. 2. Again we have qualitative agreement, namely $\sigma_T/\sqrt{\sigma_2}$ increases in magnitude as the projectile becomes more fully stripped. Our calculations for lighter projectiles also indicate that the model of McGuire *et al.*[5] provides slightly better agreement with experiment. Thus our simple calculation demonstrates that we qualitatively understand how the bound projectile electrons affect the single- and double-ionization cross sections of helium.

VII. CONCLUSION

We have presented new measurements for direct single and double ionization of helium by neutral and low charge-state ions. These data, when combined with previously measured cross sections obtained from the literature, indicate that the two-step mechanism is the dominant double ionization mechanism above approximately 0.1 MeV/u and this mechanism dominates until the impact energy is larger than approximately 0.5 MeV/u times the projectile charge squared. The cross sections for partially stripped ion impact were shown to scale with an average effective projectile charge that is a function of the degree of target and of projectile ionization. By using theoretical models for $Z_{\text{eff}}(b)$ and a simple calculation, cross sections for single and double ionization or helium were calculated for various partially stripped ion impact. The calculations demonstrate that we qualitatively understand how the bound projectile electrons influence the single- and double-ionization cross sections.

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