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Relativistic electron- and proton-impact ionization of highly stripped heavy ions determined from projectile-electron loss in H_2 and He

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We show that electron- and proton-impact ionization cross sections for highly stripped heavy ions can be deduced from the projectile-electron-loss cross sections determined by collisions with a H_2 and a He target. We measure electron loss for 100- and 380-MeV/u Au^{52+}, and 405-MeV/u U^{86+} in H_2 and He targets, and extract the electron- and proton-impact ionization cross sections. Our results are compared with calculations and with channeling experiments.

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Although electron impact ionization of ions can be studied by crossed beams of electrons and ions, this method becomes difficult for highly stripped heavy ions since very large electron densities are needed to measure these small cross sections [1]. Recently, the high density of quasi-free electrons along a crystal channel has been used to study the electron impact ionization of highly stripped heavy ions by channeling the ions through a crystal along a main axial direction. Several groups have channeled ions through Si crystals to measure *L*- and *K*-shell cross sections of uranium ($Z=92$) and *M*- and *L*-shell cross sections of xenon ($Z=54$) [2,3]. Measurements of the uranium *K* shell and the xenon *M* and *L* shells are found to be larger than the calculated cross sections [2–4]. These discrepancies are not well understood and an alternative experimental technique is needed to help understand this problem.

Here we present such a technique. Briefly, in projectile ionization of a highly stripped heavy ion, the impact parameter can be small compared to the electron-nucleus separation in a low-*Z* target. The target electrons and nuclei therefore act independently [5], allowing us to separate electron and nuclear contributions to ionization by comparing targets of different *Z*.

In a recent Letter [6], Hülskötter, Meyerhof, Dillard, and Guardala showed that the measured projectile ionization cross sections of hydrogenlike 0.75–3.5-MeV/u C and O (C^{5+} and O^{7+}) in H_2 and He gas targets agreed with a plane-wave Born approximation (PWBA) calculation that included screening. Agreement, however, required the interaction between the target electrons and the projectile (antiscreening) to be taken into account. In a subsequent paper [7] we showed that the same was true for relativistic ions, 100- and 380-MeV/u Au^{52+} and 405-MeV/u U^{86+}. In this Brief Report we extend the analysis of these data and develop a model-independent [8] determination of the electron-impact ionization as well as the proton-impact ionization cross sections for these relativistic highly stripped ions. We demonstrate that this model-independent analysis of the data results in an efficient technique to measure electron-impact ionization of relativistic highly stripped heavy ions. In contrast, as will be shown below, this technique cannot be applied to low-*Z* (atomic number) projectiles such as C^{5+} and O^{7+}.

Stripping a tightly bound electron from a projectile requires an energy transfer high enough to overcome the ionization energy, *I*. The impact parameters associated with such energy transfers are typically smaller than the impact parameter $b_1=\hbar c/(I^2+2Imc^2)^{1/2}$ given by the uncertainty principle [9], where $\hbar$ is Planck's constant divided by 2π, *c* the speed of light, and *m* the electron mass. However, because the ionization energies of the projectile are quantized, collisions with impact parameters up to $b_{\max}=\hbar c\beta\gamma/I$ may also ionize the projectile [10], where β is the projectile velocity divided by c and γ is the relativistic factor. At relativistic energies $b_{\max}$ is larger than b_1.

For very large values of I, and γ not too large, the size of the projectile and the impact parameters b_1 and $b_{\max}$ are much smaller than the K shell of low-Z targets, such as H or He. As a consequence, during the ionization process the projectile electron is scattered incoherently by the target nucleus and the target electron(s). Furthermore, because the target electron binding energy is very small compared to the energies involved in the process, one can ignore the binding energy and assume that the electron is quasi free. The above discussion applies also to molecular hydrogen (H_2). Due to the large separation between the two protons in a hydrogen molecule the interference (molecular) effects on projectile ionization are negligible. The projectile-electron-loss cross section under these conditions is the sum of a contribution from the electron(s) and a contribution from the nucleus without interference,

$$\sigma_T=Z^2\sigma_p+Z\sigma_e\ , \tag{1}$$

where $Z^2\sigma_p$ is the contribution from a bare target nucleus and $Z\sigma_e$ is a contribution from the target electrons, and σ_e and σ_p are electron- and proton-impact ionization cross sections. The theoretical basis for this has been discussed by, among others, Bohr [5]. However, for projectile ionization, this highly ionized heavy-ion experiment represents the first time that the requirements for separating the electronic and nuclear contributions have clearly been met.

Applying Eq. (1) to the measured projectile ionization cross sections in both H_2 and He leads to a system of two linear equations in two unknowns, σ_e and σ_p. The analysis yields accurate results only if the electron contribution to the cross section, $Z\sigma_e$, is not negligible compared to the nuclear contribution, $Z^2\sigma_p$. This is the case if the target electron has a kinetic energy in the projectile frame much larger than the projectile ionization potential [11].

As a demonstration of this method, we reanalyzed the one-electron-loss cross sections for U^{86+} at 405 MeV/u and Au^{52+} at 100 and 380 MeV/u, all in H_2 and He, published earlier in Ref. [7] (see Table I). The above conditions are met for U^{86+}, where the ionization potential is 29.8 keV [12], making $b_{\max}$ and b_1 much smaller than the K shell of the target. For Au^{52+}, however, the ionization potential of the M shell is only 4.7 keV [12]. While b_1 is much smaller than the K shell of the target, $b_{\max}$ is of the same order. This latter case demonstrates the method's limitations: when applied to the ionization of shells with a small binding energy the interference between the target electrons and the target nucleus may not be negligible. A relative reduction of the total cross section can result due to the screening of the target nucleus by the target electrons. However, if $b_{\max}$ is only of the order of the target K shell, while the size of the projectile (or b_1) is much smaller, the interference effects between the target electron and the target nucleus may still be neglected. This is because the ionization probability, $P(b)$, for distant collisions scales roughly as b^{-2} (Ref. [10]). Thus, there is only a small probability of ionization due to large-impact-parameter collisions, so they have only a small effect on the total cross section. To estimate this interference effect we use the N_2 target data of Ref. [7] (Table I), and, comparing with the H_2 and He target data, find that even in this extreme case the effect is only about 20%. This supports our argument to neglect (within the experimental uncertainties quoted) the interference effects in the case of ionization of Au^{52+} by the He target, even though $b_{\max}$ is of the order of the K shell of the target. For low-Z projectiles, such as Li^{2+}, C^{5+}, and O^{7+} (Refs. [6,7]), b_1 is of the order of the hydrogen K shell or larger, and a separation of the electronic and nuclear contributions to the ionization of these ions is not possible.

Details of the experiment can be found in Refs. [7,13]. Briefly, we obtain the 100- and 380-MeV/u Au^{52+} and 405-MeV/u U^{86+} ions from the Lawrence Berkeley Laboratory's Bevalac. The ions pass through a 241-cm-long, 40-cm-diam gas cell target, filled with up to 5 Torr of H_2, He, or N_2 gas. We determine the one-electron-loss cross section by measuring the growth of the Au^{53+} and U^{87+} peaks, respectively, as a function of gas pressure. The ends of the cell are furnished with "flapper valves" that allow each $\sim$100-ms beam pulse to pass through a 6-mm-diam hole, but otherwise are kept closed to maintain the vacuum in the beam lines near its normal level. Downstream of the gas target cell the beam is focused by a quadrupole doublet and the charge state analyzed by a dipole magnet system. Different detector systems were used for the Au and U ions, as the data were taken in two separate runs. A position-sensitive proportional counter was used to detect the Au charge states, while a pair of

TABLE I. Measured one-electron-loss cross sections (in kbarns).

E (MeV/u)	Ion	σ_{H_2} [a]	σ_{He} [a]	Correlated error[b]	σ_{N_2}
405	U^{86+}	0.366±0.03	0.550±0.04	0.018	
100	Au^{52+}	31±3	47±5	2.9	6.9×10^2
380	Au^{52+}	15±2	21±2	1.4	3.1×10^2

[a]The total error includes both the correlated error between the measurements with H_2 and He (such as gas cell and detector efficiency effects) and the uncorrelated error (such as statistical effects).

[b]This error represents that which is correlated between the measurements with H_2 and He, because of detector position sensitivity and gas cell effects.

TABLE II. Electron- and proton-impact ionization cross sections (in kbarns). All cross sections are given for the loss of one projectile electron.

E (MeV/u)	Ion	σ_e[a]	σ_e (PWBA)[b]	σ_e (Lotz)[c]	σ_e (PB)[d]	σ_p[a]	σ_p (PWBA)[b]
405	U^{86+}	0.091±0.028	0.087	0.055	0.055	0.092±0.020	0.109
100	Au^{52+}	7.5±3.0	8.0	7.1		8.0±2.2	8.8
380	Au^{52+}	4.5±1.4	3.6	3.0		3.0±1.0	3.7

[a]Calculated using the data of Table I. The error is calculated from the correlated and uncorrelated errors in Table I.
[b]Reference [14].
[c]Extrapolated from Ref. [16], using the tables of Refs. [12,17].
[d]Extrapolated from Ref. [15], which excludes the contribution from K-shell ionization.

scintillator-photomultiplier combinations was used to detect the two U charge states.

Table I gives the measured total cross section for each gas target. Errors include statistical contributions, uncertainties in the cell pressure and effective length, and detector response. Extending the analysis of Ref. [7], we subdivide the errors into those that are correlated with each target, and those that are uncorrelated, also shown in Table I. The electron- and proton-impact ionization cross sections deduced from the data of Table I are listed in Table II. The table shows that σ_e and σ_p are nearly equal. These results reflect the fact that the electrons and protons have equal velocities in the projectile frame of reference, and that the associated kinetic energy of the electron is much larger than the projectile ionization potential [11]. Table II also compares our deduced proton-impact ionization cross sections with a PWBA calculation based on Ref. [14]. The results are consistent with the PWBA values.

In Table II we also compare our electron-impact ionization results with the calculations of Pindzola and Buie (PB) [15], a semiempirical calculation of Lotz [16], and a PWBA calculation [14]. We compare our results at 100-, 380-, and 405-MeV/u projectile energies with calculated electron-impact ionization cross sections at energies of 54.9, 208, and 222 keV, respectively. The U results agree with the PWBA calculation but are 65% larger than the values extrapolated from Lotz or from PB. We do not understand the origin of this disagreement. However, our M-shell Au results agree with Lotz, as well as with the PWBA calculation.

In contrast, L- and M-shell electron-impact ionization cross sections of 27-MeV/u Xe ions measured in channeling experiments [3] are found to be larger than those of Lotz by about a factor of 4. A uranium L-shell cross section measured by channeling [2], however, finds no such discrepancy. These differences are not well understood. An accurate measurement of the cross sections using the channeling technique requires that the electron densities encountered by the ions be known, and that account is taken of the electron losses by the (much larger) nuclear-impact ionization from ions that are not well channeled. Also, because of the high electron density in the crystal and the finite size of the channels, one has to ensure that density-dependent effects, such as excitation with subsequent electron loss, do not affect the measurements [4]. These potential systematic problems are absent in our gas target technique. In particular, low gas density minimizes the possibility of multiple-step processes affecting the measurements.

We conclude that this method is able to investigate electron-impact ionization of many of the highly charged ions that can be measured by channeling, but has the advantage of using a lower density, large thickness target whose parameters are well characterized and accurately controlled.

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