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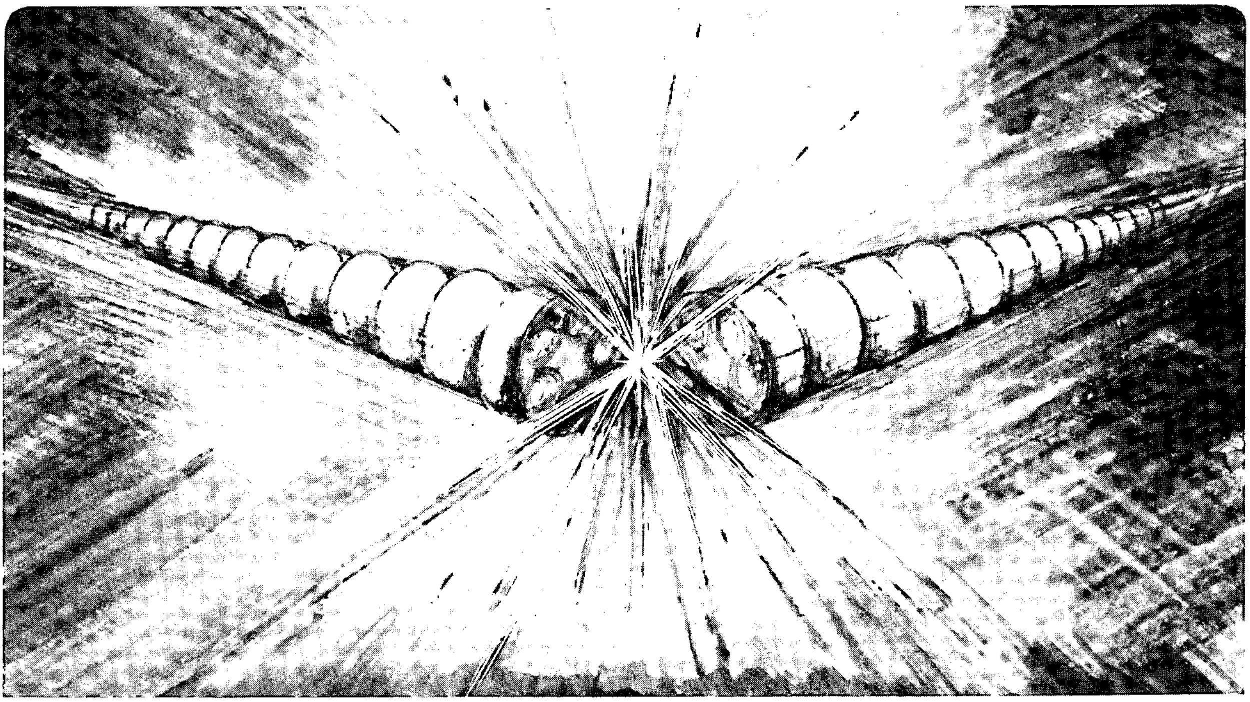

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Relativistic Electron and Proton Impact Ionization of Highly Stripped Heavy Ions Determined from Projectile Electron Loss in H_2 and He

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Abstract

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.

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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] However, 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] Measurements of electron impact ionization cross sections, using the channeling technique, 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 shed light on this problem.

Here we present such a technique. In channeling, the electrons that constitute the dense target are found in the middle of the crystal channel. A similar situation exists for low-Z atomic targets, such as hydrogen and helium, whose loosely bound electrons constitute a moderately dense target.[5] The present method is able to investigate electron impact ionization of many of the highly charged ions which 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. Low gas density minimizes the possibility of multiple-step processes affecting the measurements.

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 $b_1 = hc/(I^2+2Imc^2)^{1/2}$ given by the uncertainty principle, where h is Planck's constant, c the speed of light, and m the electron mass. However, because the binding energies of the projectile are quantized, collisions with impact parameters up to $b_{max} = hc\beta\gamma/I$ may also ionize the projectile,[6] 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. Collisions with impact parameters $b < b_1$ are customarily called "close collisions" and collisions with impact parameters b such that $b_1 < b < b_{max}$ are called "distant collisions."

For very large values of I, the size of the projectile and the impact parameters b_1 and b_{max} are much smaller than the K-shell of the low-Z (atomic number) target. As a consequence, during the ionization process the projectile electron is scattered incoherently by the target nucleus and the target electron(s). 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. 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.[7]

Since the nuclear contribution to the ionization cross section is proportional to Z^2, while the target electron contribution[8] is proportional to the number of electrons, Z, measurements of the total ionization cross sections in both H_2 and He may be combined to yield the electron impact ionization. The analysis yields accurate results only if the electron contribution to the cross section is not negligible compared to the nuclear contribution. This is the case if the target electron has a kinetic energy in the projectile frame much larger than the projectile ionization potential.

As an application of this method, we measured 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. The ionization potential of U^{86+} is 29.8 keV,[9] 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.[9] While b_1 is much smaller than the K-shell of the target, b_{max} is of the same order. This shows the method's limits: when applied to the ionization of shells with a small binding energy the interference between the target electrons and the 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 can still be neglected. This is because the ionization probability, P(b), for distant collisions goes roughly as b^{-2} (Ref. 6). 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. In order to estimate this interference effect we use an N_2 target as an extreme case.

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 diameter gas cell target, described in Ref. 10, filled with up to 5 Torr of H_2, He, or N_2 gas. Figure 1 shows the beamline from the gas cell to the detector. 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 ~100-ms beam pulse to pass through a 6-mm diameter hole, but otherwise are kept closed to maintain the vacuum in the beam lines near its normal level. While the valves are open, end effects add a ±3% uncertainty to the effective thickness of the gas cell. Thin lips were placed on the flapper valves[11] to reduce the background due to slit scattering. Additional details concerning the gas cell and the method may be found in Refs. 10 and 12.

Downstream of the gas target cell the beam is focused by a quadrupole doublet and the charge state analyzed by a dipole magnet system, as shown in Fig. 1. 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. A pair of scintillator-photomultiplier combinations was used to detect the two U charge states.

Figures 2a and 2b show the fraction of projectile ions which have been ionized, as a function of pressure, for H_2 and He targets. Analysis of the Au data from the first several points, assuming a linear dependence on target thickness, yields a result that varies by less than 3% from a quadratic fit to the entire data set.[10] The non-zero fraction at zero pressure for the U data is due to slit scattering.

Table 1 gives the measured total cross section, $\sigma_T = Z^2\sigma_p + Z\sigma_e$, where $Z^2\sigma_p$ is the contribution from a bare target nucleus and $Z\sigma_e$ is a contribution from the target electrons. σ_e and σ_p are electron and proton impact ionization cross sections. Errors include statistical contributions, uncertainties in the cell pressure and effective length, and detector response. The errors can be subdivided into those that are correlated with each target, and those which are uncorrelated, also shown in Table 1.

Solving the above equation simultaneously for H_2 and He, we obtain the electron and proton impact ionization cross sections listed in Table 2. As expected, at these high energies σ_e and σ_p are nearly equal at equal velocities. We use the values of σ_e and σ_p for Au^{52+}, deduced from the H_2 and He data, to estimate the total cross section for a N_2 target. Large screening effects due to interference between the target electrons and the target nucleus are expected. If we assume the contrary, that there is no interference, and use the above formula, we obtain $\sigma_{N_2} = 8.89 \times 10^5$ barns for 100 MeV/u Au^{52+}, and $\sigma_{N_2} = 3.57 \times 10^5$ barns at 380 MeV/u. In this extreme case, the values are only off by about 20% compared to the measured cross section listed in Table 1. 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.

Table 2 compares our electron impact ionization results with the calculations of Lotz,[13] Pindzola and Buie,[14] and a Plane Wave Born Approximation (PWBA) based on Ref. 15. Our Au results are consistent with the PWBA and the Lotz calculations. The U results agree with the PWBA calculation but are larger than the other theoretical values. Table 2 also compares our deduced proton impact ionization cross sections with a PWBA calculation.[15] The results are consistent with the PWBA values.

We conclude that this new method is suitable to measure electron and proton impact ionization cross sections for highly stripped heavy projectiles at large velocities. The well characterized large target thickness and low gas density enable this method to yield accurate measurements of the cross sections.

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Table 1

Table 1. 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 2

Table 2. Electron and proton impact ionization cross sections (in kbarns).[a]

E(MeV/u)	Ion	σ_e[b]	σ_e(PWBA)[c]	σ_e(Lotz)[d]	σ_e(PB)[e]	σ_p[b]	σ_p(PWBA)[c]
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] All cross sections are given for the loss of one projectile electron.

[b] Calculated using the data of Table 1. The error is calculated from the correlated and uncorrelated errors in Table 1.

[c] Ref. 15.

[d] Extrapolated from Ref. 13, using the tables of Refs. 9 and 16.

[e] Extrapolated from Ref. 14, which excludes the contribution from K-shell ionization.

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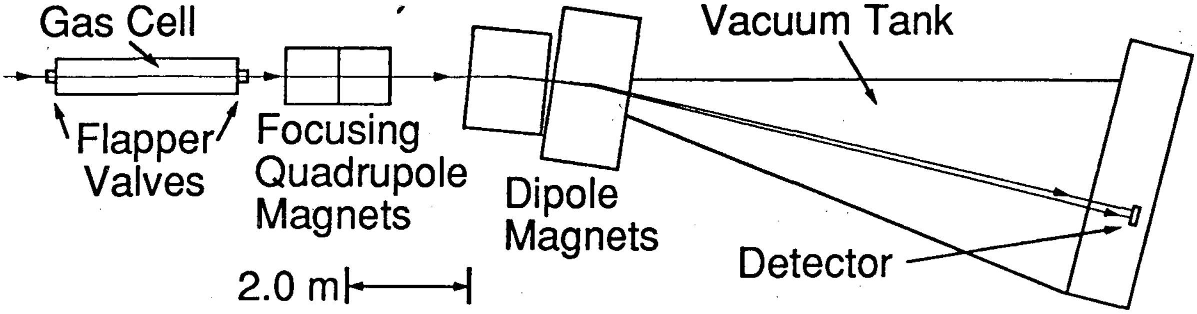

Figure 1

Diagram of the beamline from the gas cell to the detector. The charge states are separated by the dipole magnets.

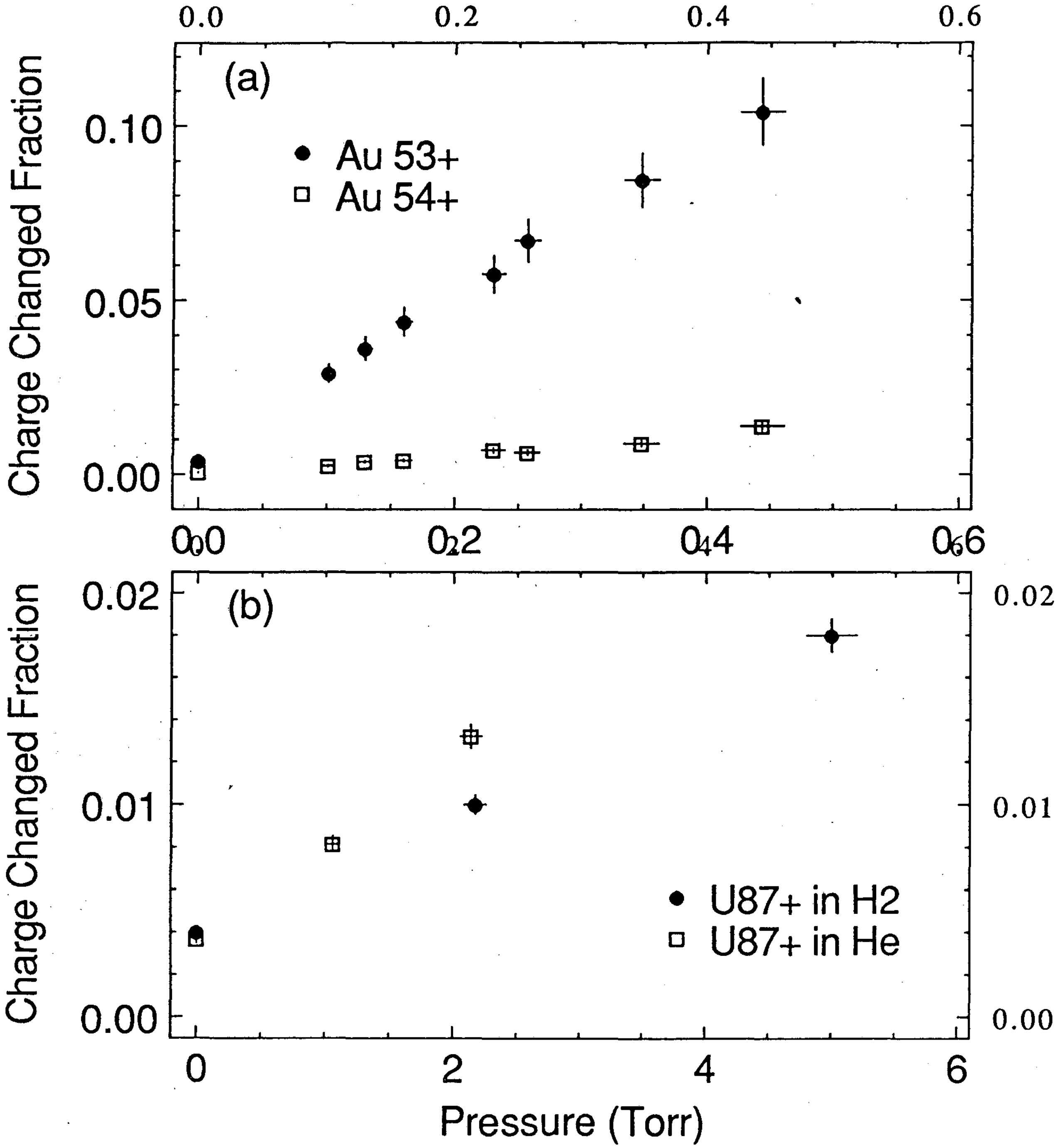

Figure 2

Charge changed fraction for 100 MeV/u Au^{52+} on H_2 (a) and 405 MeV/u U^{86+} (b) as a function of pressure.

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