Measurements of the total charge-changing cross sections for collisions of target gases with a 1-MeV K^+-ion beam

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(Received 26 June 2008; published 22 September 2008)

The sum of ionization and charge-exchange cross sections of several gas targets (H_2, N_2, He, Ne, Kr, Xe, Ar, and water vapor) impacted by a 1-MeV K^+ beam are measured. In a high-current ion beam, the self-electric field of the beam is high enough that ions produced from the gas ionization or charge exchange by the ion beam are quickly swept to the sides of the accelerator. The flux of the expelled ions is measured by a retarding field analyzer. This allows accurate measuring of the total charge-changing cross sections (ionization plus charge exchange) of the beam interaction with gas. Cross sections for H_2, He, and Ne are simulated using classical trajectory Monte Carlo method and compared with the experimental results, showing good agreement.

DOI: 10.1103/PhysRevA.78.032709 PACS number(s): 34.50.Fa, 34.10.+x, 34.50.Gb, 34.70.+e

I. INTRODUCTION

Knowing cross sections for interaction of a fast ion beam with gas targets is important for many applications, such as ion-beam lifetimes in accelerators [1], inertial fusion [2], collisional and radioactive processes [3], etc. Most of the experiments are focused on charge-changing processes for the projectile and neglect the target charge-changing cross section; nevertheless there are many important issues which require precise knowledge of ionization and charge-exchange cross sections for the target gases. For example, electron clouds can form inside the accelerator due to residual gas ionization and cause two-stream instabilities [4]. Formation of the electron clouds and the beam loss due to stripping causes severe limitations on parameters of the vacuum system for the heavy ion synchrotron SIS18 at GSI [5,6]. Beam interaction with the remaining background gas and gas desorbed from walls limits intensity of bunches at the Relativistic Heavy Ion Collider (RHIC) [7]. Pressure rise from ion losses at the low-energy antiproton ring [8,9] brought concerns for the large hadron collider [10], similarly, it is of great concern for the positron damping ring of the international linear collider [11], as well as for other high-current, high-intensity accelerators and ion beam injectors.

Experimental data for charge-changing cross section for complex atoms are scarce in the literature [12,13]. That is why the U.S. Heavy-Ion Fusion Science Virtual National Laboratory initiated measurements of cross sections in a series of experiments on GSI linear accelerator UNILAC [14] and Texas A&M synchrotron [15–18]. When experimental data and theoretical calculations are not available, approximate formulas are needed; therefore, the study of the scaling of cross sections with energy and target or projectile nucleus charge is now underway to approximate the values of cross sections in a broad range of energies and charge states [15,19,20].

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Whereas values of stripping and charge-exchange cross sections for projectiles are relatively easy to measure by measuring the charge state of a projectile after passing through a gas cell; measurements of ionization cross sections of the gas target are harder to accomplish, because the degree of gas ionization is small and it is difficult to determine the quantity of ions formed due to ionization. Fortunately, having an ion beam with large space-charge greatly simplifies the measurements, because all formed ions are swept radially to the walls in such beam.

We propose a method to measure total cross sections (ionization and charge exchange) of the background gas by measuring the flux of expelled ions formed by the ion beam ionization and charge exchange. Measurements were performed making use of the High-Current Experiment (HCX) facility [21] at Lawrence Berkeley National Laboratory that provides 180 mA of K^+ ion beam during 5 μs. The target gas was added by leaking gas in the beam transport section. The experimental results were compared with the classical trajectory Monte Carlo (CTMC) method calculations, which show good agreement.

II. DESCRIPTION OF EXPERIMENTAL TECHNIQUE AND SIMULATION METHOD

Collision of a fast K^+ ion beam with a background gas leads to mainly two processes:

$$K^+ + g^0 \rightarrow K^+ + g^+ + e^- \quad \text{(ionization)},$$

$$K^+ + g^0 \rightarrow K^0 + g^+ \quad \text{(charge exchange)}.$$

Gas ionization produces electrons (e^-) and cold ions (g^+), whereas the charge-exchange process transfers electrons from gas atoms (g^0) to the fast potassium ions (K^+) and thus produces fast potassium atoms and cold ions of background gas. Cold ions are expelled during the beam passage by the beam positive space-charge potential towards the walls.

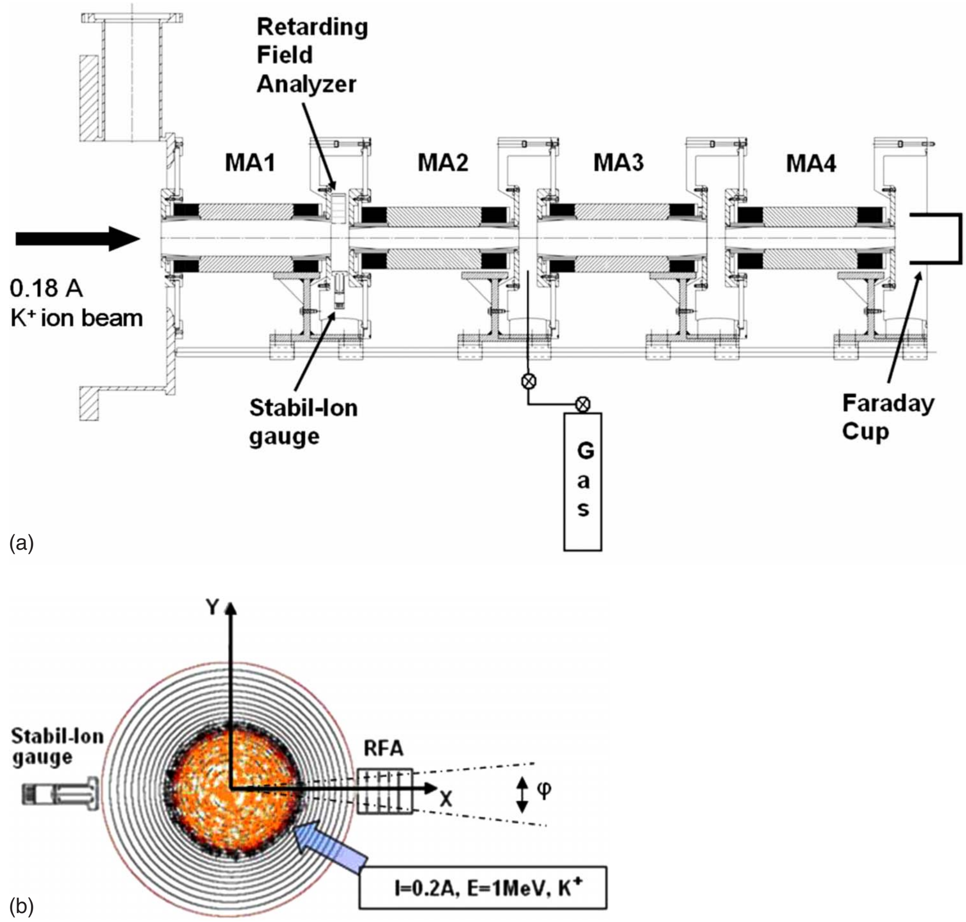

FIG. 1. (Color online) Experimental setup for total cross-section measurements in the beam transport section of the high current experiment. (a) Longitudinal view of the experiment. The background gas is leaked between quadruple magnets 2 (MA2) and 3 (MA3) and increases the background pressure from 10^{-7} Torr to 10^{-6} Torr. A RFA measures the amount of expelled ions produced from the K^+ ion beam interaction with the background gas concurrently with the measurements of a Stabil-Ion gauge and a Faraday cup. (b) Transverse view of the experiment showing the Stabil-Ion gauge and RFA positioning relative to the beam. The contours show simulated electric equipotentials, only ions expelled within the azimuthal angle φ are able to reach the RFA collector.

A. Description of experimental technique

In general, measuring ionization cross section typically involves passage of an ion beam through a gas target at low pressure [22], so that the mean free path is much larger than the gas target length and only single collision occurs in a gas target. In the simplest method, an ion beam crosses a gas cell producing ions and electrons along its path; which are forced by an applied electric field transverse to the beam velocity towards electrodes. The currents are measured simultaneously with the ion beam current, which is caught by a Faraday cup. More sophisticated methods can also perform:

(1) Energy loss analysis of beam particles, which constitutes a signature of certain inelastic collisions;

(2) Mass and/or charge analysis of the recoiling target, which gives the charge state distribution of recoil ions and can distinguish between dissociative and nondissociative ionization for molecular gases;

(3) Coincidence analysis to detect final charges of both scattered and recoil particles, therefore giving full information on final states of target and projectile. A complete characterization of differential ionization cross sections would involve measurement of direction, velocity, and charge of the scattered projectile, the recoiling target, and one or more produced electrons.

If the target gas density n is low enough to ensure single collision conditions in the gas cell, the cross section for production of positive or negative charge ($\sigma_\pm$) is given by

$$\sigma_\pm = \frac{I_\pm}{nlI_0}, \tag{2.1}$$

where I_+ and I_- are the ion and electron currents, n is the gas cell density, l is the length of collection electrodes parallel to the beam, and I_0 is the projectile beam current.

Here, we focus on measurements of total charge-changing cross sections only. The experimental setup for total cross-section measurements is shown in Fig. 1. In this experiment the beam current of 180 mA produces a space-charge beam potential of approximately 2 kV. The beam space charge in the drift region between quadruple magnets produces radial electric field that expels the ions produced by the beam in collisions with the background gas in $\ll 1$ μs, which is short compared with the 5 μs beam duration. Ions are expelled uniformly in the radial direction due to beam axial symmetry in the drift region, see Fig. 1(b). A planar retarding field analyzer (RFA) [23] measures the fraction of the ion current that is expelled and crosses the aperture. The beam current and background pressure are obtained from concurrent measurements with Faraday cup and a Stabil-Ion gauge placed after and at the same RFA axial position, respectively, see Fig. 1(a). Because single ionization and charge transfer are the major processes, Eq. (2.1) can be used to obtain the total cross section,

$$I_{G^+} = I_{K^+}\frac{P}{KT}\sigma_{\text{Total}} l \frac{\varphi}{360}, \qquad (2.2)$$

where I_G+, I_K+, P, K, T, σ_{Total}, l, φ are the expelled ion current measured with the RFA, the beam currents measured with the Faraday cup corrected for the time of flight, the pressure measured with the Stabil-Ion gauge, the Boltzman constant, the room temperature, the total cross section, the axial length of the aperture, and the azimuthal angle in degrees corresponding to RFA aperture as viewed from the pipe center, respectively.

After several measurements without gas leak at nominal vacuum conditions, the total cross section 3.17×10^{-19} m^2 was obtained. The residual gas analyzer (RGA) shows that most of the background gas is water vapor, thus it can be assumed that the measured cross section is for water vapor.

Other measurements were performed by leaking various gases in a controlled way to increase the background pressure by a factor of 10, from 10^{-7} Torr to 10^{-6} Torr, which assures that the main background gas component is known while allowing measuring cross sections using Eq. (2.2).

B. Description of simulation method

The classical trajectory Monte Carlo method (CTMC) was utilized for calculation of the ionization and charge-exchange cross sections. Classical mechanics approaches are simple to apply and yield fairly reliable total cross sections for collision processes at intermediate energies [24]. The CTMC was originally developed by Abrines and Percival [25] and has been used to investigate various collision systems and processes. CTMC method consists of computation of the electron trajectory in an atom when another ion or atom is passing by at a certain impact parameter. The cross section is obtained from the rate of occurrence of the outcome of the collision. The electron can remain close to one of the nuclei or it can move far away from both of them. If the electrons remain close to the target or projectile nuclei and the electron kinetic energy is smaller than the attractive potential to the nucleus, the electron is assumed to be trapped by target or projectile nuclei. If the electron is trapped by the target nucleus, no ionization or charge exchange event occurs, but if the electron is trapped by the projectile nucleus, the charge exchange event happens. Conversely, if the electron moves away from the target and projectile nuclei, ionization takes place. The atomic potentials can be determined either using the Thomas-Fermi theory or Hartree-Fock theory, which include orbital effects. The Hartree-Fock atomic wave equations are solved by the use of Slater determinants [26]. The results must be averaged over all possible initial electron positions and impact parameters; this methodology is described with more details in Ref. [27] and will be further described in future work [28]. Calculations show that the Thomas-Fermi theory does not describe accurately ion potential at the outer edge of the potassium ion, even though potassium nucleus has relatively high charge Z (Z =19) and Thomas-Fermi model describes well most of the potential. The difference in atomic potentials gives error of about 20% compared with the calculations utilizing the more accurate Slater model taken from Ref. [26]. Therefore, in the following, we only use the latter model for ion and atom potentials.

TABLE I. Total cross sections measured using the whole magnetic transport section as a gas cell.

Gas	Total cross section (m^2)	Standard deviation (m^2)
H_2	1.35×10^{-19}	1.55×10^{-20}
N_2	2.98×10^{-19}	2.98×10^{-20}
He	5.62×10^{-20}	5.70×10^{-21}
Ne	1.19×10^{-19}	1.01×10^{-20}
Kr	5.20×10^{-19}	6.83×10^{-20}
Xe	7.11×10^{-19}	7.68×10^{-20}
Ar	3.71×10^{-19}	4.38×10^{-20}
H_20	3.17×10^{-19}	4.81×10^{-20}

III. RESULTS OF MEASUREMENTS AND SIMULATIONS

Table I shows value of cross sections measured in H_2, N_2, He, Ne, Kr, Xe, and Ar gases. The beam current and the background pressure are measured concurrently with a Faraday cup located after the magnets and an ion gauge located inside the gap A, respectively.

The background pressure is obtained by adjusting the Stabil-Ion gauge measurement with the calibration factor for the different gas species provided by the manufacturer. The data are not adjusted to remove a small error caused by the background gas contribution, which is minimized by the fact that the leaked gas is flowing in the direction of the magnetic section exits, where most of the vacuum pumps are located. The last line of Table I estimates the water vapor contribution into the cross section. The errors for the experimental data are in the order of 10%-15%, which includes the beam reproducibility of ~5%. Conservatively assuming that the Stabil-Ion gauge used in the measurements is uncalibrated with expected accuracy of ~6% and the errors add in quadrature, thus, the total error is approximately 16%.

Results of simulations using the CTMC method for the ionization and charge exchange cross sections for the interaction of 1-MeV K^+ with H_2, He, and Ne are summarized in

TABLE II. Ionization and charge-exchange cross sections for the interaction of 1-MeV K^+ with H_2, He, and Ne. Atomic and ion potentials are taken from Ref. [26].

Gas	Charge-exchange cross section (m^2)	Ionization cross section (m^2)
H_2	5.92×10^{-20}	3.00×10^{-20}
He	4.10×10^{-20}	1.10×10^{-20}
Ne	9.46×10^{-20}	3.91×10^{-20}

Table II. For a 1-MeV K^+ beam, the values of charge-exchange cross sections are 2–4 times higher than the ionization cross sections.

Previous work [29] shows that the capture cross section of 600 KeV K^+ ion impacting H_2 is 7×10^{-20} m^2, which gives the lower limit of the H_2 cross section and is in agreement with the experimental and calculated values.

Figure 2 is a plot of the measured values of the total cross sections versus the ionization energy. Apparently if the ionization energy is higher, it is harder to remove electrons so the probability of the electron removal is smaller. A dash-dotted line was placed to display this trend.

Figure 3 shows a CTMC theoretical prediction for charge-changing cross sections of H and He as a function of projectile energy.

In the low-energy region, i.e., when the projectile velocity is much slower than the least tightly bound electron in the target molecule, the charge-exchange process dominates over the ionization. When projectile velocity becomes much faster than the velocity of the least tightly bound electron in the target atom, charge exchange quickly decreases [12]. The ionization cross section decreases with the projectile energy, approaching for large energies the $\frac{1}{E}\ln(E)$ dependence of Bethe's formula [20]. Therefore, in the high-energy region, i.e., when the projectile velocity is much faster than the least tightly bound electron in the target molecule, the ionization dominates over the charge-exchange mechanism, having a larger cross section.

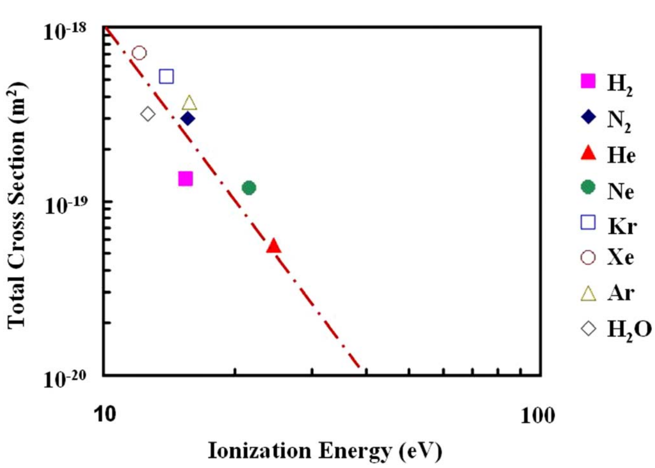

FIG. 2. (Color online) Cross sections versus target ionization energy. A dash-dotted line is displayed to show that the total cross section varies inversely with the ionization energy.

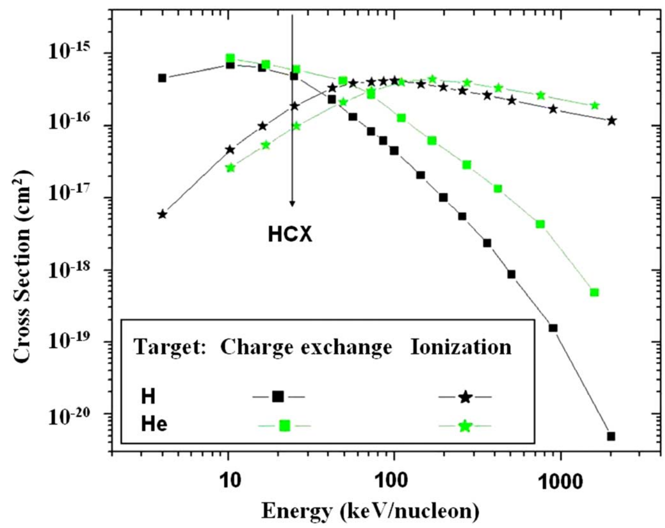

FIG. 3. (Color online) Charge-exchange and ionization cross sections of atomic H and He target ions interacting with K^+ ions, predicted using CTMC calculations. The HCX parameters (1-MeV K^+ ion) correspond to 25 keV/nucleon.

IV. CONCLUSIONS

Total charge-changing (ionization plus charge exchange) cross sections are measured in the High-Current Experiment. In this experiment the beam current of 180 mA produces a space-charge beam potential of approximately 2 kV. Such a large radial electric field expels the ions produced by the beam in collisions with background gas. The gas target was introduced by leaking gas into a transport channel of the ion beam. The background gas pressure is raised from 10^{-7} Torr to 10^{-6} Torr using a regulated gas nozzle. A planar retarding field analyzer placed in the transport section measures the expelled ion current concurrently with measurements of background pressure of an ion gauge, allowing for the calculation of the total charge-changing cross sections.

The classical trajectory Monte Carlo method is used to determine the ionization and charge-exchange cross sections of a 1-MeV K^+ ion interaction with atomic Ne, He, and H. The simulation results show an agreement of less that 35% of the experimental data (Table III). The comparison with other multielectron targets (Ar, Kr, Xe) is underway as it requires simulation of multielectron systems. Such simulations are complex because in classical simulations inner atomic electron-electron collisions cause ionization events

TABLE III. Comparison of calculated values of the total cross sections with experimental data for interaction of 1-MeV K^+ with H_2, He, and Ne. The total error in experimental data is about 16%.

Cross Section	Experiment (m^2)	Slater model (m^2)
H_2	1.35×10^{-19}	0.89×10^{-19}
He	5.62×10^{-20}	5.20×10^{-20}
Ne	1.19×10^{-19}	1.34×10^{-19}

even without the projectile, which are forbidden by quantum mechanics. The method to avoid such artificial ionization events is being developed [28].

ACKNOWLEDGMENTS

The authors wish to thank Claude Lyneis and Daniela Leitner who provided several gas cylinders used in the experiments, Tak Katayanagi who built the RFA, Wayne G. Greenway who maintained HCX, Craig Rogers and William L. Waldron who provided electronic support, and Grant Logan and Larry Grisham for fruitful discussions. This work was supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics and Office of Fusion Energy Sciences, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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