Scaling rule for target ionization by highly charged ions at low-to-intermediate velocities

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(Received 26 October 1995)

Cross sections for ionization of He by highly charged Cl^{q+}, Cu^{q+}, and I^{q+} ($q=6-10$) impact at velocities from 1.6 to 3.1 a.u. were measured. These results are compared with other experimental and theoretical results available over a wide velocity range. A universal scaling rule for target ionization by nearly bare, highly charged ions at low to intermediate velocities (0.2–3.5 a.u.) is reported.

PACS number(s): 34.50.Pa

Scaling relations for impact ionization cross sections are important both for understanding fundamental mechanisms and for various practical applications. Several such attempts have been made. Based on a classical model due to Bohr, Knudsen [1] has pointed out that at high collision velocities ($v>1$ a.u.) the ionization cross section σ divided by projectile charge q depends only on the scaled velocity $v/\sqrt{q}$. In a different approach, Gillespie [2] developed a scaling rule within the Bethe-Bohr approximation, $\sigma/(q^2\sigma_B) = e^{-\lambda(v/\sqrt{q})^{-2}}$, where σ_B is the Bethe cross section for the ionization of H by fast protons, and λ is a free parameter obtained by fitting the formula to experimental data. Although Gillespie's scaling formula gives a better description of the experimental data at lower velocities [3] than Knudsen's, they both fail in the low-velocity region due to their perturbative nature.

For $v<1$ a.u., theoretical analyses based on the hidden-crossing theory have predicted several scaling relations for direct ionization of H which depend on the specific ionization mechanism [4,5]. Wu *et al.* [6] recently measured cross sections for ionization of He by slow ($v=0.2-1.7$ a.u.), highly charged, bare ions. In an analysis following the Bohr-Lindhard picture, they found that, if the measured cross sections as a function of collision velocity are plotted as $\tilde{\sigma}=\sigma/q$ against $\tilde{v}=v/q^{1/4}$, the data fit a universal curve at these low velocities. Due to the limitation of available facilities, there is a gap in the intermediate velocity region ($2<v<5$ a.u.), where no data are available for impact ionization by heavy bare ions. On the other hand, these data are very much needed to bridge the gap between different scaling rules for ionization at low and high velocities. In this work, we first established that partially stripped Cl ions ($q=6-10$) could be used to replace the bare ions in this difficult to access velocity region. Then, we tested the scaling relation by Wu *et al.* [6] with these highly stripped ions. Further tests of the scaling relation for different targets were also investigated.

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The measurements were performed at the EN tandem facility at the Oak Ridge National Laboratory. The experimental setup is very similar to one previously reported [7]. Projectiles of a given energy and charge were obtained from the accelerator, and directed through a gas cell of length 5 cm with low-density He gas of pressure 0.1 mTorr. After collision, the projectile ions were charge state analyzed by electrostatic deflection and detected by a position-sensitive channel-plate detector. Recoil ions were extracted by an electric field of 1 kV/cm and detected by a channel-plate detector. The recoil charge state was determined by measuring the time-of-flight difference between the detection of the recoil and projectile [7]. Typical charge-state impurities due to collisions with background gas were less than 3%. They increased to as high as 6% after putting in the He target gas. For nonbare projectiles, corrections must be made for apparent ionization due to double collisions in which electron capture by the projectile is followed by projectile electron loss, or vice versa. At least one of these two collisions happens in the He gas cell. (At these velocities, the double collision correction for ionization by bare ions is negligible [6,8].) The corrections here were performed following the method described by Shinpaugh *et al.* [9]. The correction ranged from 2–3 % for Cl^{q+} to about 10% for I^{q+}, where core electrons are more vulnerable to the ionization. To avoid systematic errors arising from the use of different experimental apparatus in later comparisons, the measured cross sections were put on an absolute scale by normalizing the single capture cross section for Cl^{7+} at $v=1.69$ a.u. to the same cross section measured for N^{7+} [6]; i.e., we made an assumption that Cl^{7+} has the same single capture cross section as N^{7+} does at $v=1.69$ a.u. This is partially supported by the fact that single-electron capture by N^{7+} at low velocities mainly populates $n=3$ and 4 states [10]. Further justification can be seen by comparing single capture by bare O^{8+} [10] with that by Ar^{8+} [11,12] which, like Cl^{7+}, has a neonlike structure.

To answer the question whether one can replace bare ions by partially stripped ions for ionization cross-section measurements, ionization cross sections for $q=6$ and 7 isotachic ions are plotted in Fig. 1 along with the bare projectile data from Ref. [6]. It is evident that the cross sections for Cl^{6+} and C^{6+}, and Cl^{7+} and N^{7+} are almost identical. By contrast, the ionization cross sections for copper and iodine ions

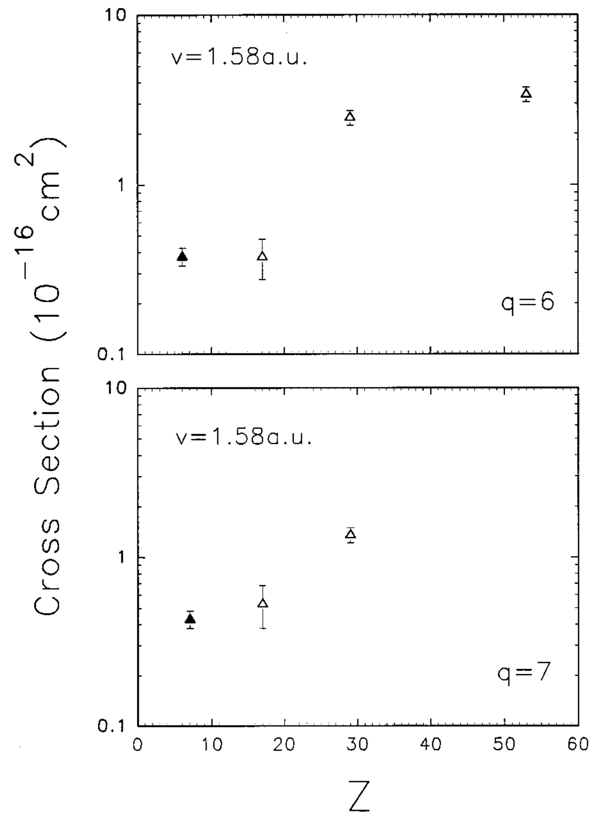

FIG. 1. He single-ionization cross sections by $q=6$ and 7 isotachic ions at the velocity of 1.58 a.u. as a function of projectile nuclear charge Z. The data for bare projectiles (filled symbols) are from Ref. [6].

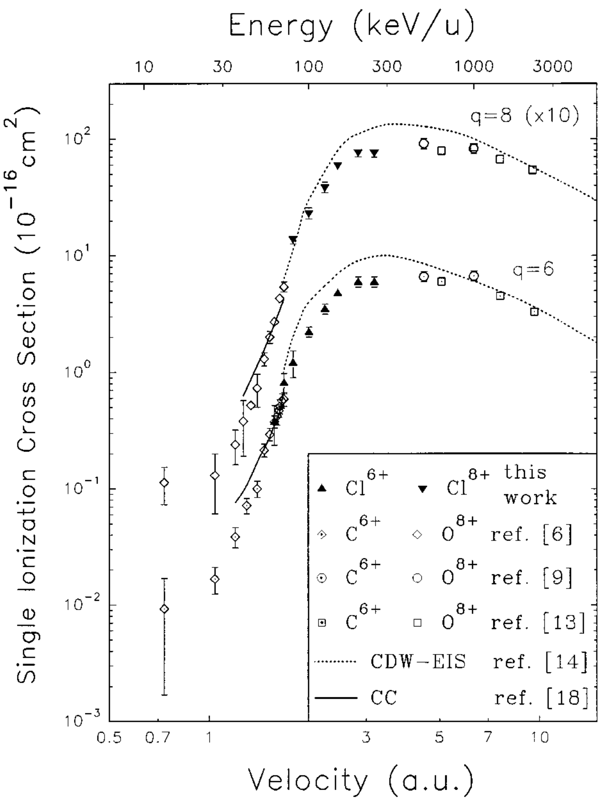

FIG. 2. Cross sections for single ionization of He by C^{6+} (Cl^{6+}) and O^{8+} (Cl^{8+}). Both experimental and theoretical cross sections for O^{8+} (Cl^{8+}) have been multiplied by 10. The theoretical cross sections are continuum distorted wave-eikonal initial-state (CDW-EIS) calculation [14] and close-coupling (CC) calculations [18].

are much larger. This is mainly due to contributions from transfer excitation (electron transfer plus projectile excitation) followed by reemission of one electron via autoionization. Such contributions for iodine ions have been proved [7] by measuring zero-degree electron spectra is coincidence with projectiles which did not display a change in charge. These contributions increase with the number of projectile core electrons, leading to an increase in apparent "direct ionization" cross sections. For Cl ions in this experiment ($q=6$–10), this mechanism requires excitation of the K- or L-shell electrons to M or higher shells, which is unlikely at these collisions velocities. On the other hand, previous measurements with bare ion projectiles [6] have shown that ionization at these velocities occurs at impact parameters (~ 3 a.u. for O^{8+}) which are much larger than the mean radius of the core electrons of these Cl ions. Thus, for example, the Cl^{7+} ion we used here is essentially equivalent to a bare N^{7+} ion in ionizing He (Fig. 1).

The target single ionization cross sections for Cl^{6+} and Cl^{8+} are plotted in Fig. 2 together with the C^{6+} and O^{8+} data of Refs. [9] and [13]. Our Cl data at intermediate velocities link the low-velocity [6] and high-velocity data [9,13]. They show that ionization cross sections reach their maxima at velocities around 3 a.u. (or 300 keV/u). At intermediate to high velocities, the experimental cross sections are compared with the CDW-EIS (continuum distorted wave eikonal initial state) calculations by Fainstein, Ponce, and Rivarola [14]. The calculations predict very well the velocity dependence of the ionization cross section, including the region where the cross section is at its maximum. At high velocities, the calculations are in very good agreement with experiments, while at velocities below 7 a.u. (1 MeV/u) the model overestimates the experimental results. The overestimation by CDW-EIS calculations at intermediate velocities is largely due to the approximation for He target wave functions used. The same theory for an atomic H target gives excellent agreement with experiments at both intermediate and high velocities [15]. Wang [16] demonstrated that, by using different types of approximate He states, the CDW-EIS cross sections can differ by as much as 20%. A better result is expected by using better, orthogonal initial and final He states, such as Hartree-Fock wave functions [17]. The CDW-EIS model is not valid for ionization at low velocities due to the importance of transitions via intermediate bound states of the target and projectile. At these velocities, recent close coupling calculations by Wang *et al.* [18] are very successful in reproducing the experimental data (Fig. 2). The hidden-crossing theory, which has been very successful in calculating the ionization of H atoms [4,5,19], is not yet available for two-electron targets.

The scaling proposed by Wu *et al.* [6] is based on a classical picture due to Bohr and Lindhard [20,21], who described charge transfer and ionization in terms of a velocity-independent "release radius" and a velocity-dependent "capture radius." The ionization is important only when the

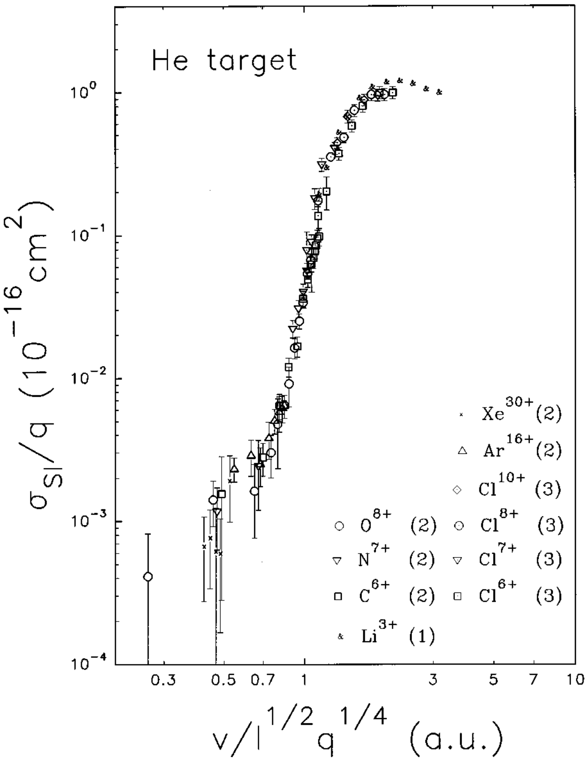

FIG. 3. He single-ionization cross sections plotted as reduced cross sections (σ_{SI}/q) against reduced velocities ($v/I^{1/2}q^{1/4}$). The data are from Refs. [22] (1), [6] (2), and this work (3).

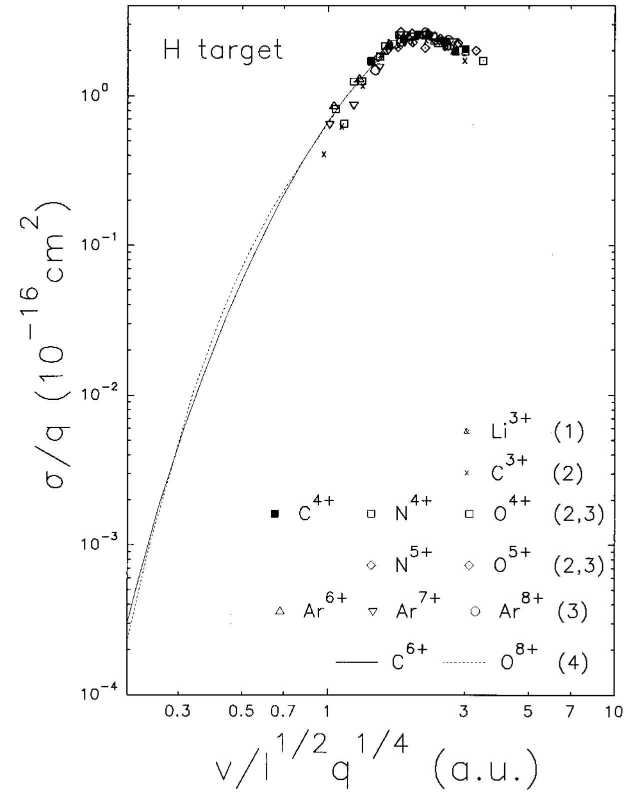

FIG. 4. The same plot as Fig. 3, but for a H target. The experimental measurements are from Refs. [23] (1), [24] (2), and [25] (3). The lines are the theoretical cross sections from Ref. [5].

release radius is larger than the capture radius. This occurs only for projectile velocities $v > v_{\rm min} \equiv I^{1/2}q^{1/4}$, where I is the ionization potential of the target (atomic units are used). Therefore, when comparing ionization at low velocities by differently charged ions, one has to bear in mind this "threshold" for ionization. A better description can be expected if $v_{\rm min}$ is used as the unit of velocity. Single-ionization cross sections of He are plotted in Fig. 3 as $\tilde{\sigma} = \sigma/q$ versus $\tilde{v} = v/v_{\rm min} \equiv v/I^{1/2}q^{1/4}$. The intermediate velocity data from this work and Ref. [22] (Li^{3+}) are shown to fit a universal curve along with those low velocity data form Ref. [6]. A scaling formula of $\tilde{\sigma} = A\tilde{v}e^{-C/\tilde{v}}$ was proposed in Ref. [6], which worked very well at $0.6 < \tilde{v} < 1.5$ a.u. (the coefficient A and C were found by fitting the formula to the experimental data). But from Fig. 3, the universality of the scaling relation is apparently valid over a wider velocity region, i.e., at all velocities below the region where the ionization cross section reaches its maximum. For velocities above the ionization cross section maximum, the ionization cross section follows a $\sigma/q = f(v/\sqrt{q})$ scaling relation [1,2].

Figure 4 shows a plot of ionization cross sections of H versus projectile velocity. There is a lack of experimental data below 1-a.u. velocity, where the theoretical cross sections from Ref. [5] are plotted. The experimental data available [23–25] at intermediate velocities fit a universal curve very well. Based on their hidden-crossing model, Janev, Ivanovski, and Solov'ev [5] proposed a more sophisticated reduced velocity form for a H target, $\tilde{v} = v(1+\delta)/(1+\delta q^{1/4})$. Here δ is a free parameter, and is found to be 0.275 by fitting their scaling formula ($\tilde{\sigma} = A\tilde{v}e^{-C/\tilde{v}}$) to their theoretical calculations for He^{2+},

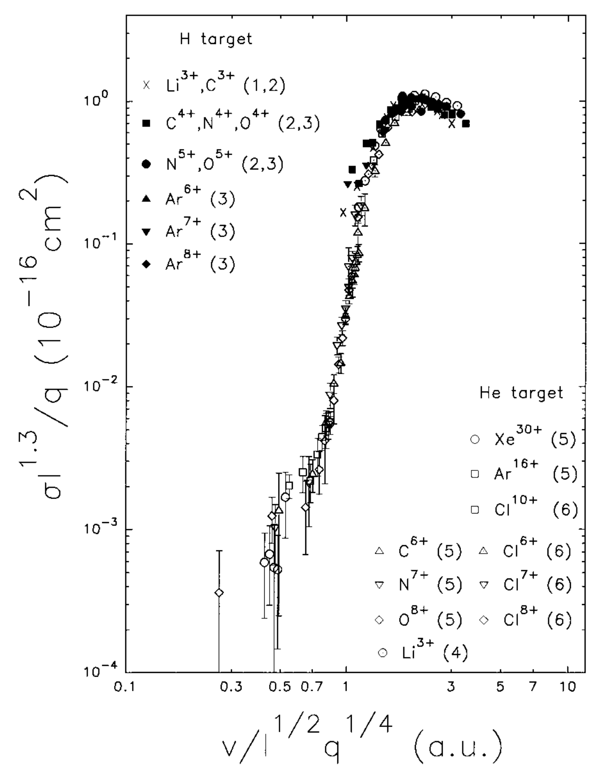

FIG. 5. Reduced plot of single-ionization cross sections for highly charged ions on H and He targets. The experimental data are taken from Refs. [23] (1), [24] (2), [25] (3), [22] (4), [26] (5), and from this work (6).

C^{+6}, and O^{8+}. From Fig. 4, where their theoretical cross sections are plotted according to our simple scaling form, it seems that the simple scaling form $\tilde{v}=v/I^{1/2}q^{1/4}$ works for these theoretical cross sections nearly as well. Figure 4 suggests that the real value for δ in the theory of Janev, Ivanovski, and Solov'ev may be larger than 0.275 (note that $I^{1/2}$ in our simple form is a numerical constant for a fixed target, e.g., 0.71 for a H target here).

It is of interest to try a more general form which can accommodate different targets. We chose a generalized reduced cross section and velocity as

$$\tilde{\sigma}=\sigma I^{\xi}/q, \quad \tilde{v}=v/I^{1/2}q^{1/4}, \tag{1}$$

where ξ is an adjustable scaling parameter. The value of ξ was determined by a best fit to the experimental data for H and He targets shown in Figs. 3 and 4, and was found to be $\sim$1.3. However, any value between 1.2 and 1.4 can fit the data nearly as well. It is therefore unrealistic to attach any physical significance to the exact value of ξ. More measurements at low velocities for H and other targets would be very helpful in understanding the obtained value of ξ.

In summary, ionization cross sections of He by highly charged Cl^{q+} $(q=6-10)$ ion impact at intermediate velocities were measured. These results were compared with other experimental and theoretical results over a wide velocity range. The CDW-EIS calculations are very successful at intermediate to high velocities. Only close-coupling calculations are available for He at low velocities, and they are in good agreement with the experimental results [6]. The scaling rule previously found by Wu *et al.* [6] for He target atoms at low velocities has been further tested and found to be valid at intermediate velocities ($v \leqslant 3.5$ a.u.), as well as for a different target (H). A more general scaling relation which includes the target dependence is proposed.

We are grateful to Y. D. Wang for many discussions. This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences under Contract No. DE-AC05-84OR21400 with Lockheed Martin Energy Systems, Inc. W. W. was supported in part by an appointment to the Oak Ridge National Laboratory Postdoctoral Research Associates Program administered jointly by the Oak Ridge Institute for Science and Education and Oak Ridge National Laboratory.

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