Observation of Direct Ionization of He by Highly Charged Ions at Low Velocity

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We have observed direct target ionization of He at low velocity (0.2 to 1.7 a.u.) by highly charged ions of C^{6+}, N^{7+}, O^{8+}, Ar^{16+}, and Xe^{30+}. The measured single ionization cross sections increase rapidly with increasing velocity. The cross sections, divided by the charge of the incident projectile, are found to lie on a universal curve when plotted versus the ratio of the projectile velocity to the classical Bohr-Lindhard velocity limit for ionization. Impact parameter information was determined for O^{8+} on He collisions and suggests that single target ionization happens over an impact parameter range very similar to that for single capture.

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When a charged ion impinges upon a neutral target, a target electron may be transferred into a projectile ion orbit (capture) or lost directly into the target continuum (ionization). Electron capture and ionization compete in the collisions. In fast collisions, ionization is the dominant process, whereas capture is expected to dominate strongly over ionization in slow collisions. The general situation was well understood by Bohr and Lindhard [1,2] more than 40 years ago. In their classical picture, when the projectile approaches the target, an active electron of the target can be released at internuclear distances smaller than a certain critical value (release radius) where the force exerted by the projectile balances the binding force exerted by the target. If the total energy of the released electron is negative with respect to the projectile, it will be captured to the projectile. Otherwise, the process leads to a direct ionization. This picture leads to the condition that ionization should occur for a projectile velocity $v > v_{\min} \equiv q^{1/4} I^{1/2}$, where q is the projectile charge and I is the ionization energy of the target electron. The crossover between the dominance of the two processes occurs where the projectile velocity v is larger than $v_{\min}$. In spite of this history, direct target ionization by bare highly charged projectiles for velocities near and below $v_{\min}$ has not been previously measured experimentally, partially because $v_{\min}$ occurs in an intermediate velocity range inaccessible at the high velocity end of most EBIS and ECR sources and at the low velocity end of most Van de Graaff and LINAC accelerators.

Direct ionization by highly charged ions in slow collisions has drawn considerable attention recently, partly driven by a continuing controversy concerning the mechanism involved. A molecular-orbital approach based on the analytical continuation of adiabatic potential curves in the complex plane of internuclear distance has been recently developed [3–5]. This approach has identified two major different mechanisms whereby the direct ionization can occur. Electrons can either be promoted "directly" into the continuum through a sequence of molecular promotions occurring at small internuclear distances (S process) or they can be trapped on the "saddle point" between the two receding Coulomb centers, having followed a series of crossings at progressively large internuclear distances (T process). Both of these processes can be treated for the simplest one-electron collision systems [6,7] using the "hidden crossing" method of Solov'ev and Ovchinnikov [8,9]. Indeed, saddle point electrons have been at the heart of intense theoretical and experimental debate for some years now, with no real consensus as to whether they have been observed [10–13].

The purpose of this Letter is to report the first experimental observations of direct target ionization by highly charged bare and nearly bare projectiles in this low velocity region, and to establish experimentally the characteristics of the cross sections for this process. We find that the cross sections follow an approximate scaling law similar, but not identical, to ones suggested in Refs. [4] and [7] for the T process.

The experiment was carried out in the J. R. Macdonald Laboratory at Kansas State University (KSU). The experimental apparatus has been described in detail elsewhere [14,15]. Highly charged projectiles were extracted from the KSU CRYEBIS sitting on a platform that can reach to 160 kV. The charge-state-impurity-cleaned projectile beam crossed a He target jet, which was collimated by a glass capillary array. After the collision, the projectiles were charge state analyzed by a parallel-plate electrostatic deflector and then detected by a position sensitive detector. He ions produced in the collision region were extracted at right angles to the beam by an electric field and sent to another position-sensitive detector. The strength of the extraction field was set high enough (60 V/cm for Ar^{16+}) to ensure that all recoil ions were extracted by the field. The recoil charge states were determined by the time-of-flight technique using coincidences between the recoil ions and the projectile ions. Corrections for events due to random coincidences are important for the ionization channel because of the high counting rate of the main beam, and were made by assuming that random coincidences are uniformly distributed along the time axis. The

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double collision correction for ionization is negligible because of its very small cross section and the low density gas jet target we used [14].

The cross-section ratios of single target ionization (SI) over single capture (SC) are plotted as a function of collision velocity in Fig. 1. For the three lightest projectiles (C^{6+}, N^{7+}, and O^{8+}), the ratios increase very rapidly around $v_{\min}$. Since SC cross sections for these systems are quite flat over this velocity region [14,15], the rapid increase of the SI/SC ratio is caused by the strong onset of the target direct ionization. For Ar^{16+} and Xe^{30+} on He, whose $v_{\min}$ we cannot reach in our experiment, SI remains very small, more than 2 orders of magnitude below single capture. The Ar^{16+} results are 1 order of magnitude smaller than what we reported earlier [14]. The earlier erroneous results came from a subtle problem with random time-position coincidences inherent in the attempt to measure a very weak channel in the presence of a much stronger one (capture) [16]. Cederquist *et al.* [17] reported earlier rather large cross sections for direct ionization of Xe by Xe^{q+} ($15 < q < 39$) for $v \ll v_{\min}$, and their work partially stimulated the present experiment. However, our results for the same system give cross sections more than an order of magnitude lower than those, and attempts to explain the discrepancy between the two experiments continue. We include in Fig. 1 an I^{16+} datum at $v = 2$ a.u., which is the ratio of the experimental single ionization cross section by Datz *et al.* [18] to the theoretical (over barrier model [19]) single capture cross section by a $q = 16$ ion impact.

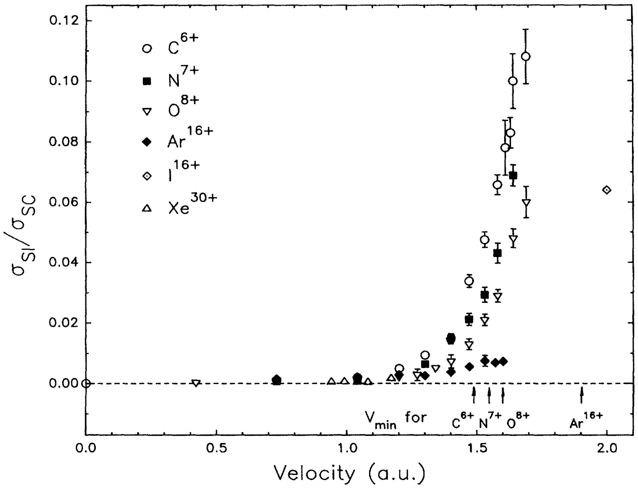

FIG. 1. The ratio of the single ionization cross section (σ_{SI}) to the single capture cross section (σ_{SC}) for He. The I^{16+} datum is the ratio of the experimental SI cross section at 2.0 a.u. [18] divided by the theoretical (overbarrier model [19]) SC cross section for an ion with $q = 16$. The classical Bohr-Lindhard limit for ionization, $v_{\min}$, for $q = 6$, 7, 8, and 16 projectiles is indicated.

We have put our measured SI cross sections on an absolute scale by normalizing our total single projectile charge change cross section for O^{8+} at $v = 0.42$ a.u. to the same cross section measured by Bliman *et al.* [20]. In the case of O^{8+} on He, for which extensive data for capture and ionization are available over a wide range of velocities [20–27], our data are compared to those data in Fig. 2. The overall picture shows that the crossover between the dominance of capture and ionization should occur between $v = 2$ and 3 a.u.

The SI/SC ratios for C^{6+}, N^{7+}, and O^{8+} are about the same (~0.038) at $v_{\min}$ (Fig. 1), suggesting that single ionization in the crossover region may be scalable. Since single capture at low velocity is velocity insensitive and scales with q for highly charged ions according to the over barrier model [19], the single ionization can be scaled as a reduced cross section σ_{SI}/q. For the velocity, $v_{\min} = q^{1/4}I^{1/2}$ suggests that the velocity might be scaled as a reduced variable proportional to $v/v_{\min}$, $\tilde{v} = vq^{-1/4}$. The resulting scaled SI cross sections are plotted in Fig. 3 versus this reduced velocity. We include also other experimental data for higher velocities [18,21,22,28]. The data show a universal curve around $\tilde{v} \sim 1$ a.u., equivalent to the velocity region around $v_{\min}$. We have fitted part of these data (Li^{3+}, C^{6+}, N^{7+}, O^{8+}, and Ar^{16+}) for $0.6 < \tilde{v} < 1.5$ by a curve of the form

$$\sigma_{SI}/q \simeq A(vq^{-1/4})\, e^{-C/vq^{-1/4}}, \qquad (1)$$

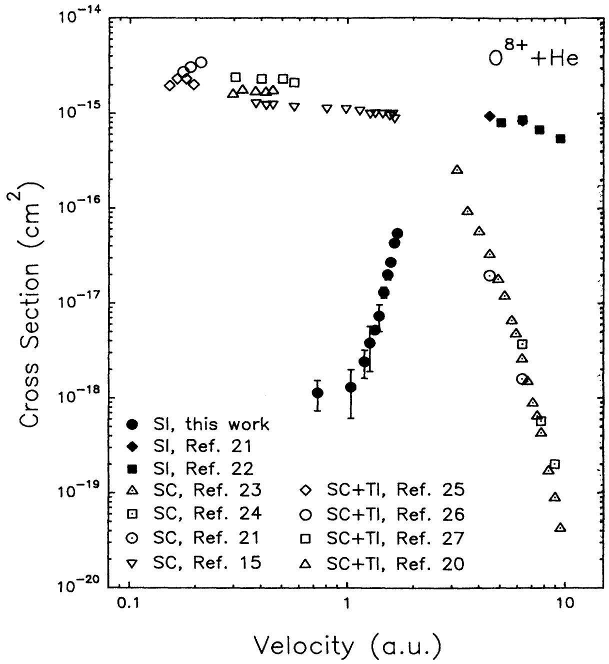

FIG. 2. Single ionization (SI) and single capture (SC, total single projectile charge change, i.e., SC + TI, at low velocities) cross sections for O^{8+} on He. The data indicate that the crossover between dominance of capture and ionization should occur between $v = 2$ and 3 a.u.

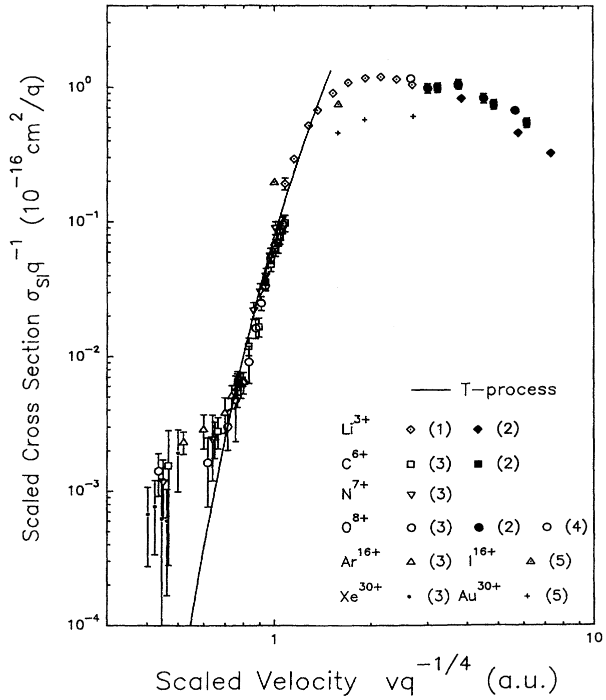

FIG. 3. He single ionization cross section plotted as the reduced cross section (σ_{SI}/q) versus the reduced velocity $(vq^{-1/4})$. The experimental data are (1) Ref. [28], (2) Ref. [22], (3) this work, (4) Ref. [21], and (5) Ref. [18].

where A and C from the fit are (v and q in atomic units) 110×10^{-16} cm^2 and 7.24, respectively. The resulting fit is plotted in Fig. 3, and agrees with the data quite well for scaled velocities below the velocity maximum. Bárány and Ovchinnikov [4] give a similar, but not identical, scaling expression for the T process in the limit of very high Z ions on atomic hydrogen. Janev, Ivanovski, and Solov'ev [7] give a similar expression from an empirical fit to calculated cross sections for the T process for light ions on H, but with a slightly more complicated Z scaling of the reduced velocity. To our knowledge, no prediction for highly charged ions on He is available. We do not claim that our fit is unique. Note that the superpromotion model would be expected to be valid only in the region below the velocity corresponding to the cross-section maximum. The excess of cross section above the fit at velocities below $\tilde{v} = 0.6$ may be partially due to the importance of the S process and the recently discovered radial decoupling process (D process) [29], which are expected to dominate over the T process at lower velocities [4,7,13]. However, we point out that the error bars on the data are quite large here and that history teaches us to be suspicious of measurements that are barely above background (Fig. 3). It is almost impossible to distinguish among these superpromotion processes from the total cross-section measurements alone. A better separation between S and T processes could be made by measuring the ionized electrons, because the S process predicts electrons with a velocity about that of the projectile, while the T process predicts that electrons move with the saddle point velocity $v_s = v/(1 + \sqrt{q})$, smaller than the projectile velocity v [4,13]. The failure of the scaling of Fig. 3 at high velocities is expected because the Born approximation predicts that the scaled cross section is a universal function of $\tilde{v} = vq^{-1/2}$ [30].

The flight-time information between the detection of the projectile and the recoil, and the position at which the recoil hit the recoil detector, were used to determine the recoil transverse momentum $P_\perp$ [15] in O^{8+} + He collisions for (unscaled) velocities of 1.34, 1.47, and 1.53 a.u. The $P_\perp$ distribution for SI is compared to that for SC in Fig. 4 for O^{8+} at $v = 1.34$ a.u. The behaviors at other velocities are approximately the same. The distributions are very similar for SI and SC, suggesting that SI at these velocities happens over the same impact parameter region as does SC. That SC and SI have similar impact parameter dependence at velocities around $v_{\min}$ qualitatively agrees with the close coupling calculations by Wang [31] for C^{6+} on He and by Toshima [32] for O^{8+} on H.

In conclusion, this experiment reports the first experimental cross sections for direct ionization of a light target by bare and nearly bare highly charged ions in the very low velocity region. The velocity for which ionization becomes a particular fraction of single capture increases rapidly with the projectile charge and scales proportional to the classical Bohr-Lindhard limit for ionization. The scaling relation we found from the experiment has a form similar to that expected theoretically for an atomic hydrogen target for the T superpromotion process ("saddle point ionization"). Using recoil momentum spectroscopy, we determined the transverse momentum transfer dependence for each reaction channel in O^{8+} colliding with He. The

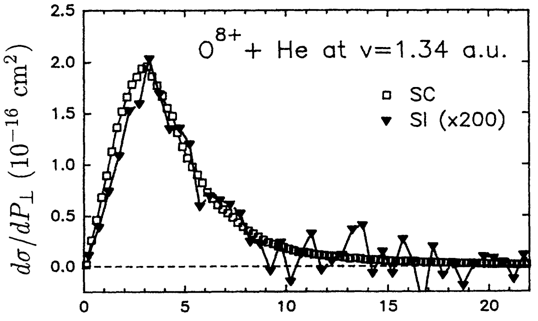

FIG. 4. Recoil transverse momentum distribution for single ionization (SI, triangles) and single capture (SC, squares) for O^{8+} on He. The negative counts seen for SI are caused by background subtractions, and the oscillations are due to the statistics.

distributions for single target ionization are very similar to those for single capture, suggesting that direct ionization occurs in an impact parameter range about the same as that for single capture.

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