High-Velocity Limit for the Ratio of Helium Double-to-Single Ionization for Highly Charged, Bare-Ion Impact

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The ratio R of helium double-to-single ionization cross sections was measured for Ne^{10+} and Ni^{28+} projectiles at velocities of $0.39 \lesssim v_P/c \lesssim 0.93$ intending to explore the high-velocity limit of R for highly charged ion impact. For Ne^{10+} projectiles R was observed to become independent of v_P for $v_P/c \gtrsim 0.73$ and an asymptotic experimental value $R=(2.57\pm0.10)\times10^{-3}$ has been established. This is in good agreement with experimental results for proton, antiproton, electron, and positron impact and in excellent accordance with the theoretical prediction of $(2.59\pm0.03)\times10^{-3}$.

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The most simple and therefore fundamental dynamical many-electron problem in atomic collision physics is the simultaneous transfer of two helium electrons into excited or continuum states by energetic charged particle or photon impact. The central potential of the helium nucleus is comparably weak and the correlated motion of the two electrons before, during, and after the collision plays an essential role in such a situation. Thus, static and dynamic correlation between the electrons both have considerable influence on the magnitude of even total cross sections for helium double ionization (σ^{2+}). This becomes evident by the fact that any independent particle model, neglecting this correlation, underestimates σ^{2+} at small perturbations by the projectile dramatically. While in such an approximation the ratio R of double-to-single ionization for charged particle impact is decreasing with about the square of the projectile velocity (v_P), one finds experimentally [1,2] a constant value at large v_P, which is independent of the velocity.

In this so-called high-velocity limit, the perturbation by the projectile is so small that the probability for its simultaneous and independent interaction with both target electrons (so-called "two-step" mechanism), which is the reason for double ionization in an independent electron model, can be completely neglected. Double ionization is induced by only one single interaction of the projectile with one target electron (single ionization). It solely occurs due to the electron-electron interaction and the ratio $R=\sigma^{2+}/\sigma^{1+}$ therefore is extremely sensitive to the details of the time-dependent electronic motion. This is underlined by the fact that R is about a factor of 5 larger for energetic photon [3] than for charged particle impact. As a further consequence, the high-velocity limit of R is predicted to be independent of the sign of the projectile charge q and velocity v_P. Systematic experiments with singly charged projectiles for electron [4,5], proton [6], antiproton [7,8], and positron [9] impact indeed yielded identical ratios within the experimental errors between 0.24% and 0.28%. This value is in good agreement with theoretical results of *ab initio* calculations by Ford and Reading [10] for charged particle impact of $R=0.259\%$.

For highly charged ion impact it is expected that R should settle at the same asymptotic value. Since in first order the perturbation is proportional to $q^2/(v_P^2 \ln v_P)$, the only difference should be that higher velocities are needed to reach the limit. In a first experiment for N^{7+} impact [11] a weak v_P dependence of R was observed at energies between 10 and 30 MeV/u. Thus, it was speculated that the high-velocity limit for highly charged ions might have been reached already and be considerably above the asymptotic value for low-q projectiles. In subsequent publications of different authors, it was estimated that the high-v_P limit of R for N^{7+} projectiles should be reached only for velocities close to the velocity of light. It was argued that the observed large experimental value for the ratio can be attributed to the contribution of the "two-step" mechanism to the double ionization cross section [12,13] or to an interference term between "shake-off" and "two-step" processes [14]. These arguments were supported by a more recent experimental data point for N^{7+} projectiles at 40 MeV/u, reported by the same authors [15], which lies significantly below the former results and thus suggests a decreasing tendency of R towards higher energies. However, as has been stated by McGuire [2], the "high-v_P limit (was) not well established for large Z_P" and it was neither evident whether a high-velocity limit does exist for highly charged projectile impact nor what its value would be.

Using bare Ne and Ni projectiles, delivered by the new heavy-ion synchrotron (SIS) of GSI (Darmstadt), we measured the ratio of helium double-to-single ionization systematically for projectile energies between 80 MeV/u and 1.5 GeV/u. This corresponds to projectile velocities between 39% and 93% of the speed of light, so that we

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are able to provide a definite experimental answer to the question for the high-velocity limit of R for highly charged ion impact.

The experiments were performed at the new atomic physics experimental area about 150 m downstream of the SIS (for details see [16]). Typical beam currents in the experiment ranged between 10^4 and 2×10^6 particles per spill (spill length $3s$–$5s$). The gas target, operated at typical pressures between 0.5 and 5×10^{-4} Torr, was separated from the beamline vacuum (10^{-7} Torr) by thin 6 μm Mylar foils mounted before and after the interaction region. The target pressure was measured with a viscosity manometer with an accuracy of about 1%.

Helium ions, created in the target area by the projectiles, were extracted perpendicular to the ion beam by a homogeneous electric field of 140 V/cm up to 280 V/cm over a total length of 9 cm. After a drift path of about 18 cm the helium ions are postaccelerated (-2500 V) and detected by a two-dimensional position sensitive channel plate detector in "chevron" configuration (40 mm active diameter, position resolution better than 0.2 mm) Identical detection and extraction efficiencies for both recoil-ion charge states were guaranteed by measuring the He^{2+}-to-He^{1+} intensity and the He^{1+} and He^{2+} position as a function of the extraction voltage.

Separation of the recoil-ion charge states was achieved using a conventional time-of-flight technique (TOF), the TOF being provided by a recoil-ion–projectile coincidence. A thin plastic scintillator (2 mm thick) downstream of the interaction region recorded the projectiles with an efficiency very close to 100%. With a time resolution of about 10 ns, He^{1+} and He^{2+} ions are well separated in the time spectrum (see Fig. 1) and are clearly distinguished from background events.

The whole apparatus, time resolution, the recoil-ion transport, and detection efficiency, as well as the electronic setup, was tested off-line, before the experiment using a pulsed electron beam. The ratio of helium double-to-single ionization by electron impact obtained in our tests was compared to results of other experiments [4] and good agreement was obtained.

Special care was taken for the evaluation of the time spectra. As a result of the high stop rate (up to 10^6 ions/s) on the time-to-amplitude converter (TAC), there is a certain probability that a "true start" (a true He^{1+} or He^{2+} recoil ion) is stopped by the "wrong" projectile before the signal of the coincident projectile arrives. In the time spectrum (Fig. 1) those "lost coincidences" show up as an increased "background" before each time peak (due to the low He^{2+} intensity compared to real background events this behavior is only visible for the He^{1+} time peak). Fitting an exponential function to the background the stop rate can be determined and the lost coincidences can precisely be calculated for both charge states (see solid line in Fig. 1 for He^{1+}).

In Fig. 2 our ratios of double-to-single ionization for energetic Ne^{10+}, Ni^{28+}, and previous data for Kr^{36+} projectiles are shown together with results for proton (p^+), antiproton (p^-), electron (e^-), positron (e^+), and N^{7+} impact as a function of the projectile velocity (lower scale: in atomic units; upper scale: in MeV/u). For Ne^{10+} projectiles a velocity-independent value of R is observed for $v_P \gtrsim 97.3$ a.u. (0.4 GeV/u) within the experimental error bars of about 10% for each single value at 0.4, 0.8, and 1.5 GeV/u. This gives us confidence that the asymptotic high-velocity limit has been reached and a value of $R = 0.257\% \pm 0.010\%$ has been established. In Table I our result for highly charged ion impact is compared to the high-v_P limit observed for other projectiles and good agreement within the experimental uncertain-

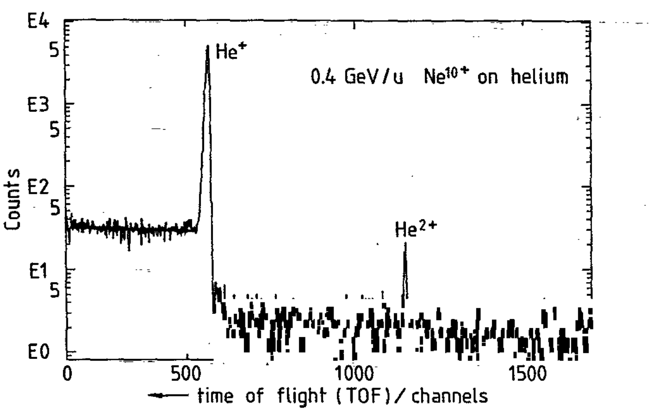

FIG. 1. Recoil-ion time-of-flight spectrum for 400 MeV/u Ne^{10+} on He. Full line: Exponential fit through the "lost coincidences" (see text).

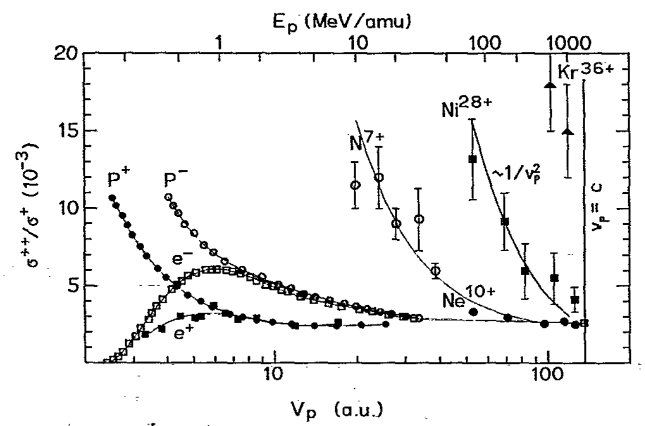

FIG. 2. Ratio R of helium double-to-single ionization for different projectiles as a function of the projectile velocity (lower scale: in atomic units) and energy (upper scale: in MeV/u) Ne^{10+} (full circles, present work); Ni^{28+} (full squares, present work); Kr^{36+} (full triangles [16]); N^{7+} (open circles, for projectile energies between 10 MeV/u and 30 MeV/u [11] and 40 MeV/u [15]); positrons (e^+, small full squares [9]); the lines with different symbols for electrons (e^- [4]), protons (p^+ [7]), and antiprotons (p^- [7,8]) are fits through the experimental data. Open square close to the line $v_P = c$ (velocity of light) is for electron impact [5].

TABLE I. High-velocity limit of the ratio R of helium double-to-single ionization for different projectiles. The theoretical value in the first Born approximation is identical for all the different projectiles.

Projectile	Z_P	R_{exp} [%]	Reference	R_{theo} [%] [a]
Ne	+10	0.257±0.010	[Present]	
e^-	−1	0.260	[5]	
e^+	+1	0.260±0.03	[9]	0.259±0.003
p^+	+1	0.249±0.010	[6]	
p^-	−1	0.28	[8]	

[a]Reference [10].

ties can be stated.

Also noted in Table I is the only *ab initio* theoretical result of first Born calculations for proton and α-particle impact using correlated two-electron wave functions for the helium atom generated from s, p, and d single electron orbitals [10]. This value is in excellent agreement with our experimental result. In the calculation the ratio is independent of the projectile velocity and charge. In addition, since the single ionization cross section scales exactly with Z_P^2 (first Born approximation) the ratio is also independent of the sign of the projectile charge justifying a comparison with the experimental results for all the different projectiles. The theoretical ratio given in Table I is the average of the energy independent values from Table I of Ref. [10]. The error bar given is the mean standard deviation of the results at different energies.

First data of Heber and collaborators at energies up to 30 MeV/u have been considered to be nearly independent of the projectile velocity [11]. However, taking into account a more recent data point at 40 MeV/u [15] the N^{7+} results show about the expected velocity dependence of $R=a/v_P^2+b$ (with $a=5.5$ and $b=2.5\times10^{-3}$; see thin solid line in Fig. 2) within the error bars. They fit into the overall behavior of our data even if a closer comparison with the present results give the impression that their ratios might be somewhat too large. It is very obvious that the high-velocity limit had not been reached in these experiments.

Increasing the projectile charge state from $q=+10$ to $q=+28$ for bare Ni impact, the high-velocity limit cannot be reached anymore even at velocities close to the speed of light ($v_P/c=0.93$). As pointed out previously [12], this is due to the larger perturbation by the Ni^{28+} projectile where contributions by the two-step mechanism are still important. The observed velocity dependence of R which is very close to a $1/v_P^2$ behavior (solid line in Fig. 2) underlines this argument. Berg and collaborators [12] estimated the onset of the asymptotic high-v_P regime to be around $q/v_P\leq0.05$ (v_P in atomic units). On the basis of our and previous data for positive particle impact this value has to be slightly revised to $q/v_P\lesssim0.1$. Thus, the highest projectile charge state for which the limit can be expected to be reached is around $q=13$. Previous data for Kr^{36+} impact display the expected velocity dependence; the ratios, however, are far above the limit which is qualitatively understandable from the above arguments (within the systematics of the present data for Ne^{10+} and Ni^{28+}, which have been measured under improved experimental conditions, the ratios obtained previously for Kr^{36+} appear to be too large; the reason for this is unknown).

Going to velocities of 93% of the speed of light [$\gamma=2.6$, $\gamma=(1-\beta^2)^{-1/2}$ with $\beta=v_P/c$] one might expect that relativistic effects, like the retardation of the Coulomb potential or the increasing influence of the magnetic interaction, should have to be considered. From this it is not obvious on first glance that a high-velocity limit of R indeed exists. It has been shown, however [17], that the cross sections for innershell ionization are decreasing until $\gamma\approx3$ which implies that the contribution of two-step processes to the double ionization cross section should also decrease. Therefore it is plausible that the high-velocity limit, established for Ne^{10+} projectiles with maximum energies of $\gamma=2.61$, cannot be affected by an increased two-step contribution due to the relativistic effects. However, one could expect that R will increase with increasing γ for Ni^{28+} projectiles where the asymptotic limit was not reached in the present experiment. In a very recent theoretical study on the basis of classical Monte Carlo calculations [18], cross sections for delta-electron emission differential in the electron energy and emission angle were calculated for energetic U and Xe on H collisions and no influence of the magnetic interaction onto the delta-electron emission characteristics has been observed for $\gamma\leq4$. Therefore, a change of R due to dynamical electron-electron interaction in the high-velocity limit also is very unlikely in the present investigation.

However, increasing γ to $\gamma\geq4$, which cannot be reached by the GSI heavy-ion synchrotron, the impact parameter dependence for single ionization has been calculated to change. The total cross section starts to increase slowly [$\sim\ln(v_P)$] and it might be expected that the high-velocity limit for R will change due to a change in the dynamic electron-electron correlation. Surprisingly this has not been observed for relativistic electron impact [5]. The value of R at $\gamma=79$ was found to be identical to results at very low energies of $\gamma=1.03$ [4] and no change in the ratio was observed for $40\leq\gamma\leq79$ [5].

In conclusion, we have experimentally established the high-velocity limit for the ratio of helium double-to-single ionization for highly charged bare ion impact. So far it was neither evident whether the limit exists nor what its value will be. Further experimental studies will concentrate on the measurement of cross sections differential in the recoil-ion transverse momentum, which is, as has been demonstrated before, a good measure of the internuclear impact parameter [19]. One main emphasis of these future studies will be put on the exploration of the difference between the ratio for positive or negative ion impact at lower projectile velocities. Because of the huge Z_P variations possible at the GSI accelerator facility the role of higher-order Born terms for the two-step contribution can be investigated in great detail which is the second goal of future experimental work.

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