Ionization of helium by impact of negative B, O, and F ions

F. Zappa, A. L. F. de Barros, L. F. S. Coelho, Ginette Jalbert, S. D. Magalhães, and N. V. de Castro Faria
Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68528, Rio de Janeiro, 21941-972, Rio de Janeiro, Brazil
(Received 18 March 2004; published 3 September 2004)

Single and double ionization processes for helium under the impact of B, O, and F anions were studied in the 1.1–1.9 a.u. velocity range. Coincidence cross sections were measured for direct ionization (DI), i.e., no projectile electron loss, and single (SL) and double projectile electron loss. The results show that DI is dominated by large impact parameters and SL is essentially the elastic scattering of the extra electron by the target. The cross section ratios taken between double and single helium ionization for single and double loss are projectile independent and grow almost linearly with the velocity.

DOI: 10.1103/PhysRevA.70.034701 PACS number(s): 34.50.Fa, 34.90.+q

Single ionization of atoms by electrons, photons, or bare ions is reasonably well described, at least for large velocities, but understanding double ionization, even for such simple projectiles, requires a description of electron-electron correlations within the atom. As a result much effort has been made in measuring single and double ionization cross sections in collisions with such structureless projectiles, although there are still unanswered questions [1,2]. Similar studies employing not so simple projectiles, namely, nonbare positive ions, neutral atoms, and negative ions (anions), have proved to be less amenable to theoretical analysis [3], and this has led to a smaller number of studies [4,5]. In particular, the vast experimental literature for proton impact is not mirrored in a similar situation for H and H^- projectiles: only two papers to our knowledge give data on ionization by H^- impact, and none for other anions [5,6]. Nevertheless, anionic projectiles seem to be good candidates to clarify the electron correlation effects in a collision, as they themselves are the result of such effects. The use of anionic atomic projectiles also avoids the competition between electron capture and impact ionization, two important collisional mechanisms for multiple-electron processes.

Anions are very interesting by themselves, for instance, several plasma physics applications led to many studies of physical processes associated with these ions [7]. About 80% of the stable atoms [8] have a corresponding anion, and even though they usually present small electron affinities and only one bound state, the ground state, they are easily available in negative ion sources used in many accelerators. Theoretical studies of anions, on the one hand made more interesting due to the electron correlation within the anion, are made more difficult by this same correlation. One interesting example is the recent comparison of the two-electron quantum dot, the H^- ion, and the He atom, all possessing two electrons at distinct correlation levels [9].

In previous papers we described several collision experiments, beginning with the study of electron detachment from fast anions with np^3 configurations (C^-, Si^-, and Ge^-) by atoms of He, Ne, and Ar, using a method developed in our laboratory [10,11]. Total detachment cross sections were then measured, with several interesting results being obtained. They can be summarized as follows: (a) cross sections for each target having almost the same velocity dependence and (b) target-independent factors scaling all the data to three curves, one for each gas. In addition to these results, each cross section curve had a conspicuous maximum σ_m at a projectile-independent velocity v_m. Afterward we extended this study to anions of the second and third periods [12], with the same trends being observed, all this showing the need for complementary data including distinct aspects of these same collisions.

In the present experiment single and double ionization processes for helium under the impact of B, O, and F anions were studied in the 1.1–1.9 a.u. velocity range. These anions all belong to the second line of the periodic table and their properties are summarized in Table I. The final charge states of the projectile and the target were measured in coincidence, leading to the cross sections for the following processes:

$$X^- + \mathrm{He} \to \begin{cases} X^- + \mathrm{He}^+ + e, & \text{single direct ionization (DI-S)}, \\ X^- + \mathrm{He}^{2+} + 2e, & \text{double direct ionization(DI-D)}, \end{cases} \quad (1)$$

$$X^- + \mathrm{He} \to \begin{cases} X + \mathrm{He}^+ + 2e & \text{single ionization -- single loss(SL-S)}, \\ X + \mathrm{He}^{2+} + 3e & \text{double ionization — single loss (SL-D)}, \end{cases} \quad (2)$$

$$X^- + \mathrm{He} \to \begin{cases} X^+ + \mathrm{He}^+ + 3e, & \text{single ionization -- double loss (DL-S)}, \\ X^+ + \mathrm{He}^{2+} + 4e, & \text{double ionization -- double loss (DL-D)}, \end{cases} \quad (3)$$

TABLE I. Atomic numbers (Z), electron affinities (EA), and ionization energies (I) for the elements used as projectiles: boron, oxygen, and fluorine.

Element	Z	EA (eV)	I (eV)
Boron	5	0.2797	8.26
Oxygen	8	1.4611	13.55
Fluorine	9	3.4012	17.34

where X^- represents the B^-, O^-, and F^- anions, "ionization" means target ionization, and "loss" refers to projectile electron loss. Two ionization and three loss cases were studied: single (S) and double (D) ionization; and single (SL), double (DL), and no loss, or direct ionization (DI). In addition to the basic interest in measuring these cross section values, we were interested in the double ionization of helium as its study is the simplest way to understand electronic correlation in atoms (Ref. [1] and references therein). Hence, obtaining the ratio between double and single ionization cross sections of helium, which contains basic information on this correlation with the added advantages of smoothing experimental fluctuations and removing normalization factors, was one of the major motivations of the present work.

The experiments were performed in our 1.7 MV tandem. This accelerator, originally designed for industrial work or scientific research on materials science, has a sputter negative ion source which can produce virtually all the atomic anions of the periodic table of elements, as well as negative molecular and cluster ions. The technique employed in previous work [10–12] using the stripper gas as target did not allow direct measurement of the target final charge state, as the stripper (a 1-cm-wide and 47-cm-long cylinder) is placed at the high voltage terminal between two 1-m-long accelerator tubes.

The technique employed in the present work allows such measurement but required a radical change in our approach. In brief, an anion beam of a few microamperes is produced by the sputter source and accelerated toward the terminal where some anions lose one or more electrons by colliding with the stripper gas. Subsequently, at the end of the accelerator, the neutral species capture electrons in the residual gas, giving rise to a new high energy anion beam of a few picoamperes which is deflected by the magnet. This technique has some inconveniences which were circumvented. First, the diversity of ion beams presenting similar Em/q^2 values hinders the magnetic selection. Second, the beam currents after collimation present low values, especially at high energies. Finally, absolute values for the total cross sections, easily obtained in our original method [10–12], are more difficult to obtain. On the other hand, as the target now is a conventional gas target or a jet placed in a chamber outside the accelerator, charged particles coming from the target can then be analyzed in charge and mass by means of a time-of-flight spectrometer.

The setup is very similar to the one already described [11]. The anionic beam traverses the scattering chamber, where the gas jet and the time-of-flight spectrometer are located. The exiting projectiles are electrostatically analyzed before and after the target, and identified in a surface barrier detector, while the recoil target ions are detected by a channeltron. In this way it is possible to measure coincidences between the different projectile charge states and the target charge states or charged fragments. The normalization to determine the target density and absolute target ion detection efficiencies was done by measuring He ionization by 1 MeV protons and using the value of its cross section 21.4×10^{-18} cm^2 [13].

The experimental values are shown in Tables II–IV, the standard deviations being 20% on average. As a first comment, the cross sections for each channel differ by a factor near 2 for distinct projectile species at similar velocities (for instance, F^- at $v = 1.46\ v_0$, O^- at 1.5, and B^- at 1.6). This is not so surprising for double loss processes, where the energy required to eject two electrons from the anion varies by a factor near 2 (see Table I), but it is a remarkable result for the other two processes, as the electron affinities may differ by more than one order of magnitude. Electron affinities should be relevant both in the direct ionization case, through the survival probability of the anion, and in the single loss case, through the minimum energy required to eject the electron from the anion, but, nevertheless, this did not occur.

Our present direct ionization values, when compared with other values existing in the literature, are slightly lower than the ionization of He by protons [13], a positive projectile. Also, our values are essentially the same as obtained with positive oxygen at velocities near 1.4 a.u. [14]. This may be qualitatively understood by assuming that contributions to this channel are dominated by impact parameters in which the target "sees" the projectile essentially as a point charge (i.e., large impact parameters) [15,16].

TABLE II. Helium single and double ionization cross sections σ_{1j}^{q+} for B^- projectiles, where q and j are the respective final charge states of the target and the projectile (uncertainties ≈20%).

	DI σ_{11}^{q+} (10^{-18} cm^2)		SL σ_{10}^{q+} (10^{-18} cm^2)		DL σ_{11}^{q+} (10^{-18} cm^2)	
v (a.u.)	He^+	He^{2+}	He^+	He^{2+}	He^+	He^{2+}
1.6	37	1.4	48	3.1	46	4.0
1.7	42	1.6	82	5.1	30	3.5
1.8	45	2.0	74	5.7	36	6.5
1.9	56	2.7	57	4.4	31	3.6

TABLE III. Helium single and double ionization cross sections σ_{1j}^{q+} for O^- projectiles, where q and j are the respective final charge states of the target and the projectile (uncertainties ≈20%).

	DI σ_{11}^{q+} (10^{-18} cm^2)		SL σ_{10}^{q+} (10^{-18} cm^2)		DL σ_{11}^{q+} (10^{-18} cm^2)	
v (a.u.)	He^+	He^{2+}	He^+	He^{2+}	He^+	He^{2+}
1.3	68	2.4	50	2.1	42	2.2
1.4	62	2.6	58	3.2	56	3.4
1.5	64	2.6	64	3.4	57	4.6
1.6	57	3.6	57	3.2	51	5.5
1.7	66	3.1	64	6.5	53	7.5

TABLE IV. Helium single and double ionization cross sections σ_{1j}^{q+} for F^- projectiles, where q and j are the respective final charge states of the target and the projectile (uncertainties ≈20%).

	DI σ_{11}^{q+} (10^{-18} cm^2)		SL σ_{10}^{q+} (10^{-18} cm^2)		DL σ_{11}^{q+} (10^{-18} cm^2)	
v (a.u.)	He^+	He^{2+}	He^+	He^{2+}	He^+	He^{2+}
1.13	39	0.0	55	2.3	36	1.0
1.23	45	2.4	56	2.7	34	1.3
1.31	50	1.7	70	3.3	52	2.7
1.38	56	2.3	69	5.0	68	3.9
1.46	52	1.6	98	6.7	66	5.1

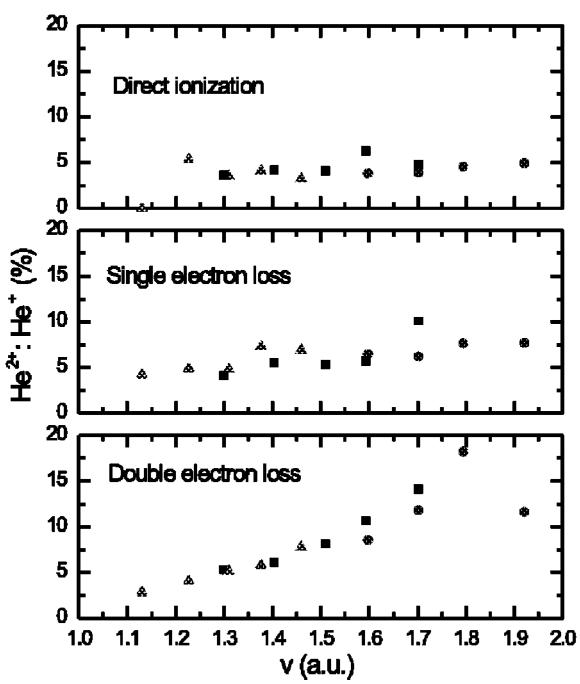

FIG. 1. Ratio between production cross sections for He^{2+} and He^+ ions by impact of B^- (circles), O^- (squares), and F^- (triangles) in the direct ionization (no loss), single loss, and double loss cases. The uncertainties are ≈20%.

On average, the double loss cross section is only slightly smaller than the one for single loss. This is interesting because double electron detachment cross sections have nearly half the value of those for the single electron process, as we have already measured [11]. One possible explanation is that the SL of the projectile is essentially the elastic scattering of this electron by the target, while the DL includes different processes that induce a larger degree of target ionization.

Figure 1 shows the present work values for the ratios between double and single ionization cross sections in the direct ionization and single and double loss cases. The DI ratios are basically velocity independent, their values lying between 3% and 6%. They are of the same order of magnitude as those obtained with positive projectiles as He^+ [16] and Li^+ [14]. The SL and the DL data increase with the relative velocity, more markedly for the latter, which increases by a factor of 7 in the measured velocity range. This process is usually treated at large velocities with perturbative methods [1], which lead to a power series in the Z/v parameter. In the present velocity range the dominant process is considered to be two step, where the projectile interacts with the two target electrons independently, and the perturbative approach does not apply as Z/v exceeds unity [1].

Concluding, for the three processes the results do not show any important dependence on anion properties such as atomic numbers or affinities. Another interesting fact is that DI, SL, and DL cross sections with helium ionization are of the same order of magnitude. Also, the sum of these cross sections is not very much smaller than the total cross sections for anion detachment [10–12]. A third and last point is that the cross section ratios, taken between double and single helium ionization, present distinct behaviors for the three processes. The ratios for single and double loss are nearly projectile independent and grow almost linearly with the velocity, more markedly for the latter. The direct ionization ratios are velocity independent, this latter fact reflecting interactions with large impact parameters.

This work was partially supported by the Brazilian agencies CNPq, FUJB, and FAPERJ.

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