Dominant Screening Process in the Projectile Electron Loss for F\(^-\) + Ar Collisions

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A comparison between projectile electron loss cross sections for negative, F\(^-\), and positive, He\(^+\), projectiles is presented for collisions with Ar target. The behavior of the two collision systems is similar for the projectile electron loss with target ionization. For projectile electron loss without target ionization (the so-called screening electron-loss process), quite different situations are presented for the studied positive and negative projectiles. For He\(^+\) + Ar, the loss without target ionization collision channel is negligible for intermediate-to-low energies. On the other hand, for F\(^-\) + Ar, this collision channel is the dominant one in the total projectile electron loss at intermediate-to-low velocities. The roles played by the electron capture by the projectile collision channel and by the very different binding energies for negative and positive projectiles are discussed.

Keywords: Anion; Negative ions; Collision; Projectile electron loss

I. INTRODUCTION

Collisions between many-electron ionic projectiles and many-electron targets often occur in nature. Cross sections for these collisions are important parameters in the modeling of technological applications. However, a rigorous theoretical description of the multiple-ionization collision channels is a difficult task [1]. The experimental cross section data available are still scarce especially for anionic projectiles [2, 3]. Regarding projectile electron-loss the identification of two dynamically different collision processes, often called screening and antiscreening processes [4, 5], sheds light on the problem of the physical description of the collisions.

The beam-attenuation experimental technique allows the determination of the total projectile destruction cross section [6–8]. This cross section corresponds to the sum of single and all multiple projectile-electron-loss collision channels, regardless of the target final charge state. The collision channel for which the projectile loses one or more electrons and the target remains in the ground state is therefore included in those measurements. This latter collision channel is often called screening projectile electron loss (also called projectile elastic loss), since the field of the target nucleus, screened by their electrons, ionizes the projectile with no target excitation or ionization [4, 5].

Projectile electron loss also takes place with markedly different dynamics, in the so-called antiscreening process (sometimes named two-center electron-electron correlation process). Here the projectile-electron-target-electron interaction is responsible for the projectile electron loss. The target electron is the ionizing agent of the projectile and, due to the energy and momentum transfer to the projectile, has a high probability of being ionized simultaneously with the projectile electron. Thus, coincidence measurements for projectile and target final charge states can at least partially separate experimentally the screening and antiscreening processes specifying the cross sections \(\sigma^{p,q}\) for the projectile (p) and target (q), final charge states [9, 10].

For positive ions there are at least two factors that complicate this experimental approach to the problem.

(i) The screening projectile electron-loss accompanied by the symmetrical process in the projectile frame of reference (namely the target direct ionization) produces the same final charge states as the antiscreening does. Experimental techniques like COLTRIMS can separate these collision channels (e.g. [11, 12]) but they will be indistinguishable in integrated cross sections obtained only by final charge-state coincidence measurements. The He\(^+\) + He and C\(^3+\) + Ne are examples of collision systems for which the simultaneous screening ionization of both target and projectile masks the antiscreening contribution to projectile electron loss. For He\(^+\) + He this is an important effect in the intermediate-to-low velocity range [9, 10]. For C\(^3+\) + Ne the effect is even stronger and the antiscreening contribution becomes negligible for low velocities [1].

(ii) The antiscreening process has an energy threshold similar to the one found in electron impact ionization [4, 5, 13]. The screening process is therefore, in principle, prominent below the antiscreening threshold. However, for low collision velocities electron capture by the projectile is very probable for positive ions and there is a strong coupling between the collision channels [1, 14, 15].

Anion projectiles offer a vast field to study the different dynamics of screening and antiscreening processes. This paper analyzes the F\(^-\) + Ar collision system in the intermediate velocity range, from 0.3 to 1.5 atomic units. For this collision system the screening contribution dominates the total projectile electron loss cross sections for intermediate-to-low velocities, in opposition to the case of positive projectiles illustrated by the He\(^+\) + Ar collision system. Possible effects of the absence of electron capture collision channel and of high asymmetry in projectile and target binding energies are discussed. Details on the experimental determination of F\(^-\) + Ar cross sections plus a comparison between F\(^-\) and other anionic projectiles, regarding projectile electron loss, will be presented in future work [16].
II. ANTISCREENING: NEGATIVE VERSUS POSITIVE PROJECTILES

Figure 1 compares the projectile electron loss with target ionization for F\(^-\) + Ar [16] and He\(^+\) + Ar [17, 18] collision systems. Cross sections are shown as a function of the projectile velocity divided by

\[ \nu_{th} = \left( \frac{(I_P + I_T)}{\text{Ry}} \right)^{1/2} \nu_0, \]

where \( I_P \) and \( I_T \) are, respectively, the first projectile and target ionization potentials in Rydberg units (Ry), and \( \nu_0 \) is the Bohr velocity. The parameter \( \nu_{th} \) is a velocity characteristic of the antiscreening threshold and is equal to 1.19 \( \nu_0 \) for F\(^-\) + Ar and 2.27 \( \nu_0 \) for He\(^+\) + Ar. Cross sections are summed over contributions for final target charge states from 1 to 4.

Both data sets show the well known energy threshold for the antiscreening loss, although there may be contributions from the competing process for simultaneous projectile and target ejection discussed in the previous section. It is reasonable that the absolute values are higher for the F\(^-\) projectiles since it has more electrons than the He\(^+\) projectile. The overall behavior is similar for the studied negative and positive projectiles in the overlapping \( \nu/\nu_{th} \) region of Fig. 1.

III. SCREENING: NEGATIVE VERSUS POSITIVE PROJECTILES

Figure 2 shows projectile charge-changing cross sections for He\(^+\) + Ar collisions. The projectile electron loss without target ionization (circles), which contains the screening contribution, is small at low velocities. Actually, DuBois [14] estimated this contribution to be zero within the experimental errors of his measurements. An estimate for the upper bound of these uncertainties is represented by the dashed line in Fig. 2. DuBois made his estimate by subtracting from the total electron loss cross sections the partial cross sections for channels with charged final states. Thus corresponding uncertainty was obtained combining in quadrature estimated experimental errors in total electron loss cross sections and in antiscreening electron-loss cross sections. The screening contribution increases with velocity and is of the same order of magnitude of the antiscreening (squares) for the higher velocities represented in Fig. 2. Electron capture by the projectile (triangles) is by and large the dominant collision channel at low velocities but decreases very fast as the velocity increases and is irrelevant in the velocity range where screening and antiscreening are of the same order of magnitude (\( \nu \approx 5\nu_0 \) in Fig. 2).

Figure 3 compares F\(^-\) + Ar projectile electron-loss cross sections (single + multiple) for collision channels with and without target ionization. The channel without target ionization corresponds to the screening mechanism (except for possible contributions from simultaneous projectile loss and target excitation, with posterior target fluorescent decay). This channel clearly dominates the total electron loss for intermediate-to-low velocities. The situation is opposite to that found, for instance, in the He\(^+\) + Ar collisions (see Fig. 2). Two suggestions are offered to explain this behavior. One possibility is the absence of the electron capture collision channel for the anion projectile, since there is no stable doubly-charged atomic anion. The coupling between electron capture and other collision channels could, thus, be fundamental for positive low velocity projectiles and absent for negative projectiles. Another point to be considered is the high asymmetry in the projectile and target binding energies for F\(^-\) + Ar collisions. This may result in a higher probability to lose a projectile electron without ionizing the target in the case of negative projectiles.
FIG. 3: Projectile electron-loss cross sections (single + multiple) as a function of projectile velocity for $F^-$ + Ar collisions. Squares, loss with target ionization [16]: $F^- + Ar \rightarrow \sum_{q>0} F^{p^+} + \sum_{q>0} Ar^{q^+}$. Circles, loss without target ionization (obtained combining data from Refs. [16] and [7]): $F^- + Ar \rightarrow \sum_{p>1} F^{p^+} + Ar^0$.

FIG. 4: Cross sections for the $F^-$ + Ar and $He^+$ + Ar collision channels with no charge-changing of either target or projectile. (I) Solid symbols are used for $F^- + Ar$: stars, target total direct ionization [16]; $F^- + Ar \rightarrow \sum_{p>1} F^{p^+} + Ar^0$; circles, projectile electron loss without target ionization (see Fig. 1). (II) Open symbols are used for $He^+$ + Ar: stars, target total direct ionization [20]; x-center stars, target direct ionization [14]; Circles (and dashed line), see Fig. 2.

Figure 4 highlights this asymmetry comparing projectile screening electron loss (the projectile elastic loss) and the target direct ionization, for both $F^-$ + Ar and $He^+$ + Ar collision systems. Solid circles represent $F^-$ electron loss without target ionization. Solid stars represent total target direct ionization for the $F^-$ projectile. Open circles represent $He^+$ projectile electron loss without target ionization. Open and x-center stars represent total target direct ionization for the $He^+$ projectile. Cross sections are shown as a function of the projectile velocity divided by

$$v_{ext} = (I_{e,jec}/\text{Ry})^{1/2} v_0,$$

where $I_{e,jec}$ is the first ionization potential (in Rydberg units) of the only collision partner (projectile or target) that has one or more ejected electrons. The parameter $v_{ext}$ is a velocity characteristic of the screening electron loss and of the direct ionization process. It is equal to 0.500 $v_0$ for $F^-$, 1.08 $v_0$ for Ar, and 2.00 $v_0$ for $He^+$. Cross sections are summed over contributions for final charge states $q$ from 1 to 4 for $Ar^{q^+}$, 0 to 2 for $F^{p^+}$, and 1 to 2 for $He^{q^+}$.

Projectile screening electron loss and target direct ionization are collision channels symmetric in the exchange of projectile and target frames of reference. With the projectile velocity parameterization used, $F^- + Ar$ screening electron loss and $He^+ + Ar$ direct ionization clearly show maxima at the same velocity region of Fig. 4. The two other collision channels presented in Fig. 4 are also consistent with maxima in the same velocity region but unfortunately the velocity range of available experimental data is too narrow to check this point.

Figure 4 shows screening electron loss much larger than target direct ionization in $F^- + Ar$ collisions, for which projectile binding energy (3.40 eV) is smaller than the target binding energy (15.8 eV). For $He^+ + Ar$ the situation is the opposite. The projectile binding energy (54.4 eV) is larger than the target binding energy (15.8 eV) and target direct ionization is much larger than projectile screening electron loss.

IV. SUMMARY

A comparison between projectile electron loss cross sections for negative, $F^-$, and positive, $He^+$, projectiles is presented for collisions with Ar target. The behavior of the two collision systems is similar for the projectile electron loss with target ionization (the antiscreening electron-loss process).

For projectile electron loss without target ionization (basically the screening electron-loss process), quite different situations are presented for the studied positive and negative projectiles. For $He^+ + Ar$, the loss without target ionization collision channel is negligible for intermediate-to-low energies. For $F^- + Ar$, this collision channel is the dominant in the total projectile electron loss at intermediate-to-low velocities. These different behaviors for positive and negative projectiles can be understood, at least in broad lines, considering two points: (I) coupling with the capture collision channel does not exist for negative projectiles; and (II) projectile binding energies are much smaller for the projectile than for the target in the case of anion-atom collisions. For cation-atom collisions the situation is usually the opposite one with binding energies higher for the projectile than for the atomic target.

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