Accelerating multiple scattering of the emitted electrons in collisions of ions with atoms and molecules

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Abstract

Double differential cross-sections for electron emission were measured in the collisions of N⁺ ions with N₂, Ne and Ar targets in the 700–1500 keV impact energy range. We studied the target atomic number dependence of the Fermi-shuttle type acceleration mechanism. The experimental double differential cross-sections are in good agreement with the theoretical values obtained from CTMC calculations for argon target. According to the calculations, multiple scattering contribution to the Ar spectra above 300 eV is significant.
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1. Introduction

Double differential spectra of electrons ejected in ion–atom and ion–solid collisions provide detailed information about the ionization dynamics. During the past decade special emphasis has been laid on the emission of the fast electrons in collisions of heavy partners (see e.g. [1] and the references therein). Significantly enhanced emission of fast electrons above the binary encounter energy was observed in both ion–atom [2–5] and ion–solid collisions [6–9].

In some cases, fast electrons have been identified as originated from double [3,4] or multiple [5,9] scattering by the projectile and target cores. Since the moving projectile ion is much heavier than the electron, such kind of multiple scattering
of the electron also accelerates it. The process is often denoted as Fermi-shuttle acceleration [1], referring to Fermi's idea [10] for explaining the origin of high-energy cosmic rays as acceleration of charged particles by giant magnetic fields moving in space.

For atomic collisions, the first theoretical evidence of the Fermi-shuttle acceleration was found by Wang et al. [11], within a non-perturbative quantum mechanical model. Another non-perturbative approach, which turned out to be successful in describing this complicated process, is the classical trajectory Monte-Carlo (CTMC) method [5,12,13]. In what follows, we use the language of classical physics to talk about the phenomenon.

Fig. 1 shows an example for Fermi-shuttle type acceleration from a classical viewpoint [1]. The displayed triple scattering sequence is denoted by P–T–P. The starting step (P) is a collision between the heavy projectile ion (moving with a velocity $V$) and the target electron. As a result, the electron is scattered forward with about two times the projectile velocity, $2V$. In the second step (T), the liberated electron is backscattered on the target field. Then, in Fig. 1, this T-step is followed by a third scattering on the projectile ion again (P). Finally the electron leaves the collision region with a velocity of $4V$.

The acceleration is originated from the P steps. The velocity of the electron is increased by $\sim 2V$, in every $180^\circ$ electron scattering by the incoming projectile, while only the direction of its motion is changed by the scattering on the target field. Binary encounter (BE) ionization of the target is signed with P, whereas the corresponding projectile ionization (electron loss) is denoted by T. Longer sequences can be referred to as, for instance, P–T–P or T–P–T–P. Target ionization sequences start with a P process, and emit electrons up to the velocity $2nV$ in forward and backward directions ($n$ is the number of encounters with the projectile). For electron loss sequences (starting with T), the final velocity is $(2n + 1)V$.

At present, our knowledge about the above processes is rather limited. Double [3,4], triple and quadruple [5] sequences already have been identified, but we do not know much about the importance of the multiple scattering processes at low projectile velocities ($<0.3$ au). Some indications have been found [1] that even longer sequences may significantly contribute to electron emission in such slow collisions.

In the present work, we measured double differential cross-sections for electron emission in collisions of 700–1500 keV N+ ions with N2, Ne and Ar targets ($v_{\text{proj}} = 1.4–2$ au). We study the target atomic number ($Z_T$) dependence of the yield of the Fermi-shuttle type triple and quadruple scattering in these collisions. We consider the present work as a starting point of a systematic study, a combined experimental and CTMC analysis of a wide range of collision systems. Here we report the first results.

2. Experiment

The experiment was carried out at the beamline of the 5 MV Van de Graaff accelerator in ATOMKI, Debrecen, Hungary. A beam of N+ ions has been directed to gas jet targets of N2, Ne and Ar in the scattering chamber. The emitted electron energies have been analyzed with the ESA-21 electron spectrometer [14], which is a combination of a spherical and a double pass cylindrical mirror.
The spherical mirror focuses the electrons from the scattering plane to the entrance slit of the cylindrical energy analyzer. The electrons are detected simultaneously by 13 channeltrons between 0° and 180° relative to the beam direction. Accordingly, a complete angular distribution can be taken in one sweep. The density of the target gas was kept constant by regulating the buffer pressure with a magnetic valve controlled capacitive manometer. The overall pressure in the chamber was $5 \times 10^{-5}$ and $2 \times 10^{-7}$ mbar with and without gas, respectively.

The absolute normalization was performed by collecting spectra in 1.5 MeV proton–argon collisions and comparing them with the reference data of Rudd et al. [15]. The experimental uncertainty of the absolute cross-sections has been estimated to be less than 40% for above 120 eV electron energy, and less than 60% below 120 eV.

3. Results and discussion

The measured double differential electron spectra for forward, perpendicular and backward electron emission are displayed in Figs. 2–4. The data were collected at two projectile energies, at 1 MeV for N$_2$ and Ne targets, and at 0.75 MeV for Ar target. We intended to compare the backscattering cross-sections (T process) for N$_2$ and Ne targets. This cross-section is expected to scale with $\frac{Z^2}{A}$ [1.5]. Accordingly, N$_2$ ($2 \times 7^2 = 98$) and Ne ($10^2 = 100$) should provide similar results for the second (P–T) and higher order scattering processes.

For the molecular nitrogen target (1 MeV N$^+$ + N$_2$ collisions system, Fig. 2), the expected higher order (P–T–P and P–T–P–T) structures are not well separable. This is mostly due to the presence of strong target and projectile Auger lines. Only the double P–T scattering is seen at around 2$V$ (~180 eV) in the 90° and 150° spectra. The agreement with preliminary CTMC calculations is within the uncertainties, but the poor statistics of the CTMC data has not allowed a quantitative comparison yet.

For the 1 MeV N$^+$ + Ne collision system (Fig. 3), the spectra are simpler. As expected, the P–T scattering contribution at 90° and 150° is similar in magnitude to that of the N$_2$ target. It is clearly
seen that the entire Ne spectrum is practically structureless compared to that of N₂. We have no calculations for this collision system yet, but we may recall the results of an earlier study [13]. CTMC calculations for carbon–neon collisions provided strong P–T, T–P, P–T–P, T–P–T and
P–T–P–T yields, but their sum had shown up a practically structureless electron spectrum due to the almost equal strength of target and projectile ionization \[13\].

For 0.75 MeV N\(^+\) + Ar collisions (Fig. 4) all the expected target ionization structures (P, P–T, P–T–P and P–T–P–T) clearly appear in the spectra. The significantly higher multiple scattering yield, compared to Ne and N\(_2\), is due to both the lower projectile velocity and the higher target atomic number.

In Fig. 4, the agreement between the experimental data and the CTMC calculations looks almost perfect at 30\(^\circ\) observation angle. Only around \(V\) and \(3V\) can one find slightly lower calculated cross-sections. This is due to the fact that the CTMC calculations have been performed only for the target ionization yet. Projectile ionization (electron loss) contributions are expected to improve the agreement at all angles.

An important feature of the CTMC calculations is that the development of the individual collision “events” can be analyzed (see e.g. Fig. 5), and associated with single or multiple scattering events. This way, the theoretical weights of the single and multiple scattering contributions can be derived. The observed good agreement with experiment indicates that the relative yields are realistic.

The surprising result of such an analysis was that a significant (>50\%) part of the CTMC electrons, “emitted” above 300 eV in the 0.75 MeV N\(^+\) + Ar collisions, was identified as liberated in P–T–P or P–T–P–T processes. In conclusion, the first result of our systematic study is that accelerating multiple scattering may even significantly contribute to the high-energy electron emission in atomic collisions of the 1–2 au projectile velocity range.

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References