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B. Sulik
Hungarian Academy of Sciences

Karoly Tokési
Hungarian Academy of Sciences

Akos Kover
Institute for Nuclear Research Hungarian Academy of Sciences

S. Ricz
Hungarian Academy of Sciences

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Continuous electron spectra from 150 keV/u C^+ + He, Ne, Ar collisions at electron emission angles from 0° to 180°

B. Sulik [a,*], Cs. Koncz [a], K. Tőkési [a], Á. Kövér [a], S. Ricz [a], Gy. Víkor [a,1], J.-Y. Chesnel [b,2], N. Stolterfoht [b], D. Berényi [a]

[a] *Institute of Nuclear Research of the Hungarian Academy of Sciences ATOMKI, P.O. Box 51, H-4001 Debrecen, Hungary*

[b] *Hahn–Meitner Institute, Glienickerstr. 100, D-14109 Berlin, Germany*

Abstract

Electron spectra in the 20–550 eV energy range and in the full angular range of 0–180° were measured by the impact of 150 keV/u C^+ ions on He, Ne and Ar atoms. Double differential cross sections for electron emission have been determined. We observed an unexpected, broad structure around 300 eV electron energy at backward emission angles relative to the beam direction. Our calculations support the hypothesis that the new structure is due to double scattering of the target electrons on the screened fields of the projectile and the target. The calculations also show that both electron-emitting partners are multiply ionized in the collision. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Experimental study of the different processes leading to electron emission in dressed ion–atom collisions at the intermediate impact energy region is essential for understanding the collision dynamics. At high impact energies, first order perturbation theories can rather accurately predict ionization cross sections. In case of slow ion impact, molecular orbital models can provide a satisfactory description. Intermediate energy collisions, however, are too fast to use molecular orbital models, and too slow to treat them by first order perturbation theories. Higher-order processes become important in the ejection of electrons both from the projectile and the target. Detailed knowledge about such collision systems is also desirable for many applications. The ionization cross section shows a maximum in this energy region. In case of energetic ion impact in solids, e.g., a significant part of the energy is transferred to the solid by the decelerated ions which captured a few electrons.

* Corresponding author. E-mail: sulik@atomki.hu

[1] Present address: Department of Atomic Physics, Stockholm University, S-10405 Stockholm, Sweden.

[2] Present address: Centre Interdisciplinaire de Recherche Ions-Lasers, Unité Mixte (No. 6637) CEA-CNRS-ISMRA-Université de Caen, 6 Bd Maréchal Juin, F-14050 Caen, France.

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There are many possible mechanisms contributing to the electron ejection in dressed ion–atom collisions. The ionization of the target, for example, may be due to the interaction between the screened projectile nucleus and a target electron, or between a projectile electron and a target electron (two-center dielectronic process). By interchanging the words ‘projectile’ and ‘target’, one gets the corresponding contributions for the electron loss. Transitions associated with multiple ionization and charge transfer may also contribute to the electron emission from the projectile and the target.

Experimental identification and separation of the different processes leading to electron emission can be based on coincidence techniques and/or the measurement of the double differential electron emission cross section. In the latter case, multiple ionization and multiple scattering of the electrons may exhibit as new structures in the electron spectra compared to those appearing at higher impact energies or lighter projectile ions. Studies of the details of electron emission in heavier dressed ion–atom collisions in the intermediate energy region are rather scarce [1–4]. No measurements have been performed at 0° or 180° electron emission angles in these works.

In the present work, we report measurements of the double differential cross section (DDCS) for electron emission in the 20–550 eV energy range and in the full angular range of 0–180°, in 150 keV/u C^+ + He, Ne and Ar collisions.

2. Experimental method

The experiment was performed at the beam line of the 5 MV Van de Graaff accelerator of ATOMKI, Debrecen. Singly charged carbon ions with 150 keV/u impact energy have been directed to the scattering chamber. In order to achieve an absolute normalization, we also measured the spectra of continuum electrons emitted in 1.5 MeV proton–argon collisions for comparison with the reference data of Rudd et al. [5].

A nozzle was used to introduce the He, Ne or Ar target gases to the collision region. The electron spectra were measured with a triple-pass electrostatic electron spectrometer (ESA-21) [6]. The first part of it is a spherical mirror analyzer which transports the electrons from the collision plane to the entrance slit of the high resolution double cylindrical mirror analyzer. At the exit slits, 13 channeltrons detect the electrons simultaneously from 0° to 180° relative to the beam direction. Based on the reproducibility of our spectra, and the published errors of the reference data [5], we estimate the error of our cross sections 40% above 50 eV electron energy. Between 20 and 50 eV, we estimate it less than 60%.

3. Results and discussion

The measured spectra, displayed at selected emission angles in Fig. 1, show many characteristic structures of the double differential electron emission. On the ‘background’ of the soft-collision part of the target ionization contribution, the electron loss peak appears at 81 eV, i.e., at the cusp energy at all angles. The electron loss peak is relatively less intense for He target. For Ne target, a forward–backward enhancement and a minimum of the electron loss intensity around 90° indicates that ionization processes are strongly affected by interference effects, which are characteristic for low energy elastic electron atom scattering [7]. A more complicated interference pattern is present for the argon target.

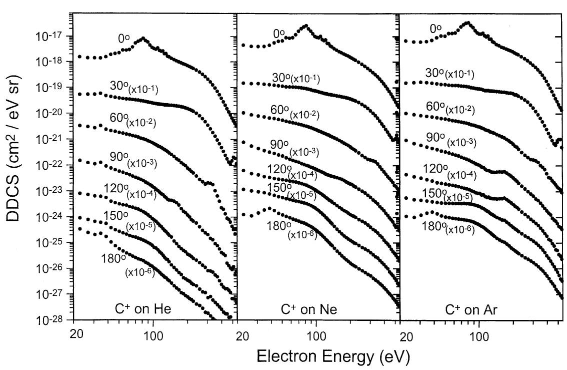

Fig. 1. Experimental double-differential cross sections for electron emission in 1.8 MeV (a) C^+ + He, (b) C^+ + Ne, and (c) C^+ + Ar collisions as a function of the ejected electron energy. Notice the broad structure for Ne and Ar targets around 300 eV at backward emission angles.

The Doppler-shifted carbon K-Auger group originating from the moving projectile is clearly seen as being energy-shifted with the observation angle (at 180°, e.g., it stays around 30 eV). A rather strong target-Auger group (Ar LMM) also exhibits in the spectra taken with Ar target. It is centered around 150 eV. This value corresponds to a high degree (about 50%) of multiple M-shell ionization associated with the ionization of the Ar L-shell.

The Compton-profile of the target outer shells is relatively broad compared to the projectile velocity (2.45 a.u.). Accordingly, the hard-collision binary-encounter process does not show a well defined peak at forward emission angles where the electron loss contribution is relatively large even at higher energies. For backward angles, however, a clearly visible broad structure appears around the zero-degree energy of the binary-encounter peak, at about 300 eV. It is significantly more intense for neon and argon than for helium target. A similar peak-structure at large angles has been observed recently by Bechtold et al. [8] for rather different collisions systems, namely in fast (5.9 MeV/u) heavy ion–heavy target collisions. It has been explained by a double scattering mechanism for the target electrons in the strong fields of the projectile and the target consecutively.

In order to study the mechanism responsible for the appearance of the above structure at our collision velocity, we performed a set of calculations in different approximations. The starting point was the first-Born (1B) approximation according to the formalism given by DuBois and Manson [9]. The screening effect and the two-center dielectronic process have been calculated according to Ref. [10]. These calculations overestimated the measured cross sections in all the investigated cases. As a second step, we performed impact-parameter first-Born calculations (IPB) for the screening contributions using the SCA code of Schiwietz and Grande [11,12]. The calculated cross sections for ionization were found to be identical in 1B and IPB. Moreover, IPB calculations shown that the calculated maximum value of the total vacancy production probability per electron (dominated by ionization) was found to be much larger than unity. The calculated probability values lie between 3 and 5 for the outer target shells and the C^+ L-shell by Ne or Ar atoms. This obviously unphysical result demonstrates that we are out of the region of validity of first order perturbation theories.

As the simplest correction to the first-order results, we utilized the unitarization method proposed by Sidorovich et al. [13]. Within this model, the corrected probability is $p_i^{corr} = p_i(1 - e^{-\sum p_i})/\sum p_i$ for a particular transition p_i, where the summation runs over all the possible final states except the initial state. We found that the average degree of ionization is rather large in all cases, even in the unitarized first-Born (U1B) approximation.

The results of the 1B and U1B calculations are compared with the experimental data in Fig. 2. The results are displayed only for Ne target at 150° emission angle, where the agreement is the best between the 1B results and experimental data. Even here, the experiment is rather purely reproduced by both the 1B and U1B theories. However, when comparing the experimental data with the U1B results, the new structure around 300 eV can be clearly observed above the calculated curve.

At this level of the analysis, it was obvious to consider this structure as being produced by multiple electron scattering in the screened fields of the nuclei of both collision partners, very similarly to the the large angle scattering process has been observed recently by Bechtold et al. [8] in fast collisions (see above). Kinematically, the most likely process is an enhanced probability forward scattering of a target electron by the projectile nucleus (zero-degree binary-encounter with an energy of about four times the cusp-energy), followed by a second scattering in the (screened) field of the target nucleus.

A simple qualitative analysis of the above possibility has been performed by calculating the differential elastic scattering cross sections of the two considered 'free'-electron scattering by the method of partial waves. The first step is a scattering of an electron traveling with the velocity of the projectile v_p by the screened field of the projectile ion. Large cross section at backward angles in the projectile frame means a strong forward scattering in the laboratory frame. The second scattering of these electrons (with a velocity of $2v_p$) may happen in the

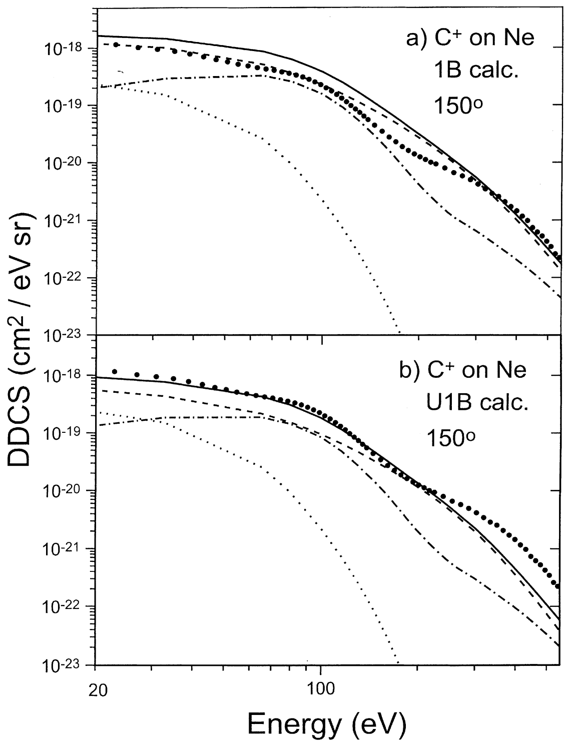

Fig. 2. Comparison of the results of the first-Born (1B) and the unitarized first-Born (U1B) calculations with the experimental data for the double-differential electron-emission cross section in 1.8 MeV C^+ + Ne collision at 150° emission angle. Symbols: experiment, lines: first-order Born calculation as follows: dashed line: target ionization by the screened projectile nucleus; dashed-dotted line: projectile ionization by the screened target nucleus; dotted line: target ionization by dielectronic ($e^- - e^-$) processes; full line: sum of all contributions (the contribution of the projectile ionization by dielectronic process is negligible).

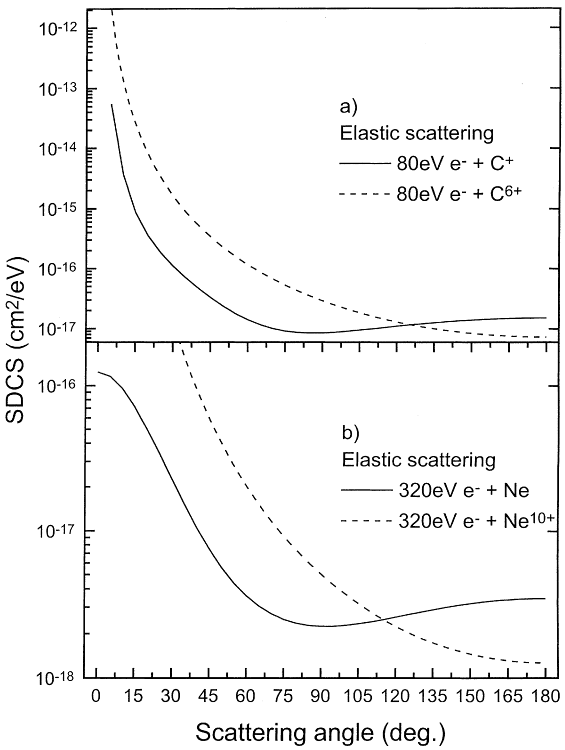

Fig. 3. Differential cross sections for the elastic scattering of (a) free electrons of 80 eV energy in the projectile frame, scattered by the screened field of the projectile, and (b) free electrons of 320 eV energy in the laboratory frame, scattered by the screened field of the Ne target. The dashed lines show the Rutherford cross sections by the bare nuclei for comparison.

field of the target atom. The results of the calculations for the neon target are shown in Fig. 3, together with the Rutherford cross sections by the bare nuclei for reference. Since the probability of the backward scattering seems to be strong in the screened field of both the C^+ projectile and the Ne target, we conclude that double scattering is non-negligible in the investigated nuclear charge and impact velocity region. We would like to note here that the above mechanism can be identified as an example for the "Fermi-shuttle" mechanism [14] which was considered and searched for in Ref. [15], and later was found at forward angles [16] by Suarez and coworkers.

We also tested the above hypothesis by using a nonperturbative two-center model, i.e. performing classical trajectory Monte-Carlo (CTMC) calculations for the carbon–neon collision system with analytic screening model-potentials [17] for both the projectile and the target. The results of the CTMC calculations are displayed in Fig. 4, for three emission angles. The target and projectile contributions are shown also separately. One may find that there is a good general agreement between experiment and theory. It is important, that the 150° CTMC data show a very similar structure to the corresponding experimental spectrum. We conclude that the CTMC calculations strongly support the conclusion that the new structure is due to double scattering of the target electrons in the screened fields of the projectile and the target

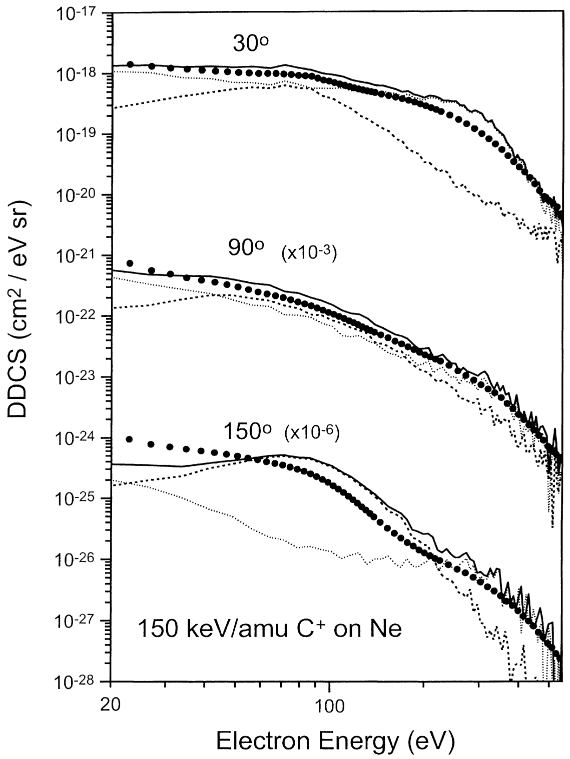

Fig. 4. Comparison of screened potential CTMC calculations with experimental data for Ne target. Symbols: experiment; dotted line: calculated target ionization contribution; dashed line: calculated electron loss contribution; full line: full theory. Both experiment and theory are averaged over ±30° windows of the polar emission angle.

consecutively. We continue both the experimental and theoretical work to study the impact ion-energy and the target atomic number dependence of the process, and to extend the measurements to higher energies of the emitted electrons. The present results also demonstrate that intermediate velocity heavy ion–heavy atom collisions might provide a useful tool to study the Fermi-shuttle mechanism [14,15] experimentally.

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