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Relativistic Electron Transport Through Carbon Foils

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Abstract

We present a theoretical study of convoy electron emission resulting from transmission of relativistic 390 MeV/amu Ar^{17+} ions through carbon foils of various thicknesses. Our approach is based on a Langevin equation describing the random walk of the electron initially bound to the argon nucleus and later in the continuum. The calculated spectra of ejected electrons in the forward direction exhibit clear signatures of multiple scattering and are found to be in good agreement with recent experimental data.

1. Introduction

During the last few decades, the angular and energy distributions of electrons ejected in ion-atom and ion-solid collisions have been studied extensively. Comparative analysis of spectra from ion-atom and ion-solid collisions provides the opportunity to extract detailed information about dynamic screening and multiple scattering in the solid.

The so-called convoy electron peak (CEP) provides a good field for these studies. This peak is usually observed in the spectra from ion-solid collisions for electrons ejected with velocities, $\boldsymbol{v}_e$, close to the projectile velocity $\boldsymbol{v}_P$. In the limit of very thin foils and for fast ions, the spectrum from ion-solid collisions is expected to resemble the result of a single ion-atom collision. That is, it should exhibit a cusp-like feature known as the electron loss to the continuum (ELC) peak, which originates in a direct transition from the initial state of the electron onto the low-lying continuum of the ion. In turn, for increasing foil thickness the dynamics of the ion-solid interaction becomes quite complex and leads to a redistribution of the electronic states prior to detection which ultimately changes the shape of the CEP.

In this article we investigate the effect of multiple collisions on the CEP in relativistic ion-solid interactions ($v_P = 97$ a.u.). This work is motivated by recent measurements of the spectra of electrons emitted in the forward direction for 390 MeV/amu Ar^{17+} ions traversing carbon foils of different thicknesses [1,2]. The characteristics of these ions (i.e. very fast and highly charged) provide a unique opportunity to study the sequence of multiple excitations leading to the CEP. This is due to the fact that collisional mean free paths are long and collisions are relatively soft. Thus, one can experimentally follow the sequential excitation process over large distances in considerable detail. We calculate the spectrum of emitted electrons using a classical transport theory (CTT) [3] which is based on a microscopic Langevin equation for projectile-centered electrons. We show that the width and intensity of the CEP exhibit a nonmonotonic behavior as a function of the foil thickness, which is a direct consequence of multiple sequential collisions. Atomic units will be used unless otherwise stated.

2. Theory

In this section we provide a brief description of our classical transport theory (CTT) for the present collision system. A more detailed description can be found elsewhere [3]. For the present collision velocity and foil thicknesses, we have found that target electrons do not contribute significantly to the CEP (i.e. electron capture cross sections are very small). Therefore, we focus on the transport of the electron initially bound in the $Ar^{17+}(1s)$ projectile prior to entering the foil.

Within the CTT, the state of the electron is represented by a probability density in phase space. Initially, the state of the electron is given by a microcanonical ensemble with the quantum binding energy of the ion, which mimics the momentum distribution of the quantum state. The time evolution of the electron is given by a reduced Liouville equation which is solved by test particle discretization (i.e. Monte Carlo sampling). Microscopically, the dynamics of each test particle is governed by a Langevin equation involving both a deterministic Coulomb force and a stochastic force acting on the electron,

$$\dot{p} = -\frac{Z_P r}{r^3} + \sum_{\alpha} \sum_{i} \Delta p_i^{\alpha} \delta(t - t_i^{\alpha}), \tag{1}$$

where Z_P is the projectile charge, and r and p are the position and momentum of the electron in the frame of the ion. Equation (1) represents a random walk along Kepler orbits. The jumps among orbits are caused by the stochastic sequence of momentum transfers Δp_i^{α} delivered to the electron at the times t_i^{α}. These momentum transfers represent the multiple collisions between the projectile electron and other particles in the solid and are responsible for ionizing the electron. After electrons exit the foil, collisional momentum transfers cease but the time evolution must be continued to $t \to \infty$ because of the long range Coulomb interaction between the electron and the projectile.

The index α in Eq. (1) denotes the different types of elastic and inelastic collisions suffered by the electron. Elastic

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collisions represent elastic scattering of the electron at the screened heavy nuclei in the solid and they provide the most significant contribution to the excitation and ionization of deeply bound states. Inelastic collisions consist of single-particle-single-hole and collective excitations of electrons in the foil. The probability distributions of impulsive momentum transfers and flight times, $(p_i^\alpha, \Delta t_i^\alpha)$, between "kicks" are determined from the relativistic differential inverse mean free paths for free electrons [4], which are calculated using first order perturbation theory. In order to account for the large energy gap for excitation of deeply bound states, an energy dependent minimum momentum transfer is imposed.

Elastic momentum transfers are calculated from the differential elastic cross section for the scattering of electrons at the screened target cores. Inelastic momentum transfers are obtained from a realistic dielectric function of the foil as a function of the frequency and wavevector [5]. We consider both longitudinal (non-relativistic) and transverse (relativistic) excitations [6–8]. In the present approach the dielectric function for carbon is approximated as a sum of five Drude-type functions [5]

$$\varepsilon(q,\omega) = \varepsilon_1 + \mathrm{i}\,\varepsilon_2 = \left(1 - \sum_{j=1}^{5} \chi_j(q,\omega)\right)^{-1} \tag{2}$$

with

$$\chi_j(q,\omega) = \frac{\omega_{pj}^2}{\left(\omega_{0j} + c^2\left(\sqrt{q^2/c^2+1} - 1\right)\right)^2 - \omega^2 - \mathrm{i}\eta_j\omega}. \tag{3}$$

To evaluate the constants ω_{pj}, ω_{0j} and η_j for $j = 1..5$ we use optical data for carbon [9] and fit the limit $\varepsilon(q = 0, \omega)$. The extension to finite momentum transfer q is achieved via a relativistic dispersion relation (see Eq. (3)).

3. Results

Figure 1 shows the fractions Ar^{17+} and Ar^{18+} ions as a function of foil thickness. The agreement between theory and experiment is reasonable good, indicating the validity of the CTT. The figure also shows that the present collision system provides a good testing ground for studying sequential multiple collisions since experimental data can be obtained for various interesting limits. For very thin foils, a very small fraction of Ar^{17+} is ionized and, therefore, single ionizing collisions play a dominant role. In turn, for the thickest foils in the figure most of the Ar^{17+} ions are ionized and multiple scattering dominates.

Figure 2 shows the calculated electron emission spectra into a forward cone with angular resolution $\Delta\theta = \pm 1^\circ$ for five foil thicknesses. The intensities of each spectrum have been normalized such that the maximum of the spectrum is unity. The number by each curve denotes the actual intensity of each spectrum relative to the one in Fig. 2c. Both the relative intensity and the shape of the CEP provide clear evidence of the different stages of the random walk executed by the electron prior to ionization. For very thin foils (e.g. $50\,\mu\mathrm{g/cm}^2$, Fig. 2(a)), very few collisions have taken place and, therefore, the intensity of the CEP is small. Because the probability for having large momentum transfers

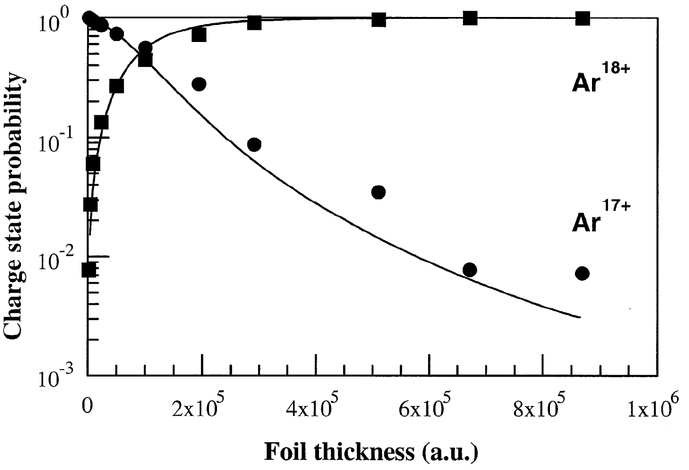

Fig. 1. Outgoing fractions of Ar^{17+} and Ar^{18+} ions as a function of foil thickness resulting from the transmission of 390 MeV/amu Ar^{17+} ions through amorphous carbon foils: Experiment [13] (symbols); present simulation (solid lines).

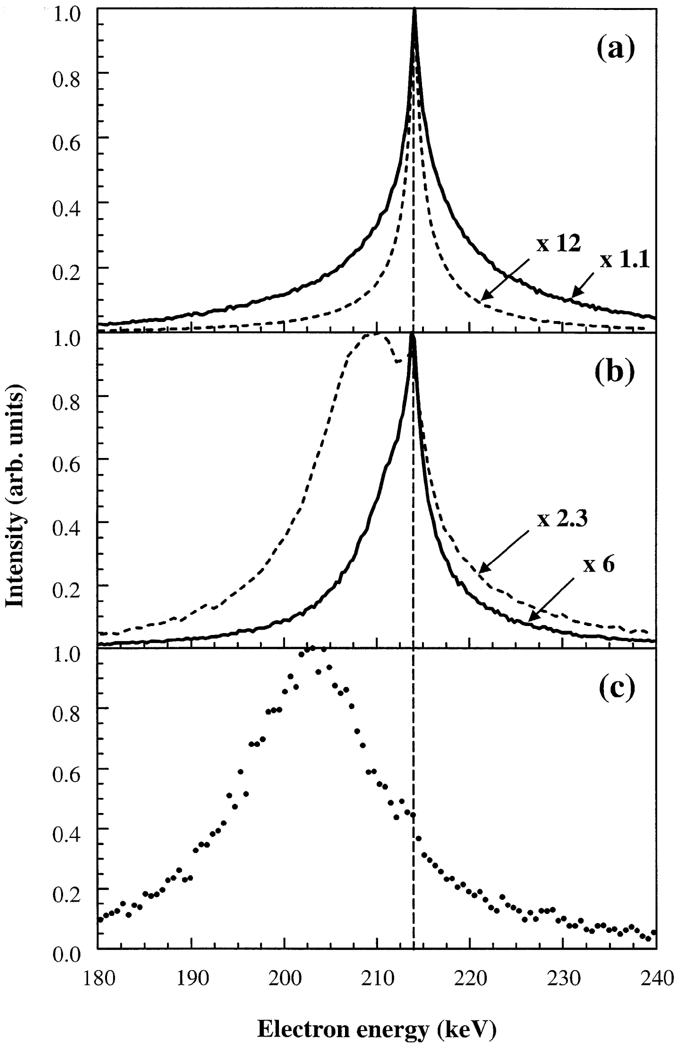

Fig. 2. Convoy electron spectra resulting from the transmission of 390 MeV/amu Ar^{17+} ions through amorphous carbon foils of different thicknesses: (a) $50\,\mu\mathrm{g/cm}^2$ (full line) and $530\,\mu\mathrm{g/cm}^2$ (dashed line); (b) $3080\,\mu\mathrm{g/cm}^2$ (full line) and $5400\,\mu\mathrm{g/cm}^2$ (dashed line); (c) $9190\,\mu\mathrm{g/cm}^2$. The acceptance angle is $\Delta\theta = \pm 1^\circ$. The maxima of the convoy peaks are normalized to one. The numbers by each curve represent the relative intensity of the spectrum with respect to the spectrum in (c). The vertical dashed line indicates the energy where the electron velocity equals the projectile velocity.

required for ionization is small, the CEP in this case closely reflects single collision conditions and the peak is associated with direct transitions from the initial state of the electron to the continuum. The CEP shape adopts the form of a symmetric ELC cusp-like structure centered at an electron energy $\frac{1}{2}v_p^2$ (denoted by the vertical line in the figure). As the foil thickness is increased from 50 μg/cm^2 to 530 μg/cm^2, the intensity increases since more Ar^{17+} ions have lost the remaining electron by multiple collisions. In addition, the cusp-like ELC peak becomes narrower, indicating that production of low-lying continuum is governed by a different mechanism. Our simulations show that much of the cusp is due to ionization of excited states of Ar^{17+} which became populated as a result of an excitation process in a preceeding collision. That is, with increasing foil thickness Rydberg states become strongly populated and they become the precursor to ionization. This yields a decreasing width of the cusp for two reasons. First, smaller momentum transfers are sufficient to ionize the excited states and they yield narrower energy distributions. Secondly, the width is directly related to the Compton profile of the electron prior to ionization and the width of the Compton profile decreases as the energy level of the electron increases [10].

For foil thicknesses larger than 1000 μg/cm^2, the intensity decreases with increasing foil thickness since most of the Ar^{17+} ions have been fully stripped (see Fig. 1). In these cases, the shape of the CEP is determined to a large degree by post-ionization transport of free electrons (i.e. multiple collisional transitions between continuum states). At 3080 μg/cm^2 a shoulder becomes visible in the spectrum for electron velocities smaller than v_p. This shoulder becomes a broad peak at 5400 μg/cm^2 which is well separated from the cusp at $v_e = v_p$ [11]. Thus, for the range of foil thicknesses in Fig. 2(b), the electron spectra can be characterized by a "double peak structure". For very thick foils (e.g. 9190 μg/cm^2) almost no hint of the ELC cusp is visible in the spectrum and the CEP becomes broader and is shifted to lower electron energies. The shift of the peak is due to the stopping of free electrons along their paths (i.e. due to inelastic collisions with the solid). The resulting energy loss of our Monte Carlo simulation is in good agreement with the semi-empirical Bethe formula [12]. In addition, stochastic collisions are responsible for deflecting electrons from the forward direction, for broadening of the angular distribution (i.e. angular straggling), and for decreasing the intensity of the CEP.

We have compared our predictions for the present system with recent experimental data. Figure 3 shows an example of such a comparison for a foil thickness of 5400 μg/cm^2. The calculations in the figure have been convoluted with the experimental detector acceptance function involving an acceptance angle of $\Delta\theta = \pm 1^\circ$ and an energy resolution of $\Delta E = \pm 8$ keV. Very good agreement is observed between the theory and experiment and a similar good agreement has been found for other foil thicknesses (not shown). The large experimental energy resolution smoothes out the spectra of ejected electrons but is good enough to test the dependence of the CEP width on the foil thickness. We find that the experimental data yield a non monotonic behavior of the CEP, as displayed in Fig. 2.

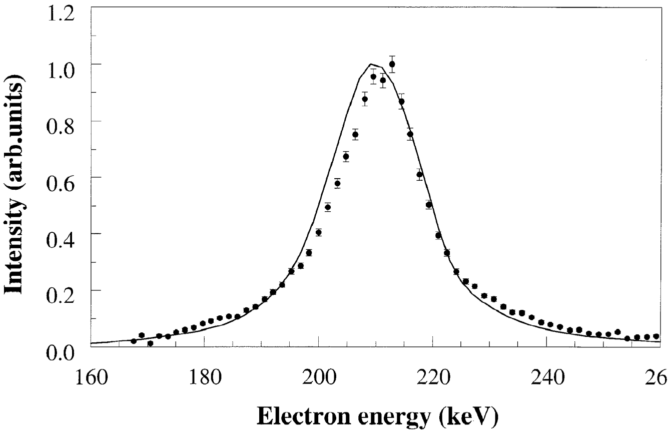

Fig. 3. Comparison of the calculated (full line) and measured (symbols) convoy electron spectrum resulting from the transmission of 390 MeV/amu Ar^{17+} ions through an amorphous carbon foil of 5400 μg/cm^2. The calculation has been convoluted with the experimental energy ($\Delta E = \pm 8$ keV) and angular ($\Delta\theta = \pm 1^\circ$) resolutions.

In summary, we have performed a simulation of the spectra of electrons emitted at forward angles due to the impact of a highly charged relativistic argon ion on carbon foils. We have shown that the width and the intensity of the convoy electron peak exhibits a nonmonotonic behavior as a function of foil thickness due to sequential excitation of the initially bound electron and the random walk after ionization. A more detailed study of this problem is under way [13].

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