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R. A. Sparrow

Ronald E. Olson
*Missouri University of Science and Technology*, olson@mst.edu

D. Schneider



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LETTER TO THE EDITOR

# Electron emission from foils induced by energetic heavy-ion impact

R A Sparrow†, R E Olson† and D Schneider‡

† Physics Department, University of Missouri-Rolla, Rolla, MO 65401, USA
‡ High Temperature Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

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**Abstract.** Doubly-differential cross sections have been measured and calculated for the electron emission produced by collisions of 3.5 MeV $u^{-1}$ $U^{38+}$ on thin carbon foils. The electron emission is observed in both forward and backward directions. Calculations are in reasonable agreement with the experimental results in both shape and absolute magnitude. At intermediate foil thicknesses, a double binary peak structure is observed that is due to 0° binary electrons being elastically scattered to angle $\theta$ along with those that are produced at $\theta$ and suffer no large-angle scattering events in the foil. Absolute electron yields show that several hundred electrons are released per ion impact. The computed time evolution of the forwardly emitted electrons indicates that the electrons tend to follow the ion for thin foils, but precede the ion in thick foils.

The study of electrons emitted from foils by the transit of energetic, heavy ions has been the subject of several experimental investigations (see, for example, Toburen *et al* 1982). However, theoretical developments have lagged behind the experimental ones due to the difficulty in accurately predicting the multiple ionization of a target by the impact of a highly-charged ion. The development of the $n$-body classical trajectory Monte Carlo ($n$CTMC) method for ion–atom collisions (Olson *et al* 1989) provides some understanding of these collisions.

There are several practical reasons why the dynamics of electron emission by heavy-ion impact is attracting interest. One reason is because accelerated heavy ions are now being used in radiotherapy (Kraft 1987, Toburen *et al* 1989). Another reason is that the heavy ions present in cosmic rays, albeit a small component, have detrimental effects on space-based computer systems (Dressendorfer 1989). Moreover, heavy-ion inertial nuclear fusion schemes are in critical need of a complete understanding of beam–pellet shell interactions.

This letter presents experimental results for the impact of multiply-ionized heavy ions on thin carbon foils. The systems studied experimentally are 3.5 MeV $u^{-1}$ $U^{38+}$ on 20 and 44 $\mu$g cm$^{-2}$ carbon foils. A theoretical model has been developed which utilizes information about the multiply-ionized electrons from the $n$CTMC method. The ionized electrons produced in single collisions of the ion with the carbon target are then numerically transported until they exit the foil, using simultaneous energy loss from $dE/dx$ measurements and angular scattering from elastic quantal calculations. Hence, the angular and energy straggling of the electrons are treated simultaneously, removing the necessity to make assumptions about the electrons' paths from their initial scattering angle (Schiwietz *et al* 1990). In this work we treat fast electrons, $E_{el} \geqslant 100$ eV, to remove the distraction of electron–surface interactions and potentials.

The set-up for the 3.5 MeV $u^{-1}$ $U^{38+}$ experiment has been described previously (Schneider *et al* 1989). The ion beam was produced at the Super HILAC of the Lawrence Berkeley Laboratory. Ion beam currents of 5 to 10 nA were collimated to a spot size of 4 mm$^2$ prior to entering a magnetically shielded scattering chamber. The ion beam was at normal incidence to the carbon foils and was collected in a Faraday cup. The secondary electron emission was detected by an electrostatic 90° parallel-plate analyser which could be moved to different angles with respect to the incident ion beam. The intrinsic energy resolution of the analyser is 8% (FWHM), the solid angle is $6 \times 10^{-4}$ sr, and its overall efficiency is 30%. The base pressure in the chamber was kept at about $3 \times 10^{-7}$ Torr.

The absolute doubly differential electron emission yields were determined (Schneider *et al* 1989, Schiwietz *et al* 1990) with an error of ±40%, which is primarily due to uncertainties in the collected charge and detector efficiency. The relative uncertainty with regard to electron emission angle is typically ±15%.

The theoretical method will be briefly described in this letter. A full description and the intermediate benchmarks used to validate the theory will be given later in a full paper on the subject. The model is a numerical one and is not based on the Landau and Goudsmit–Saunderson transport methods that have been conventionally applied to this problem (Lencinas *et al* 1990). The carbon foil is assumed to be amorphous.

For the calculations considered here, 20 000 multiply-charged ions were passed through the foils. At each collision with a carbon atom (approximately 20 collisions/$\mu$g/cm$^2$), an $n$CTMC calculation was performed in order to obtain the initial burst of electrons which are then transported through the solid. The projectile ion was assumed to maintain its initial charge state as it traversed the foil. A Hartree–Fock-based model potential was utilized to represent the electron screening on the partially-stripped projectile ion (Garvey *et al* 1975, Green *et al* 1969). All six target electrons were explicitly included in the target representation.

The electrons released at each collision of the projectile with the target were then transported through the solid using an energy loss $\mathrm{d}E/\mathrm{d}x$ determined by the Bethe–Block method which was normalized to experimental results (Lencinas *et al* 1990). The angular scattering of these electrons was determined by partial-wave quantal calculations of the elastic differential cross sections evaluated at each electron energy assuming a static Hartree–Fock interaction for the carbon. The azimuthal scattering angle of the electron was randomized, and its position coordinates recorded. Each secondary electron was numerically followed until it either exited the foil or its translational energy decreased to below 100 eV. When the electron exited the foil, its energy and angle was recorded for subsequent determination of the doubly differential electron yields. These cross sections were also integrated over all angles and energies to determine the total electron yield produced per ion impact. Since a real-time event file was calculated, it was also possible to present the time dependence of the emitted electrons relative to the position of the projectile in the foil. In total, about $10^{10}$ collisions were numerically evaluated, requiring several hours on a desktop workstation computer. The electron transport was benchmarked against experimental results for the angular and energy straggling of monoenergetic electrons incident on thin carbon foils (Lencinas *et al* 1990). Excellent agreement between theory and experiment was realized.

The doubly differential electron yields for 3.5 MeV $u^{-1}$ $U^{38+}$ ion impact on a 44 $\mu$g cm$^{-2}$ carbon foil are given in figure 1. Both the experimental and theoretical results are on an absolute basis and have not been normalized with respect to one another. In general, there is agreement within a factor of two between the calculations and the experimental results. Major discrepancies are present, however, in the binary peak region around 6 keV electron energies for scattering at angles less than 40°. At backward angles, there is good agreement in the shapes of the electron yields, but the experimental magnitudes are underestimated by approximately a factor of three. The total electron yield per ion is calculated to be 254, and rises to 373 and 533 electrons/ion for 100 and 1000 $\mu$g cm$^{-2}$ thick foils, respectively. Experimental results indicate that the yield should saturate at approximately 900 electrons emitted per ion for a very thick target and at an equilibrium charge state for the U ion (Rothard *et al* 1990). Since the equilibrium charge state of the 3.5 MeV $u^{-1}$ projectile in solids is closer to 50+ (Berg *et al* 1988), a $q^2$-scaling of the experimental result is 520 electrons/ion, which is in reasonable agreement with the calculations for $U^{38+}$.

Closer examination of the 3.5 MeV $u^{-1}$ $U^{38+}$ results around 40° reveals an interesting double-peak structure present in both theory and experiment for both 20 and 44 $\mu$g cm$^{-2}$ foils (figure 2). To help interpret the results, we also present

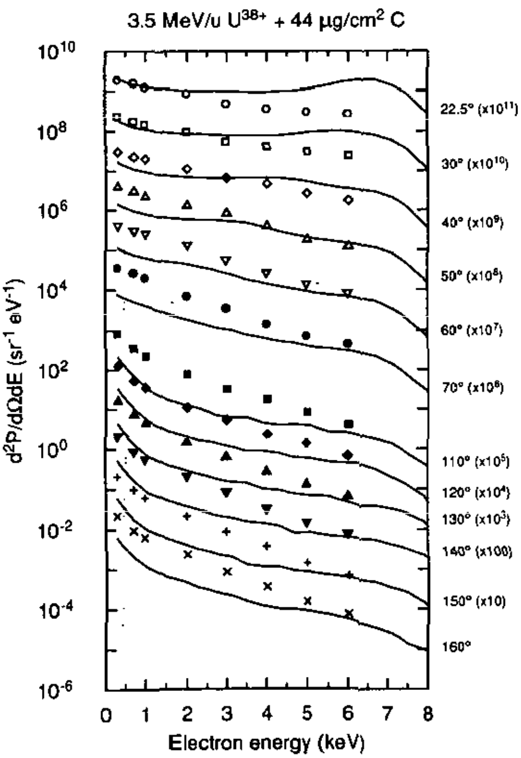


**Figure 1.** *Doubly differential electron yields for 3.5 MeV $u^{-1}$ $U^{38+}$ passing through a 44 $\mu$g cm$^{-2}$ carbon foil.* The data points are absolute experimental results and the curves are the results of the calculations described in the text.

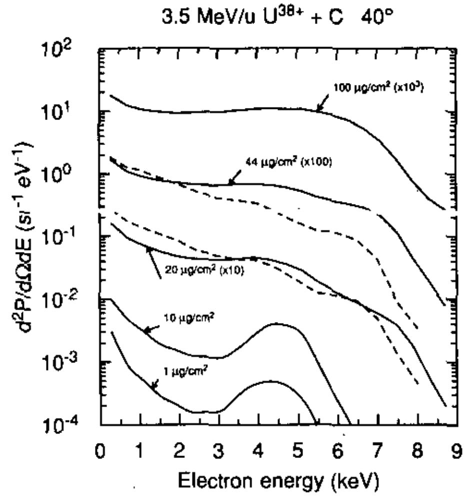


**Figure 2.** Binary peak structure for 3.5 MeV $u^{-1}$ $U^{38+}$ ions passing through carbon foils of varying thicknesses. The full curves are calculated results, while the broken curves for 20 and 44 $\mu$g cm$^{-2}$ foils are the data which also display the double binary peaks at ejected electron energies of approximately 4.5 and 7.6 keV.

calculations for 1, 10 and 100 $\mu$g cm$^{-2}$. Here, for the very thin foils one observes a well pronounced binary peak at

$$E_e = 2m_e(\mu/m_e)^2 v^2 \cos^2\theta$$

where $\mu$ is the reduced mass of the electron–projectile system, $m_e$ the electron mass, and $\theta$ the electron's initial ejection angle. For a 3.5 MeV $u^{-1}$ projectile scattering an electron to 40°, this corresponds to an electron energy of 4.5 keV. However, as the foil thickness is increased, a shoulder develops which extends to 7.6 keV. These electrons are binary electrons initially produced by a hard collision between projectile and target electron with the electron scattered to 0°. Subsequent collisions of these hot electrons with foil constituents give rise to wide angle scattering. Since the average energy loss, $dE/dx$, is small for fast electrons, there is little energy loss for the electrons originally born in a 0° scattering event with the projectile.

In many applications, it is important to know the time evolution of the electrons emitted from a thin target. This information is directly available from our numerical evaluations. The 3.5 MeV $u^{-1}$ $U^{38+}$ projectile on carbon foils was used to illustrate the different behaviour with foil thickness. In figure 3 are shown the percentages of total electrons emitted as a function of the position of the projectile in 1, 10 and 100 $\mu$g cm$^{-2}$ carbon foils. In the forward direction, $\theta < 90°$, we find only 12% of the electrons being emitted, before the projectile exits, for a very thin foil of 1 $\mu$g cm$^{-2}$, while with a thick foil of 100 $\mu$g cm$^{-2}$ almost 75% of the electrons precede the projectile. Moreover, for the thick foil, a major fraction of the electrons are emitted just as the projectile exits the foil. The reason for such behaviour is that the range of the slow electrons produced in the foils is sufficiently small for these electrons to be absorbed in a thick foil and never exit. Only the electrons born in hard collisions with the projectile deep in the foil find their way to the surface. For backward-emitted electrons a different behaviour is found (figure 3). Here, the electrons tend to be slow (figure 1), so that in thin foils the projectile has exited the foil before they are emitted. For thick targets, however, a major fraction of the electrons are emitted while the projectile is still in the foil, the reason being that the slow electrons scattered to backward angles have reduced ranges and are predominantly born near the entrance of the projectile in the foil.

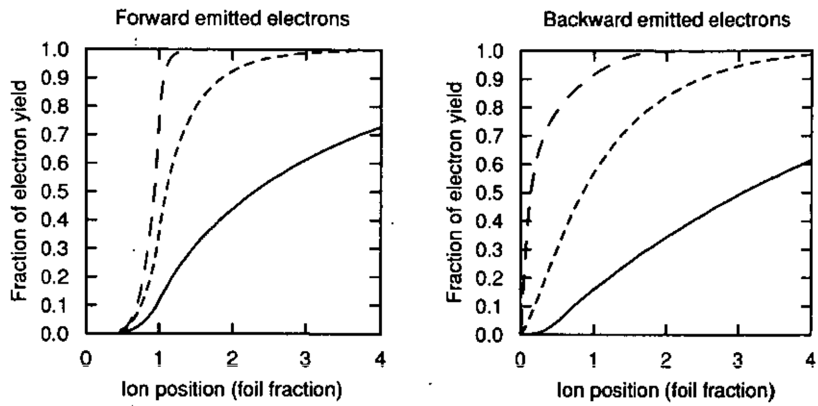


**Figure 3.** Cumulative electron yields emitted in the forward and backward directions as a function of the ion's position relative to the foil; the full, short-broken, and long-broken curves were calculated for 1, 10 and 100 $\mu$g cm$^{-2}$ foil thicknesses, respectively. The absolute yields were 36, 118 and 351 electrons/ion in the forward direction, and 2.4, 18.4 and 22.4 electrons/ion in the backward direction for the respective foil thicknesses listed above.

In conclusion, a new theoretical method for electrons produced in dense targets has been developed that employs a recent single-collision model ($n$CTMC) that improves the understanding of multiple-ionization collisions. Numerically intensive calculations are then used to transport the secondary electrons through the target. The electrons' energy losses and angular scattering are treated simultaneously. An interesting double binary peak has been observed for intermediate foil thicknesses, and confirmed by these calculations. Because the ion and electron positions are computed as a function of time, it is possible to predict the time evolution of the electrons relative to the position of the projectile inside and past the foil. Different time dependencies are presented, and are directly related to the foil thickness.

There is room for considerable improvement and sophistication of the theoretical model. A complete model should include the charge-state evolution of the projectile as it approaches its equilibrium charge in the foil. In the cases presented, the ion charge state was less than the thick solid target equilibrium charge state; this effect has not been accounted for in the calculations. Moreover, excitation and electron capture by the projectile with the subsequent stripping of these excited electrons has not been included either. On a similar system, 8 MeV $u^{-1}$ $U^{68+}$, we found the electron capture to excited states, followed by impact ionization of these electrons, to be a minor component of the electron yields and only contribute approximately 20% to the doubly differential electron yields at low electron energies. However, even with the above complications, the application of basic atomic collision models to dense targets is a challenging problem with many obvious applications.

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