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# Experimental study of electron ejection by heavy ion irradiation of solids: Observation of forward and backward emitted electron jets

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## Abstract

Doubly differential cross sections for electron emission induced by the passage of swift heavy ions such as $F^{q+}$ (1.5–2.0 MeV/u) through thin solid foil targets were measured at the Tandem accelerator of the JR Macdonald Laboratory at Kansas State University. The complete angular distribution of electron emission up to 4000 eV (beyond the maximum of the "binary encounter" electron peak) was determined as a function of the projectile charge state ($q = 5$ and 9) and the target material in a wide $Z$ range: C ($Z = 6$), Al ($Z = 13$) and Au ($Z = 79$). Electrons emitted from the foils between 0 and $\pm180°$ with respect to the beam axis were energy and angle analysed by means of a toroidal electrostatic electron spectrometer equipped with a 2D position sensitive channelplate detector. In addition to low energy cascade electrons, electrons from collective excitation (plasmons), target Auger electrons, convoy electrons and binary encounter electrons, we also observe a new feature never before seen in electron angular distributions: narrow electron jets ("spikes") emitted along the ion beam axis in forward and backward directions. This observation is made possible by the good angular resolution of our spectrometer and the possibility to record the entire angular distribution in a single run. 

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## 1. Introduction

The passage of fast ions through solid matter and the structure of the induced ionisation track have stimulated research since the early days of the discovery of the atomic structure of matter (see, for example, Bohr's famous paper of 1948 [1]). However, quantitative information on the spatial and temporal evolution of the potential distribution in the plasma along the ion track is still scarce. It is difficult to detect a characteristic signature of the ion track structure in the very moment of its

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birth, or during the very short duration of existence of the plasma-like state even though the track extends through the whole foil and thus represents a spatial structure of significant size. "Direct" information on the track structure can only be obtained during the extremely short lifetime of the track (estimated to be $10^{-14}$ s or less).

Material modification or damage due to electronic energy deposition by swift ions in condensed matter are strongly dependent on the details of the subsequent electron transport where the deposited energy is distributed along and around the ion trajectory. A significant fraction of the electrons is ejected from a zone near the solid surface and electron emission is thus one possible sensitive probe for ion–solid interactions [2,3]. In this paper, we report on measurements of electron momentum distributions recorded with a toroidal electrostatic electron spectrometer and the observation of strong very narrow spike-like electron emission jets into small angular regimes of $\pm 2°$ at emission angles of $\theta = 0°$ and 180° induced by fast ions traversing thin solid foils.

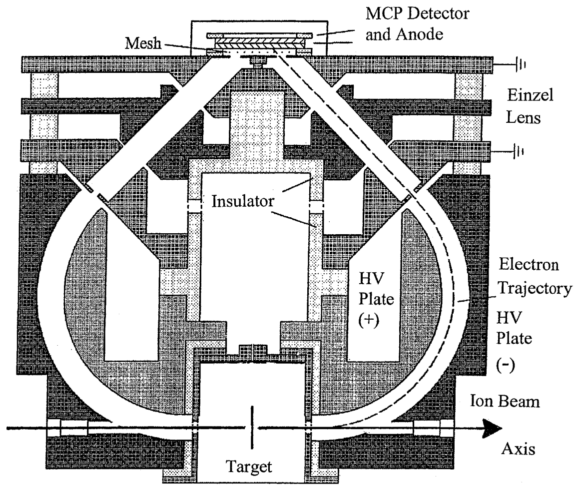


Fig. 1. Cross section of the toroidal spectrometer. All electro-optical elements of the instrument possess rotation symmetry with respect to an axis through the centre of the target and the MCP detector assembly (perpendicular to the ion beam axis). Electrons emitted in a plane perpendicular to the diagram plane are energy analysed while passing between the toroidal high voltage (HV) plates. The complete range of emission angles $\theta$ of electrons between 0° through 180° to 360° with respect to the beam is thus covered. Also shown are trajectories of emitted electrons reaching the position sensitive MCP detector.

## 2. Experiment

The experiment was performed at the 7.5 MV Tandem accelerator of the JR Macdonald Laboratory at Kansas State University with a toroidal electron spectrometer designed by one of us (S.H.). Its cross section is shown in Fig. 1 and it is described in detail in [4,5]. This figure presents a cut through the spectrometer, which is rotational symmetric around the axis through the centre being perpendicular to the ion beam axis. The target region is shielded by a metallic cylinder set on ground potential and thus the electric field in the target area has no detectable effect. The collimated ion beam (spot less than $0.2 \times 0.2$ mm$^2$) enters through a hole of 6 mm diameter and hits the foil or gas target in the centre of the target cylinder. The projectiles leave the spectrometer through a second hole in the outer electrode.

Electrons, emitted in the toroidal plane (perpendicular to the toroidal axis) are energy analysed by the toroidal electrodes. The electron pass energy is determined by the spectrometer voltage and the geometrical spectrometer factor. The solid angle is 0.15 sr, the angular resolution 1.5° and the energy resolution 2%. Electrons with a kinetic energy up to about 5 keV can be detected. After leaving the toroidal shells, the electrons are focussed by a truncated cone lens onto the position sensitive microchannelplate (MCP) detector equipped with a wedge- and strip-anode for the identification of the electron's angular position. The apparatus was intensively used for the measurement of electron emission in ion–gas target collisions (see e.g. [6]). Here, we present data obtained with thin solid foil targets.

## 3. Electron momentum and energy distributions

As an example for a doubly differential electron momentum distribution, the integrated count rate

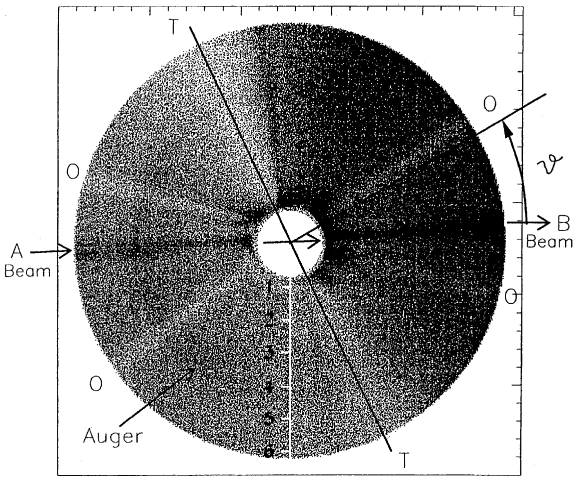


Fig. 2. Momentum distribution of electrons emitted in collisions of $F^{6+}$ (2 MeV/u) with a carbon foil (thickness 10 μg/cm$^2$). The radius reflects the electron momentum (in atomic units, from 1 to 6 a.u.). Angular position B corresponds to the polar angle 0° and position A to 180°, respectively. The positions T indicate the target orientation.

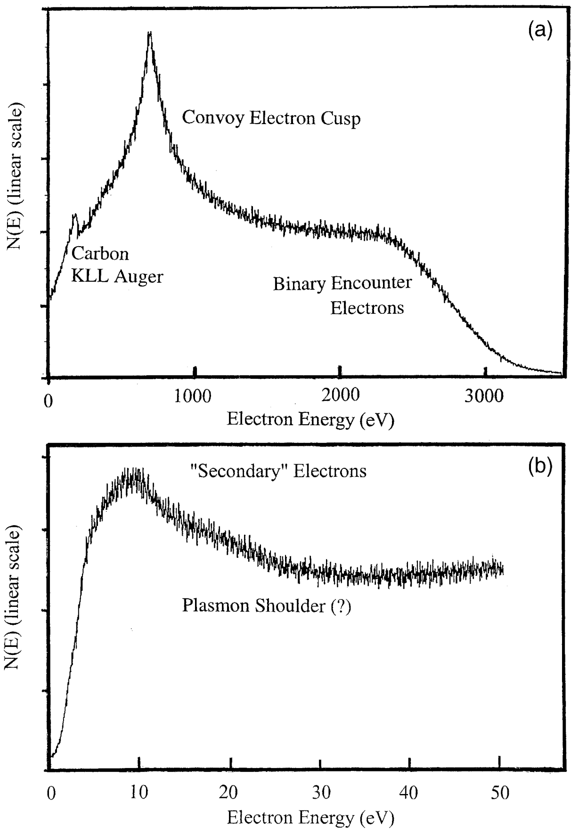


Fig. 3. Angle integrated energy distributions $N(E)$ for collisions of $F^{9+}$ (1.5 MeV/u) with a carbon foil (thickness 5 μg/cm$^2$); (a) high electron energy, (b) low energy part of the electron emission spectrum.

density is shown for 2 MeV/u $F^{6+}$ projectiles impact on 10 μg/cm$^2$ carbon foil in Fig. 2. Polar co-ordinates are used and the electron emission angle is measured with respect to the projectile beam direction. The radius reflects the electron momentum in atomic units. Indicated are the target axis (T)–(T), the beam direction (A)–(B) and the angular position of four obstacles (O) related to the design of the ring aperture in the metallic cylinder (see Fig. 1). Electron momenta range from $p_e \approx 1$ a.u. ($E_{min} \approx 13.6$ eV) up to $p_e \approx 6.1$ a.u. ($E_{max} \approx 510$ eV). The cusp momentum corresponding to electrons travelling with projectile velocity is $p_e = 8.9$ a.u. (corresponding to $E_{cusp} = 1097$ eV, but being outside the range covered in this figure).

The carbon KLL-Auger line is visible as a faint ring structure at about 4.4 a.u. (265 eV). At the position of the toroid obstacles (O), the intensity has the expected minima (the angular width of the obstacles is 3°). The target holder (T) is mounted in a plane which intersects the beam direction under 105° and 285°. Furthermore, one observes a significantly higher electron emission cross section in forward direction than in backward direction. We mention that this effect is much more pronounced with gold targets ($Z = 79$) than with carbon targets ($Z = 6$).

By integrating over the ejection angle, one can obtain the energy distribution $N(E)$. Such electron energy distributions $N(E)$ induced by 1.5 MeV/u $F^{9+}$ projectiles interacting with a 5 μg/cm$^2$ carbon foil are shown in Fig. 3. In the high energy part of the energy distribution (Fig. 3(a)), one observes carbon KLL-Auger electrons, the convoy electron cusp peak and binary encounter electrons. In the low energy region as shown in Fig. 3(b), low energy "secondary" electrons and, possibly, the plasmon decay shoulder from the collective excitation (longitudinal oscillation) of valence electrons [7] can be observed.

## 4. Angular distributions: electron spikes

All these structures are in principle well known [3,7]. A new feature is, however, observed from a closer inspection of the angular distribution of emitted electrons (Fig. 2). At $\theta = 0°$ and 180°, we obtain a strongly enhanced count rate which appears as a sharp and very narrow ridge (about 4° wide in emission angle), which can be regarded as a kind of electron jet. This structure can be seen as a distinct spike in the integrated electron angular distribution of Fig. 4. This new, never before observed spike structure, was observed independently for different projectiles over a wide range of collision energies. After a first series of experiments with C and Al foil targets [5], we recently performed a new series with different C and Au targets exposed to 1.5 MeV/u $F^{q+}$ beams ($q = 5$ and 9) and confirmed the previous results.

It is important to note that up to now, angular distributions were obtained by step-by-step measurements of electron spectra at different emission angles [3]. The present measurements allow for the first time a complete imaging of the entire angular distribution with significantly higher angular resolution. Only in this way, by a complete and simultaneous look at the angular emission characteristics, it became possible to observe the electron jets for the first time. The steep and narrow ridge in electron emission is visible in the backward direction for electrons up to twice the velocity of the projectile, $v_e = 2v_{projectile}$. The intensity decreases with increasing momentum. In the forward direction, it is only seen up to the cusp velocity, $v_e \leqslant v_{projectile}$.

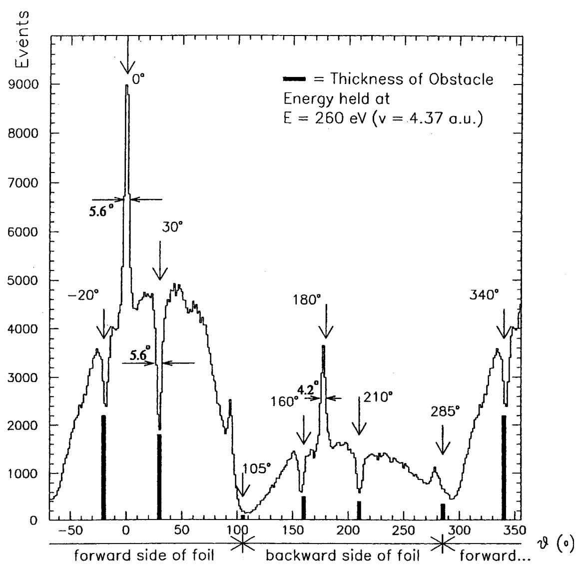


Fig. 4. Angular distribution, i.e. electron count rate versus emission angle $\theta$; electron velocity and energy held constant at 4.37 a.u. and 260 eV, respectively. Projectile: $F^{6+}$ at 2 MeV/u.

The physical origin of this new phenomenon is still unclear. A tentative explanation, nevertheless, may be a "nuclear-track" channelling effect. One may imagine that the plasma potential channels forward- and backward-emitted electrons below certain emission angles and energies back into the track, thus acting like a lens. If this picture holds, one should find an enhanced electron emission at 0° and 180° with respect to beam direction. We surmise that these jet-like structures coinciding exactly with the beam direction are closely related to the electronic polarisation wake trailing the projectile [8]. We note that manifestation of collective wake-related effects [9] and minima in angular distributions at 180° in electron emission angular distributions were indeed reported [10].

Assuming the wake potential in the track to have damped oscillatory structure along the beam direction [8], we observe that the gradient of such a potential is formally equivalent to a succession of accel–decel lenses used in charged-particle focussing. The effect of this plasma focussing depends on the plasma potential gradients, its depths and the plasma lifetime. All previous attempts to identify signatures of track focussing effects have been unsuccessful beside the very recent investigation of Xiao et al. [11], who found evidence for track guided electrons by measuring the cusp electron profile with high resolution. Electron-jet emission phenomena were also observed in laser–solid interaction [12]. Furthermore, angular directed fragment emission has been reported [13] and was attributed to the track focussing effect in the evaporation of molecules from solid surfaces.

## 5. Conclusion

We present first evidence for electron jets emitted into the forward and backward directions along the projectile ion beam axis. A possible explanation may be channelling-like motion of quasi-free ionisation electrons in the nuclear-track potential (“track focussing”). However, other explanations cannot be excluded at the present time. It is particularly intriguing that similar effects exist in laser–solid interactions, which are explained by multiphoton absorption and magnetic focussing effects. The fact that the spikes in ion–solid interaction are only observed for electron velocities $v_e \leqslant v_{projectile}$ up to projectile velocity in forward direction is a strong argument towards the proposed explanation related to the perturbation induced in the solid behind the projectile.

The observation of this spike-like electron emission may provide for the future the opportunity to extract precise information on short living induced nuclear tracks in solids. These measurements are important in view of the relevance of the experimental cross sections for electron emission for model calculations in radiobiology and radiotherapy with heavy ions where the increase of the radiobiological effectiveness is a consequence of the inhomogeneous dose distribution in particle tracks reflecting the energy spectrum of this electron emission.

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