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Electron Emission from Surfaces
How Do Fast Atomic Projectiles Extract Electrons from Solids?

The emission of electrons from solid surfaces induced by atomic particles is studied via the coincident detection of the projectile energy loss and the number of emitted electrons. This new type of »translation energy spectroscopy« applied to atom-surface scattering allows one to investigate in detail the relevant electronic processes, i.e., to relate the dissipation of projectile energy to the emission of a specific number of emitted electrons. With this method we could clear up the different microscopic interaction mechanisms for the emission of electrons from insulator and metal surfaces and explain the at first sight surprising feature of a more efficient emission of electrons tightly bound in crystals of insulators compared to clean metal surfaces.

Electron emission induced by impact of atomic particles on solid surfaces is of substantial interest in fundamental research and technological applications. As examples we mention particle detectors, surface analytical tools, or plasma wall interactions. Two different groups of emission processes are of particular relevance: (1) kinetic emission (KE) where energy of impinging projectiles is transferred to electrons in the solid, and (2) potential emission (PE) where internal excitation energies of projectiles are converted into electronic excitations of the target [1]. In our studies performed over recent years in close collaboration with Profs. HP. Winter and F. Aumayr from TU Vienna (Austria) and Dr. Roncin (LCAM Orsay, France) we have concentrated on studies on kinetic emission (KE) phenomena making use of a setup that combines in a coincident manner the benefits of energy loss spectroscopy with the detection of a specific number of emitted electrons. With this experimental technique, we have studied in detail KE from solid surfaces, i.e. metal as well as insulator targets, and could contribute to an understanding of the relevant microscopic interaction mechanisms [2, 3]. This holds, in particular, for the kinematic threshold behaviour of KE which was only vaguely known so far.

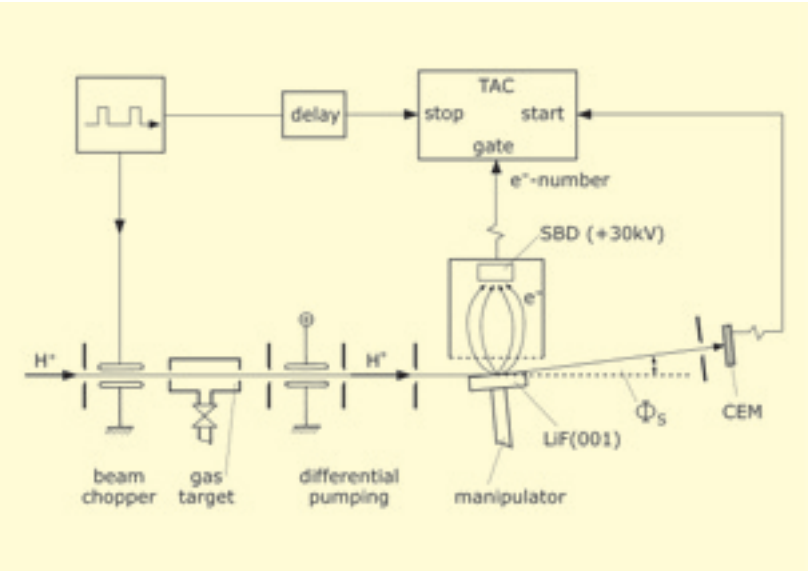


Fig. 2
Sketch of experimental setup for coincident TOF-electron number studies.

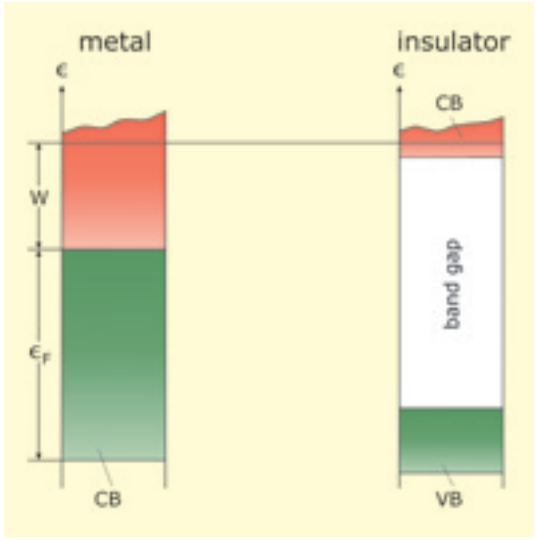


Fig. 1
Sketch of electronic energy diagram for metal (left panel) and insulator (right panel).

For the emission of electrons from a solid target, their binding energies play an important role, since the transfer of energy from atomic projectiles to electrons of the solid has to be sufficiently large in order to reach vacuum energies. In Fig. 1 we show a sketch of electronic energy diagrams for a metal and an insulator. Metals are characterized by a continuum of conduction band states occupied up to the »Fermi-level« so that electrons have to overcome at least the work function W (typically 4 to 5 eV for clean metals) in order to pass the solid-vacuum interface. Insulators (ionic crystals) have a flat valence band with electronic binding energies of typically 10 eV and a conduction band separated by a broad band gap.

For an estimate on the electron emission process from a solid target we consider the maximum energy transfer to an electron of kinetic energy E_e and mass m_e in a classical binary collision with an atomic projectile of mass M. From conservation of momentum and energy, one finds for an electronic binding energy with respect to vacuum E_b a threshold electron emission at a projectile energy

$$E_{th} = \frac{M}{2m_e}\left(E_e - \sqrt{E_e\,(E_e + E_b)} + \frac{E_b}{2}\right) \qquad (1)$$

This amounts for collisions, e.g., of H atoms with an Al surface (E_e = 10.6 eV = Fermi energy, E_b = W = 4.3 eV = work function) to E_{th} = 168 eV (v_{th} = 0.082 a.u.; a.u. = »atomic unit«), whereas for LiF ($E_e \approx$ 4 eV = width of F2p valence band, E_b = 12 eV) we find E_{th} = 1836 eV (v_{th} = 0.271 a.u.). The resulting E_{th} for the insulator is about one order of magnitude higher than for the metal surface which is in contrast with the experimental findings (see below).

In our studies with the setup displayed in Fig. 2 we could clear up this problem and identify the relevant interaction mechanisms. In an UHV chamber at a base pressure of some 10^{-11} mbar pulsed beams of H or He atoms with energies ranging from some 100 eV to some 10 keV are scattered under a grazing angle of incidence Φ_{in} (typically 1 to 2 deg) from a clean and

flat surface of a crystal. Scattered projectiles are recorded by means of a channelplate which serves as start detector of our time-of-flight (TOF) system for recording the overall projectile energy loss. Electrons emitted from the target are recorded by a surface barrier detector (SBD) at a potential of about 25 keV where the pulse heights are proportional to the number of electrons emitted during single collision events [5]. This coincident combination of the two detection channels allows one to relate the overall electronic excitations to the emission of a specific number of electrons. We used neutral atomic projectiles, i.e., H and He atoms here, since ions may give rise to contributions from potential emission (PE) of electrons.

Since in our method SBD pulse heights are recorded only when an event is registered by the channelplate detector, we can also obtain accurate information on events related to the emission of no electron (noise level of SBD). This is the basis for precise measurements of low total electron yields γ from measured probabilities W_n for a specific number n of emitted electrons [5] via

$$\gamma = \sum_{0}^{\infty} n\, W_n \Big/ \sum_{0}^{\infty} W_n \qquad (2)$$

For low γ W_0 will dominate the electron number spectrum, but for non-coincident detection with a free running SBD this information can not be obtained.

From a plot of TOF-spectra (energy loss) vs. SBD pulse height (electron number) as shown in Fig. 3 one can directly identify the relevant electronic excitation and emission processes. The discrete peak structures present in the spectra reflect the broad band gap of ionic crystals (about 14 eV for LiF). The most intense peak in the lower left corner stems from projectiles which are elastically scattered under channeling conditions in front of the topmost layer of surface atoms with a negligible transfer of energy to the crystal lattice (less than 1 eV) [6]. The second peak in the left column (0 electrons) shows an additional energy loss of 12 eV [7]; the resulting excitation process proceeds without emission of an electron and is ascribed to the production of a surface exciton, a local electron-hole pair. Also the production of a second exciton can be identified in the spectrum. In the second column (1 electron) we find events combined with the emission of one electron, emission of one electron and production of one and more excitons. The mean energy loss for emission of an electron is slightly larger than for the production of an exciton and amounts to 14 eV. In the third column (2 electrons) we find events related to the emission of two electrons, emission of two electrons plus production of one exciton, etc.

From the data presented in Fig. 3 we derive relative intensities and probabilities for the emission of 0, 1, and 2 electrons and the production of a specific number of excitons. The full bars in Fig. 4 represent the

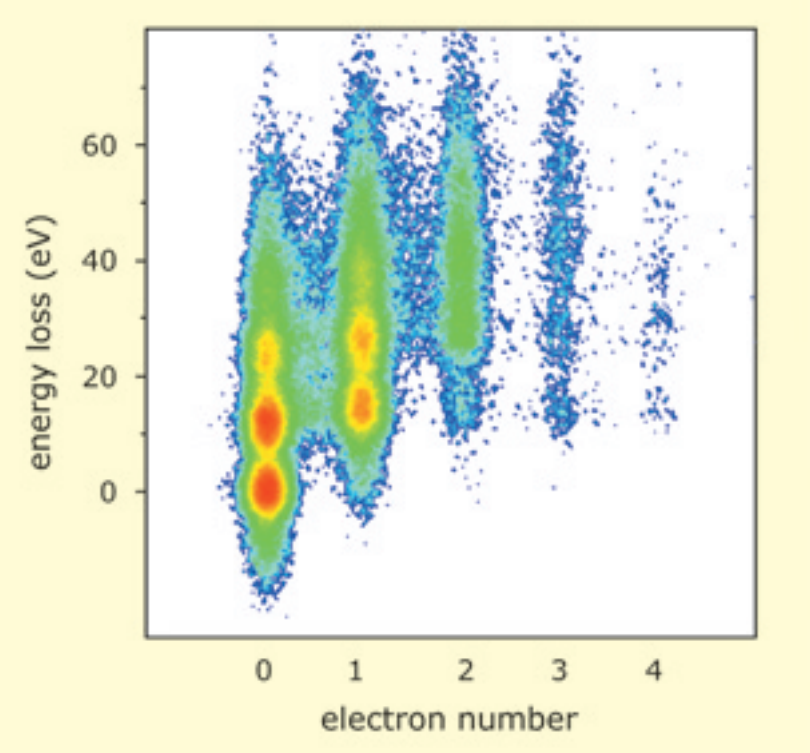


Fig. 3
2D plot of coincident TOF (vertical axis, »energy loss«) and SBD spectra (horizontal axis, »electron number«) for scattering of 1 keV hydrogen atoms from LiF(001) under Φ_{in} = 1.8 deg.

Elektronenemission
Die Emission von Elektronen aus Festkörpern spielt eine große Rolle in vielen technischen Anwendungen; induziert durch atomare Teilchen ist diese Grundlage von Teilchendetektion, Oberflächen-Analytik, Plasma-Wand-Wechselwirkungen, etc. Dabei ist insb. der Übertrag kinetischer Energie der einfallenden Teilchen auf die Elektronen des Festköpers wichtig, dessen mikroskopisches Verständnis angesichts der hohen Relevanz der Prozesse bisher noch erstaunlich wenig entwickelt ist. Durch die Methode der koinzidenten Kombination einer Flugzeitspektroskopie und des Nachweises der Anzahl emittierter Elektronen können die inelastischen Prozesse der Wechselwirkung in unmittelbare Relation zur Emission von Elektronen gebracht werden. Durch die hohe Genauigkeit der Messung sehr kleiner Elektronenausbeuten läßt sich erstmals das Schwellenverhalten der Emissionsprozesse im Detail studieren.

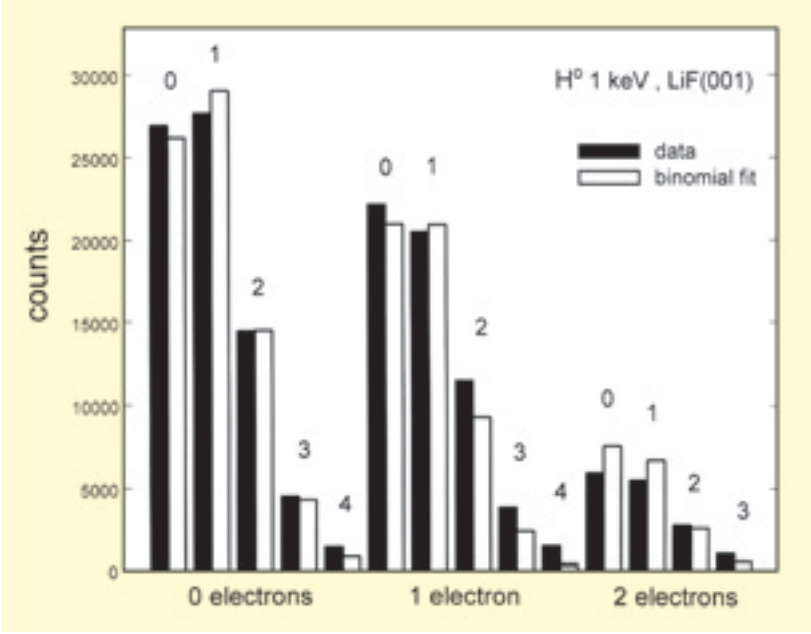
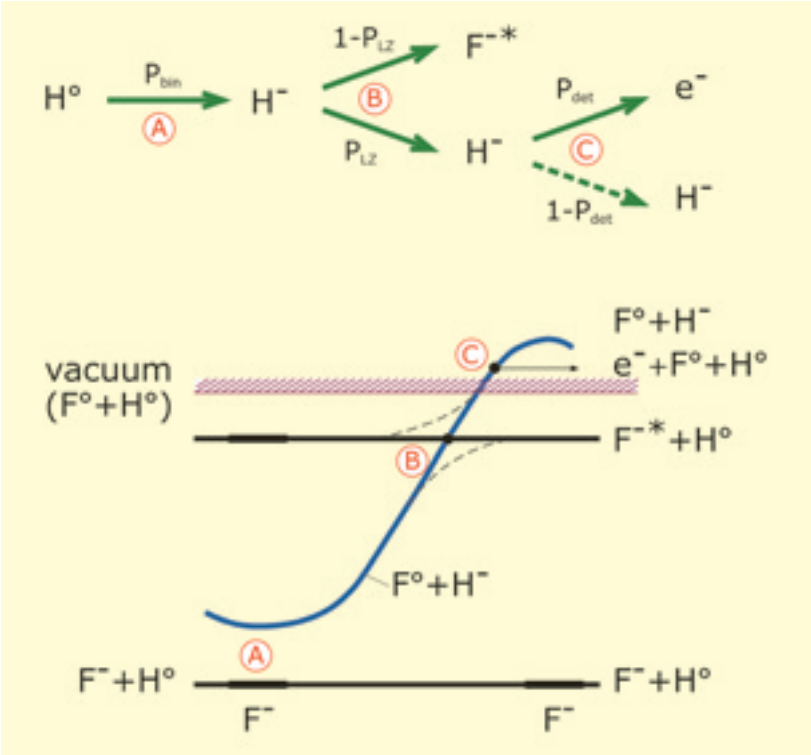


Fig. 4
Bar graph of intensities for spectra shown in Fig. 3 for emission of specific number of electrons and production of excitons (number at bar). Full bars: experiment, open bars: analysis of data in terms of binomial statistics with parameters derived from interaction model.



experimental data, the open bars the result of a statistical analysis in terms of an interaction model sketched in Fig. 5.

Key feature of the interaction model is the formation of a negative ion in a local capture event of an electron from a halide site. Since this »active site« is embedded in the lattice of an ionic crystal, there is an additional binding by surrounding positive charges (»Madelung potential«) which results in a substantial increase of binding energies of negative ions and a reduction in the energy defect in collisions of atoms with anions. As a consequence, one finds a high probability for electron capture. In the further sequence of the collision, a level crossing with an exciton level takes place. Electrons result eventually from the detachment of the negative ions at further lattice sites with probability P_{det}. With these model assumptions we succeeded to describe the threshold behaviour for the electronic excitation and emission processes in a consistent manner. In this respect it is important to note that our method provides total electron emission yields from measured electron number distributions (cf. Fig. 3) with unprecedented accuracy. This holds, in particular, for very small yields close to the kinematic threshold for electron emission.

Electron emission from metal surfaces proceeds via a different mechanism. This can be directly seen from the spectrum in Fig. 6 recorded for scattering of 12 keV He atoms from an aluminum surface under a grazing angle of incidence of 2.2 deg where no discrete structures in the projectile energy loss are present. Simple reason for this observation is the electronic structure of metals with a continuum of conduction band states and with the highest energy for occupied states at the Fermi level (electron energy E_F and velocity v_F) (cf. Fig. 1). From data as shown in the figure we derive total electron yields and energy loss spectra resolved with respect to the emission of a specific number of electrons.

We interpret our experiments on electron emission from metal targets in terms of a simple classical model of binary encounters between a projectile atom and conduction electrons [8]. In such elastic collisions of electrons with a heavy particle, the initial electron

Fig. 5
Sketch of interaction path (upper part) and interaction model (lower part) comprising potential energy curves for scattering of hydrogen atoms from LiF(001) under grazing angle of incidence.

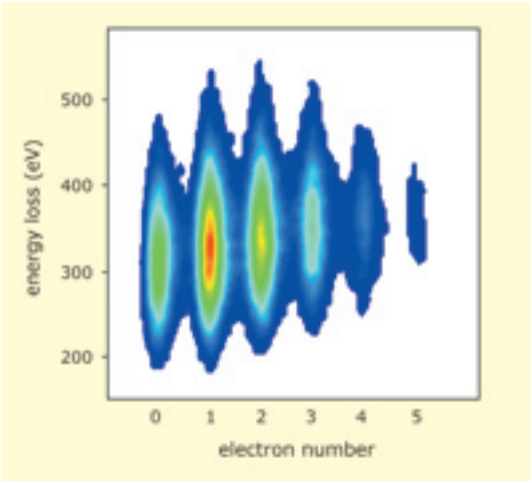


Fig. 6
2D plot of coincident TOF (vertical axis, »energy loss«) and SBD spectra (horizontal axis, »electron number«) for scattering of 12 keV He atoms from Al(111) under Φ_{in} = 2.2 deg

momentum is reversed with respect to the direction of the incident atoms plus momentum $2m_e v_p$ (m_e = electron mass, v_p = projectile velocity). In the framework of a description of the density of states in the free-electron approximation, the electronic excitations can be considered by a shift of the Fermi sphere in momentum space by momentum $2m_e v_p$ [3]. In this approach, electron emission can take place for electron momenta (energies) $m_e v_e$ ($E_e = m_e v_e^2/2$), if $E_e > E_F + W$. This condition results in a threshold for KE at a projectile energy as given by eq. 1. Furthermore one can derive from the model with simple phase space arguments a threshold law for the KE yield with a quadratic dependence on projectile velocity.

In Fig. 7 we show total electron yields as function of projectile velocity for impact of He atoms on Al(111) at a grazing angle of incidence of 1.9 deg. The measured total yields can be fitted near threshold fairly well by a quadratic dependence on velocity. The threshold velocity slightly deviates from the value derived from eq. 1 using the Fermi energy for bulk electron densities. This is attributed to the feature that for grazing collisions projectiles reach a distance of closest approach to the surface plane (about 2 a.u. here) where electron density and resulting Fermi velocity (energy) are smaller than within the bulk.

Fig. 8
Mean electron energy transfer as function of projectile energy for He atoms scattered from Al(111) under 1.9 deg. Solid curves: model calculations.

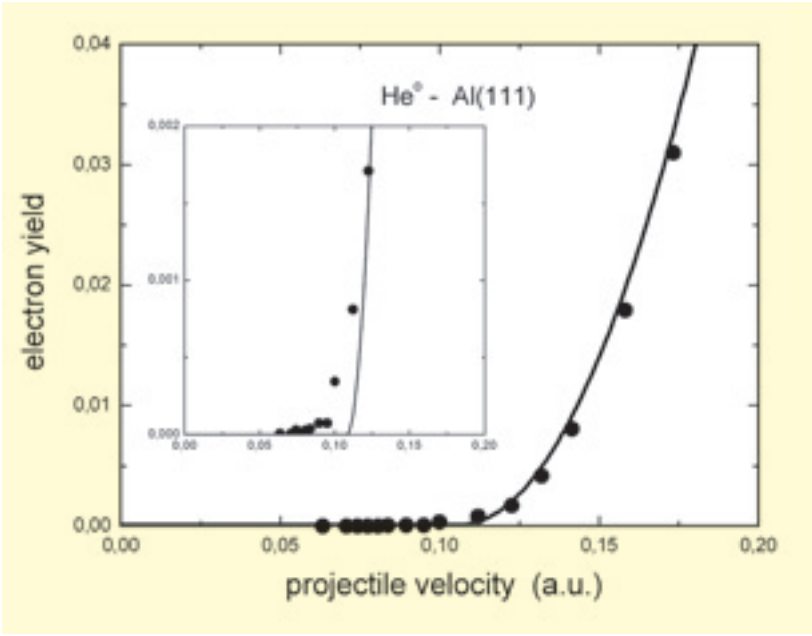
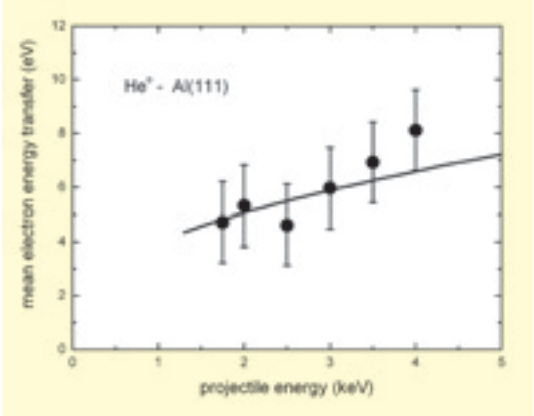


Fig. 7
Total electron yield as function of projectile velocity for He atoms (full circles) scattered from Al(111) under 1.9 deg. Solid curve: model calculations. Inset: vertical scale enlarged by factor of 20.

A closer inspection of the data shown in Fig. 6 reveals a small but defined shift between energy loss spectra for different numbers of emitted electrons. The additional energy loss is caused by the mean energy transfer to conduction electrons to reach vacuum energies. In Fig. 8 we show the difference of the mean energy loss related to the emission of no and one electron for He atoms scattered from Al(111) as function of projectile energy. Near the kinematic threshold (E_{th} = 0.7 keV) the energy transfer is close to the work function of the target and increases with increasing projectile



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energy. The solid curve in the figure represents calculations where the phase space for occupied and empty electronic metal states is obtained from the model of the shifted Fermi sphere mentioned above [3]. An important conclusion of this study comes from a comparison of this energy transfer with the overall energy loss of projectiles which amounts to about 50 eV at 2 keV. In this near threshold region total electron yields are 1 % so that only one per mille of the energy dissipated in the metal results in the emission of electrons.

In conclusion, particle induced electron emission from insulator and metal surfaces proceeds under very different microscopic interaction mechanisms. For (ionic) insulators the formation of transient negative ions is responsible for the extraction of electrons from the solids, whereas for metals energy transfer to conduction electrons is achieved in binary encounters. These findings explain the at first sight surprising fact that the surfaces of ionic crystals are more efficient electron emitters under atomic particle bombardment than metals.

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