Electronic stopping of slow protons in transition metals

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When an ion propagates in matter, it loses energy due to interaction with nuclei and electrons of the target – also called nuclear and electronic stopping, respectively. The mean energy loss per path length is given by the stopping power $S = dE/dx$. Alternatively, the electronic stopping cross section ε (SCS) is defined as

$$\varepsilon = \frac{1}{n}\frac{dE}{dx},$$

where n is the atomic density of the target. Electronic stopping is well understood for large ion velocities. For slow ions, electronic stopping of a point charge in a free electron gas (FEG) is known to be proportional to ion velocity, $S \propto v$, [1 - 3]. This also holds for a FEG-metal like Al [4], as long as v is smaller than the Fermi velocity of the target electrons.

Results for noble metals show a deviation from this velocity proportionality at $v \sim 0.2$ a.u.: for gold with an excitation threshold of the d-electrons of ~ 2 eV, at $v < 0.2$ a.u. the electronic SCS is dominated by the excitation of 6*s*-electrons, while for $v > 0.2$ a.u. also the *d*-band contributes [5 - 7].

For transition metals the *d*-band exhibits a high density of states (DOS) at the Fermi level, E_F, which is the basis of their high chemical reactivity. Consequently, it is demanding to produce high purity samples for electronic stopping measurements of slow ions and to minimize the influence of possible surface oxide layers and bulk impurities like hydrogen, which would impede precise measurements of electronic stopping powers in these materials.

In this contribution the low velocity electronic SCS for H^+ ions in Ni and Ta are presented. While Ni features a filled d-band with high DOS(E_F), but very low DOS($E > E_F$), the d-band of Ta is only partly filled with high DOS below and above E_F. For Ni the energy loss data were obtained from energy spectra of hydrogen ions backscattered from a high purity sheet and from nanometer Ni films of various thicknesses, prepared in-situ. Since target composition is a critical point, the samples have been analysed by x-ray induced photoelectron spectroscopy (XPS), Auger electron spectroscopy (AES) and elastic recoil detection (ERD).

The SCS of Ni and Ta are compared to data of Au [6] and Pt [8]. As can be seen in Fig. 1, at v > 0.2 a.u. (1 keV protons), Ni exhibits the lowest and Ta the highest electronic SCS, although the integrated DOS of Ni and Ta yield 11 and 5 electrons per atom, respectively. While for Ni and Pt, the experimental SCS data can be quantitatively described in terms of a FEG model, this does not hold for Ta, for which an absurdly high number of conduction electrons would be required to explain the highly efficient electronic stopping. We trace this observation back to the fact, that only Ta features high DOS both, below and above E_F so that excitation across E_F can take place with high probability. Further experiments are needed to confirm this thesis.

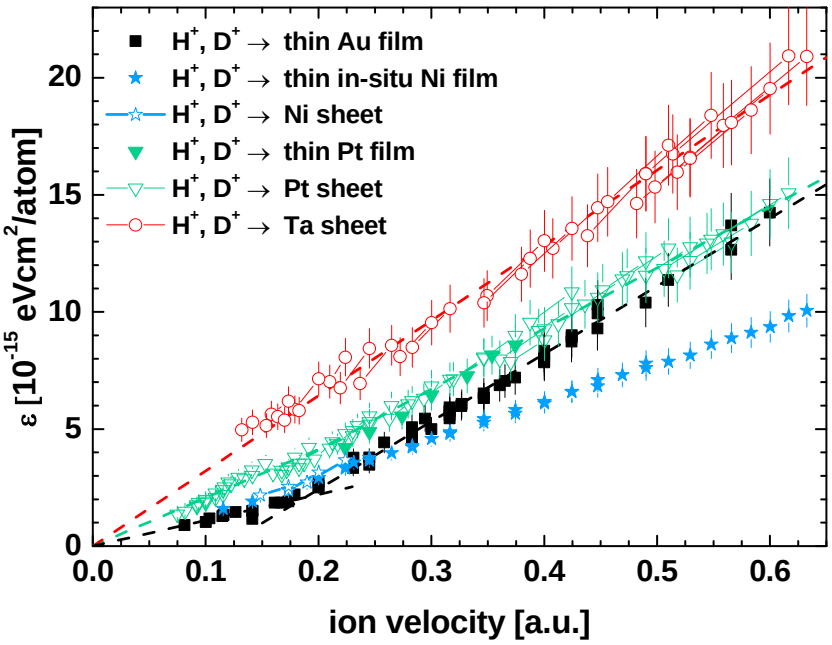

Fig. 1: Electronic stopping cross section ε of H^+ ions in Au [6], Pt [8], Ni and Ta as a function of the primary ion velocity.

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