JKU JOHANNES KEPLER UNIVERSITÄT LINZ

ATOM UND OBERFLÄCHEN PHYSIK

Electronic stopping of slow protons in transition metals

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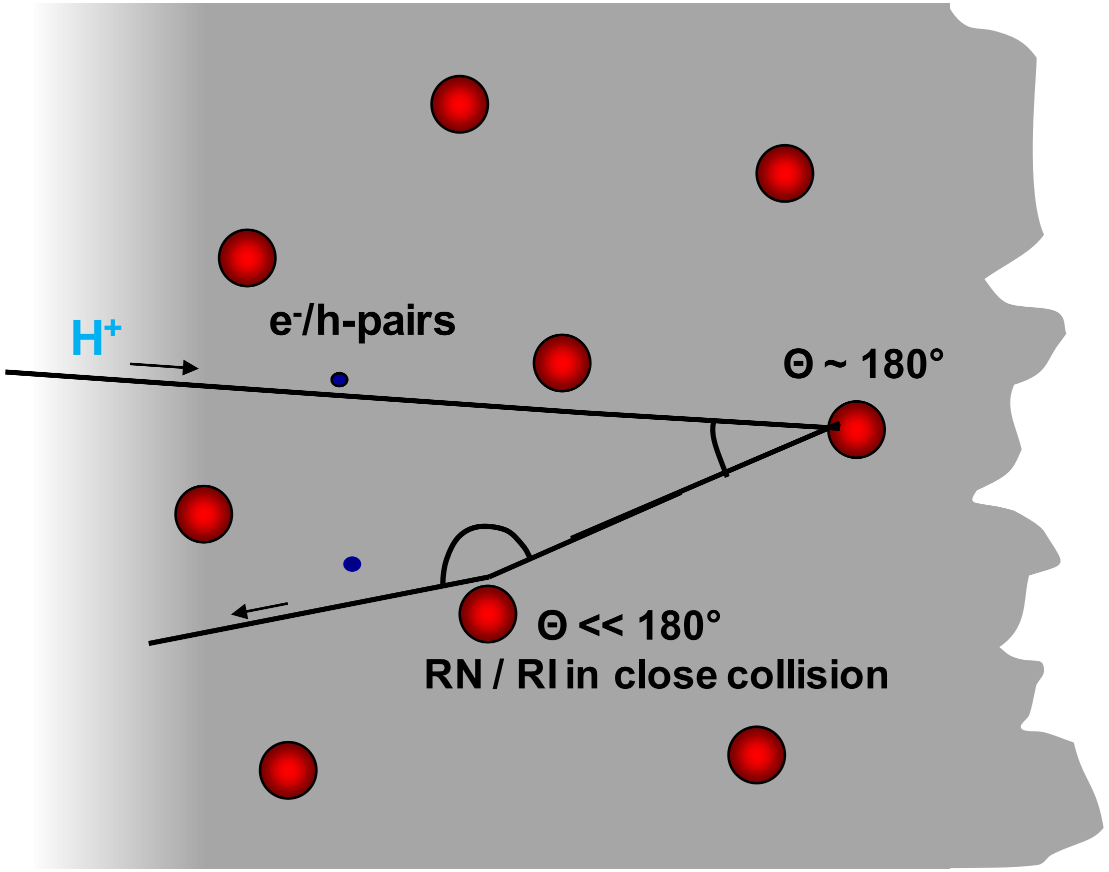
OUTLINE

- Interactions of ions with matter
- Electronic stopping: state of the art
- Transition metals
  - Impurities and characterization (ERD, XPS)
- Data evaluation
  - Spectrum width and height
- Electronic stopping of H^+ in transition metals (Ni, Pt, Ta)

ENERGY LOSS OF IONS IN MATTER

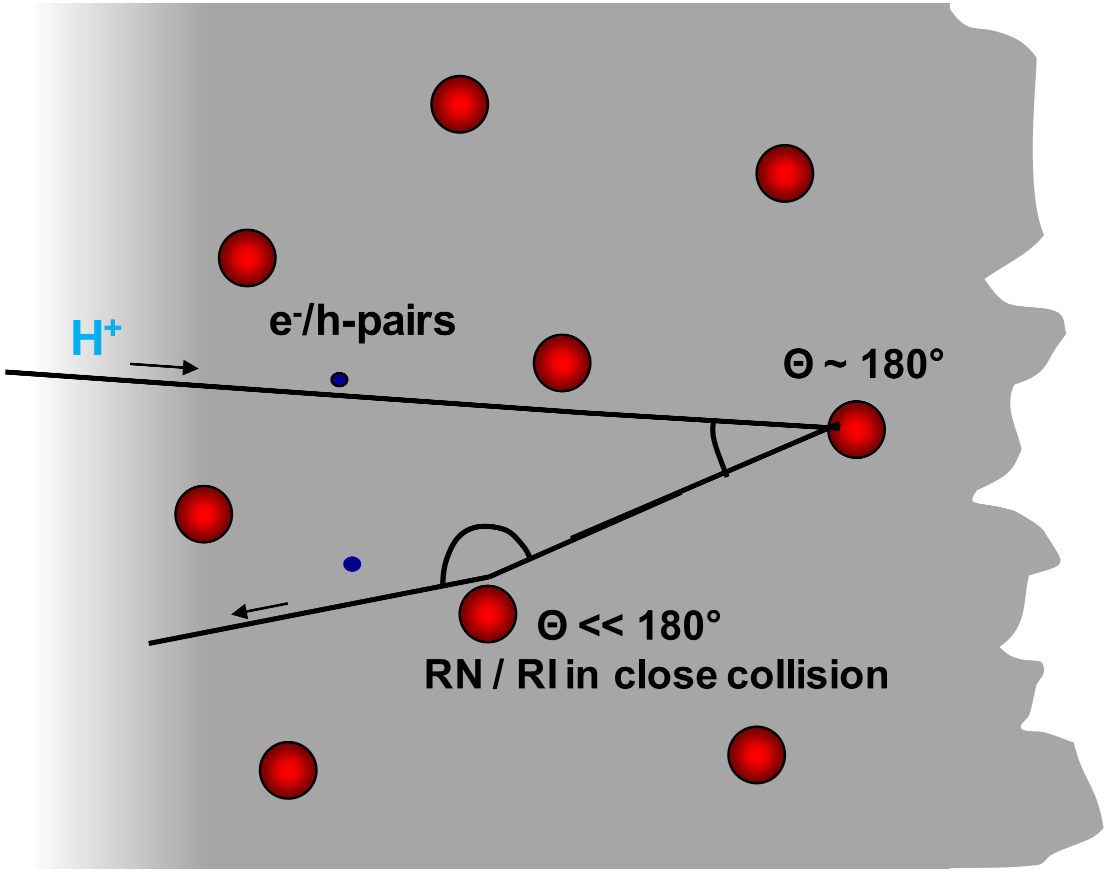
- Charge exchange
- Large angle scattering
- Nuclear and electronic stopping



ENERGY LOSS OF IONS IN MATTER

- Charge exchange
- Large angle scattering
- Nuclear and electronic stopping
- Stopping power $S = -\frac{dE}{dx}$
- Electronic stopping cross section

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



ENERGY LOSS OF IONS IN MATTER

- Slow ions ($v < v_F$)
  ≡ **strong perturbation**
- Theory: free electron gas (FEG)

$$S = Q(Z_1, r_s)\, v$$

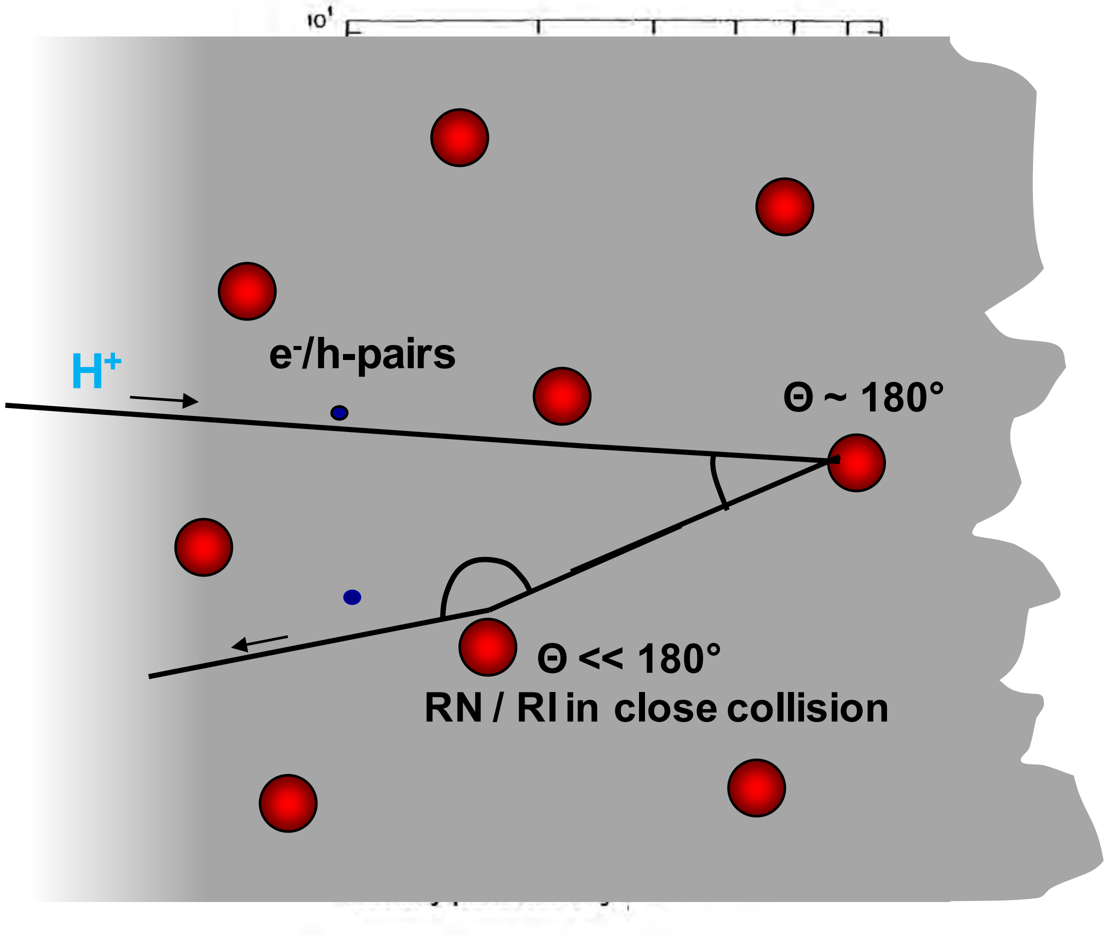
Q … friction coefficient

r_s… density parameter

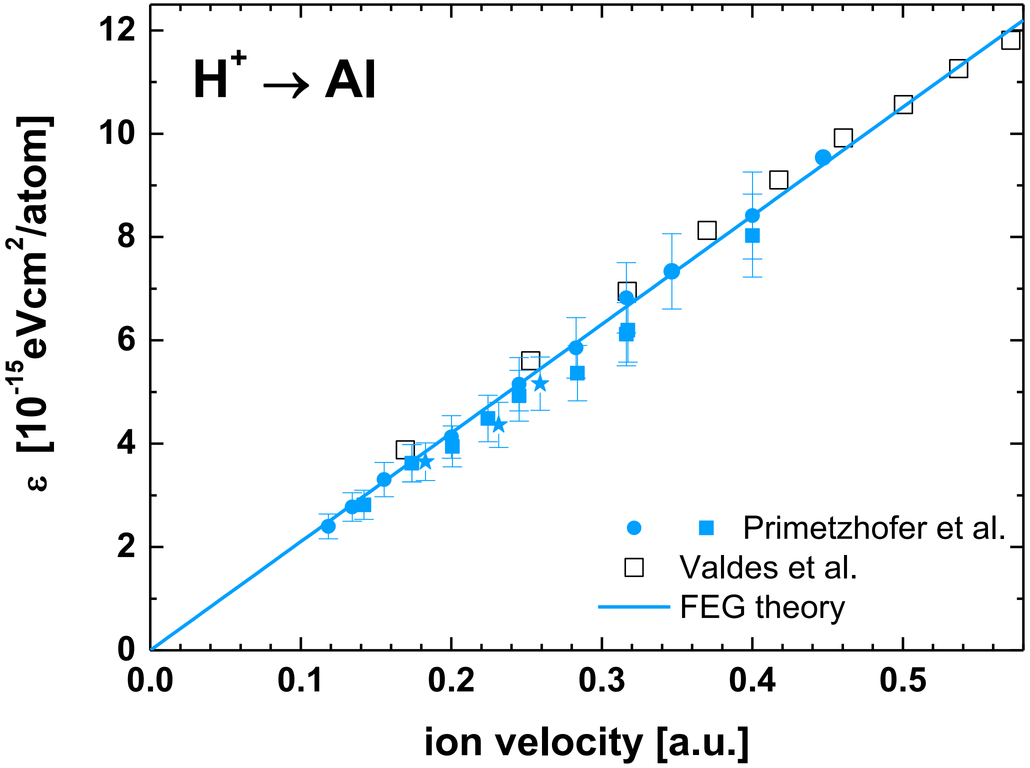
with $r_s = \left(\frac{3}{4\pi n_e}\right)^{1/3}$

n_e… electron density of FEG

E. Fermi & E. Teller (1947)



ELECTRONIC STOPPING IN A FEG LIKE METAL
$H^+ \rightarrow Al$

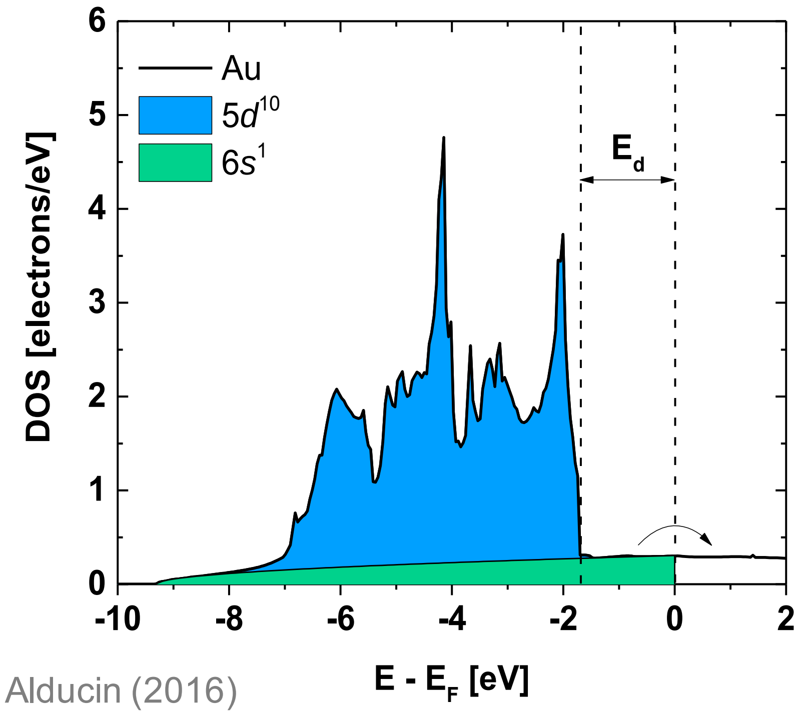


D. Primetzhofer et al (2011)
Valdes et al (1993)

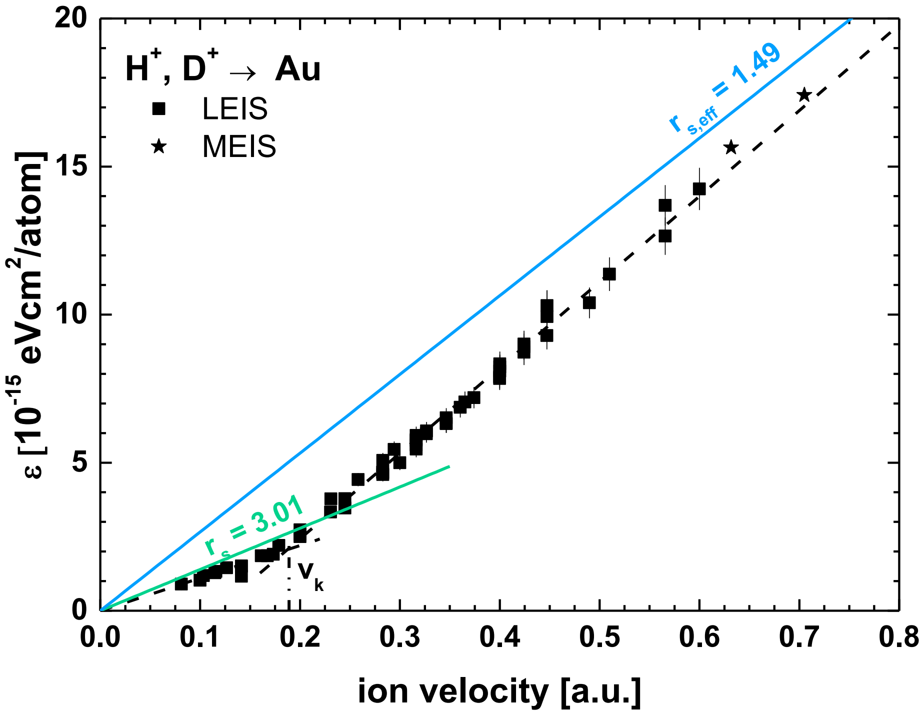
- Al ≡ FEG like metal
- density parameter: r_s = 2.12
- $\frac{dE}{dx} = Q \cdot v$

ELECTRONIC STOPPING BEYOND FEG:
noble metal – Au

$$\frac{dE}{dx} \neq Q \cdot v$$



M. Alducin (2016)

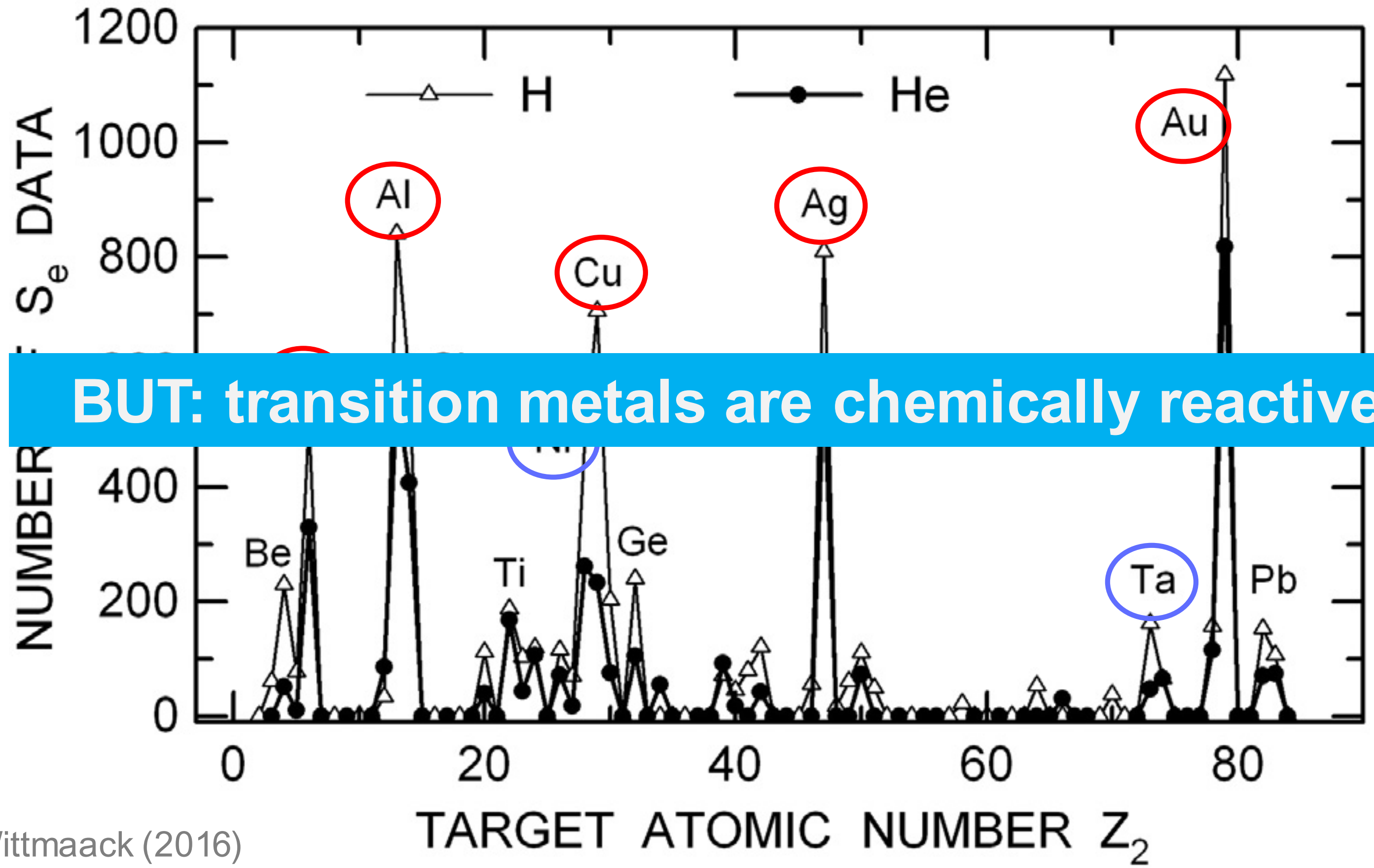


FEG + d-electrons

LEIS: S.N. Markin et al (2008)
MEIS: D. Primetzhofer (2012)

TRANSITION METALS: WHY?

Frequency of stopping power measurements:



K. Wittmaack (2016)

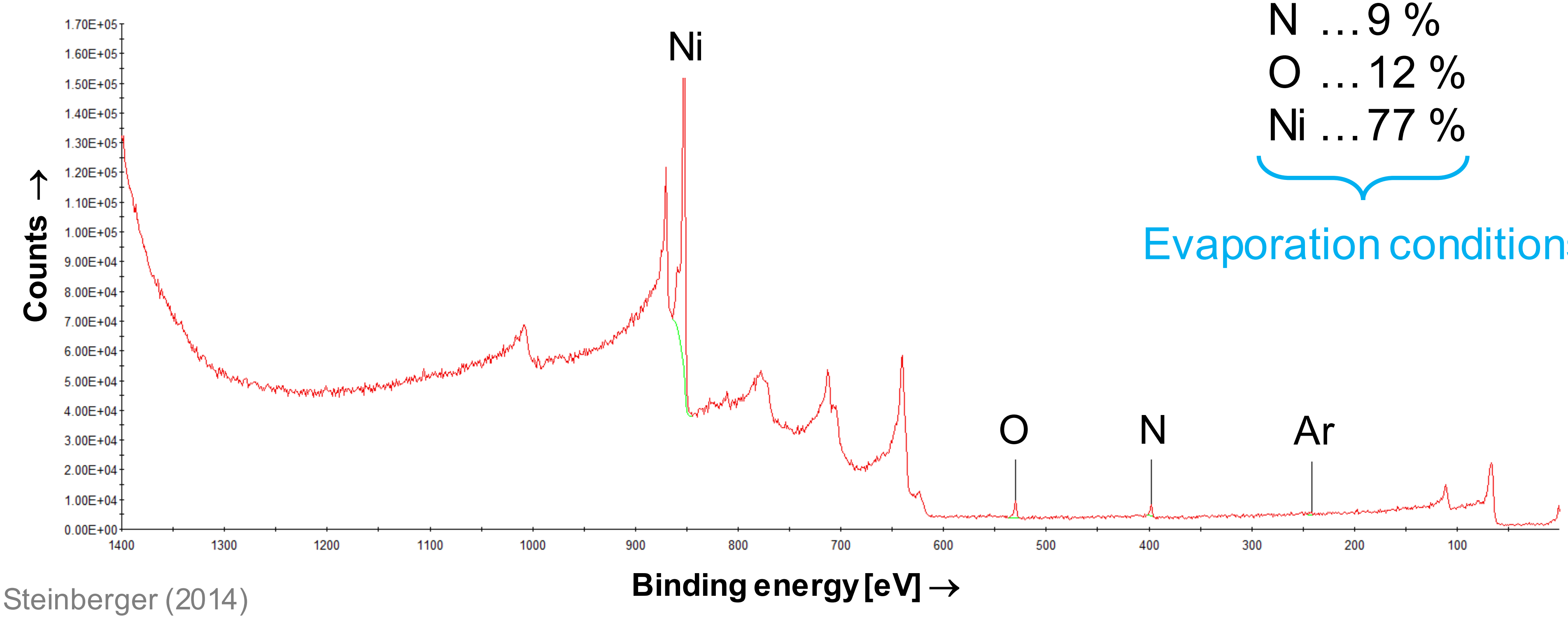
BUT: transition metals are chemically reactive

TRANSITION METALS: IMPURITIES?
ex-situ Ni film

XPS on sputtered sample:

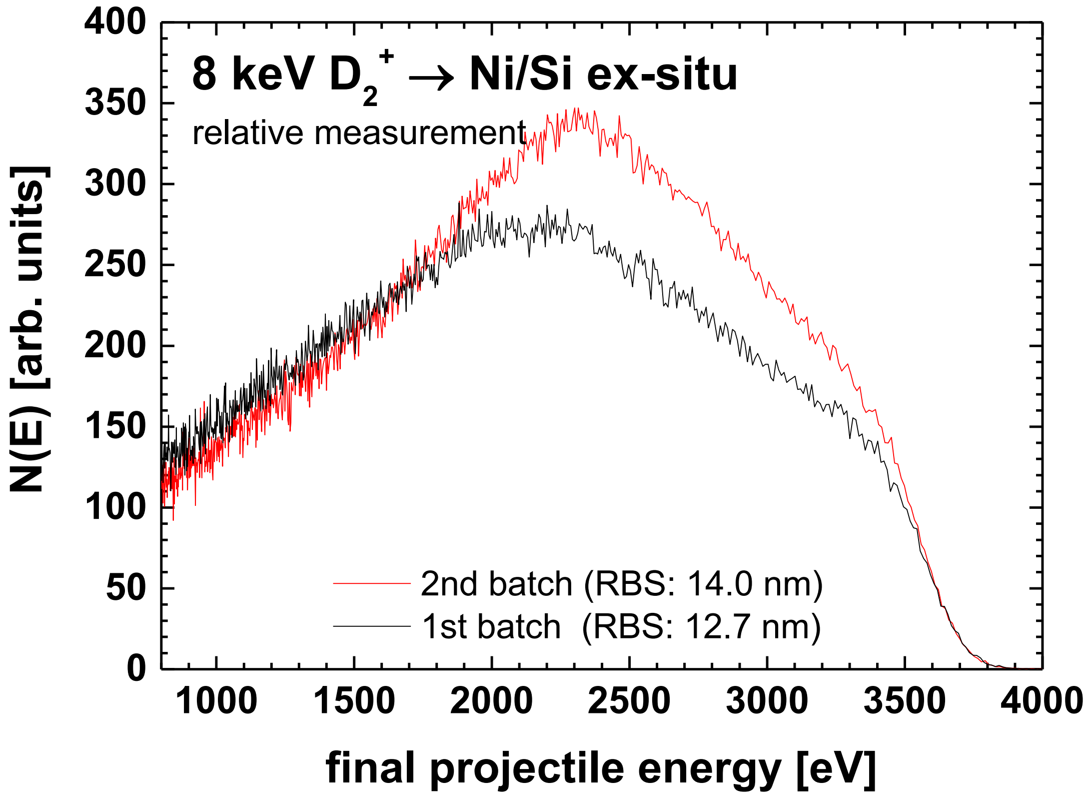
Ar … 2 %
N … 9 %
O … 12 %
Ni … 77 %

Evaporation conditions!?



R. Steinberger (2014)

DIFFERENT IMPURITY CONCENTRATIONS



- Constant primary charge
- Identical $d\sigma/d\Omega$

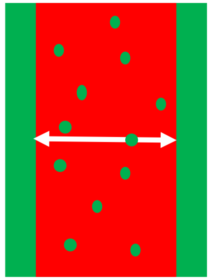
$$\rightarrow H(kE_0) \propto \frac{1}{\varepsilon(E_0)}$$

$$\Delta E_{BS} \propto \varepsilon(E_0)$$

Changes in height & width ↔ impurities!

STOPPING CROSS SECTION MEASUREMENT

- **Target areal density** $n\Delta x$ (RBS):
  - □ areal density (atoms / cm^2) $n\Delta x \rightarrow$ SCS $\varepsilon = \frac{1}{n}\frac{dE}{dx}$
  - □ ideal case: $\left.\frac{dE}{dx}\right|_{exp} = \left.\frac{dE}{dx}\right|_{metal}$



$n\Delta x_{expt} = n\Delta x_{metal}$

- □ impurities $\rightarrow$ $\Delta E = \Delta E + dE$

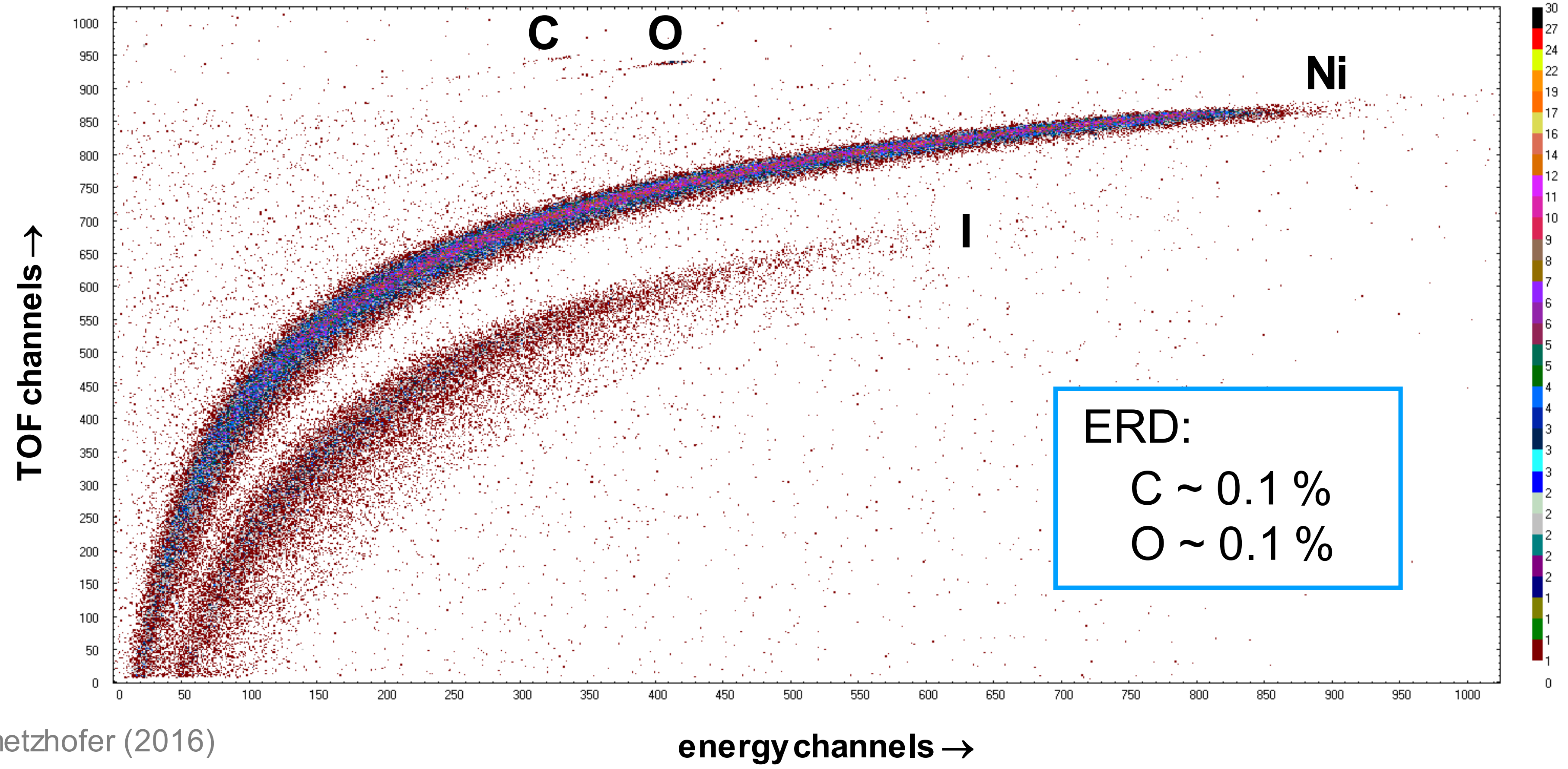
$\downarrow$

measured energy loss

$$\left.\frac{1}{n}\frac{dE}{dx}\right|_{expt} = \frac{\Delta E_{metal} + dE_{impurities}}{n\Delta x_{metal}} > \left.\frac{1}{n}\frac{dE}{dx}\right|_{metal}$$

$\rightarrow$ **measured SCS is too high**

TRANSITION METALS: IMPURITIES?
thick high purity Ni sheet

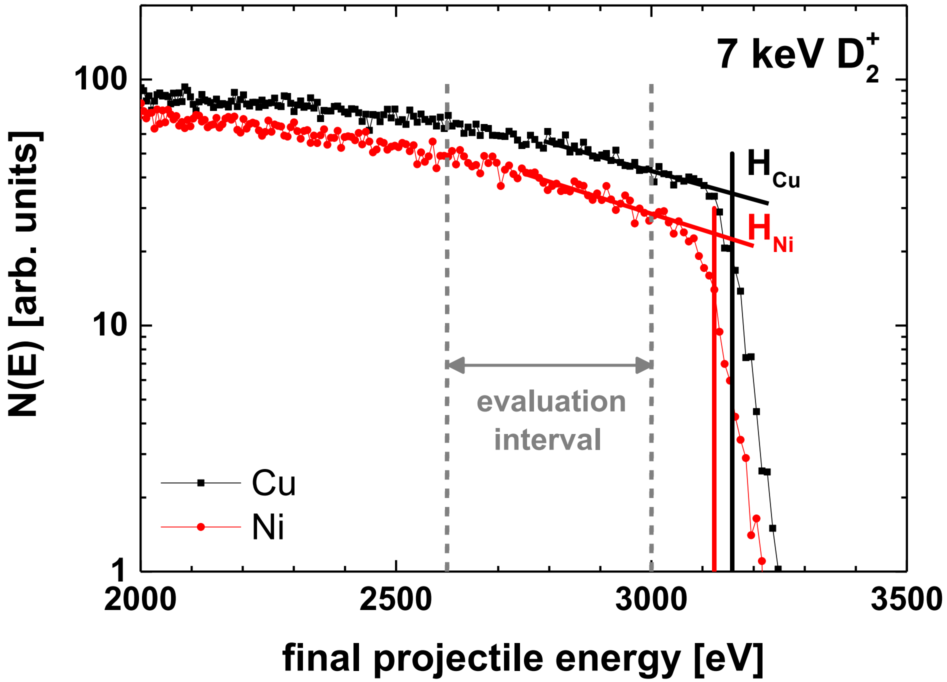


D. Primetzhofer (2016)

DATA EVALUATION – spectrum height
thick Ni sheet

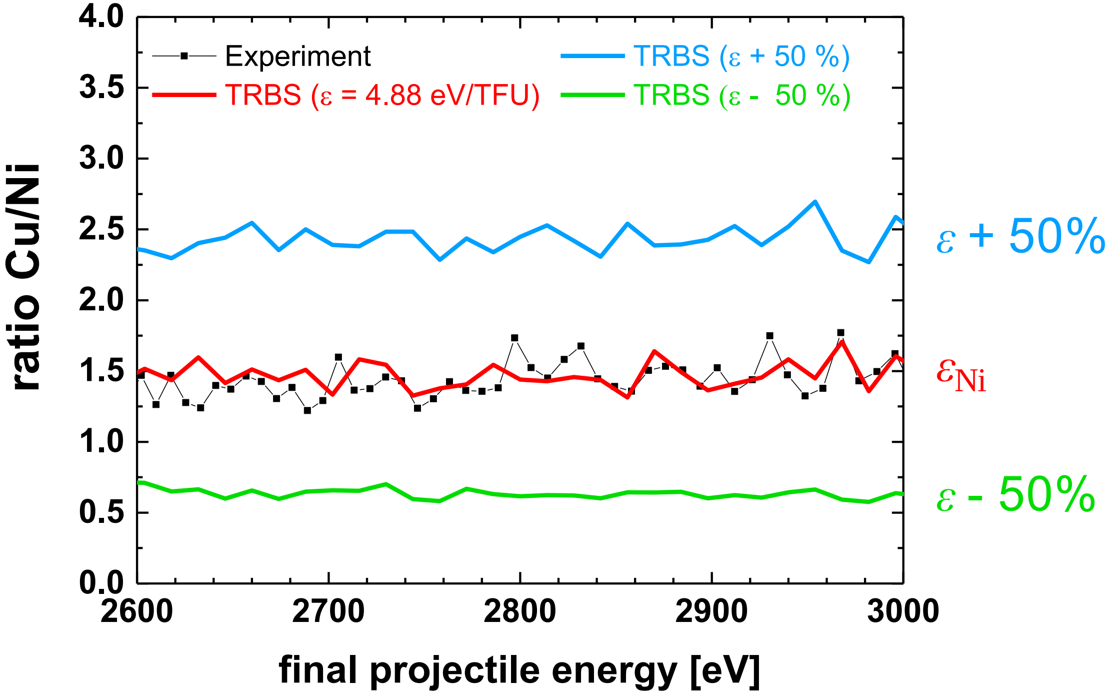
Spectra measured for Ni, Cu → $H_{\mathrm{Cu}}, H_{\mathrm{Ni}}$

$$\frac{H_{\mathrm{Cu}}}{H_{\mathrm{Ni}}} = \frac{d\sigma_{\mathrm{Cu}}}{d\sigma_{\mathrm{Ni}}} \cdot \frac{[\varepsilon]_{\mathrm{Ni}}}{[\varepsilon]_{\mathrm{Cu}}}$$



To consider **multiple scattering**:

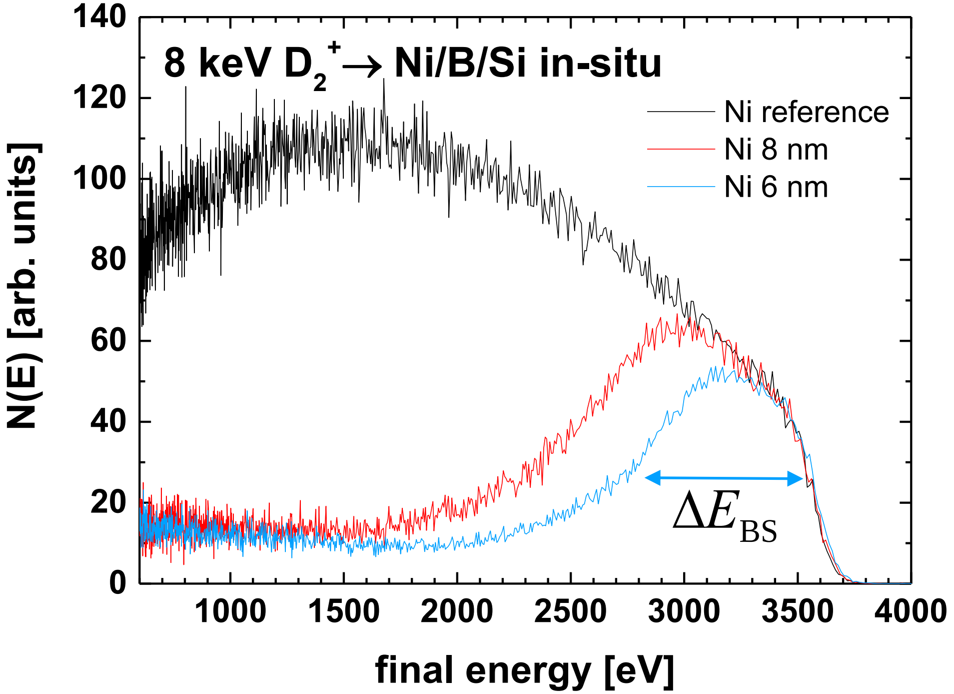
→ comparison to MC – simulations with $\varepsilon_{\mathrm{Ni}}$ as only parameter



TRBS handles multiple scattering not perfectly well → limited energy range

DATA EVALUATION – spectrum width
Ni nm layers

spectra measured for Ni sheet vs. in-situ nm-Ni films (6 nm, 8 nm)



- Spectrum widths: $\Delta E_{BS} = [\varepsilon] \cdot n\Delta x$

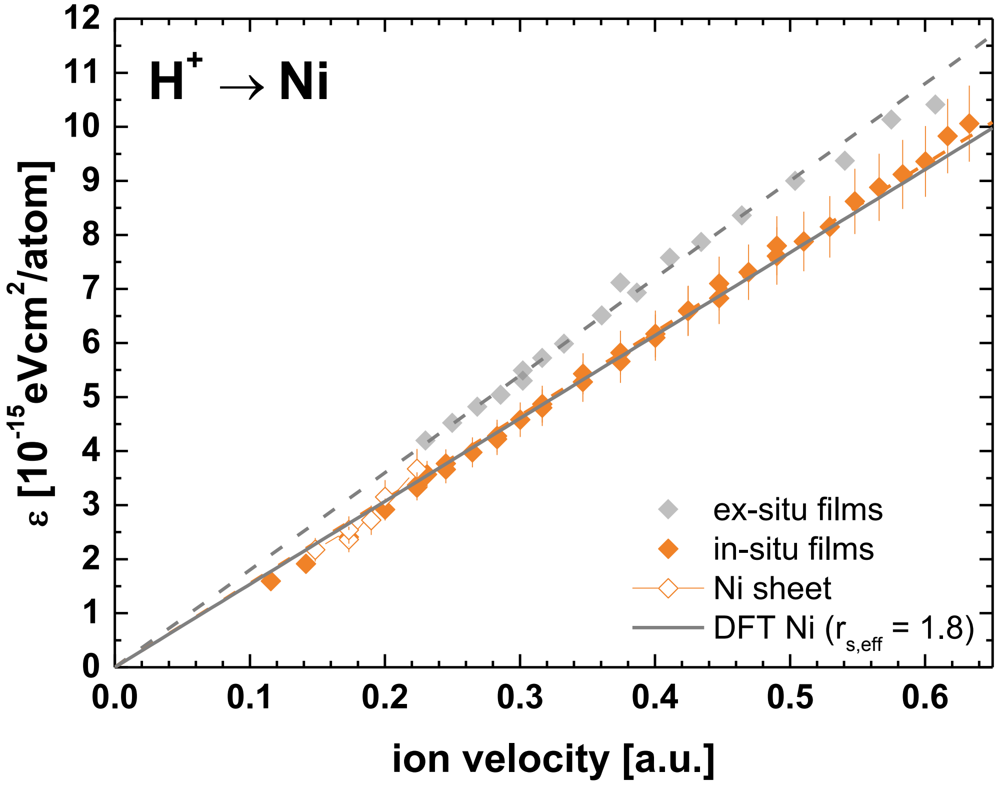
- Spectrum heights coincide

→ identical SCS $\equiv [\varepsilon]_{Ni}$

→ avoid bulk impurities!

→ use of **thick sheets** and / or **in-situ films**

RESULTS:
$H^+ \rightarrow Ni$



- $\frac{dE}{dx} = Q \cdot v$

Impurities: measured SCS is too high!

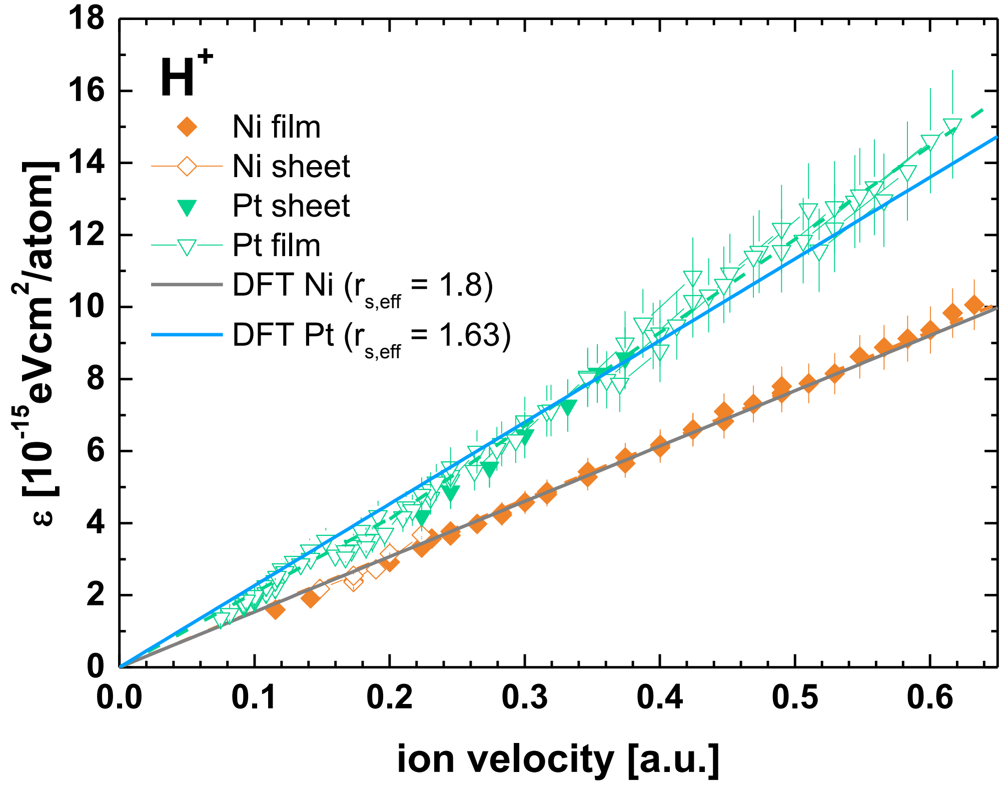
- density parameter: calculated from experimental plasmon energies

Ni: $r_{s,eff} = 1.8$

D. Isaakson (1981)

Results

$H^+ \rightarrow$ Ni
$H^+ \rightarrow$ Pt



Pt: D. Goebl et al (2012)

- $\frac{dE}{dx} = Q \cdot v$
- density parameter: calculated from experimental plasmon energies

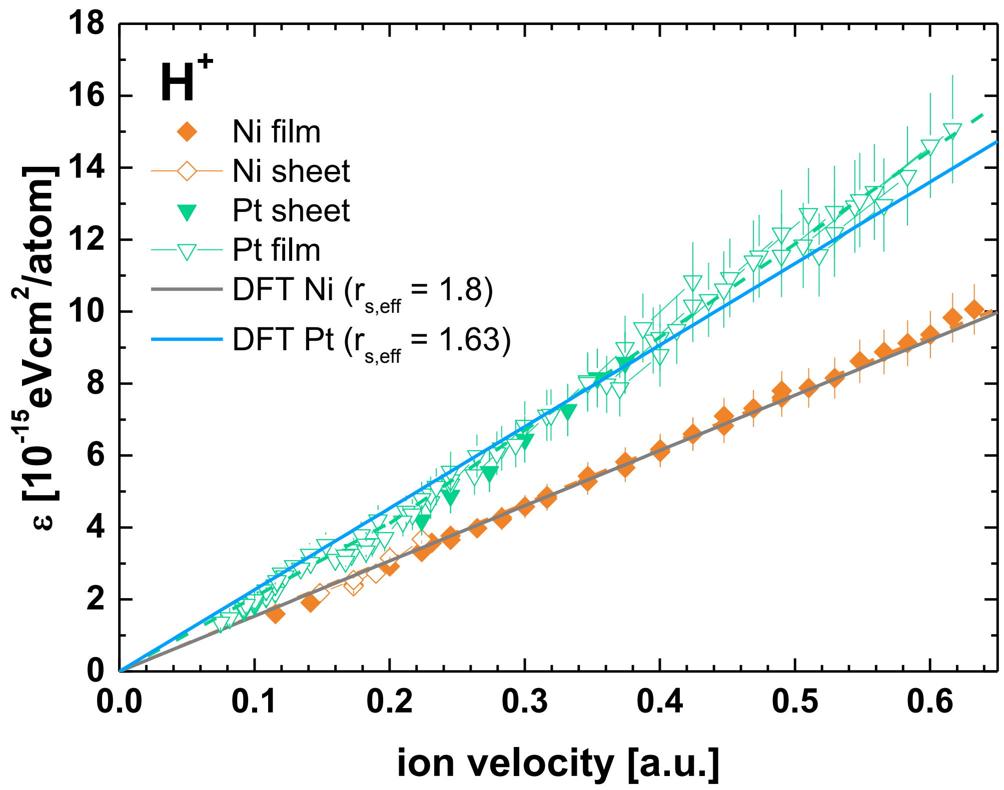
Ni: $r_{s,eff} = 1.8$

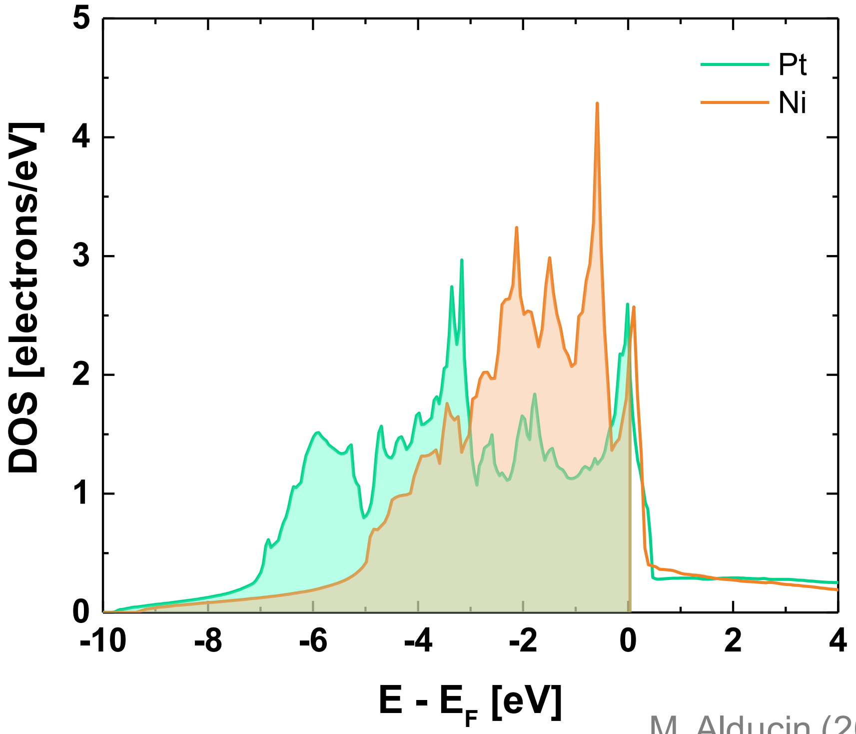
Pt: $r_{s,eff} = 1.63$

D. Isaakson (1981)

Results

$H^+ \rightarrow Ni$
$H^+ \rightarrow Pt$



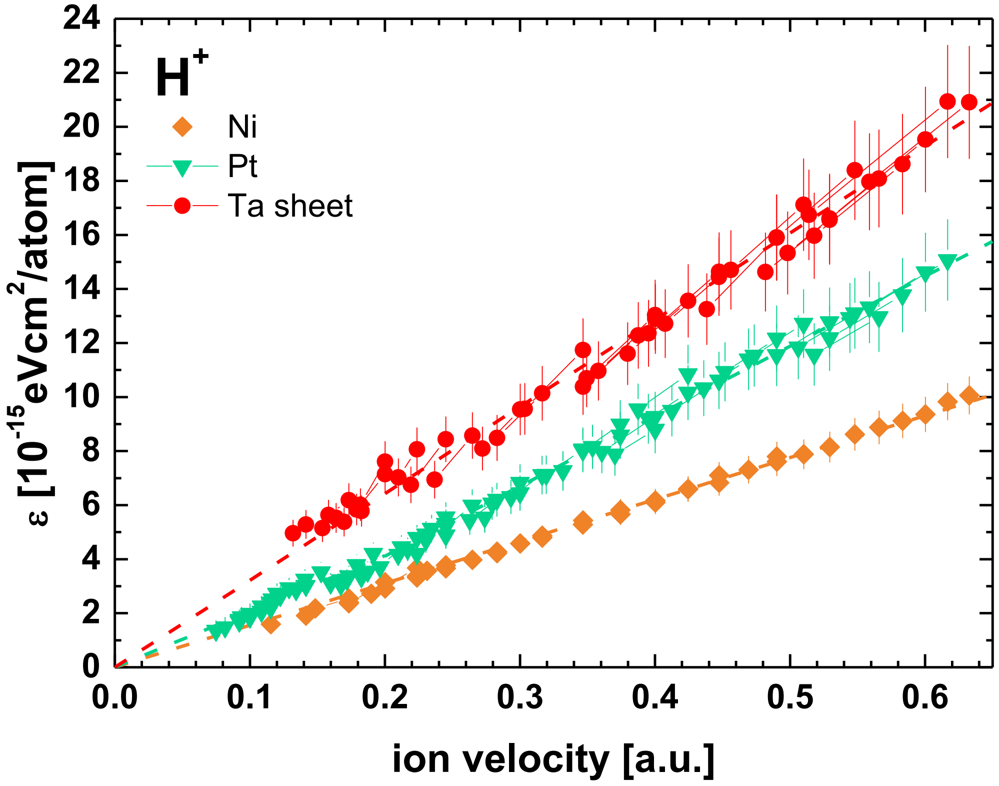


M. Alducin (2016)

Pt: D. Goebl et al (2012)

Results

$H^+ \rightarrow Ni$
$H^+ \rightarrow Pt$
$H^+ \rightarrow Ta$

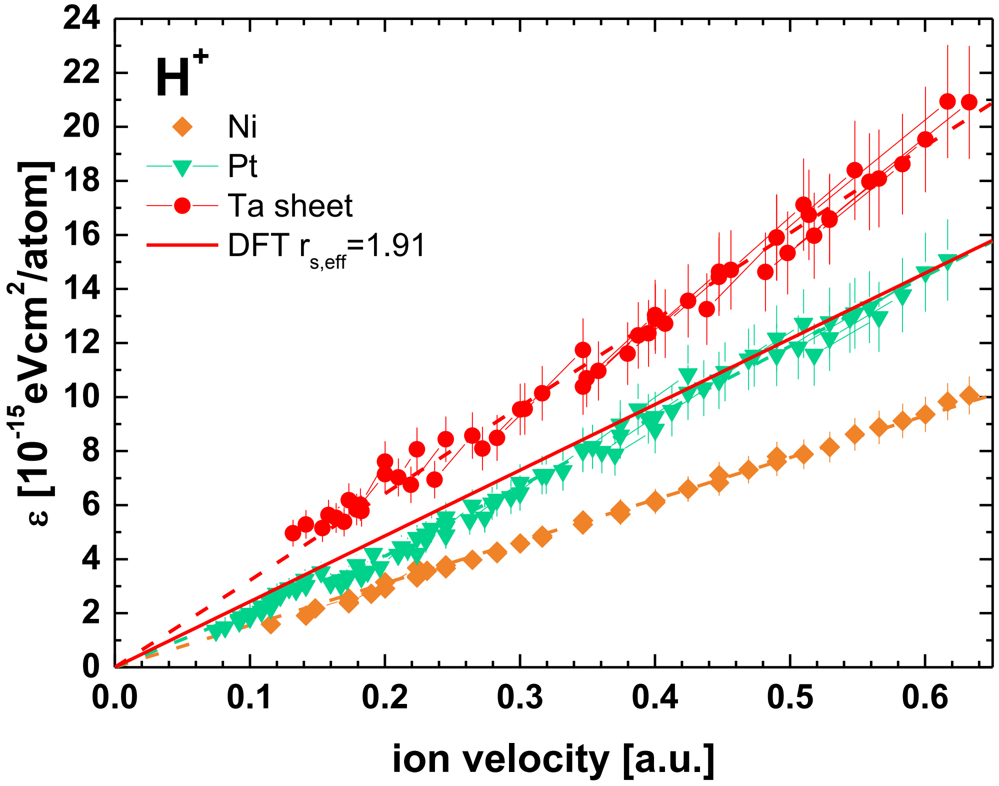


Pt: D. Goebl et al (2012)

- $\frac{dE}{dx} = Q \cdot v$

Results

$H^+ \rightarrow$ Ni
$H^+ \rightarrow$ Pt
$H^+ \rightarrow$ Ta



Pt: D. Goebl et al (2012)

- $\frac{dE}{dx} = Q \cdot v$
- density parameter: calculated from experimental plasmon energies

Ni: $r_{s,\text{eff}} = 1.8$

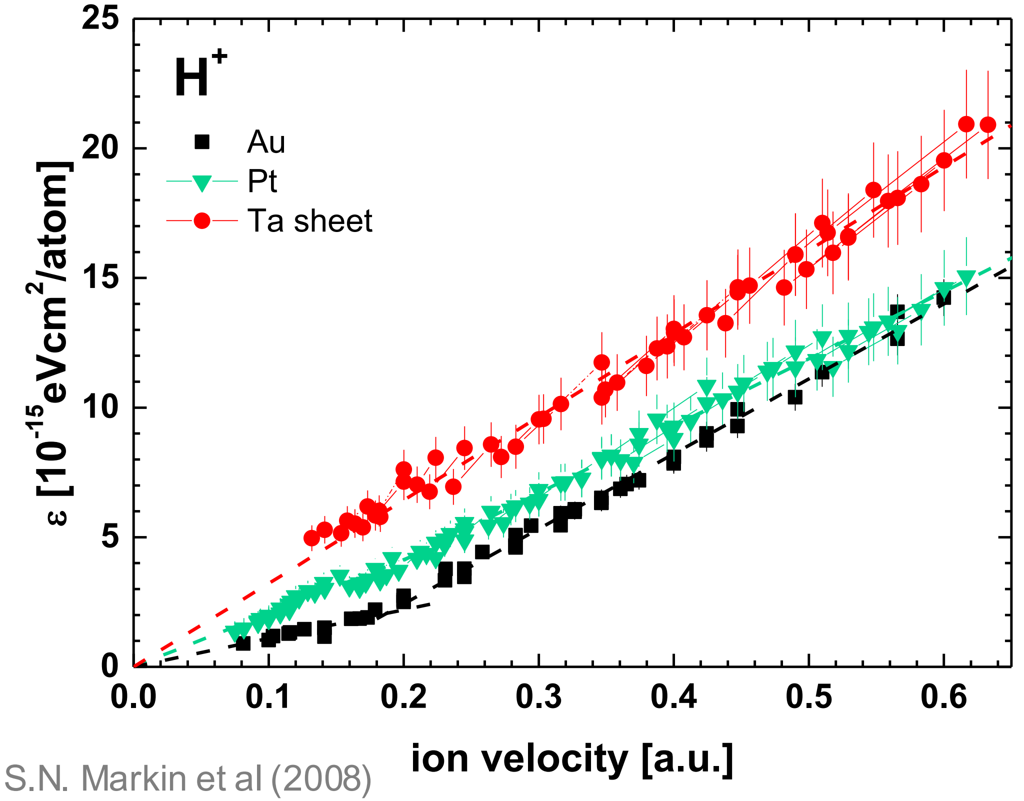
Pt: $r_{s,\text{eff}} = 1.63$

Ta: $r_{s,\text{eff}} = 1.91$ ☹

D. Isaakson (1981)

Results

$H^+ \rightarrow Au$
$H^+ \rightarrow Pt$
$H^+ \rightarrow Ta$

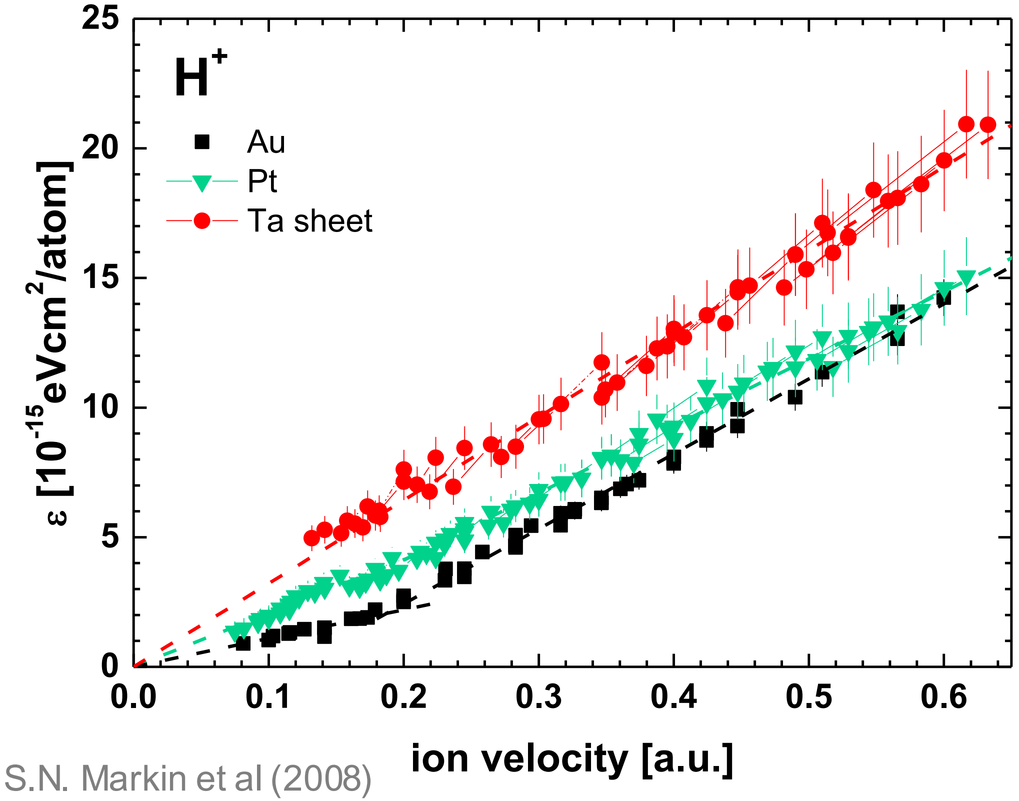


- Au: $dE/dx \not\propto$ v
- Pt, Ta: $dE/dx \propto$ v

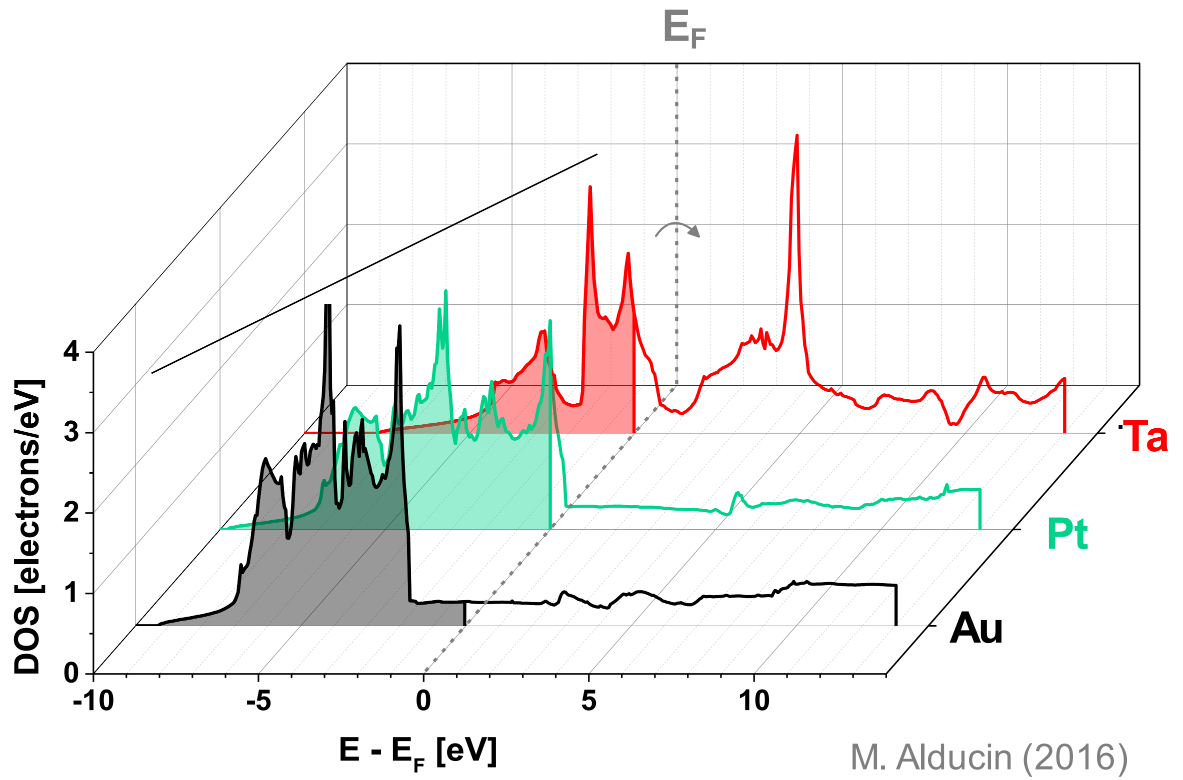
Au: S.N. Markin et al (2008)
Pt: D. Goebl et al (2012)

Results

H^+ → Au
H^+ → Pt
H^+ → Ta



Au: S.N. Markin et al (2008)
Pt: D. Goebl et al (2012)



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- Au, Pt: **full *d*-band**
  → low DOS ($E > E_F$)
- Ta: **partly filled *d*-band**
  → high DOS ($E > E_F$)

OUTLOOK

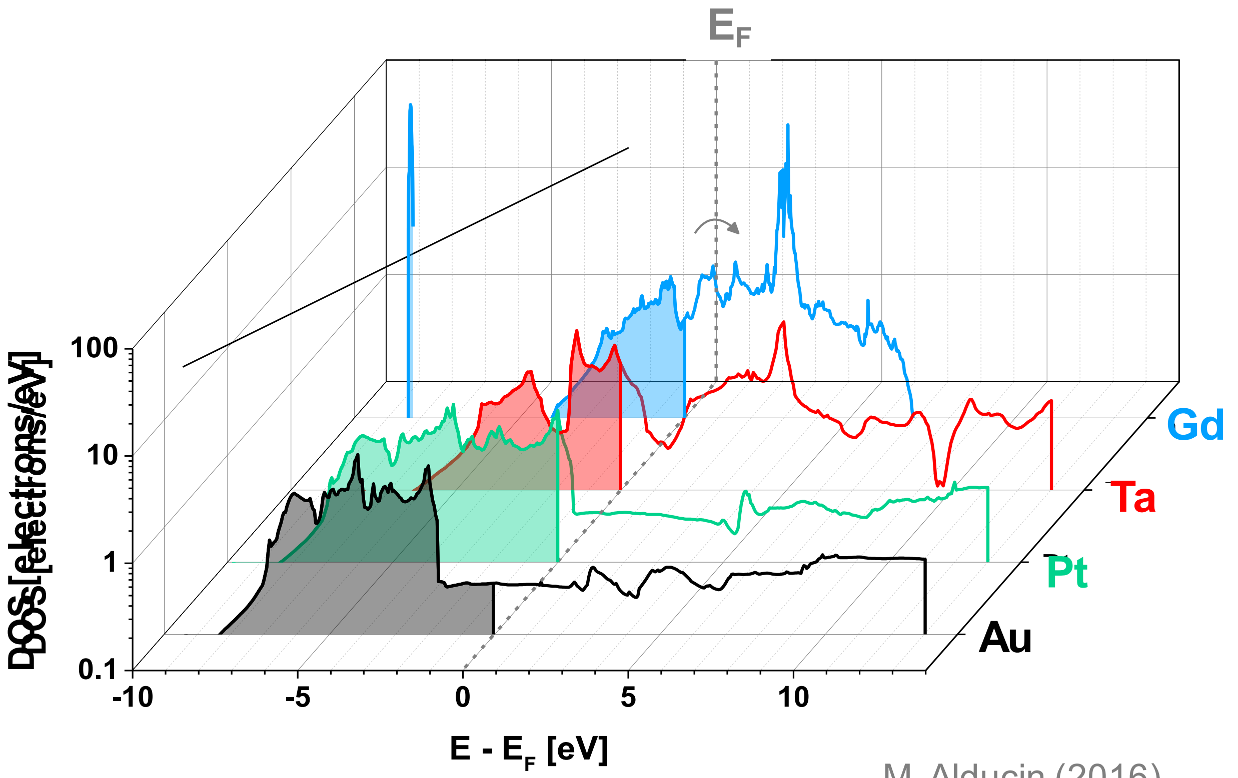
- Electronic stopping in rare earth metals:

  Gd: **partly filled f-band**

  → high DOS ($E > E_F$)

- But:

  even more difficult to get clean rear earth metals



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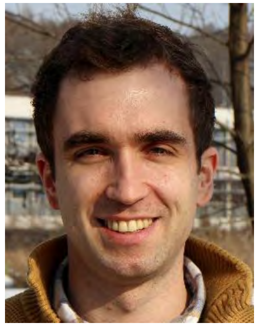

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