The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

SMR.1744 - 27

SCHOOL ON ION BEAM ANALYSIS AND ACCELERATOR APPLICATIONS

13 - 24 March 2006

Low energy scattering

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Low Energy Ion Scattering

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March 2006

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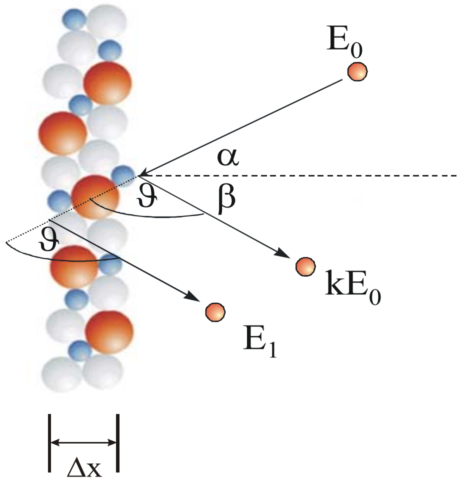
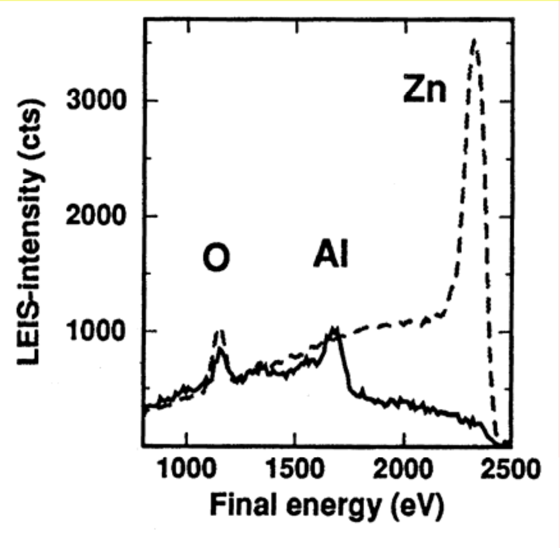
Institute of Experimental Physics
Department of Atomic Physics and Surface Science

Overview:

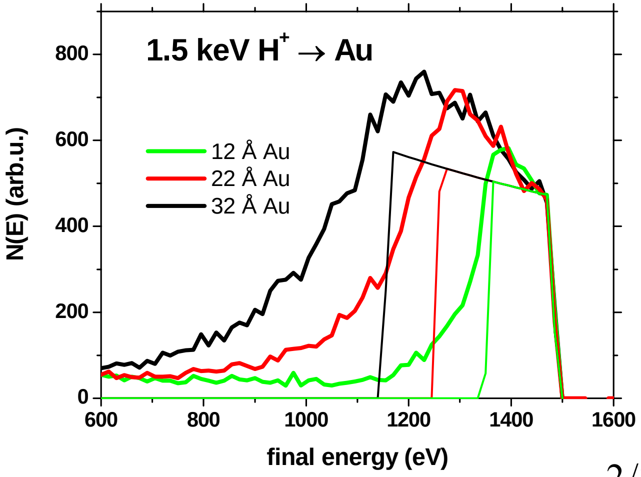
- **Low energy ion scattering:**
  - RBS, MEIS (high energies)
  - LEIS (low energies)





- **Quantitative analysis surface**
  - structure
  - composition

- **Quantitative analysis of nanometer layers**
  - composition, depth profiles
  - depth resolution
  - mass resolution



Contents:

ion scattering: RBS ↔ LEIS

- ➢ scattering by nuclei → scattered yield
- ➢ interaction with target electrons → slowing down

Low energy ion scattering (LEIS)

- ➢ Electrostatic analyzer: ESA-LEIS
- ➢ Time-Of-Flight: TOF-LEIS

ESA-LEIS:

- ➢ instrumentation → static ESA-LEIS
- ➢ ions detected → ion fraction P+
- ➢ noble gas ions:
  - ➢ neutralisation → surface sensitivity
- ➢ applications: quantitative surface analysis → examples

TOF-LEIS (Time-of-flight)

- ➢ instrumentation → static TOF-LEIS
- ➢ ions and neutrals detected
  - surface structure analysis
  - neutral spectrum: shape, depth information
  - depth resolution → depth analysis → applications

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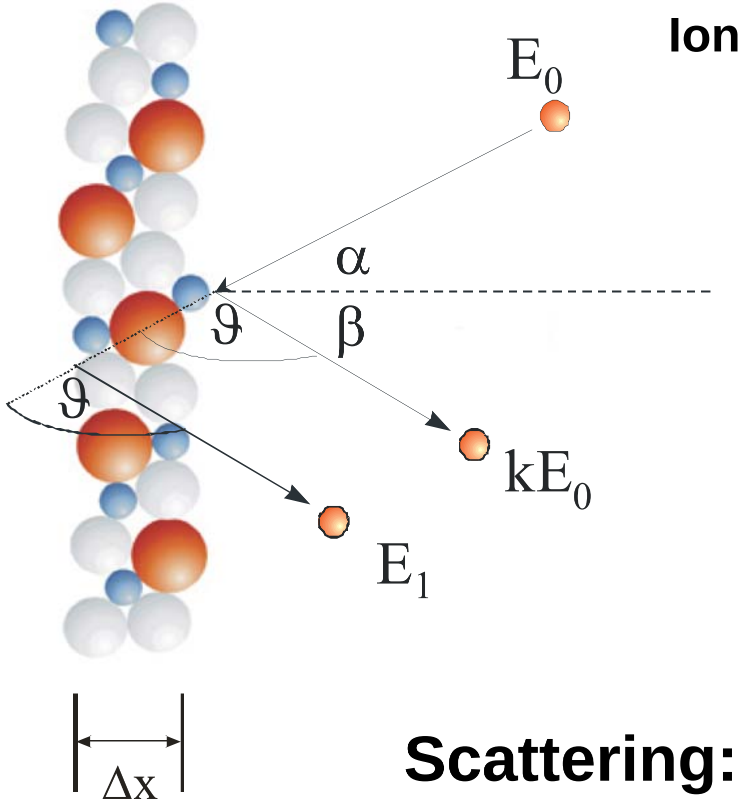
Ion scattering:

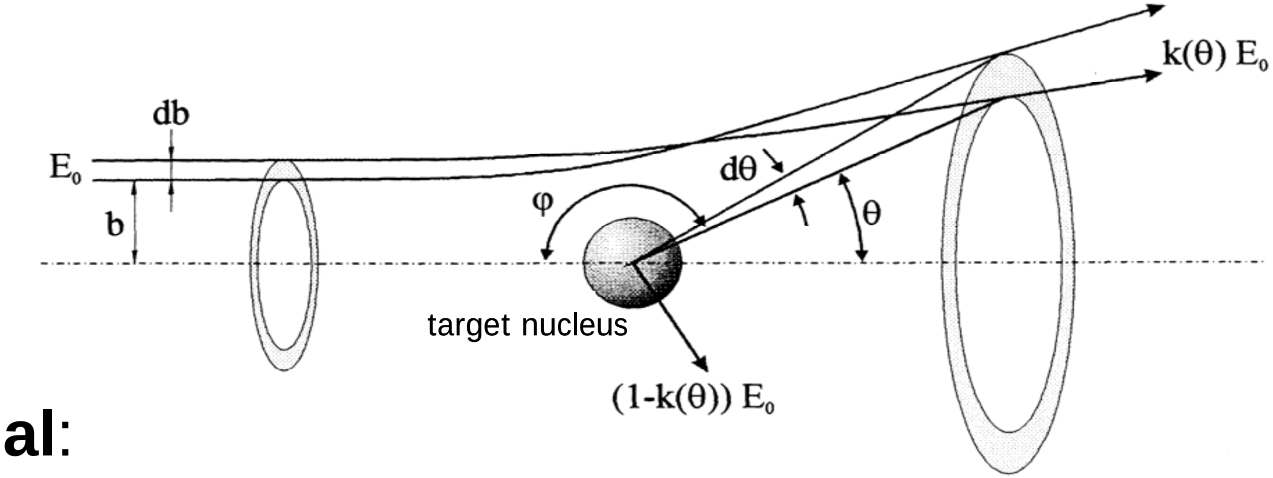
Target: Z_{i2}, M_{i2}



Ion: Z_1, M_1

Scattering: - by target nuclei
- by target electrons

Scattering by target nuclei



Scattering potential:

$$\boxed{V(r) = \frac{Z_1 Z_2 e^2}{r} \Phi(r/a)}$$

$\Phi(r/a)$ ... screening function
(electronic screening of nucleus)

Impact parameter b $\leftrightarrow \theta \rightarrow$ Scattering cross section $d\sigma/d\Omega$
$\rightarrow$ Scattering probability dp

$$\boxed{\mathbf{dp = ndx\ (d\sigma/d\Omega)}}$$

Scattering potential

Scattering point charge by point charge: $V_C(r) = Z_1 Z_2 e^2/r$ (Coulomb)

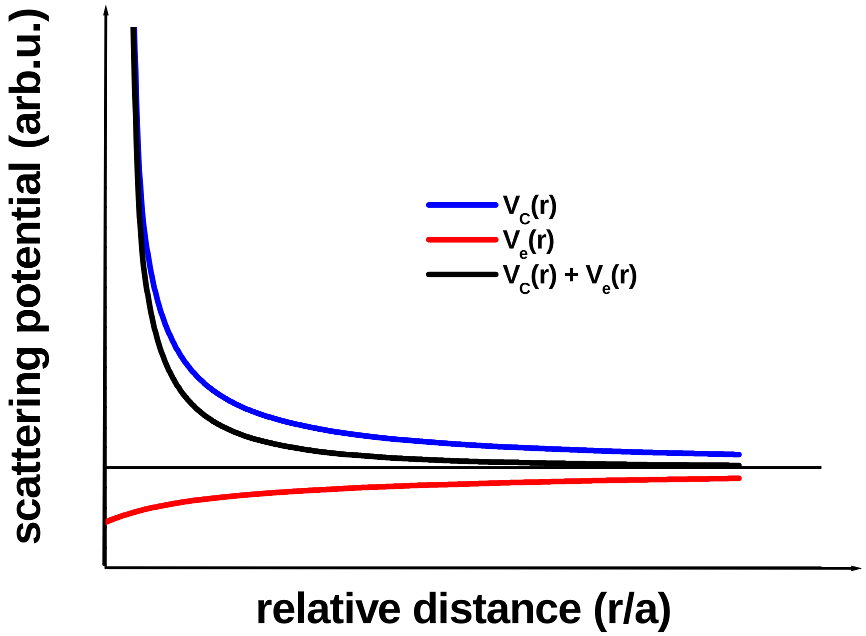
Scattering dressed charge by neutral atom:

$$V(r) = \underbrace{V_C(r)} + \underbrace{V_e(r)} = V_C(r)\cdot\underbrace{\Phi(r/a)}$$

interaction with: nucleus electrons

interaction is: repulsiv attractive

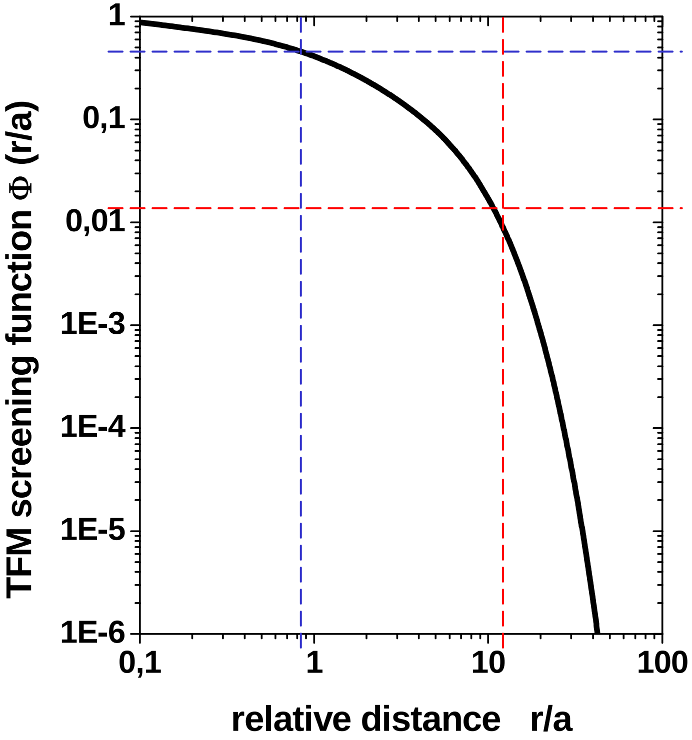
screening function



Screening function $\Phi(r/a)$ (Thomas-Fermi-Molière)

$$V(r) = V_C(r)\cdot\Phi(r/a)$$

$$\Phi\left(\frac{r}{a}\right) = \sum_{i=1}^{3} b_i \exp(-c_i\, r/a) \text{ with } a = \underbrace{\frac{0.8852\cdot a_0}{\sqrt[3]{\left(\sqrt{Z_1}+\sqrt{Z_2}\right)^2}}}_{\text{screening length } a \approx 0.2\ \text{Å}}$$



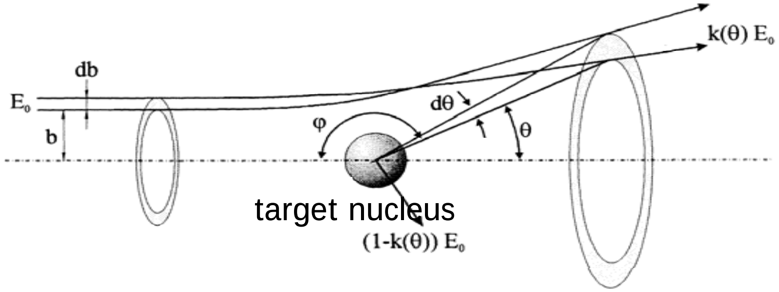
Limiting cases:
$\Phi(r/a \to 0) = 1$
$\Phi(r/a \to \infty) = 0.$

in any case: $\Phi(r/a) \leq 1$

Scattering cross section dσ/dΩ

$V(r) = V_C(r) \rightarrow$ Rutherford cross section

$$\frac{d\sigma_R}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4\,E \sin^2 \frac{\theta}{2}} \right)^2$$



Scattering cross section $d\sigma/d\Omega$

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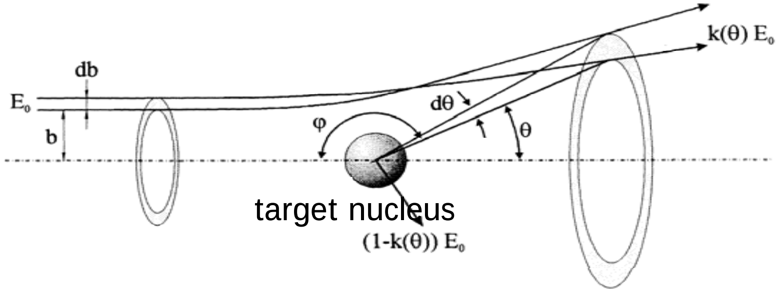

$V(r) = V_C(r)\cdot\Phi(r/a) \rightarrow$

$$2\pi b\,db \equiv d\sigma = \left| \frac{d\sigma(\theta, E)}{d\Omega} \cdot \underbrace{2\pi \sin\theta\, d\theta}_{d\Omega} \right|$$

$\rightarrow$ relevant quantity is $$\boxed{\frac{d\sigma}{d\Omega} = -\frac{b}{\sin\theta}\frac{db}{d\theta}}$$

[from b(θ)]

Scattering cross section $d\sigma/d\Omega$

$V(r) = V_C(r)$ → Rutherford cross section

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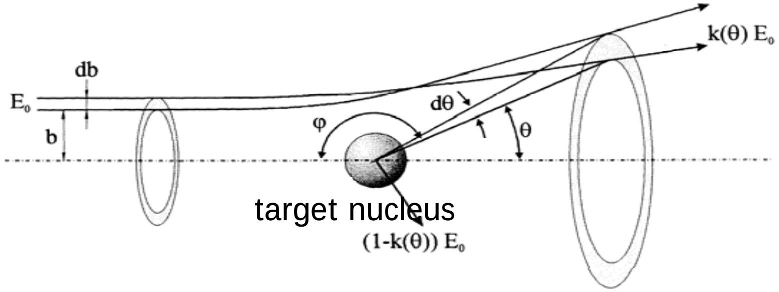
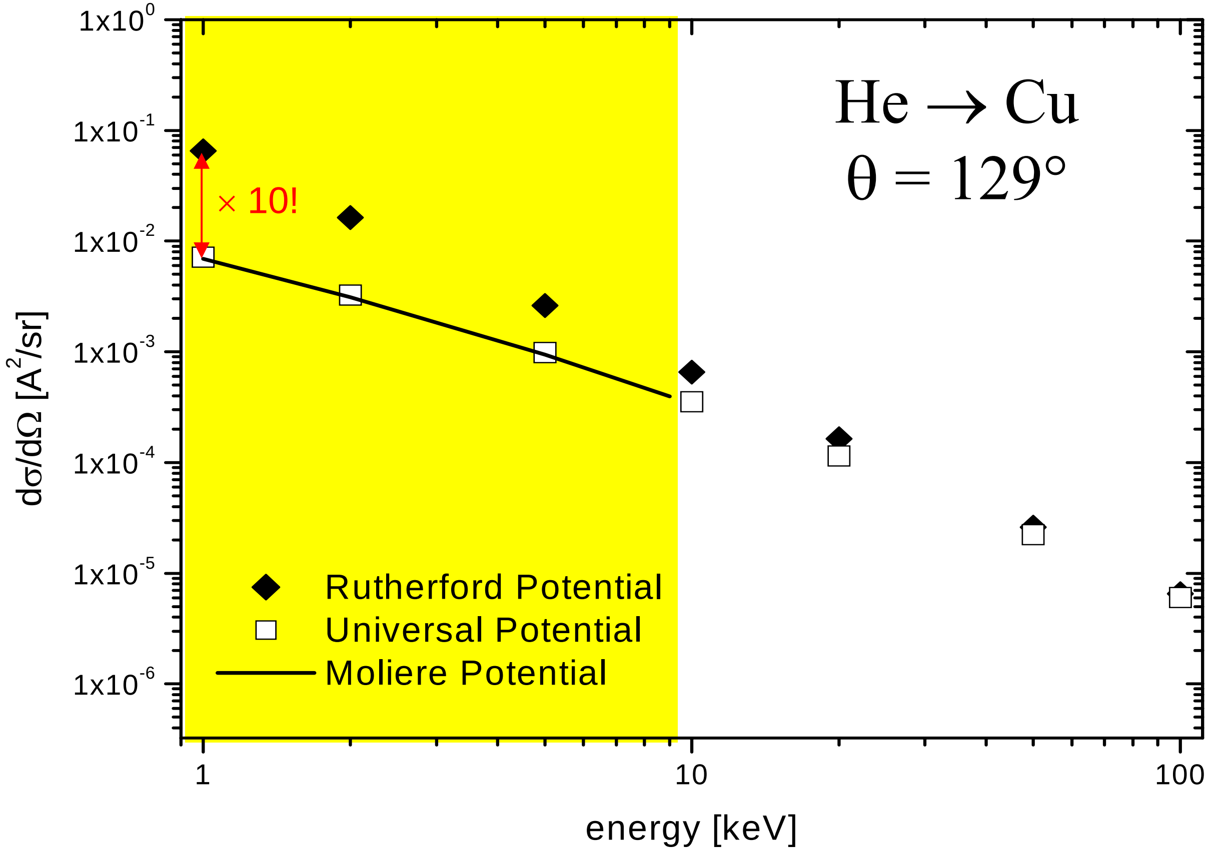


$V(r) = V_C(r)\cdot\Phi(r/a)$ → $$2\pi b\,db \equiv d\sigma = \left|\frac{d\sigma(\theta,E)}{d\Omega}\cdot\underbrace{2\pi\sin\theta\,d\theta}_{d\Omega}\right|$$

→ relevant quantity is $$\frac{d\sigma}{d\Omega} = -\frac{b}{\sin\theta}\frac{db}{d\theta}$$ [from b(θ) ... or θ(b)]

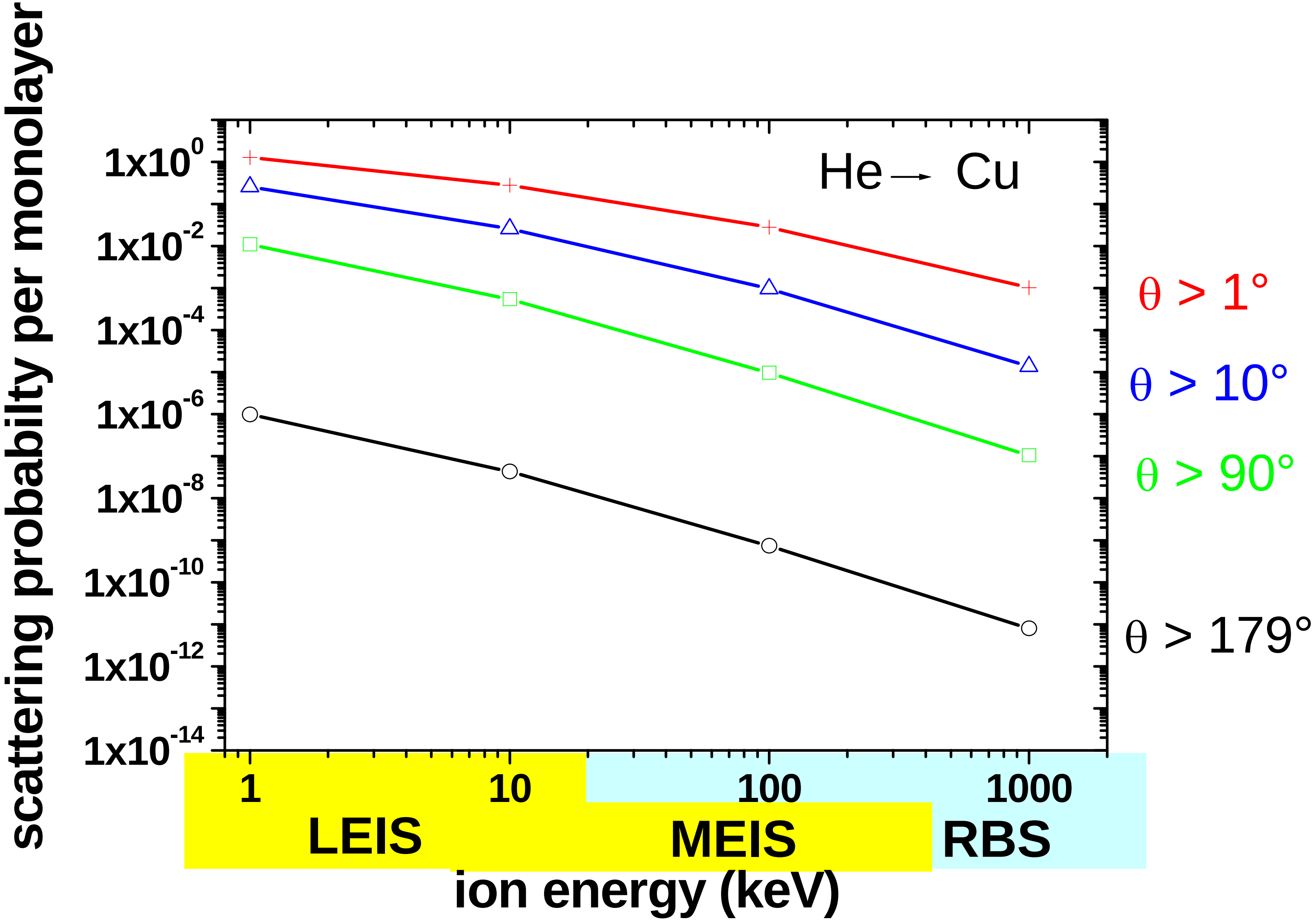
$db/d\vartheta$ is obtained from $$\theta(b) = \pi - 2\int_{R_{min}}^{\infty}\frac{b\,dr}{r^2\sqrt{1-\frac{b^2}{r^2}-\frac{V(r)}{E}}}$$ (scattering integral)

Scattering cross section



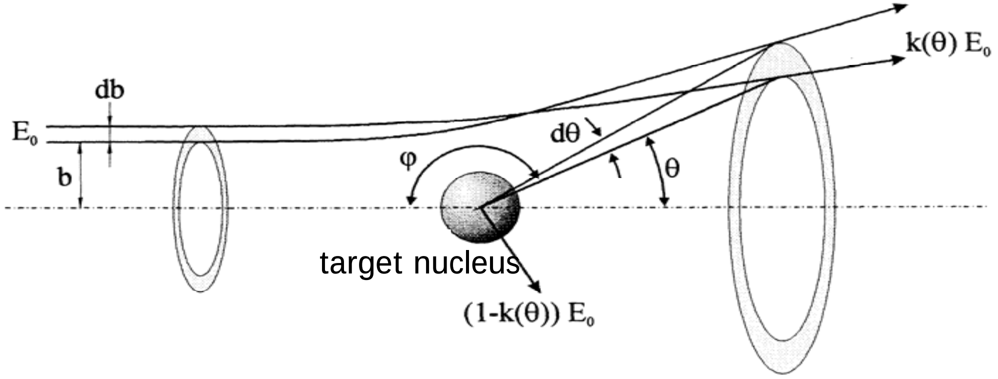
There are different models for $\Phi(r/a)$: Thomas-Fermi-Molière
universal potential
etc.

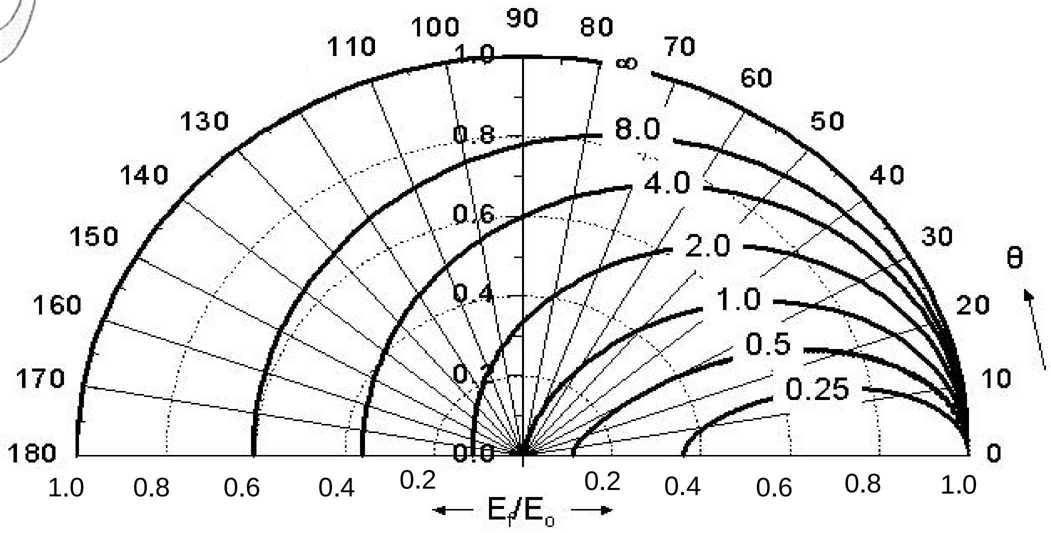
Integral scattering probability:



Collisional energy loss (binary collision)

kinematic factor: $$k \equiv \frac{E_1}{E_0} = \left\{ \frac{\left[1-(M_1/M_2)^2 \sin^2\theta\right]^{1/2} + (M_1/M_2)\cos\theta}{1+(M_1/M_2)} \right\}^2 \qquad \text{for } M_1 \le M_2$$





Interaction with target electrons

- kinematics: electron´s mass $M_2 << M_1$

Interaction with target electrons

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→ scattering angle negligible

→ small energy losses per collision

BUT with high probability

Interaction with target electrons

- kinematics: electron´s mass $M_2 << M_1$

→ scattering angle negligible

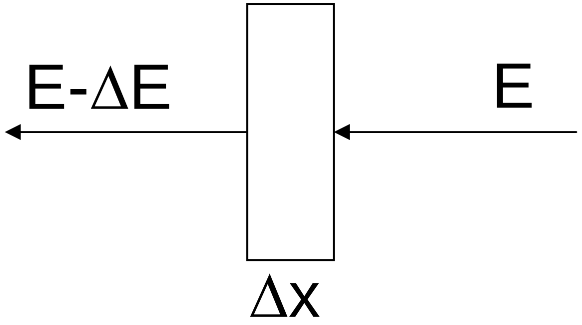
→ small energy losses per collision

BUT with high probability

→ **Continuous slowing down („friction force“)**

→ **Stopping Power:**

$$\mathbf{S = \lim_{\Delta x \to 0} \Delta E / \Delta x \equiv dE/dx}$$



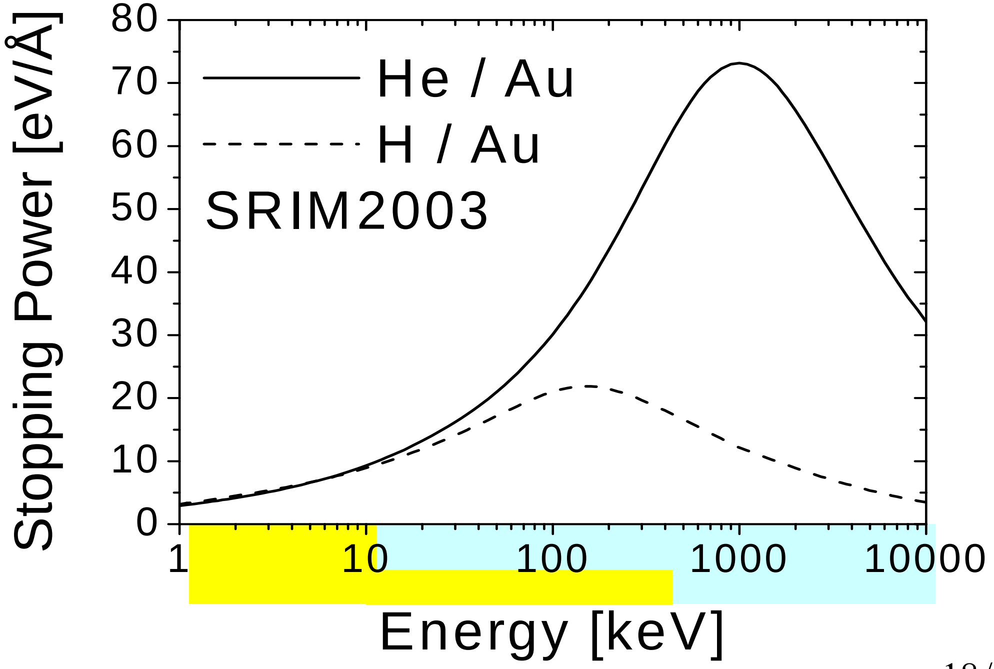
Stopping Power

- Energy loss dE per path length dx: S = dE/dx

- Stopping cross section: $\varepsilon = S / n = dE / ndx$

RBS: $S \propto \frac{Z_2}{v^2} \ln\left(\frac{2 m_e v^2}{I}\right)$

LEIS: $S \propto v$ (like friction force)



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TOF-LEIS (Time-of-flight)

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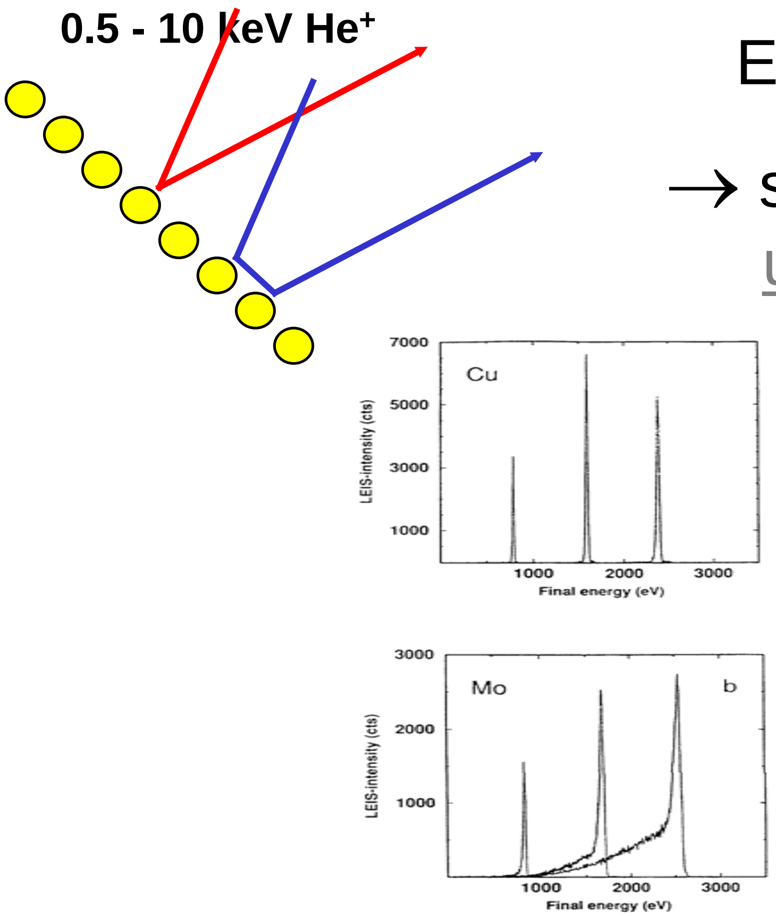
ESA-LEIS (electrostatic analyser used)



ESA → detection of scattered ions

→ sensitive for outermost atomic layer

usually: binary collisions dominiate
double collisions negligible

TOF-LEIS (time-of-flight analyser used)

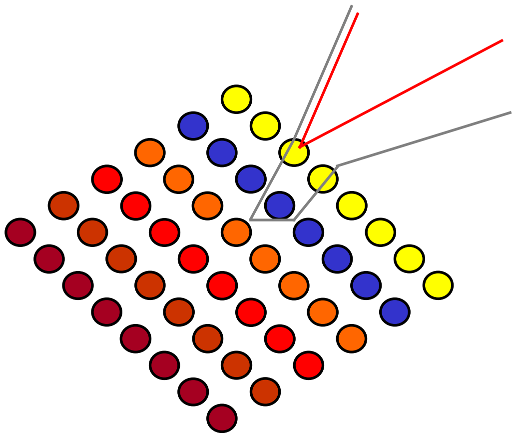
→ detection of scattered neutrals + ions

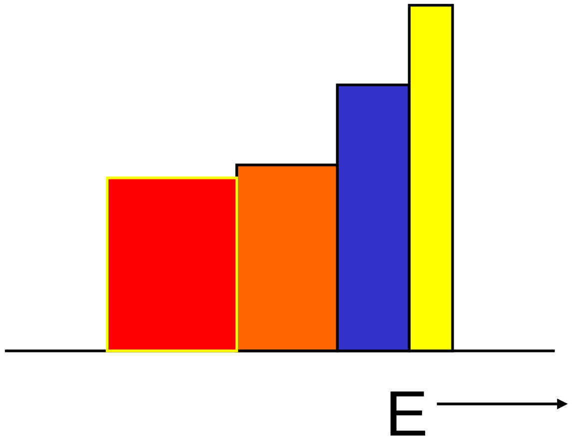
→ no surface sensitivity
like RBS at low energies

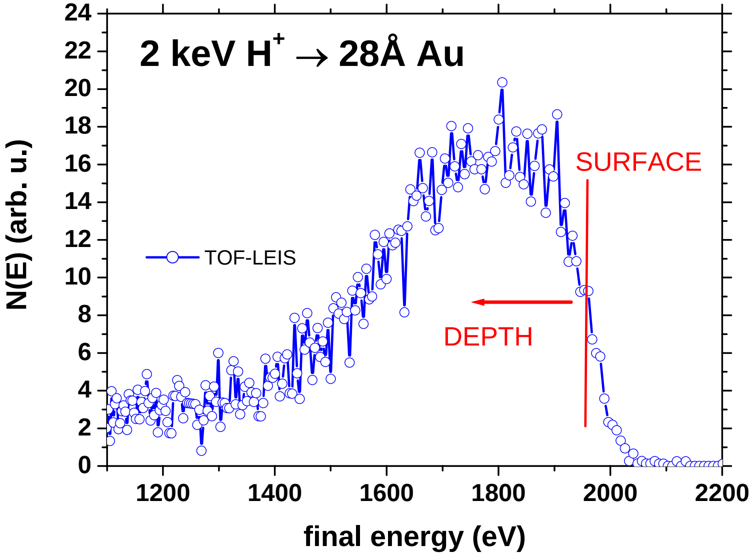
→ <u>but:</u> no single scattering!

→ information about nm-layers

0.5 - 10 keV H^+, He^+







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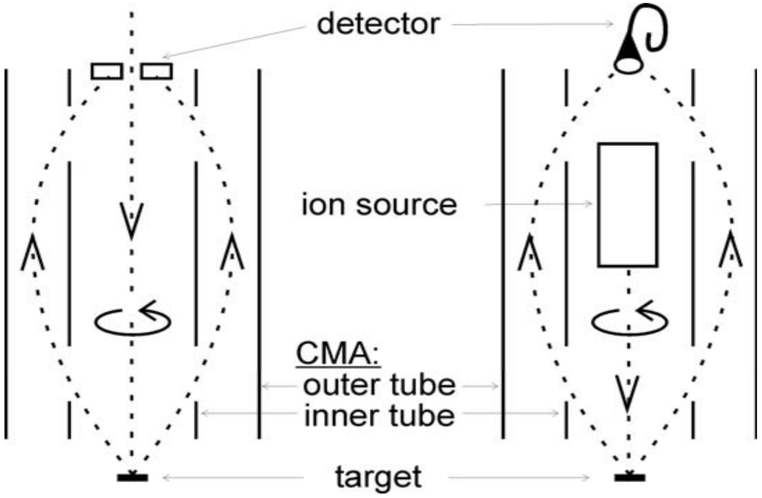
ESA-LEIS Instrumentation:

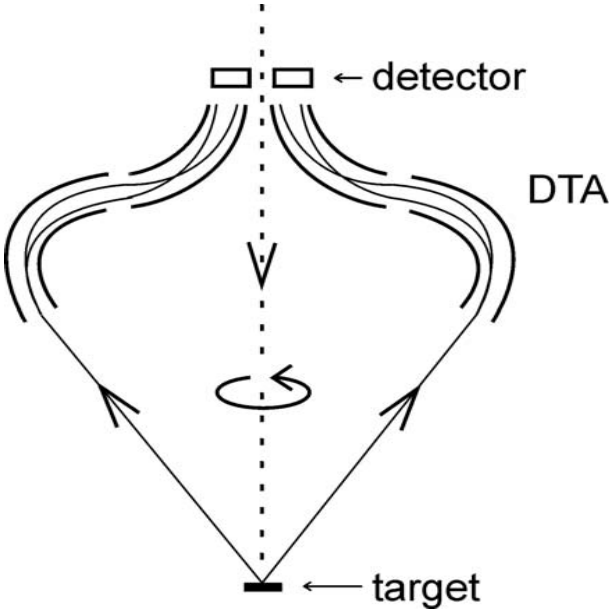
Cylindrical Mirror Analyzer (CMA):

only ions with $E_f \in [E, E + dE]$
are transmitted, with $dE \propto E$



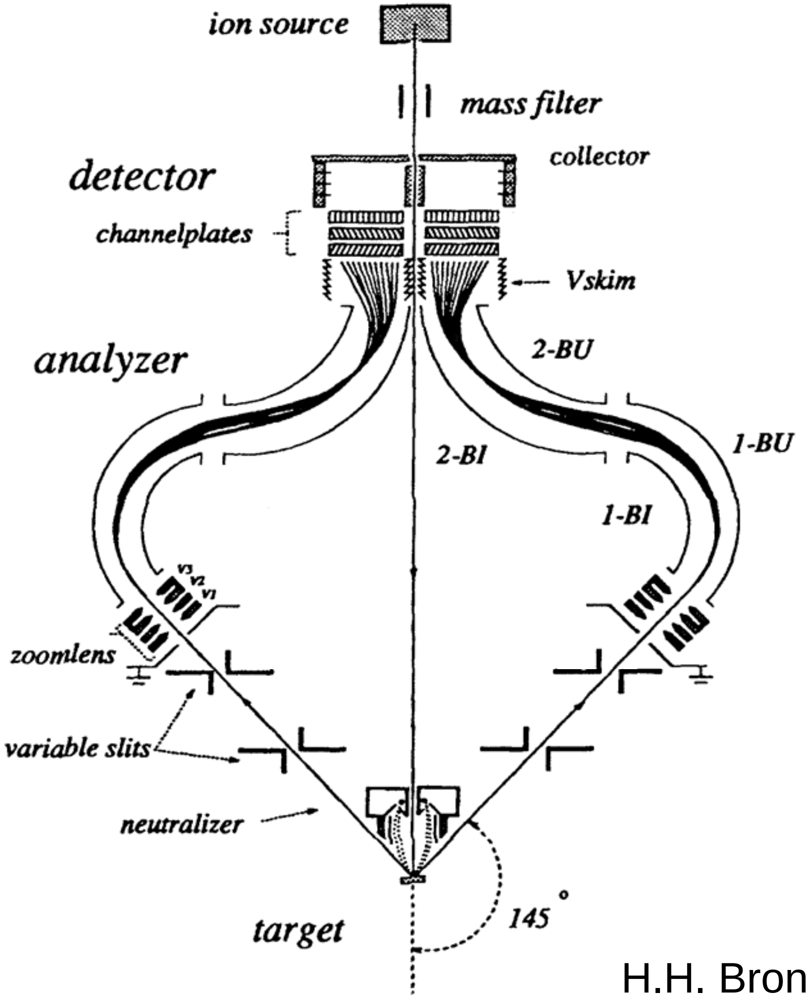
Double Toroïdal Analyser (DTA):

ions with $E_f \in [E_{min}, E_{max}]$
are transmitted simultaneously



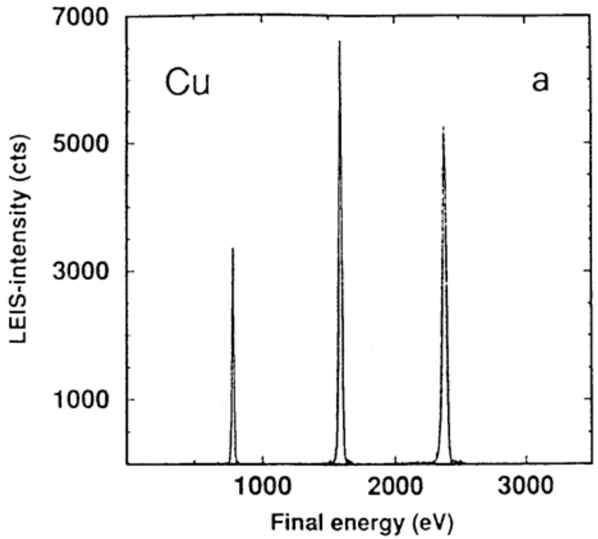
ESA-LEIS Instrumentation (static LEIS):

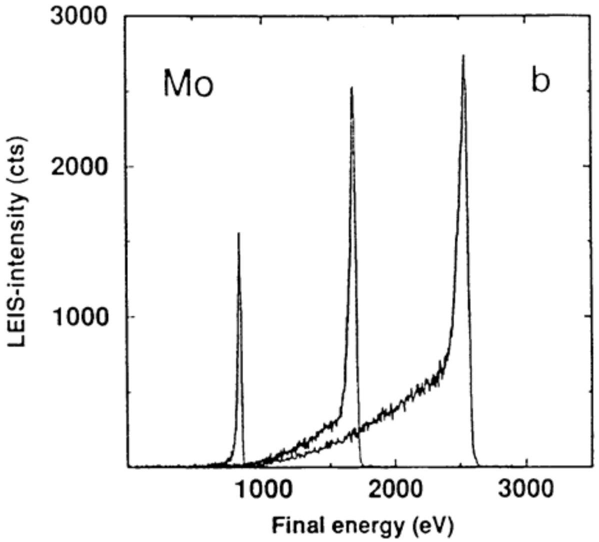
CALIPSO

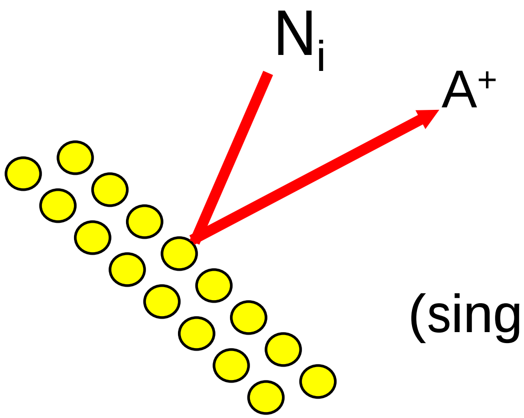


H.H. Brongersma, Eindhoven university

$^4He^+$ ion spectra (ESA)







(single scattering)

$$A^+ = \overbrace{\frac{N_i}{\cos\alpha}}^{\text{\# proj.}} \cdot \frac{d\sigma}{d\Omega} \cdot \overbrace{(nd)_0}^{\text{\# atoms/area}} \cdot \Omega \cdot P^+ \cdot T_+$$

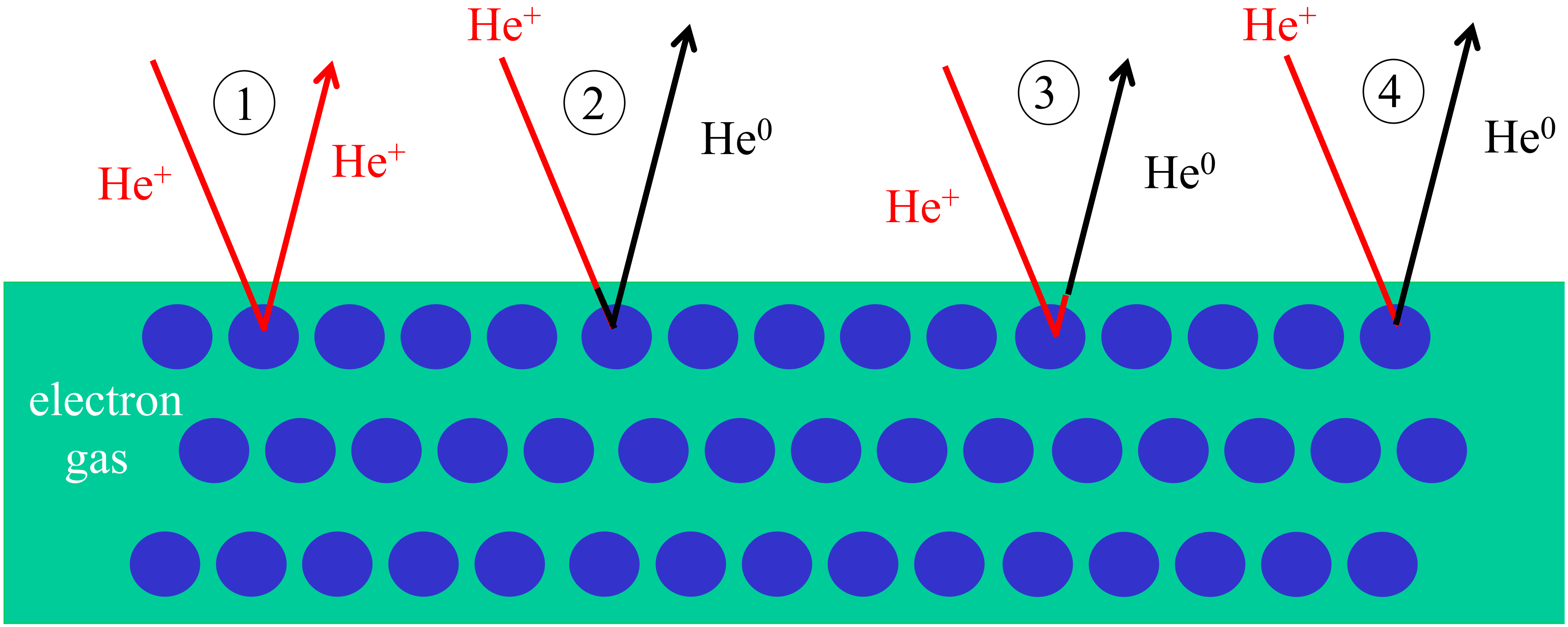
$P^+ = N_+/[N_+ + N_0]$… ion fraction

$$\boxed{A^+ = \frac{N_i}{\cos\alpha} \cdot \frac{d\sigma}{d\Omega} \cdot (nd)_0 \cdot \Omega \cdot P^+ \cdot \eta_+}$$

ion yield A^+ depends on:

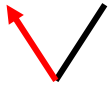
+ N_i … number of ions
+ α … angle of incidence
0 $d\sigma/d\Omega$ … scattering cross section
? P^+ … ion fraction
+ Ω … solid angle
+ η_+ … detection efficiency for ions

Neutralization in LEIS:

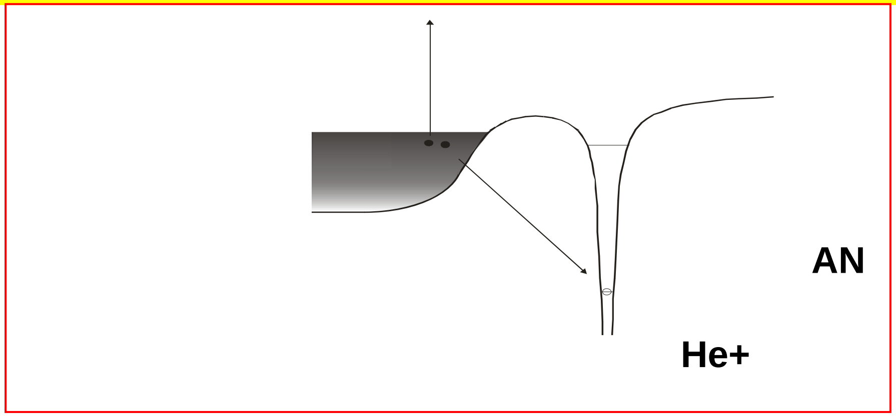


① ② ③ : Auger neutralization or resonant neutralization

④ : collision induced neutralization 

reversed path: collision induced ionization 

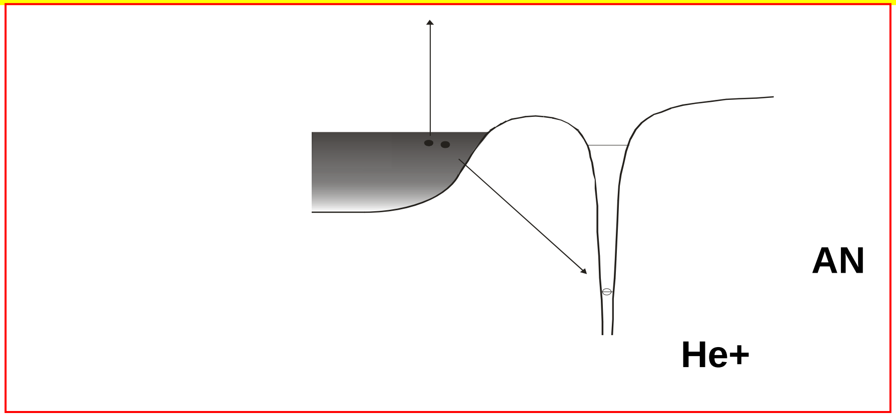
Ion fraction P^+ : neutralisation mechanisms



important for He^+!

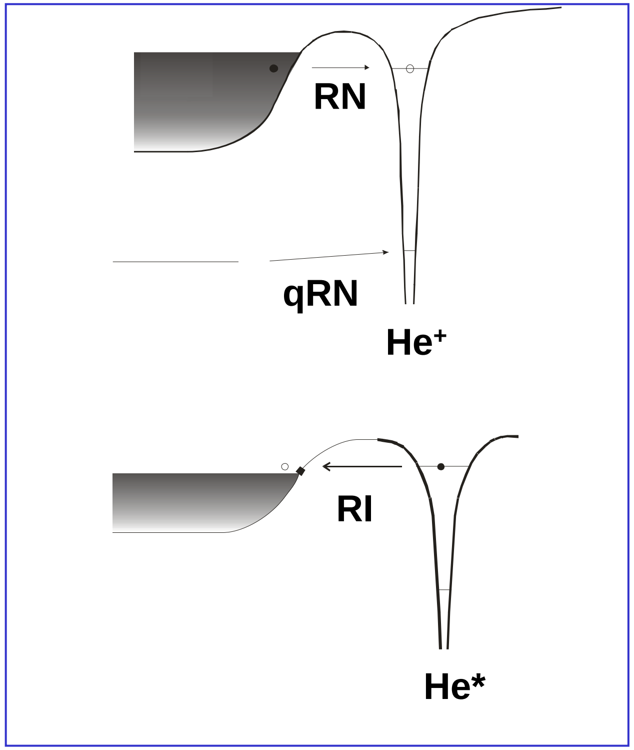
- Auger neutralisation (AN)

Ion fraction P^+ : neutralisation mechanisms



important for He^+!

- Auger neutralisation (AN)
- Resonant neutralisation RN (ionization RI)



in general not for He^+!

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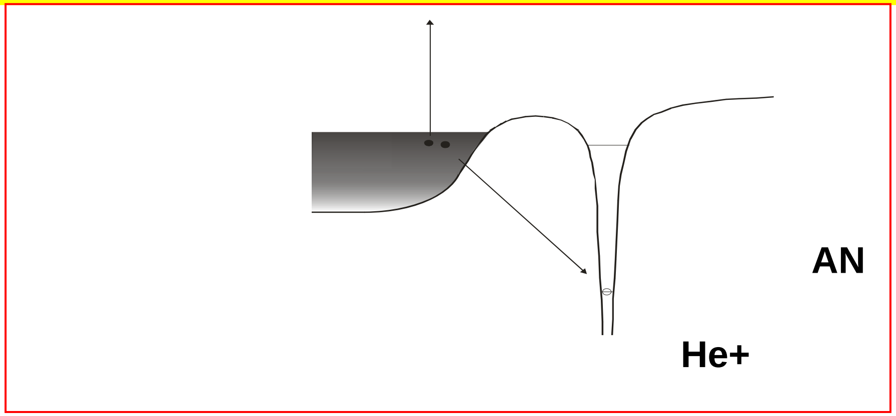
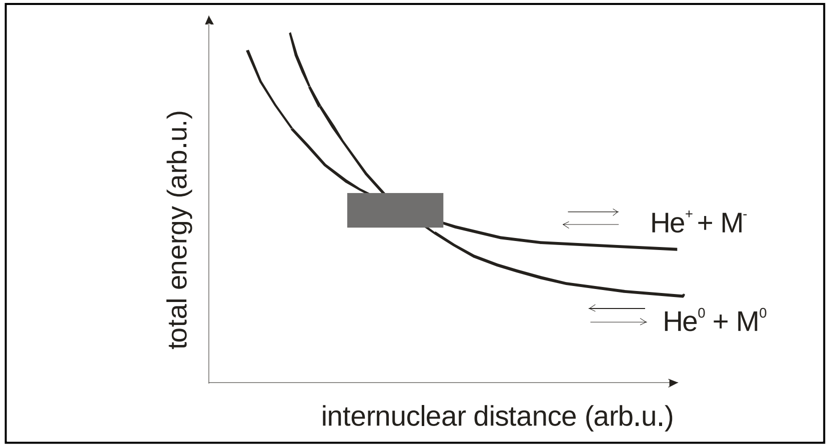
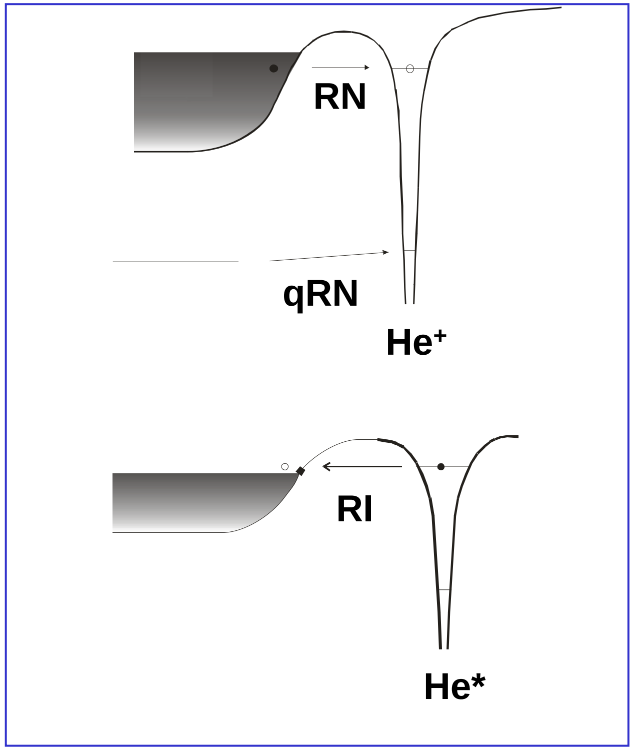


important for He^+!

- Auger neutralisation (AN)
- Resonant neutralisation RN (ionization RI)
- collision induced charge exchange
  important for He^+



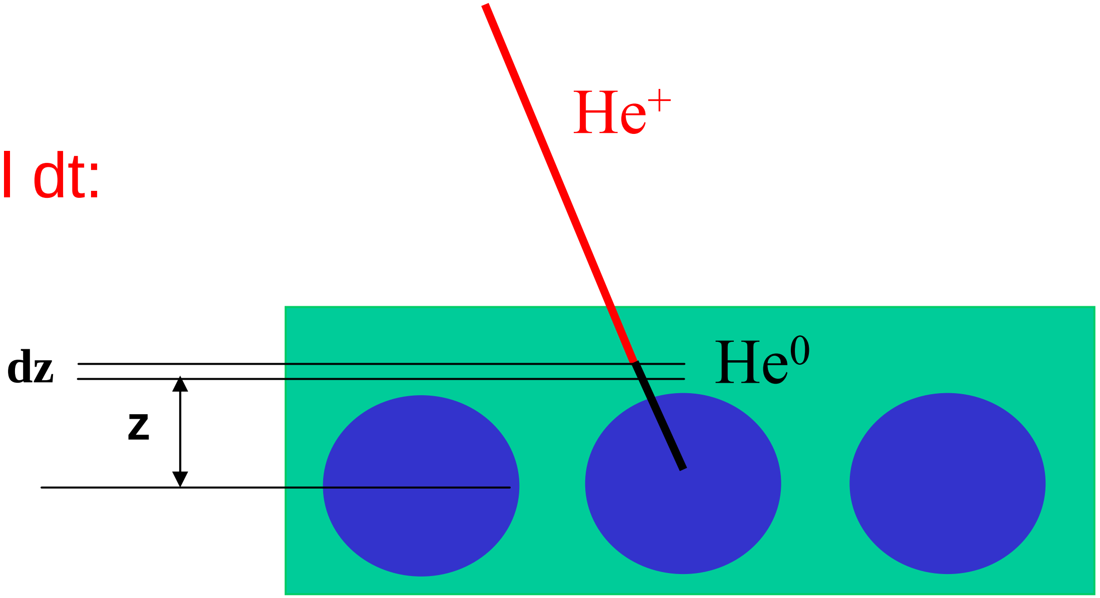


in general not for He^+!

Auger neutralisation on incoming path:

decrease of P^+ in time interval dt:

$$dP^+ = -\,P^+\cdot\underbrace{\Gamma_A}_{\text{neutralization probability in } [z,\, z+dz]}dt$$



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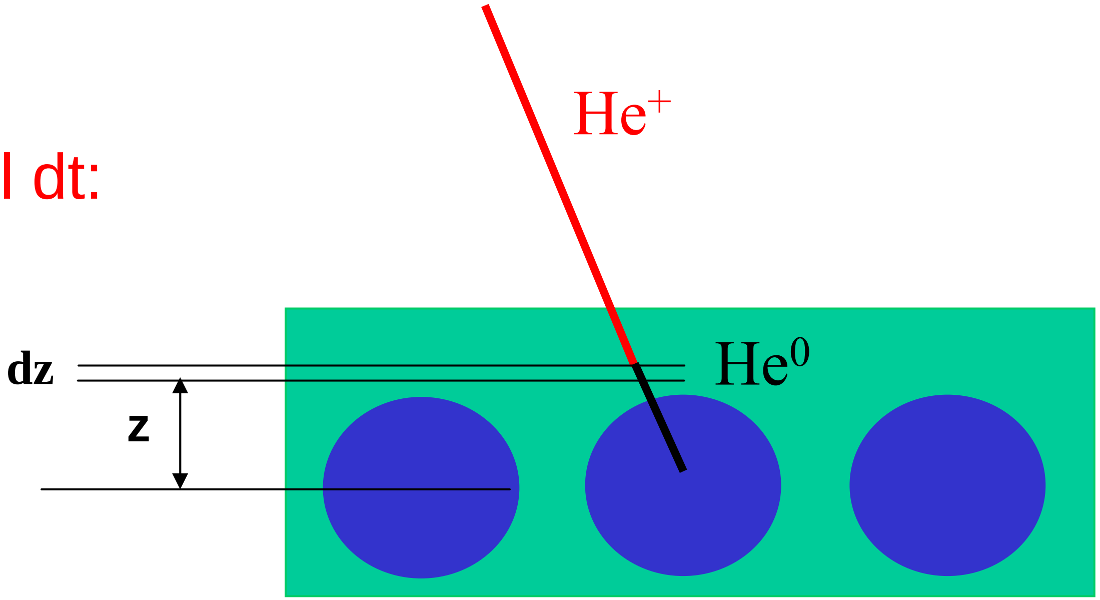


→ fraction of surviving ions:

$$P^+ = \exp\{-\int dt\,\Gamma_A(z)\} = \exp\{-\int dz\,\Gamma_A(z)\,dt/dz\} \approx \exp(-v_c/v_\perp)$$

$$v_c = \int dz\,\Gamma_A(z)$$

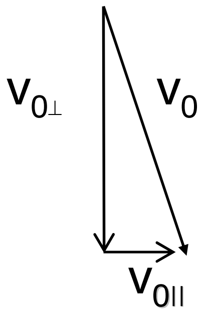
$$v_\perp = 1/v_{0\perp}$$

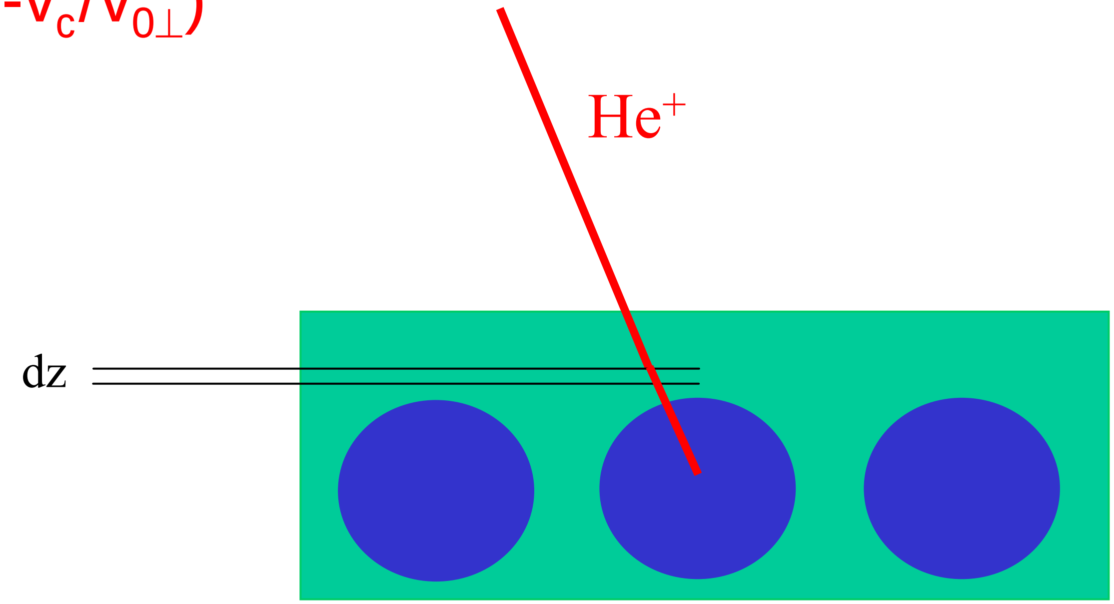
$$\boxed{P^+ \approx \exp(-v_c/v_{0\perp})}$$

Auger neutralization on in- and outgoing path

survival probability on the way in: P_{in}^{+}

$$P_{in}^{+} = \exp(-v_c/v_{0\perp})$$





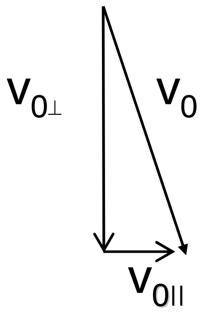
Auger neutralization on in- and outgoing path

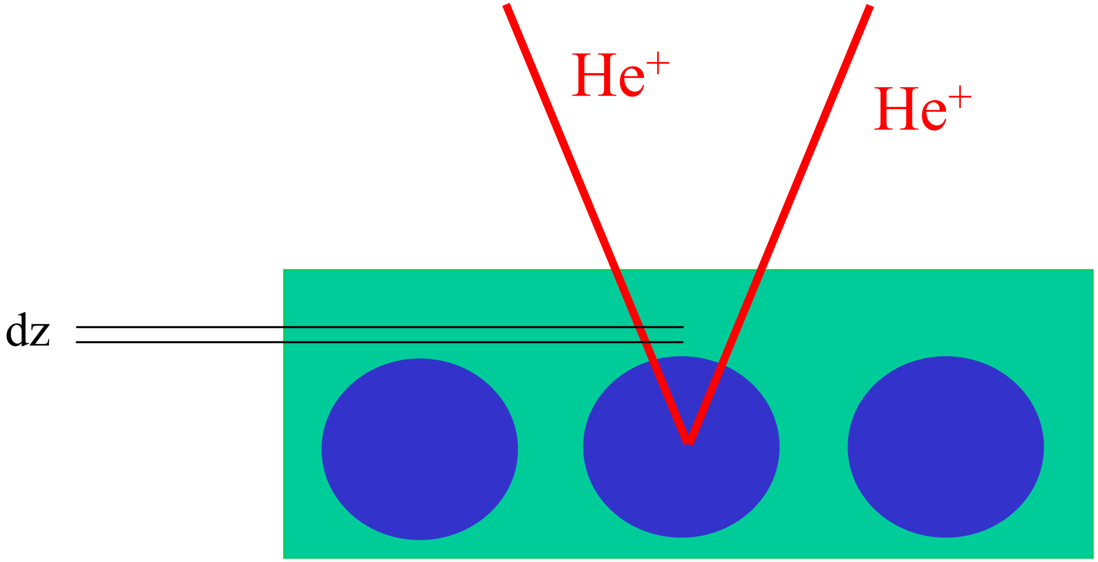
survival probability on the way in: P_{in}^{+}

on the way out: P_{out}^{+}

$P_{in}^{+} = \exp(-v_c/v_{0\perp})$

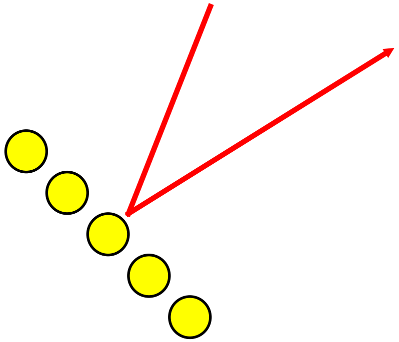
$P_{out}^{+} = \exp(-v_c/v_{f,\perp})$





Probability to survive in charge state He^+

premise: no resonant neutralization (He^+!)
no collision induced charge exchange ($E < E_{th}$)



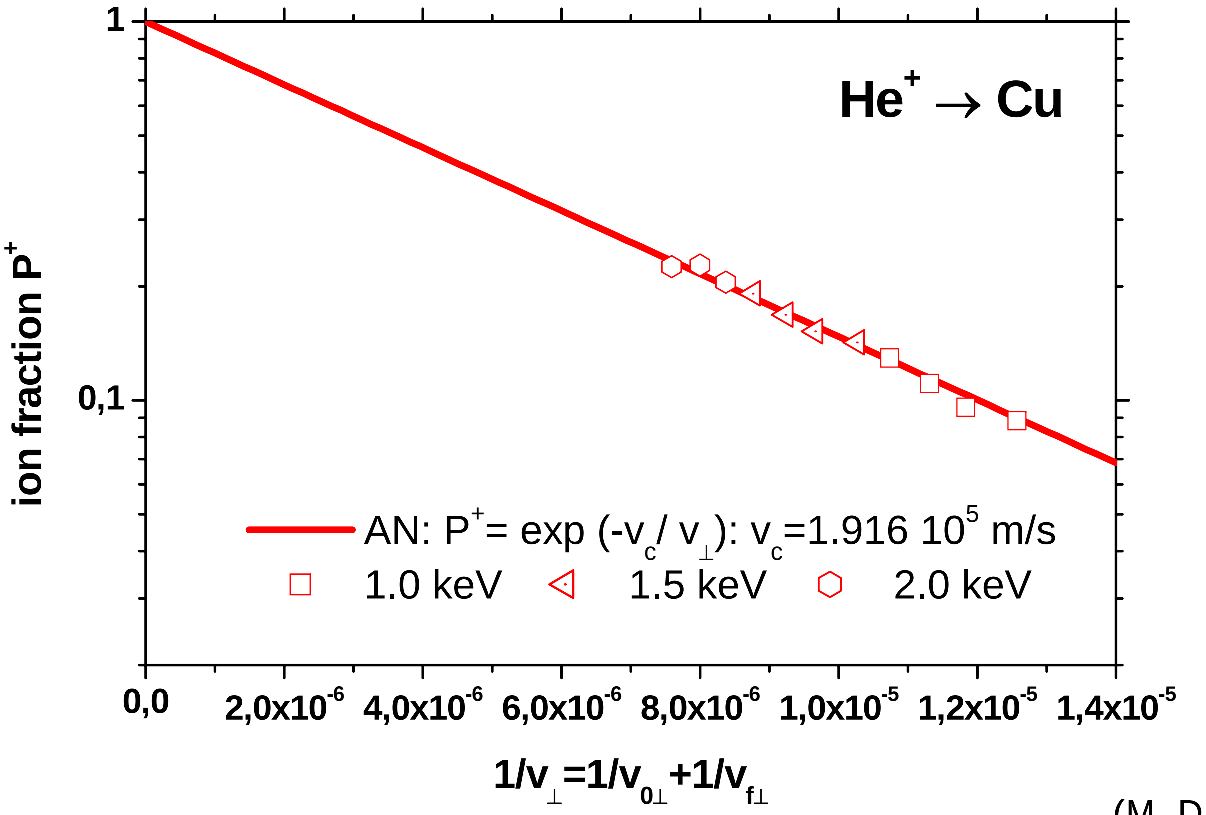
$$\boxed{P^+ = P^+_{in} \cdot P^+_{out}}$$

$$\underbrace{\quad\quad\quad\quad}_{\text{survival probability}}$$

$P^+ = \exp[-v_c(1/v_{0\perp} + 1/v_{f\perp})]$ ... pure AN

Example: ^{4}He → Cu

$E < E_{th}$: $P^+(v_\perp)$! ... ion fraction depends only on $v_\perp$



variation of $v_\perp$ via

- variation of energy
- variation of geometry

→ one single curve!!

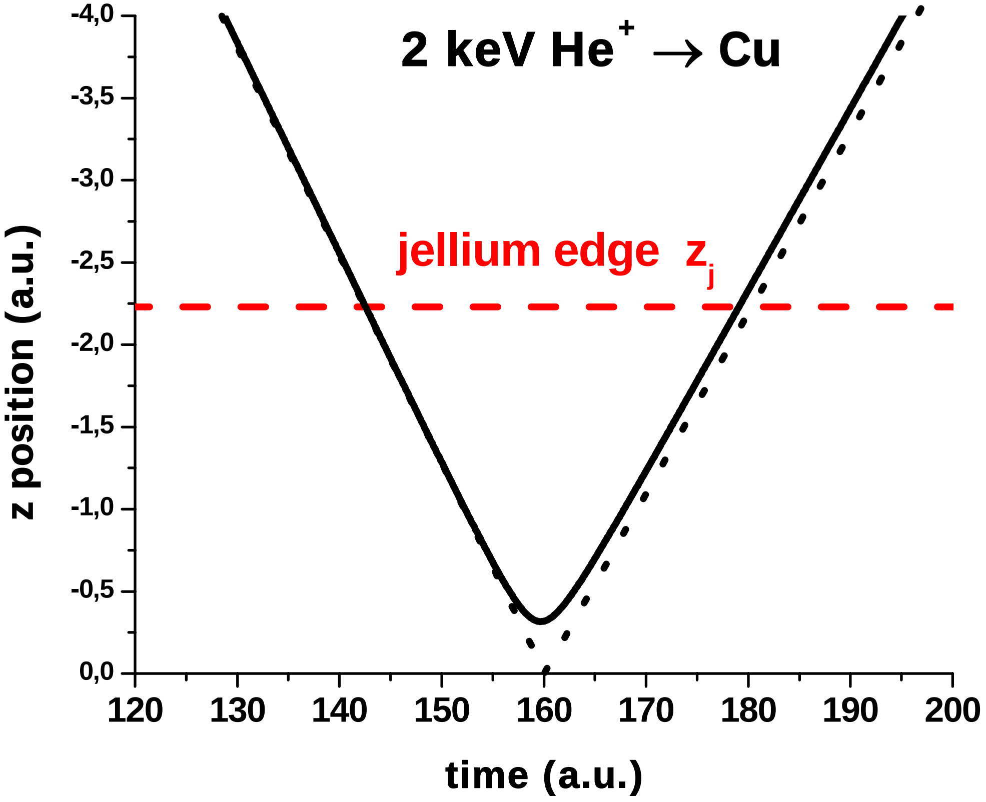
→ Auger neutralization

(M. Draxler 2002)

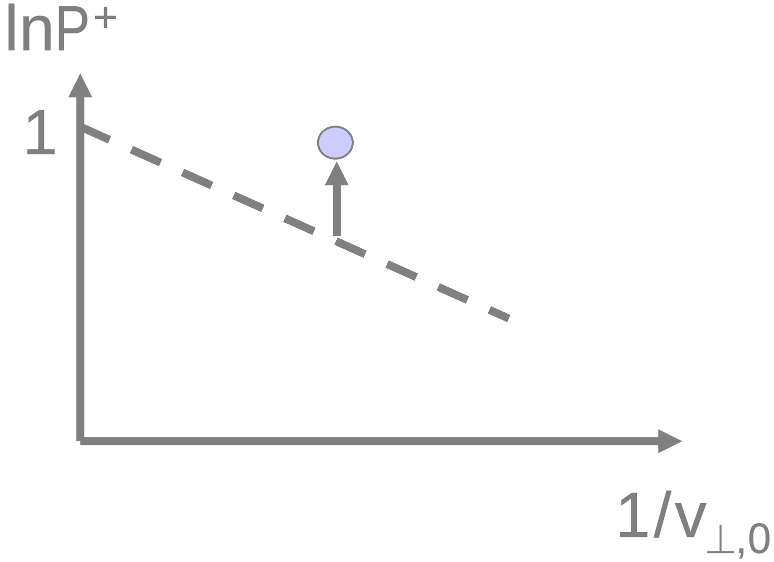
Trajectory effects

$$P^{+} = e^{-\int dt\, \Gamma_A(z)} \approx e^{-\Delta t\, \Gamma_A}$$

$$\Delta t < 2z_j/v_\perp$$

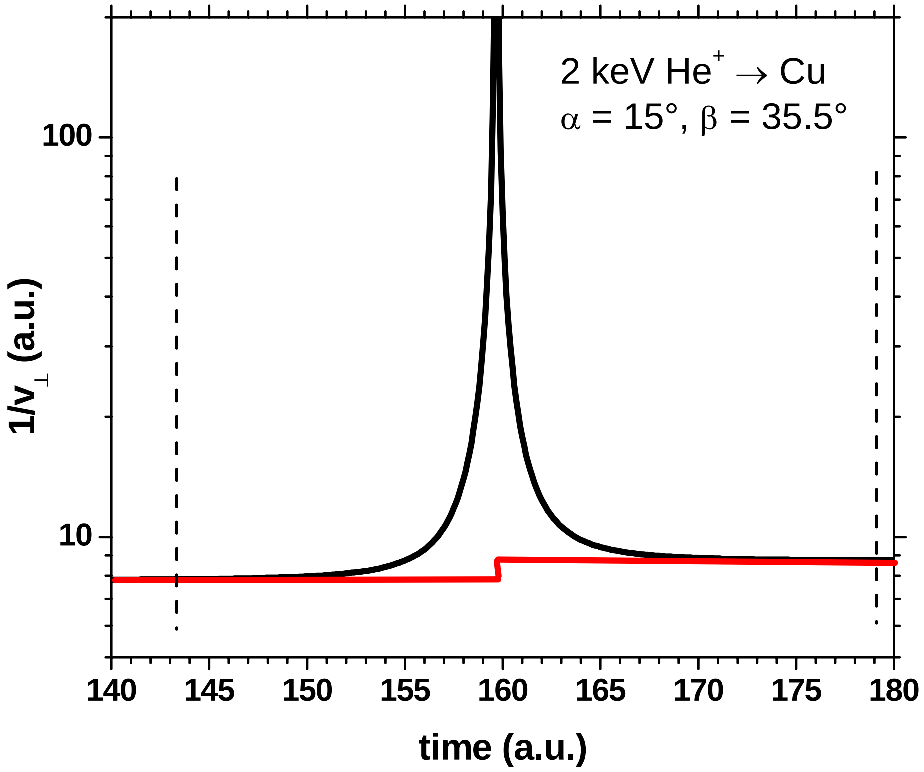


$$P^{+} > e^{-v_c/v_\perp}$$

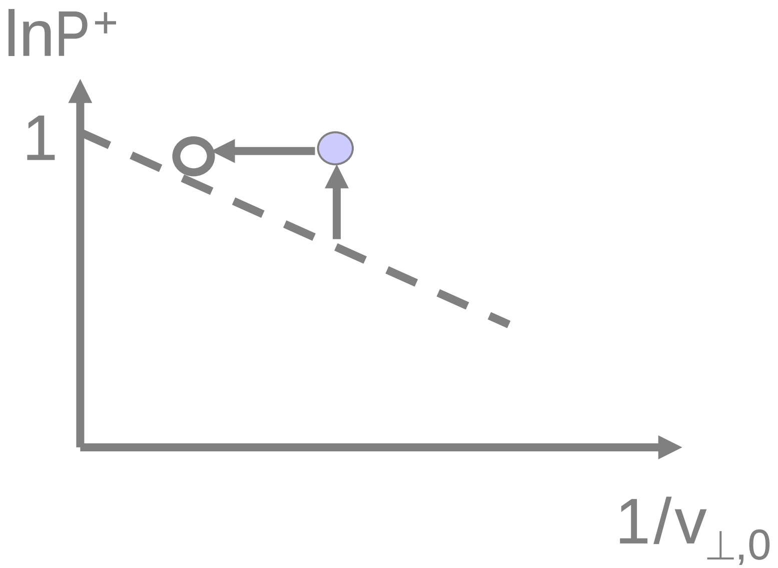


(Valdés 2004)

Trajectory effects



$$\left\langle \frac{1}{v_\perp} \right\rangle > \boxed{\frac{1}{v_{\perp,0}}}$$



Consequences?

interaction time shorter, $<v_\perp>$ smaller

$$P^+ = \exp[-\int_{z_{min}}^{z_{jellium}} dz\, \Gamma(z)/v_\perp(z)] = \exp[-<1/v_\perp> \cdot v_{c,\,eff}]$$

P^+ from experiment: a priori correct (hopefully)
$1/v_\perp$ is larger than estimated by $1/v_{\perp,0}$
v_c results too large

$$P^+ = \exp[-f_{corr} \cdot v_c / v_\perp]$$

$$f_{corr} = \frac{<1/v_\perp>}{1/v_\perp} \cdot \frac{v_{c,eff}}{v_c}$$

f_{corr} small correction?

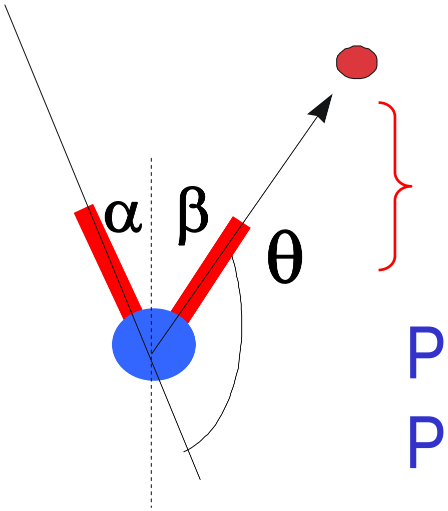
Auger neutr. ↔ collision induced processes

- projectiles: noble gas ions (e.g., He^+)

Auger neutralization AN

collision induced neutralization CIN

collision induced reionization CIR



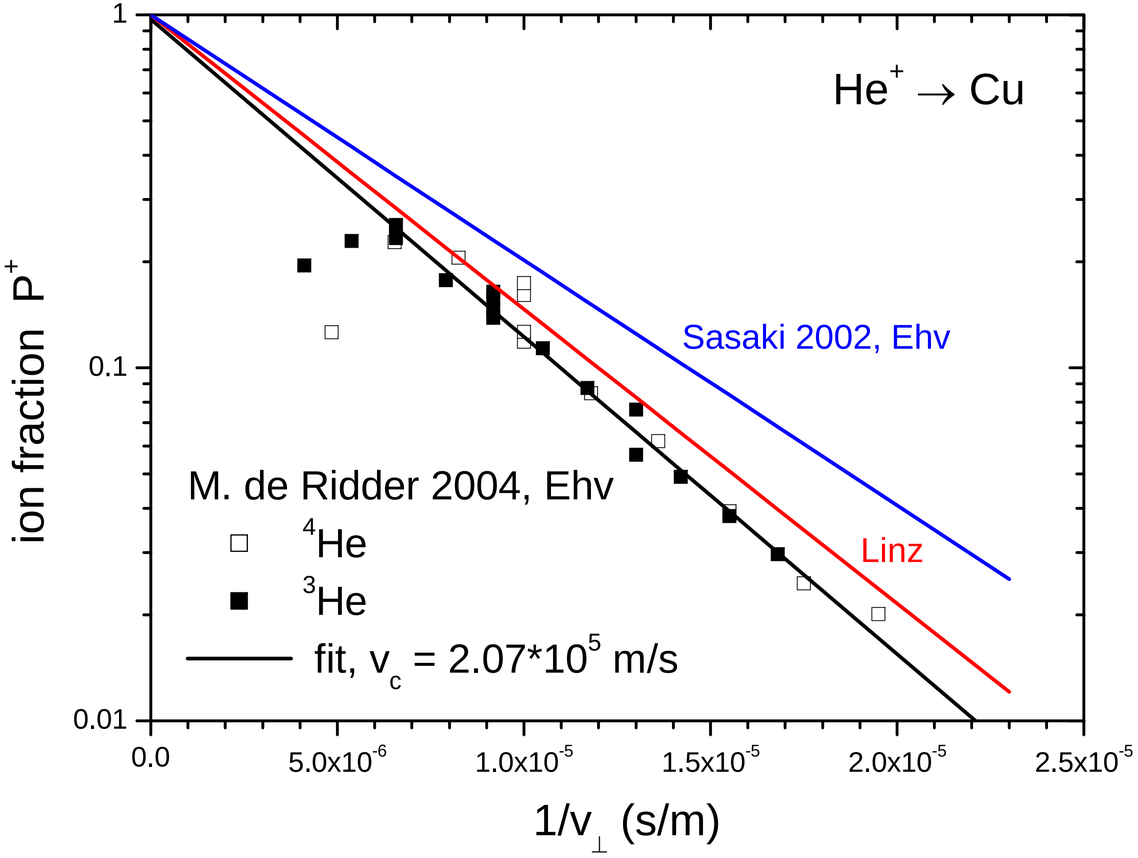
AN: $P^+(v_\perp)$

$P_{CIN}(E,\theta)$

$P_{CIR}(E,\theta)$

Comparison Eindhoven – Linz:

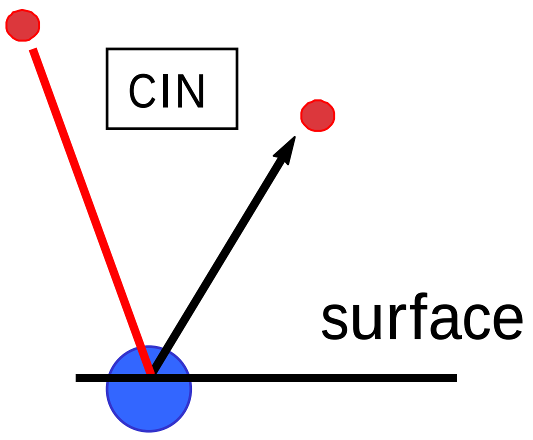
Eindhoven group: variation of energy



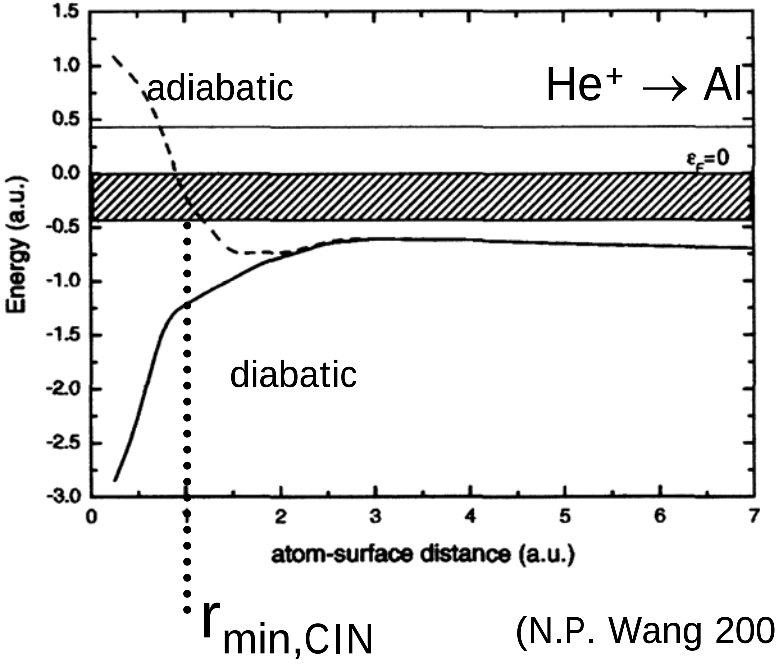
De Ridder & Linz:
good quantitative
agreement!

Collision induced processes

$r < r_{min} \rightarrow$ overlap of orbitals $\rightarrow$ electron promotion



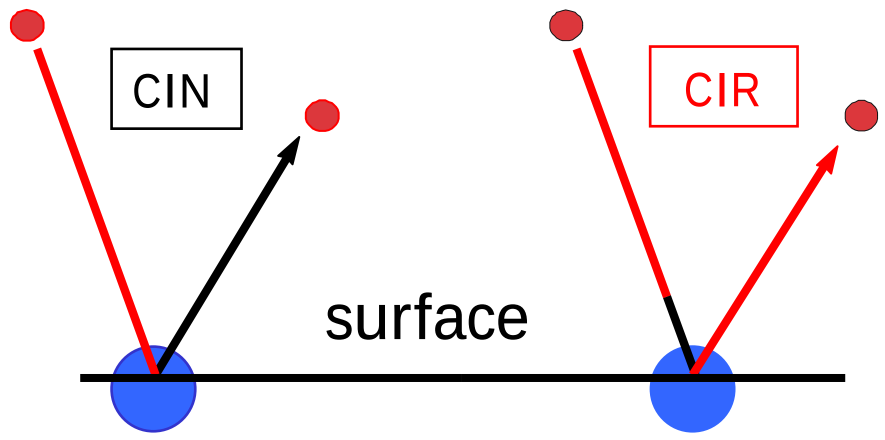
neutralization



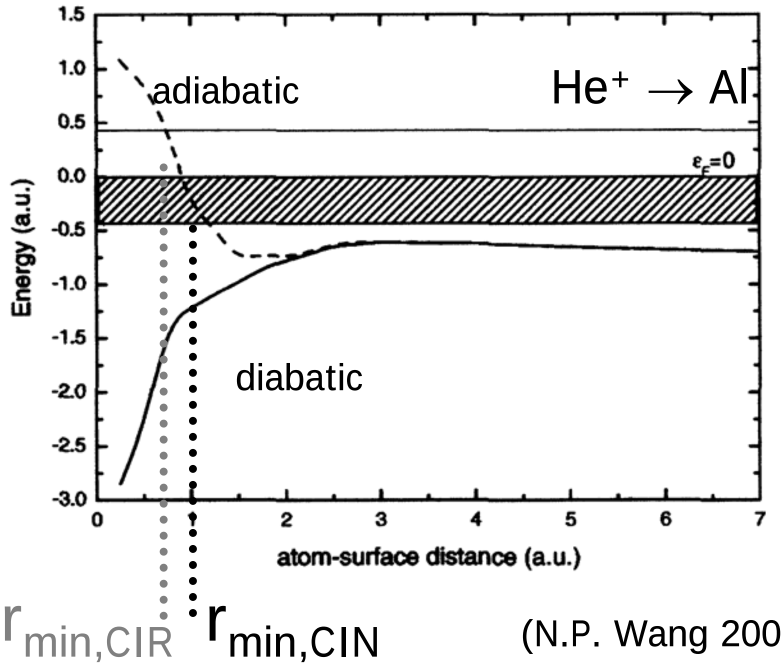
(N.P. Wang 2001)

Collision induced processes

$r < r_{min} \rightarrow$ overlap of orbitals $\rightarrow$ electron promotion



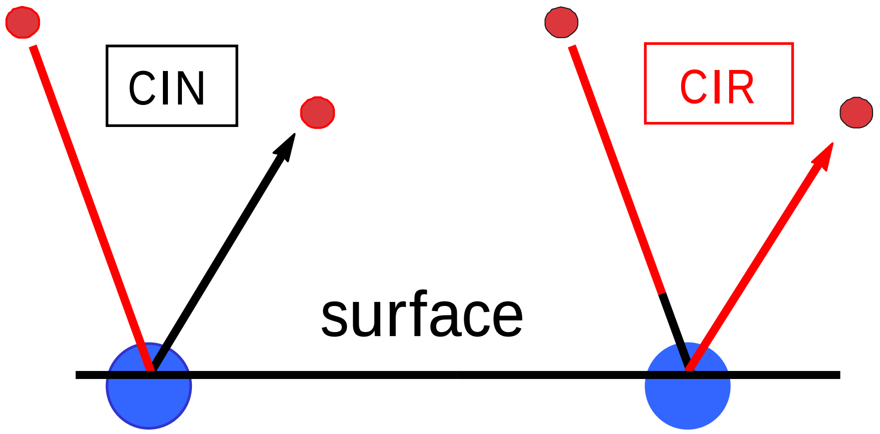
neutralization **reionization**



(N.P. Wang 2001)

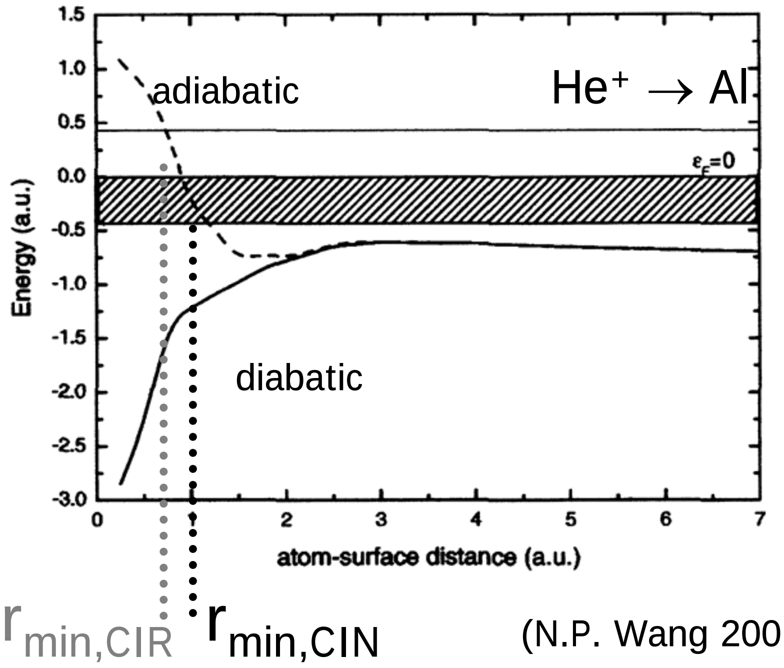
Collision induced processes

$r < r_{min}$ → overlap of orbitals → electron promotion



neutralization

reionization



(N.P. Wang 2001)

$r < r_{min} \leftrightarrow E > E_{th}$

$$\begin{cases} \text{Cu:} & r_{min} \approx 0.1\ \text{Å} & \leftrightarrow E_{th} \approx 2\ \text{keV} \\ \text{Au:} & r_{min} \approx 0.3\ \text{Å} & \leftrightarrow E_{th} \approx 1.5\ \text{keV} \\ \text{Al:} & r_{min} \approx 0.5\ \text{Å} & \leftrightarrow E_{th} \approx 0.4\ \text{keV} \end{cases}$$

Neutralisation ↔ ion fraction P^+

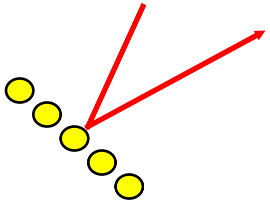
ion fraction $P^+ = N_+/(N_+ + N_0)$ $\left\{ \begin{array}{l} \text{survivals} \\ \text{reionised projectiles} \end{array} \right.$

AN: $P^+(-v_c/v_\perp)$

collision: $P_{CIN}(E, \theta)$, $P_{CIR}(E, \theta)$

Neutralisation ↔ ion fraction P^+

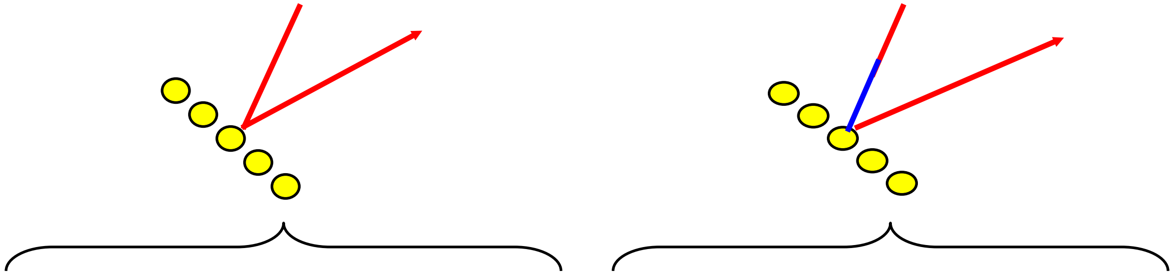
$E > E_{th}$:



$$P^+ = \overbrace{\underbrace{P^+_{in}\cdot(1-P_{CIN})\cdot P^+_{out}}_{\text{survivals}}}$$

Neutralisation ↔ ion fraction P^+

$E > E_{th}$:

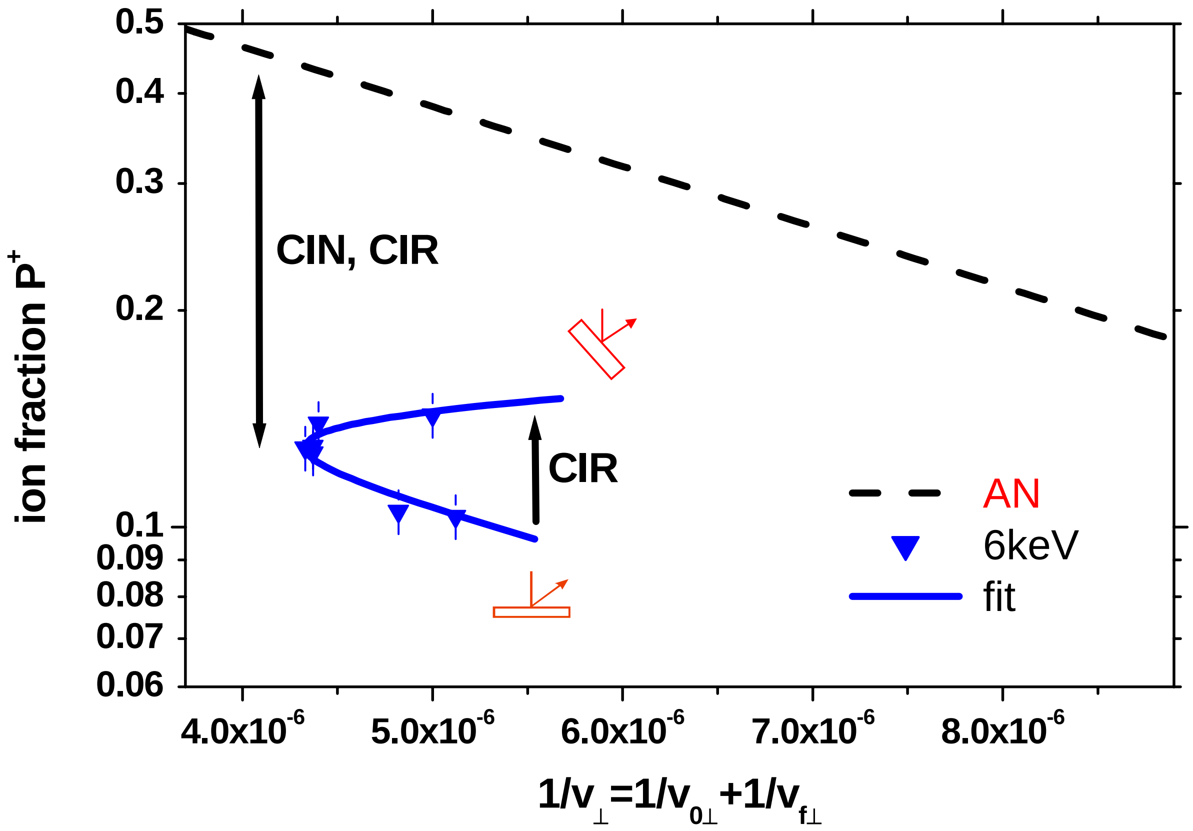


$$\boxed{P^+ = \underbrace{P^+_{in}\cdot(1-P_{CIN})\cdot P^+_{out}}_{\text{survivals}} + \underbrace{(1-P^+_{in})\cdot P_{CIR}\cdot P^+_{out}}_{\text{reionised projectiles}}}$$

$P^+ = P^+(E, \theta, v_\perp) \rightarrow P^+(\alpha)$ @ given E, θ

^{4}He → Cu

$E > E_{th}$: $P^+(v_\perp, \alpha)$



fixed energy ↔ P_{CIN}, P_{CIR} constant

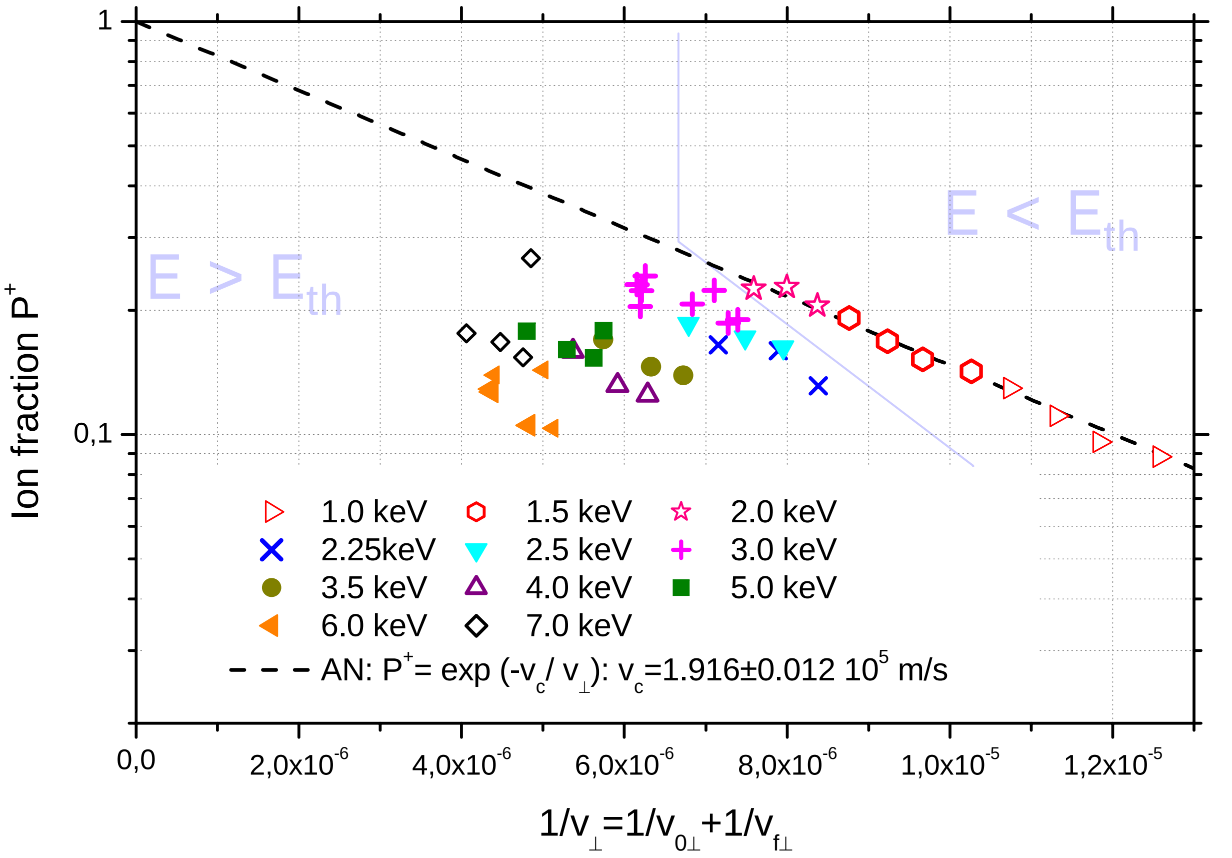
variation of $v_\perp$ by variatio of geometry

→ ‚boomerang' shape

→ $P_{CIN} > P_{CIR}$

(M. Draxler 2004)

$^4He \rightarrow Cu$



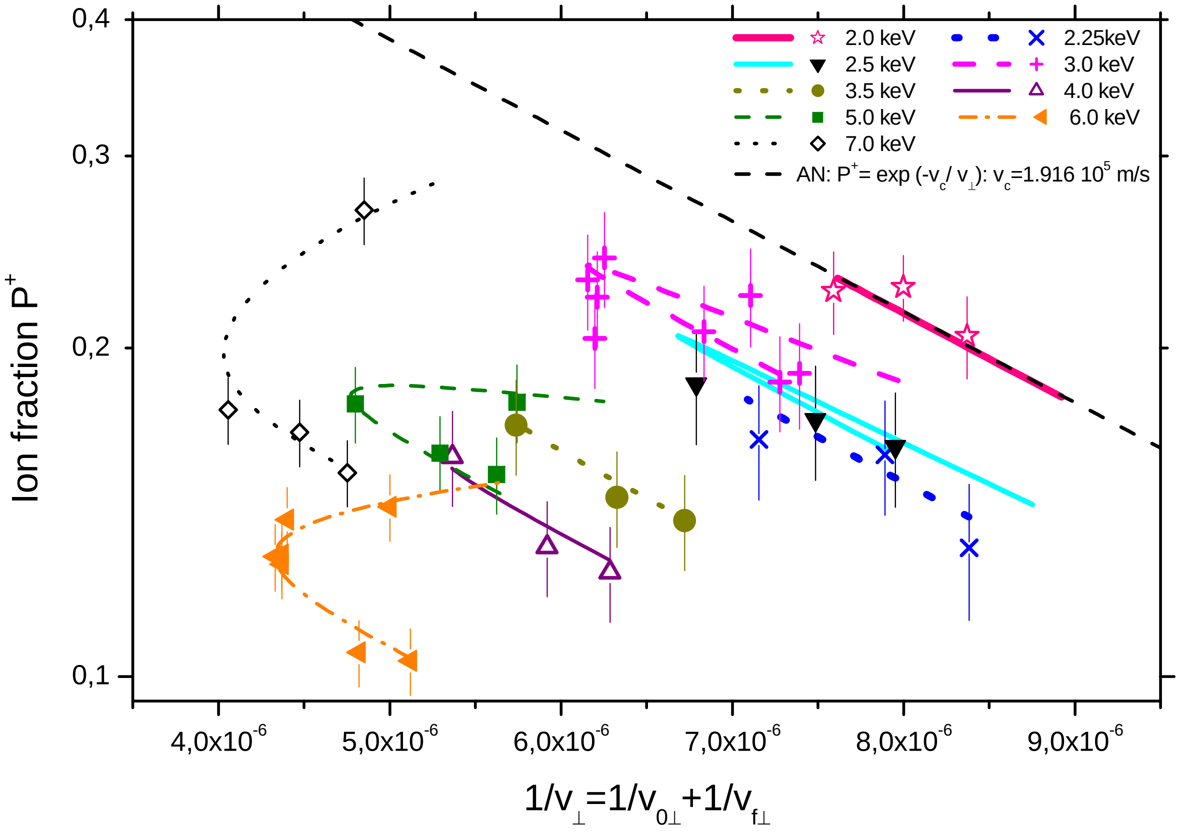
(M. Draxler 2002)

$E < E_{th}$: $P^+(v_{\perp})$

$E > E_{th}$: $P^+(v_{\perp}, \alpha)$

^{4}He → Cu

High energy regime in more detail:



variation of $v_\perp$ by

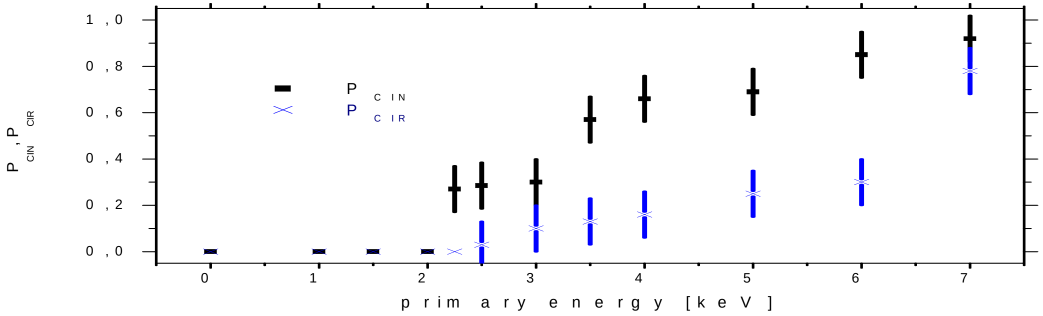
- variation of energy
- variation of geometry

→ AN

→ CIN, CIR

→ $P_{CIN} >> P_{CIR}$

$P_{CIN}(E)$, $P_{CIR}(E)$



$P_{CIN} > P_{CIR}$

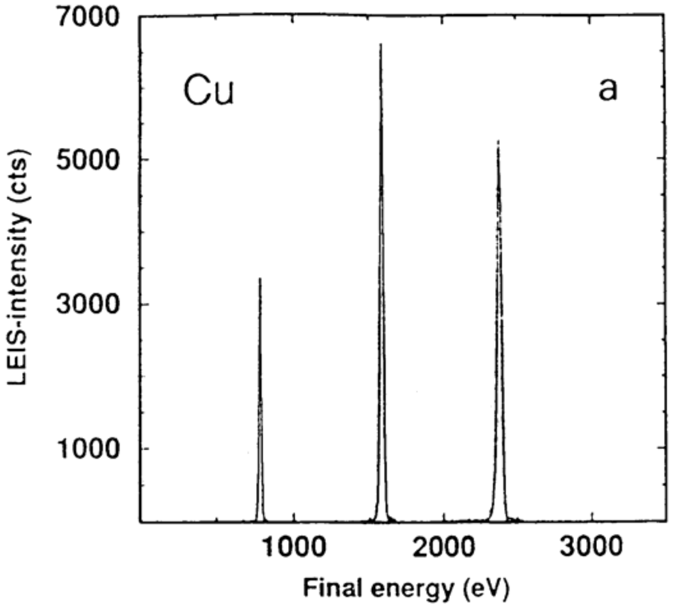
P_{CIN}↑ , P_{CIR}↑ with E ↑

P_{CIN}, P_{CIR} at higher E?

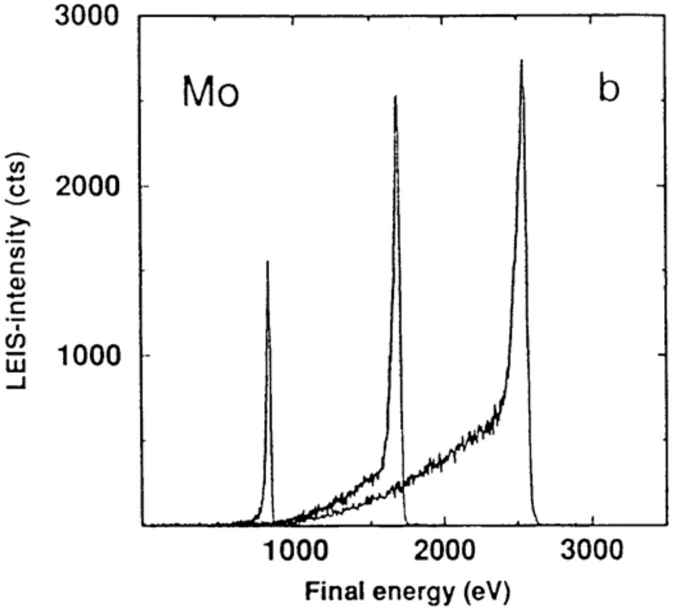
(M. Draxler 2002)

Shape of ion spectra

Cu: threshold for reionization
is high (E_{th} = 2.1 keV)
→ no reionization background
for E < 3 keV



Mo: threshold for reionization is
low (E_{th} = 0.4 keV)
→ reionization background
down to E < 1 keV

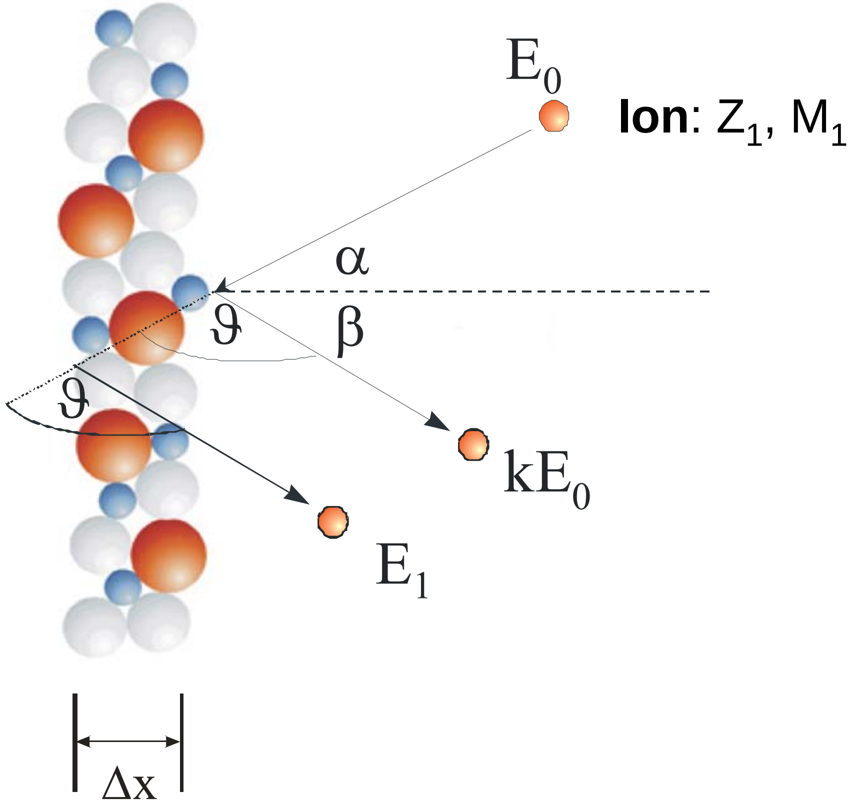


Applications: surface composition analysis

(concentrations c_j of j atoms, j = „dark blue“, „light blue“ and „red“)

$$A_j^+ = \frac{N_0}{\cos\alpha} \cdot \frac{d\sigma_j}{d\Omega} \cdot (nd)_{j,0} \cdot \Omega \cdot P_j^+ \cdot \eta_+ = c_j S_j$$

Target: Z_{j2}, M_{j2}



Quantitative surface composition analysis

Surface concentration of element j

basis:

$$\boxed{A_j^+ = \frac{N_0}{\cos\alpha} \cdot \frac{d\sigma_j}{d\Omega} \cdot (nd)_{j,0} \cdot \Omega \cdot P_j^+ \cdot \eta_+ = c_j S_j}$$

sensitivity factor for element j

Main question: does P^+ depend on surface composition?

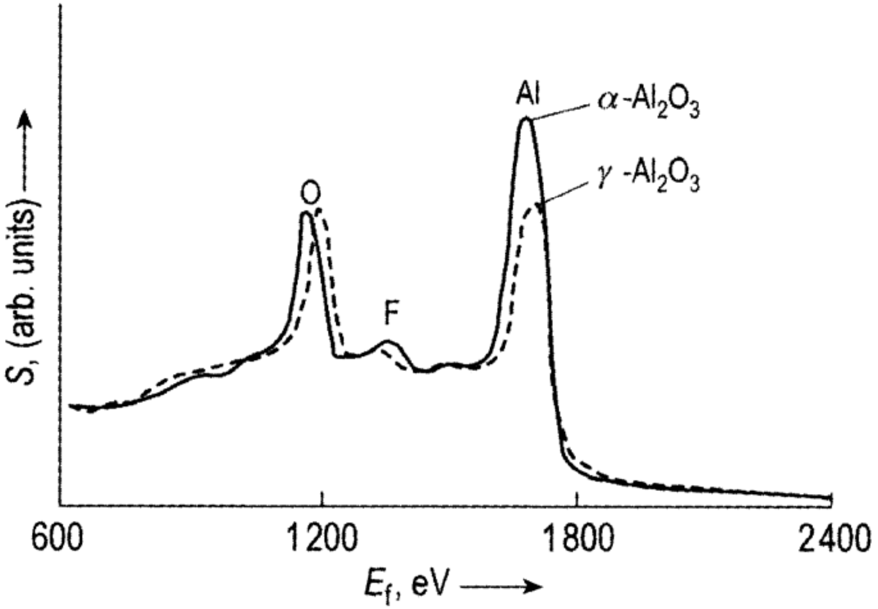
↔ are there „matrix effects“?

No matrix effects ↔ S_i does not depend on other elements present in the surface.

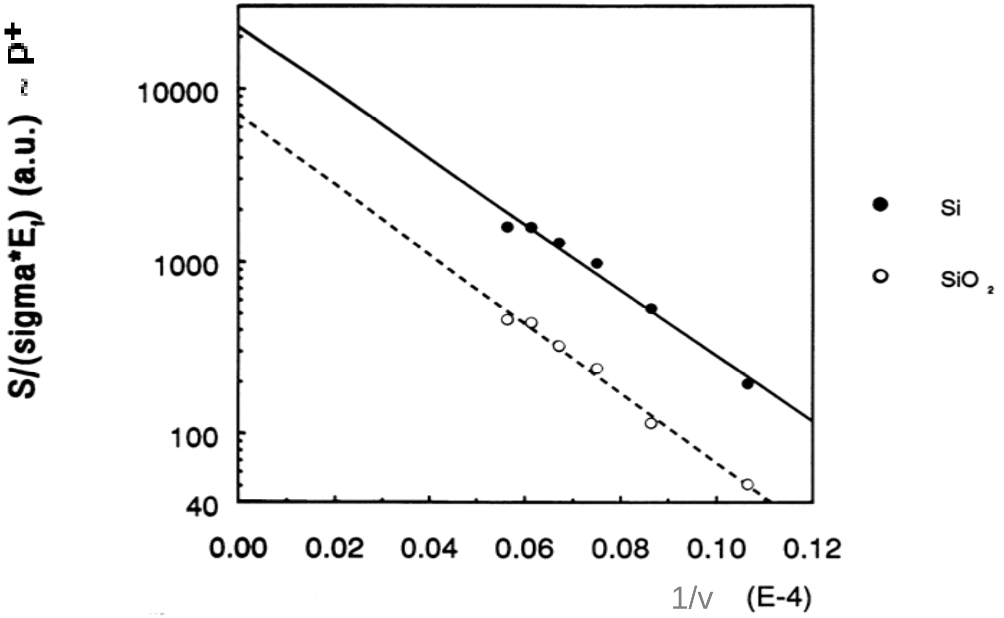
How to prove the absence of matrix effects?

Quantitative LEIS: Usually NO Matrixeffects
(↔ P^+ does not depend on chemical environment)

.... not even in oxides (SiO_2, Al_2O_3)!



(G.C. van Leerdam, 1991)

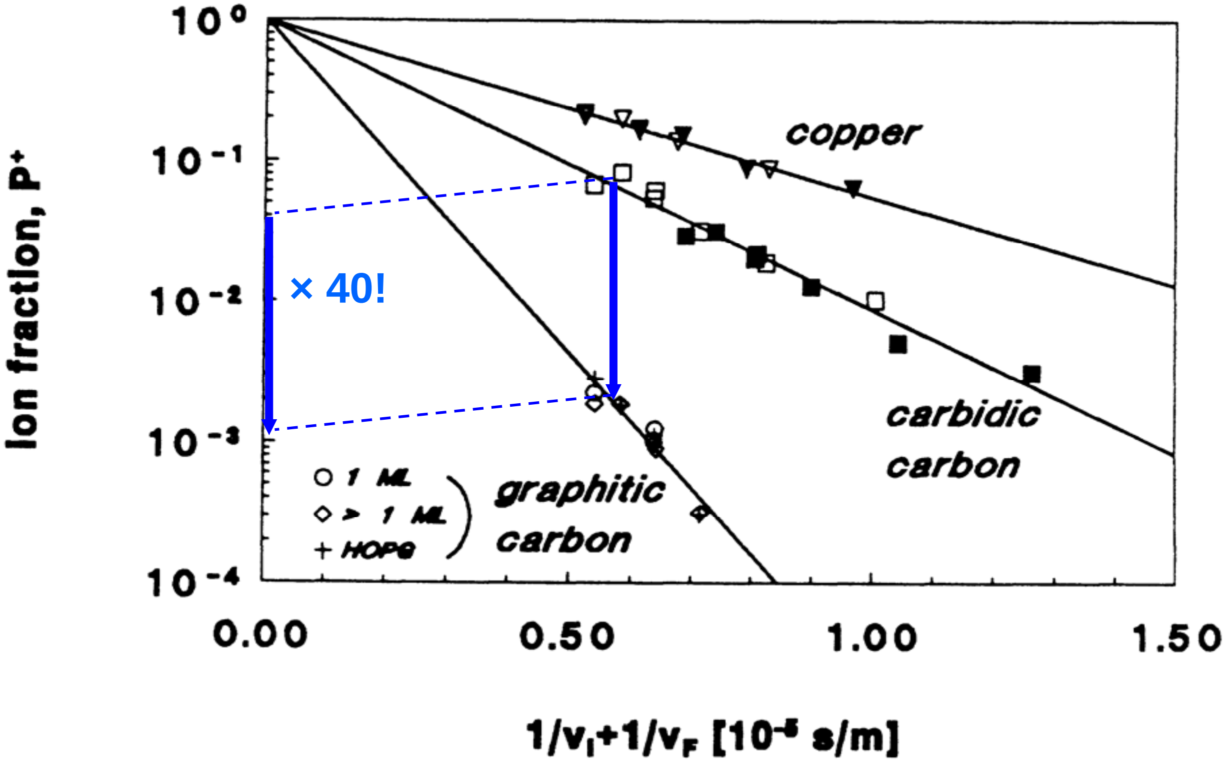


(J.P. Jacobs, 1991)

…but sometimes P^+ does depend on chemical state

... for instance: Carbon (graphitic - carbidic)

→ yield is dependent on binding partner.



(L.C.A. van den Oetelaar, 1994)

Summary charge exchange processes

✓ model system to study P^+

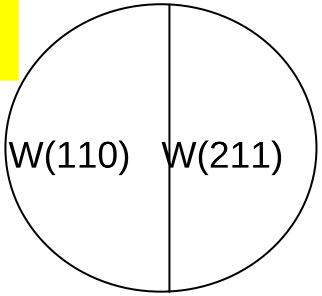
✓ „local“ ↔ „non-local“ neutralisation in LEIS

✓ P^+ is a rather complex quantity

? Is P^+ well behaved?

What about quantitative surface composition analysis?

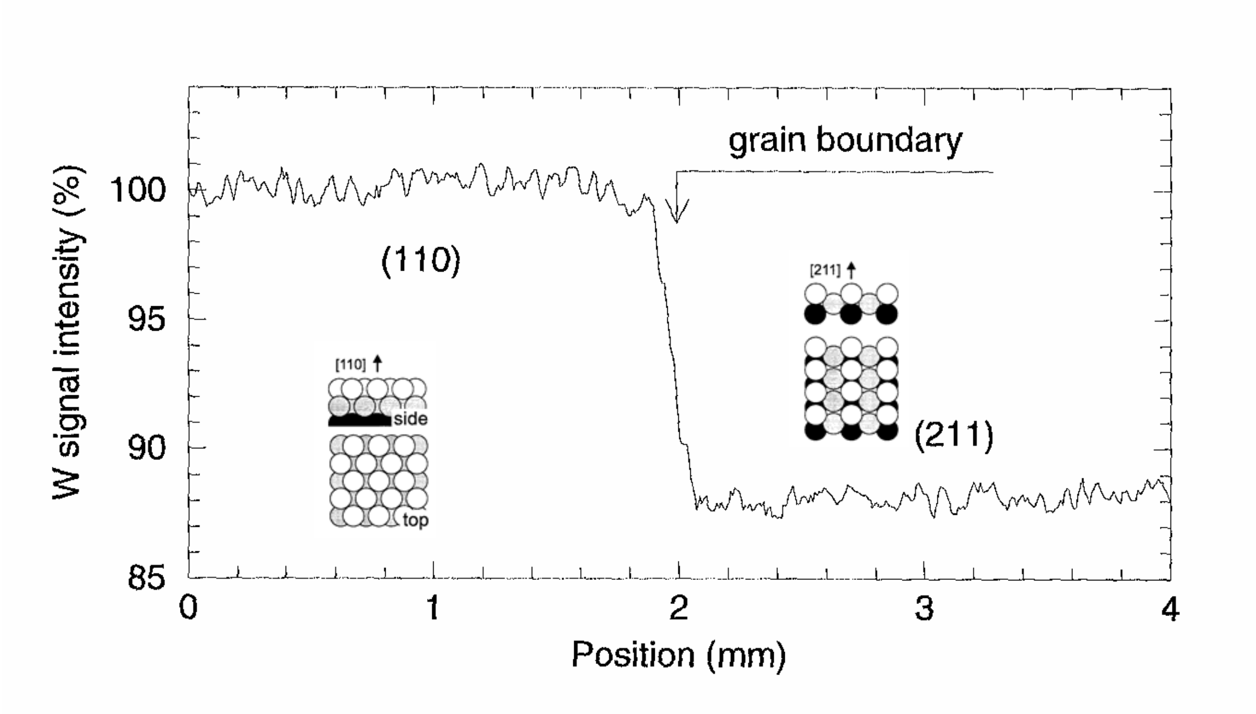
He$^+$ → bicrystal W(110), W(211)



surface atomes/cm^2: $n_{211}/n_{110} = 0.58$

signal ratio : $n_{211}/n_{110} = 0.88$

→ different neutralisation or deeper layers contributing



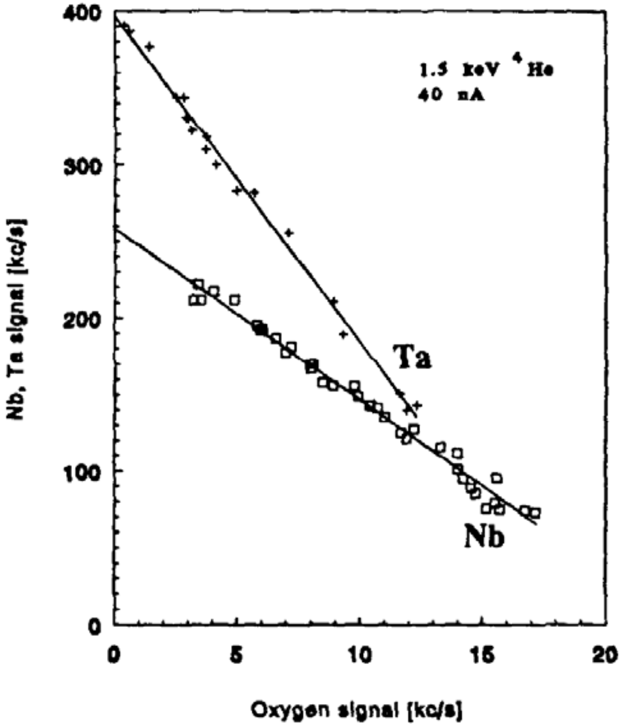
Cortenraad (2000)

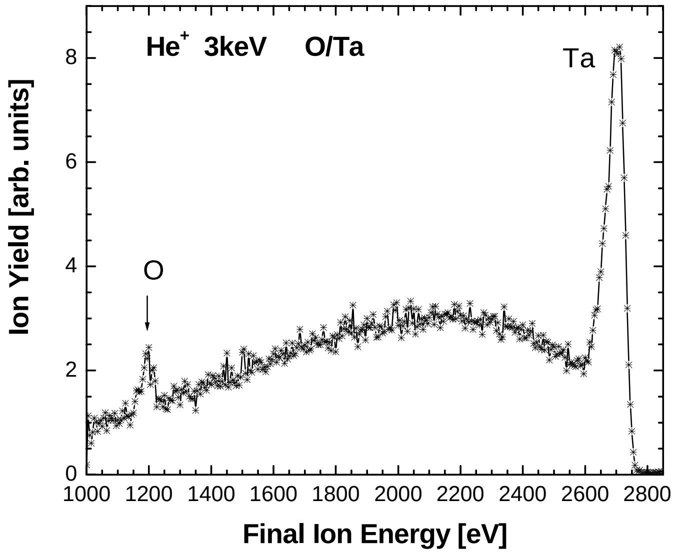
Two elements (O, W) in the surface

$$c_O + c_{Ta} = 1$$

$$A_O^+ = c_O S_O$$

$$A_{Ta}^+ = c_{Ta} S_{Ta}$$





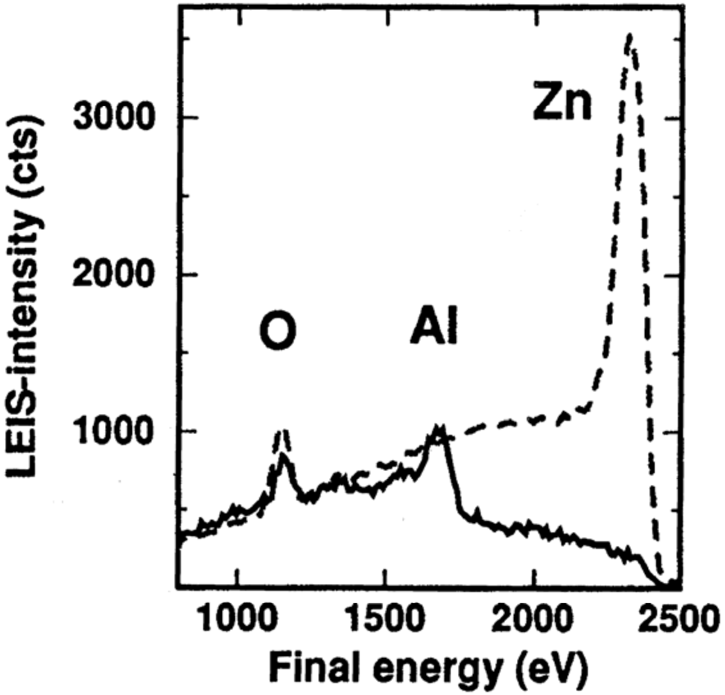
$$\rightarrow \boxed{\frac{A_O^+}{S_O} + \frac{A_{Ta}^+}{S_{Ta}} = 1}?$$

→ is plot A_{Ta}^+ vs. A_O^+ linear?

→ indeed no matrix effects!

Application: surface composition of a spinel

$ZnAl_2O_4$ zinc aluminate spinel*)



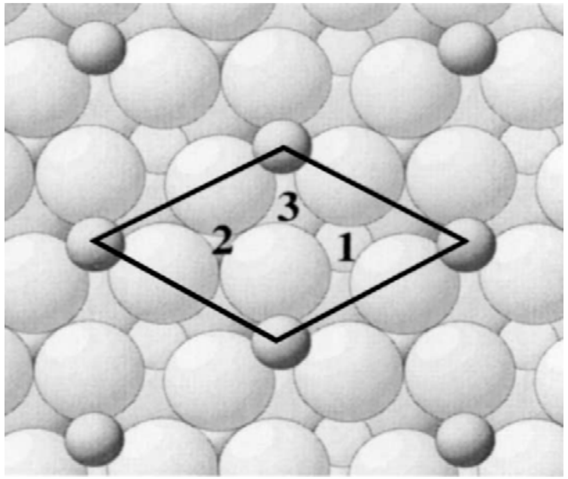
LEIS is sensitive to Zn (see ZnO)

no Zn visible in spinel surface!

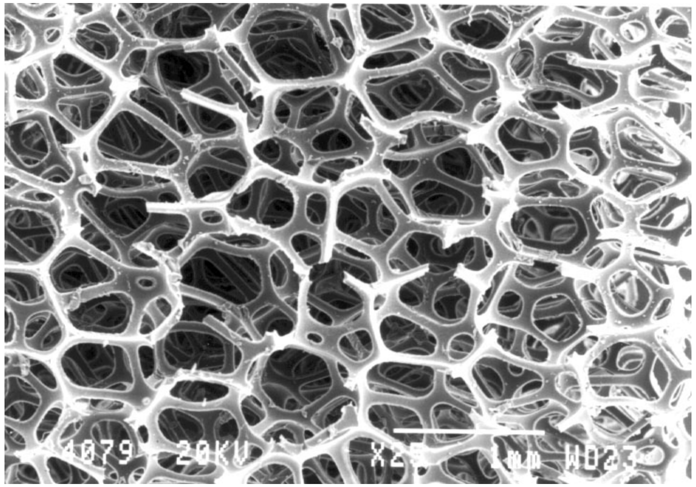
*) as bulk ceramic: used as a structural and high-temperature material.
with high-surface area: useful as catalysts and catalytic supports

Influence of surface roughness?

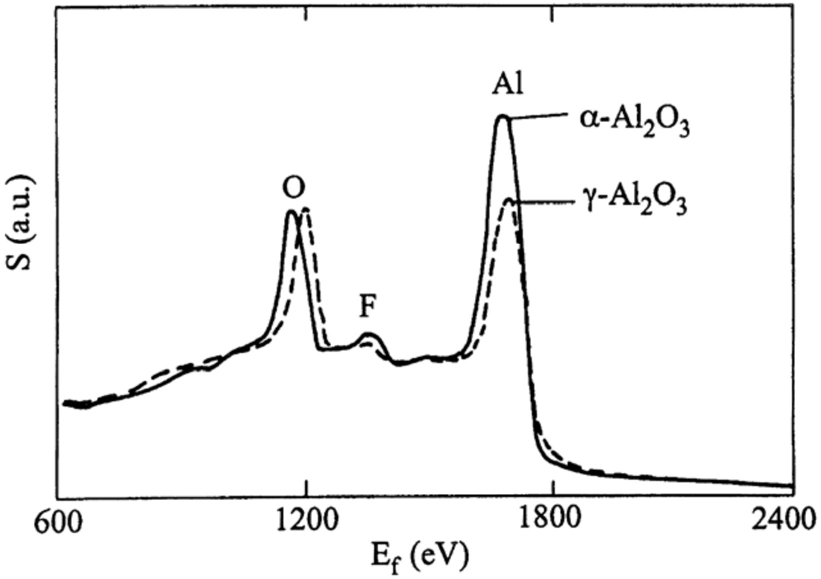
α Al_2O_3



γ Al_2O_3

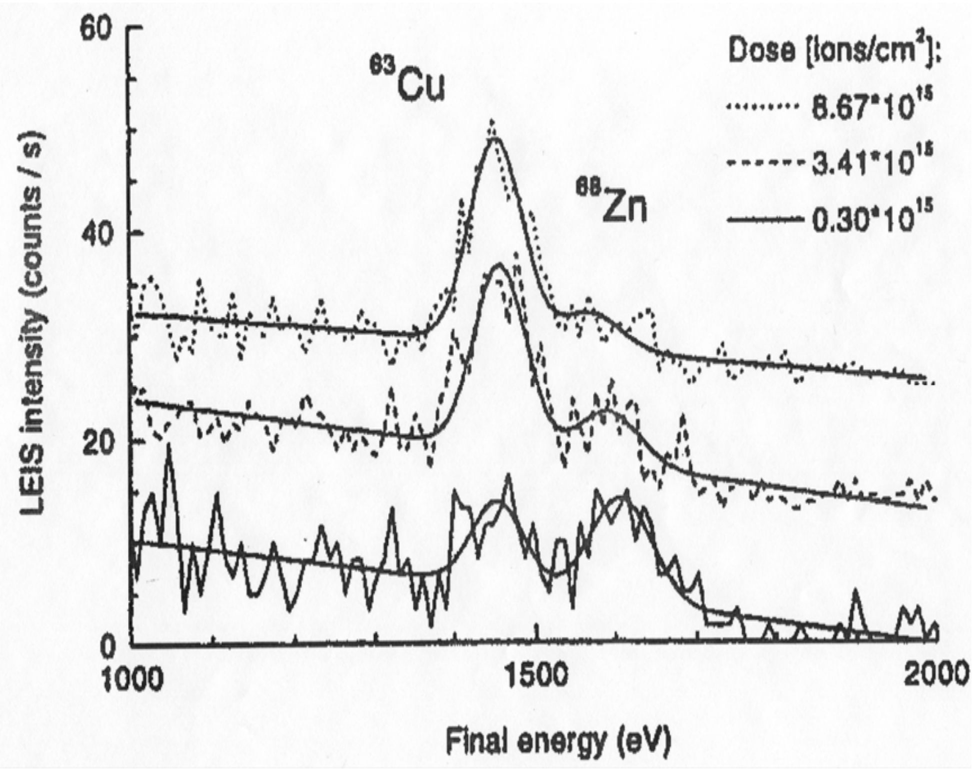


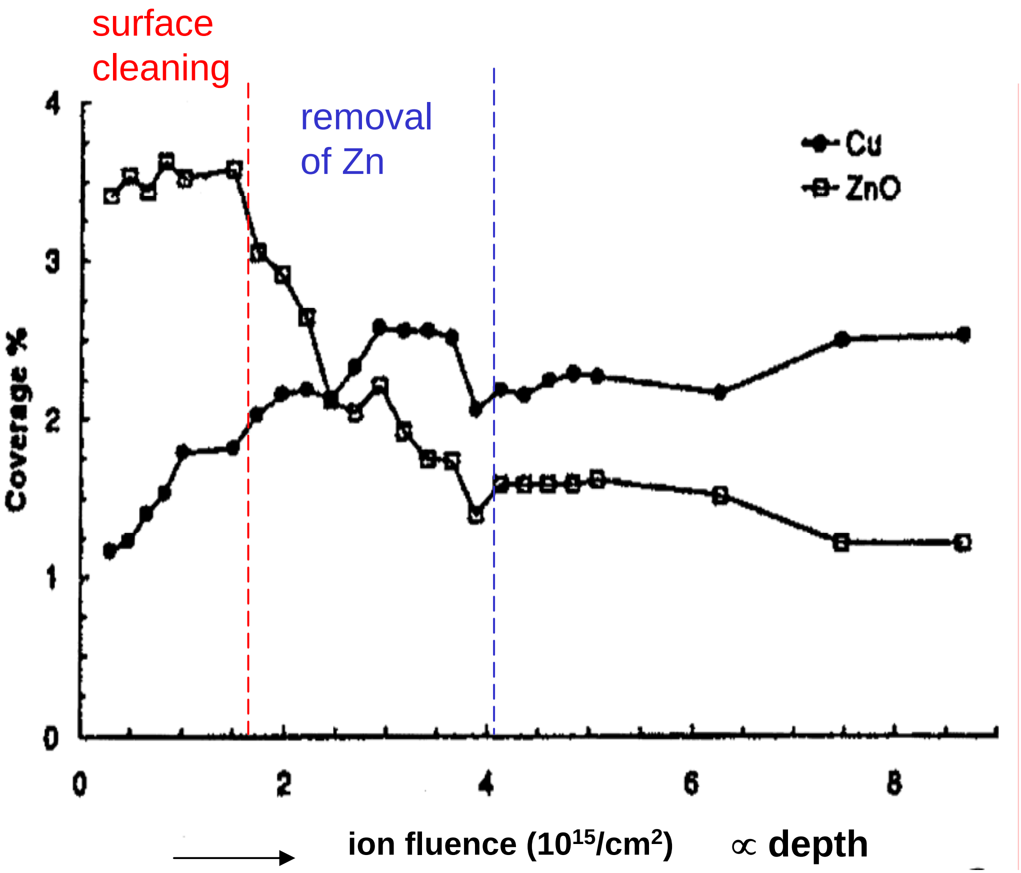
LEIS analysis for surface composition:



Analysis of a real Cu/ZnO/SiO_2 catalyst

ceramic sponges are easily destroyed by ion bombardment → static LEIS: quantitative surface composition is possible!





Contents:

ion scattering: RBS ↔ LEIS

- scattering by nuclei → scattered yield
- interaction with target electrons → slowing down

Low energy ion scattering (LEIS)

- Electrostatic analyzer: ESA-LEIS
- Time-Of-Flight: TOF-LEIS

ESA-LEIS:

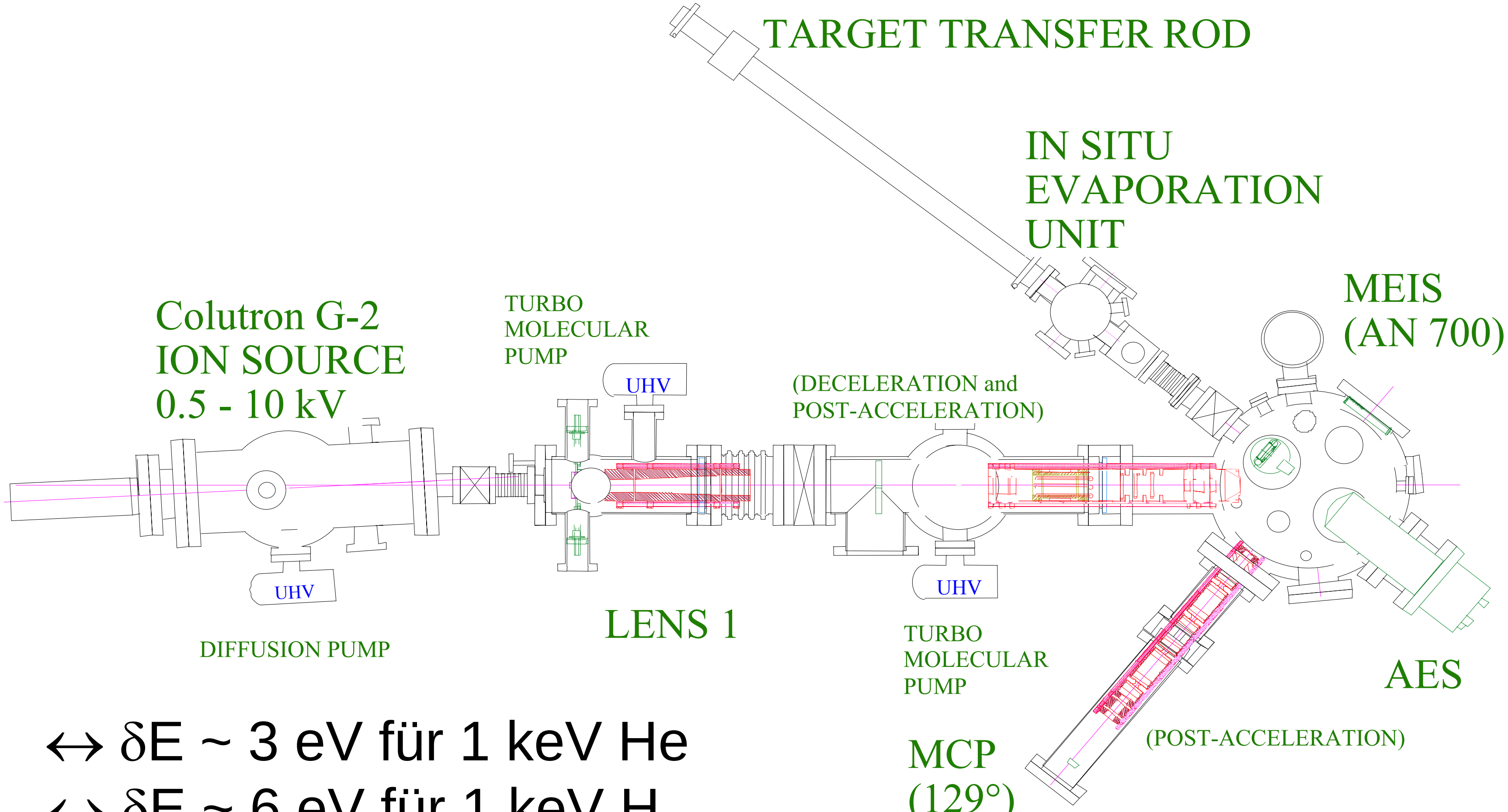
- instrumentation → static ESA-LEIS
- ions detected → ion fraction P+
- noble gas ions:
  - neutralisation → surface sensitivity
- applications: quantitative surface analysis → examples

TOF-LEIS (Time-of-flight)

- instrumentation → static TOF-LEIS
- ions and neutrals detected
  - surface structure analysis
  - depth resolution → depth analysis → applications
  - neutral spectrum: shape, depth information

Static TOF-LEIS - ACOLISSA

Advantages: - fluence < 10^{12} ions/cm^2
- ions **and/or** neutrals

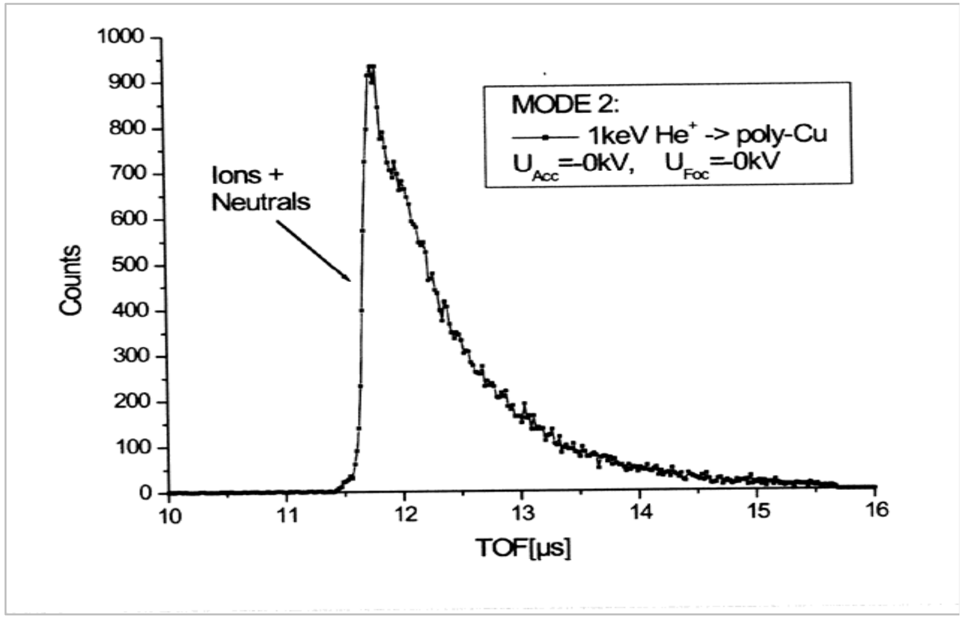


$\delta t \sim 5$ ns $\leftrightarrow \delta E \sim 3$ eV für 1 keV He
$\leftrightarrow \delta E \sim 6$ eV für 1 keV H

(M. Draxler, 2004)

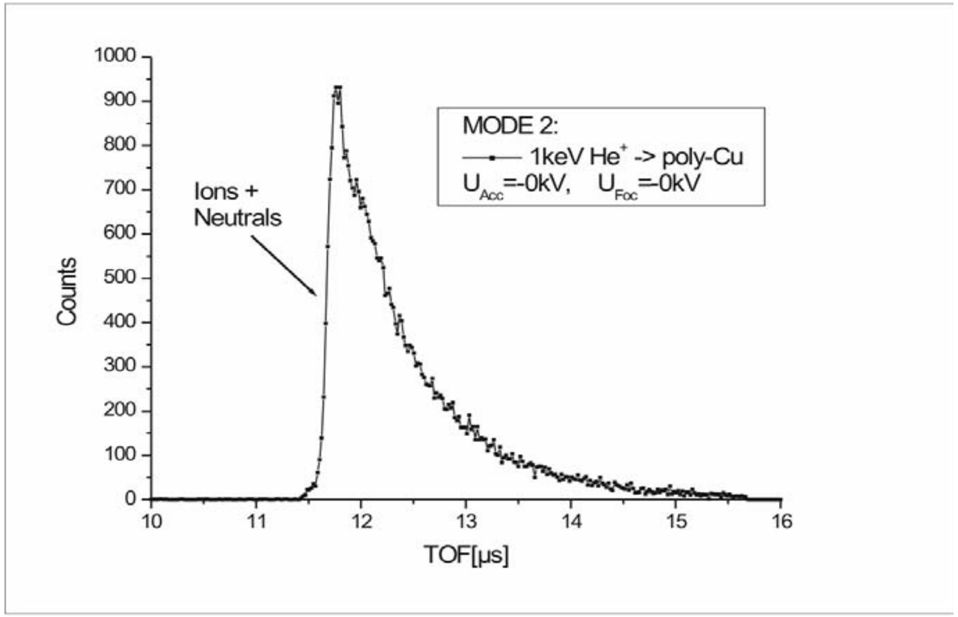
Static TOF-LEIS

no post-acceleration
→ ions + neutrals

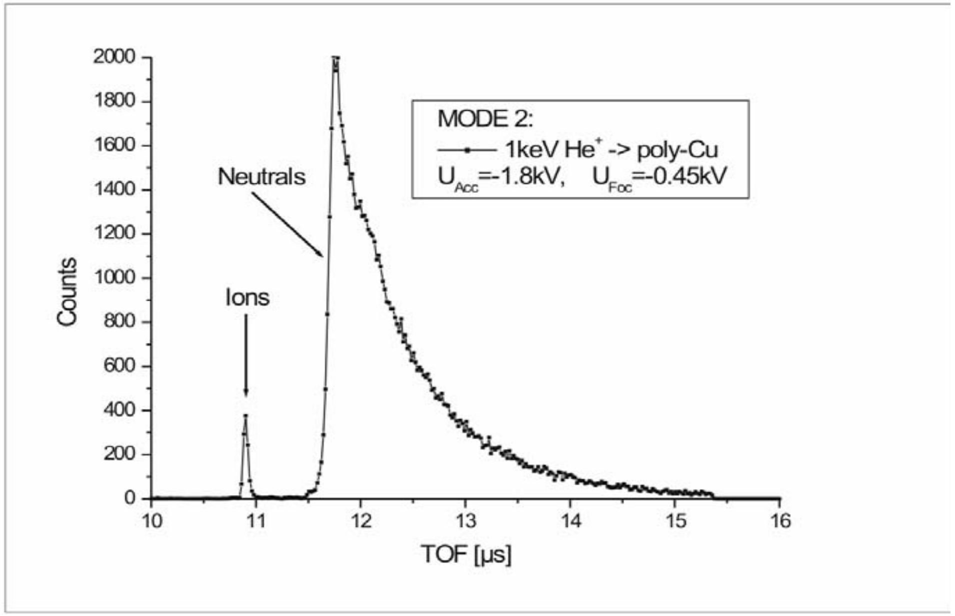


Static TOF-LEIS

no post-acceleration
→ ions + neutrals



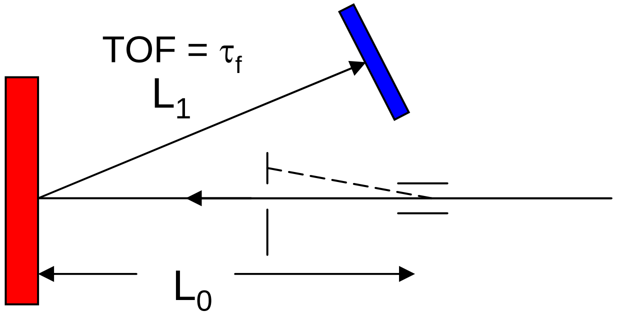
with post-acceleration
→ ions / neutrals separated



(M. Draxler, 2002)

Conversion TOF spectrum → energy spectrum

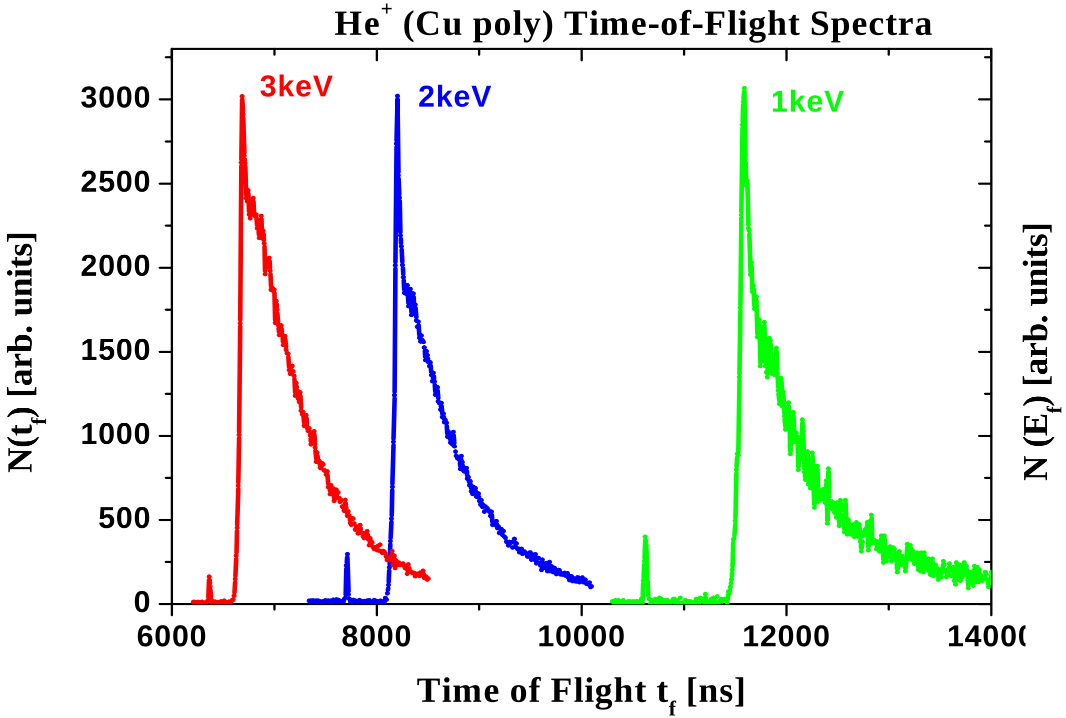
Classical mechanics: $E_f = (M/2)v_f^2 = (M/2)\cdot(L_1/\tau_f)^2$

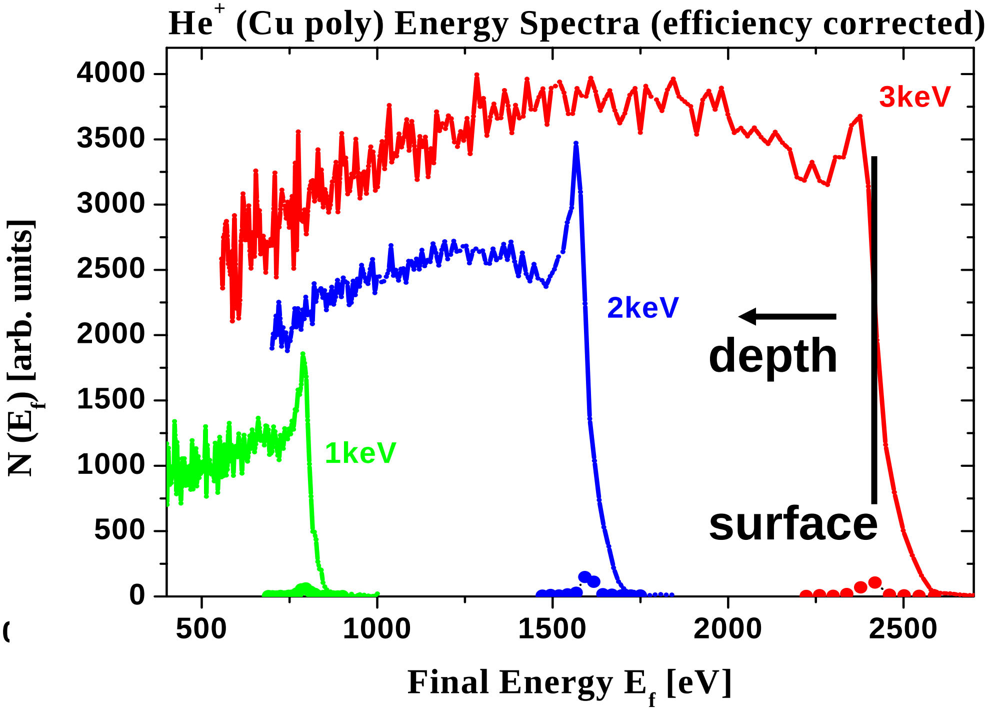


$$\frac{dE_f}{d\tau_f} = -2\frac{M}{2}\frac{L_1^2}{(\tau_f)^3} = -2\frac{E}{\tau_f}$$

particle conservation: $\underbrace{N(E_f)dE_f}_{\text{\# particles in one energy-channel dE}} = \underbrace{N(\tau_f)d\tau_f}_{\text{\# particles in one TOF channel } d\tau_f}$

Conversion TOF spectrum → energy spectrum

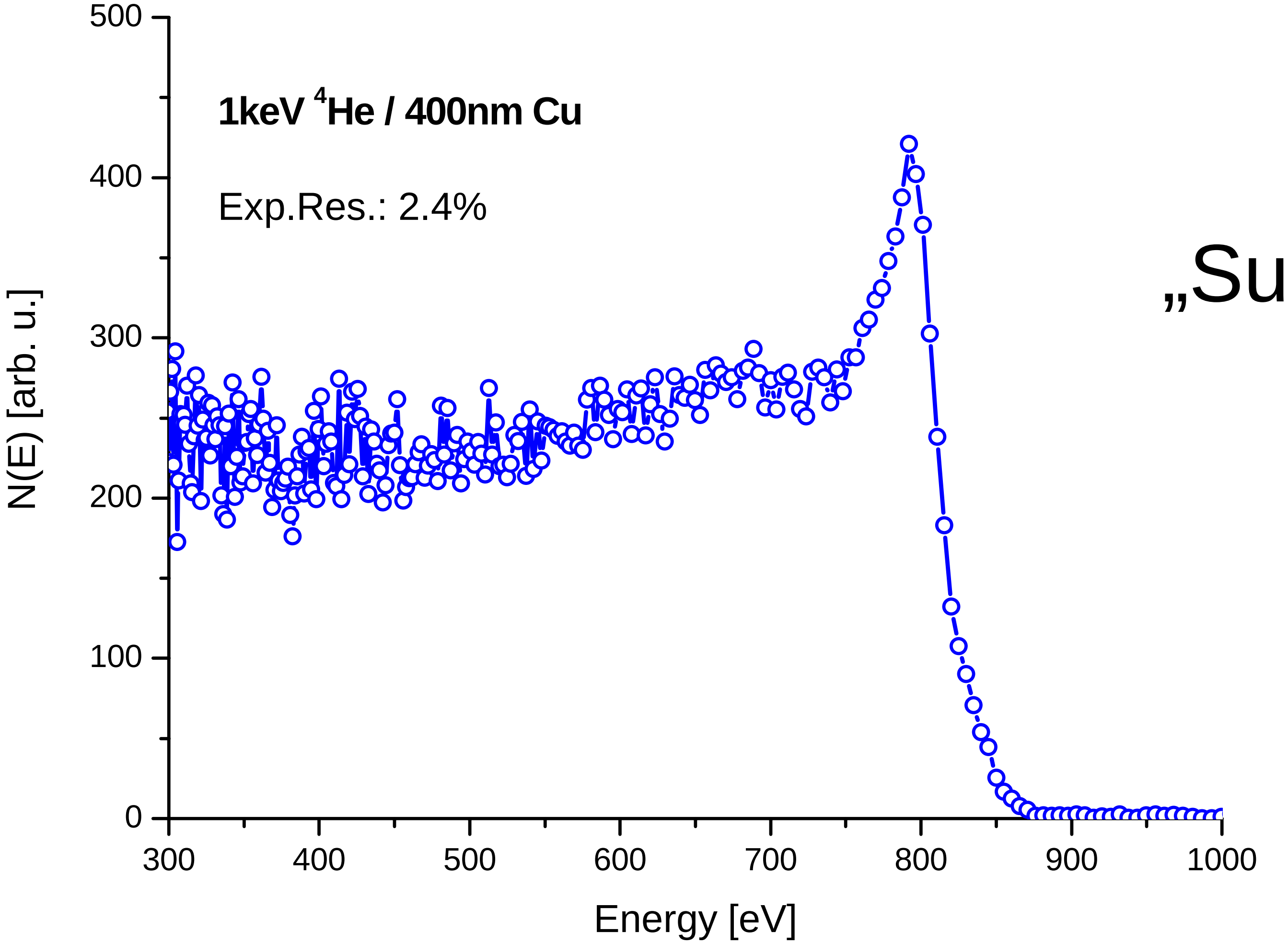

He$^+$ (Cu poly) Time-of-Flight Spectra


He$^+$ (Cu poly) Energy Spectra (efficiency corrected)

ions: surface peak (As in ESA spectra)

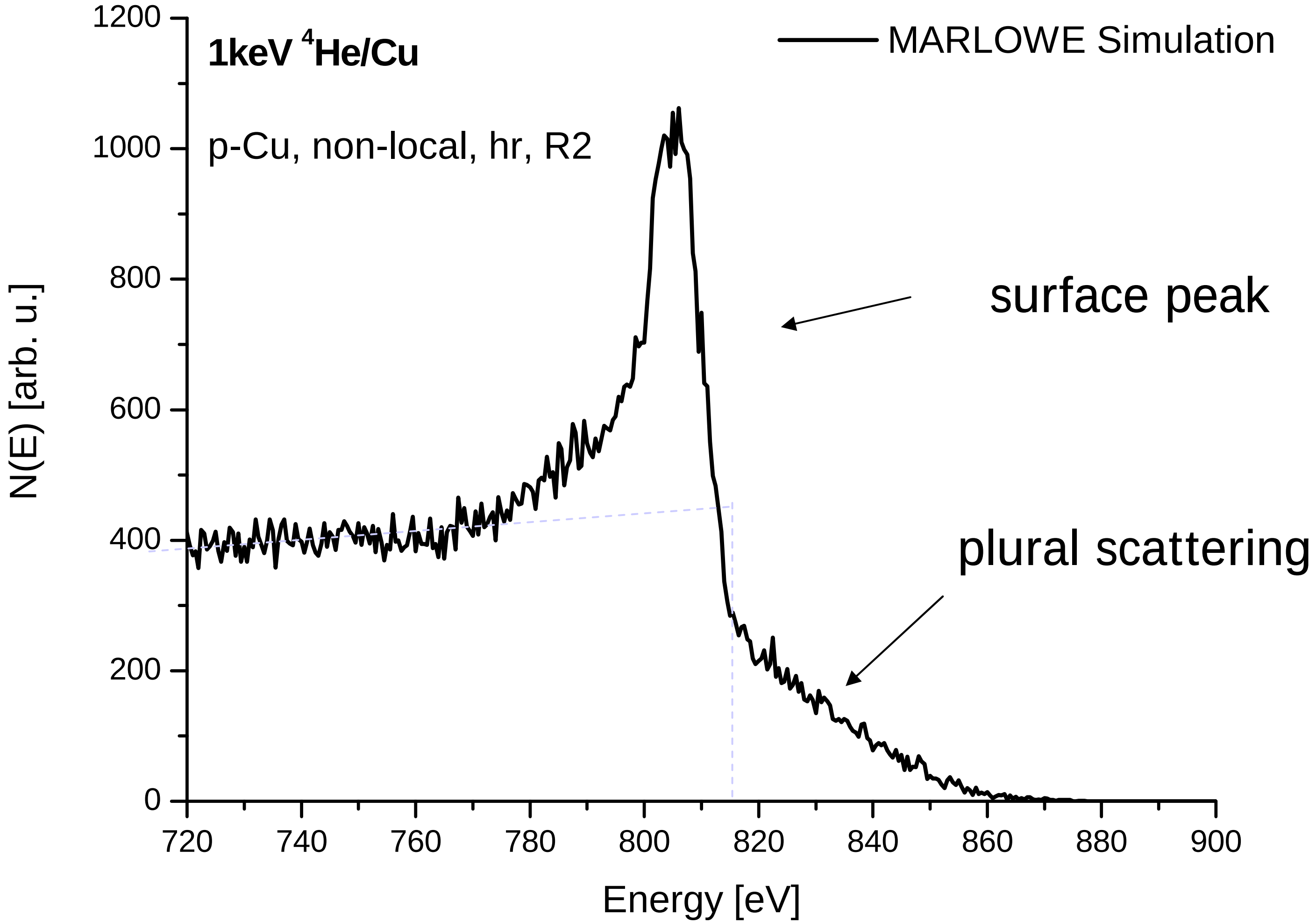
neutrals: much higher intensity than in ion spectrum
neutral spectrum has a surface peak,
contains also information from deeper layers

Energy spectrum

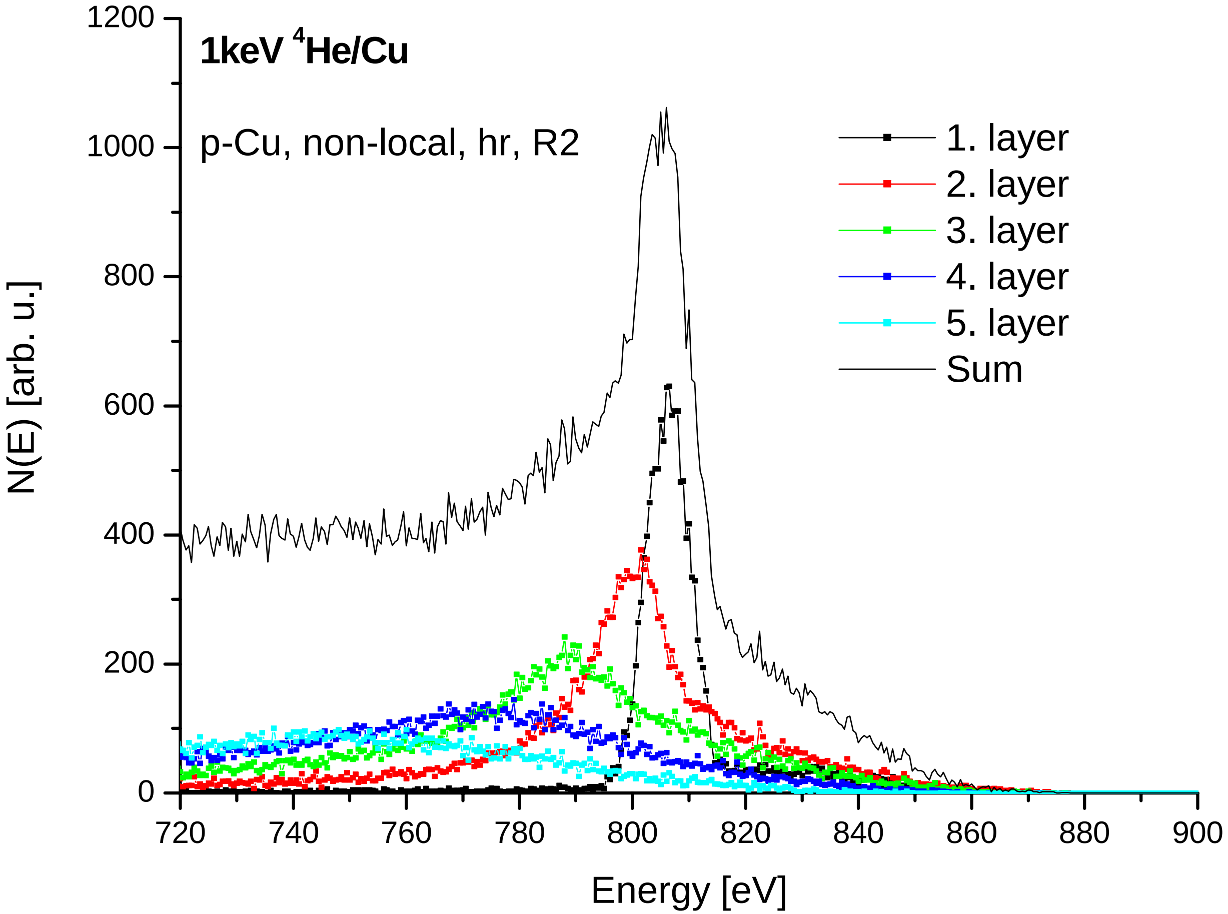


„Surface peak“

MARLOWE-simulation (Monte-Carlo)



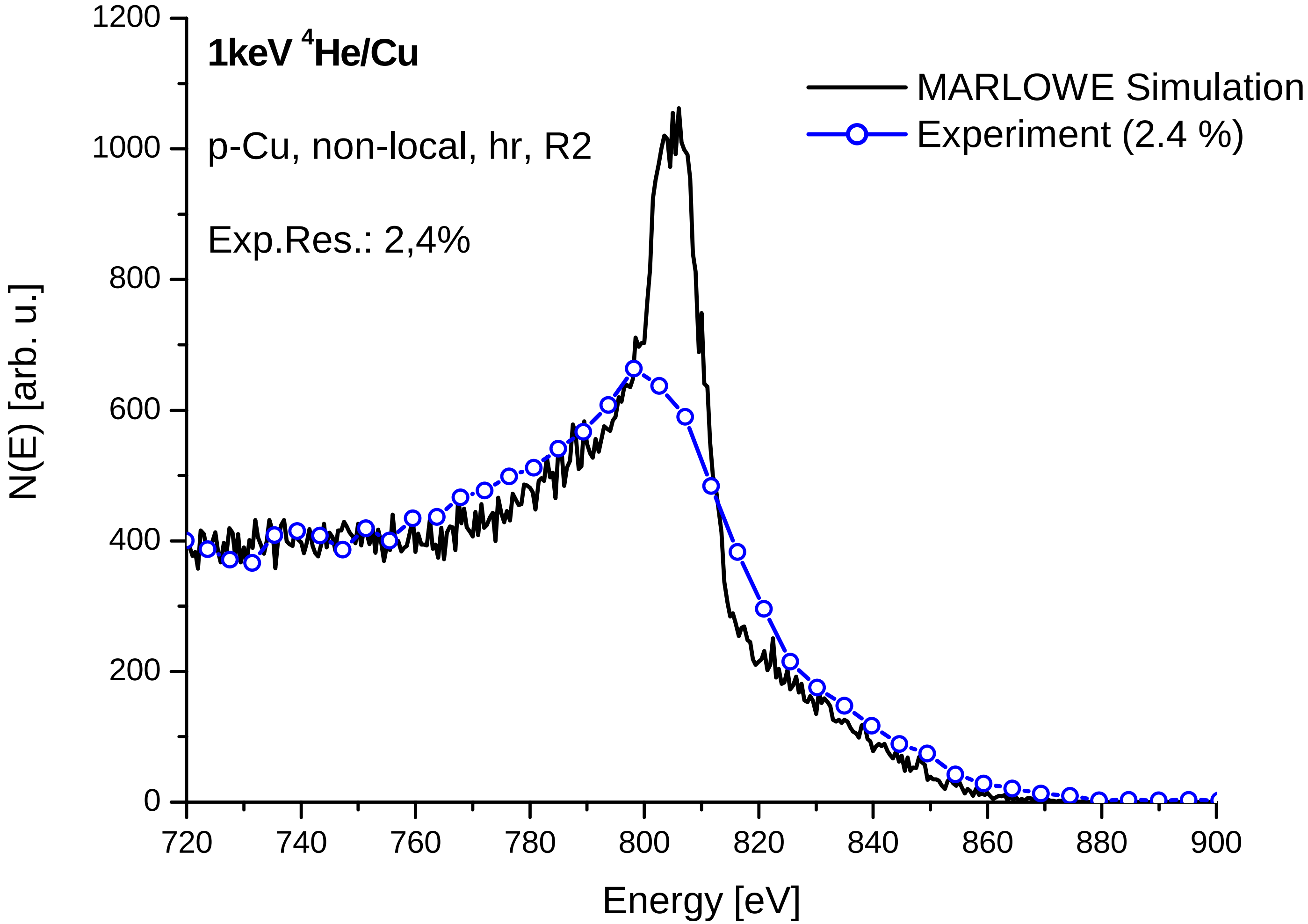
Explanation of surface peak:



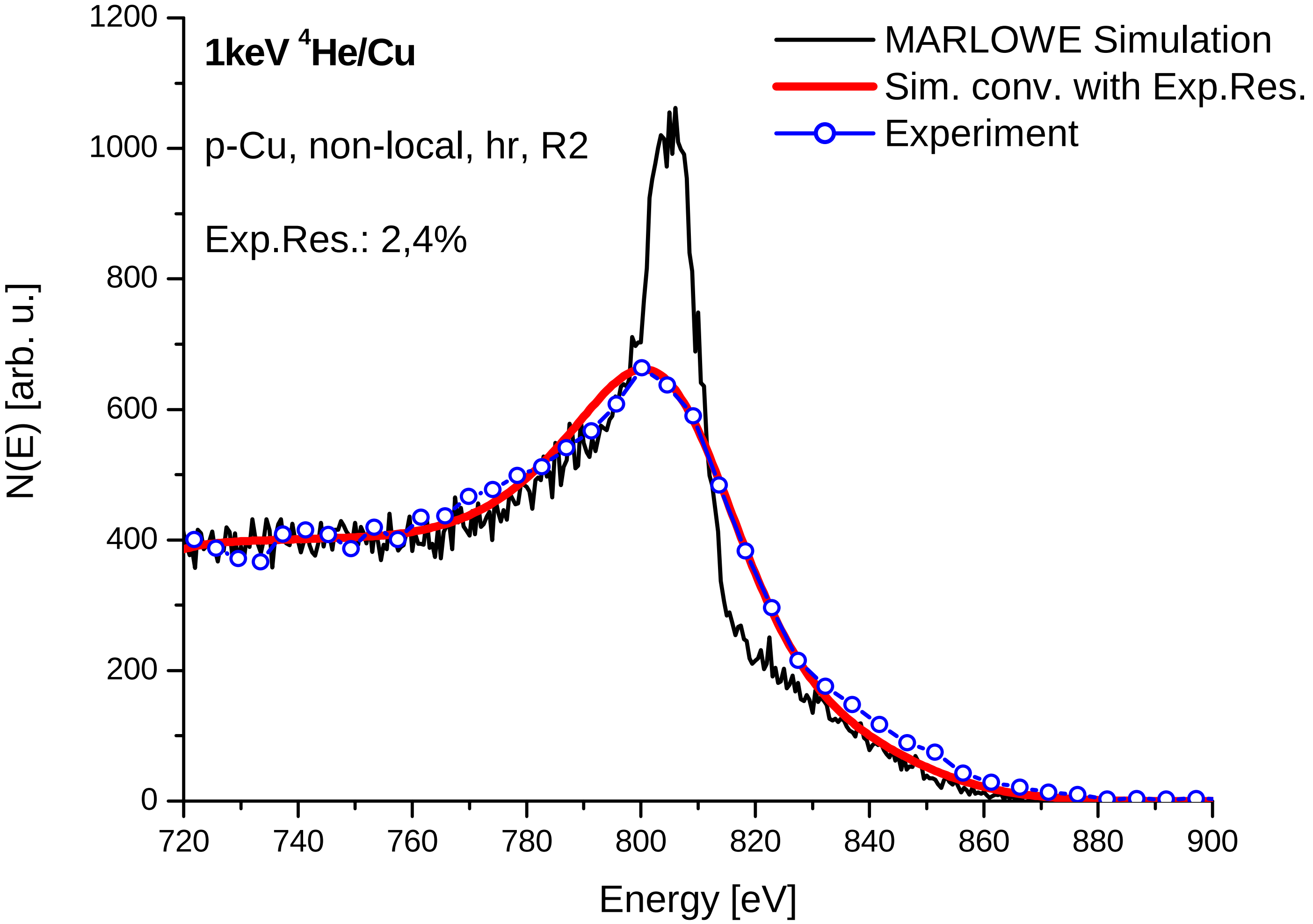
Surface peak due to (1) single scattering → multiple scattering

(2) shift of deeper layers due to stopping power

Experiment vs. simulation

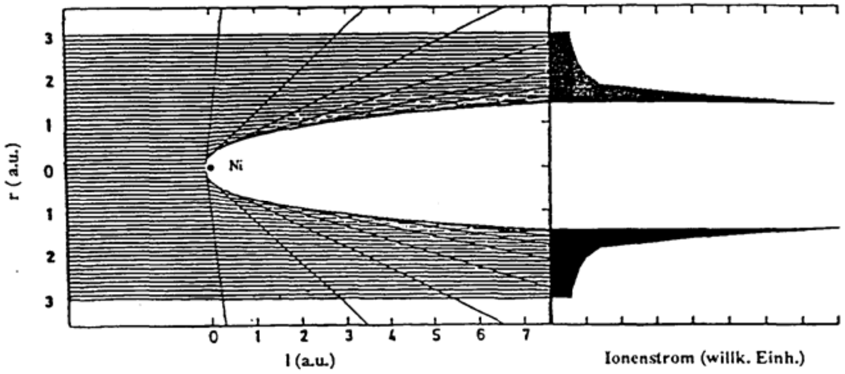


Experiment vs. simulation



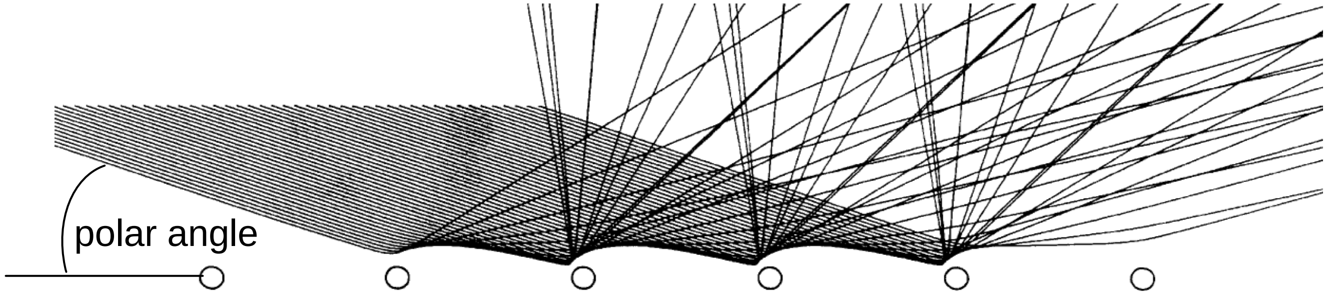
Surface structure analysis: ^{4}He+ → Cu crystal

Channeling → flux enhancement:



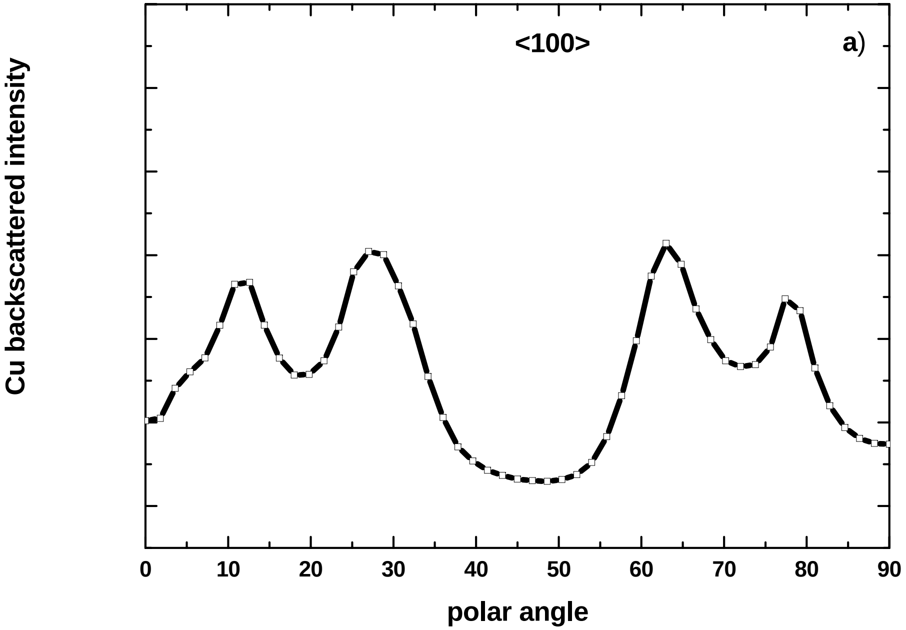
5 kV Helium⁺ auf Nickel

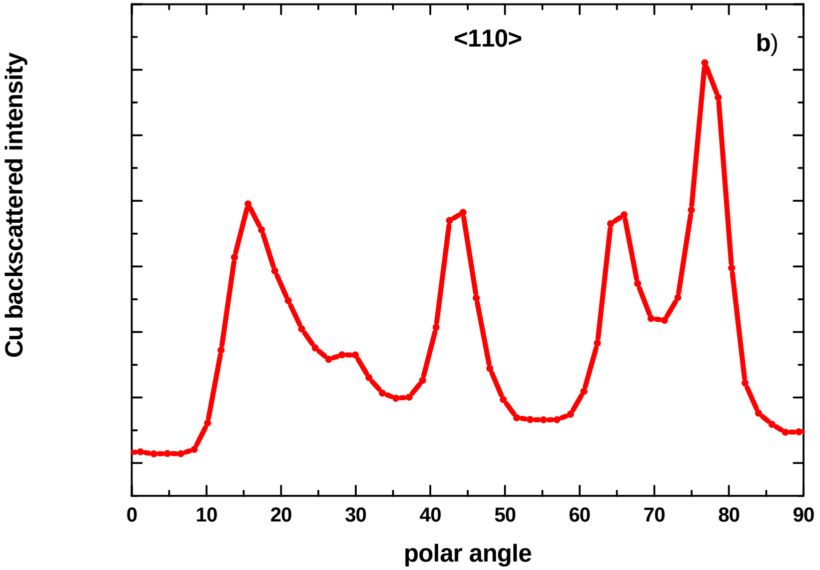
Focussing collisions at certain angles → intensity peaks:



Surface structure analysis: ^{4}He+ → Cu crystal

experiment: 179° scattering @ 3 keV

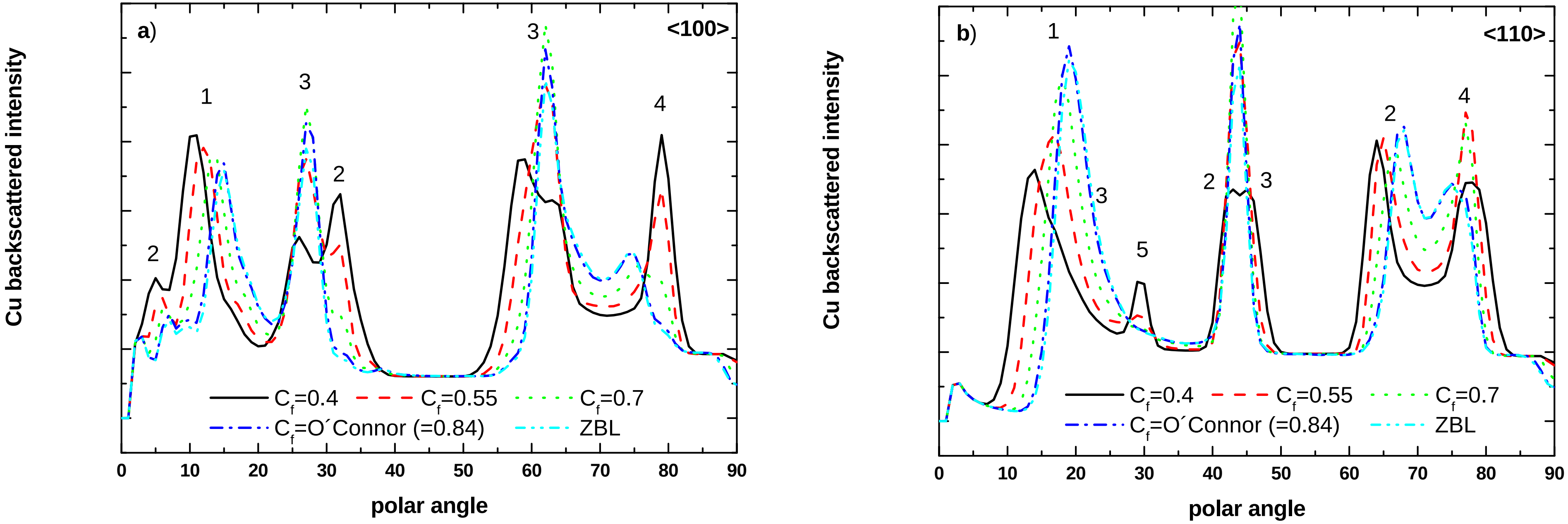




(Draxler 2005)

Surface structure analysis: ^{4}He+ → Cu crystal

Comparison experiment - Monte-Carlo simulations:

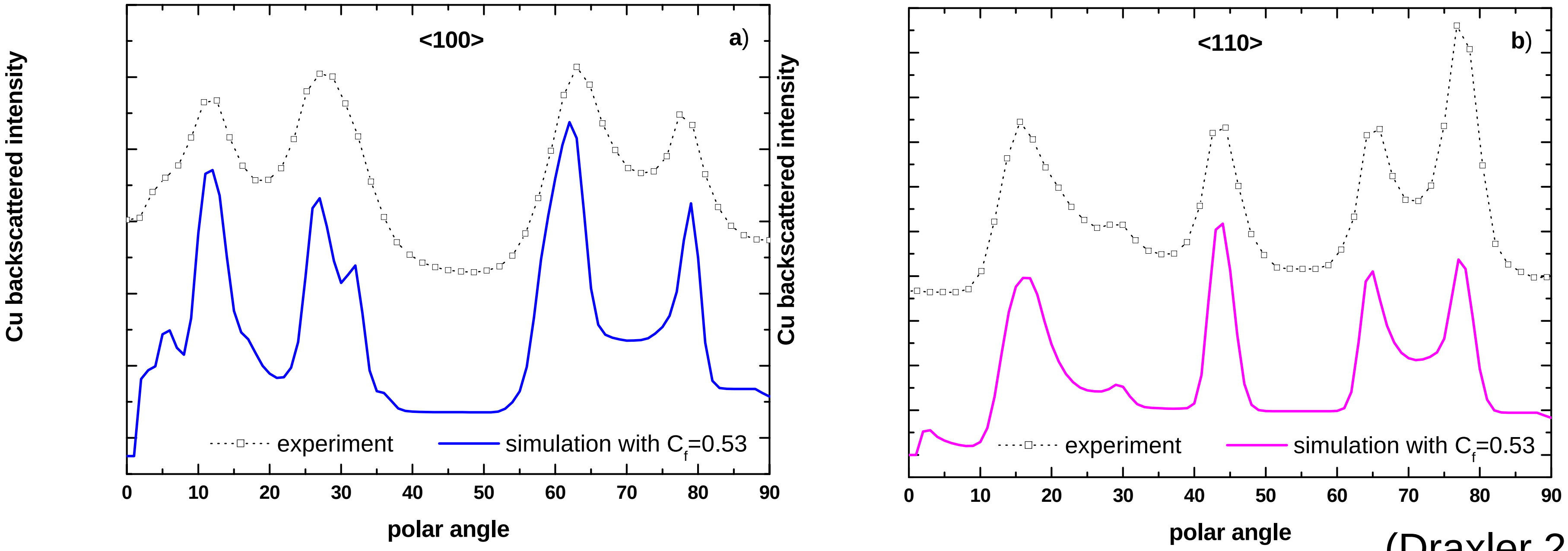


(Draxler 2005)

→ channeling is sensitive to the scattering potential
(screening length a = $C_f \cdot a_{TFM}$

Surface structure analysis: ^{4}He+ → Cu crystal

Comparison experiment - Monte-Carlo simulations:



(Draxler 2005)

→information on scattering potential (screening length $a \approx a_{TFM}/2$)

→ information on the scattering cross section

Time resolution ↔ depth resolution

time resolution $\delta\tau$ ↔ energy resolution δE ↔ depth resolution δx

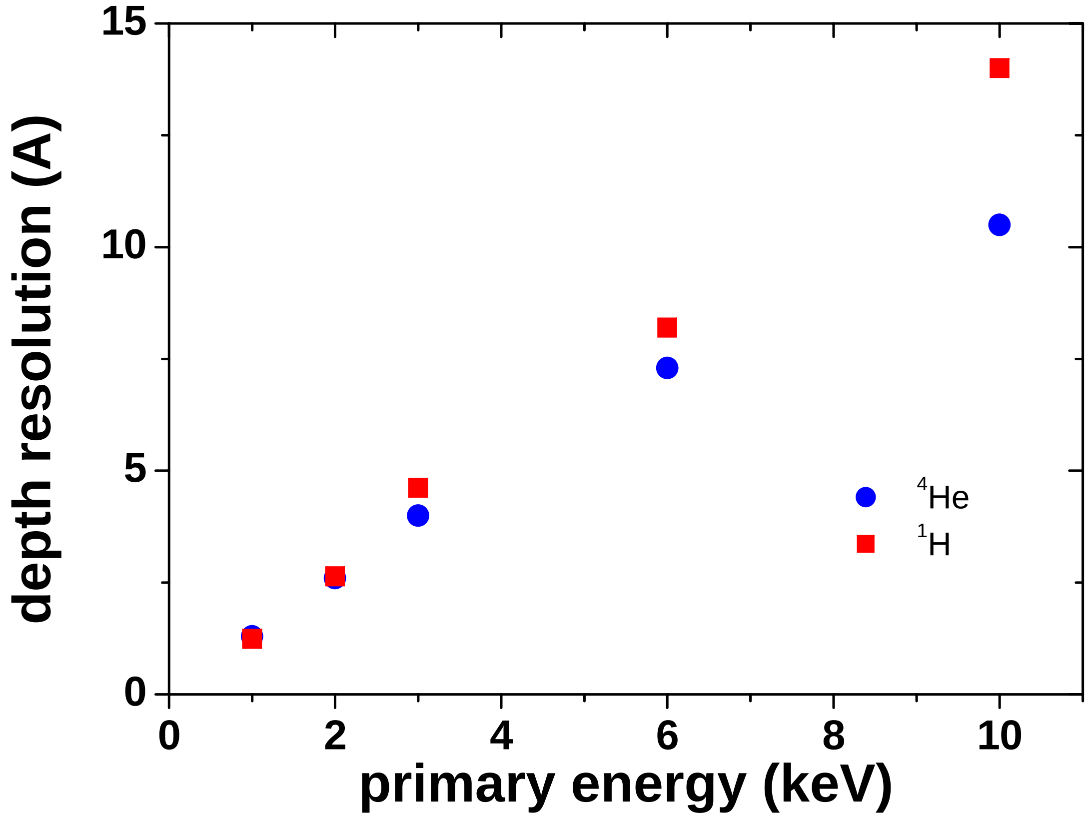
$\delta E = 2E\delta\tau/\tau$ (similarly as $\underbrace{\text{in RBS}}$)

typ. example: $dt = 10\,\text{ns}$, $L_1 = 0.67\ \text{m}$

1 keV He^+: $\tau_f = 3.4\ \mu\text{s} \rightarrow dt/\tau_f = 0.3\%$!

Depth resolution in LEIS

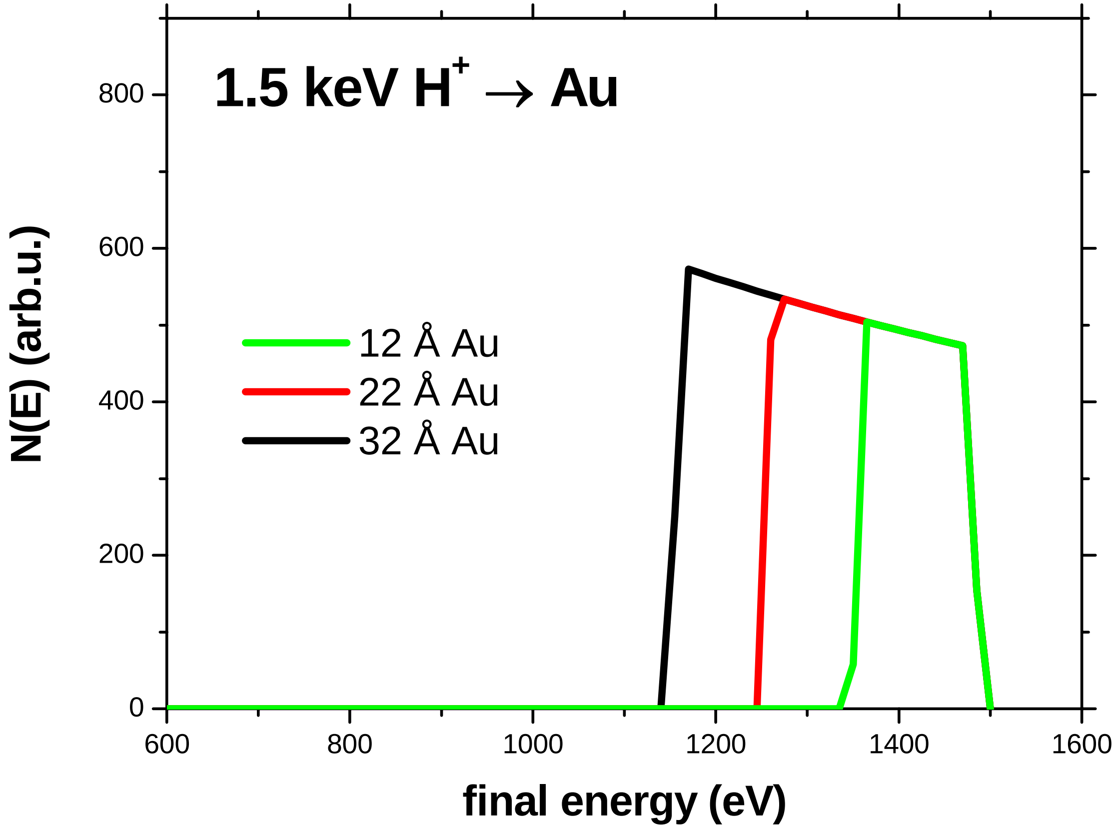
$\delta\tau$ = 10 ns, $\alpha = \beta$ = 25°, SRIM stopping:



larger $\Delta x \rightarrow$ higher E!

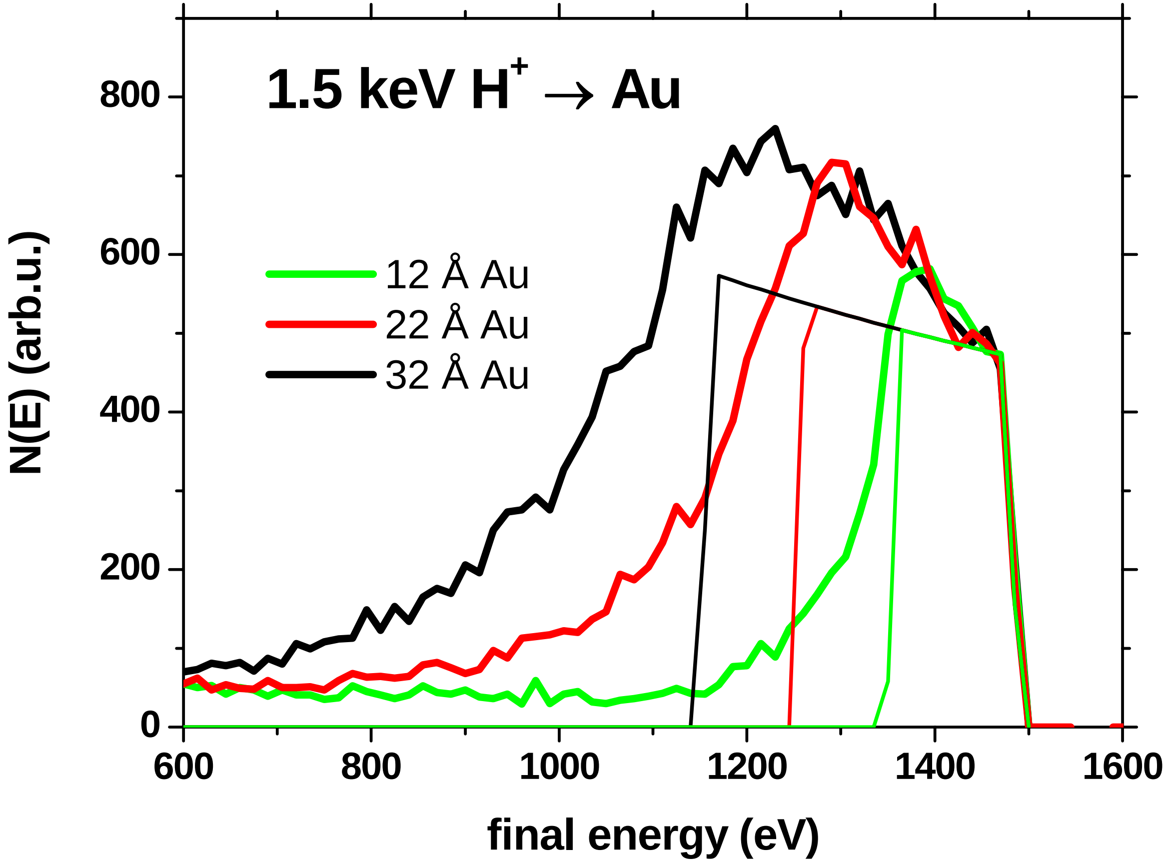
LEIS: spectrum width ↔ depth

single scattering model: $\Delta E_{LEIS} \propto \Delta x$



multiple scattering ???

TRBS simulation of LEIS:



TRBS:

- ✓ Monte-Carlo
- ✓ amorphous target
- ✓ dE/dx (non-local)
- ✓ multiple scattering

multiple scattering

→ low energy edge
→ plateau height

Application to nm layers

how to keep multiple scattering low?

use protons as projectiles (low Z_1)
use ‚high‘ energies (rather 5 keV than 500 eV)

how to optimize depth resolution?

use low energies ($\delta x \propto E$)

→ compromise resolution ↔ multiple scattering

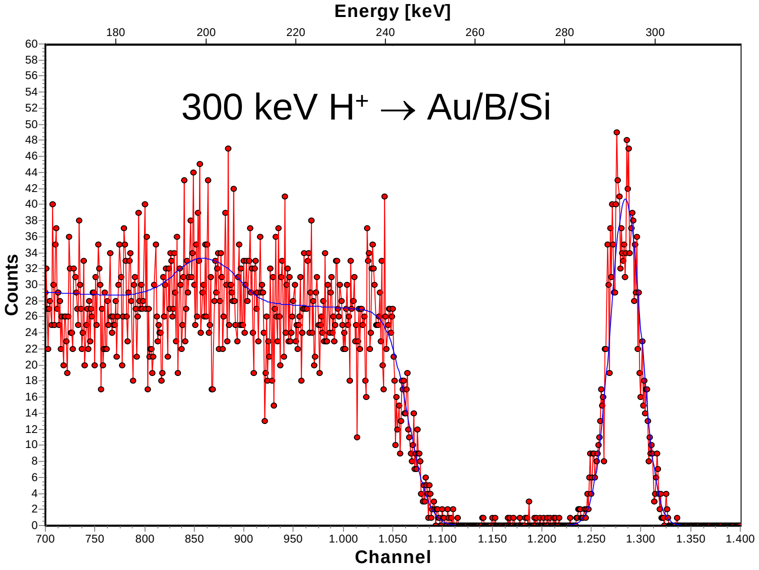
2.6nm Au/B – thickness inhomogeneity

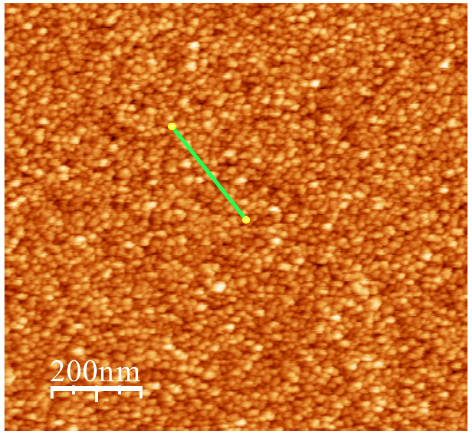
Au evaporated onto B substrate

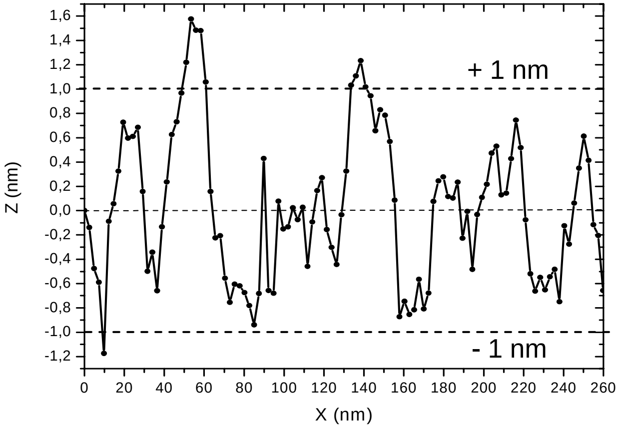
RBS for thickness (SIM-NRA): **26Å ± 5%**

atomic force microscopy for

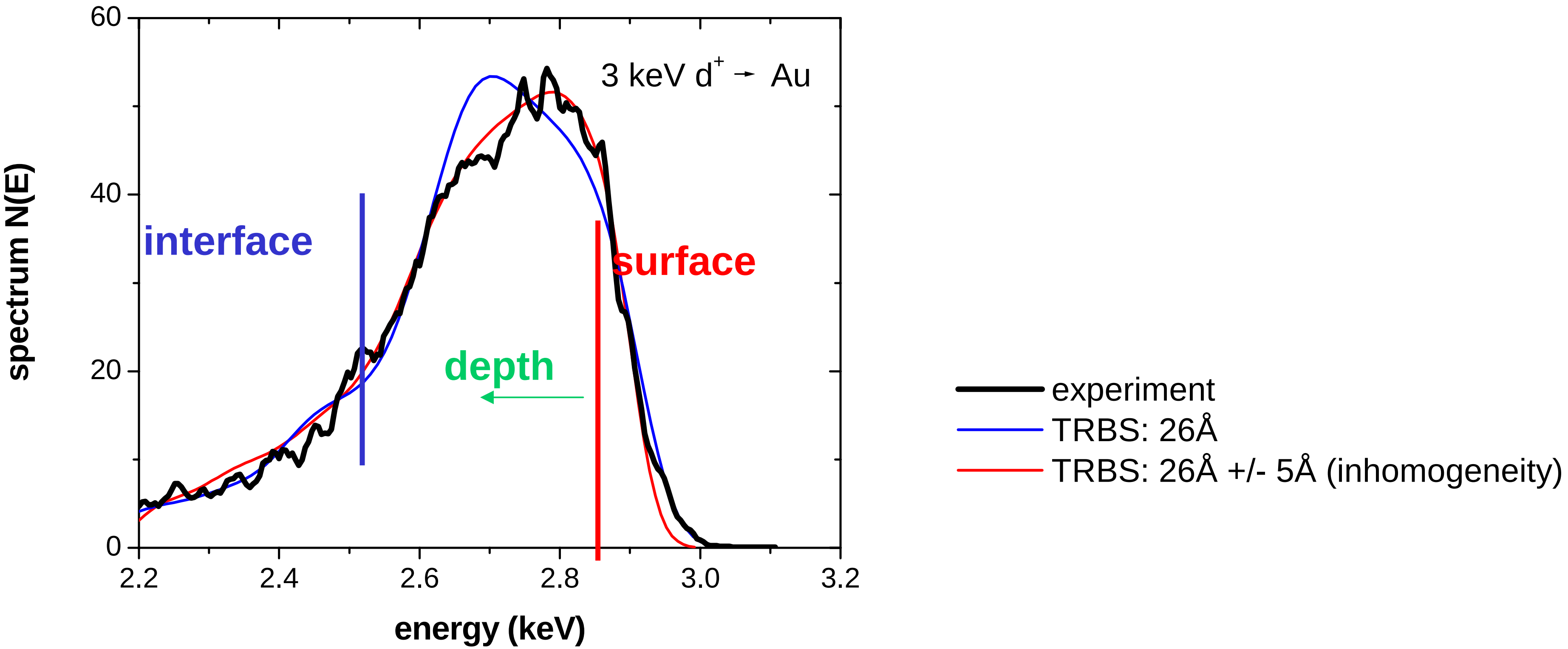
surface inhomogeneity: ± **5Å**







3 keV $H^+ \rightarrow$ 2.6nm Au/B



LEIS quantitative for nm layers !?

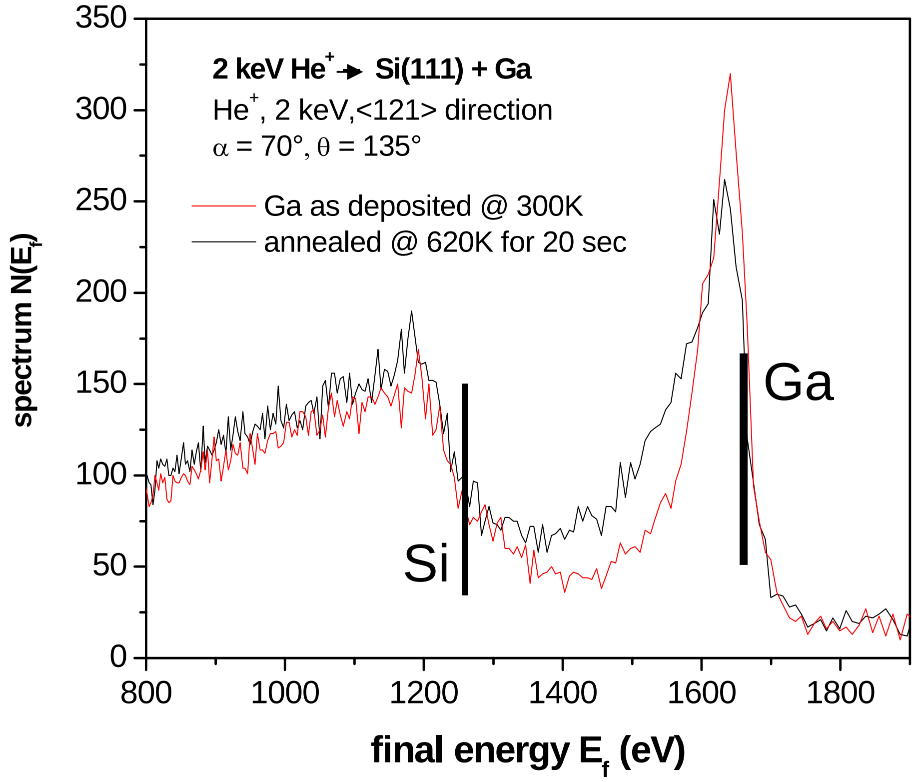
Ga/Si(111) (evaporated in situ, quartz reading: 6Å)

2 keV He^+ for structure analysis: ~ 20Å (comparison to TRBS)

→ annealing → broadening of Ga peak (change in topography):
- either thickening of clusters or
- diffusion into Si

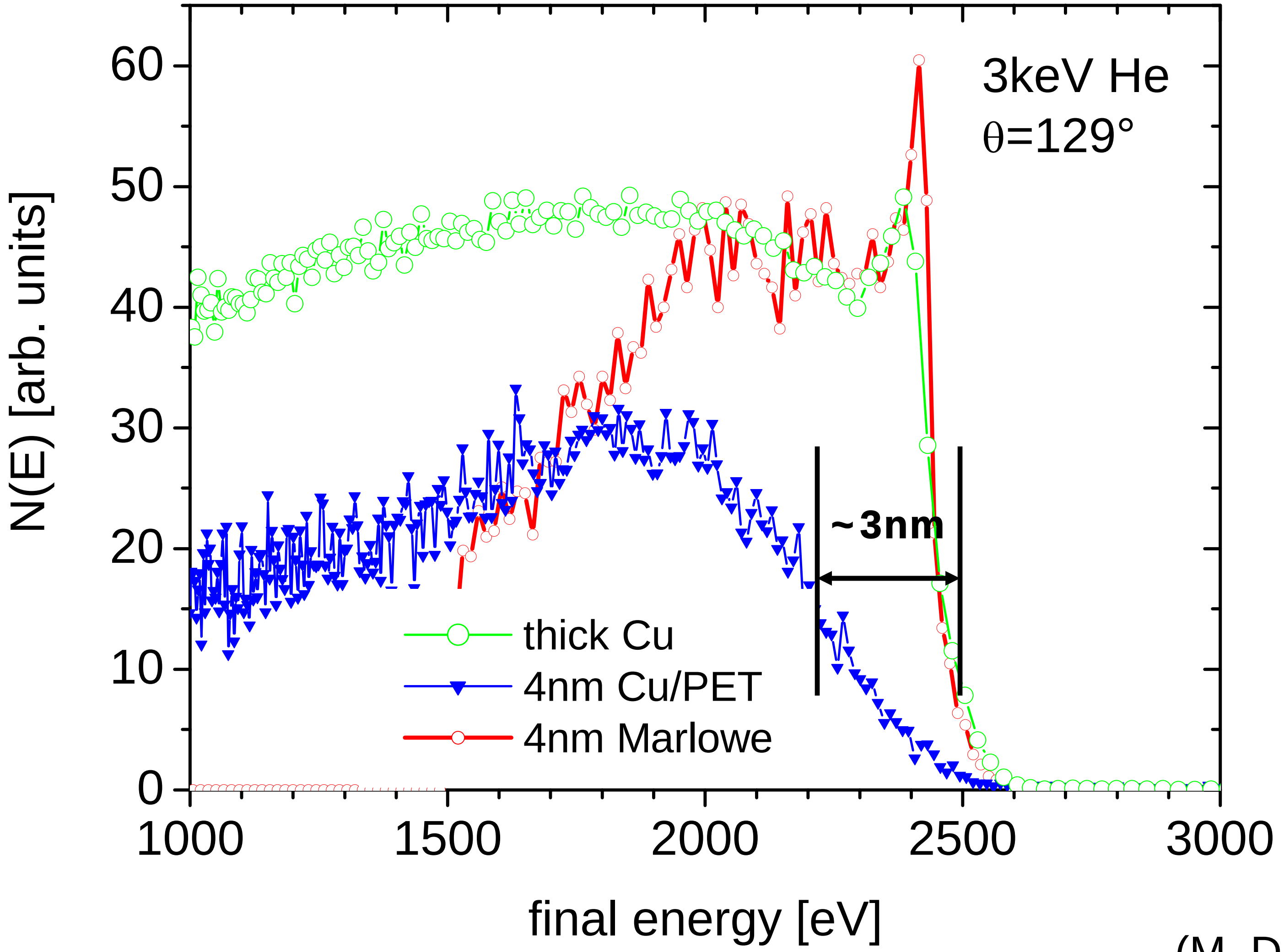
→ sharp Si edge with and w.o. annealing

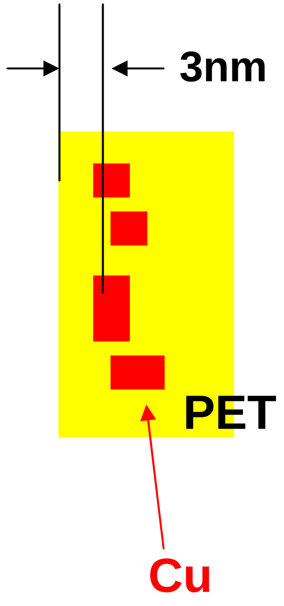
→ major part of Si is free of Ga



(M. Kolibal 2005)

Technical application: Cu/PET





(M. Draxler, 2004)

Summary:

- **ESA-LEIS & TOF-LEIS:**
  - **single crystals**
    surface structure
    surface composition
    neutralization
  - **thin films**
    surface composition
    neutralization
    growth modes

.....

Acknowledgment

- JKU Linz / Austria:
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FWF

Thank you

Quantitative LEIS

↔ **Matrixeffects in P^+?**

Is $Y_A^+ = c_A \cdot \eta_A$?

Element A .... Concentration c_A

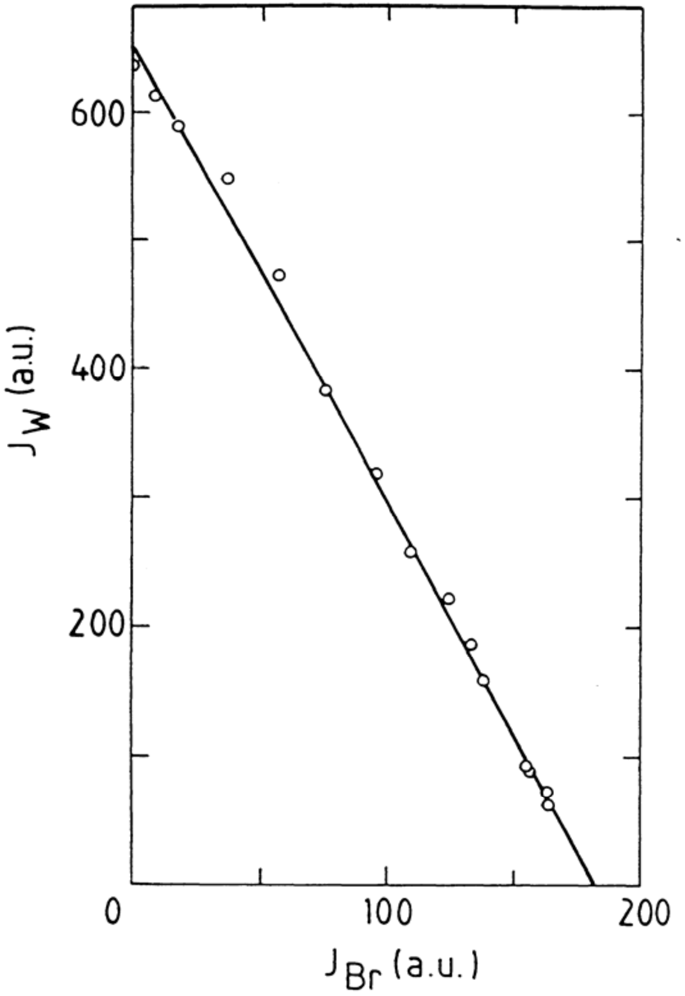
.... Sensitivity factor η_A

Test: Adsorption of Br on W

$$\theta_{Br} + \theta_W = 1$$

$$c_{Br} + c_W = 1$$

$$Y_W^+/\eta_W + Y_{Br}^+/\eta_{Br} = 1$$



(H.H. Brongersma, 1981)