INSPYRE 15-16 July 2025

Rutherford backscattering spectrometry

Campostrini Matteo, Rigato Valentino,

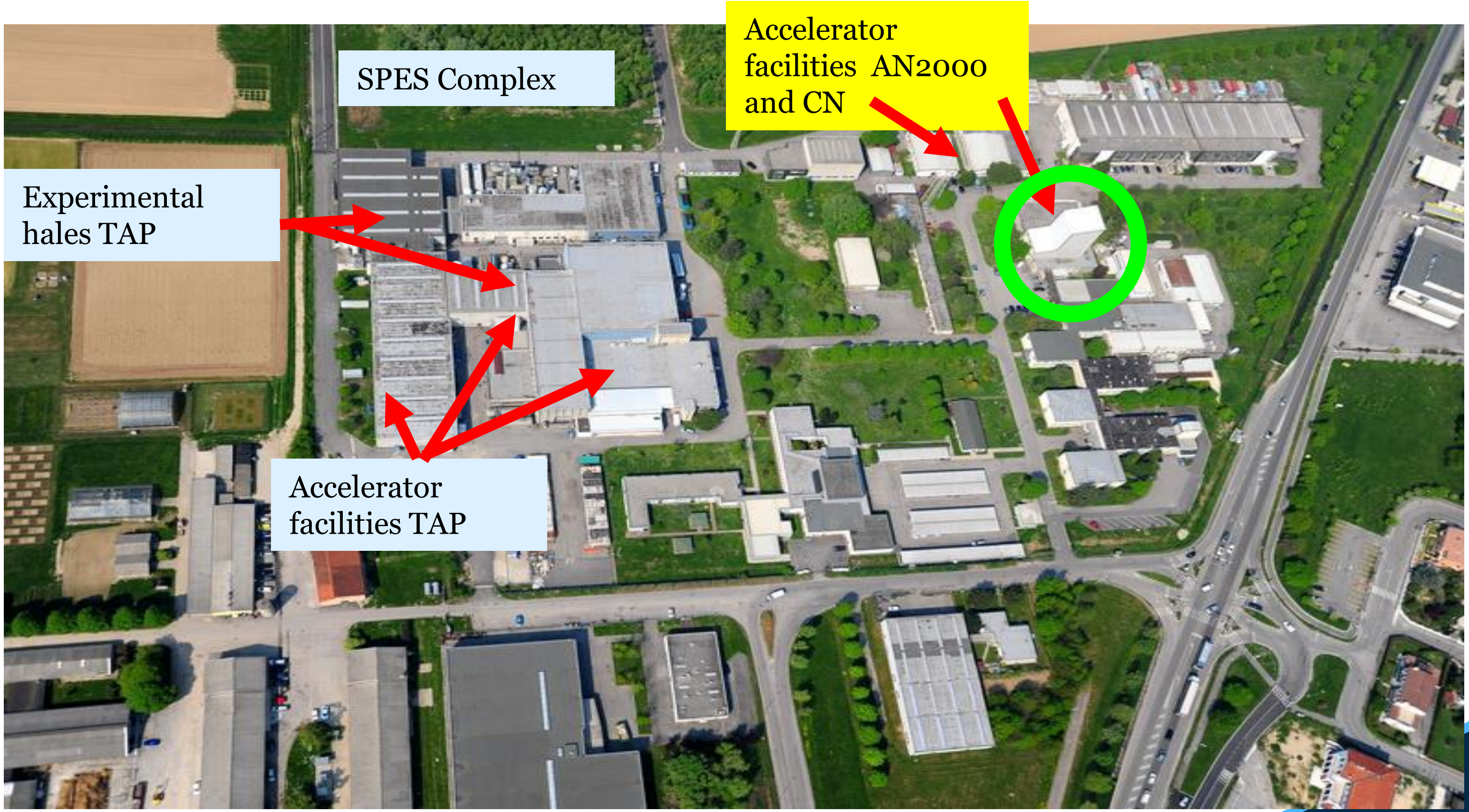
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Legnaro

Out line:

- Introduction
- Application of RBS/EBS: some examples
- Apparatus description
- RBS theory (short)

- Experimental session:
  data acquisition and analysis

Where we are…


SPES Complex
Accelerator facilities AN2000 and CN
Experimental hales TAP
Accelerator facilities TAP

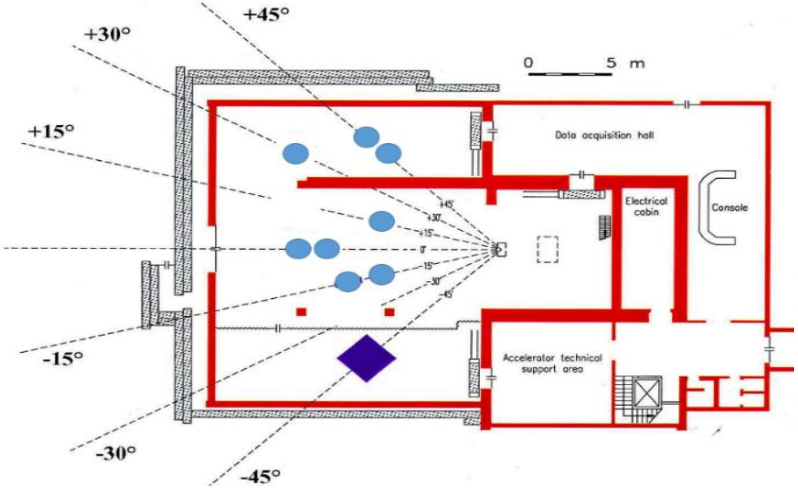
CN accelerator facility

Accelerator CN: Van De Graaf single-end

Energy: 0.8 ÷ 12 MeV

Ion beams : H^{+}, D^{+}, $^{4}He^{+}$, $^{4}He^{++}$, $^{3}He^{++}$

Beam lines: 7



Material characterization (thin film)
Neutron source
Physics experiment
Detector testing
Material irradiation
……….

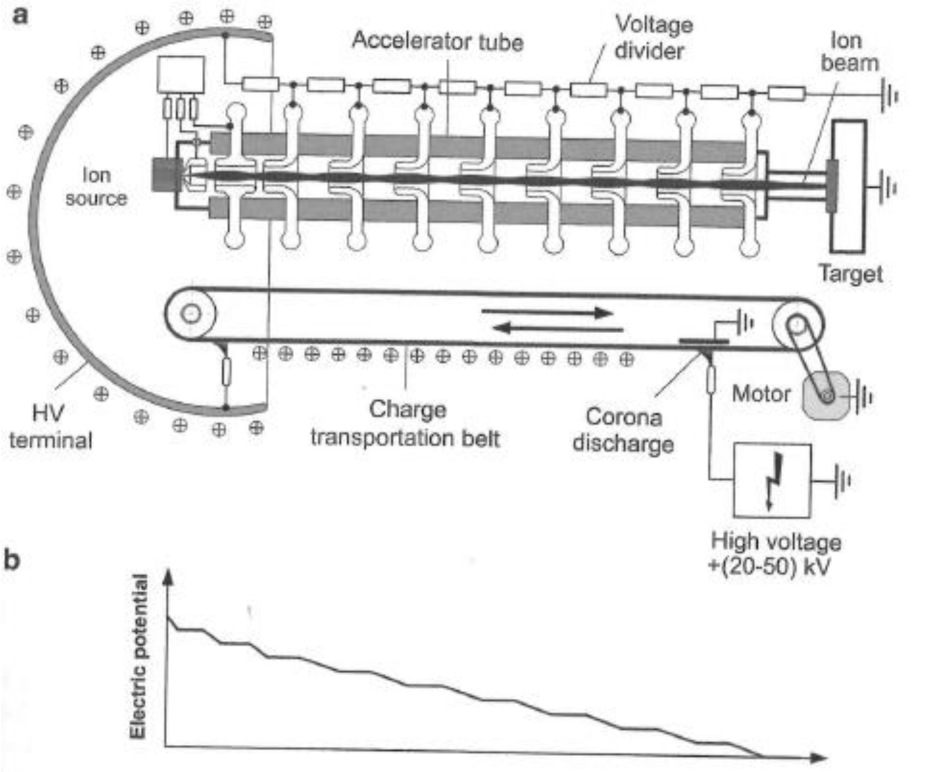
CN accelerator facility

Accelerator CN: Van De Graaf single-end

Energy: 0.8 ÷ 12 MeV

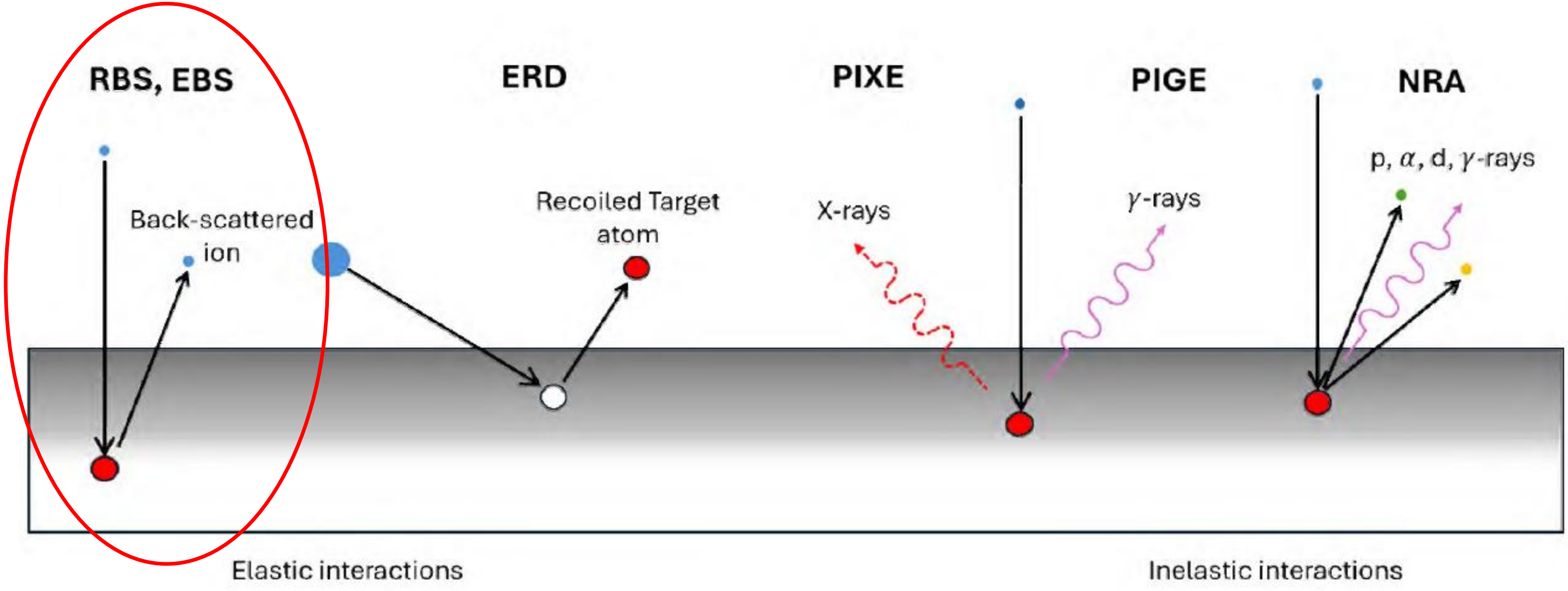
Ion beams : H^+, D^+, $^4He^+$, $^4He^{++}$, $^3He^{++}$

Beam lines: 7



3.45 Scheme of the Van de Graaff generator (a) and (b) the accelerating potential

ION BEAM ANALYSIS (IBA)



Why EBS/RBS?

Advantages:

- Allows elemental discrimination, compositional analysis
- Quantitative analysis (typically 2-5%) for almost all elements without requiring calibrated standards.
- Very sensitive to heavy elements (ppm)
- Depth profile analysis
- Excellent depth resolution (eg: 2-5 nm under optimal conditions)
- Non-destructive analysis

Disadvantages:

- Less sensitive to light elements (other NRA IBA are used in parallel)
- Complex analysis
- Very expensive apparatus… we need a particles accelerator

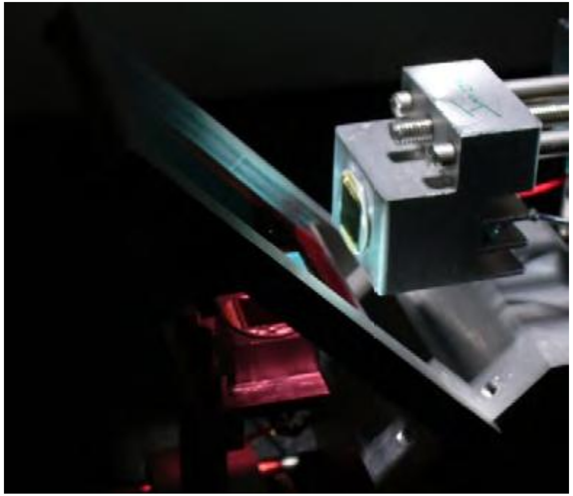
Applications:

<u>Surfaces physics and engineering…</u>

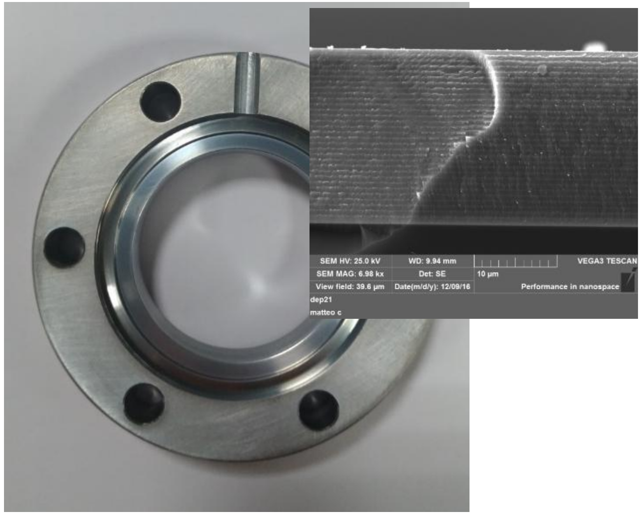
semiconductor, space, metallurgical, energy and quantum and nano-technology and other industrial fields,

Where EBS/RBS? -> some examples

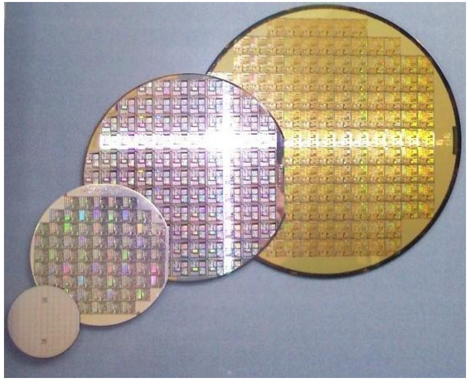
Surface functionalization is the modification of a material's surface properties to obtain characteristics that differ from those of the original bulk material.



Optical filters for photovoltaic applications (University of Trento)



Reinforcement coatings for mechanical applications in vacuum components (Industry partners)

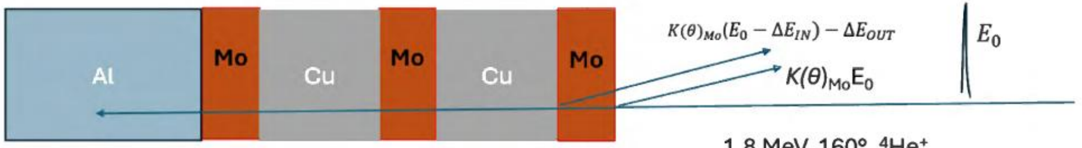


Fabrication of ultra-compact electronic components (Industry partners)

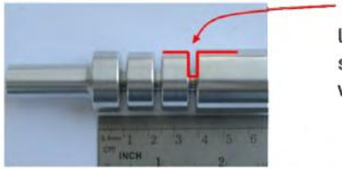
8

Where EBS/RBS? -> some examples

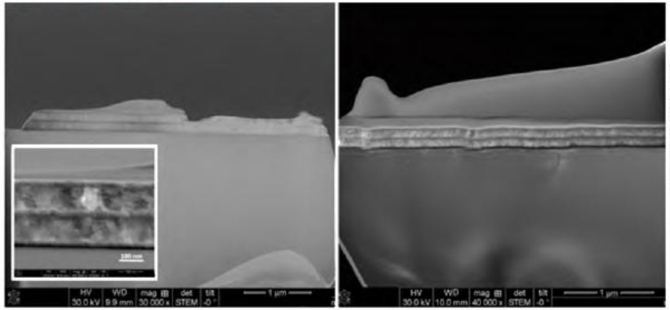
Surface functionalization is the modification of a material’s surface properties to obtain characteristics that differ from those of the original bulk material.

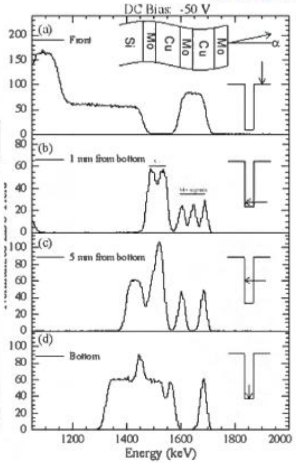


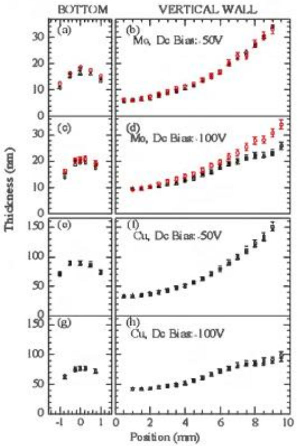
1.8 MeV, 160°, $^4He^+$
Microprobe (µRBS)
Beam size: 20 µm



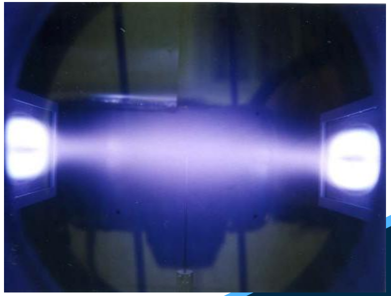
Mo/Cu metallic nano-layers deposited by ionized sputtering inside a trench with aspect ratio = 5.







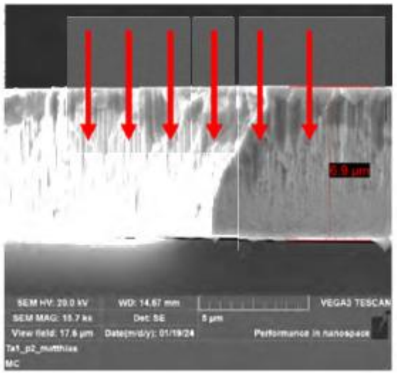
Protection nanostructured coating in accelerator components



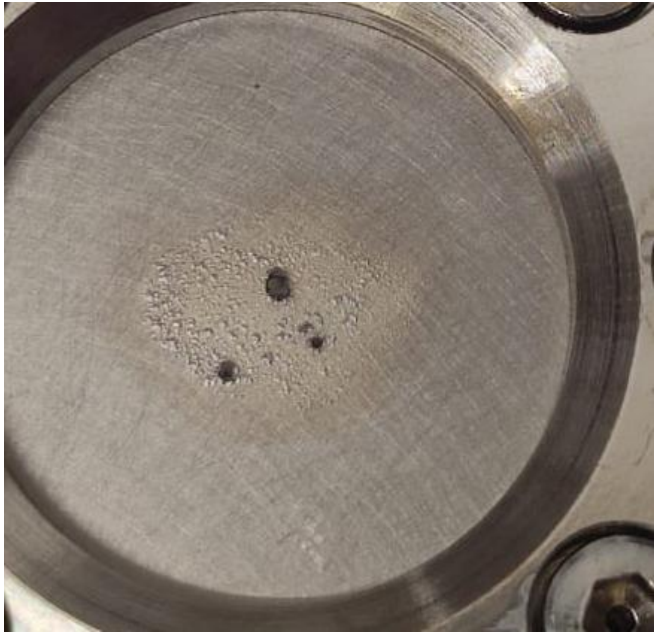
Where EBS/RBS? -> some examples

Coating Failures: High dose irradiation of He bubbles are created at a depth of about 2.4 µm and cause surface blisters.

SEM cross section image



Tantalum (6.9 µm) coating deposited onto copper is continuously irradiated with He+ ions (1.5 MeV).



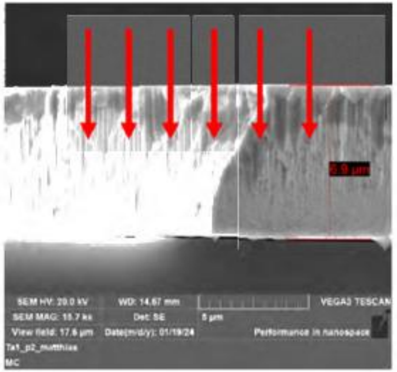
Tantalum nitride irradiated with few C of He^{+} at Felsekeller laboratory (Dresden)

10

Where EBS/RBS? -> some examples

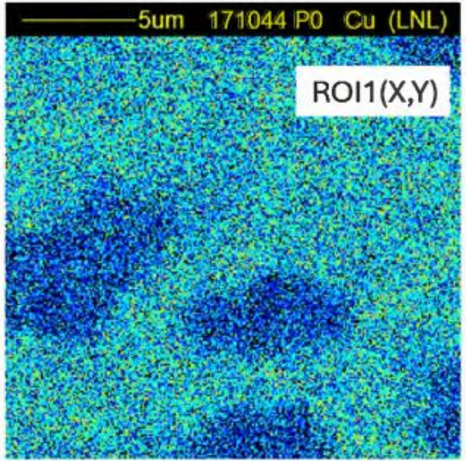
Coating Failures: High dose irradiation of He bubbles are created at a depth of about 2.4 µm and cause surface blisters.

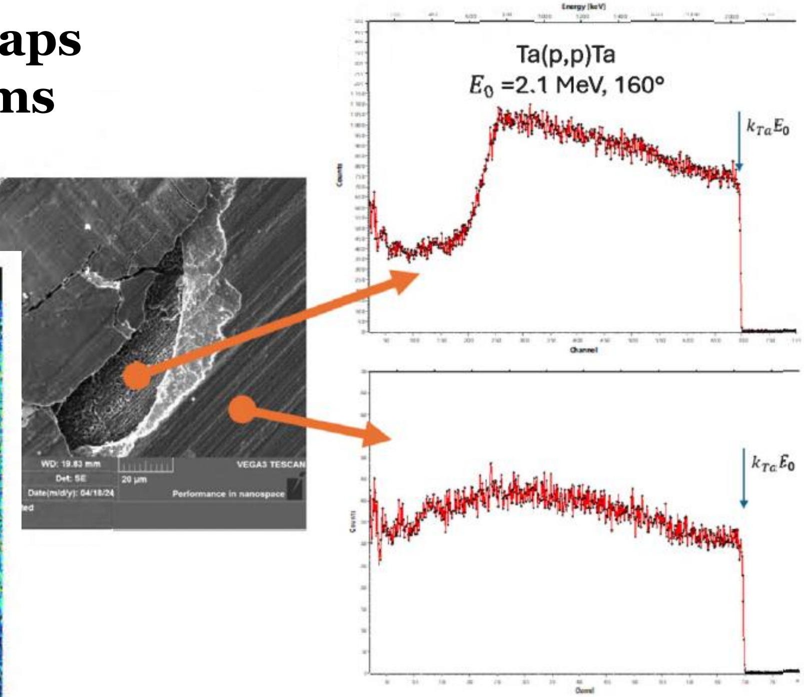
SEM cross section image



Tantalum (6.9 µm) coating deposited onto copper is continuously irradiated with He+ ions (1.5 MeV).

µRBS 2-D maps using µ-beams





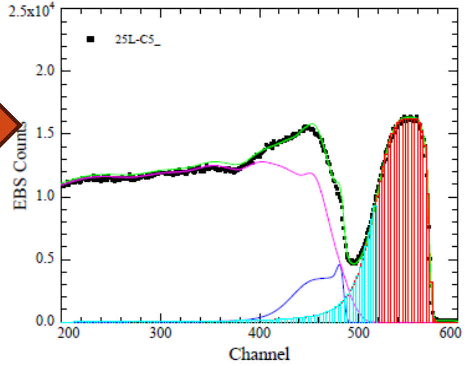
11

Where EBS/RBS? -> some examples

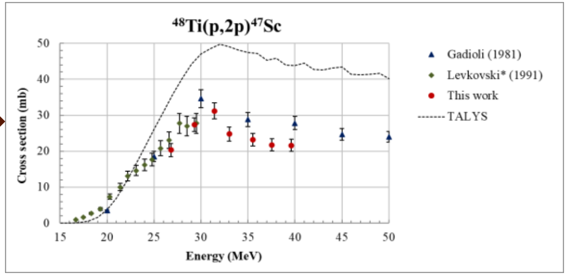
Thin film analysis for medical application: radioisotope for therapy

1) Target production

2) EBS characterization



3) Nuclear cross section measurement



AIMS

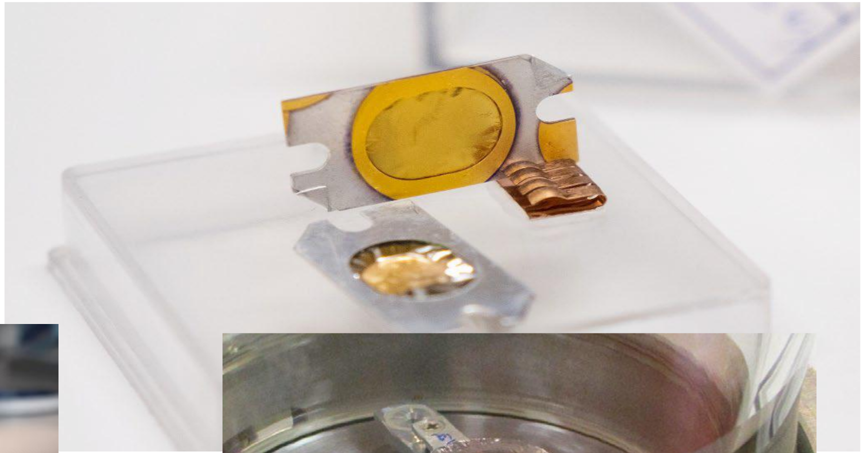
Find the optimal irradiation conditions to maximize the production of radiopharmaceuticals.

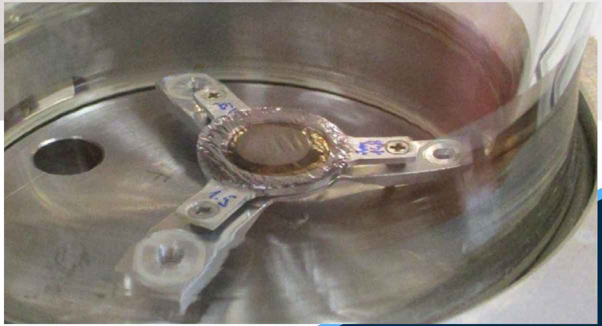
12

Where EBS/RBS? -> some examples

Thin film deposition for nuclear physics

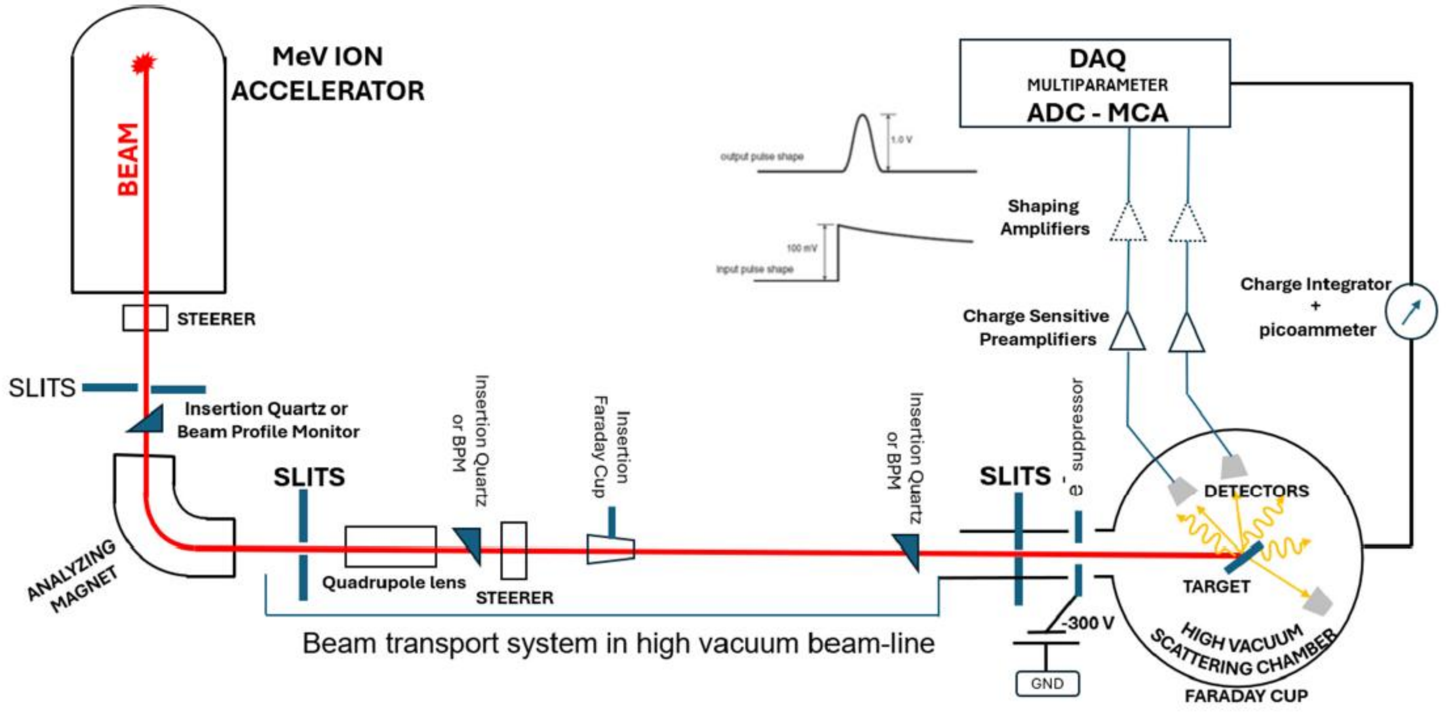
Development of materials for nuclear physics experiments



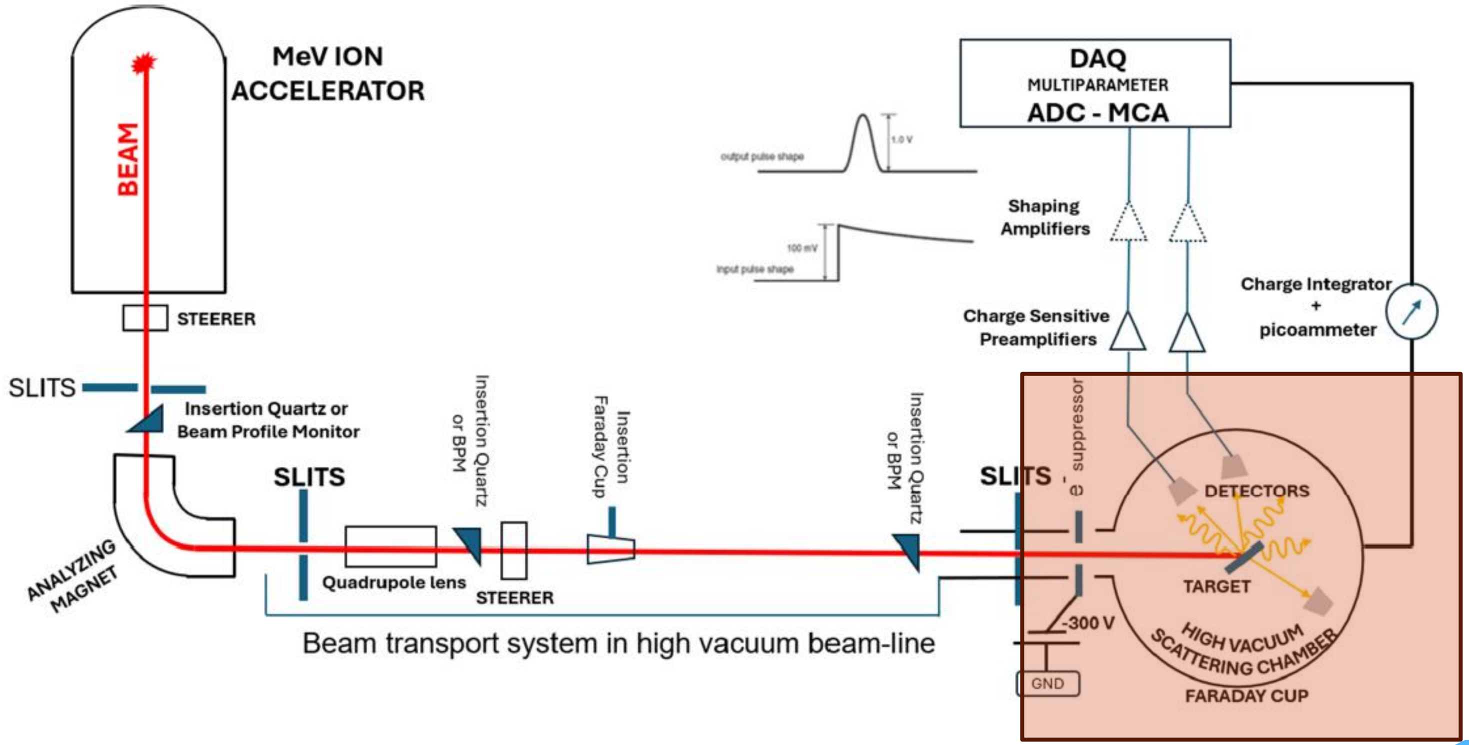


13

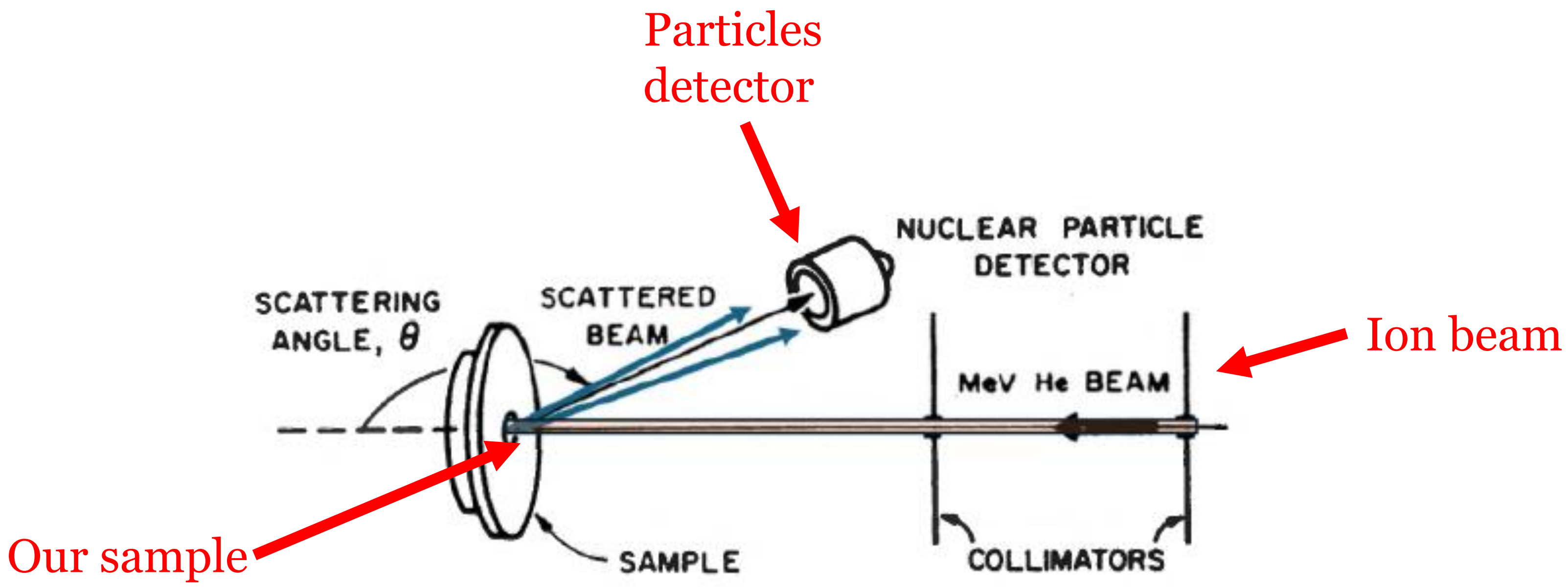
Simplified illustration of the equipment used for EBS



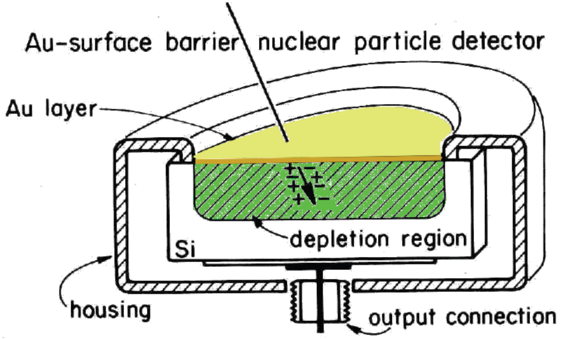
Simplified illustration of the equipment used for EBS



Simplified illustration of the equipment used for EBS: inside scattering chamber



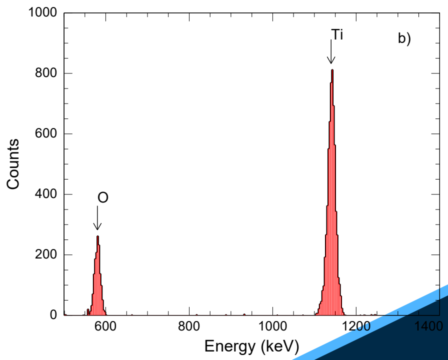
Simplified illustration of the equipment used for EBS: signal processing



DETECTOR

Shaping amplifier

ADC



Sorry but we need some theory before to start…

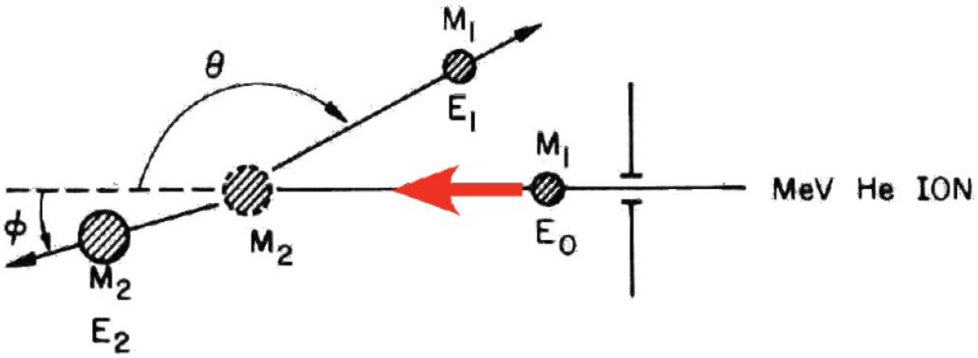
Elastic process

- Kinematics of elastic collisions -> Compositional analysis
- Rutherford cross section -> Quantitative analysis

Inelastic process

- Energy loss and Stopping power -> depth profile

Kinematics of elastic collisions -> Compositional analysis



Schematic representation of an elastic collision between a projectile of mass M_1 and energy E_0 and a target mass M2 which is initially at rest.
After the collision, the projectile and target mass have energies E1 and E2 respectively. The angles θ and ϕ are positive as shown.
All quantities refer to a laboratory frame of reference.

Reactions are written in the format

X(a,b)Y

which is to be translated

TARGET NUCLEUS (*projectile, emitted particle*) RESIDUAL NUCLEUS

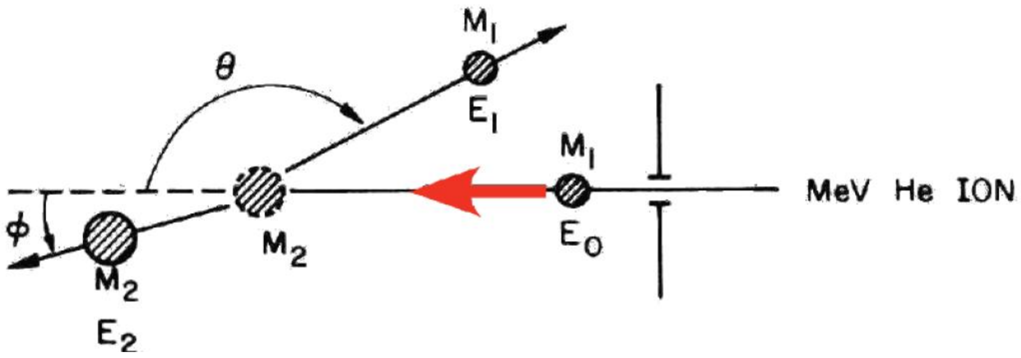
In an elastic reaction a=b, X=Y

Examples:

$Ta(^4He,^4He)Ta$ same as $Ta(\alpha,\alpha)Ta$

$^{12}C(p,p)^{12}C$ same as $^{12}C(^1H, ^1H)^{12}C$

Kinematics of elastic collisions -> Compositional analysis



$$\frac{E_1}{E_0} = \left[\frac{(M_2^2 - M_1^2 \sin^2\theta)^{1/2} + M_1 \cos\theta}{M_1 + M_2}\right]^2$$

$$E_1 = K_{M_2} E_0$$

Kinematic factor

M1<M2 !!!

E_o= ion energy (known)

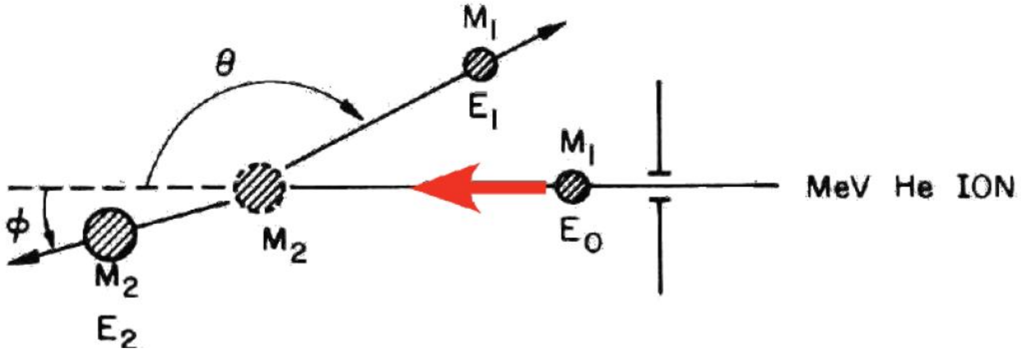
M1= ion mass (known)

θ= scattering angle (known)

E1 = energy of backscattered particle (known) we can measure that using silicon detector

M2= unknown

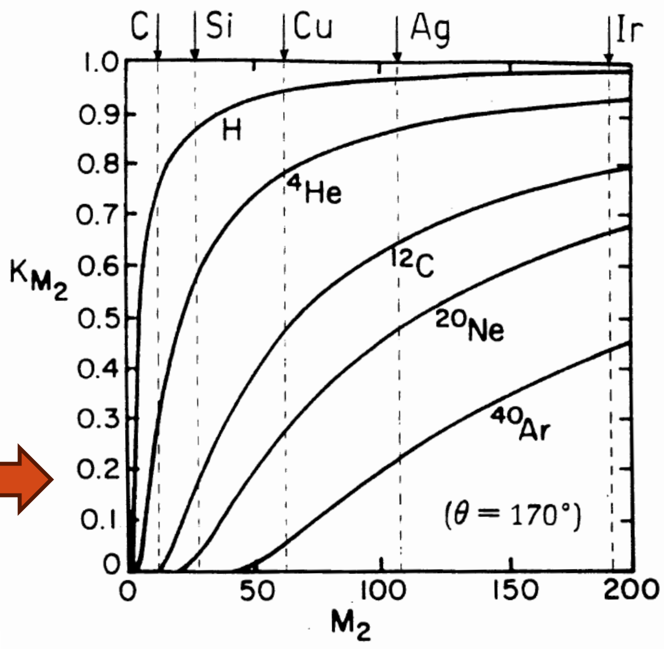
Kinematics of elastic collisions -> Compositional analysis



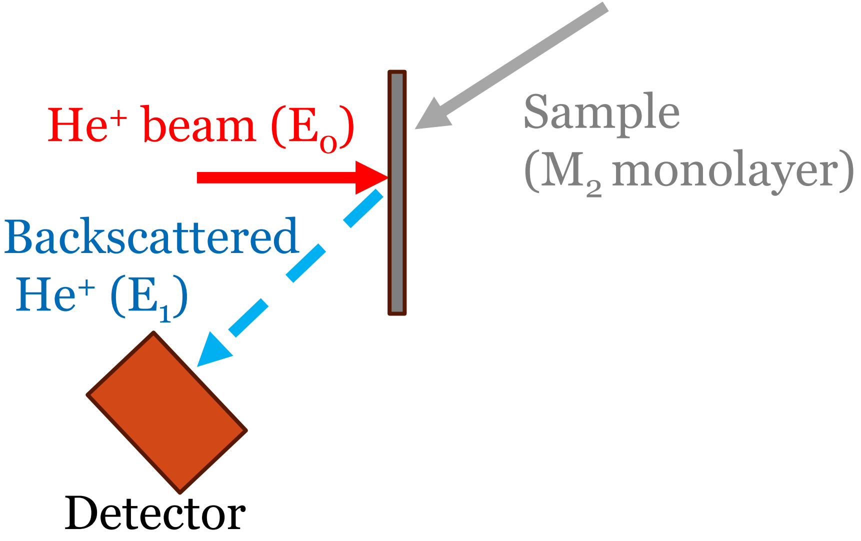
$$\frac{E_1}{E_0} = \left[\frac{(M_2^2 - M_1^2 \sin^2\theta)^{1/2} + M_1 \cos\theta}{M_1 + M_2} \right]^2$$

$$E_1 = K_{M_2} E_0$$

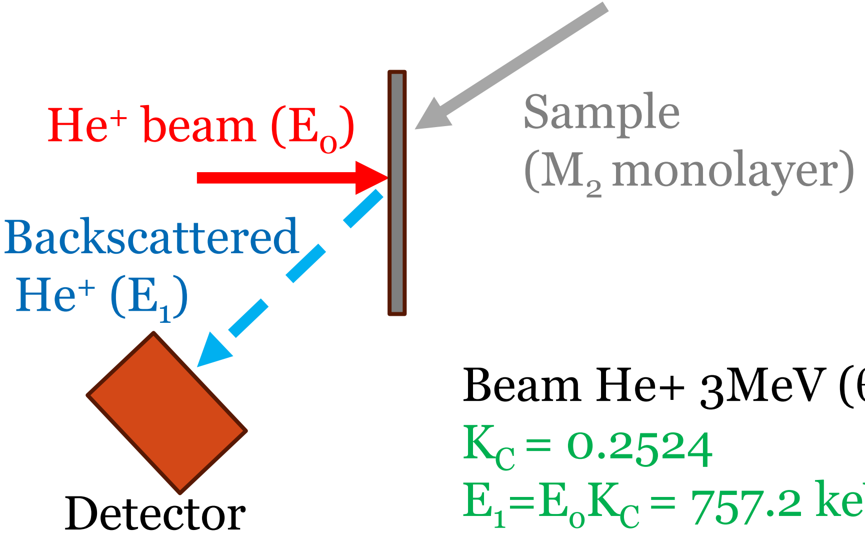
Kinematic factor



Kinematics of elastic collisions -> example



Kinematics of elastic collisions -> example



Beam He+ 3MeV (θ=160°)

$K_C = 0.2524$

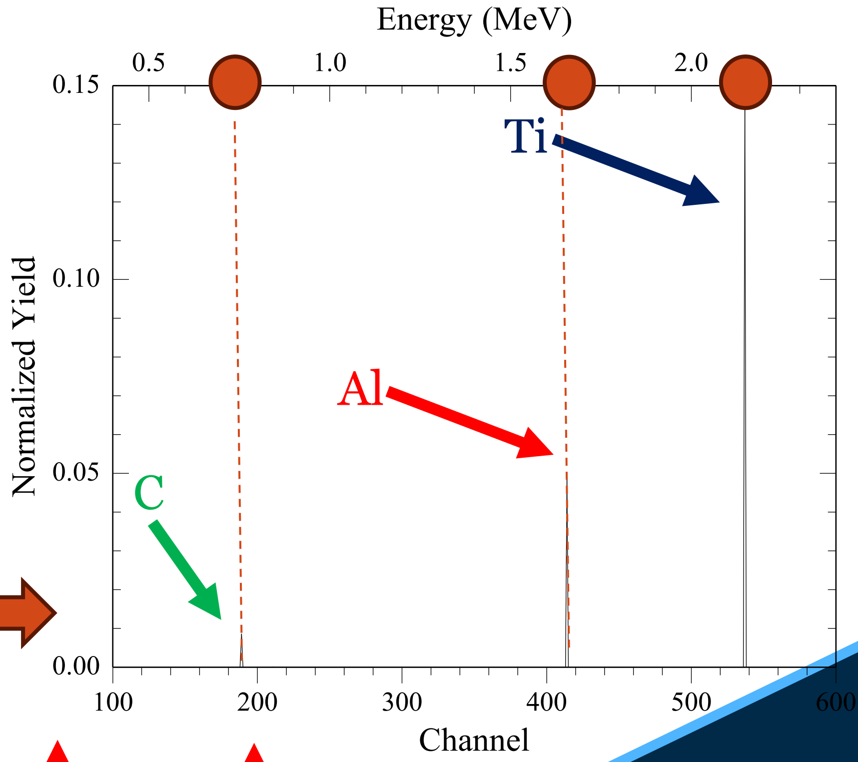
$E_1 = E_o K_C = 757.2$ keV

$K_{Al} = 0.5522$

$E_1 = E_o K_{Al} = 1.657$ MeV

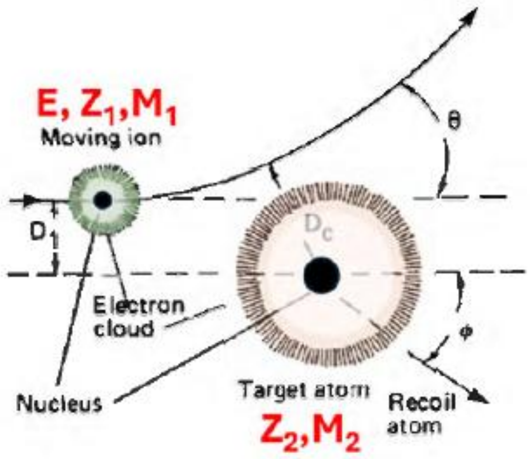
$K_{Ti} = 0.7169$

$E_1 = E_o K_{Ti} = 2.151$ MeV



↑ M_2 ↑ K

Rutherford cross section: Interaction between two point-like charges

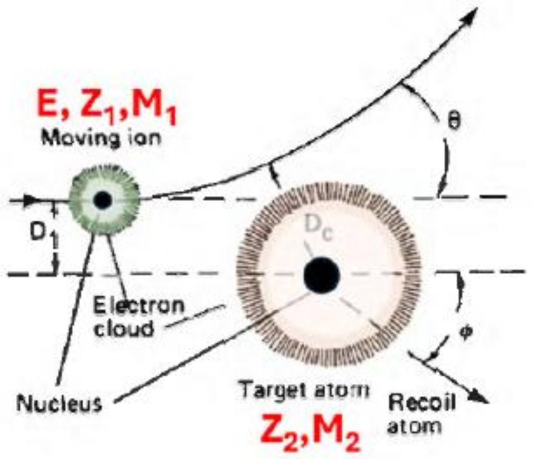


$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{2E\sin^2\theta}\right)^2 \frac{[\cos\theta + (1-\mu^2\sin^2\theta)^{1/2}]^2}{(1-\mu^2\sin^2\theta)^{1/2}}$$

The cross section represents the **probability** (σ) of an elastic collision occurring and detected by the detector (Ω).

Assumptions
- Point-like charged particles
- Neglect shielding of electron cloud
- Distance of closest approach large enough that nuclear force is negligible

Rutherford cross section: Interaction between two point-like charges



$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{2E\sin^2\theta}\right)^2 \frac{[\cos\theta + (1 - \mu^2\sin^2\theta)^{1/2}]^2}{(1 - \mu^2\sin^2\theta)^{1/2}}$$

$\mu = M_1/M_2$

E = energy of the projectile immediately before scattering

$$\sigma(E,\theta) = (1/\Omega)\int_\Omega (d\sigma/d\Omega)d\Omega$$

Ω is the detector solid angle (~10^{-3} sr)

Assumptions
- Point-like charged particles
- Neglect shielding of electron cloud
- Distance of closest approach large enough that nuclear force is negligible

Rutherford cross section -> example with single material

Beam He+ 3MeV (θ=160°)

$K_C = 0.2524$

$E_1 = E_0 K_C = 0.7572$ MeV

$\sigma = 0.017$ (1E-24 cm²/ster)

$K_{Al} = 0.5522$

$E_1 = E_0 K_{Al} = 1.657$ MeV

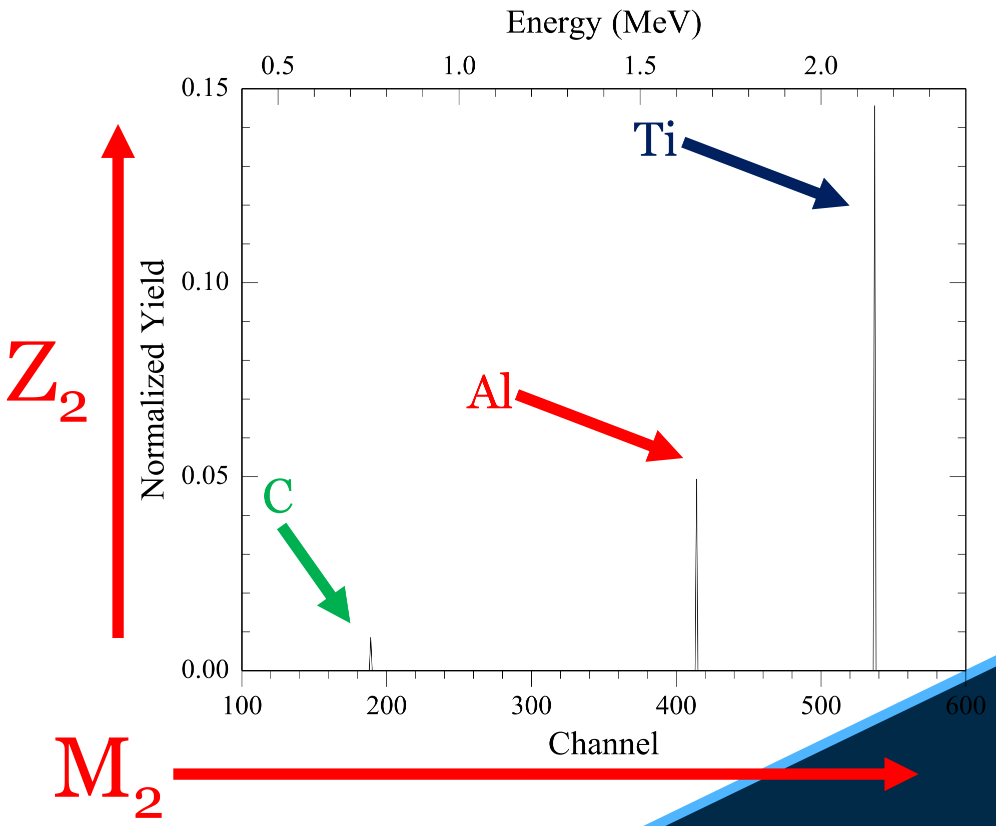
$\sigma = 0.094$ (1E-24 cm²/ster)

$K_{Ti} = 0.7169$

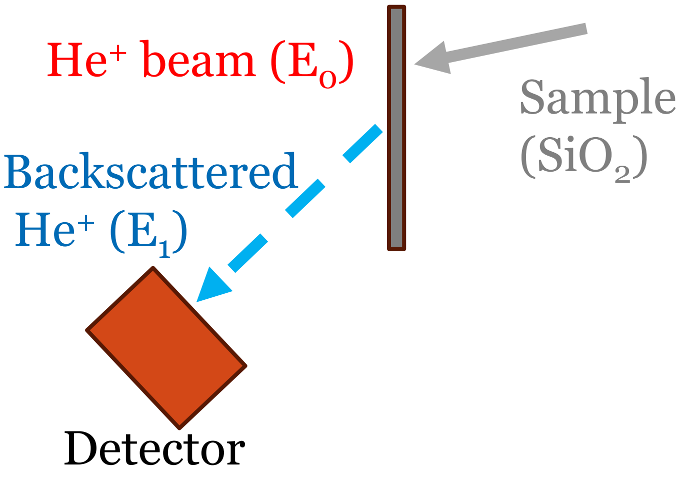
$E_1 = E_0 K_{Ti} = 2.151$ MeV

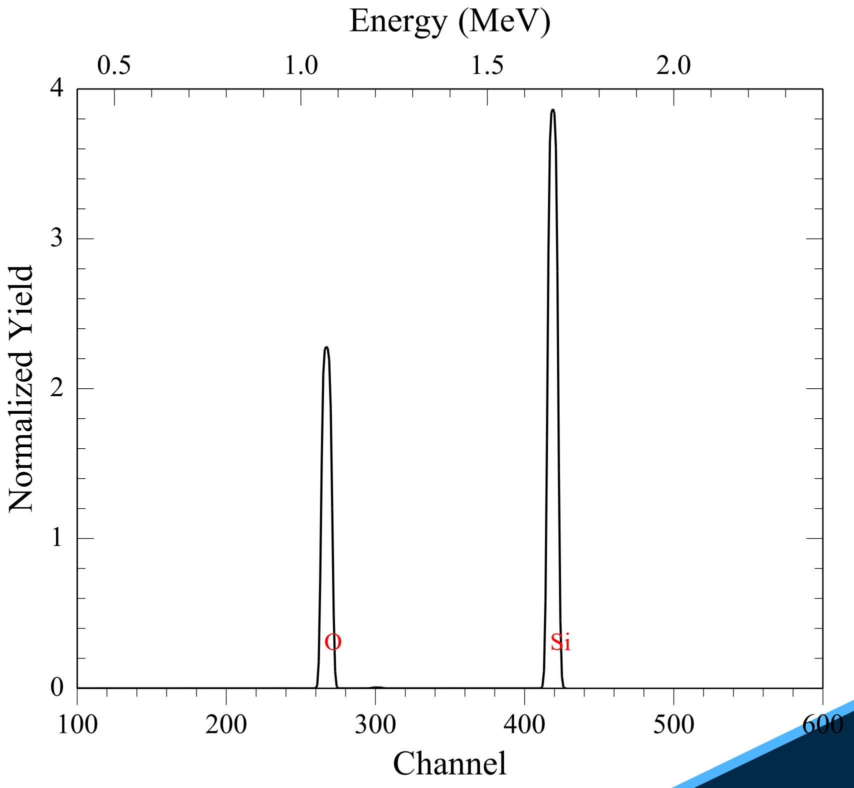
$\sigma = 0.278$ (1E-24 cm²/ster)

↑ Z_2 ↑ σ



Rutherford cross section -> example with composite material





Beam He+ 3MeV (θ=160°)
Material SiO_2
Composition 33.3% Si + 66.6% O
σO = 0.033 (1E-24 cm2/ster) * 0.666
σSi = 0.110 (1E-24 cm2/ster) * 0.333

Sorry but we need some theory before to start…

Elastic process

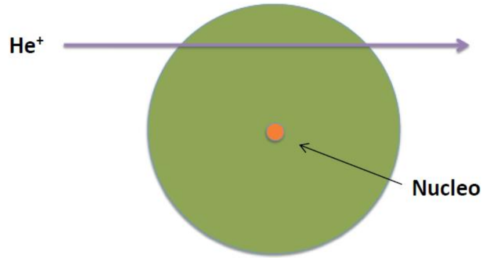
- Kinematics of elastic collisions -> Compositional analysis
- Rutherford cross section -> Quantitative analysis

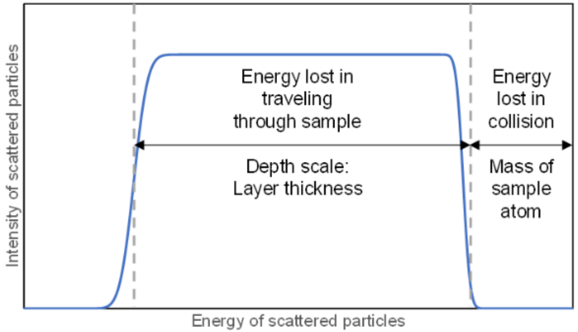
Inelastic process

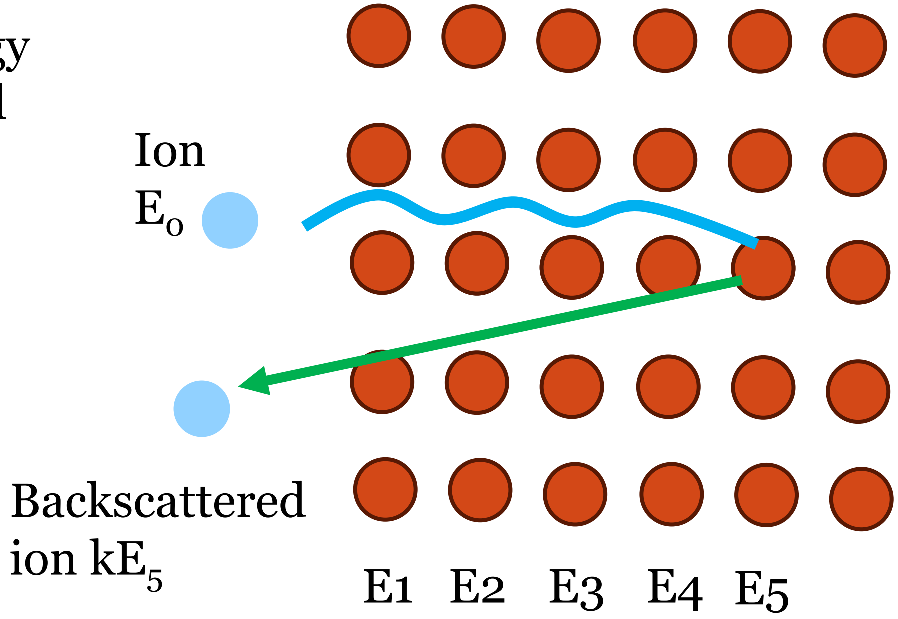
- Energy loss and Stopping power -> depth profile

Energy loss and Stopping power -> depth profile

An ion passing through matter loses energy due to interactions with the electron cloud of the atoms in the material.





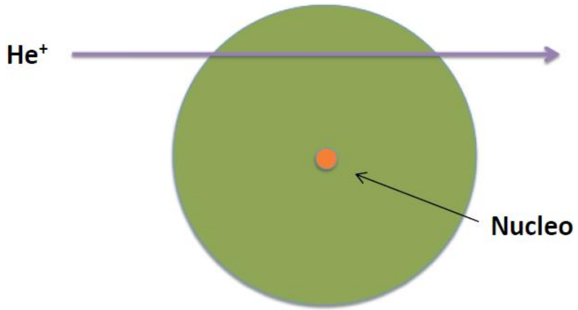


Stopping power -> depth profile

Stopping power is a physical quantity that describes how quickly a charged particle loses energy as it travels through a material. Inelastic process between the ion and the **sample electron cloud**

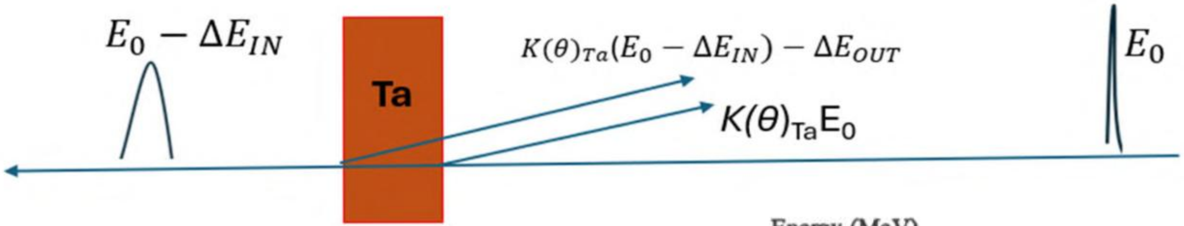
S: **Stopping power**
dE: energy loss
dx: distance traveled in the material
It is typically expressed in **MeV/µm** or **keV/nm**.

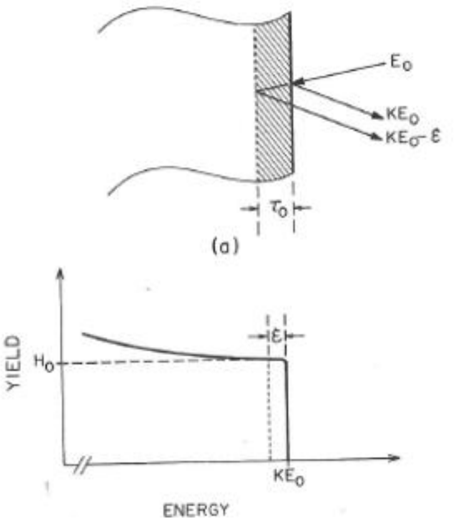
$$S = -\frac{dE}{dx}$$

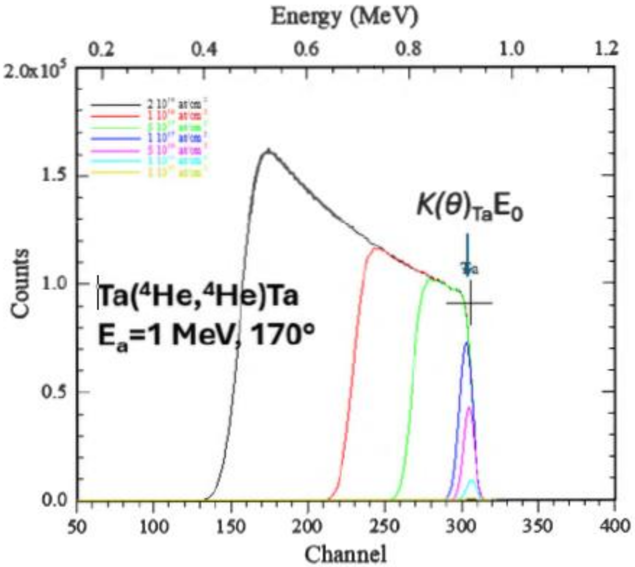


The depth profile is a representation of the elemental composition of a material as a function of depth. It provides information about how chemical elements are distributed within the sample, allowing identification of layers, concentration gradients, or possible subsurface impurities.

Stopping power -> depth profile







The spectrum of bulk material is the convolution of signal produced by every material layer

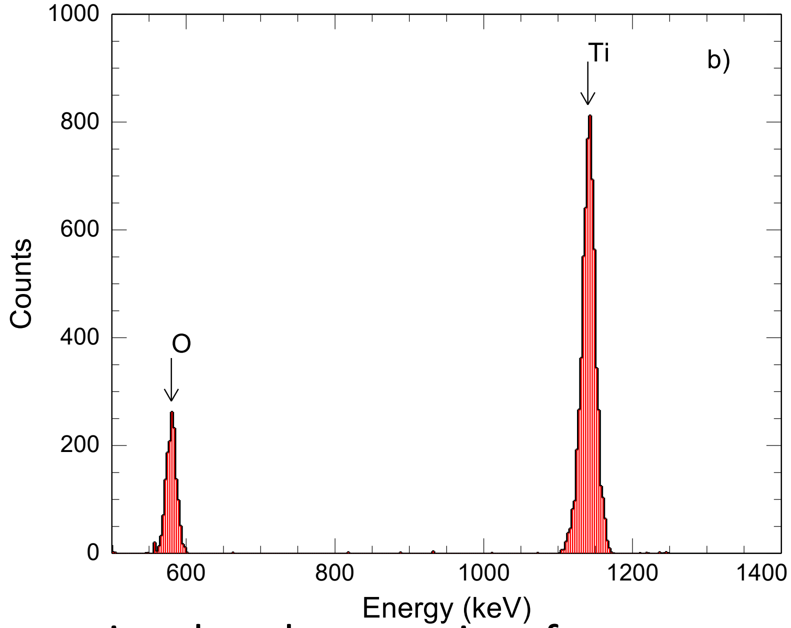
$$\Delta E = \boldsymbol{E}(\Delta a) - E_0 = -\int_0^{\Delta a} \frac{dE(\boldsymbol{E}(x), x)}{dx} dx$$

$$\Delta a(E) = \int_E^{E_0} \left(\frac{dE}{da}(E)\right)^{-1} dE$$

stopping cross section

Quantitative analysis

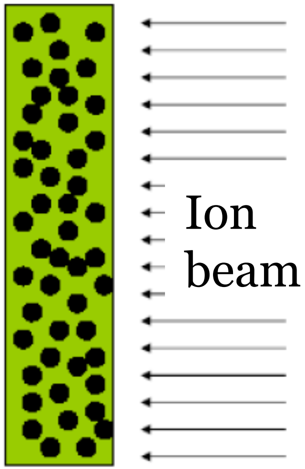
$$Y = \sigma\, \Omega\, Q\, N_s / \cos\theta$$



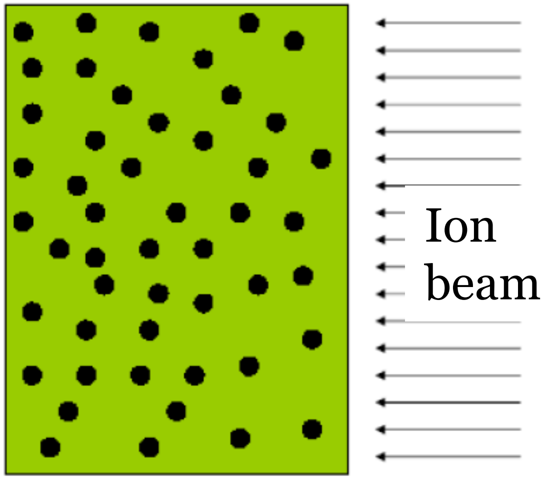
Y = number of counts (peak integral)
σ = cross section [cm^2] (probability)
Ω = solid angle [msr] (detector dimension)
Q = charge [number of ions]
N_s = number of atoms in areal unit [at/cm^2] (proportional to the quantity of atoms in our sample)

N_{Ti}/N_O = stoichiometry of material TiO_2

Areal density is a physical quantity that describes the amount of mass (or another parameter, such as charge or number of atoms) distributed over a unit surface area.



Same areal density, but different density and than different physical thickness

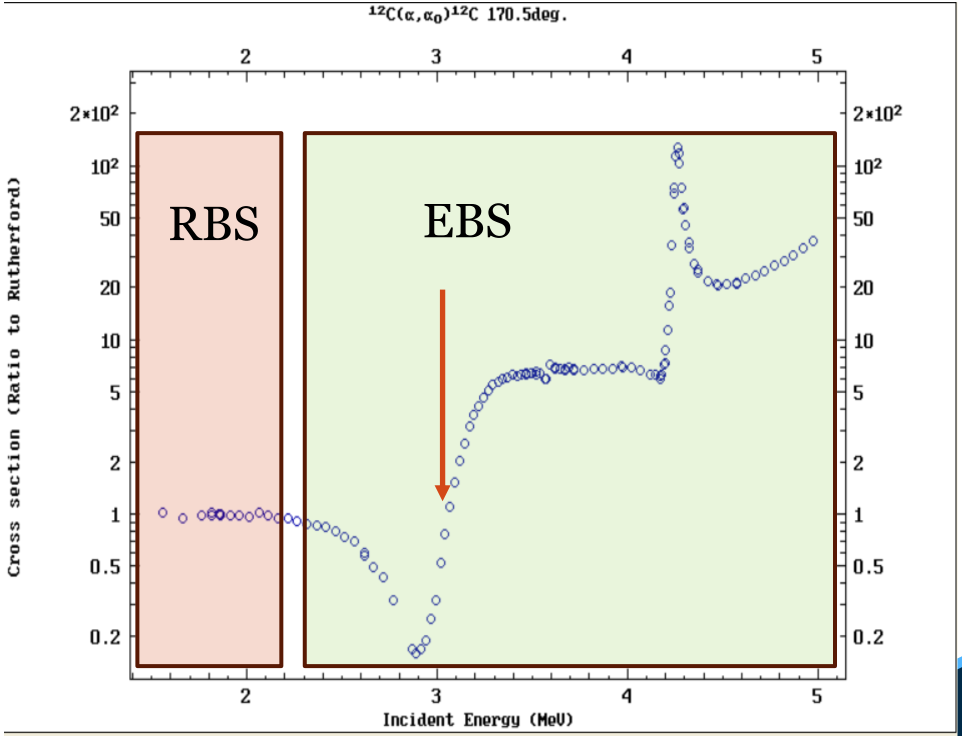


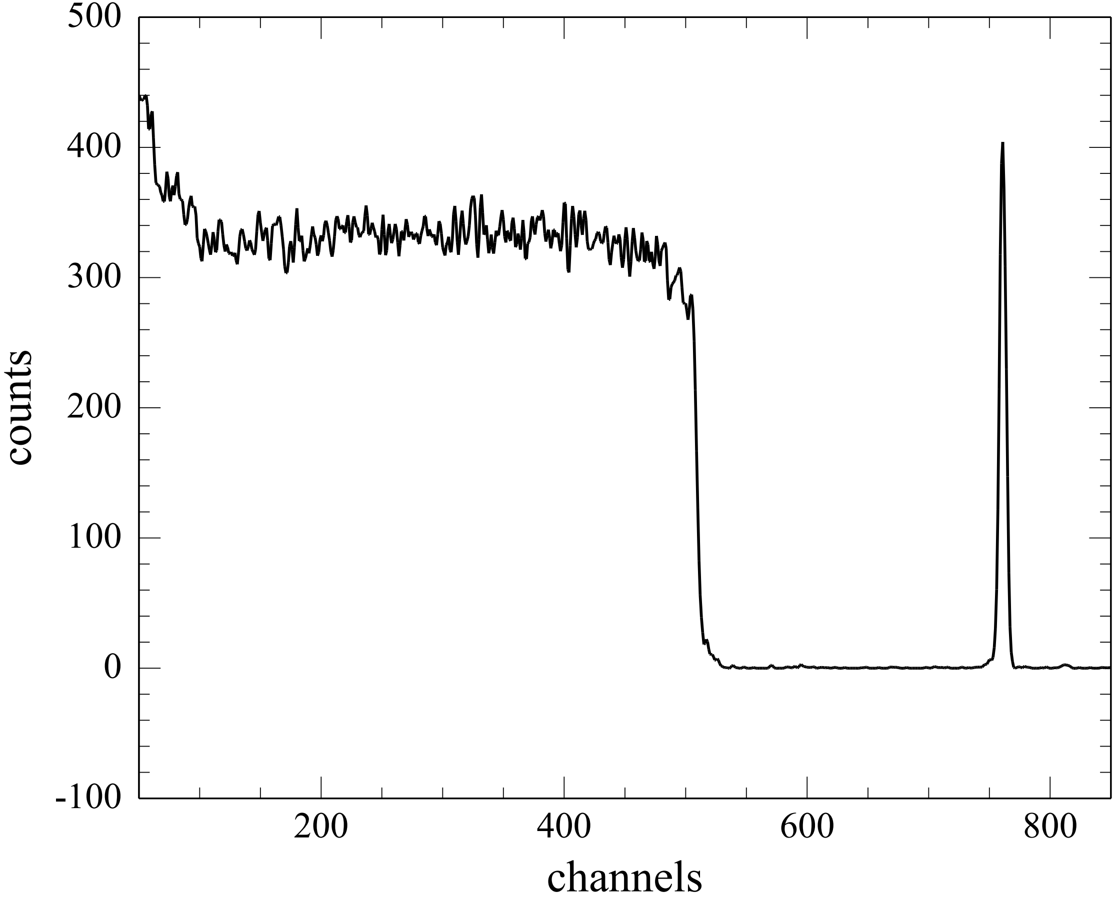
EBS vs RBS

RBS formula is valid only in specific condition and depends by ion, ion energy and target material

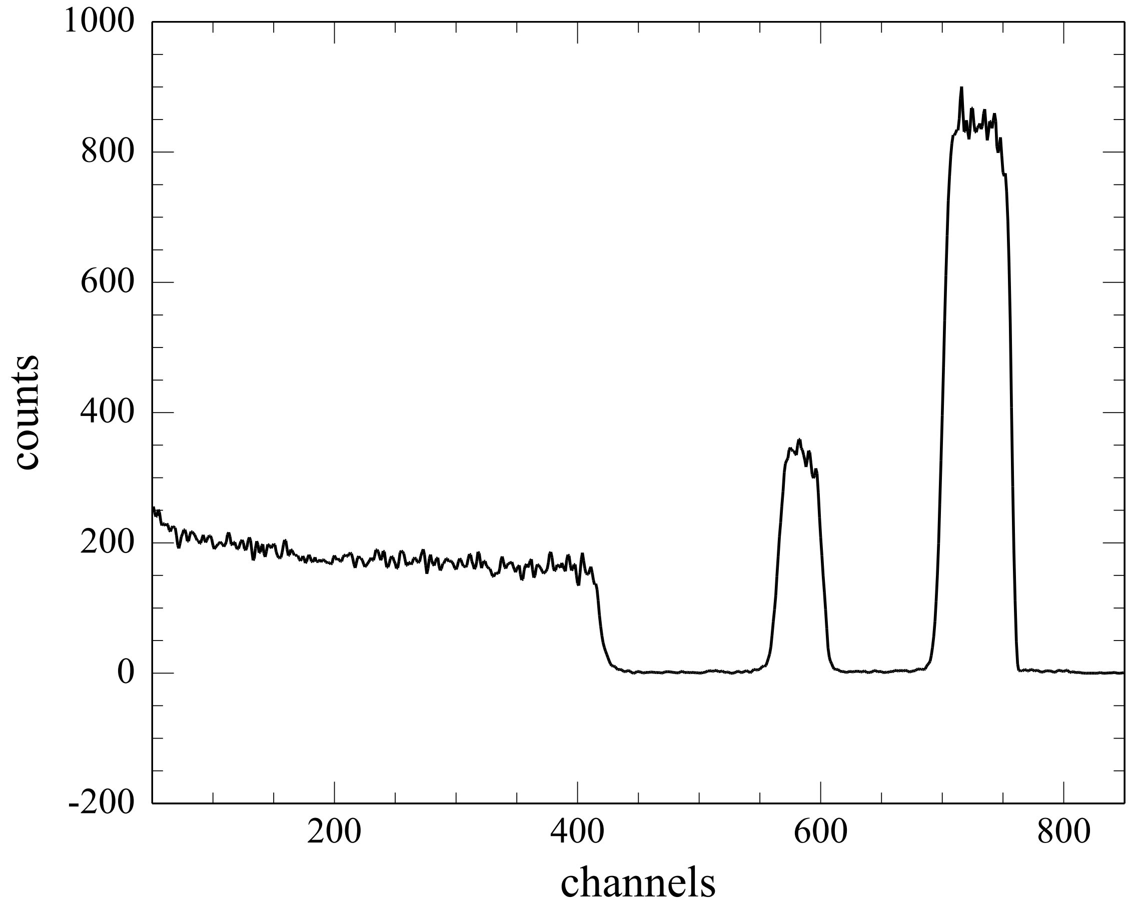
EBS is the generic technique

We have 3MeV of alfa beam!!!

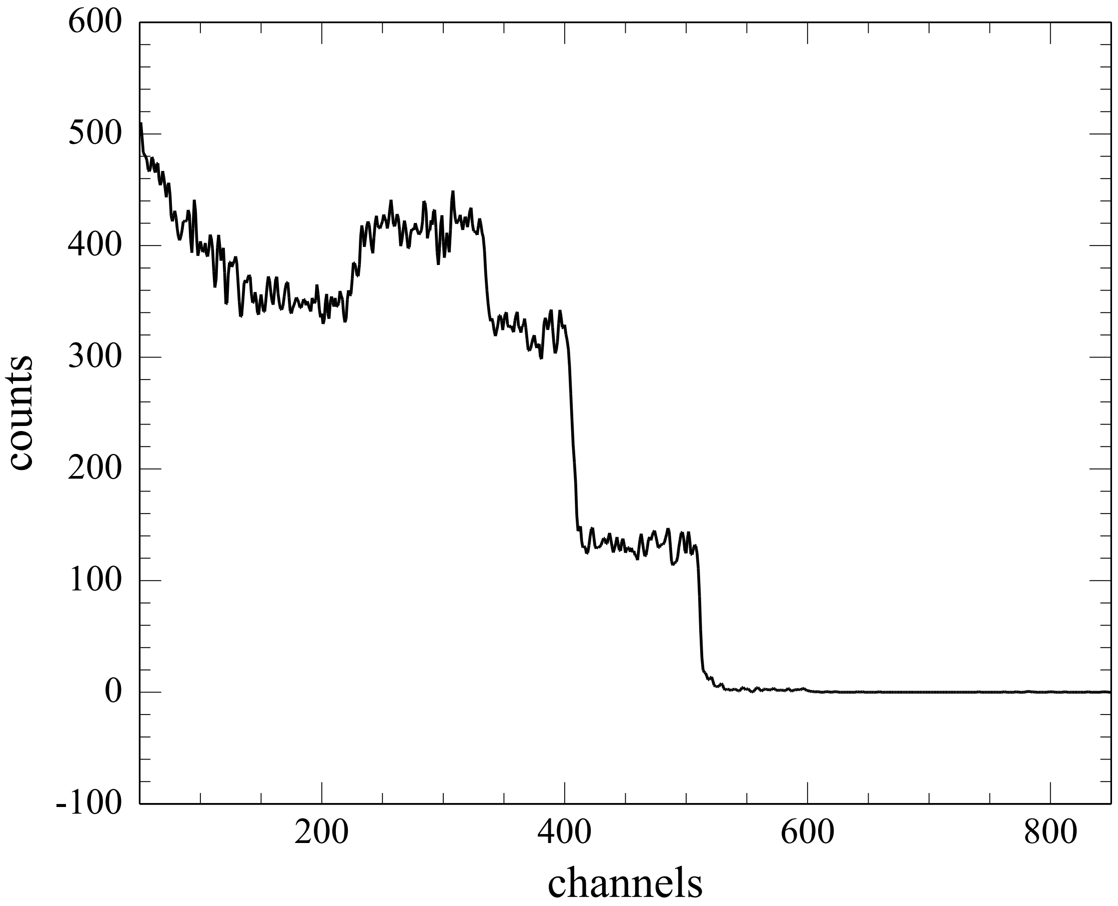




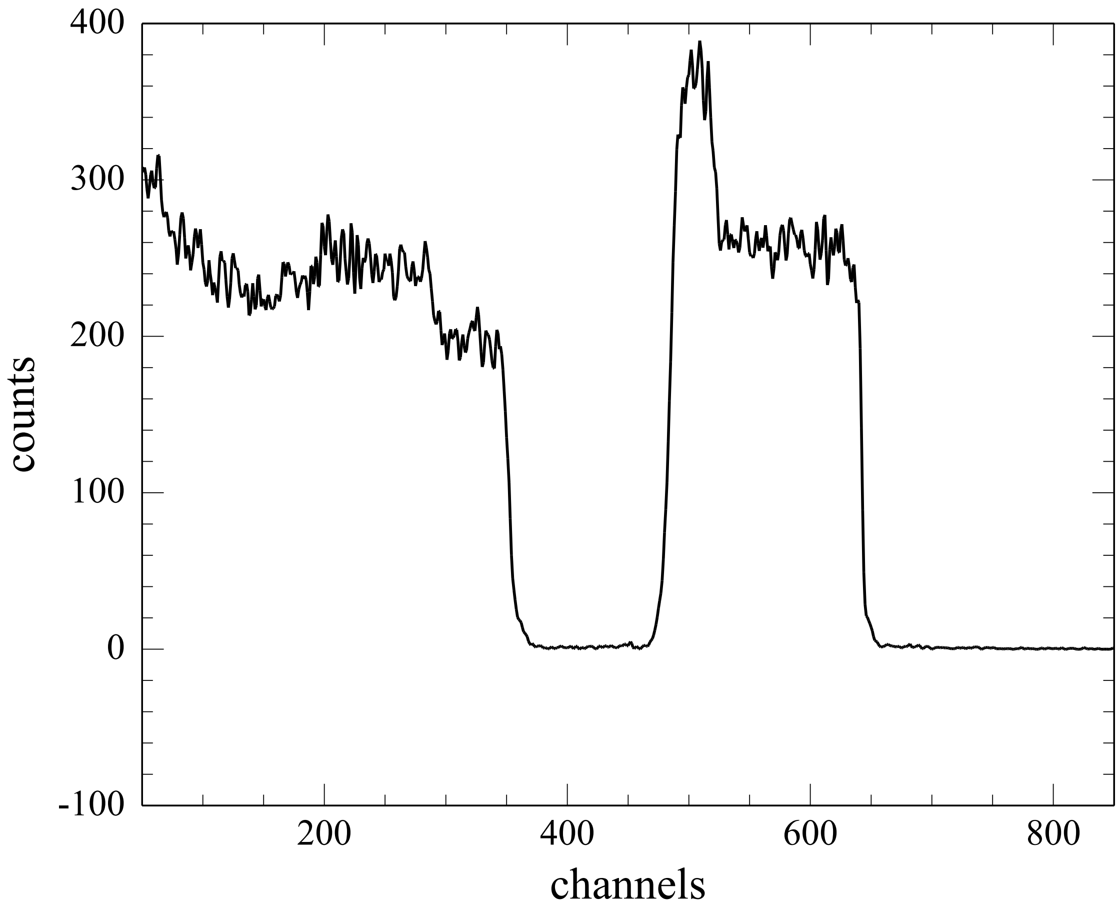
Sample 1
Pd/Si



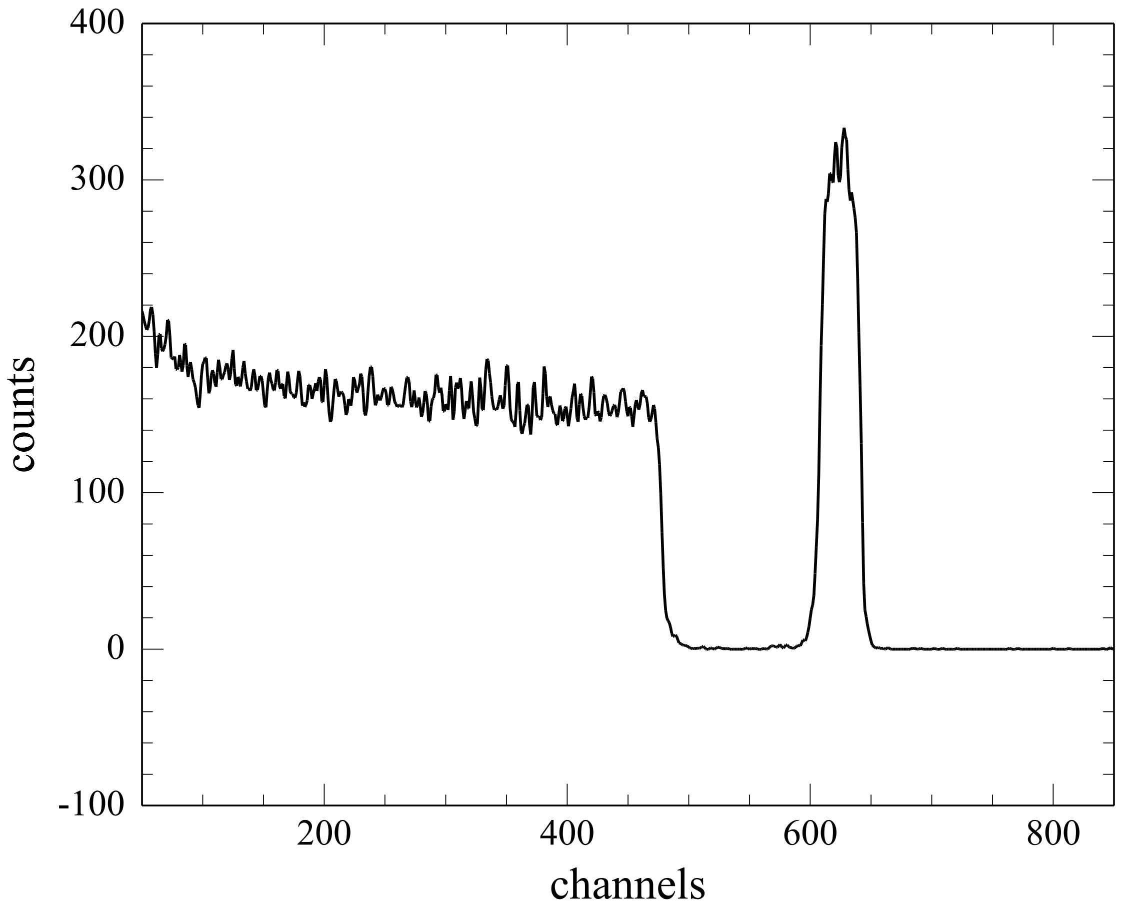
Sample 2
Ru/Cr/Si



Sample 3
SiO_2/Si



Sample 4
TiN/Ti/Si



Sample 4
Ti/Si