Ion Beam Techniques:

Rutherford Backscatering and Nuclear Reaction Analysis

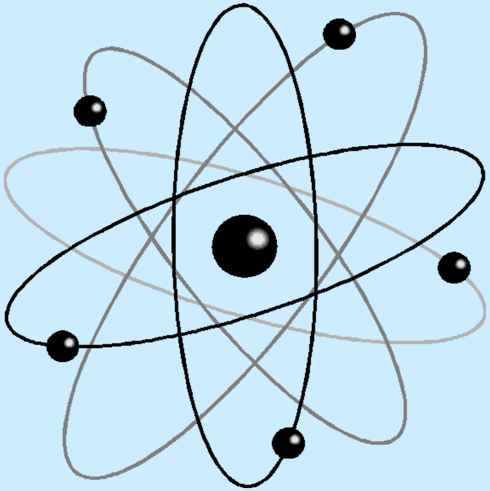
Eduardo Alves
Instituto Superior Técnico (IST)- Universidade de Lisboa
Instituto de Plasmas e Fusão Nuclear and LATR
Estrada Nacional Nº 10, km 139,7
2695-066 Bobadela, Portugal

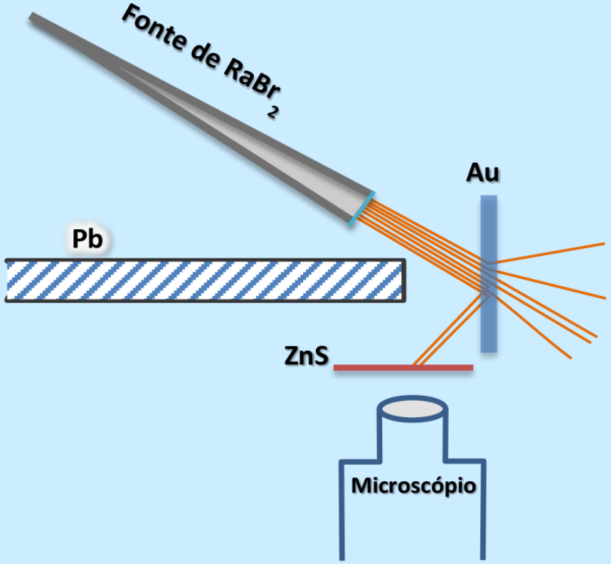
Summary

- Introduction
- Rutherford backscattering : ***Aim*** and ***concepts***
- **Rutherford Backscattering Spectrometry (RBS)**
  - Scattering cross section – ***Quantity***
  - Kinematic factor – ***Chemical species***
  - Electronic stopping – ***Thickness***
  - eEnergy straggling- ***Depth resolution***
- ***NRA/PIGE***
  - Theoretical aspects
  - Cross sections

….Long time ago!

- **(Ernest) Rutherford Atomic Model (Phil. Magazine 21, 669-688 (1911)**



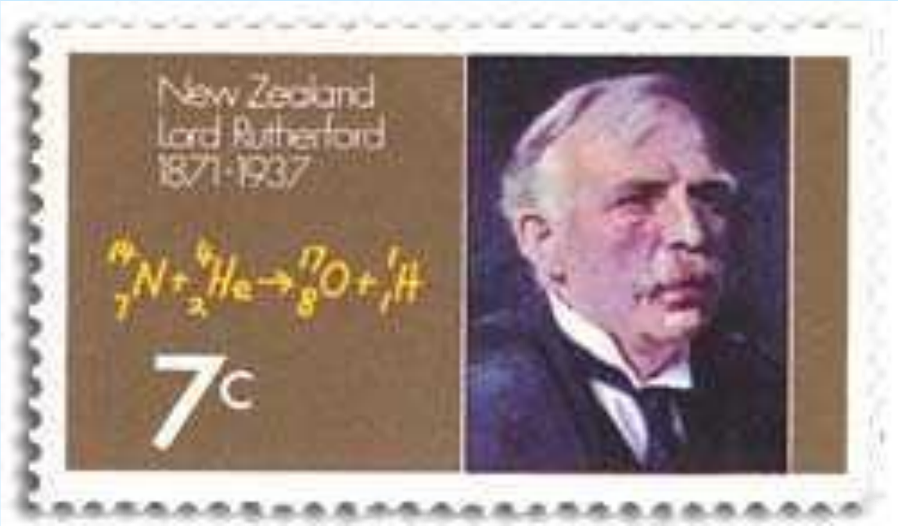


- **First gas detector, Rutherford-Geiger (Geiger –Müller tube)**

Rutherford experiment

- **First artificial nuclear reaction** **(Phil. Magazine 6, 537-587 (1919)**

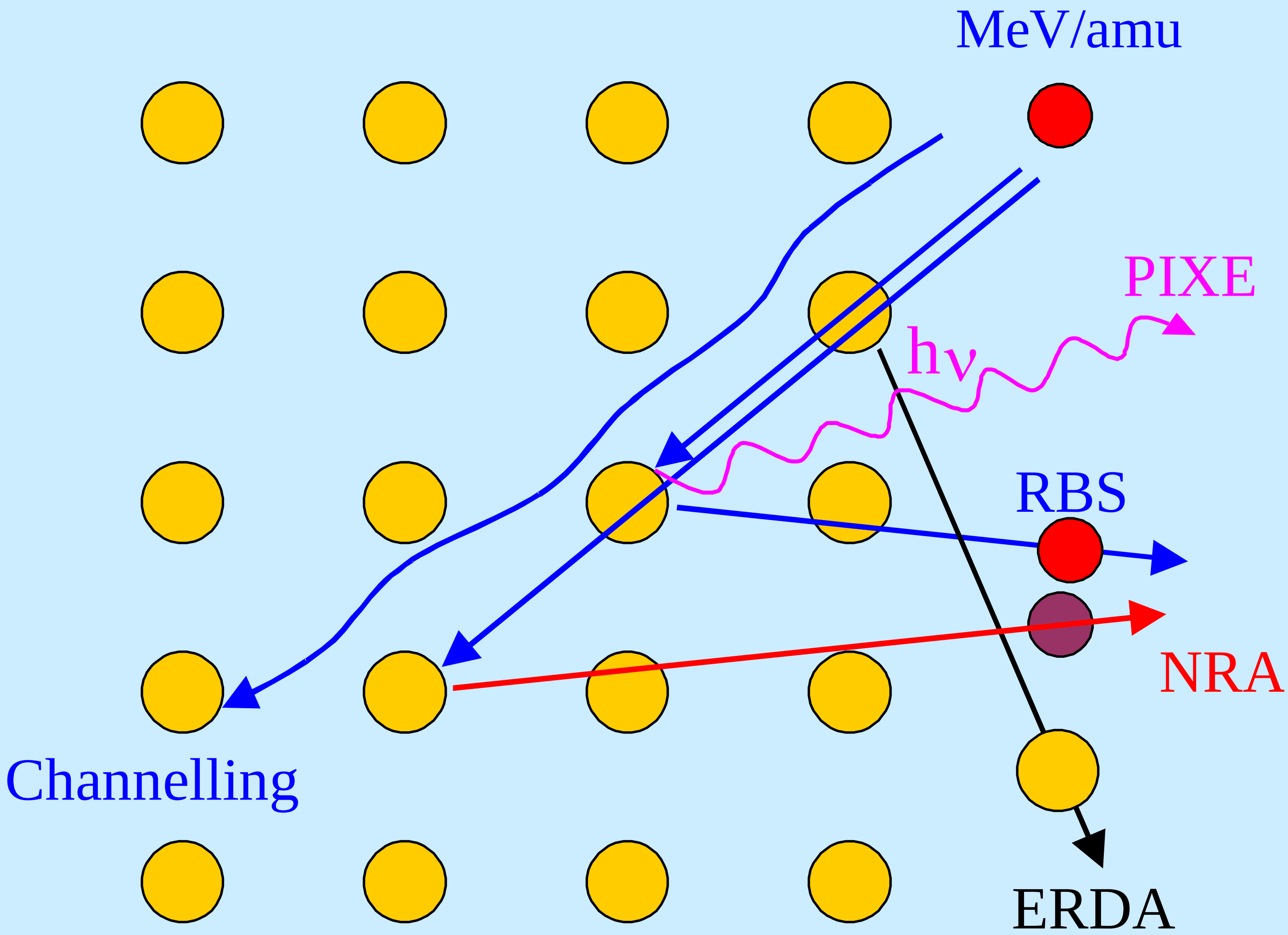
….again Ernest Rutherford (1919)



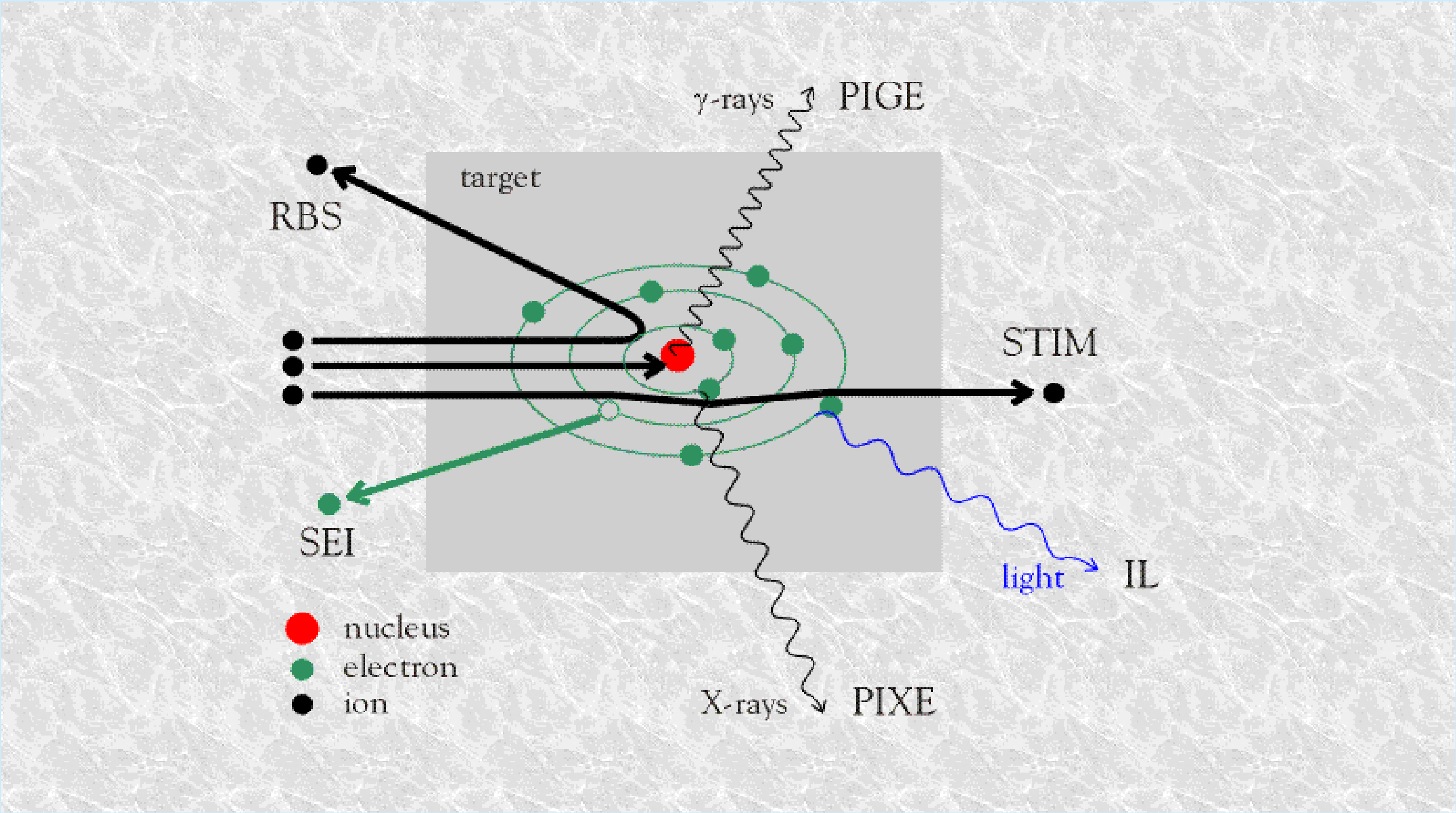
- **First electrostatic accelerator, Cockcroft e Walton, 1932**

- **The secrets of the nucleus were ready to be unveil.**

Ion beam -Matter Interactions

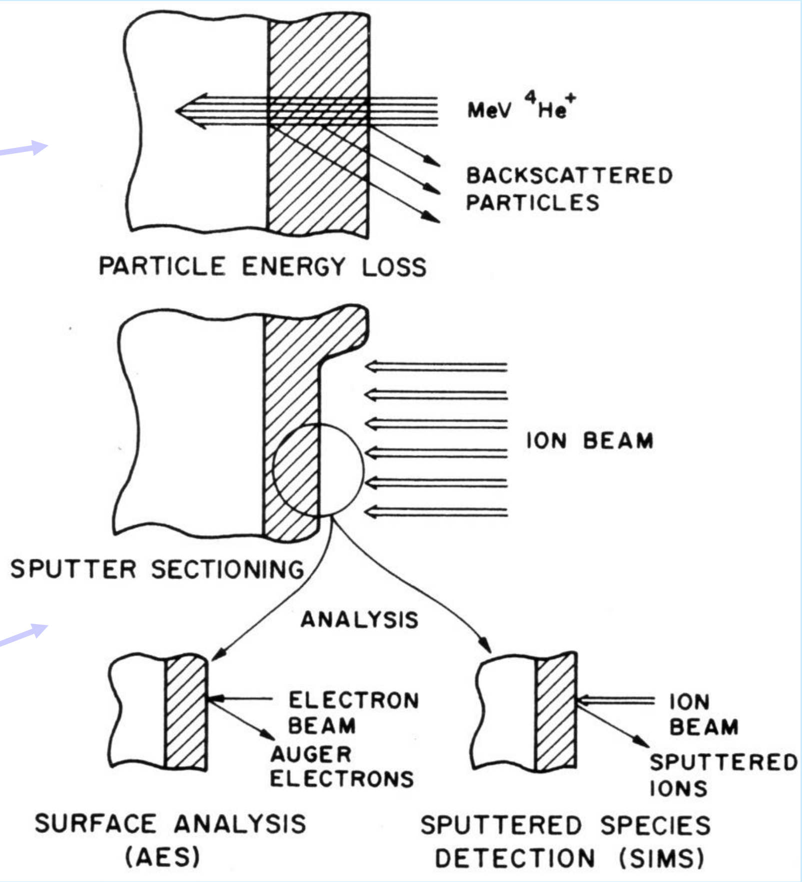


Ion-Atom Interactions



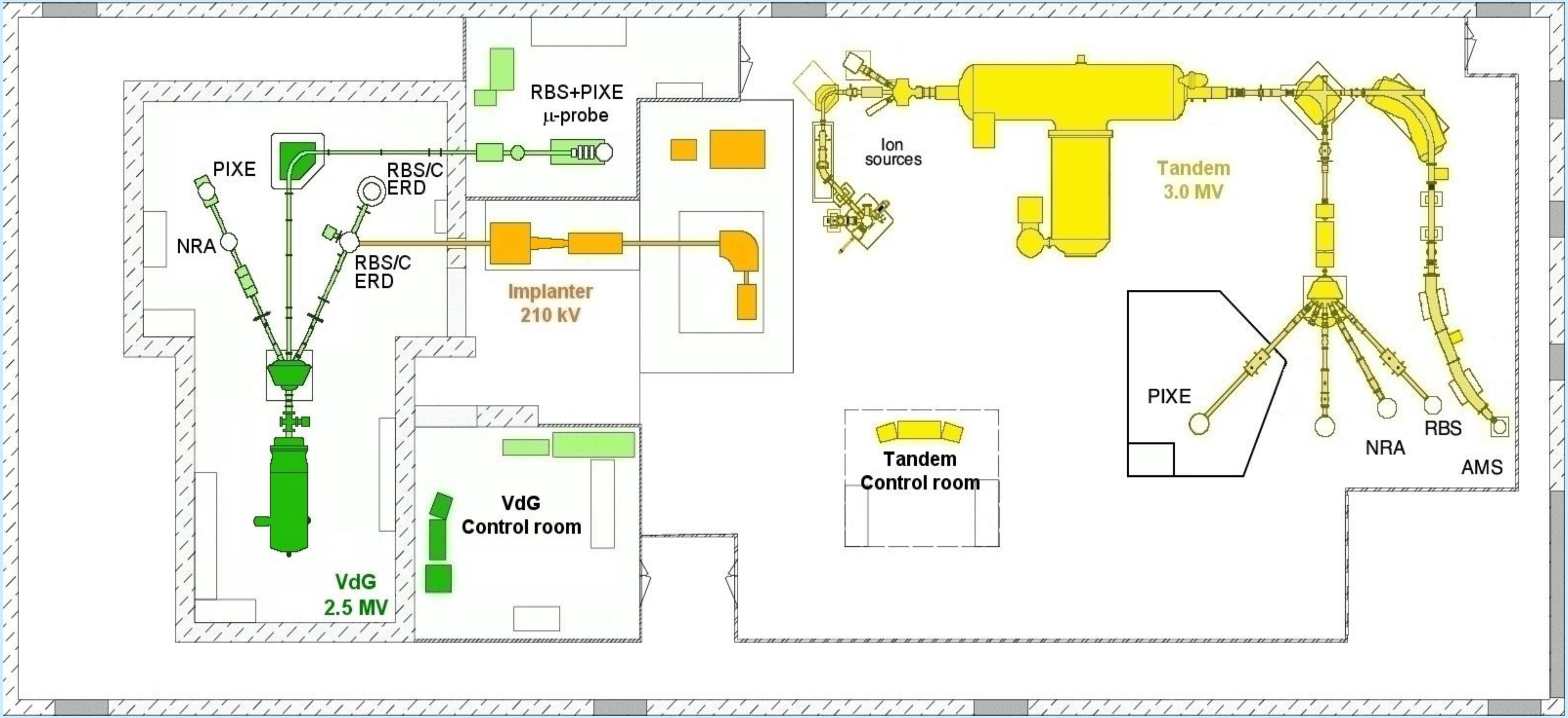
Ion Beam Analysis

- **scattering** : RBS (MEIS, LEIS, ISS,…)
- nuclear **reactions**, e.g. $^{14}N(d,a)^{12}C$
  $^{18}O(p,a)^{15}N$
- **Electronic excitaion: X-ray** emission: PIXE
  :Ligh: Ionoluminescence
- Recoils: ERDA



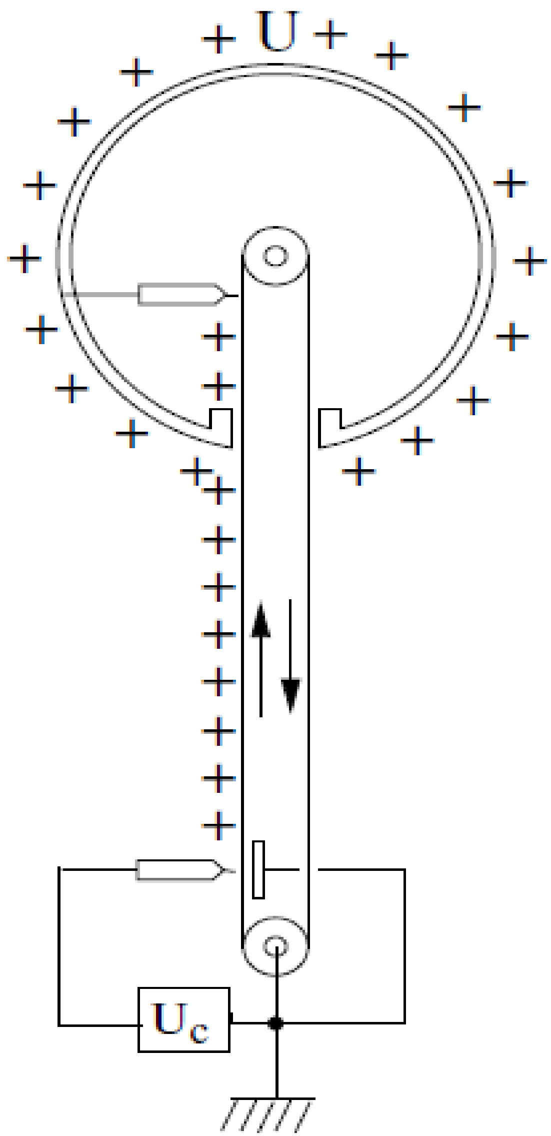
- **sputtering** : SIMS
  depth profiling (AES, XPS)
  (negligible in RBS – high E, low Z)

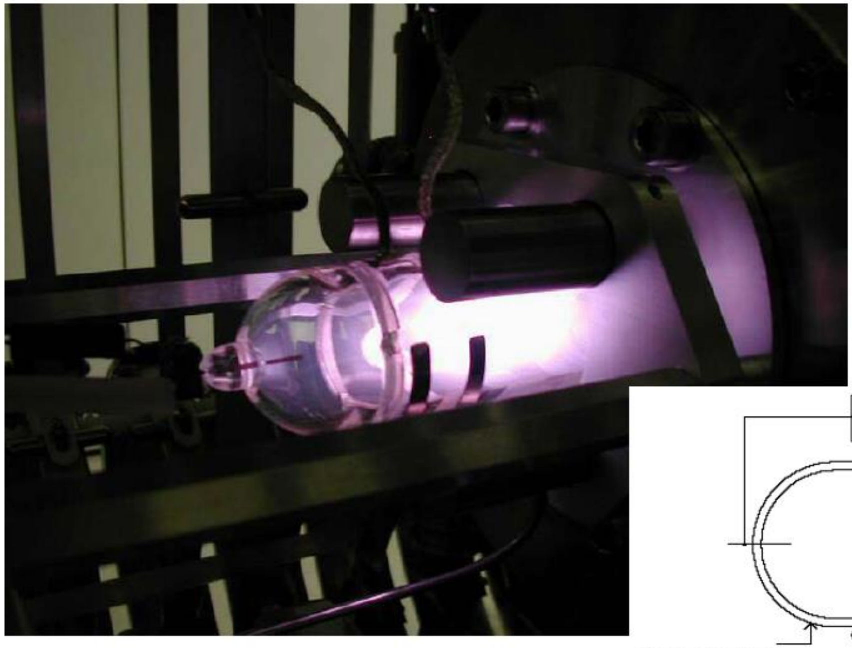
Ion Beam Laboratory portrait



E. Alves, IST-LATR (ealves@ctn.ist.utl.pt) CTN-2017

Accelerators-Van de Graaff

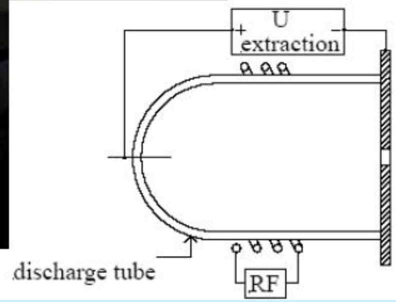




P= 10^{-3} Torr

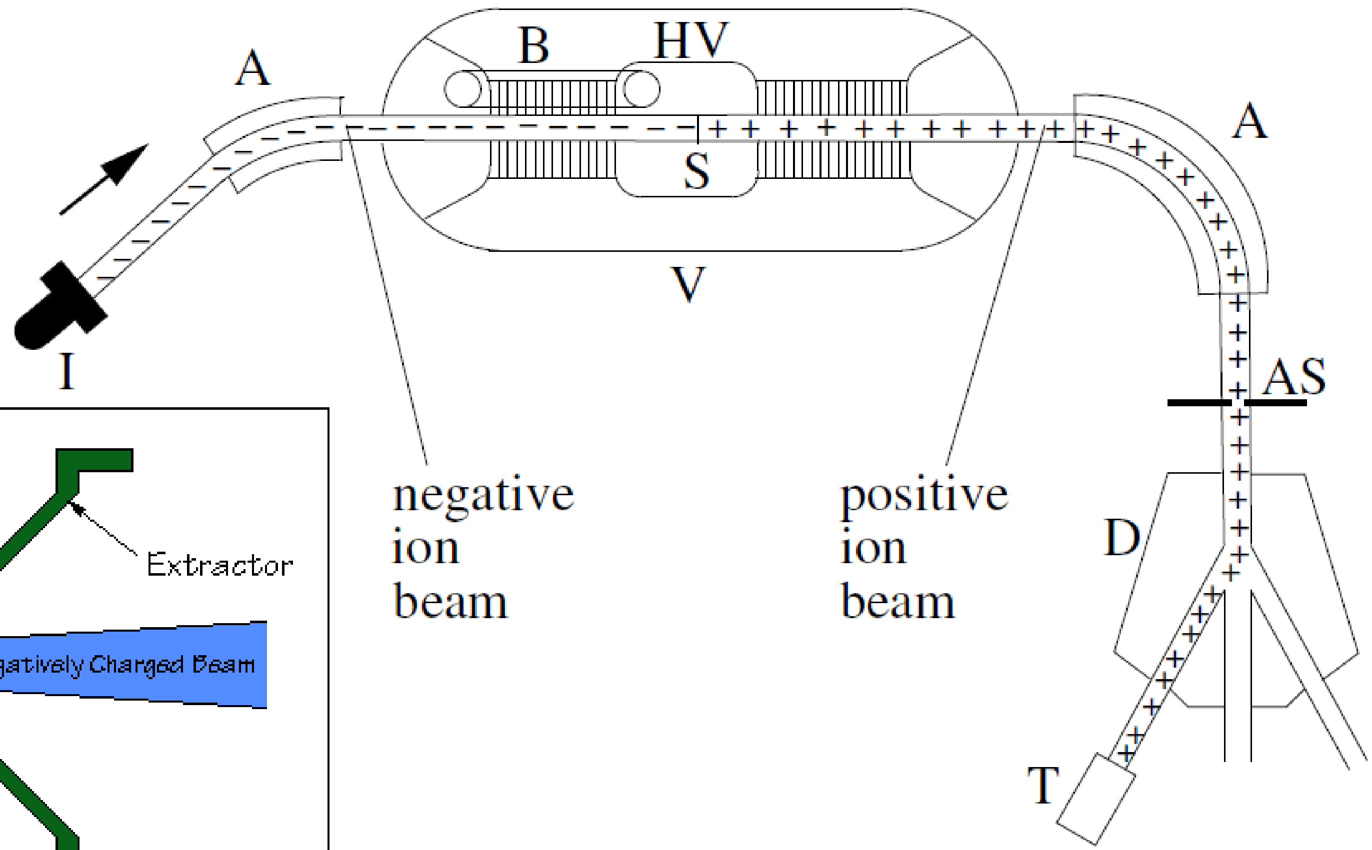
RF 10-30 MHz

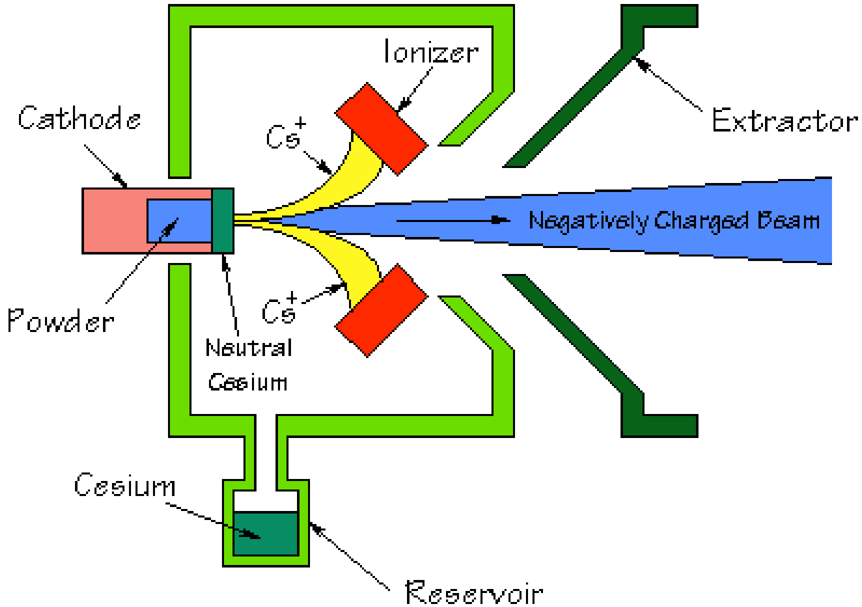
Beam current up to 20 mA



RF Ion source

Accelerators-Tandem





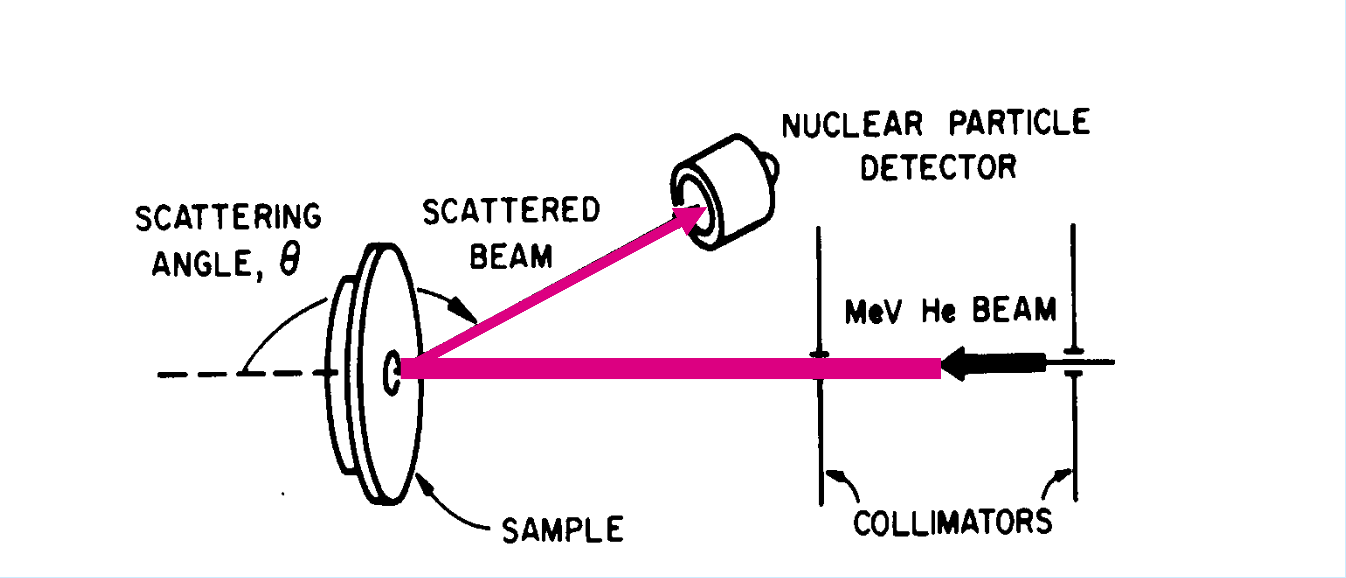
SNICS II Schematic Diagram

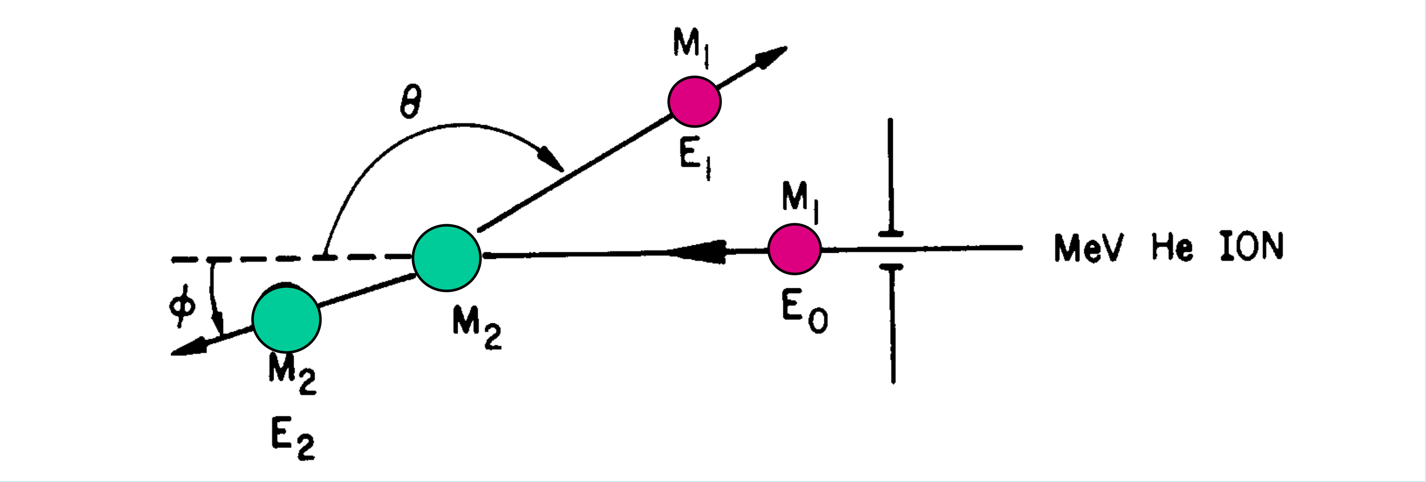
TÉCNICO LISBOA

Relevant Characteristics of IBA

Technique	Acronym	Scattering I = ion S = Sample	Sample information	Typical Elemental sensitivity
Particle Induced X-ray Emission	**PIXE**	**S(I,x-ray)S**	**Trace and major elements in top 10-20 mm of sample**	**10 to 100 ppm**
Rutherford Backscattering Spectrometry	**RBS**	**S(I,I)S**	**Surface depth profile (up to 2000 nm)**	**1%**
Nuclear Reaction Analysis	**NRA**	**S(I,I')S'**	**Light elements in heavy matrix**	**Down to few ppb**
Elastic Recoil Detection Analysis	**ERDA**	**S(I,S)I**	**Light elements in surface μm**	**0.1%**
Particle Induced X-ray Emission	**PIGE**	**S(I,γ-ray)S'**	**Light elements in heavy matrix**	**1% or better**
Ion-induced Electron Microscopy	IEM	S(I,e)S	Surface topography	Low
Channeling Contrast Microscopy	CCM	<S>(I,I)<S>	Crystallinity, orientation, substitutionality of heavy elements in light matrix	1 %
Scanning Transmission Ion Microscopy	STIM	S(I,I)S	Areal density of samples thin enough to transmit the beam (up to 50 μm)	n.a.
Channeling Scanning Transmission Ion Microscopy	CSTIM	<S>(I,I)<S>	Crystallinity, beam damage in samples thin enough to transmit the beam (up to about 50 μm)	n.a.
Ion Microtomography	IMT	S(I,I)S	3D structure and density of samples up to 50 μm thick	10 %
Ionoluminescence	IL	S(I,light)S	Oxidation state of transition metals, presence of trace rare earths, radiative defects and other properties of the band gap	Can be ppb

Rutherford backscattering





Strength of RBS

- RBS is a reliable and accurate method for ***directly*** and ***non-destructively*** determining the composition of an alloy as a function of depth.

- The analysis relies on ***absolute calculations,*** without the need for ***standards*** for quantification.

- No influence of ***chemical, electronic, magnetic,optical and structural properties*** of the sample (hence no modelling required).

Basic concepts of backscattering

qualitative/quantitative information of a (thin film) sample

based on : - the ***Rutherford atomic model*** (electron cloud surrounding the nucleus)

- classical scattering in a ***central force*** field : ***Coulomb repulsion***

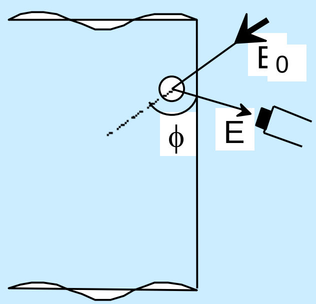
1. energy transfer during the collision of M_1 and M_2 (kinematic factor) → ***identity*** of the target atoms

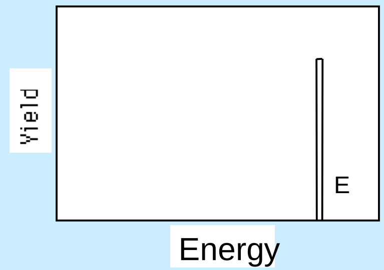
2. cross section in central force field (scattering cross section) → ***concentration*** of target atoms

3. energy loss of particle (stopping cross section) → ***depth*** profiles

Rutherford backscattering: Concepts

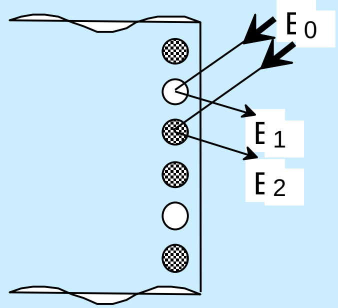
What?

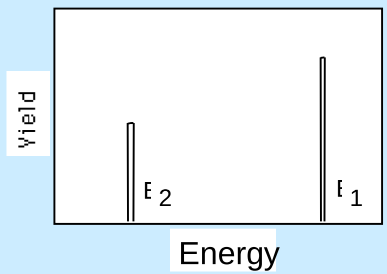




$$K = E/E_0 = \left[\frac{\left(M^2 - m^2 \sin^2\phi\right)^{1/2} + m\cos\phi}{M + m} \right]^2$$

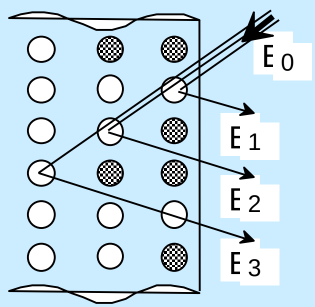
How much?

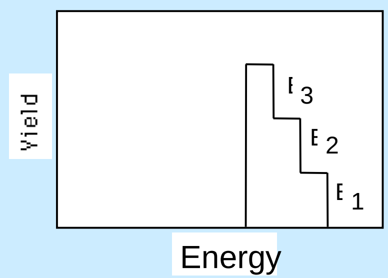




$$\sigma(\phi) = \left(\frac{Z_m Z_M e^2}{4\,E} \right)^2 \frac{4}{\sin^4\phi} \frac{\left[\left[1 - (m/M)^2 \sin^2\phi \right]^{1/2} + \cos\phi \right]^2}{\left[1 - (m/M)^2 \sin^2\phi \right]^{1/2}}$$

Where?





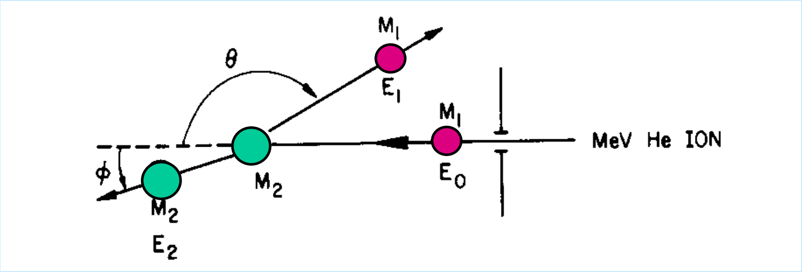
$$\Delta E/\Delta t = K \cdot \left.\frac{dE}{dt}\right|_{E_0} + \left.\frac{dE}{dt}\right|_{E'_0} / |\cos\phi|$$

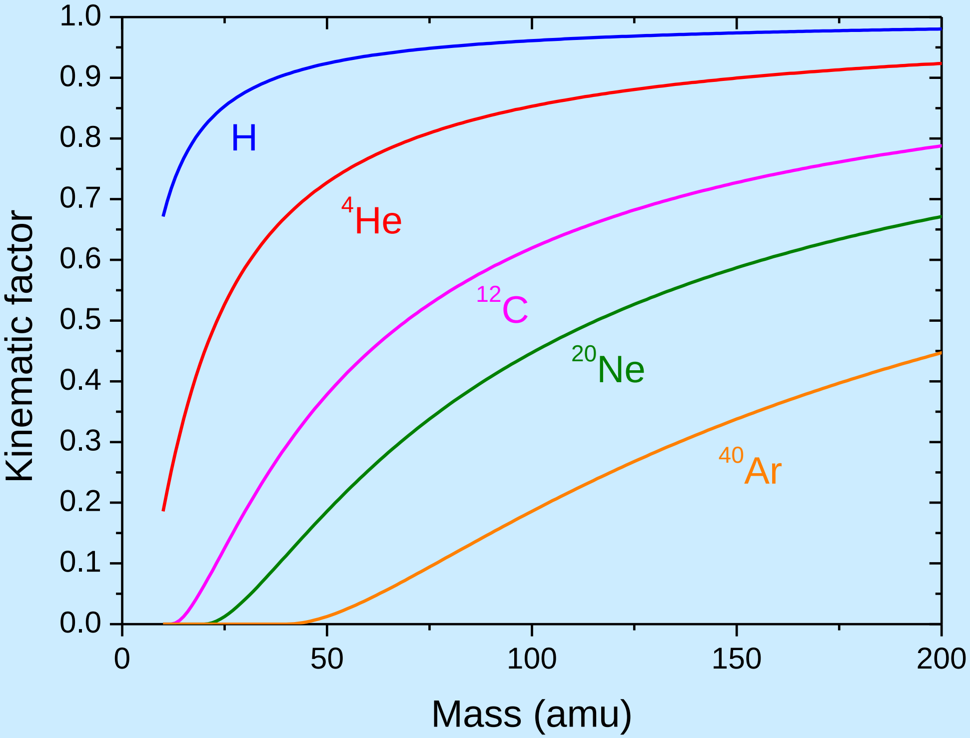
Kinematic factor

$$E_1 = KE_0$$

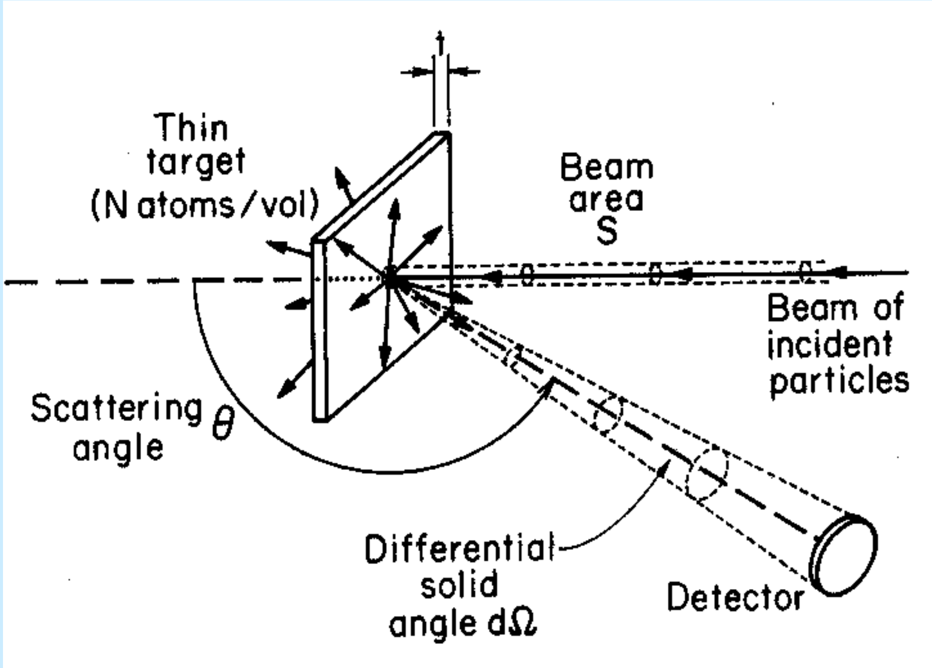
$$K = \left(\frac{M_1 \cos\theta \pm \sqrt{M_2^{\,2} - M_1^{\,2} \sin^2\theta}}{M_2 + M_1} \right)^2$$

measure E_1 → determine mass M_2





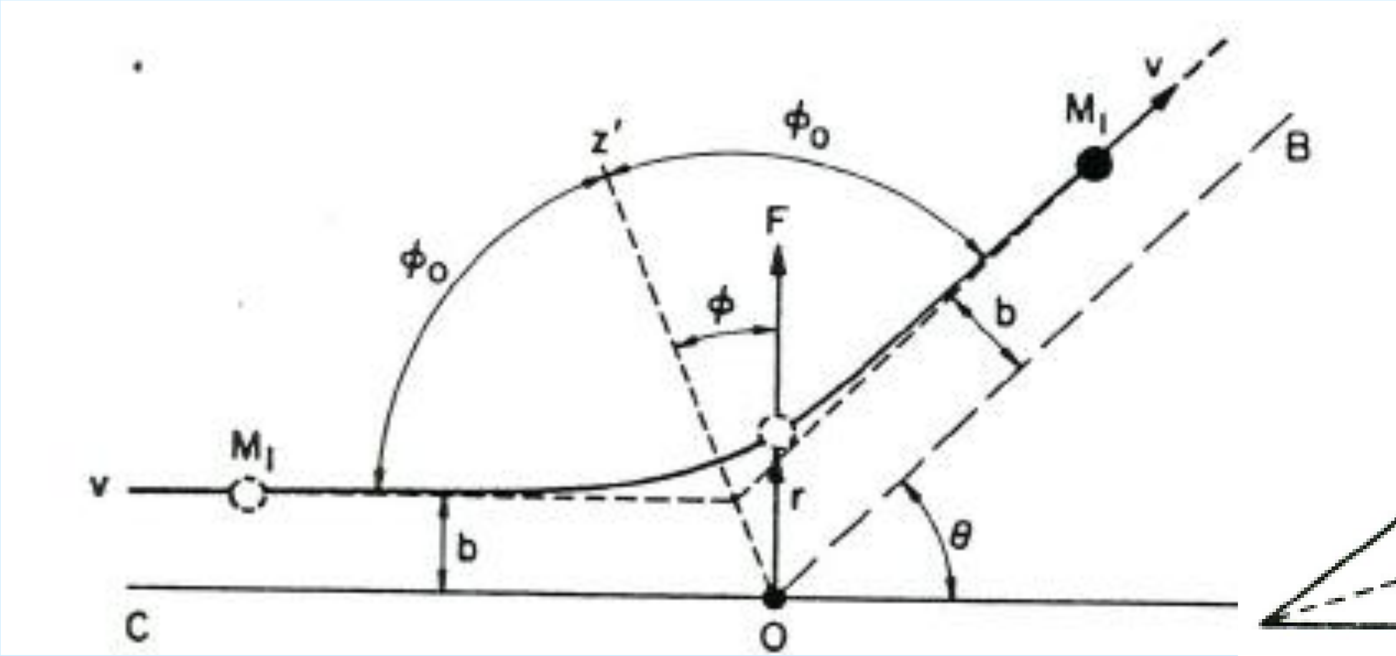
Scattering cross section

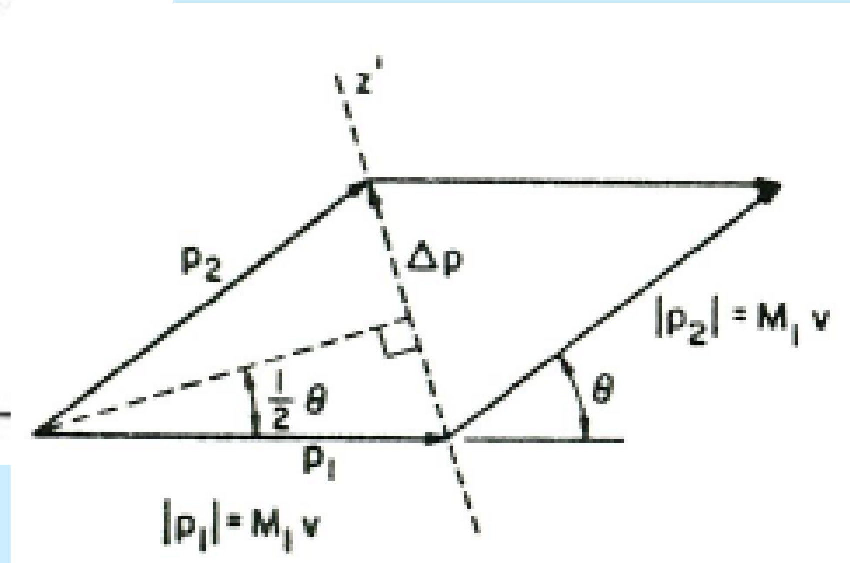


$$\sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)}$$

based on (unscreened !) Coulomb repulsion

Rutherford Cross Section





$$\Delta p = 2M_1 v \sin\frac{\theta}{2}.$$

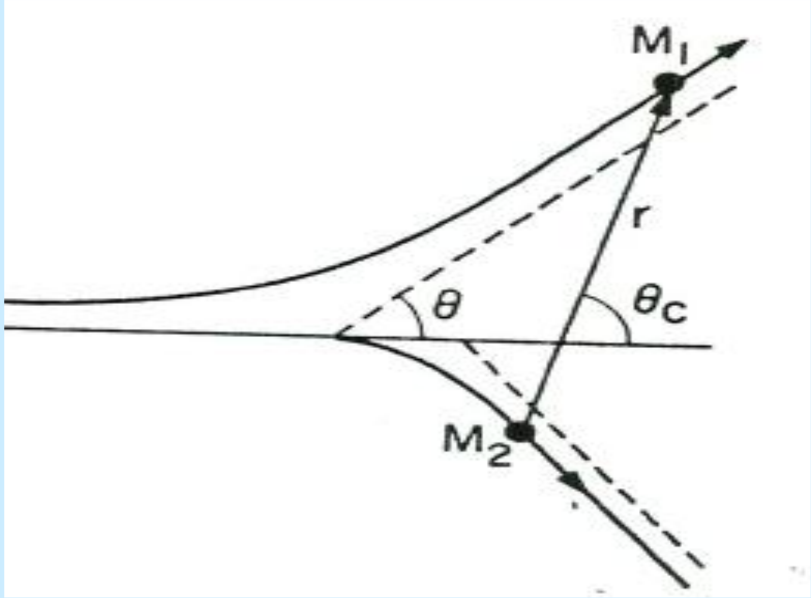
Conservação Momento Linear

$$\sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E}\right)^2 \frac{1}{\sin^4 \theta/2}.$$

$$M_1 r^2 \frac{d\phi}{dt} = M_1 v b$$

Conservação Momento Angular

Caso geral



$$\tan\theta = \frac{\sin\theta_c}{\cos\theta_c + M_1/M_2},$$

$$\sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E}\right)^2 \frac{4}{\sin^4\theta} \frac{(\{1-[(M_1/M_2)\sin\theta]^2\}^{1/2}+\cos\theta)^2}{\{1-[(M_1/M_2)\sin\theta]^2\}^{1/2}},$$

$$M_1 \ll M_2$$

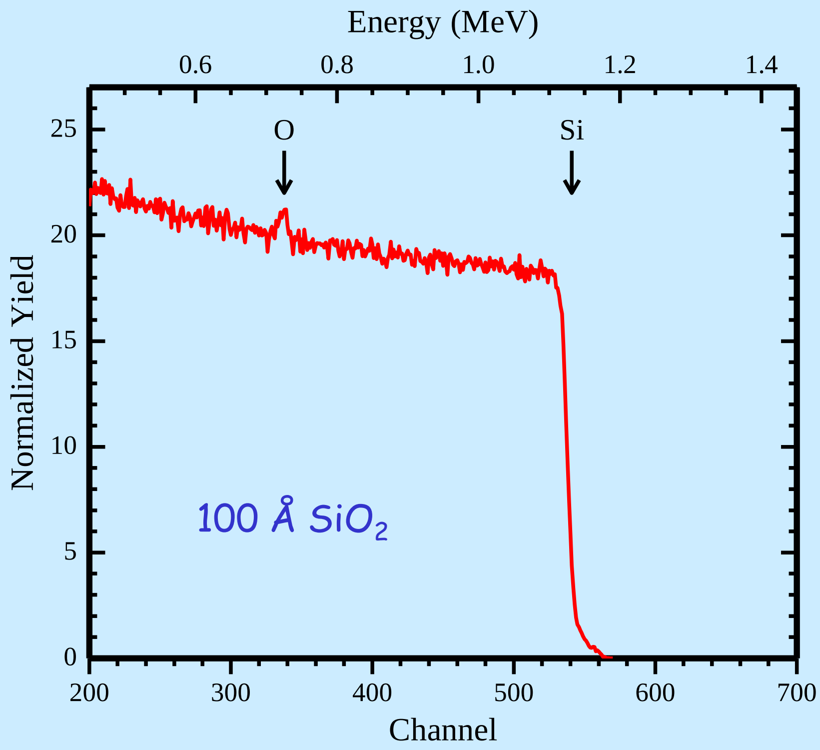
$$\sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E}\right)^2 \left[\sin^{-4}\frac{\theta}{2} - 2\left(\frac{M_1}{M_2}\right)^2 + \cdots\right]$$

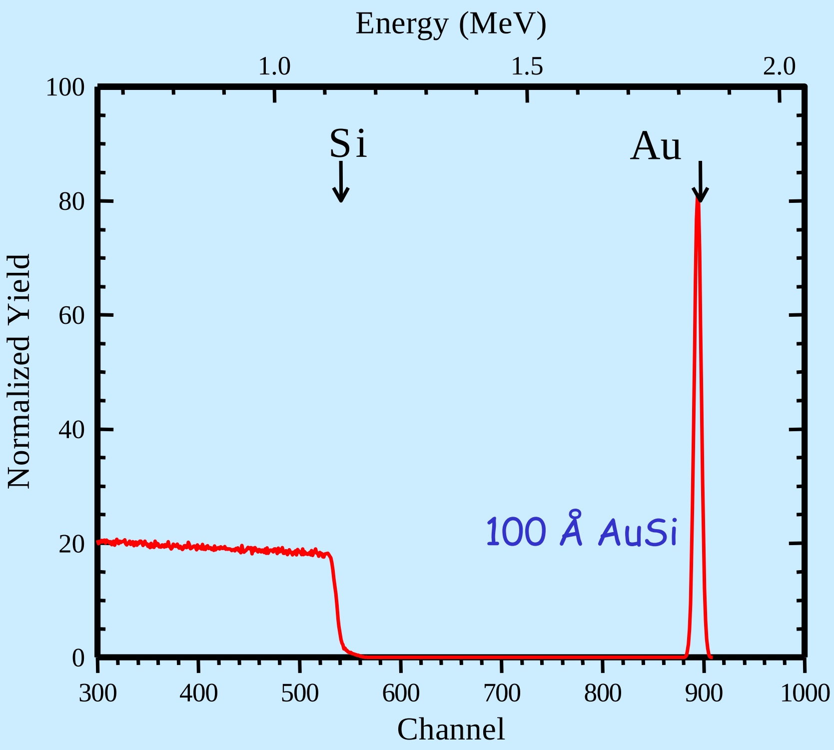
Scattering cross section

Large scattering cross section for :

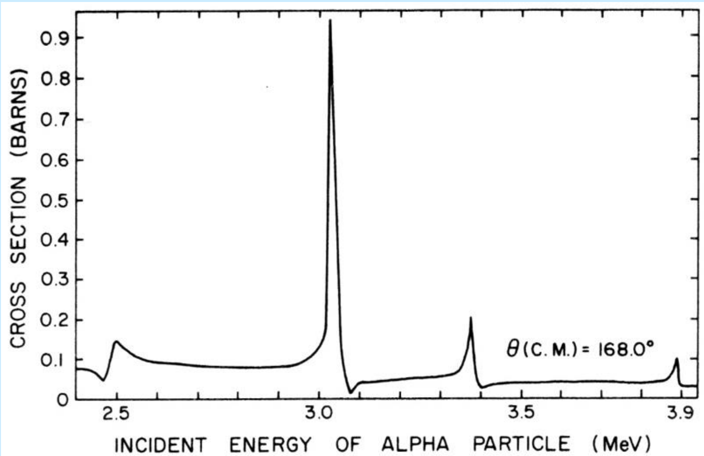
$$\sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

- heavy ***ions*** (Li in stead of He)
- heavy ***target atoms***
- ***low energy***
- small scattering ***angle***

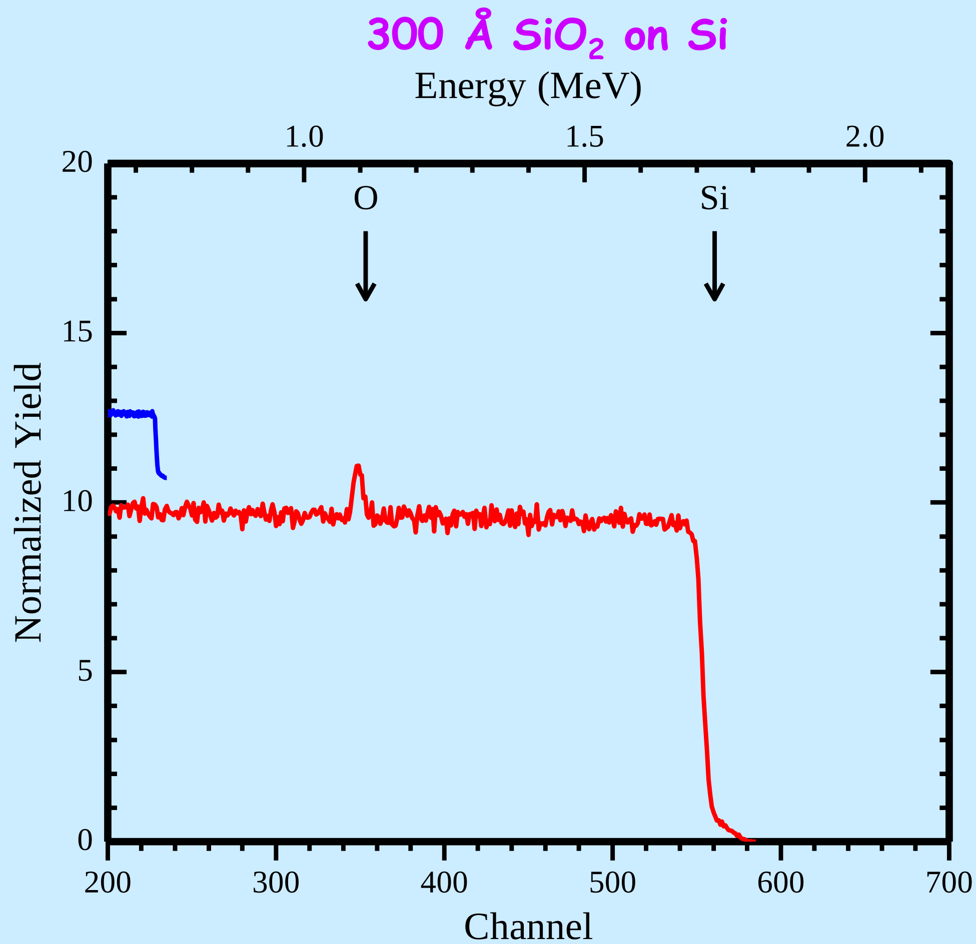




Non-Rutherford scattering



Sharp resonance at E = 3.045 MeV



Collisions with target Ions and Electrons

$\rightarrow$ Total Energy loss

Nuclear Interactions: – Elastic collisions with nucleus $\rightarrow$ **Nuclear energy loss**

Electronic interactions – Inelastic collisions with electrons (excitation, ionization) $\rightarrow$ **Electronic energy loss**

Total energy loss:

$$-\frac{dE}{dx} = -\left.\frac{dE}{dx}\right|_{nucl} + -\left.\frac{dE}{dx}\right|_{elect} \qquad S = -\frac{1}{N}\frac{dE}{dx}$$

(energy loss due nuclear reactions and elastic collisions with bound electrons are ignored)

Energy loss in RBS

nuclear versus electronic stopping

- elastic collisions with nuclei

  large discrete energy losses

  significant angular deflection

  [responsible for generation of displaced atoms]

  backscattering

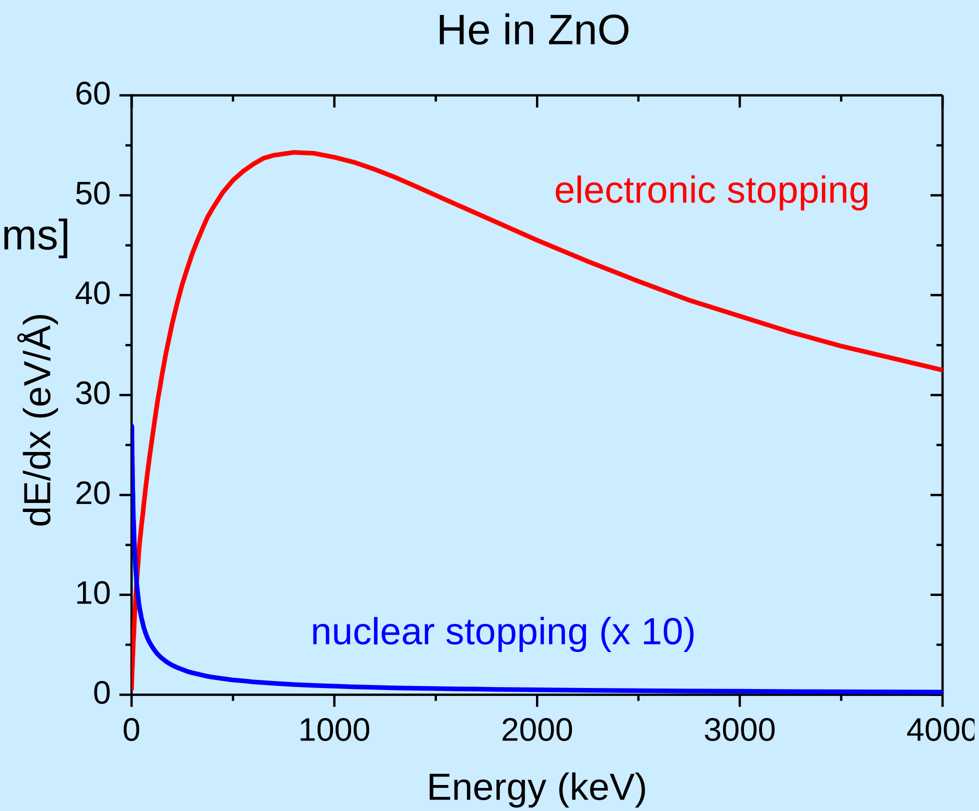
- (in)elastic collisions with electrons

  much smaller energy losses per collision

  negligible deflection

  negligible damage

  slowing down

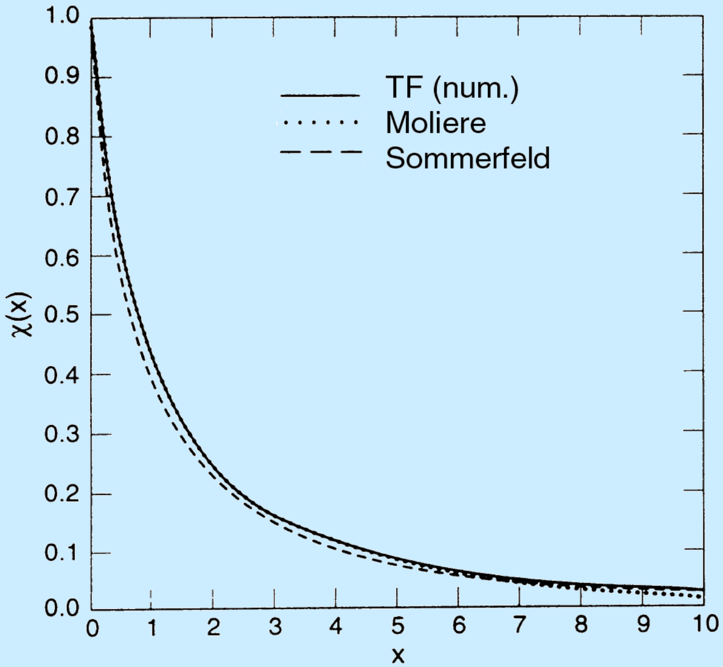


Interaction Potential

$$V(r) = \frac{Z_1 Z_2 e^2}{r}\chi(r)$$

$a_0 < r < r_0$

Thomas-Fermi model:
Screening function



$$\frac{d\chi^2}{dx^2} = \frac{\chi^{3/2}}{x^{1/2}} \quad \text{com} \quad r = x a_{TF} \quad \text{e} \quad a_{TF}{}^{3/2} = \frac{3\pi\hbar^3}{4(2m_e)^{3/2} e^3 Z_{eff}{}^{1/2}}$$

Nuclear stopping cross section

Large energy losses and trajectory changes: Defect production (Collision cascades, $\tau \sim 10^{-14} \ldots 10^{-13}$ s)

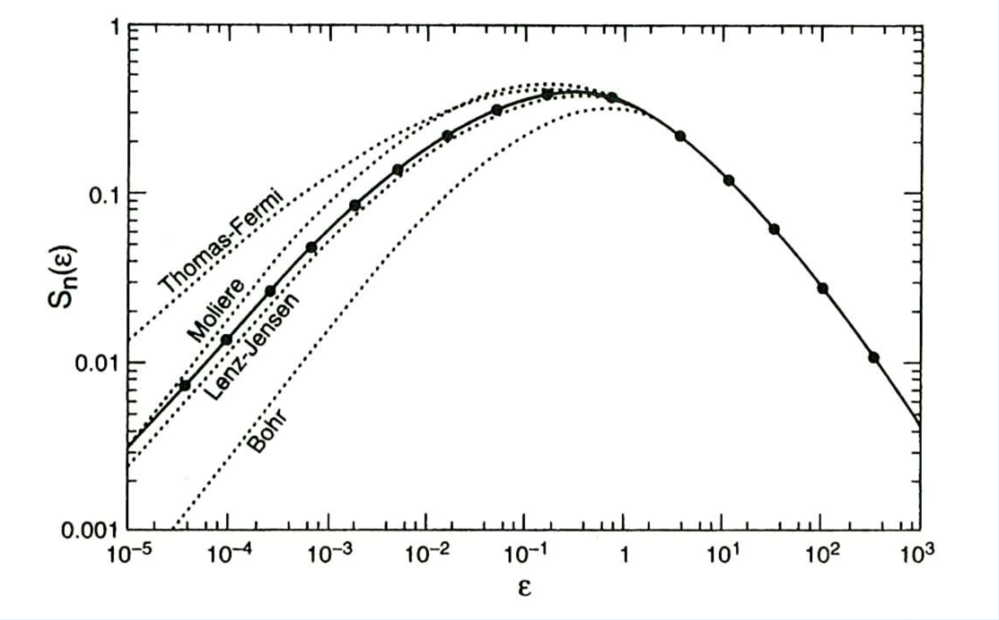
Potencial Universal ZBL

$$S_{nucl} = \frac{\ln(1+1.1383\varepsilon)}{2\left(\varepsilon + 0.01321\varepsilon^{0.261226} + 0.19593\varepsilon^{0.5}\right)}$$

para $\varepsilon \leq 30$

$$S_{nucl} = \frac{\ln(\varepsilon)}{2\varepsilon} \qquad \text{para} \quad \varepsilon > 30$$

$$com, \varepsilon = \frac{M_2 a}{(M_1 + M_2) Z_1 Z_2 e^2} \mathrm{E}$$



J. F. Ziegler, J.P. Biersack, U. Littmark, The Stopping and Range of Ions in Solids, Pergamon Press(1985)

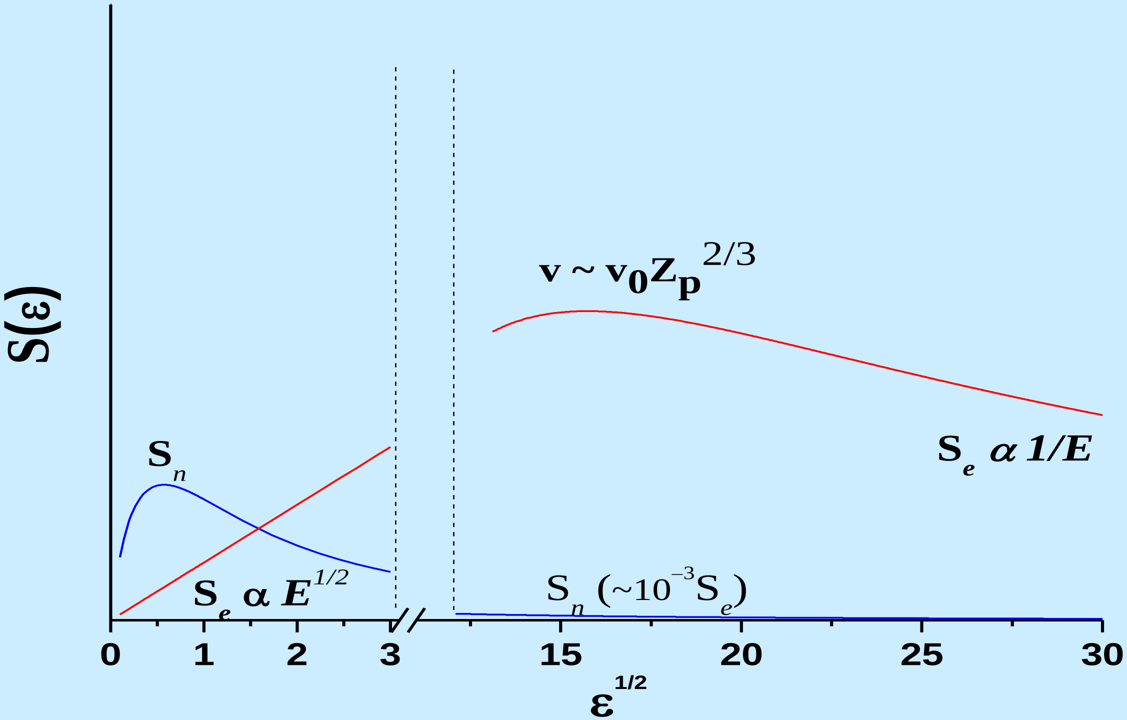
Electronic stopping cross section

Small energy losses: trajectory changes

$$S_e = k\sqrt{\varepsilon}$$ with $V < V_0 Z^{2/3}$

$$S_e(E) = \frac{4\pi Z_p^2 e^4 n_e}{N m_e v^2} ln \frac{2 m_e v^2}{I}$$

with $V > V_0 Z^{2/3}$



Energy vs. depth resolution

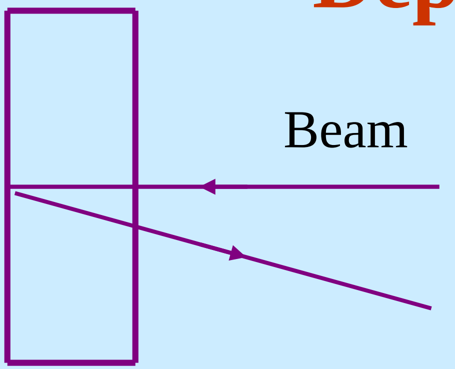
- $\Delta t = \Delta E / [S]$,

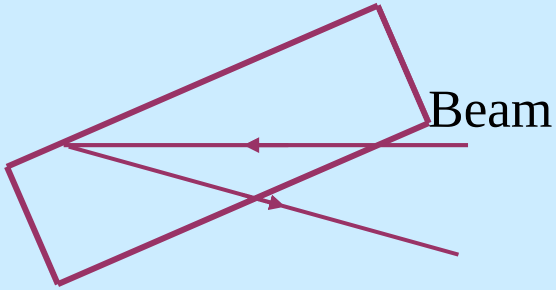
  where [S] is the effective stopping power, that is the effective energy loss per unit length, defined as

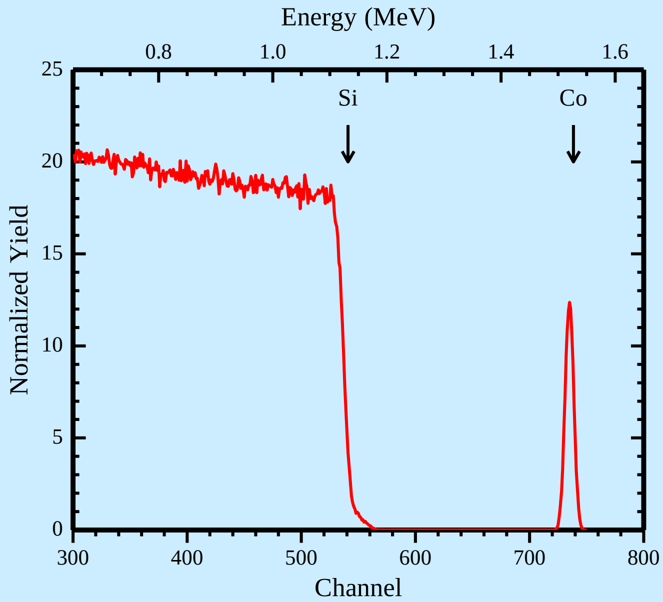
$$[S] = \left\{ K \cdot \left.\frac{dE}{dt}\right|_{E_0} + \left.\frac{dE}{dt}\right|_{E'_0} / \cos\phi_{scatt} \right\} / \cos(\alpha_{inc})$$

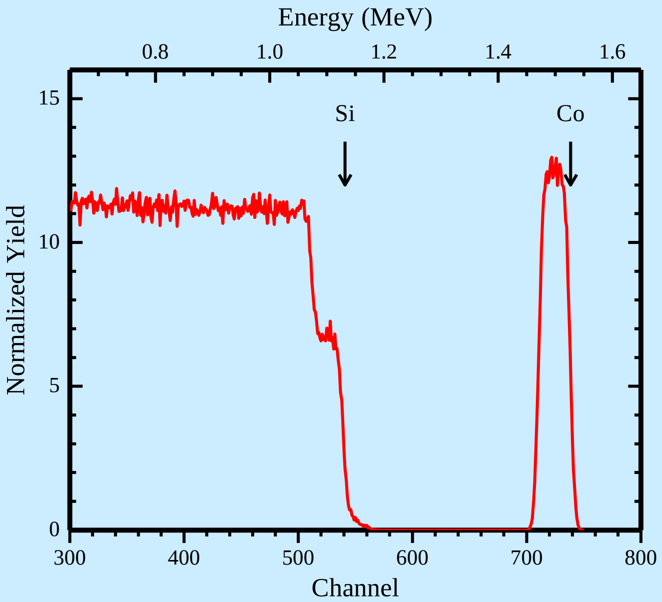
For a given energy resolution, the depth resolution is better for grazing angle of incidence.
(for the poor people limited to 15 keV Si SB detectors and He beams)

Depth resolution



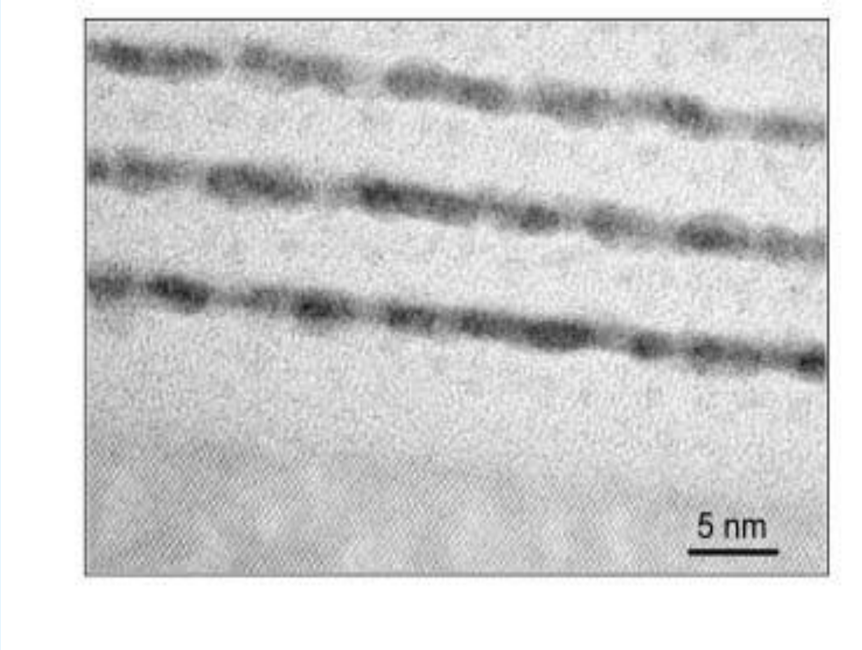


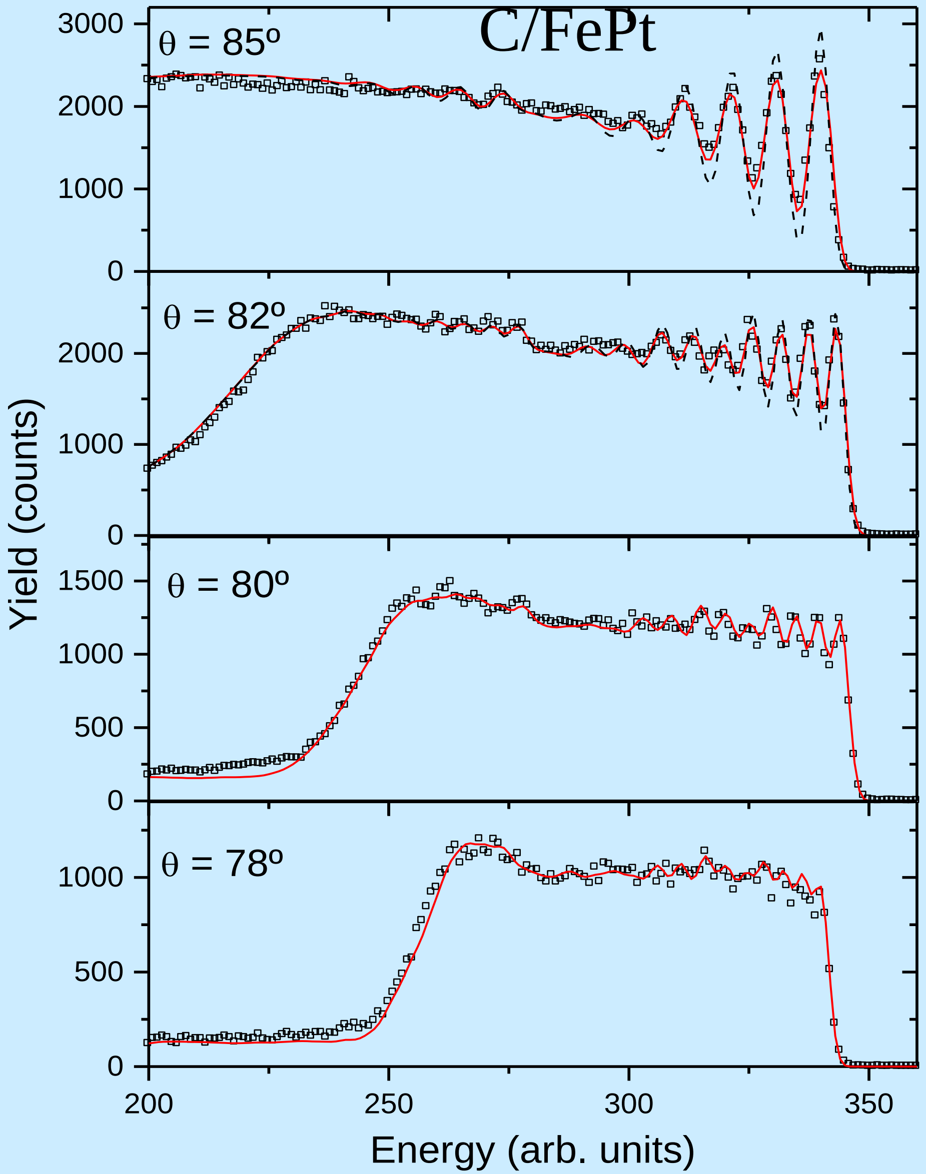




Limit : energy loss = detector resolution ≈ 15 keV ≈ 100 Å

High Resolution RBS vs TEM





We can say that:

- Analysis of simple spectra is straightforward and based on first principles Physics + stopping powers
- Almost all analysis is made with the aid of computer simulations
- Analysis of many real-life spectra requires capability of simulating Physics beyond single scattering of homogeneous-energy beams in flat layers
- This capability mostly exists

Literature:

Ion-Solid Interactions: Fundamentals and Applications
Michael Nastasi, James Mayer, James Hirvonen
Cambridge Solid State Sciences 2004

Backscatering Spectrometry
Wei_Kan Chu, James Mayer, Marc-A. Nicolet
Academic Press, 1978

Fundamentals of Surface and Thin Film Analysis
Leonard Feldman, James Mayer
Elsevier Science Publishing, 1986

Materials Characterization Using ion Beams
J. P. Thomas, A.Cachard, Plenum press 1976