PC 3242 Part II

Topic	Text Book (Zhen Cui '05)	Lectures
Optical lithography	Chapter 2	1, 2 & 3
Electron Beam Lithography	Chapter 3	4 & 5
Focused Ion Beam Technology	Chapter 4	
Low Energetic Ions (keV)		6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	8
RBS	Extra material provided	9
Light ions in lithography	Extra material provided	10
Etching	Chapter 7	10, 11
Nano Imprint Lithography	Chapter 6	12
3DP Three Dimensional Printing	Extra material provided	13

JA van Kan 2024

MeV Ions RBS

RUTHERFORD BACKSCATTERING SPECTROMETRY

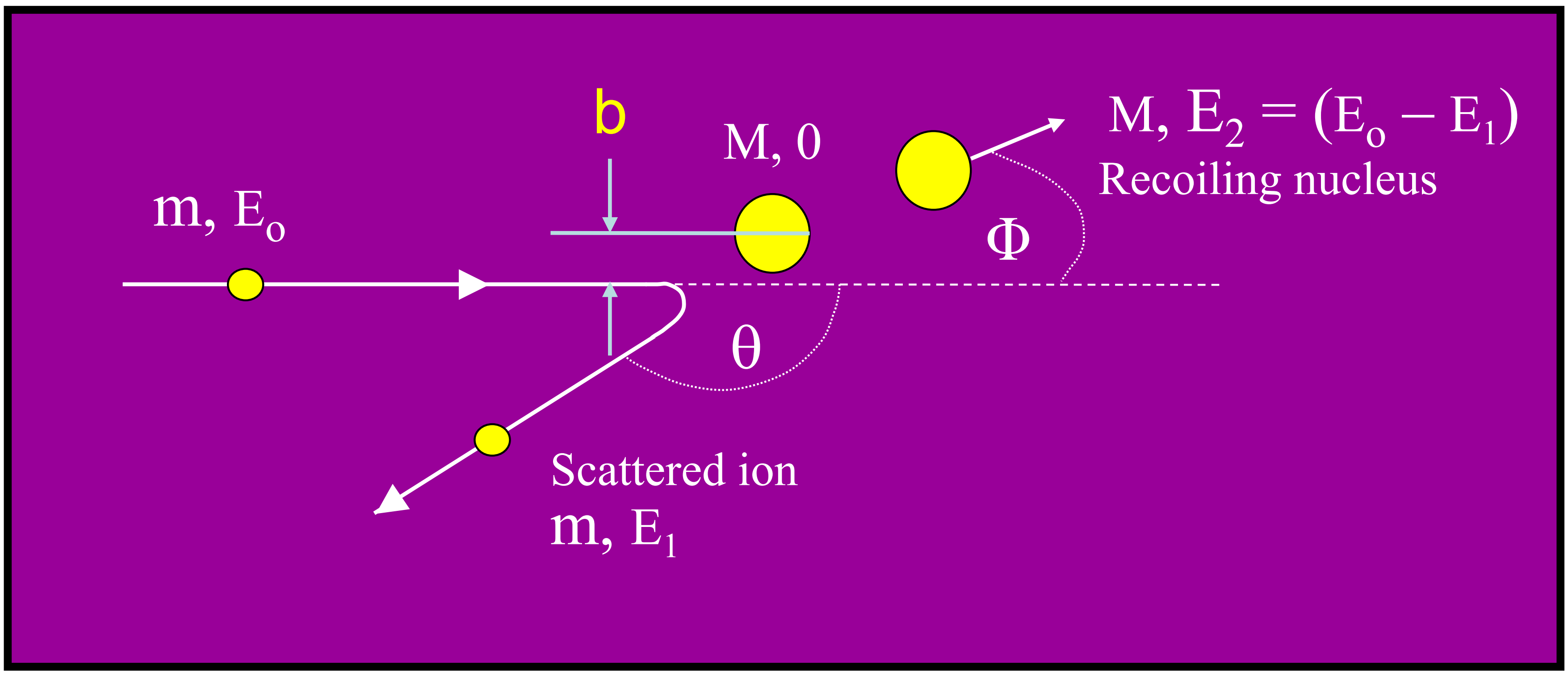
Basic Principles

MeV Ions RBS

ELASTIC COULOMB SCATTERING

	Charge	Mass	Initial Energy	Final Energy
Projectile	z	m	E_o	E_1
Target	Z	M	0	$E_2 = E_o - E_1$

The final energy E_1 of the incoming ion is a function of the angle of scatter θ from the initial direction, the ratio M/m and the impact parameter b.



K factor (laboratory frame of reference)

Conservation of energy and conservation of momentum parallel and perpendicular to the direction of incidence are expressed by the equations

$$\tfrac{1}{2}M_1 v_0{}^2 = \tfrac{1}{2}M_1 v_1{}^2 + \tfrac{1}{2}M_2 v_2{}^2, \quad \cos(180^\circ - \theta) \tag{2.1}$$

$$M_1 v_0 = M_1 v_1 \cos\theta + M_2 v_2 \cos\phi, \tag{2.2}$$

$$0 = M_1 v_1 \sin\theta - M_2 v_2 \sin\phi. \tag{2.3}$$

Eliminating ϕ first and then v_2, one finds

$$v_1/v_0 = [\pm(M_2{}^2 - M_1{}^2 \sin^2\theta)^{1/2} + M_1 \cos\theta]/(M_2 + M_1). \tag{2.4}$$

For $M_1 \le M_2$ the plus sign holds. We now define the ratio of the projectile energy after the elastic collision to that before the collision as the *kinematic factor K*,

$$K \equiv E_1/E_0. \tag{2.5}$$

From Eq. (2.4) one obtains

$$K_{M_2} = \left[\frac{(M_2{}^2 - M_1{}^2 \sin^2\theta)^{1/2} + M_1 \cos\theta}{M_2 + M_1}\right]^2 \longrightarrow \left|\frac{1/M_2}{1/M_2}\right|^2 \tag{2.6a}$$

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

Backscattering spectrometry
WK Chu 1978

MeV Ions RBS

KINEMATIC FACTOR

The **scattered** E_1 can be derived from the principles of **conservation of energy and momentum**, and is (in laboratory frame of reference):

$$E_1 = \left[\left(\frac{1}{1+\frac{M}{m}}\right) \times \left(\cos\theta + \sqrt{\left(\frac{M}{m}\right)^2 - \sin^2\theta}\right)\right]^2 E_o = kE_o$$

- The multiplication factor $k = E_1/E_0$ on the right-hand side of the equation is often referred to as the kinematic factor

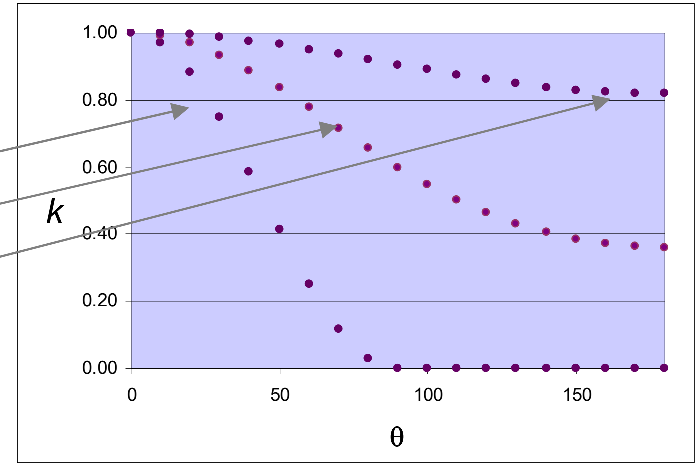
- For $M/m > 1$, k is a slow-varying function of θ,
- Maximum value of 1 at $\theta = 0$
- Minimum value at $\theta = 180^o$
- For $M/m = 1$, the value of k is zero beyond 90^o

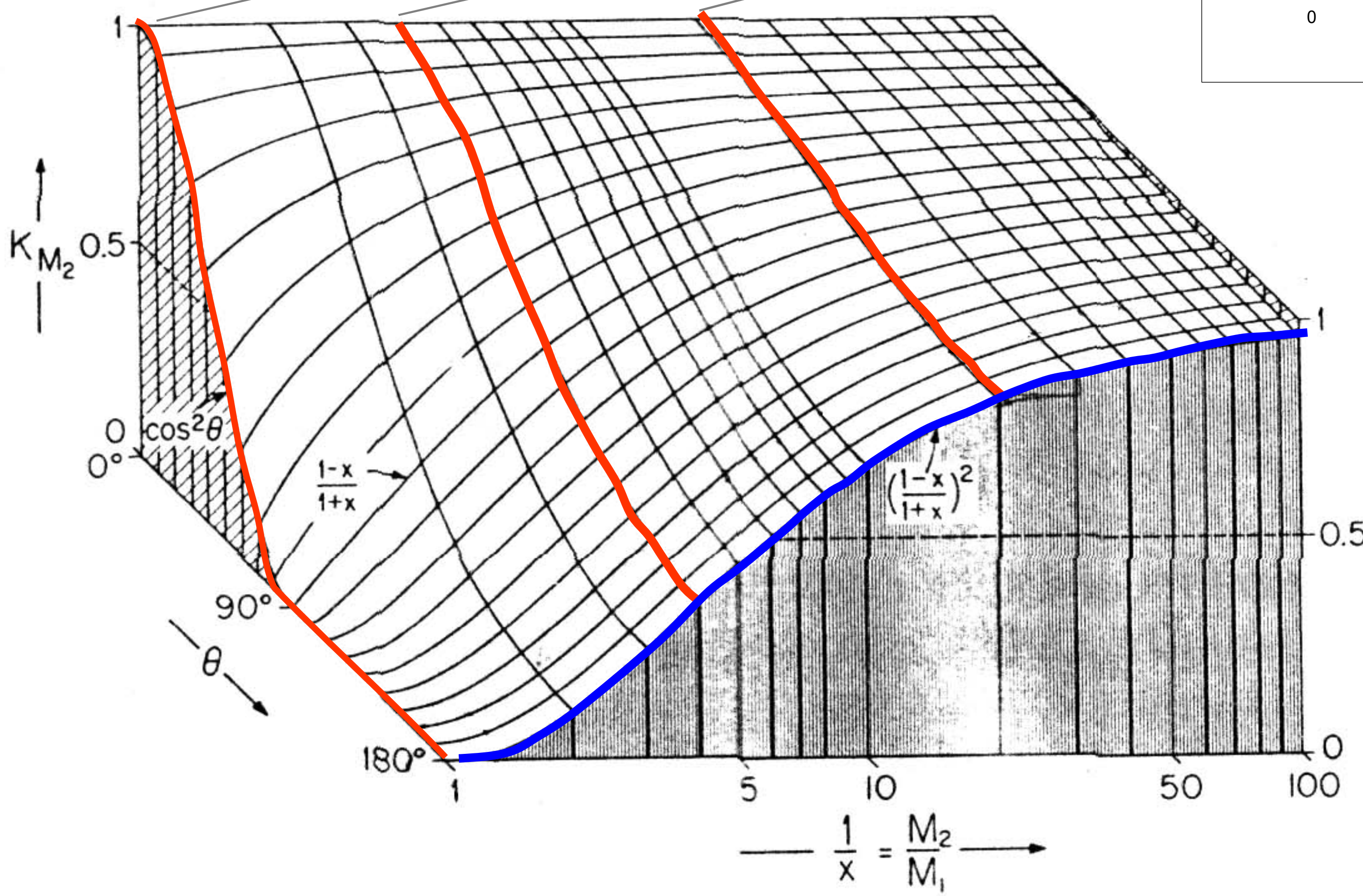
Now imagine you use an electron to hit a proton, what is the maximum E transfer?

Take M = p & m = e. At $\theta = 180^o$, k = 0.9978
For 2 MeV P $E_{e\text{-max}}$ ~4 keV (Compare SL 31 L7_8)

MeV Ions RBS

Plots of k vs θ for M/m = 1, 4, 20





The small gradient at large M/m ratios implies that mass separation is poor for higher M/m ratios.

Fig. 2.2 The kinematic factor K of Eq. (2.6b) plotted as a function of the scattering angle θ and the mass ratio $x^{-1} = M_2/M_1$.

MeV Ions RBS

Rutherford Scattering

1871-1937

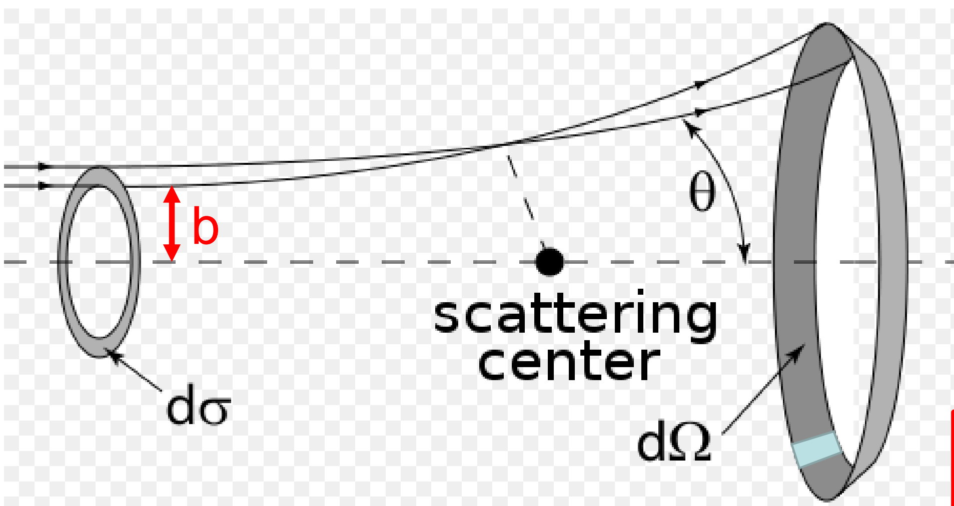
Differential scattering cross section

Repulsive scattering by a point particle.

As derived by Rutherford in 1911,
the differential scattering cross section:

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha\hbar c}{2mv_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

where α is the fine structure constant.



All particles that go through the ring on the left end up somewhere in the ring on the right.

Detector with
Solid angle Ω

$$\boxed{\frac{d\sigma}{d\Omega} = 1.296 \times \left(\frac{zZ}{E_o}\right)^2 \times \left[\sin^{-4}\frac{\theta}{2} - 2\left(\frac{m}{M}\right)^2 + \ldots\right]}$$

Approach when m<<M

The integral scattering cross section ∑:

$$\Sigma = \int_{\Omega} (d\sigma/d\Omega)\, d\Omega$$

Represents the number of scattering events detected in a solid angle Ω

MeV Ions RBS

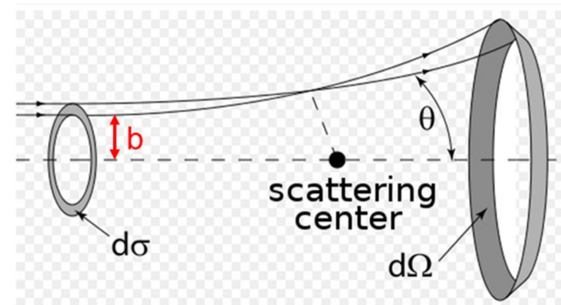
RBS YIELD FOR THIN TARGETS

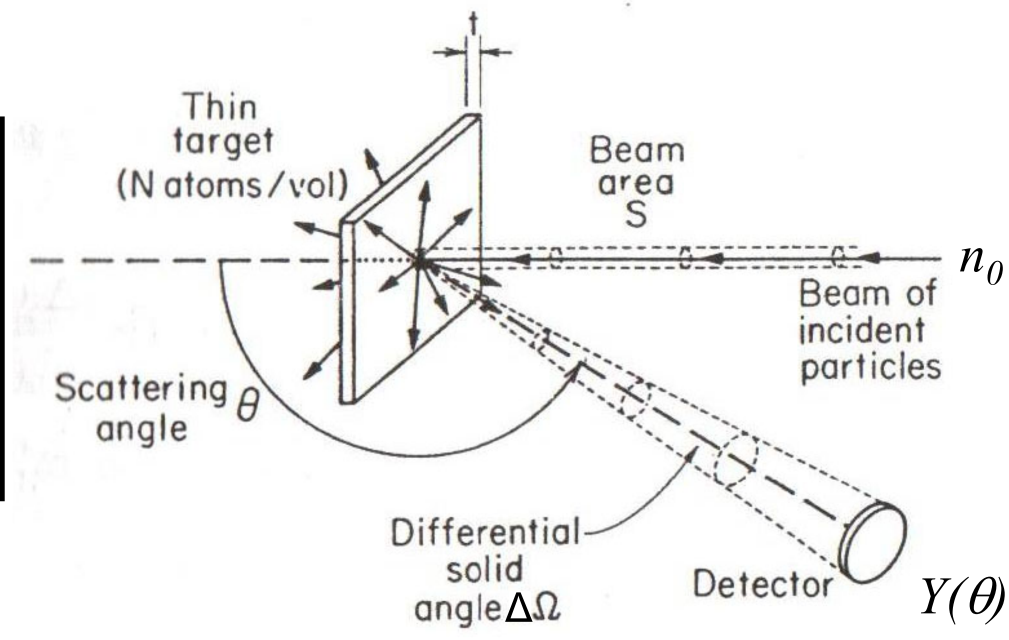
The number of backscattered ions detected by a particle detector at an angle of θ and subtending a solid angle ΔΩ at the target is called the yield. Its relation with the differential cross section is as follows for thin targets:

$$Y(\theta) = n_o n_z \frac{d\sigma}{d\Omega}\Delta\Omega \approx n_o n_z \sigma\Omega$$

⇧ Integrating over det. area

$$\sigma \equiv \frac{1}{\Omega}\int_\Omega \frac{d\sigma}{d\Omega} d\Omega$$





σ is the average differential cross section

n_o is the number of incident ions

$n_z = Nt$ (at/m^2) is the areal concentration of the target atom.

The simple relation is only valid for thin targets, namely targets which are so thin that the loss of energy by an incident proton in them is negligibly small as $\frac{d\sigma}{d\Omega}$ is a function of proton energy.

MeV Ions RBS

DIFFERENTIAL SCATTERING CROSS SECTION

The theoretical differential cross section for a given scattering angle is given by:

$$\boxed{\frac{d\sigma}{d\Omega} = \left(\frac{zZe^2}{4E_o}\right)^2 \times \left[\sin^{-4}\frac{\theta}{2} - 2\left(\frac{m}{M}\right)^2 + \ldots\ldots\ldots\ldots\right]}$$

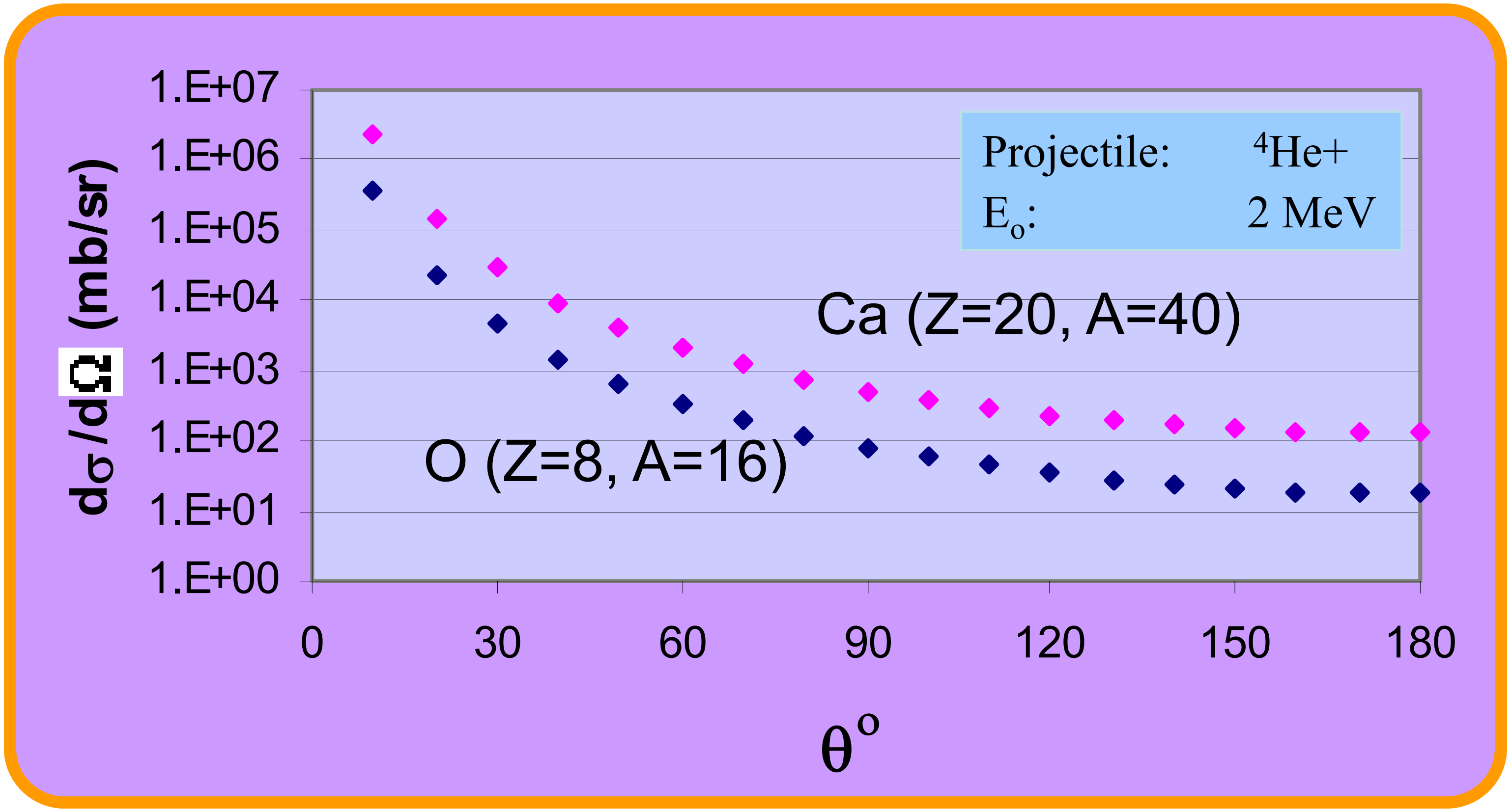
The higher order terms are usually negligible for M>m and the differential cross section can be expressed in the following form, which has the unit of mb/sr (millibarns per steradian) when MeV is used as the unit for E_o:

$$\boxed{\frac{d\sigma}{d\Omega} = 1.296 \times \left(\frac{zZ}{E_o}\right)^2 \times \left[\sin^{-4}\frac{\theta}{2} - 2\left(\frac{m}{M}\right)^2\right]}$$

MeV Ions RBS

$d\sigma/d\Omega$ versus θ

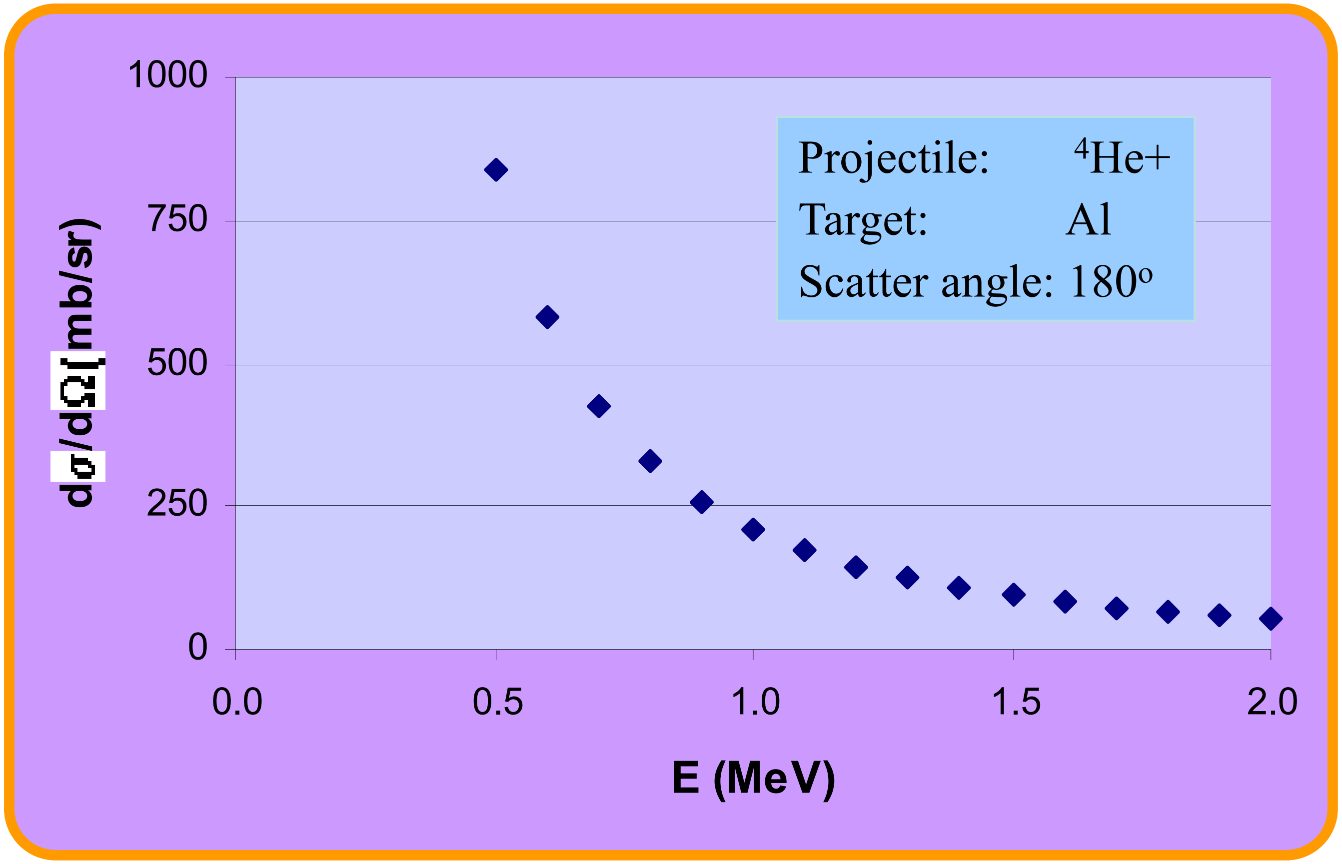
The dependence of $d\sigma/d\Omega$ on $\sin^{-4}(\theta/2)$ means that $d\sigma/d\Omega$ has very large values at small forward scattered angles and approaches infinity at 0^o. However, for $\theta = 90^o$ to 180^o, it decreases rather slowly because $\sin^{-4}(\theta/2)$ drops gradually from a value of 4 at 90^o to 1 at 180^o. The diagram below shows the plots of $d\sigma/d\Omega$ vs θ for the Coulomb scattering of 2 MeV $^4He^+$ ions for oxygen and calcium.



MeV Ions RBS

dσ/dΩ versus E_o

dσ/dΩ is inversely proportional to the square of the incident ion energy E_o, implying that it increases with decreasing E_o. This also means that for a thick target, more ions are scattered from a greater depth. The diagram below show a plot of dσ/dΩ vs E_o for the scattering of $^4He+$ from an aluminum target at θ = 180°.

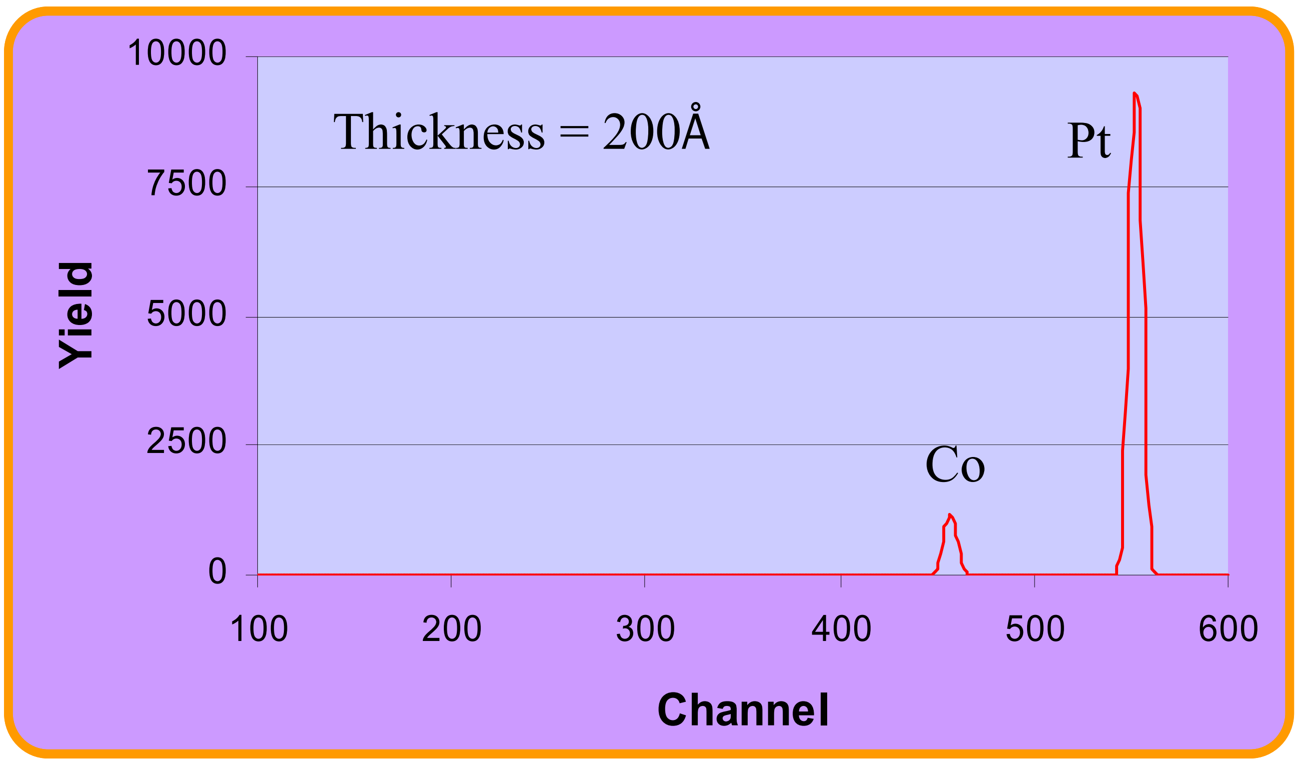


MeV Ions RBS

RBS SPECTRUM OF A THIN Pt-Co ALLOY TARGET

The diagram below shows a simulated RBS spectrum at $\theta = 160^o$
$t = 20.0$ nm (Pt-Co ratio 1:1); E_{loss} can be neglected (use SRIM to calculate).
2 MeV $^4He+$ incident ions.
The width of the Pt and the Co peaks is essentially attributable to the intrinsic resolution of the detector plus the electronic noise.

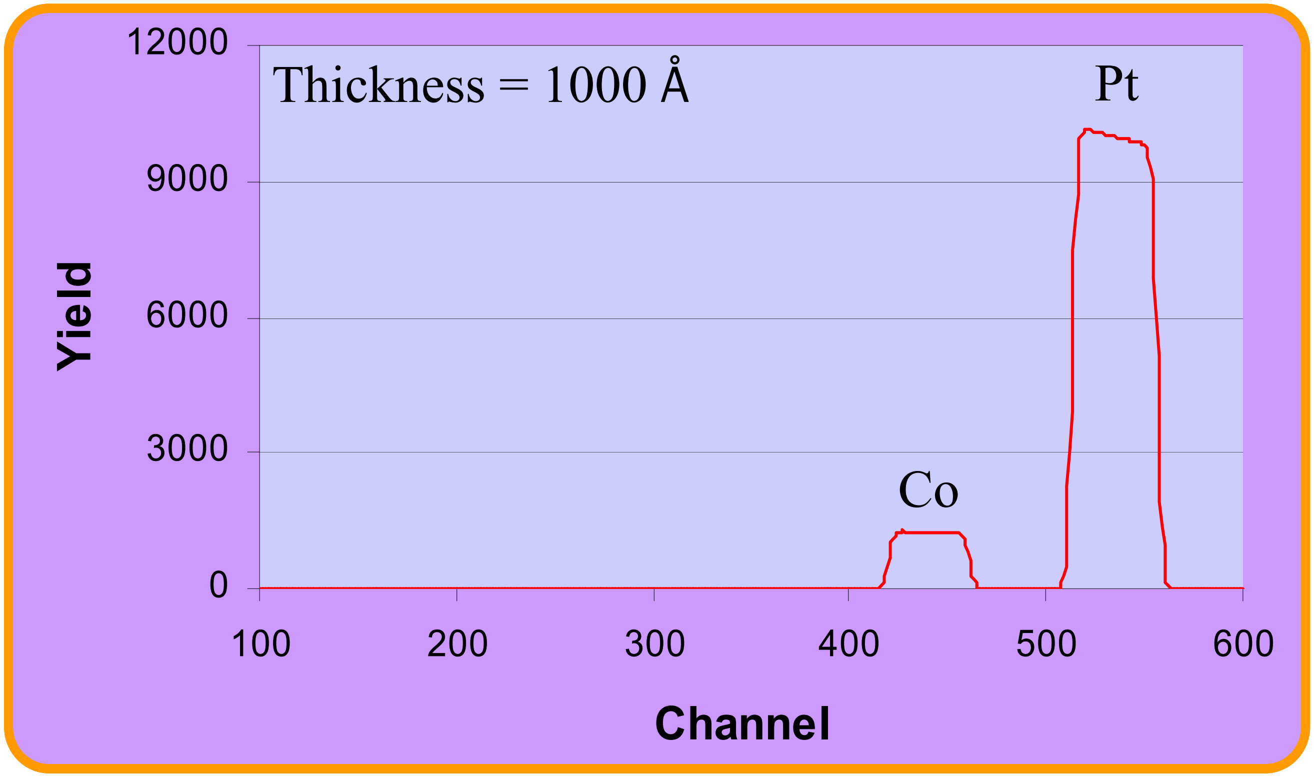
The Pt peak is much higher than the Co peak. Why?



MeV Ions RBS

EFFECT OF TARGET THICKNESS

If the thickness of the Pt-Co target is increased, the peaks would be broadened due to the loss of energy by the $^4He+$ ions in the target through the ionization process. The following simulated RBS spectrum depicts the effect for the case where the Pt-Co alloy thickness is 1000Å = 100 nm.

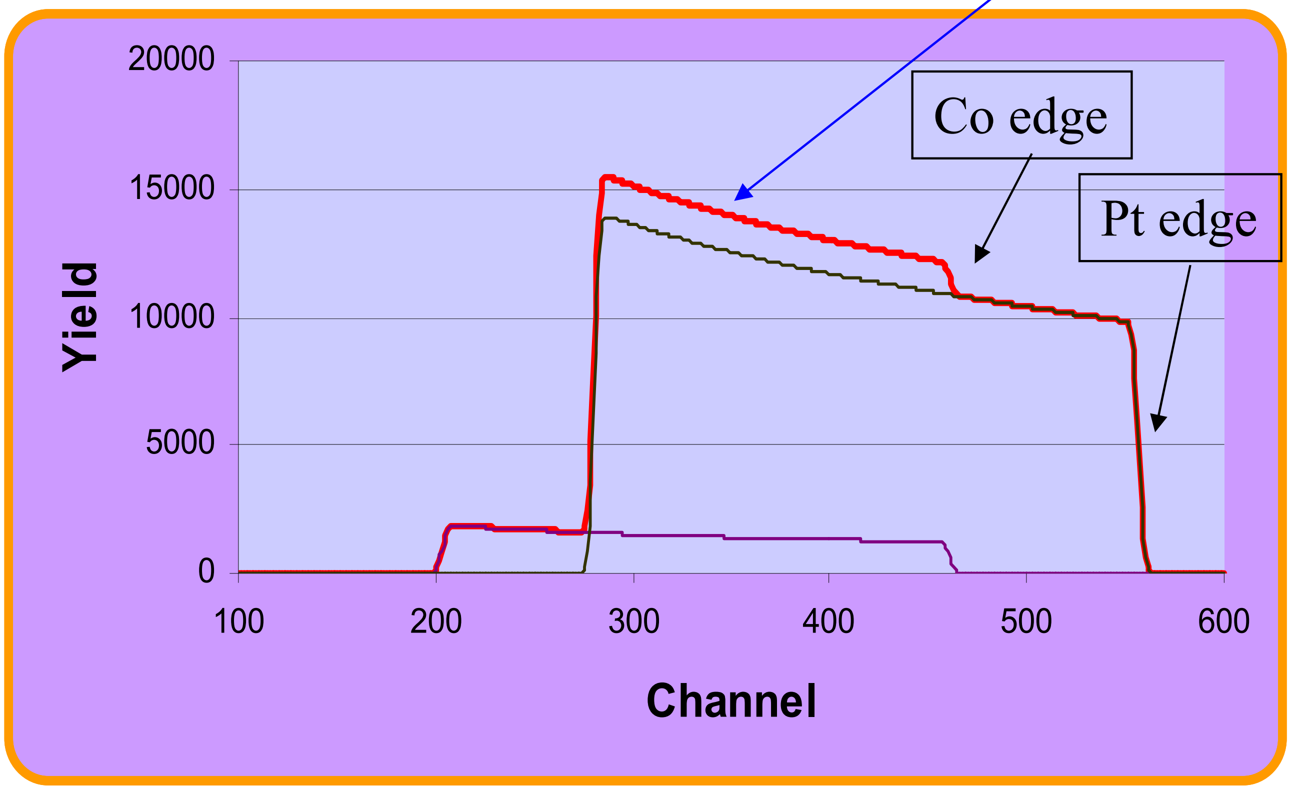


MeV Ions RBS

SIMULATED RBS SPECTRUM

Target : Pt-Co (1:1) alloy of thickness 6000Å = 600 nm.
Incident ion: 2 MeV $^{4}He^{+}$
Scatter angle: 160^{o}

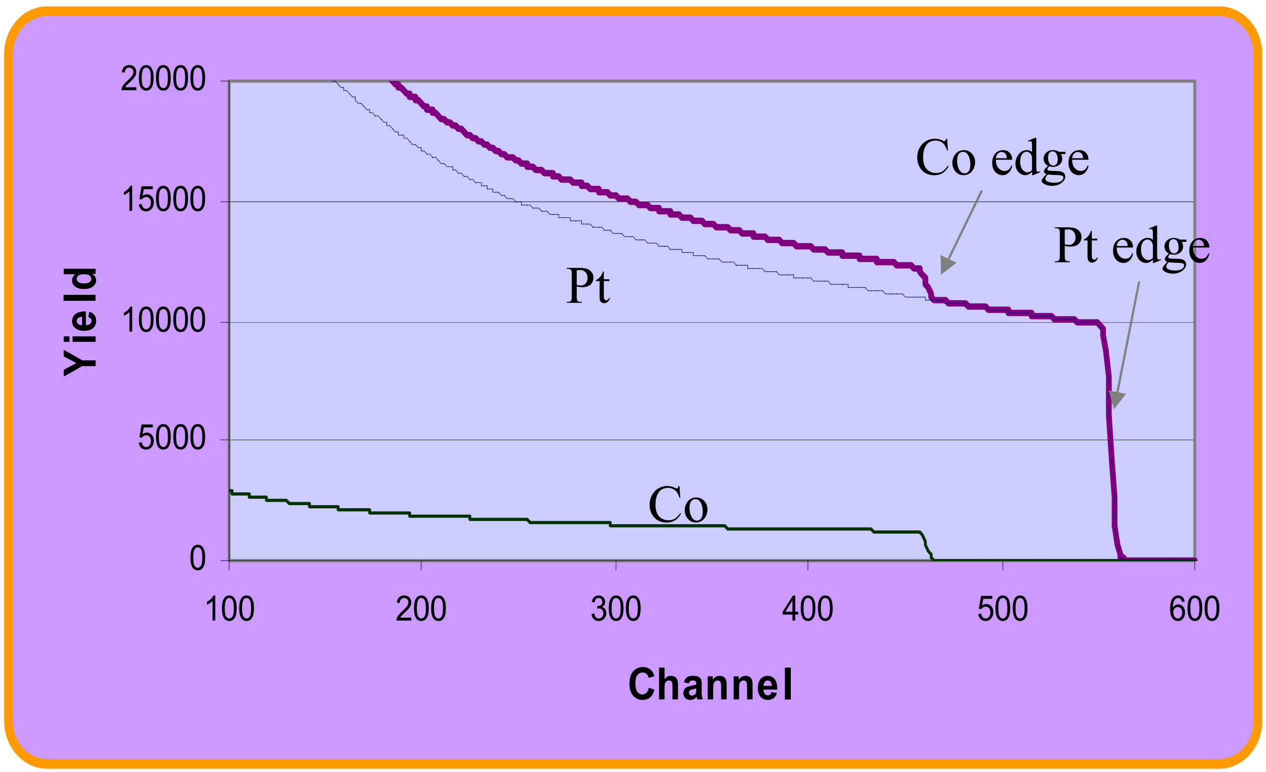
What is causing the signal to increase deeper into the sample?



MeV Ions RBS

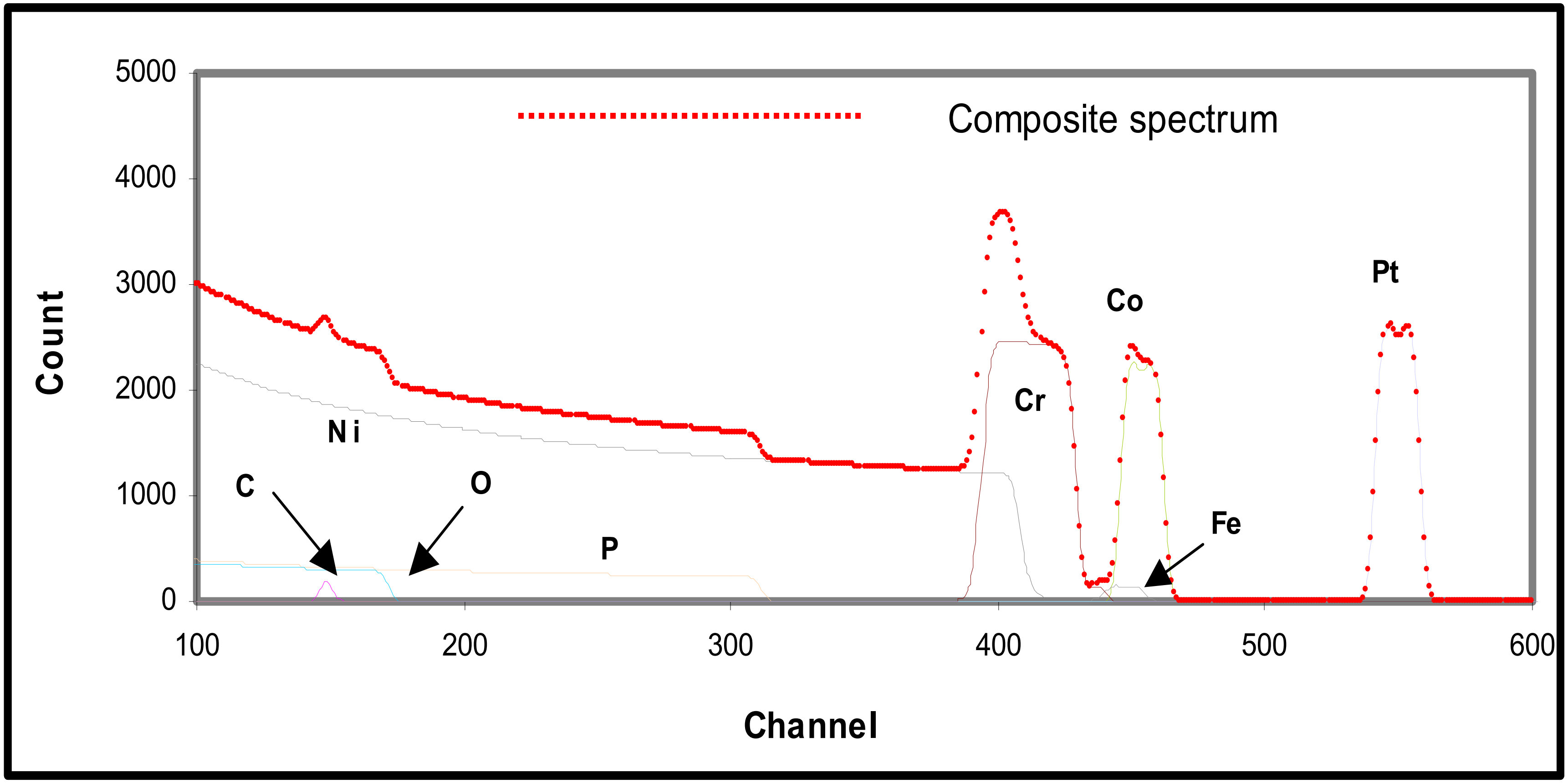
SIMULATED RBS SPECTRUM

Target : Pt-Co (1:1) alloy of thickness 12000Å = 1200 nm.
Incident ion: 2 MeV $^4He^+$
Scatter angle: 160^o



MeV Ions RBS

Example : RBS spectrum of hard-disk



Layer structure:

Protective polymeric material	(~200Å)
Co-Pt-Fe alloy	(~200Å)
Cr	(~10Å)
Co-Pt.Fe alloy	(~200Å)
Cr	(~1000Å)
$Ni_3(PO_4)_2$	(~100,000Å)
Al substrate	

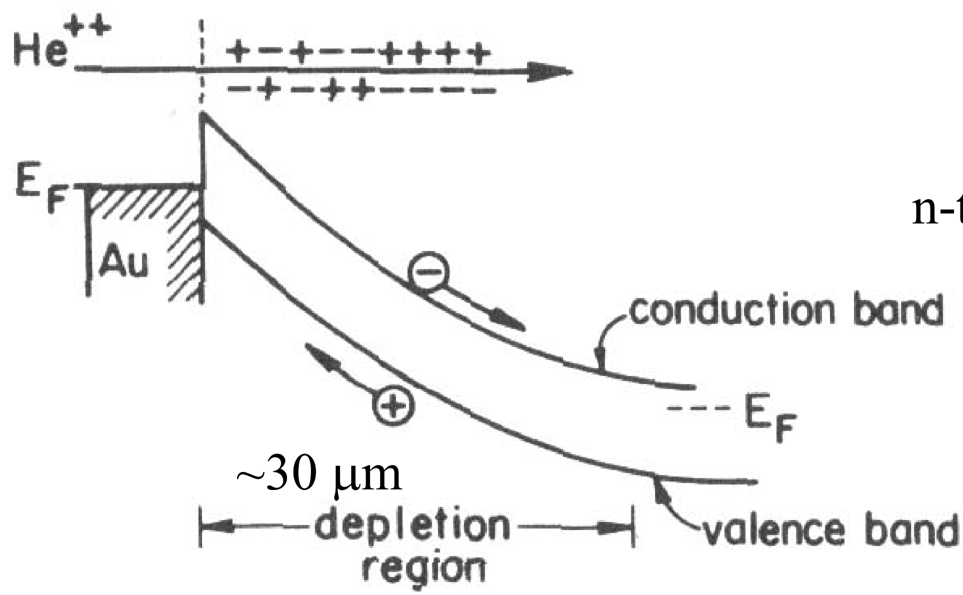
We will simulate this type of spectra in the tutorial

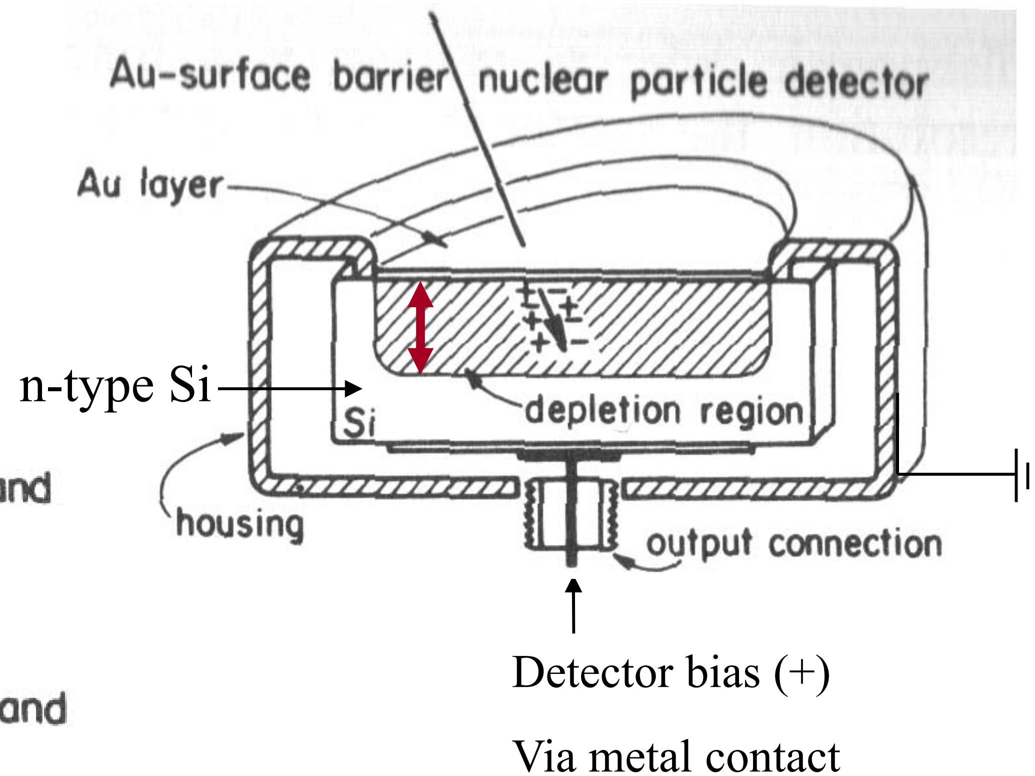
MeV Ions RBS

SURFACE-BARRIER DETECTOR – STRUCTURE

The surface-barrier detector is a charged-particle detector fabricated using high-purity n-type silicon wafer. One side of the wafer is chemically etched and a p layer is allowed to form by spontaneous oxidation. Contact to this layer is made by the evaporation of a thin gold layer.

When a bias voltage is applied in the reverse direction, a high-resistance depletion (or active) region is formed in the p-n junction. Electron-hole pairs produced by a charged-particle in this region give rise to an output signal with an amplitude proportional the kinetic energy of the incident charged-particle.





MeV Ions RBS DAQ

ELECTRONIC COMPONENTS FOR IBA SIGNAL PROCESSING:

- DETECTOR BIAS → X-RAY or PARTICLE DETECTOR
- X-RAY or PARTICLE DETECTOR → PRE-AMPLIFIER → MAIN AMPLIFIER → ANALOG-DIGITAL CONVERTER → COMPUTER
- FARADAY CUP → CHARGE DIGITIZER → COMPUTER

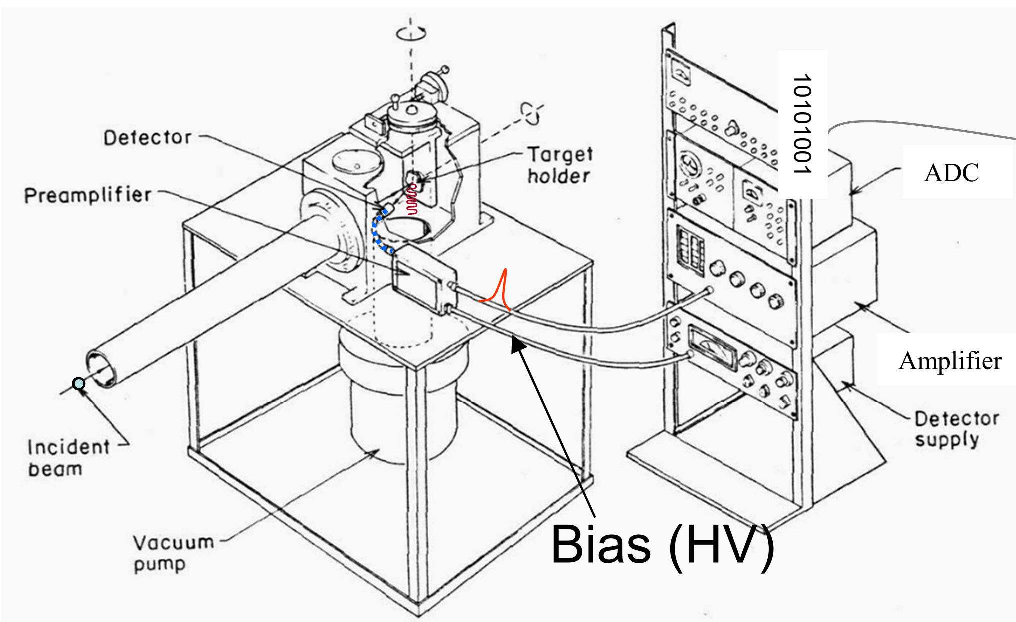
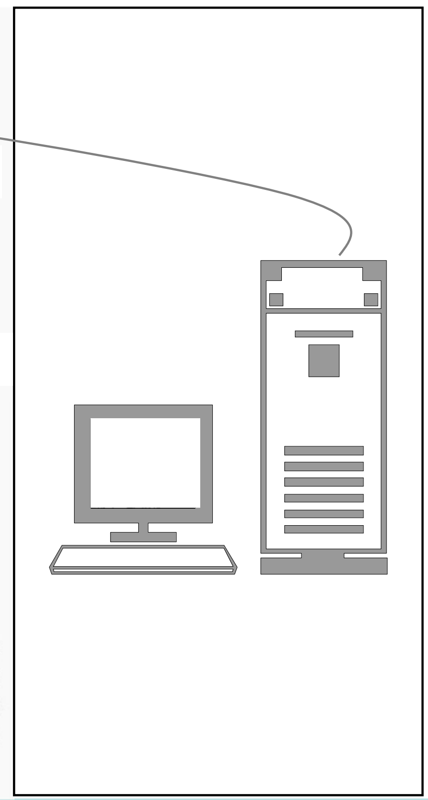


Fig. 1.5 Layout of the target chamber and electronics of a backscattering system. The ions impinge on the target in the vacuum chamber. Backscattered particles are analyzed by the detector, and the detector signal is magnified and reshaped in the preamplifier. The electronic equipment in the rack provides power to the detector and preamplifier and stores the data generated by the detector in the form of the backscattering spectra.



Multiple detector can be used simultaneously

DAQ: Data Acquisition