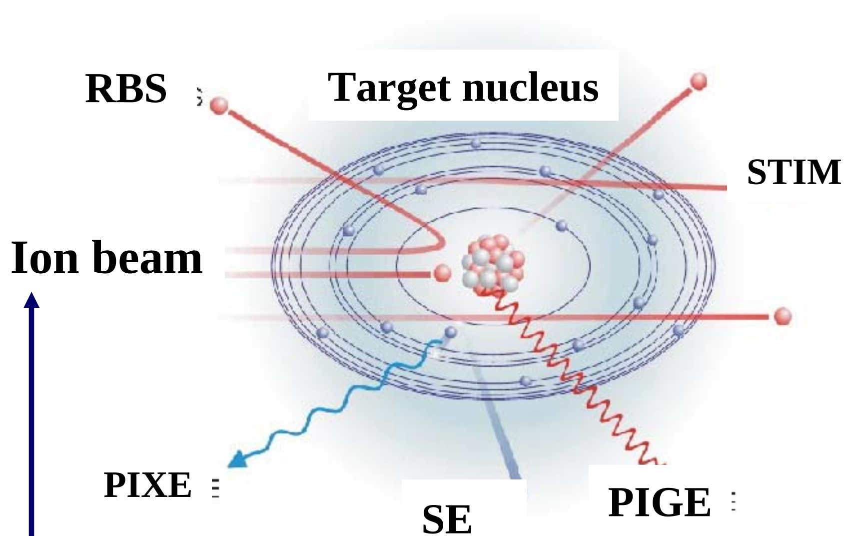
Ion-beam techniques



Electrostatic Accelerators

Van de Graaff accelerator
Pelletron
Tandem Van de Graaff

RBS: Rutherford backscattering
ERD: Elastic recoil detection
PIXE: Particle induced x-ray emission
PIGE: Particle induced gamma emission
NRA: Nuclear reaction analysis
STIM: Scanning Transm. Ion Microscopy
SE: Secondary emission
CH: Channeling

TECHNIQUE	ION BEAM	ENERGY (MeV)
PIXE	H^+	1 - 4
RBS	$^4He^+$, H^+	≤ 2
ERD	$^{35}Cl+$, $^{20}Ne+$ $^3He+$, $^4He+$	2 - 40
NRA	H+, D+	0.4 - 3

Some literature on ion beam analysis

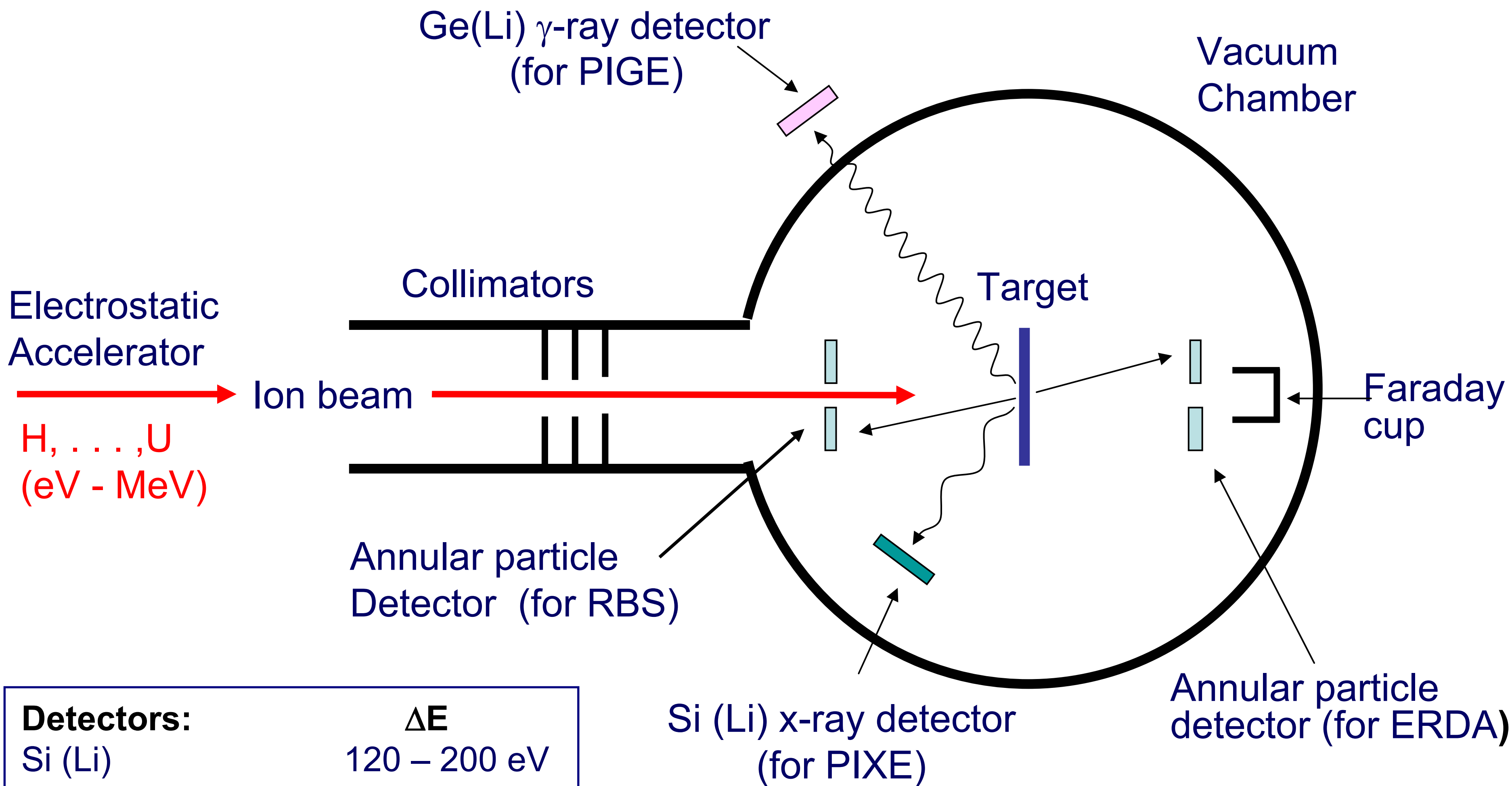
PIXE: A Novel Technique for Elemental Analysis
Sven A. E. Johansson and John L. Campbell
Publisher: John Wiley & Sons, 1988

Materials Analysis using a Nuclear Microprobe
M B H Breese, D N Jamieson and P J C King
Publisher: John Wiley & Sons, 1996

Handbook of Modern Ion Beam Materials Analysis
Edited by Joseph R. Tesmer and Michael Nastasi
Publisher: Materials Research Society, Pittsburgh, Pa., 1995

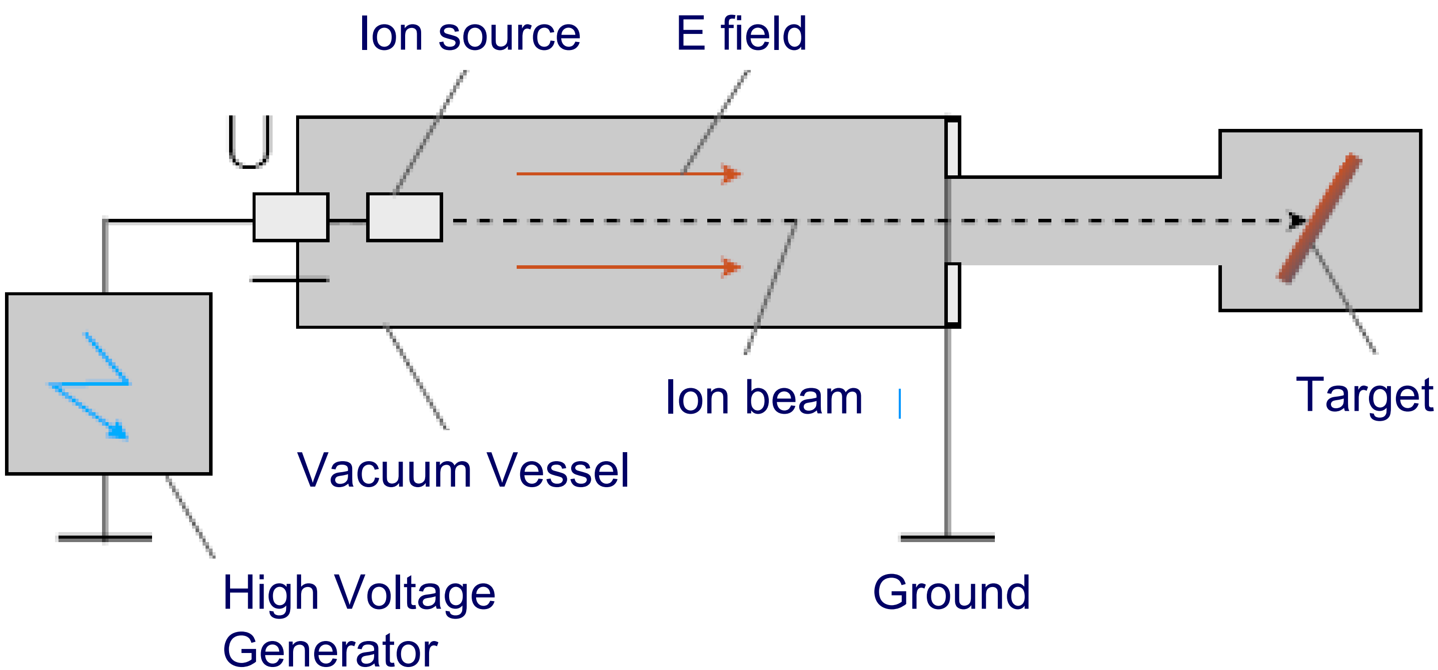
Handbook of X-Ray Spectrometry
Edited by Rene E. Van Grieken and Andrzej A. Markowicz Publisher: Marcel Dekker, Inc., 2nd Edition, 2002

Experimental Setup for Ion Beam Analysis



Detectors:	**ΔE**
Si (Li)	120 – 200 eV
Ge (high purity)	120 – 600 eV
Si (drift chamber)	150 – 200 eV
Crystal spectrometer	1 eV

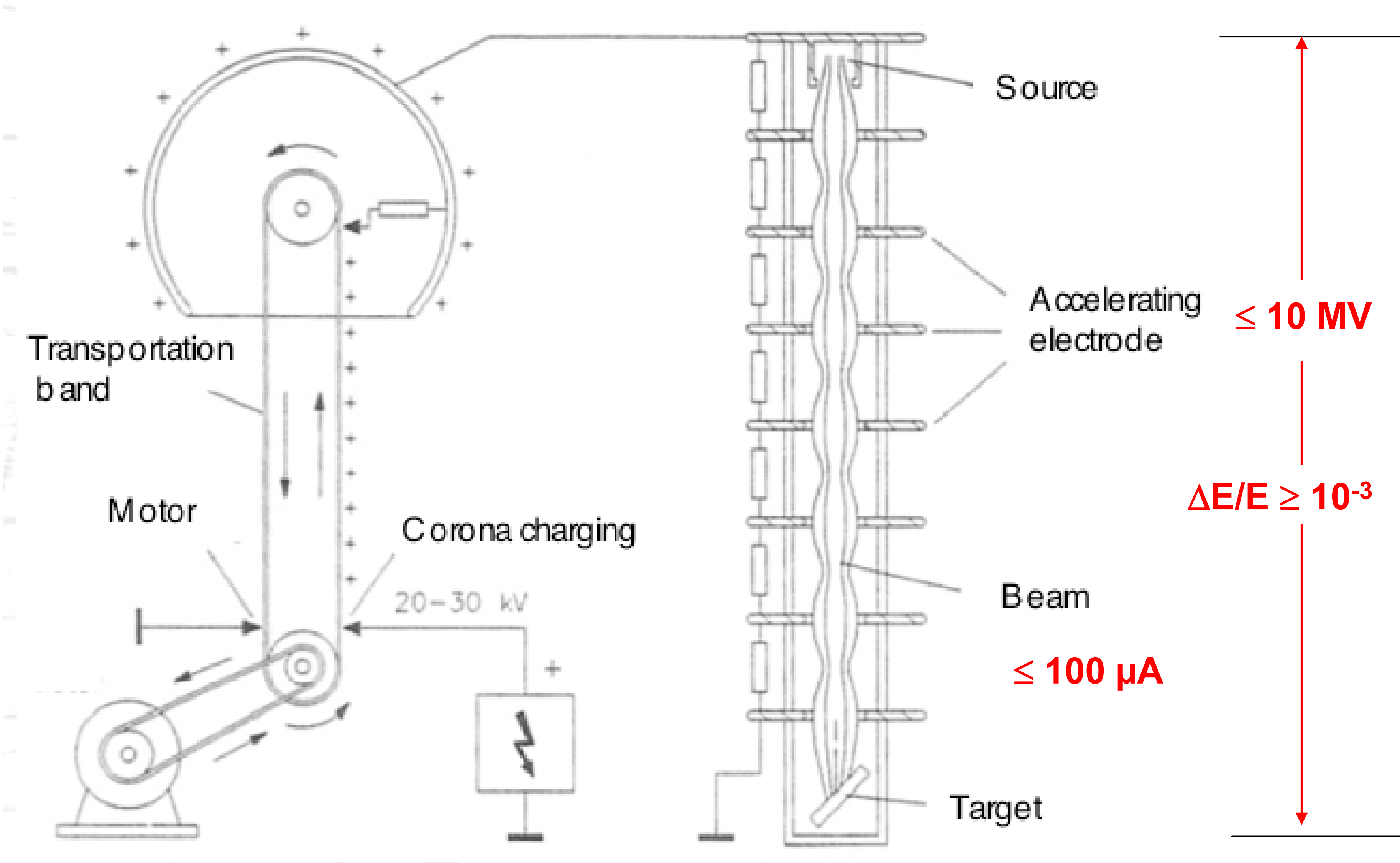
Electrostatic Accelerator



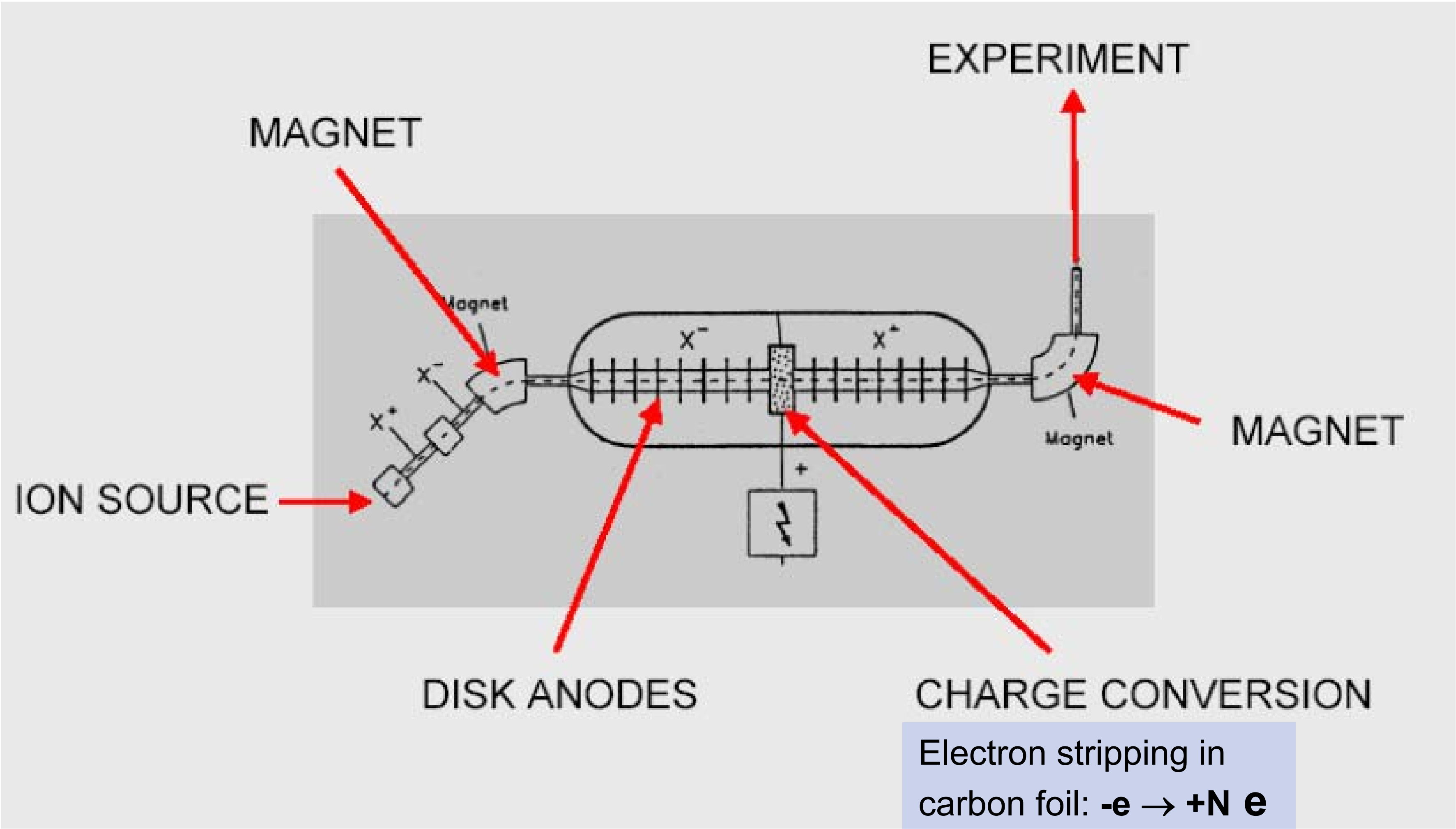
Kinetic particle energy: E_{kin} = q U = Ze U

Van de Graaff: U ≤ 10 MV
Tandem: U ≤ 20 MV
Tandem Pelletron: U ≤ 30 MV

Van de Graaff accelerator

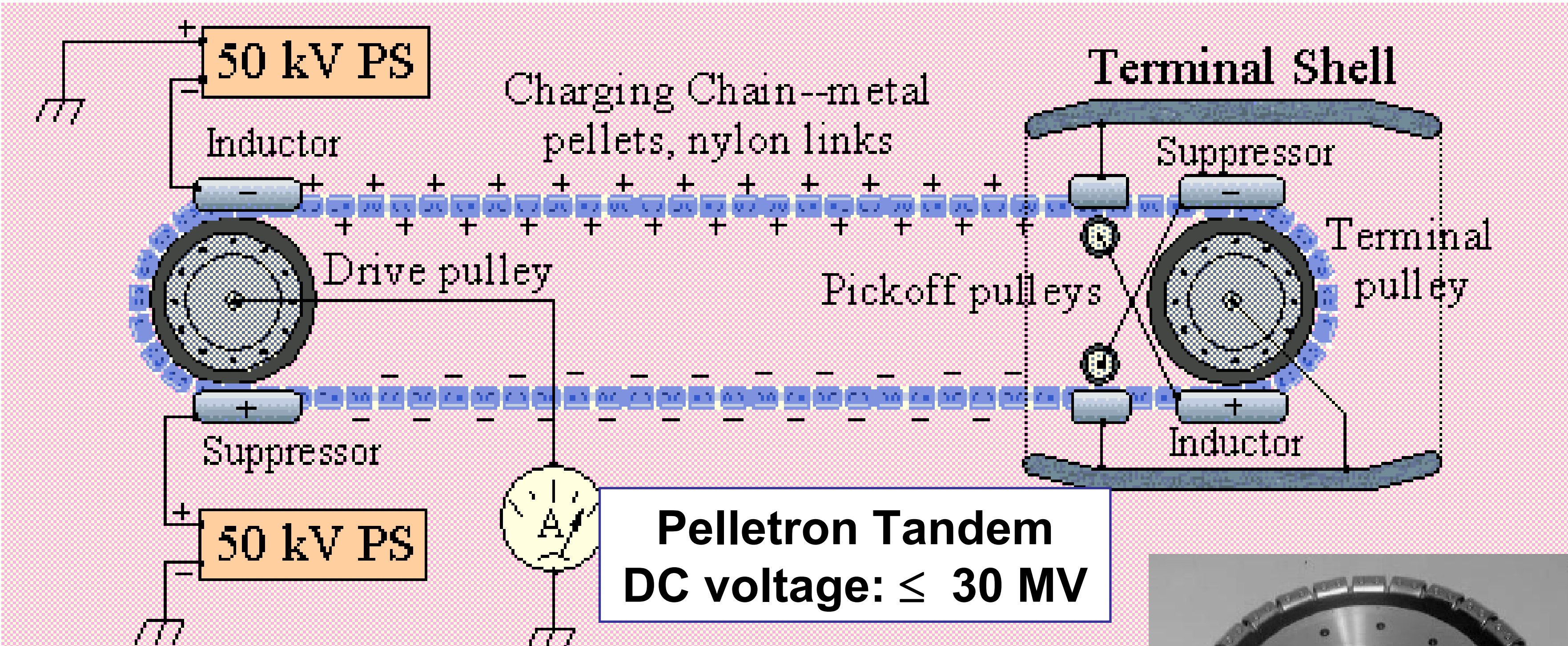


Tandem van de Graaff accelerator



Electron stripping in carbon foil: **-e → +N e**

Pelletron charging system



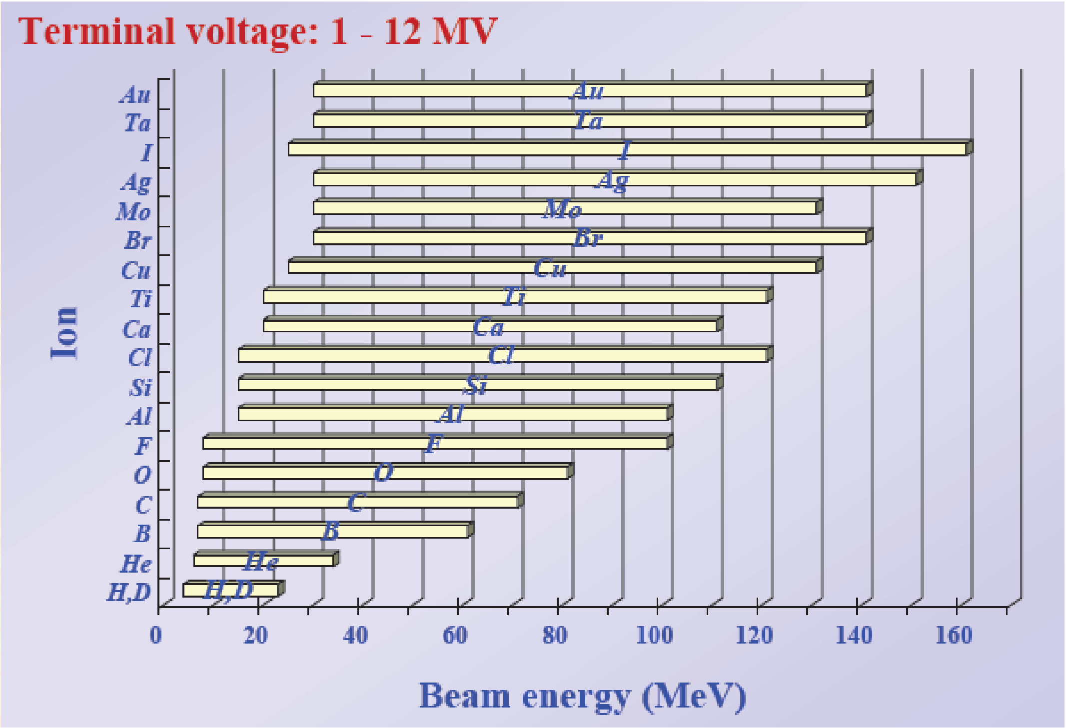
Pelletron Tandem
DC voltage: $\leq$ 30 MV

Pelletron

Rubber belt is replaced by a chain of short conductive rods connected by insulating links.
Can be operated at much higher velocity than a belt, so both the voltage and currents attainable are higher than a conventional Van de Graaff machine.

USP
8UD Pelletron
tandem accelerator

Beam energies available at
Tsukuba 12UD Pelletron tandem

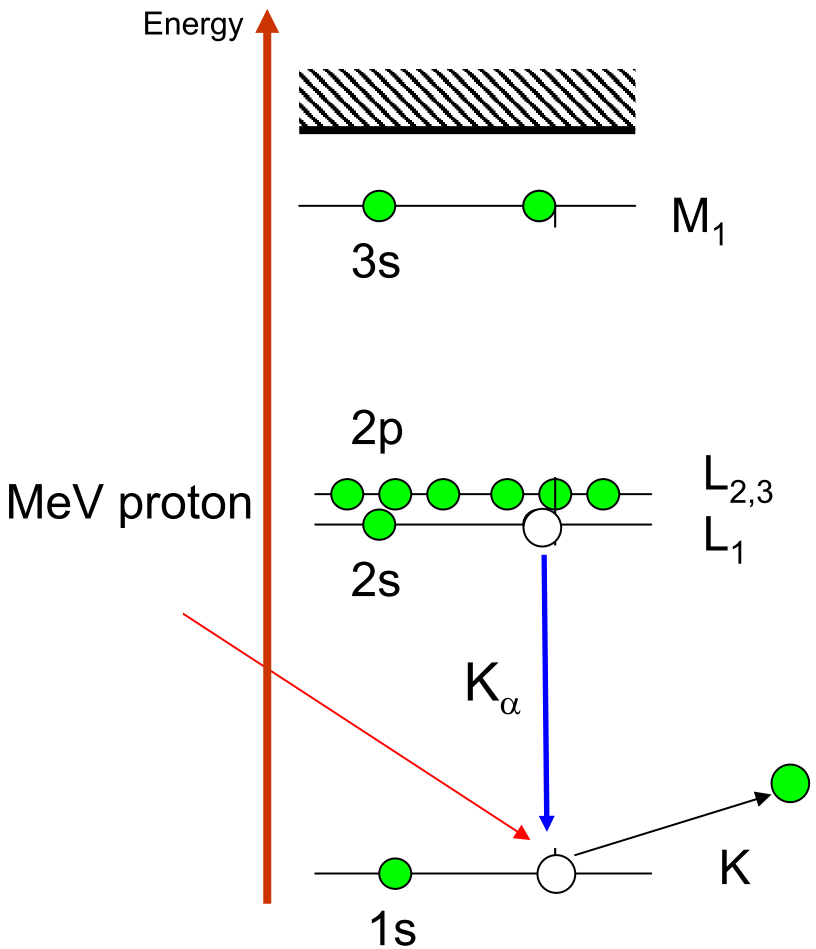


TYPICAL ION BEAMS AND INCIDENT ENERGIES USED IN VARIOUS ION BEAM TECHNIQUES

TECHNIQUE	ION BEAM	ENERGY (MeV)	REMARK
PIXE	H^+	1 - 4	Maximum sensitivity in atomic ranges 10<Z<35 and 75<Z<85
RBS	$^4He^+$, H^+	≤ 2	Non-Rutherford scattering becomes significant for energy >2 MeV
ERDA	$^{35}Cl+$, $^{20}Ne+$ $^3He+$, $^4He+$	2 - 40	Mass of incident ion must be greater than that of target nucleus. $^3He+$ and $^4He+$ are used only for the measurement of H.
NRA	H+, D+	0.4 - 3	Reactions used include (p,g) (p,p'g), (p,ag), (d,p), (d,pg)

Proton Induced X-ray Emission = PIXE

Lund Institute of Technology - 1970



Bohr:

$$E_n = -\frac{me^4}{8\varepsilon_0^2 h^2}\frac{Z^2}{n^2} = -\frac{e^2}{8\pi\varepsilon_0}\frac{1}{a_0}\frac{Z^2}{n^2} \approx -13{,}6\frac{Z^2}{n^2}\,\mathrm{eV}.$$

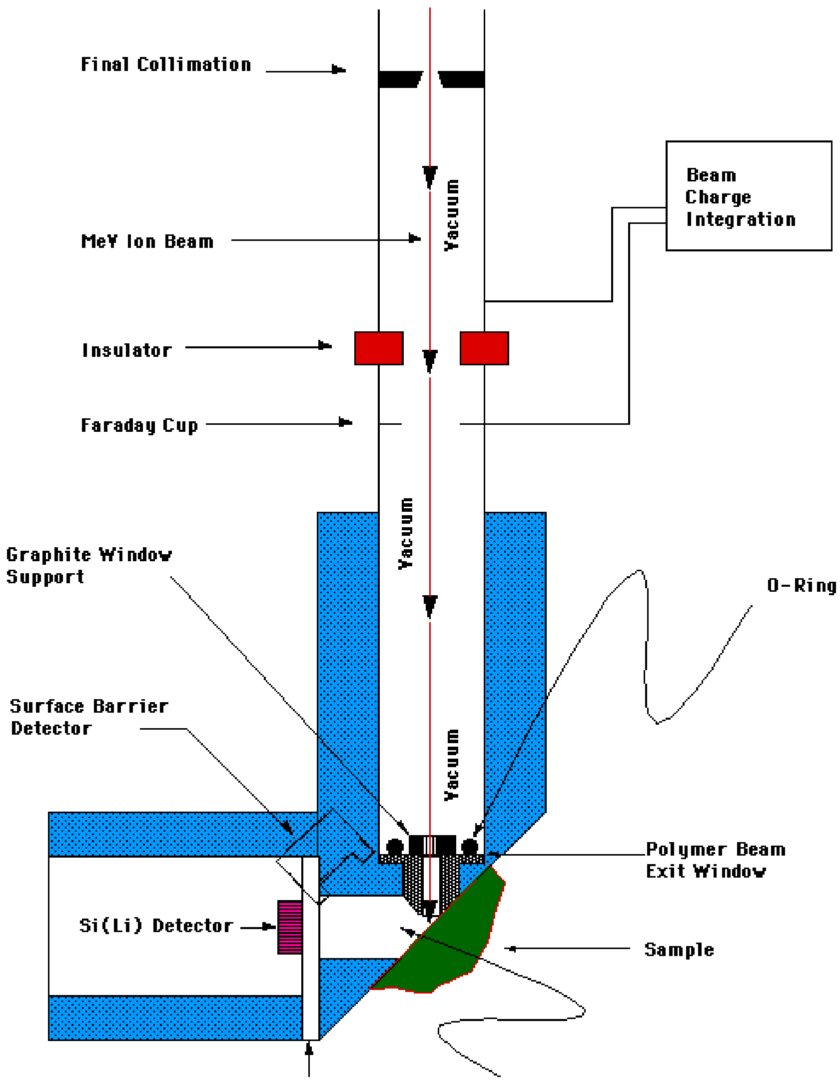
$$\Delta E = E_{n_2} - E_{n_1} = \frac{me^4 Z^2}{8\varepsilon_0^2 h^2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right),$$

K_α-line

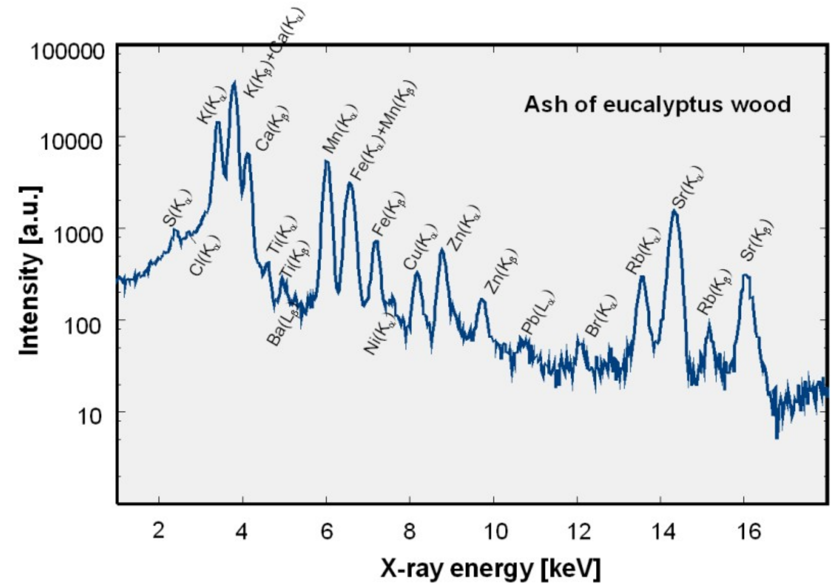
$$h\nu = (2.48 * 10^{15}\ \mathrm{Hz})(Z-1)^2$$

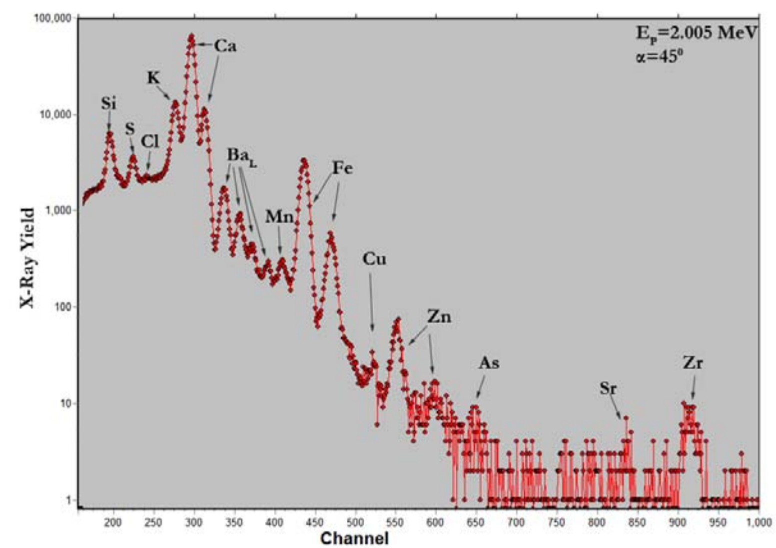
Z		E(Kα) (keV)
8	O	0.5249
20	Ca	3.69168
40	Zr	15.7751
70	Yb	52.3889
92	U	98.439

PIXE System (Harvard)

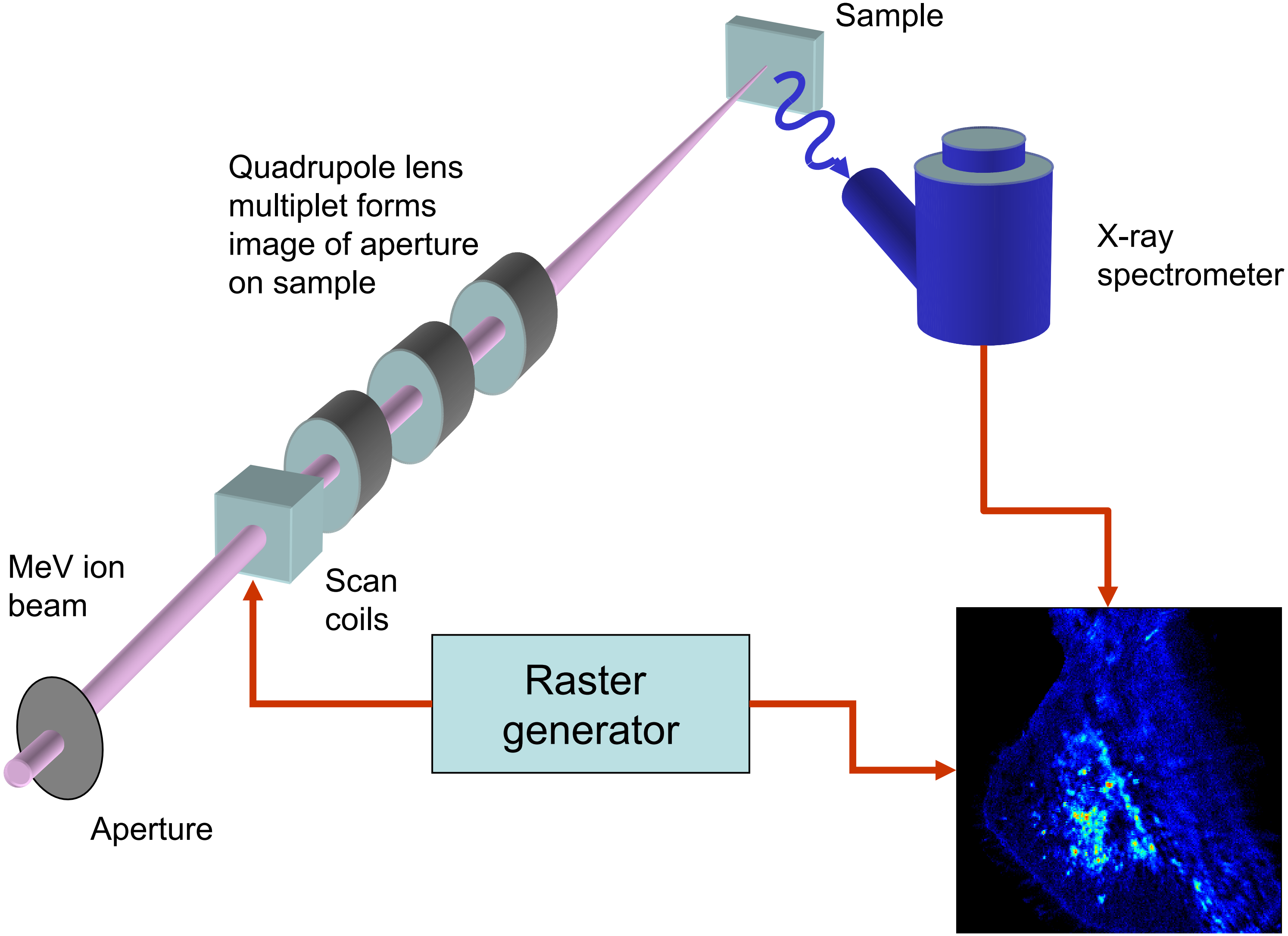


PIXE Spectra

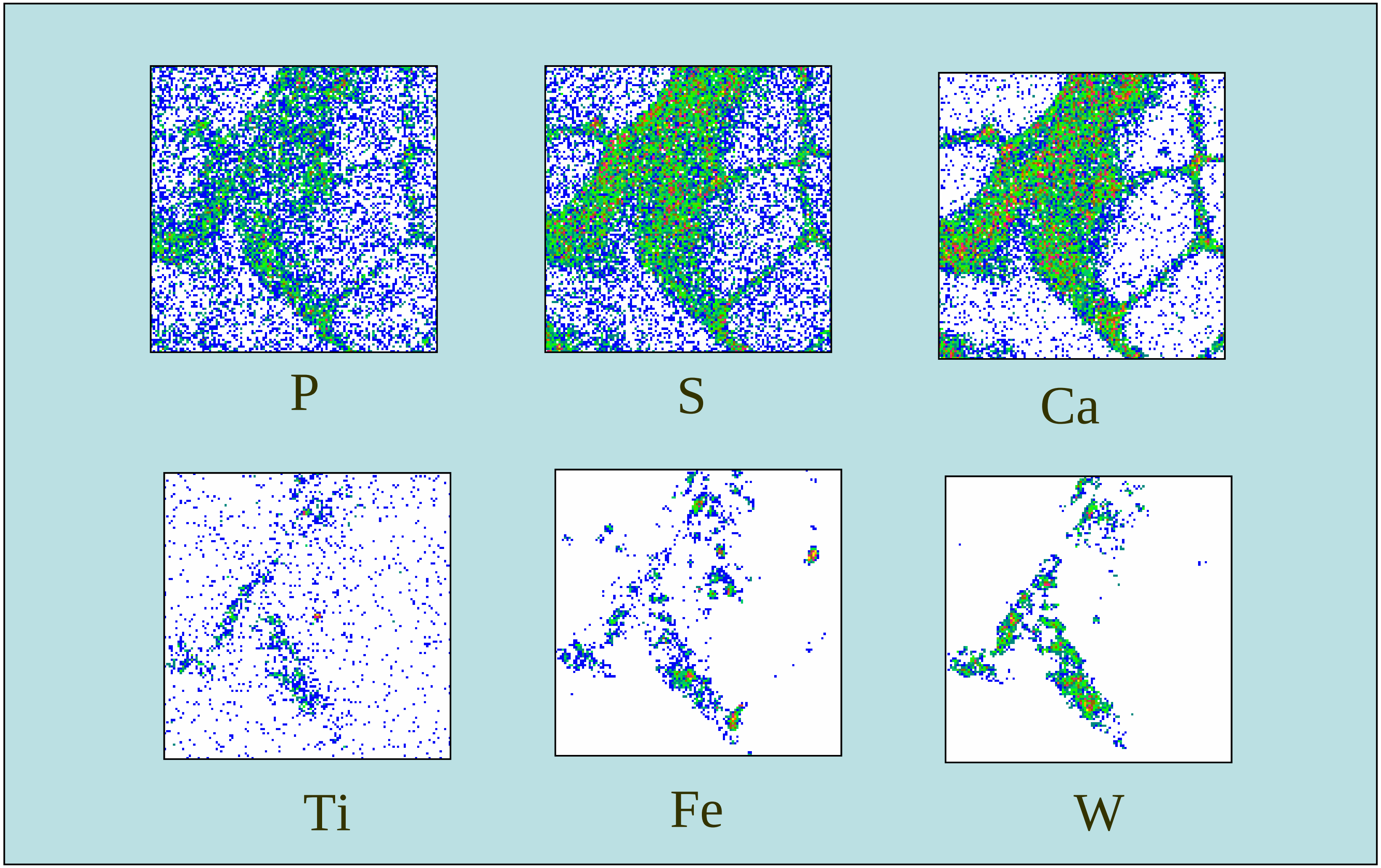




PIXE microscope



Nuclear microprobe PIXE elemental maps from 400 mm x 400 mm scan over a section of a lung tissue taken from a patient suffered from hard metal lung disease:



PIXE features

All elements with Z > 14 (Si) (Kα= 1.73998 KeV) can be analyzed. For instance in biological samples the concentrations of about 15 elements are normally determined **simultaneously.**

The method is **fast.** A typical irradiation lasts about **10 min.**

Highly sensitive: Concentrations of elements down to **a few 100 ppb (10^{-8})** can be measured.

The spatial resolution of the beam is 1 mm. The penetration depth in a solids: **~ 100 µm;** allows determinations of **elemental distributions or profiles**

High accuracy: relative errors are between 1-10 %

Small-size samples ≥ few mg

Non-destructive technique: This enables analyses of precious objects, e.g. ancient coins or paintings.

Competition to PIXE: Neutron Activation Analysis (NAA)

Neutron sources

Nuclear reactors

Nuclear reactions

3H(p,n)3He, 6Li(p,n)6Be,

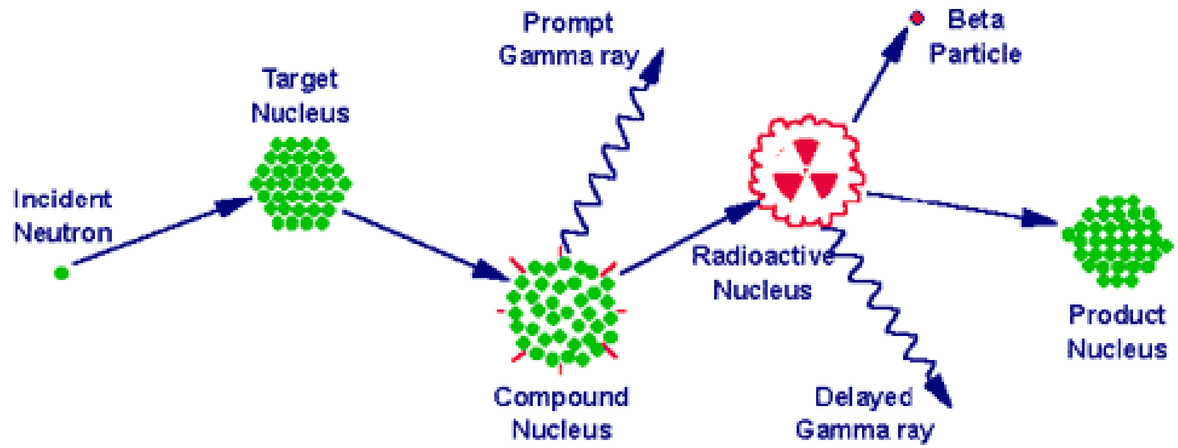
7Li(p,n)7Be, 9Be(p,n)9B,

Radioisotopes

Spontaneous fission **Cf-252**

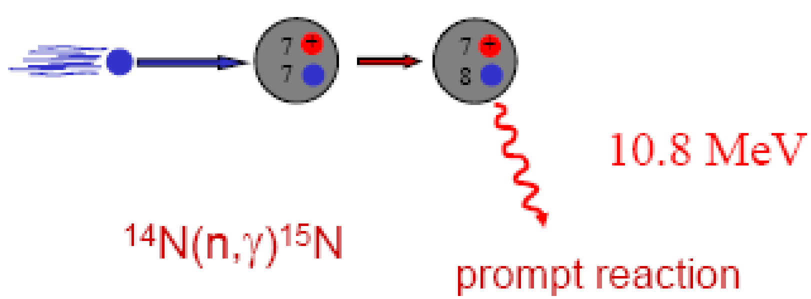
(α,n) reactions

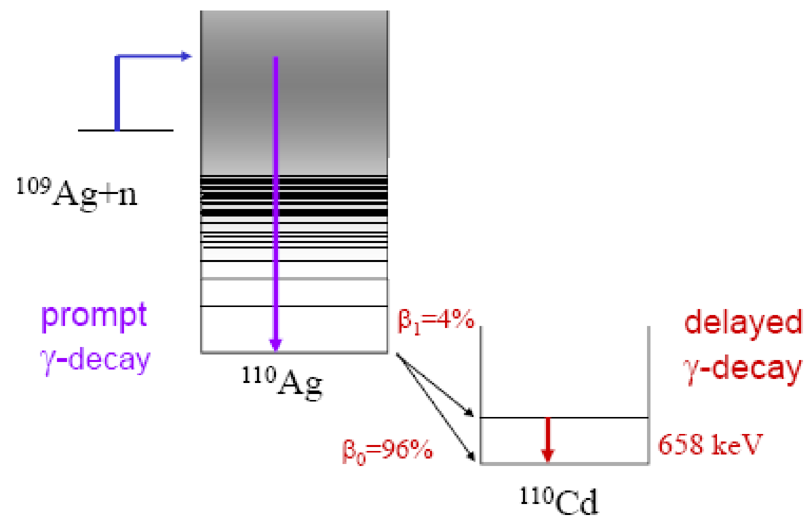
e.g. ^{241}**Am:Be**



^{109}**Ag+n** $\Rightarrow$ ^{110}**Ag*** $\Rightarrow$ ^{110}**Cd+** γ **(658 KeV)**

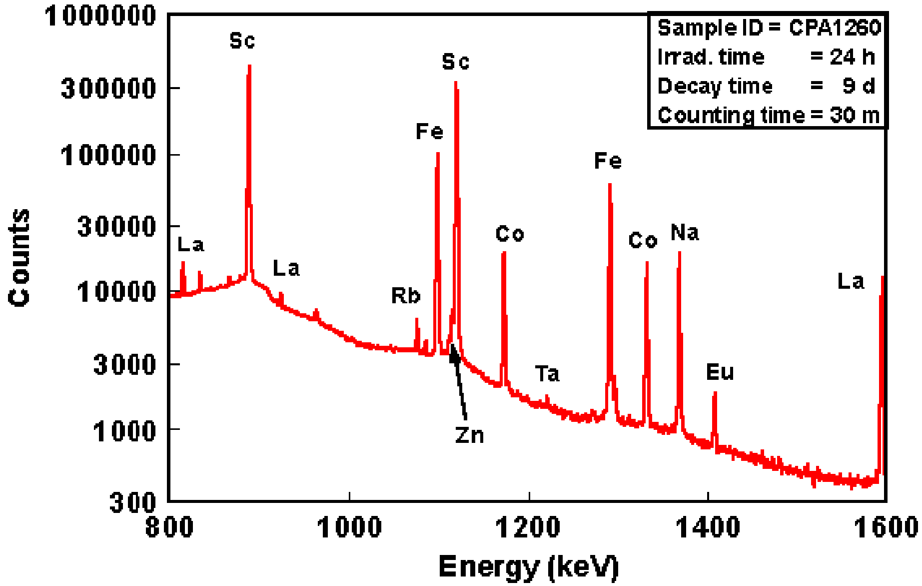
^{14}**N+n** $\Rightarrow$ ^{15}**N*** $\Rightarrow$ ^{15}**N+** γ **(10.8 MeV)**





Neutron Activation Analysis

Gamma spectrum



Sensitivity (picograms)	Elements
1	Dy, Eu
1–10	In, Lu, Mn
10–100	Au, Ho, Ir, Re, Sm, W
100–1E3	Ag, Ar, As, Br, Cl, Co, Cs, Cu, Er, Ga, Hf, I, La, Sb, Sc, Se, Ta, Tb, Th, Tm, U, V, Yb
1E3–1E4	Al, Ba, Cd, Ce, Cr, Hg, Kr, Gd, Ge, Mo, Na, Nd, Ni, Os, Pd, Rb, Rh, Ru, Sr, Te, Zn, Zr
1E4–1E5	Bi, Ca, K, Mg, P, Pt, Si, Sn, Ti, Tl, Xe, Y
1E5–1E6	F, Fe, Nb, Ne
1E7	Pb, S

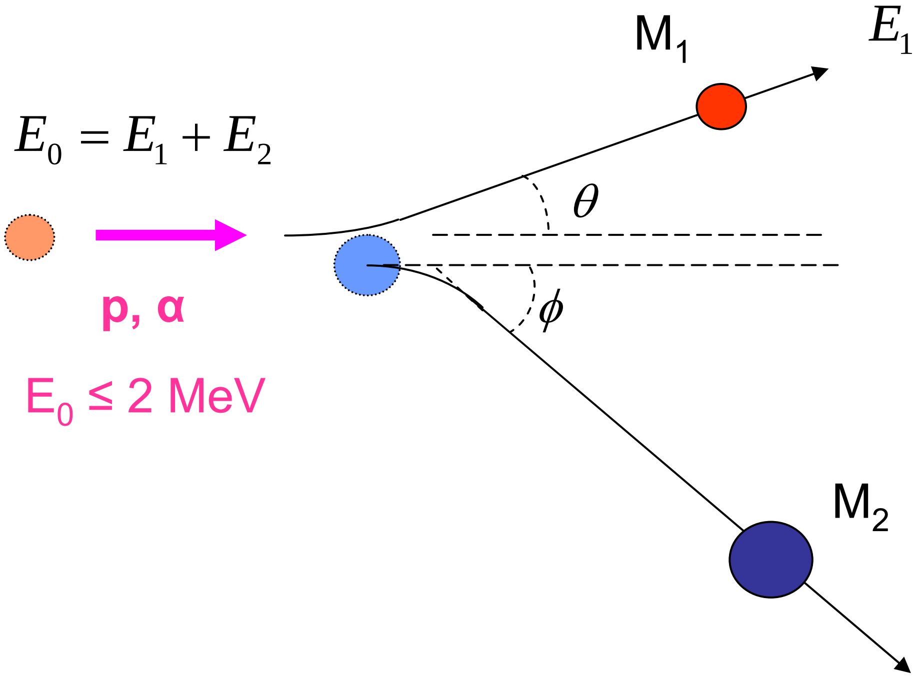
RBS - Rutherford Backscattering Spectrometry

ERD – Elastic recoil detection

Coulomb repulsion between high energy incident ions and target nuclei

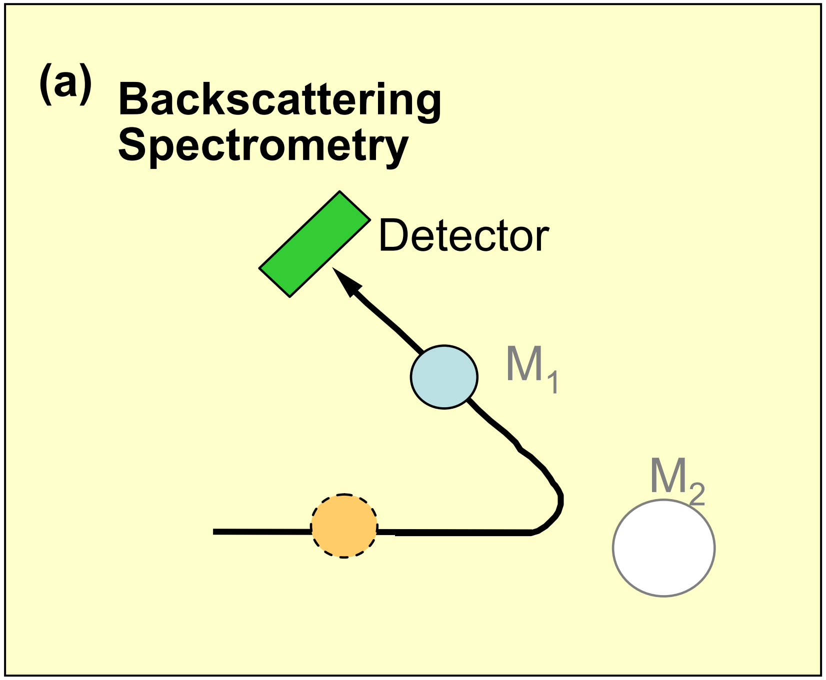
$$E_1 = E_0 K = E_0 \left\{ \frac{\cos\theta + \sqrt{(M_1/M_2)^2 - \sin^2\theta}}{1 + (M_1/M_2)^2} \right\}^2$$

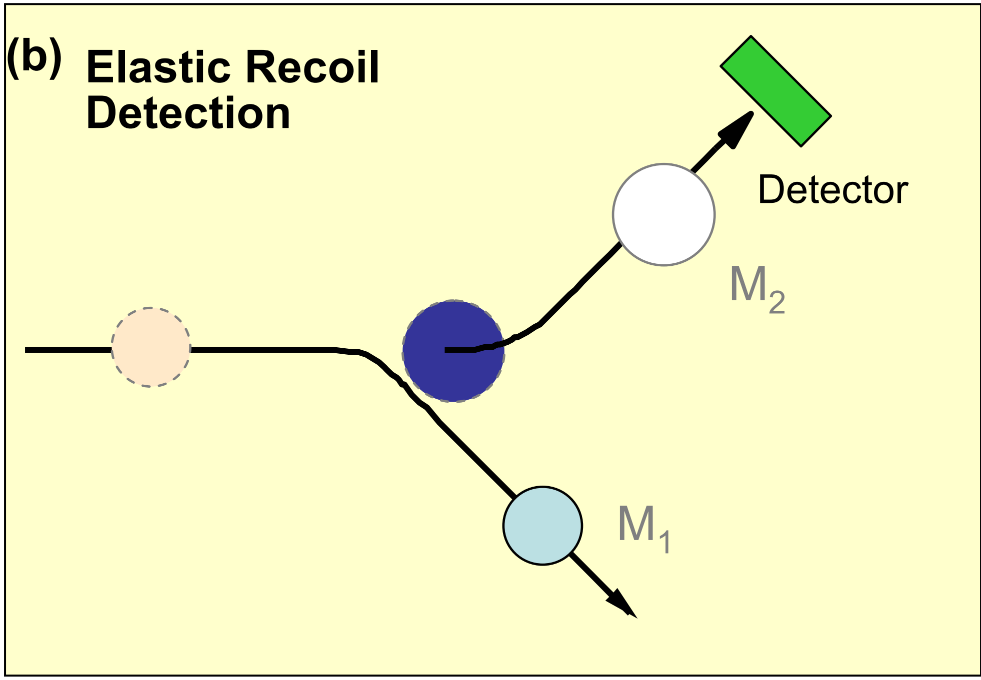
$$E_0 = E_1 + E_2$$



$$E_2 = E_0 \Lambda = E_0 \left[\frac{4 M_1 M_2}{(M_1 + M_2)^2} \cos^2\phi \right]$$

RBS vs. ERDA

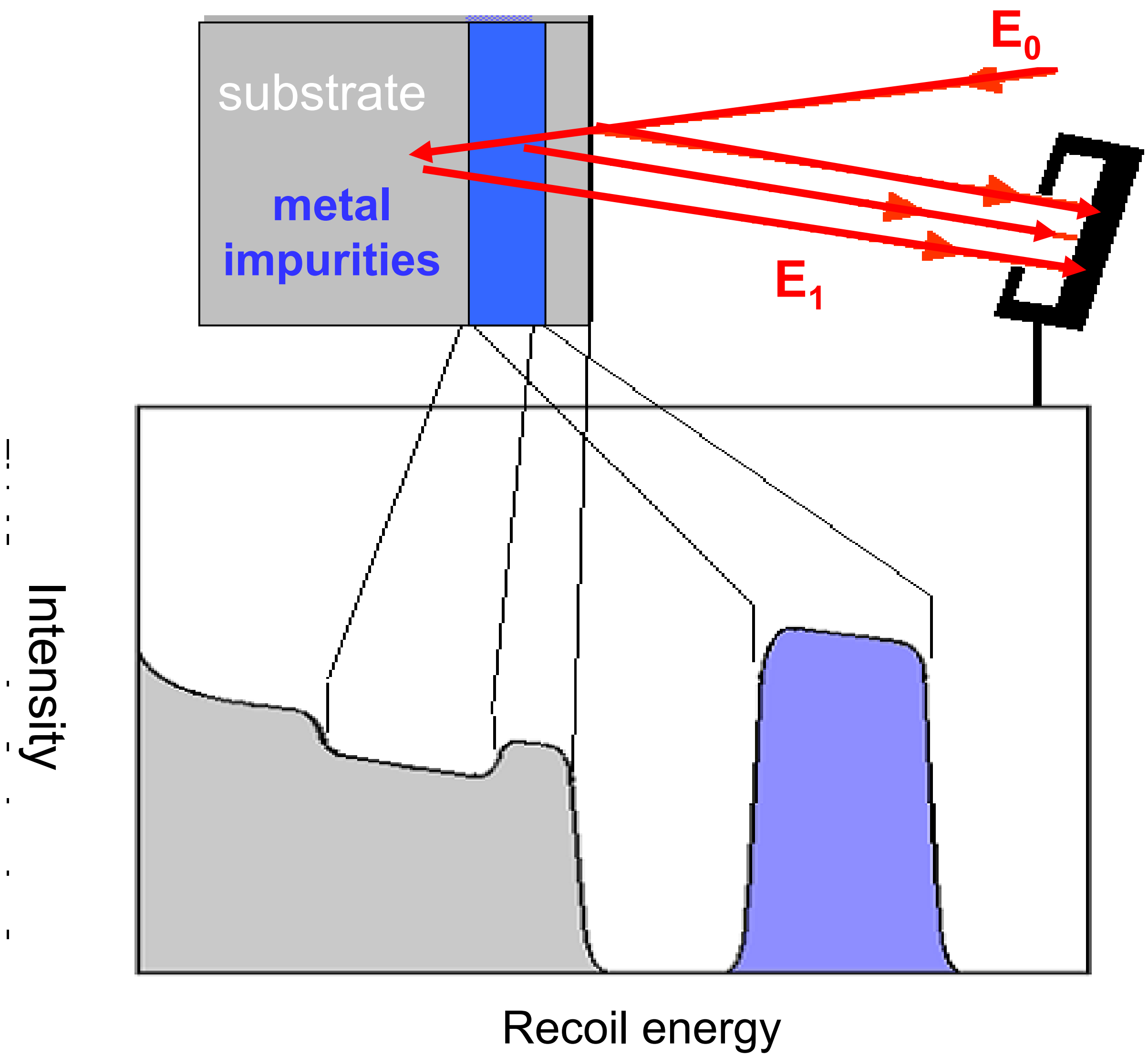


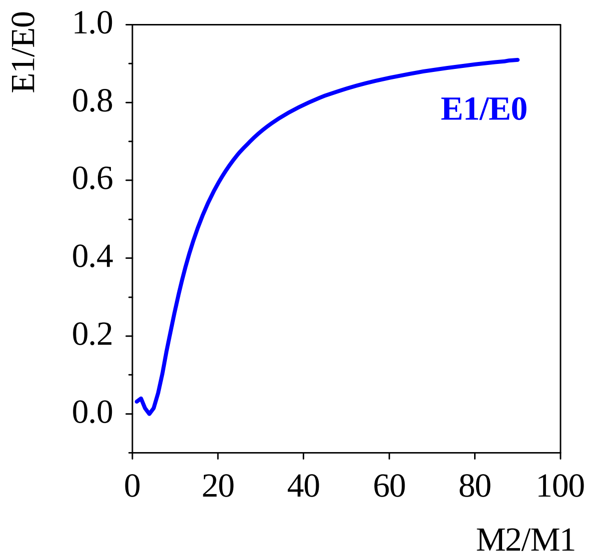


- **RBS**
  - Projectile is the detected particle $\mathbf{M_1 << M_2}$
  - Depth and mass information encoded on detected particle energy
- **ERDA**
  - The target atom is the detected particle $\mathbf{M_1 >> M_2}$
  - Depth information encoded on energy
  - Isotopic identity carried directly by recoil

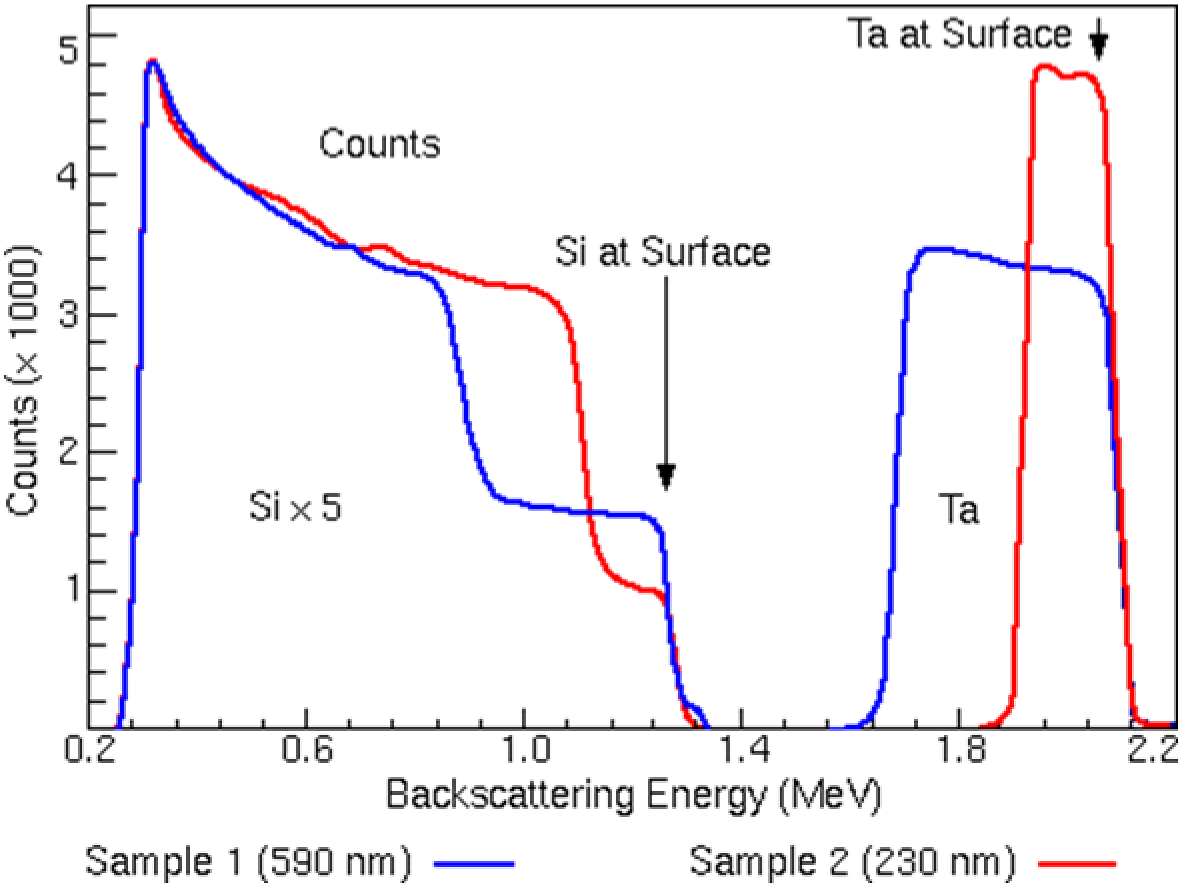
RBS (Rutherford Backscattering Spectrometry)

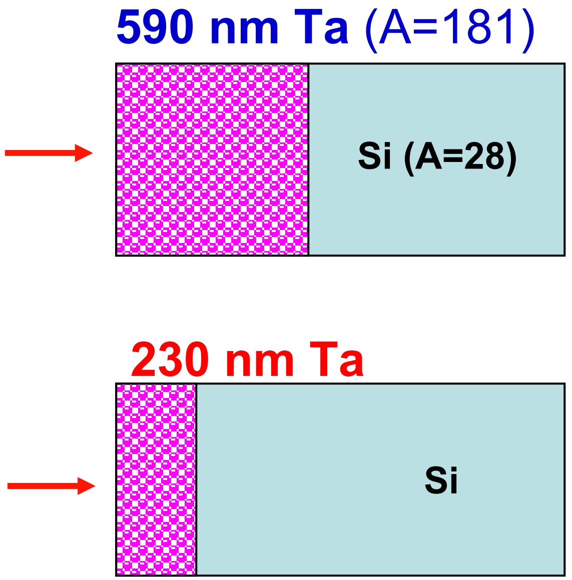
The recoil energy depends on the target mass and the path length

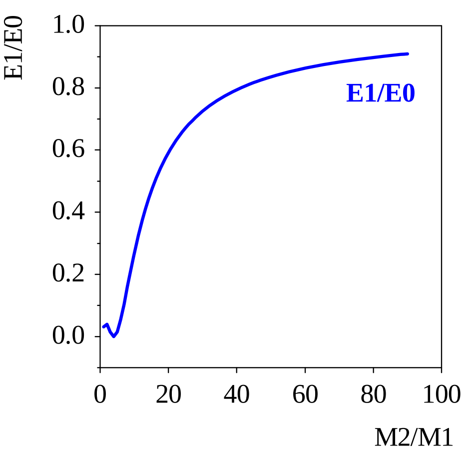




RBS spectrum of Ta implanted in Si



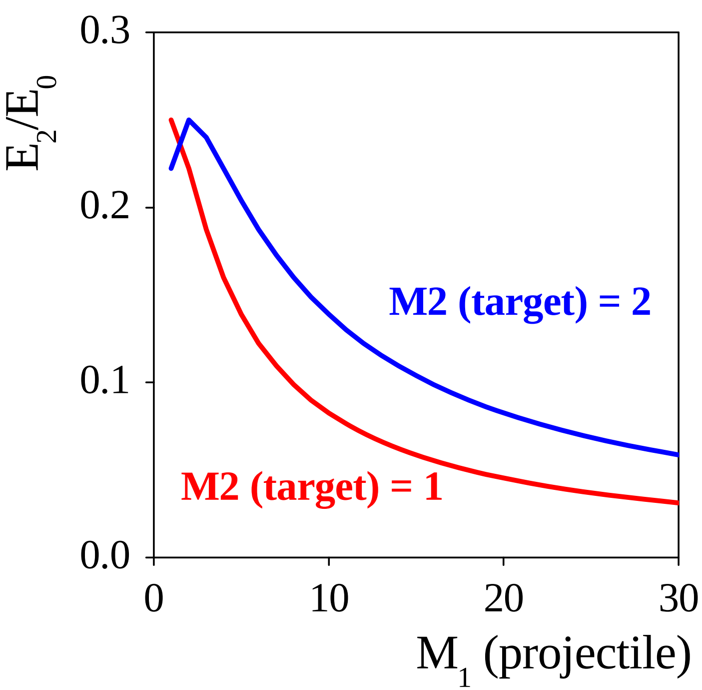


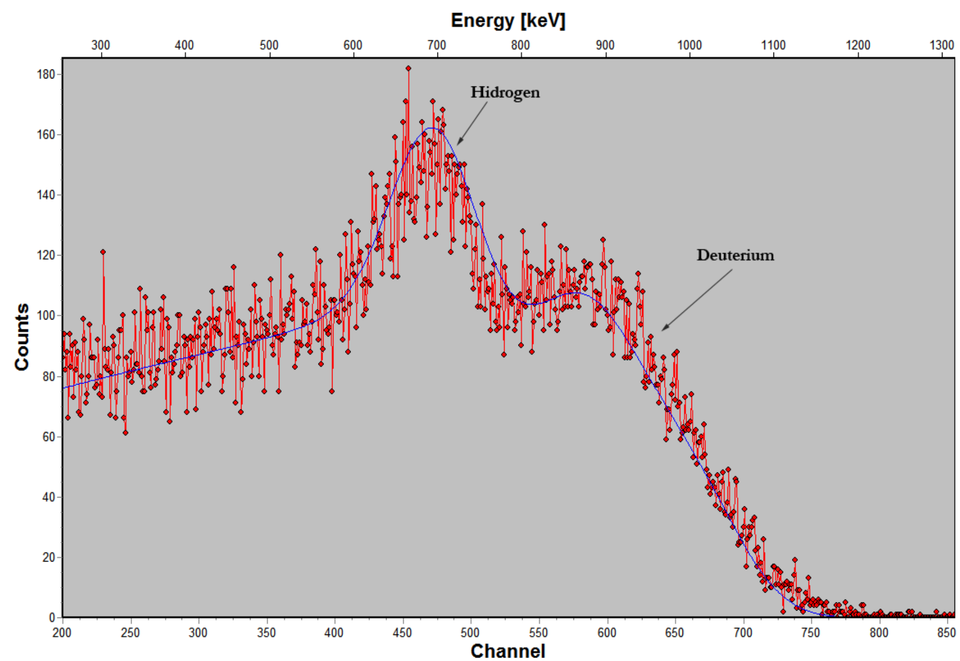


ERD – Elastic recoil detection

M (projectile) > M (target)

Analysis of the distribution of light elements (H, He, etc) in solids

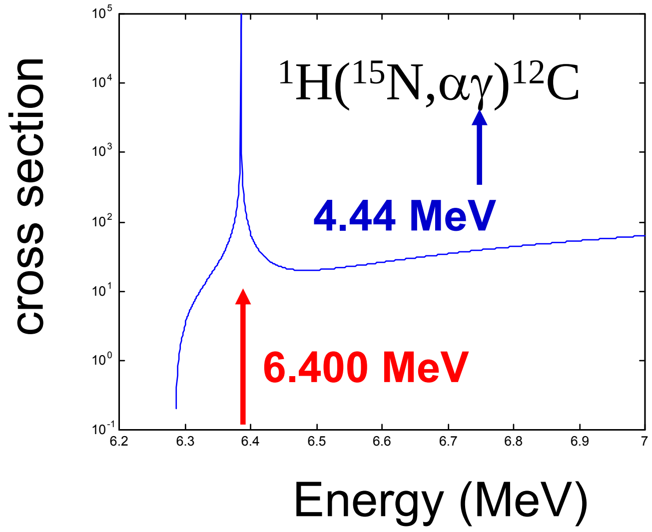


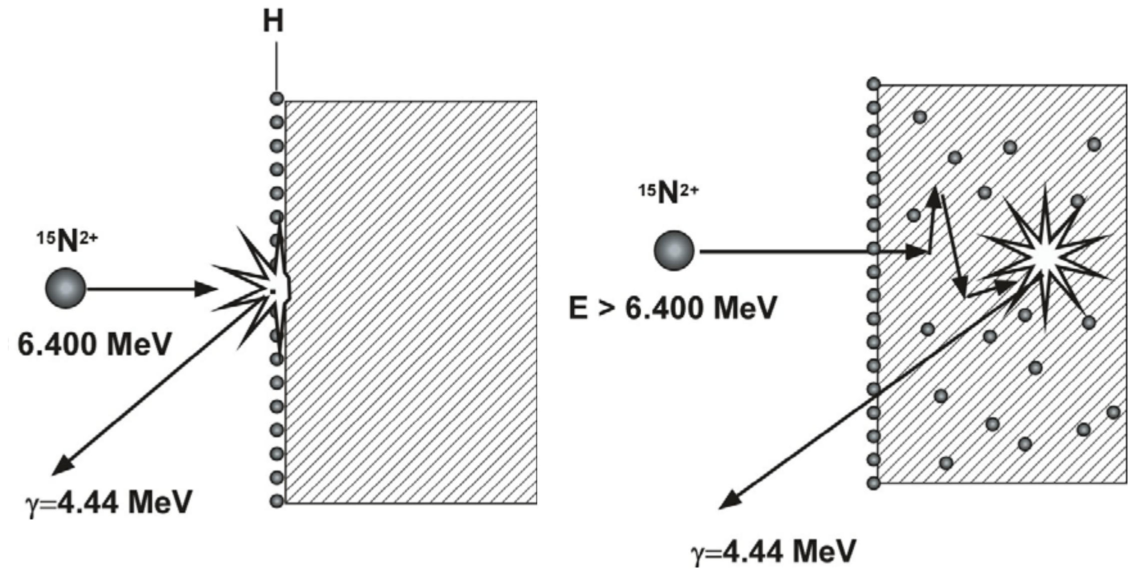


Nuclear Resonant Reaction Analysis (NRRA)

Nuclear reactions with sharp resonances are used
to study impurity concentration in solids

Example: The reaction $^{1}H(^{15}N, \alpha\gamma)^{12}C$ equiv. $^{15}N(p,\alpha\gamma)^{12}C$





NRRA with the $^{15}N(p,\alpha\gamma)^{12}C$ reaction measures the hydrogen concentration

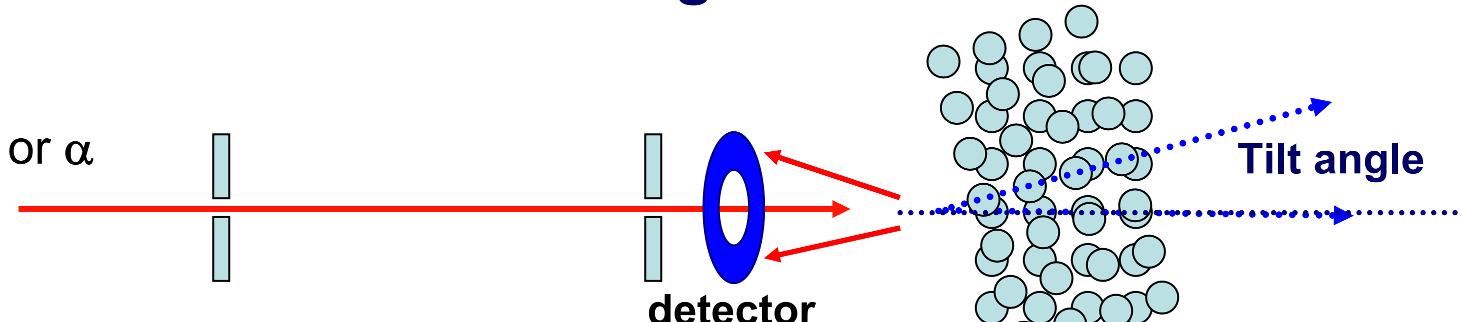
Resonances used in NRRA

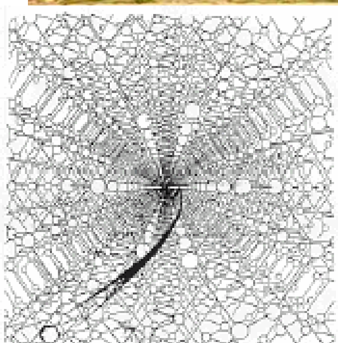
Table 15-1. Nuclear reactions used for the detection of charged particles produced in nuclear reactions (from Götz and Gärtner, 1988).

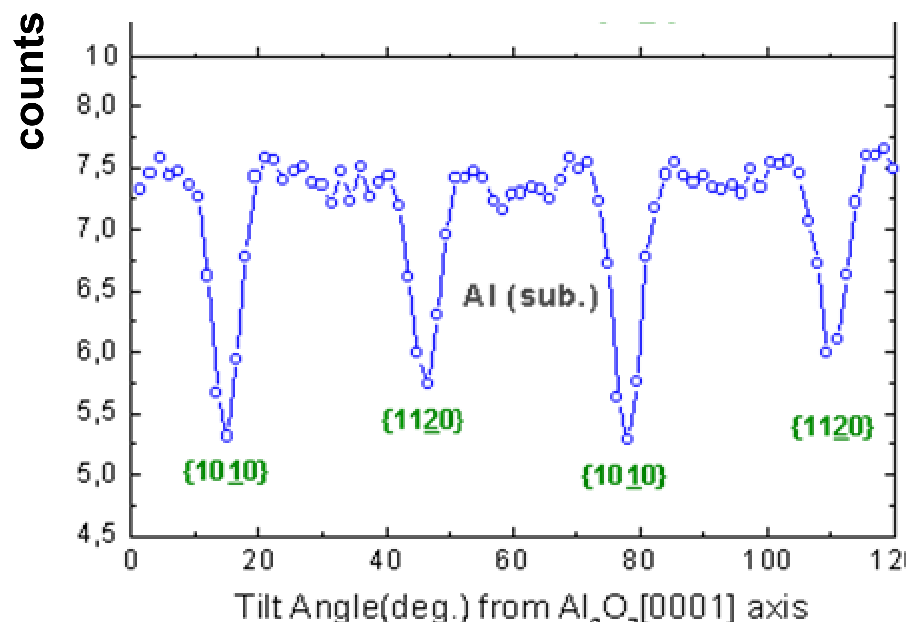
Nucleus	Reaction	Q-value Q [MeV]	Incidentenergy[1)] E_1 [MeV]	Emitted energy E'_1 [MeV]	Cross-section $(d\sigma/d\Omega)_{NR}$ [mb/sr]	Mylar thickness Z_{sf} [µm]
^{2}H	2H(d,p)3H	4.032	1.0	2.3	5.2	14
^{2}H	$^{2}H(^{3}He,p)^{4}He$	18.352	0.7	13.0	61	6
^{3}He	$^{3}He(d,p)^{4}He$	18.352	0.45	13.6	64	8
^{6}Li	$^{6}Li(d,\alpha)^{4}He$	22.374	0.7	9.7	6	8
^{7}Li	$^{7}Li(p,\alpha)^{4}He$	17.347	1.5	7.7	1.5	35
^{9}Be	$^{9}Be(d,\alpha)^{7}Li$	7.153	0.6[2)]	4.1	1	6
^{11}B	$^{11}B(p,\alpha)^{8}Be$	8.586	0.65	5.57(α_0)	0.12(α_0)	10
		5.65	0.65	3.70(α_1)	90(α_1)	10
^{12}C	$^{12}C(d,p)^{13}C$	2.722	1.20	3.1	35	16
^{13}C	$^{13}C(d,p)^{14}C$	5.951	0.64	5.8	0.4	0.6
^{14}N	$^{14}N(d,\alpha)^{12}C$	13.574	1.5	9.9(α_0)	0.6(α_0)	23
		9.146	1.2	6.7(α_1)	1.3(α_1)	16
^{15}N	$^{15}N(p,\alpha)^{12}C$	4.964	0.8[3)]	3.9	≈15	12
^{16}O	$^{16}O(d,p)^{17}O$	1.917	0.90	2.4(p_o)[4)]	0.74(p_o)	12
		1.05	0.90	1.6(p_1)	4.5(p_1)	12
^{18}O	$^{18}O(p,\alpha)^{15}N$	3.980	0.73[3)]	3.4	15	11
^{19}F	$^{19}F(p,\alpha)^{16}O$	8.114	1.25	6.9	0.5	25
^{23}Na	$^{23}Na(p,\alpha)^{20}Ne$	2.379	0.592	2.238	4	6
^{31}P	$^{31}P(p,\alpha)^{28}Si$	1.917	1.514	2.734	16	5)

1) For laboratory emission angle 150° with recoil nucleus in ground state (excited state)
2) 0.6 MeV is optimum for Be in light Z matrix and 1.6 MeV for high Z matrix
3) Maximum energy for Mylar to stop backscattered proton
4) Measured at θ=164°
5) range of α < range of proton

The Channeling Effect







Emission channeling

Determination of the position of implanted ions