Ion Beam Analysis in Materials Science
(Rutherford backscattering and related techniques)

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Outline

- Introduction:
  - General aspects of ion beam analysis
  - Equipment
- Rutherford backscattering spectrometry (RBS)
  - Introduction-history
  - Basic concepts of RBS
    - Kinematic factor (K)
    - Scattering cross-section
    - Depth scale
  - Quantitative thin film analysis
  - Pitfalls
- Particle induced x-ray emission (PIXE)
- Hydrogen Forward Scattering
- Non-Rutherford scattering and nuclear reaction analysis
- Ion channeling
  - Minimum yield and critical angle
  - Dechanneling by defects
  - Impurity location
References

**Books:**

**Review Articles:**

Ion Beam Analysis: General

- CH: Channeling
- ERA: Elastic Recoil Analysis
- RBS: Rutherford Backscattering
- NRA: Nuclear Reaction Analysis
- PIXE: Particle Induced X-ray Emission
- PIGME: Particle Induced Gamma-ray Emission
- SIMS: Secondary Ion Mass Spectrometry
- MEIS: Medium Energy Ion Scattering
- LEIS: Low energy ion scattering
- HFS: Hydrogen forward scattering

Energy (keV)

Ion Mass (amu)

Low energy  Medium energy  High energy regime

10^1  10^2  10^3  10^4

H  He  Ar

LEIS  MEIS  SIMS

RBS, CH, HFS  PIGE, PIXE, NRA

NRA  PIGE, PIXE

PIGE, PIXE
MeV Ion Beam Techniques

Particle induced $\gamma$-ray emission (PIGE)

Particle induced x-ray emission (PIXE)

Elastic recoil detection (ERA)

Hydrogen forward scattering (HFS)

Rutherford backscattering spectrometry (RBS)

$E_1 = k(m, M, \theta)E_0$

$M_1 > M_2 > m > M_3$

MeV $H^+, ^4He^+$
## Ion Beam techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Typical Applications</th>
<th>Elements detected</th>
<th>Depth probed</th>
<th>Depth resolution</th>
<th>Lateral resolution</th>
<th>Detection limit</th>
<th>Quantitative</th>
<th>Depth profiling</th>
</tr>
</thead>
</table>
| RBS       | • thin film composition and thickness  
          • impurity profiles  
          • thin film interactions and interdiffusions | B-U | 1-2μm | 20-200Å | 0.5-1mm | 1-10 at.%  
          Z<20  
          0.01-1 at.%  
          0.01-0.001 at.%  
          Z>70 | Yes | Yes |
| PIXE      | • element identification  
          • impurity analysis | Al-U | up to 10μm | poor | 0.5-1mm | 0.001 at.% | Yes | No |
| HFS       | • hydrogen or deuterium in thin films | H, d | 1μm | 500Å | 2-3 mm | 0.01 at.% | Yes | Yes |
| non-RBS   | • Composition of thin oxide, nitride, carbide films | B, C, N, O, Si | up to 10μm | 200Å | 0.5-1 mm | 0.1 at.% | Yes | Yes |
| NRA       | • profiling of light elements in heavy matrix | H, B, C, N, O, F | up to a few μm | 500-1000Å | 0.5-1mm | 0.001-1 at.% | Yes | Yes |
| Channeling | • crystalline quality of thin films  
          • lattice location of impurity in single crystal  
          • strains in pseudomorphic thin films  
          • implantation damage analysis | B-U | 1-2μm | 20-200Å | 0.5-1mm | 0.0001 at.% | Yes | Yes |
Experimental Setup
An Ideal IBA Laboratory

Arizona State University

Lawrence Berkeley National Laboratory

K. M. Yu November 2008
A compact RBS System

NEC MAS1000
Rutherford Backscattering Spectrometry (RBS)
Rutherford Backscattering Spectrometry (RBS)– a brief history

The original experiment

Alpha particles at a thin gold foil experiment by Hans Geiger and Ernest Marsden in 1909.

1) Almost all of the alpha particles went through the gold foil
2) Some of the alpha particles were deflected only slightly, usually 2° or less.
3) A very, very few (1 in 8000 for platinum foil) alpha particles were turned through an angle of 90° or more.

"We shall suppose that for distances less that $10^{-12}$ cm the central charge and also the charge on the alpha particle may be supposed to be concentrated at a point." (1911)
Surveyor V, first of its spacecraft family to obtain information about the chemical nature of the Moon's surface, landed in Mare Tranquillitatis on September 11, 1967.

"Surveyor V carried an instrument to determine the principal chemical elements of the lunar-surface material," explained ANTHONY TURKEVICH, Enrico Fermi institute and Chemistry Department, University of Chicago. "After landing, upon command from Earth, the instrument was lowered by a nylon cord to the surface of the Moon …"
General applications of RBS

- Quantitative analysis of thin films
  - thickness, composition, uniformity in depth
  - Solid state reactions
  - interdiffusion
- Crystalline perfection of homo- and heteroepitaxial thin films
- Quantitative measurements of impurities in substrates
- Defect distribution in single-crystal samples
- Surface atom relaxation in single crystals
- Lattice location of impurities in single crystals
Strengths of RBS

- Simple in principle
- Fast and direct
- Quantitative without standard
- Depth profiling without chemical or physical sectioning
- Non-destructive
- Wide range of elemental coverage
- No special specimen preparation required
- Can be applied to crystalline or amorphous materials
- Simultaneous analysis with various ion beam techniques (PIXE, PIGE, channeling, etc.)
Radiation Damage of RBS

2 MeV $^4\text{He}^+$ in Si

**COLLISION EVENTS**

**ION RANGES**

- Ion Range = 7.16 um
- Skewness = 3645.0080
- Straggle = 2307 A
- Kurtosis = -339707.2511
Basic concepts of RBS

- **Kinematic factor:** elastic energy transfer from a projectile to a target atom can be calculated from collision kinematics
  - mass determination

- **Scattering cross-section:** the probability of the elastic collision between the projectile and target atoms can be calculated
  - quantitative analysis of atomic composition

- **Energy Loss:** inelastic energy loss of the projectile ions through the target
  - perception of depth

These allow RBS analysis to give quantitative depth distribution of targets with different masses
Kinematic factor: $K$

Conservation of energy:
\[ \frac{1}{2} m_1 v^2 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 \]

Conservation of momentum:
\[ m_1 v = m_1 v_1 \cos \theta + m_2 v_2 \cos \phi \]
\[ m_1 v_1 \sin \theta = m_2 v_2 \sin \phi \]

\[ K_{m_2} = \frac{E_1}{E_o} = \left[ \frac{\sqrt{(m_2^2 - m_1^2 \sin^2 \theta)} + m_1 \cos \theta}{m_1} \right]^2 = K(\theta, m_2, m_1) \]
Kinematic Factor

\[ K_{m_2} = \frac{E_1}{E_o} = \left[ \frac{\sqrt{(m_2^2 - m_1^2 \sin^2 \theta)} + m_1 \cos \theta}{(m_2 + m_1)} \right]^2 \]

\[ K_{m_2} (\theta = 180^\circ) = \left[ \frac{(m_2 - m_1)}{(m_2 + m_1)} \right]^2 \]

\[ K_{m_2} (\theta = 90^\circ) = \frac{(m_2 - m_1)}{(m_2 + m_1)} \]

When \( m_2 \gg m_1 \):

\[ K_{m_2} (\theta = 180^\circ) \sim 1 \]
Element identification

2.5 MeV He ion with $\theta=170^\circ$

$K^{(197\text{Au})} = 0.923$
$K^{(109\text{Ag})} = 0.864$
$K^{(107\text{Ag})} = 0.862$
$K^{(65\text{Cu})} = 0.783$
$K^{(63\text{Cu})} = 0.777$
Mass Resolution, $\delta m_2$

For 180° scattering:

$$K_{m_2} = \frac{E_1}{E_0} = \left[ \frac{(m_2 - m_1)}{(m_2 + m_1)} \right]^2$$

$$\frac{\delta E_1}{E_0} = \delta \frac{(m_2 - m_1)^2}{(m_1 + m_2)^2}$$

$$\therefore \delta m_2 = \frac{(m_2 + m_1)^3}{4m_1(m_2 - m_1)} \frac{\delta E_1}{E_0}$$

For a fixed $\delta E_1/E_0$ (~0.01), heavier projectiles result in better mass resolution.

However, $\delta E_1$ for heavier projectiles is higher.
Mass Resolution: Examples

With system energy resolution $\delta E = 20\text{keV}$ and $E_0=2\text{MeV}$

For $m_2=40$

$$\delta m_2 = \frac{(40 + 4)^3}{4 \times 4(40 - 4)} \cdot \frac{20}{2000} = 1.48\text{a.m.u.}$$

For $m_2=70$

$$\delta m_2 = \frac{(70 + 4)^3}{4 \times 4(70 - 4)} \cdot \frac{20}{2000} = 3.84\text{a.m.u.}$$

Isotopes of Ga (68.9 and 70.9 a.m.u.) cannot be resolved
RBS Quantification

Backscattering Yield

For a given incident number of particles $Q$, a greater amount of an element present ($N_s$) should result in a greater number of particles scattered.

Thus we need to know how often scattering events should be detected ($A$) at a characteristic energy ($E = KE_0$) and angle $\theta$, within our detector’s window of solid angle $\Omega$. 

$N_s = N \times t$

$N_s$ = number density (atoms/cm$^3$)

$t$ = thickness

$A = \sigma \Omega N_s Q$

$\sigma$ = average cross section

$\Omega$ = detector solid angle

$Q$ = total number of incident particles

# of particles detected

Scattering Angle

Incident Particles

Scattered Particle

Detector
Scattering cross-section

Rutherford cross-section:

\[
\frac{d \sigma}{d \Omega} = \left( \frac{Z_1 Z_2 e^2}{2 E_o} \right)^2 \left[ \cos \theta + (1 - A^2 \sin^2 \theta)^{1/2} \right]^2 \frac{\sin^4 \left( \frac{\theta}{2} \right)}{(1 - A^2 \sin^2 \theta)^{1/2}} \quad A = \frac{m_1}{m_2}
\]
Scattering Yield

\[ Yield, Y \propto \sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{2E_0}\right)^2 \frac{\cos \theta + \left(1 - A^2 \sin^2 \theta\right)^{1/2}}{\sin^4 \frac{\theta}{2} \left(1 - A^2 \sin^2 \theta\right)^{1/2}} \]

\[ \propto \left(\frac{Z_1 Z_2}{E_0}\right)^2 \sim 10^{-24} \text{cm}^2 \text{[barn]} \]

Example:

Mixed Si and W target analyzed by a 2MeV He ion beam at 165° scattering angle.

\[ \sigma(\text{Si}) = 2.5 \times 10^{-25} \text{cm}^2/\text{str} \]

\[ \sigma(\text{W}) = 7.4 \times 10^{-24} \text{cm}^2/\text{str} \]

Total incident ions \( Q = 1.5 \times 10^{14} \text{ ions} \)

\( \Omega = 1.8 \text{mstr} \)

Area under Si, \( A(\text{Si}) = 200 \text{ counts} \)

Area under W, \( A(\text{W}) = 6000 \text{ counts (Nt)} \)

\( (\text{Nt})_{\text{Si}} = 3 \times 10^{15} \text{atoms/cm}^2 \)

\( (\text{Nt})_{\text{W}} = 3 \times 10^{15} \text{atoms/cm}^2 \)
Deviation from Rutherford scattering

Correction factor $F$, which describes the deviation from pure Rutherford scattering due to electron screening for He$^+$ scattering from atoms, $Z_2$, at variety of incident kinetic energies.

At very high energy and very low energy, scattering will deviate from the Rutherford type.

At low energy: screening of $e^-$ must be considered

At high energy: nuclear short range force will enhance the cross-section, the so-called “resonance scattering.”
When an He or H ion moves through matter, it loses energy through

- interactions with e⁻ by raising them to excited states or even ionizing them.
- Direct ion-nuclei scattering

Since the radii of atomic nuclei are so small, interactions with nuclei may be neglected.

\[
\frac{dE}{dx}_{\text{total}} = \left(\frac{dE}{dx}\right)_{\text{ele}} + \left(\frac{dE}{dx}\right)_{\text{nucl}} \approx \left(\frac{dE}{dx}\right)_{\text{ele}}
\]
How to read a typical RBS spectrum

Most projectile ions experience electronic stopping that results in a gradual reduction of the particle's kinetic energy (dE/dx).

At the same time a small fraction of projectile ions come close enough to the nucleus for large-angle scattering (KE).

A detected backscattered particle has lost some energy during initial penetration, then lost a large fraction of its remaining energy during the large-angle scattering event, then lost more energy in leaving the solid.
Depth Scale

\[ E_1 = K(E_0 - \Delta E_{in}) - \Delta E_{out} \]

\[ E_1 = K \left( E_0 - \frac{dE}{dx} \bigg|_{E_0} t \right) - \left( \frac{dE}{dx} \bigg|_{KE_0} \cdot \frac{t}{\cos \theta} \right) \]

Total energy loss \( \Delta E = KE_0 - E_1 \)

\[ \Delta E = \left( \frac{K}{\cos \theta_1} \cdot \frac{dE}{dx} \bigg|_{E_0} + \frac{1}{\cos \theta_2} \cdot \frac{dE}{dx} \bigg|_{KE_0} \right) \cdot t = [S_o] \cdot t \]

\([S_o]\) is the effective stopping power

Stopping cross-section

\[ \varepsilon = \frac{1}{N} \frac{dE}{dx} : \text{eV cm}^3 / \text{cm atom} = \text{eV cm}^2 / \text{atom} \]

\[ \Delta E = \left( \frac{K}{\cos \theta_1} \cdot N\varepsilon_{in} + \frac{1}{\cos \theta_2} \cdot N\varepsilon_{out} \right) \cdot t = N[\varepsilon_o] \cdot t \]
Depth scale: thin film

Thickness of film:

$$\Delta E = \left( K \left. \frac{dE}{dx} \right|_{E_0} + \frac{dE}{dx} \left. \right|_{KE_0} \right) \bullet t = [S_o] \bullet t$$

$$t = \frac{\Delta E}{\left[ S_o \right]} = \frac{\Delta E}{N[\varepsilon_o]}$$

$\varepsilon$ obtained from TRIM code or empirical energy loss data fitting
Example: layer thickness

consider the Au markers

\[ \Delta E_{\text{Au}} = E_{\text{AuF}} - E_{\text{AuB}} \]
\[ = \left[ K_{\text{Au}} \frac{\text{d}E}{\text{d}x} \bigg|_{E_0} + \frac{1}{(\cos 10^\circ)} \cdot \frac{\text{d}E}{\text{d}x} \bigg|_{E_{\text{AuB}}} \right] \cdot t \]

\[ \frac{\text{d}E}{\text{d}x} \bigg|_{3\text{MeV}} = N_{\text{Al}} \varepsilon_{\text{Al}} \bigg|_{3\text{MeV}} \]
\[ = 6.02 \times 10^{22} \cdot 36.56 \times 10^{-15} \]
\[ = 2.2 \times 10^9 \text{eVcm}^{-1} \]

\[ \frac{\text{d}E}{\text{d}x} \bigg|_{E_{\text{AuB}}} = N_{\text{Al}} \varepsilon_{\text{Al}} \bigg|_{2.57\text{MeV}} \]
\[ = 6.02 \times 10^{22} \times 39.34 \times 10^{-15} \]
\[ = 2.37 \times 10^9 \text{eVcm}^{-1} \]

\[ t = 3945\text{Å} \]

\[ \Delta E_{\text{Al}} = 165\text{keV} \]
\[ \Delta E_{\text{Au}} = 175\text{keV} \]
\[ K_{\text{Au}} = 0.9225 \]
\[ K_{\text{Al}} = 0.5525 \]

consider the Al signals

\[ \Delta E_{\text{Al}} = [K_{\text{Al}} \frac{\text{d}E}{\text{d}x} \bigg|_{E_0} + \frac{1}{(\cos 10^\circ)} \cdot \frac{\text{d}E}{\text{d}x} \bigg|_{K_{\text{El}}}] \cdot t \]

\[ t = 3937\text{Å} \]
Energy Loss: Bragg’s rule

For a target $A_mB_n$, the stopping cross-section is the sum of those of the constituent elements weighted by the abundance of the elements.

\[ \varepsilon_{A_mB_n} = m \varepsilon^A + n \varepsilon^B \]

**Example:**
the stopping cross-section $\varepsilon^{Al_2O_3}$ of $Al_2O_3$.
Given:
- $\varepsilon^{Al} = 44 \times 10^{-15} eVcm^2$
- $\varepsilon^{O} = 35 \times 10^{-15} eVcm^2$
- $\varepsilon^{Al_2O_3} = 2/5 \times \varepsilon^{Al} + 3/5 \times \varepsilon^{O}$
  
  \[ = (2/5 \times 44 + 3/5 \times 35) \times 10^{-15} \]
  \[ = 38.6 \times 10^{-15} \text{ eV-cm}^2/\text{atom} \]

\[ \frac{dE}{dx}(Al_2O_3) = N \varepsilon^{Al_2O_3} = (1.15 \times 10^{22})(38.6 \times 10^{-15}) \text{ eV/cm} \]
\[ = 44.4 \text{ eV/Å} \]
Quantitative analysis: composition and thickness

\[ A_A = \sigma_A \cdot \Omega \cdot Q \cdot (Nt)_A \]
\[ A_B = \sigma_B \cdot \Omega \cdot Q \cdot (Nt)_B \]
\[ \frac{A_A}{A_B} = \left( \frac{\sigma_A}{\sigma_B} \right) \cdot \left( \frac{(Nt)_A}{(Nt)_B} \right) = \left( \frac{Z_A}{Z_B} \right)^2 \cdot \frac{m}{n} \]
\[ \frac{m}{n} = \left( \frac{A_A}{A_B} \right) \cdot \left( \frac{Z_B}{Z_A} \right)^2 \]

\[ t = \frac{(\Delta E)_A}{[S_o]_{A}^{A_mB_n}} = \frac{(\Delta E)_B}{[S_o]_{B}^{A_mB_n}} \]
\[ t = \frac{(\Delta E)_A}{N[\varepsilon_o]_{A}^{A_mB_n}} = \frac{(\Delta E)_B}{N[\varepsilon_o]_{B}^{A_mB_n}} \]
Example: As implanted Si

\[ K_{As} = 0.809; K_{Si} = 0.566 \]

\[ [\varepsilon_o]_{Si} = 92.6 \times 10^{-15} \text{ eV} - \text{cm}^2 / \text{atom} \]

\[ [\varepsilon_o]_{As} = 95.3 \times 10^{-15} \text{ eV} - \text{cm}^2 / \text{atom} \]

\[ \Delta E_{As}^{Si} = 68 \text{ keV} \]

\[ (FWHM)_{As} = 60 \text{ keV} \]

\[ R_p = \frac{\Delta E_{As}^{Si}}{N[\varepsilon_o]_{As}} = 1420 \text{ Å} \]

\[ \Delta R_p = \frac{(FWHM)_{As}}{2.355 \cdot N[\varepsilon_o]_{As}} = 540 \text{ Å} \]

Total As dose:

\[ (Nt)_{As} = \frac{A_{As}}{(\sigma_{As} \cdot \Omega \cdot Q)} \]
When \( Y(t) \) corresponds to the yield for one energy division in the RBS spectrum:
\[
Y(t) = H(E) = \sigma \Omega Q N \delta t
\]
\[
H(E) = \sigma \Omega Q N \delta E / [S_o]
\]
\[
= \sigma \Omega Q N \delta E / N[\varepsilon_o]
\]
where \( \delta E \) is the energy/channel in the RBS spectrum.

Consider the As implanted Si example:
\[
A_{As} = \sigma_{As} \Omega Q (Nt)_{As}
\]
\[
H_{Si} = \sigma_{Si} \Omega Q N \frac{\delta E}{N[\varepsilon_o]_{Si}}
\]
\[
\frac{A_{As}}{H_{Si}} = \left( \frac{Z_{As}}{Z_{Si}} \right)^2 \left( \frac{(Nt)_{As}}{\delta E / [\varepsilon_o]_{Si}} \right)
\]

Independent of \( Q \) and \( \Omega \)
Thin film analysis

\[
\frac{y}{x} = \frac{A_Y}{A_{Ba}} \cdot \left( \frac{Z_{Ba}}{Z_Y} \right)^2
\]

\[
\frac{y}{x} = \frac{H_Y}{H_{Ba}} \cdot \left( \frac{Z_{Ba}}{Z_Y} \right)^2 \cdot \frac{[\varepsilon_o]^YBCO}{[\varepsilon_o]^YBCO} \\
\approx \frac{H_Y}{H_{Ba}} \cdot \left( \frac{Z_{Ba}}{Z_Y} \right)^2
\]
RBS simulation
Example: silicide formation

Before reaction

After reaction

Figure 3.10 Schematic backscattering spectra for MeV \(^4\text{He}\) ions incident on 1000 Å Ni film on Si (top) and after reaction to form Ni\(_2\)Si (bottom). Depth scales are indicated below the energy axes.
RBS application: silicide formation


Reaction kinetics:

RBS Application: impurity profile

Ge implanted region

1.95 MeV $^4$He$^+$

I. Sharp et al., LBNL (2004)
Pitfalls in IBA

- **Charge Integration**
  - Accurate charge integration is important for absolute quantitative measurements
    - Good faraday cup design
Pitfalls in IBA (cont.)

- Deviation from Rutherford cross-section:

\[ b = \text{distance of closest approach} = Z_1 Z_2 e^2 / E \]
\[ r_n = \text{nuclear radius} = 1.4 Z_2^{1/3} \times 10^{-5} \]
\[ r_K = \text{atomic K-shell radius} = 0.5 / Z_2 \]

In order to minimize electron screening and maintain a point charge approximation:

\[ 0.5 r_K > b > 3 r_n \]

For typical RBS: Rutherford cross section is valid (~4%)
Pitfalls in IBA (cont.)

- **Insulating samples: charging effect**

  ![Graph showing energy (MeV) vs. channel](image)

  **Severely distort the RBS spectrum**

  - Provide a supply of low-E electrons from a small, hot filament located nearby
  - Coating the surface with a very thin layer of conducting material
Pitfalls in IBA (cont.)

- **Target non-uniformity**
  - Surface roughness and interface roughness cannot be distinguished
  - Target non-uniformity will resemble diffusion

Campisano et al., 1978
Weaknesses of RBS

- Poor lateral resolution (~1mm)
- Moderate depth resolution (~100Å)
- No microstructural information
- No phase identification
- Poor mass resolution for target mass heavier than 70amu
- Detection of light impurities in a heavy matrix difficult (e.g. C, O, B in Si)
Particle Induced X-ray Emission (PIXE)
Particle Induced X-ray Emission (PIXE)

Fig. 1 The basic principle of PIXE

Incident Proton

Atom in the Sample

Cu-Fe-Ni on YAIO (110)

Counts

Energy (keV)
PIXE: Light impurity in heavy matrix

RBS

\[ \text{GaAs} \quad \text{Ga}_{1-x}\text{Mn}_x\text{As} \]

2 MeV \(^4\text{He}^+\)

PIXE

\begin{align*}
\text{Counts} & \quad \text{Counts} \\
\text{Energy (keV)} & \quad \text{Energy (keV)} \\
\begin{array}{c}
\text{Ga} \\
\text{As}
\end{array} & \begin{array}{c}
\text{Ga-K} \\
\text{As-K} \\
\text{Mn-K}_\alpha \\
\text{Mn-K}_\beta
\end{array}
\end{align*}
PIXE Application: Geology, Art, Archeology, Biology

External Beam

Graphite Window Support
Surface Barrier Detector
Si(Li) Detector
X-ray Absorber Filter Holder
Polymer Beam Exit Window
Paraffin Environment at Atmospheric Pressure
Sample
Vacuum
O-Ring

Beam Change Integration

Figure 1. External PIXE set-up at IOP.
Hydrogen Forward Scattering (HFS) (Elastic Recoil Detection Analysis ERDA)
Hydrogen Forward Scattering (HFS)

Generally known as Elastic Recoil Detection (ERD)

- Quantitative hydrogen and deuterium profiling
- Good sensitivity (~0.01 at% of H)
- Can be perform simultaneously with RBS and PIXE
- Profiling with any light element in solid (using heavy ion beam, ERD)
HFS: H implanted Si

Channeling-RBS

HFS

Reference sample

\begin{align*}
[Nt]_H &= 2.1 \times 10^{17} / \text{cm}^2 \\
R_p &= 280 \text{ nm} \\
\Delta R &= 140 \text{ nm}
\end{align*}
HFS: a-Si:H film

RBS

atomic profiles

HFS
HFS: a-SiN:H film

RBS

HFS

177 nm SiN$_{1.15}$H$_{0.013}$

Si

Courtesy: F. Hellman group, 2008
Non-Rutherford Scattering and Nuclear Reaction Analysis
Non-Rutherford elastic scattering cross sections appear when the ion energy is so high that the ion starts *penetrate the Coulomb barrier* of the target atom. When the ion penetrates the Coulomb barrier of the target atom, the scattering is from the target atom’s nuclear potential and the effect of the nuclear forces for the scattering then become significant.

- For MeV ion beams, this phenomenon can be observed in low Z projectile/target system where the Coulomb barrier is small.
- The cross-section for such nuclear resonance scattering can be many times greater than the Rutherford values.
- Such non-Rutherford scattering has been used to some extent for the detection of light elements (C, N, O, Si) in heavy matrixes.
## Non-Rutherford Cross-Sections

### Summary of Literature on Proton Elastic Scattering Cross Sections Relevant to Low-MeV Proton Backscattering Analysis

<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>Energy range</th>
<th>Scattering angle</th>
<th>Ref.</th>
<th>Cross section, remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2$H</td>
<td>2.0—2.8</td>
<td>165 c</td>
<td>51</td>
<td>$\sigma/\sigma_R \approx 130–260$; data at intervals of 100 keV</td>
</tr>
<tr>
<td></td>
<td>1.7—3.0</td>
<td>168 c</td>
<td>51</td>
<td>$\sigma/\sigma_R \approx 100–300$; data at intervals of 250 keV</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>1.2—3.1</td>
<td>164 l</td>
<td>52</td>
<td>$\sigma/\sigma_R \approx 1.2$ and 15 at 1.2 and 3.0 MeV; a broad peak in the excitation curve ($\Gamma = 500$ keV, $\sigma/\sigma_R \approx 30$) at $E_p = 1.8$ MeV</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>0.5—1.4</td>
<td>160 c</td>
<td>53</td>
<td>$\sigma/\sigma_R \approx 4–8$ and 45–70 in the smooth regions of the excitation curve at energies $E_p = 1.2–1.8$ and 2.4–3.0 MeV; broad peak ($\Gamma = 200$ keV $\sigma/\sigma_R \approx 40$) at 2.05 MeV; good agreement between data</td>
</tr>
<tr>
<td></td>
<td>0.9—3.7</td>
<td>164 l</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.3—3.0</td>
<td>167 l</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>$^9$Be</td>
<td>0.2—1.7</td>
<td>161 c</td>
<td>55</td>
<td>$\sigma/\sigma_R \approx 1–2$ and 10–11 in the smooth regions below 0.9 and 1.4–2.0 MeV, respectively; the data of Ref. 55 are significantly lower than those of Ref. 56; a broad peak ($\Gamma = 300$ keV $\sigma/\sigma_R \approx 40^{55}$ or $\sigma/\sigma_R \approx 30^{57}$); for the peak, see also Ref. 57</td>
</tr>
<tr>
<td></td>
<td>1.6—3.0</td>
<td>146 c</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.8—2.6</td>
<td>160 c</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>1.0—3.0</td>
<td>156 c</td>
<td>58</td>
<td>$\sigma/\sigma_R$ increases smoothly from 2–7 for energies 1.0–2.0 MeV; a broad peak ($\Gamma \approx 200$ keV $\sigma/\sigma_R \approx 12$) at 2.2 MeV; smooth increase of $\sigma/\sigma_R$ from 6 (at 2.4 MeV) to 13 (at 3.0 MeV)</td>
</tr>
</tbody>
</table>
Non-Rutherford Cross-Sections (cont.)

<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>Energy range</th>
<th>Scattering angle</th>
<th>Ref.</th>
<th>Cross section, remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$B</td>
<td>0.6—2.0</td>
<td>153 c</td>
<td>59</td>
<td>$\sigma/\sigma_R$ decreases from $\approx 2$ to 6 in the smooth region above 0.8 MeV</td>
</tr>
<tr>
<td></td>
<td>0.7—2.5</td>
<td>170 l</td>
<td>46</td>
<td>$\sigma$ non-Rutherford at least above 0.3 MeV; $\sigma/\sigma_R = 2.4-10$ and 2.4—15 in the smooth regions at 0.7—1.6 and 1.8—4.3 MeV, respectively; $\sigma/\sigma_R = 10$ at 2.5 MeV; the strong resonance peak ($\Gamma \approx 40$ keV, $\sigma/\sigma_R \approx 60$) at 1.74 MeV has been used for carbon detection; a low $\sigma/\sigma_R = 2$ minimum at 1.69 MeV</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>0.3—4.0</td>
<td>164 l</td>
<td>60</td>
<td>$\sigma$ non-Rutherford at least above 0.6 MeV; $\sigma/\sigma_R = 4-4.5$ and 4—9 in the smooth regions at 1.58—1.73 and 1.85—2.3 MeV; strong narrow isolated resonances at 1.74 MeV ($\Gamma \approx 5$ keV, $\sigma/\sigma_R \approx 10$) and at 3.2 MeV ($\Gamma \approx 10$ keV, $\sigma/\sigma_R \approx 50$)</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>1.4—2.3</td>
<td>170 l</td>
<td>46</td>
<td>$\sigma$ non-Rutherford above 0.7 MeV, $\sigma/\sigma_R$ increases smoothly from 1.0 at 0.7 MeV to 5.7 at 2.5 MeV; another smooth region where $\sigma/\sigma_R = 6.6—10$ between 2.7 and 3.4 MeV; resonances at 2.66 and 3.48 MeV; for angular distributions and the 2.66 MeV resonance, see Ref. 69</td>
</tr>
<tr>
<td></td>
<td>0.9—4.0</td>
<td>161 c</td>
<td>62</td>
<td>Another smooth region where $\sigma/\sigma_R$ decreases from $\approx 1.8$ to 0.5 at 2.15—2.8 MeV; natural Si target in Ref. 46</td>
</tr>
<tr>
<td></td>
<td>1.0—4.1</td>
<td>168 c</td>
<td>63</td>
<td>$\sigma/\sigma_R \approx 1.4$ and 2—1.3 in the smooth regions at 1.0—1.3 and 1.5—1.65 MeV; a resonance at 1.45 MeV</td>
</tr>
<tr>
<td></td>
<td>0.6—1.8</td>
<td>160 c</td>
<td>64</td>
<td>$\sigma/\sigma_R \approx 3.5$ and 1.75—1.12 MeV; for angular distributions and the 1.65 MeV resonance, see Ref. 69</td>
</tr>
<tr>
<td></td>
<td>1.9—3.0</td>
<td>166 c</td>
<td>65</td>
<td>$\sigma/\sigma_R \approx 1.0$ and 1—0.5 in the smooth regions at 1.5—1.8 and 2.1—1.5 MeV; a resonance at 1.45 MeV</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>0.8—2.5</td>
<td>170 l</td>
<td>45</td>
<td>$\sigma$ non-Rutherford above 0.7 MeV, $\sigma/\sigma_R$ increases smoothly from 1.0 at 0.7 MeV to 5.7 at 2.5 MeV; another smooth region where $\sigma/\sigma_R = 6.6—10$ between 2.7 and 3.4 MeV; resonances at 2.66 and 3.48 MeV; for angular distributions and the 2.66 MeV resonance, see Ref. 69</td>
</tr>
<tr>
<td></td>
<td>0.8—2.0</td>
<td>172 c</td>
<td>66</td>
<td>Another smooth region where $\sigma/\sigma_R$ decreases from $\approx 1.8$ to 0.5 at 2.15—2.8 MeV; natural Si target in Ref. 46</td>
</tr>
<tr>
<td></td>
<td>0.6—4.5</td>
<td>169 l</td>
<td>67</td>
<td>$\sigma/\sigma_R \approx 1.4$ and 2—1.3 in the smooth regions at 1.0—1.3 and 1.5—1.65 MeV; a resonance at 1.45 MeV</td>
</tr>
<tr>
<td></td>
<td>0.6—2.0</td>
<td>160 l</td>
<td>68</td>
<td>$\sigma/\sigma_R \approx 0.7$ and 1—0.5 in the smooth regions at 1.5—1.8 and 2.1—1.5 MeV; a resonance at 1.45 MeV</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>1.4—3.8</td>
<td>168 c</td>
<td>77</td>
<td>$\sigma/\sigma_R \approx 1.4$ and 2—1.3 in the smooth regions at 1.0—1.3 and 1.5—1.65 MeV; a resonance at 1.45 MeV</td>
</tr>
<tr>
<td></td>
<td>1.0—2.0</td>
<td>150 l</td>
<td>78</td>
<td>$\sigma/\sigma_R \approx 0.7$ and 1—0.5 in the smooth regions at 1.5—1.8 and 2.1—1.5 MeV; a resonance at 1.45 MeV</td>
</tr>
</tbody>
</table>
### Non-Rutherford Cross-Sections (cont.)

<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>Energy range</th>
<th>Scattering angle</th>
<th>Ref.</th>
<th>Cross section, remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}$Na</td>
<td>0.6—1.5</td>
<td>158 c</td>
<td>73</td>
<td>$\sigma/\sigma_R = 0.9-1.1$ in the smooth region at 1.0—1.4 MeV, the data from Ref. 56 are significantly lower than those of Ref. 73</td>
</tr>
<tr>
<td></td>
<td>0.5—1.0</td>
<td>160 l</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>0.7—2.5</td>
<td>170 l</td>
<td>47</td>
<td>$\sigma$ non-Rutherford above 0.8 MeV; $\sigma/\sigma_R \approx 1.05-1.1$ and 1.3—1.5 in the smooth regions at 0.85—1.4 and 1.66—1.85 MeV; resonances at 0.83, 1.48, 1.62, and above 1.9 MeV; natural Mg used as target in Ref. 47</td>
</tr>
<tr>
<td></td>
<td>0.4—3.9</td>
<td>164 l</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>1.0—2.4</td>
<td>170 l</td>
<td>48</td>
<td>$\sigma$ non-Rutherford at least above 1.0 MeV; many sharp overlapping resonances, no smooth regions wider than 50 keV above 1.2 MeV; $\sigma/\sigma_R &lt; 3$ up to 2.4 MeV; yield curve without absolute cross section scale in Ref. 75</td>
</tr>
<tr>
<td></td>
<td>1.4—2.3</td>
<td>164 l</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>$^{38}$Si</td>
<td>1.5—2.2</td>
<td>170 l</td>
<td>46</td>
<td>$\sigma$ non-Rutherford at least above 1.5 MeV; $\sigma/\sigma_R$ decreases smoothly from $\approx 2.2$ to 1 for energies from 1.7 to 2.05 MeV ($\Gamma = 15$ keV), isolated resonance at $E_{\text{inv}} = 4.79$ MeV; see also Refs. 118 to 120</td>
</tr>
<tr>
<td></td>
<td>2.0—5.0</td>
<td>165 c</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>$^{31}$P</td>
<td>1.0—2.0</td>
<td>165 l</td>
<td>79</td>
<td>$\sigma$ non-Rutherford at least above 1.0 MeV; $\sigma/\sigma_R \approx 1.05$ and 1.2 in the smooth regions at 1.0—1.2 and 1.3—1.45 MeV. Resonances at 1.25, 1.52, 1.59, 1.72—1.74, and 1.90 MeV</td>
</tr>
</tbody>
</table>
Non-Rutherford cross sections
Non-Rutherford scattering:
Example 1: SiO$_2$

**Fig. 4.** Backscattering spectra of 2.0 MeV He-RBS (a) and 1.60 MeV PRS (b) of a 1500 Å SiO$_2$ film on GaAs.
Non-Rutherford scattering: Example 1: SiC

Fig. 5. Backscattering spectra with 2.0 MeV He particles (a) and 1.50 MeV protons (b) from a sample of 2μm SiC film on Si substrate.
Nuclear Reaction Analysis (NRA)

- When the incident beam energy exceeds a certain threshold value, other energetic particles appear in the spectrum.
- The detection of these particles usually provide information which is not obtainable from RBS.
- The NRA technique is very useful as a tool for the detection and profiling of light elements in heavy matrix.
- In many cases such particle-particle NRA can be carried out in a RBS setup with only minor modifications.
### Some useful particle-particle reactions

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Reaction</th>
<th>Incident Energy (MeV)</th>
<th>Emitted Energy (MeV)</th>
<th>Approx. cross section (mb/sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2\text{H}$</td>
<td>$^2\text{H} (d,p) , ^3\text{H}$</td>
<td>1.0</td>
<td>2.3</td>
<td>5.2</td>
</tr>
<tr>
<td>$^2\text{H}$</td>
<td>$^2\text{H} (3\text{He},p) , ^4\text{He}$</td>
<td>0.7</td>
<td>13.0</td>
<td>61</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>$^6\text{Li} (d,\alpha) , ^4\text{He}$</td>
<td>0.7</td>
<td>9.7</td>
<td>35</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>$^7\text{Li} (p,\alpha) , ^4\text{He}$</td>
<td>1.5</td>
<td>7.7</td>
<td>9</td>
</tr>
<tr>
<td>$^{11}\text{B}$</td>
<td>$^{11}\text{B} (p,\alpha) , ^8\text{Be}$</td>
<td>0.65</td>
<td>5.57 ($\alpha\alpha$)</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.65</td>
<td>3.70 ($\alpha\alpha$)</td>
<td>550</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$^{12}\text{C} (d,p) , ^{13}\text{C}$</td>
<td>1.2</td>
<td>3.1</td>
<td>35</td>
</tr>
<tr>
<td>$^{15}\text{N}$</td>
<td>$^{15}\text{N} (p,\alpha) , ^{12}\text{C}$</td>
<td>0.8</td>
<td>3.9</td>
<td>15</td>
</tr>
<tr>
<td>$^{18}\text{O}$</td>
<td>$^{18}\text{O} (p,\alpha) , ^{15}\text{N}$</td>
<td>0.73</td>
<td>3.4</td>
<td>15</td>
</tr>
<tr>
<td>$^{19}\text{F}$</td>
<td>$^{19}\text{F} (p,\alpha) , ^{16}\text{O}$</td>
<td>1.25</td>
<td>6.9</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{23}\text{Na}$</td>
<td>$^{23}\text{Na} (p,\alpha) , ^{20}\text{Ne}$</td>
<td>0.592</td>
<td>2.238</td>
<td>4</td>
</tr>
<tr>
<td>$^{31}\text{P}$</td>
<td>$^{31}\text{P} (p,\alpha) , ^{28}\text{Si}$</td>
<td>1.514</td>
<td>2.734</td>
<td>16</td>
</tr>
</tbody>
</table>
NRA Example: GaNAs dilute nitride

1.3 MeV deuterium ions

$^{14}\text{N}(d,p)^{15}\text{N}$ and $^{14}\text{N}(d,\alpha)^{12}\text{C}$ reactions

GaNAs film with ~4% N

FIG. 1. Experimental NRA yields from GaNAs ((100) and random direction) and $^{14}\text{N}$ implanted Ta. Triangles and rings denote (100) and random yields, respectively. The values in the square brackets are the initial particle energies in mega-electron-volts before the mylar foil in front of the detector. Figures (a), (b), (c), and (d) corresponds to the reaction yield in different regions of particle energy.

Ion Channeling
Ion channeling
Ion Channeling

random

Planar channel

Axial channel
Ion Channeling

Kobelco Steel Group
Two important parameters to characterize channeling results:

1. Minimum yield:

\[ \chi_{\text{min}} = \frac{Y_{\text{channeled}}}{Y_{\text{random}}} \approx 0.02 - 0.06 \]

2. Critical half-angle, \( \psi_{1/2} \)

indicates presence of defects responsible for beam dechanneling
Ion Channeling: minimum yield and critical angle

Minimum Yield, $\chi_{\text{min}}$

\[ \chi_{\text{min}} = \frac{Y_{\text{channeled}}}{Y_{\text{random}}} \]

\[ \chi_{\text{min}} \approx \frac{\pi r_{\text{min}}^2}{\pi r_o^2} \sim 0.02 - 0.05 \]

Critical half-angle, $\psi_{1/2}$

\[ \Psi_c = \frac{1}{\sqrt{2}} \left( \frac{2Z_1 Z_2 e^2}{Ed} \right)^{1/2} \left\{ \ln\left[ \left( \frac{Ca}{\rho} \right)^2 + 1 \right] \right\}^{1/2} \]

where $d$ is the distance of atoms in a row, $a$ is the Thomas-Fermi screening distance, $r$ is rms thermal vibration

\[ \psi_{1/2} \sim \Psi_c \sim \left( \frac{2Z_1 Z_2}{E} \right)^2 \sim 0.5 - 1^\circ \]
Dechanneling by defects

- Perfect crystal channeling
- Small angle dechanneling - line defects
- Direct scattering - point defects

Dechanneled

Channelled

Backscattered

$^4\text{He}^+$
Homo- and Heteroepitaxy

FIG. 10.24. Random and \langle 111 \rangle channeling spectra for a 72 nm NiSi$_2$ epitaxial film on a (111) Si substrate (from Chu et al., 1980).
Channeling: Heteroepitaxy

\[ \text{\sim 530nm InN on 210 nm GaN} \]

\[ K. \ M. \ Yu \ et \ al., \ LBNL \ 2004. \]

\[ Z. \ Liliental-Weber \]
Amorphous layer analysis

(a) 

(b) 

(c) 

Energy (MeV)
Channeling: Impurity Lattice Location

Channel cross section

Lawrence Berkeley National Laboratory

K. M. Yu November 2008
Experimental techniques: combined channeling RBS/PIXE

Rutherford backscattering (RBS)

Particle-induced x-ray emission (PIXE)

**c-RBS:** crystalline quality of film (from GaAs backscattering yields)

**c-PIXE:** substitutionality of Mn atoms w.r.t. host GaAs
Channeling: Ga$_{1-x-y}$Be$_y$Mn$_x$As

Channeling RBS/PIXE:
- presence of interstitial Mn in GaAs
- [$\text{Mn}_I$] increases with Be doping
- Mn$_I$ reduces $T_C$

Examples of applications for IBA

- Thin film analysis: composition and thickness
- Multilayer analysis: identification of reaction products; obtaining reaction kinetics, activation energy, and moving species
- Composition analysis of bulk garnets
- Depth distribution of heavy ion implantation and/or diffusion in a light substrate
- Surface damage and contamination
- Providing calibration samples for other instrumentation such as secondary ion mass spectroscopy and Auger electron spectroscopy
- Defect depth distribution due to ion implantation damage or residue damage from improper annealing
- Lattice location of impurities in single crystal
- Surface atom relaxation of single crystal
- Lattice strain measurement of heteroepitaxy layers or superlattices