Development of NRA System for a 1.7 MV Tandem Accelerator

- Human Resource Development Program for Nuclear Engineering, The University of Tokyo -

Seiji Ito, Hiroyuki Matsuzaki, Akira Morita
The University of Tokyo
1. Specification of 1.7MV tandem accelerator: RAPID

Rutherford Backscattering Spectroscopic Analyzer, Particle Induced X-ray Emission and Ion Implantation Device

2. Development of New NRA system

3. Fluorine profiles in TiO$_2$ substrate using $^{19}$F(p,αγ)$^{16}$O reaction

4. Student experiment program

5. Summary
Specification of RAPID

Main usage so far:
- Ion Implantation
- RBS (Rutherford Backscattering Spectroscopy)
- PIXE (Particle Induced X-ray)

Potentially:
- Channeling, N-RBS, ERDA and NRA

**Specification**

- **Negative ion Sources**
  - Cs sputtering Type:
    - Extraction Voltage 20kV
  - Duoplasmatron Type:
    - Extraction Voltage 20kV

- **Accelerator**
  - Available voltage range: 0.1-1.7MV
  - Stability: < 30 Vrms

- **Produced beam current**
  - $H^+$: 25μA (3.4 MeV)
  - $He^{2+}$: 2.0μA (5.1 MeV)
  - $Si^{2+}$: 140μA (5.1 MeV)
  - $Au^{2+}$: 60μA (5.1 MeV)
Accelerator operation time since the installation

Fiscal years 1994 to 2011

Materials Engineering
Environmental Science
Cultural Property
New NRA System

To respond recent demand for the sensitive quantification of light elements (H, N, O, F, etc.), NRA detection system was newly developed at the end of the ion implantation line.
Outlook of New NRA System

The new NRA chamber is connected to the end port of the ion implantation chamber. It consists of the main chamber and the sample insertion port.
Main chamber

Top view of the main chamber. The special feature is a deeply scooped duct to make the BGO detector being close to the reaction position.

By this design, Large effective solid angle for the detector is realized.

Electron suppressor electrode is put in front of the target. The shape of the suppressor is specially designed to suppress secondary electrons effectively.
Target holder

Close-up of the target holder. It is made of metal stainless(sus304) plate and samples are just put on the plate. This plate can move up and down ward to select the sample to be analyzed.
A glass plate is put at the beam monitor position (a hole on the target holder metal plate) to make the beam monitor. The glass is lit by the beam and this light can be observed by a video camera set the end of the main port.

A fine copper mesh (opening 98%) is set in front of the glass to avoid charge-up.
The effect of the copper mesh

Comparison of observed ion current profiles with respect to the suppressor voltage:
(A) Beam is at the position of the metal plate
(B) Beam is at the beam monitor position (glass with mesh)

→ The mesh acts not only as charge-up suppressor but also as an electron suppressor!
Demonstration of newly developed NRA system

The NRA experiments were demonstrated using $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction. The experiment was to obtain the Fluorine depth profiles at the surface of TiO$_2$ substrate. The targets were prepared by F$^+$ ion implantation.

Target samples preparation: 3 conditions

A
- F$^+$ ion 524 keV
- Total dose: $1.0\times10^{16}$ ions/cm$^2$

B
- F$^+$ ion 524 keV
- Total dose: $5.0\times10^{16}$ ions/cm$^2$

C
- F$^+$ ion 1024 keV
- Total dose: $5.0\times10^{16}$ ions/cm$^2$

TiO$_2$ Rutile single crystal

Doped F atoms
The $^{19}\text{F}(p, \alpha \gamma)^{16}\text{O}$ reaction

The $1^{\text{st}}$ resonance (16.44MeV) (proton energy = 872keV)

The $2^{\text{nd}}$ resonance (17.5MeV) (proton energy = 935keV)

<table>
<thead>
<tr>
<th>Proton energy (keV)</th>
<th>Reaction</th>
<th>Gamma-ray energy (MeV)</th>
<th>Cross section (mb)</th>
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</thead>
<tbody>
<tr>
<td>872</td>
<td>$^{19}\text{F}(p, \alpha \gamma)^{16}\text{O}$</td>
<td>7.12, 6.92, 6.13</td>
<td>540</td>
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<tr>
<td>935</td>
<td>$^{19}\text{F}(p, \alpha \gamma)^{16}\text{O}$</td>
<td>7.12, 6.92, 6.13</td>
<td>180</td>
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</tbody>
</table>

Experimental results

$^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ reaction

Proton Energy [keV]

Relative yield [arbitrary unit]

A: 524keV; 1E16
B: 524keV; 5E16
C: 1024keV; 5E16
There observed shift of the resonant points for the 1\textsuperscript{st} resonance.
There also observed shift of the resonant points for the 2\textsuperscript{nd} resonance.
Summary of the observation

From the observation, positions (depths) of F ion doped were estimated as following.
The estimations from 1\textsuperscript{st} resonance data and 2\textsuperscript{nd} resonance data are consistent with each other.
The F ions doped with 524 keV was estimated to be at 810 – 840 nm depth.
The F ions doped with 1024 keV was estimated to be around at 1185 nm depth.

### Observation

<table>
<thead>
<tr>
<th></th>
<th>1\textsuperscript{st} resonance</th>
<th>2\textsuperscript{nd} resonance</th>
<th>Average Energy Loss*</th>
<th>Equivalent Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>872 keV</td>
<td>935 keV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B (524 keV)</td>
<td>932 keV</td>
<td>995 keV</td>
<td>(932 -&gt; 872)</td>
<td>809 nm</td>
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<tr>
<td></td>
<td>(\Delta = 60) keV</td>
<td>(\Delta = 60) keV</td>
<td>74.2 keV/\mu m</td>
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</tr>
<tr>
<td>C (1024 keV)</td>
<td>959 keV</td>
<td>1019 keV</td>
<td>(959 -&gt; 872)</td>
<td>1182 nm</td>
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<tr>
<td></td>
<td>(\Delta = 87) keV</td>
<td>(\Delta = 84) keV</td>
<td>73.6 keV/\mu m</td>
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</tr>
</tbody>
</table>

*Energy loss data are estimated by SLIM2008.
Student experiment program

The demonstrated experimental set up was applied to the student experiment program for the master course of the department of Nuclear Engineering. The results were very simple and helpful to understand the interaction between ions – target or ions – materials, thus very educational.
Summary

A NRA (Nuclear Reaction Analysis) system was developed at the RAPID accelerator facility, The University of Tokyo to meet sensitive quantification of light elements.

The NRA system has several features:
1) Chamber design for high counting efficiency.
2) Effective electron suppression.
3) Effective avoidance against charge-up by using fine copper mesh.

Especially, we found that the mesh acts not only as charge-up inhibitor but also as an electron suppressor. This indicates a possibility for the sophisticated sample holder without additional electron suppressor electrode.

The NRA experiments using $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ reaction were successfully demonstrated. Since the results were clear, this experimental setup was applied to the student experiment program.

The newly developed NRA system has great potential for the frontier research for the materials science and functional material process engineering.