Activities for Nuclear Data Measurements in Korea

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3rd Asian Nuclear Reaction Database Development Workshop
Aug. 27-29, 2012, Pohang, Korea
Activities for Nuclear Data Measurements in Korea

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We report activities for nuclear data measurements by using the pulsed neutron facility, which consists of an electron linear accelerator, a water-cooled Ta target with a water moderator, and a 12 m time-of-flight path. It can be possible to measure the neutron total cross-sections in the neutron energy range from 0.01 eV to few hundreds eV by using the neutron time-of-flight method and measured the photo-neutron cross-sections by using the bremsstrahlung from the electron linac.

We report the mass-yield distribution of fission products from \(^{nat}\)Pb, \(^{209}\)Bi, and \(^{232}\)Th with bremsstrahlung beams by using a recoil catcher and an off-line g-ray spectrometric technique. We report also the charged particle induced-reaction cross-section measurements with MC 50 cyclotron. In addition to this, we report the resonance parameters and resonance integral for gadolinium isotopes measured at a 25 m time-of-flight path with a 16-segment sodium iodide multiplicity detector in the Rensselaer Polytechnic Institute.
Activities for Nuclear Data Measurements Using Pohang Neutron Facility
Activities for Nuclear Data Measurements Using MC50 Cyclotron Facility
Activities for Nuclear Data Measurements Using a Pulsed Neutron Facility, RPI in US
Activities for Nuclear Data Measurements Using keV-Neutron Facility, JPARC, Japan
1) Neutron Total Cross-section measurements with TOF method
2) Measurement of Thermal Neutron Cross-sections and Resonance Integrals by Neutron Activation Method
3) Experiments with Bremsstrahlung Activation Method
Nuclear Data Measurements using Pohang Neutron Facility

Pohang Accelerator Laboratory

Pohang Neutron Facility based on 100-MeV e-linac

Pohang High Energy Radiation Facility with 3.0 GeV e-linac
1) Neutron Total Cross-section measurements by n-TOF method

Pohang Pulsed Neutron Facility (PNF)
1) Electron Linear Accelerator, 2) Target System
3) TOF Experimental Hall, 4) Data Acquisition System

1) Neutron Total Cross-section measurements by n-TOF method

Pohang Pulsed Neutron Facility (PNF)
1) Electron Linear Accelerator, 2) Target System
3) TOF Experimental Hall, 4) Data Acquisition System
(1) Electron Linear Accelerator

- Electron accelerator based Time of Flight system
  - Electron energy = 50 ~ 70 MeV
  - Repetition rate = Below 30Hz
  - Pulse width = 1 ~ 2 μs
  - Peak beam current = 30 ~ 60 mA
  - TOF flight length = 11.5~12m

- Target + water moderator: to produce neutron pulse
  - Ta plates + cooling system

Generated Neutron Spectrum at PNF
(2) Water Moderator for the Water-Cooled Ta-Target

Water level was fixed to 5 cm above the target surface.
(3) Data Acquisition System

Current DAQ

FADC DAQ
One 100 MHz 10-bit 8 channel FADC Module in VME crate
Measurement of Neutron Total Cross Section

1. Neutron Energy $E$ in eV corresponding to channel $I$ in TOF

$$E[eV] = \left( \frac{72.3 \times L[m]}{(I - I_0) \times W[\mu s]} \right)^2$$

$L$: flight path length
$W$: channel width

2. Experimental Set up

3. Neutron Transmission rate

$$T(E_i) = \frac{[In(E_i) - In^B(E_i)] / M_{In}}{[Out(E_i) - Out^B(E_i)] / M_{Out}}$$

4. Total Cross Section

$$\sigma(E_i) = -\frac{1}{N} \ln T(E_i)$$

$N$: atomic density

5. Total Cross Section after Purity Correction

$$\sigma = M_T \cdot \sum_j P_j \sigma_j M_j^{-1} \times 10^{-6}$$

$$\sigma_T = \frac{\sigma - M_T \cdot \sum_j P_j \times 10^{-6}}{1 - \sum_j P_j \times 10^{-6}}$$

$\sigma$: measured total cross section
$M_T$: total weight of sample
$\sigma_j$: weight of impurity sample
$P_j$: impurity in ppm
Neutron TOF Spectra for Measuring Nb Cross sections

\[ \sigma(E_j) = - \frac{1}{N_i} \sum_i T(E_j) \quad T(E_j) = \frac{[I(E_j) - IB(E_j)]}{[O(E_j) - OB(E_j)]/M_o} \]

\[ (\Delta \sigma_{stat.})_j = \frac{1}{N_i} \sqrt{\frac{[I(E_i) + IB(E_i)]}{[I(E_i) - IB(E_i)]^2} + \frac{O(E_i) + OB(E_i)}{[O(E_i) - OB(E_i)]^2}} \]
Measurements of neutron total cross-sections and resonance parameters of niobium using pulsed neutrons generated by an electron linac

Taofeng Wang · Guinyun Kim · Man-Woo Lee · Kyung-Sook Kim · Moo-Hyun Cho · Heung-Sik Kang · Won Namkung
### Foil Specifications

<table>
<thead>
<tr>
<th>Foil</th>
<th>Size (mm)</th>
<th>Weight (g)</th>
<th>Thickness (mm)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au 11</td>
<td>18×18</td>
<td>0.1863±0.0005</td>
<td>0.03</td>
<td>99.95</td>
</tr>
<tr>
<td>Au 12</td>
<td>18×18</td>
<td>0.1885±0.0005</td>
<td>0.03</td>
<td>99.95</td>
</tr>
<tr>
<td>W 1</td>
<td>18×18</td>
<td>1.2636±0.0008</td>
<td>0.2</td>
<td>99.95</td>
</tr>
<tr>
<td>W 2</td>
<td>18×18</td>
<td>1.2891±0.0008</td>
<td>0.2</td>
<td>99.95</td>
</tr>
<tr>
<td>In 1</td>
<td>18×18</td>
<td>0.1276±0.0004</td>
<td>0.05</td>
<td>99.99</td>
</tr>
<tr>
<td>In 2</td>
<td>18×18</td>
<td>0.1217±0.0004</td>
<td>0.05</td>
<td>99.99</td>
</tr>
<tr>
<td>In 3</td>
<td>18×18</td>
<td>0.1214±0.0004</td>
<td>0.05</td>
<td>99.99</td>
</tr>
<tr>
<td>In 4</td>
<td>18×18</td>
<td>0.1220±0.0004</td>
<td>0.05</td>
<td>99.99</td>
</tr>
<tr>
<td>In 5</td>
<td>18×18</td>
<td>0.1271±0.0004</td>
<td>0.05</td>
<td>99.99</td>
</tr>
<tr>
<td>In 6</td>
<td>18×18</td>
<td>0.1245±0.0004</td>
<td>0.05</td>
<td>99.99</td>
</tr>
</tbody>
</table>

2) Measurement of Thermal Neutron Cross-sections and Resonance Integrals by Neutron Activation Method
Data Analysis

\[ \sigma_{0, Ho} = \sigma_{0, Au} \times \frac{R_{Ho} - F_{Ho, Cd} R_{Ho, Cd}}{R_{Au} - F_{Au, Cd} R_{Au, Cd}} \times \frac{G_{th, Au}}{G_{th, Ho}} \times \frac{g_{Au}}{g_{Ho}} \]

or \[ R_{Ho(Au)} = \frac{N_{obs} \lambda (1 - e^{-\lambda T})}{n_0 \varepsilon I_\gamma (1 - e^{-\lambda t_i}) (1 - e^{-\lambda t_i}) e^{-\lambda t_c} (1 - e^{-\lambda t_c})} \]

\[ I_{0, Ho}(\alpha) = I_{0, Au}(\alpha) \times \frac{g_{Ho} \sigma_{0, Ho}}{g_{Au} \sigma_{0, Au}} \times \frac{CR_{Au} - F_{Au, Cd}}{CR_{Ho} - F_{Ho, Cd}} \times \frac{G_{epi, Au}}{G_{th, Au}} \times \frac{G_{th, Ho}}{G_{epi, Ho}} \]

<table>
<thead>
<tr>
<th>Nuclear reaction</th>
<th>Half-life, T_{1/2}</th>
<th>Main gamma- rays</th>
<th>Isotopic abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>165Ho(n,γ)166gHo</td>
<td>26.824 h (12)</td>
<td>80.576(2)</td>
<td>6.56(13)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1379.437(6)</td>
<td>0.922</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1581.834(7)</td>
<td>0.182(3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1662.439(6)</td>
<td>0.1191(20)</td>
</tr>
<tr>
<td>197Au(n,γ)198Au</td>
<td>2.69517 d (21)</td>
<td>411.80205 (17)</td>
<td>95.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>675.8836 (7)</td>
<td>0.084 (3)</td>
</tr>
<tr>
<td>115In(n,γ)116mIn</td>
<td>54.41 min (17)</td>
<td>416.86 (3)</td>
<td>27.7 (12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1097.3 (2)</td>
<td>56.2 (11)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1293.54 (15)</td>
<td>84.4 (17)</td>
</tr>
</tbody>
</table>

* Gamma rays used in calculations
Measurement of thermal neutron cross-section and resonance integral for the $^{165}$Ho($n,\gamma$)$^{166}$Ho reaction using electron linac-based neutron source

Van Do Nguyen$^a$, Duc Khue Pham$^a$, Tien Thanh Kim$^a$, Guinyun Kim$^b,*,$ Manwoo Lee$^b$, Kyung Sook Kim$^b$, Heung-Sik Kang$^c$, Moo-Hyun Cho$^c$, In Soo Ko$^c$, Won Namkung$^c$

$^a$Institute of Physics, Vietnam Academy of Science and Technology, 10 Dao Tan, Hanoi, Viet Nam
$^b$Department of Physics, Kyungpook National University, Daegu 702-701, Republic of Korea
$^c$Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
Thermal Neutron Cross-sections of the $^{165}\text{Ho}(n,\gamma)^{166}\text{gHo}$ reaction.
Resonance Integrals of the $^{165}$Ho(n,γ)$^{166}$gHo reaction
A. Photo-nuclear Reaction
   • Isomeric Yield Ratio Measurement

B. Photo-fission Reaction
   • Mass yield distribution
   • \((\gamma, xn)\) reaction cross section

3) Experiments with Bremsstrahlung Activation Method
Isomeric Yield Ratio Measurement

Experimental Arrangement

- Electron energy: 50, 60, 70 MeV, 2.5 GeV
- Target: thin W (50 mm × 50 mm × 0.2 mm)
## Isomeric-yield ratios

For $^{120m,g}$Sb, $^{122m,g}$Sb, $^{109m,g}$Pd, and $^{115m,g}$Cd

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Weight (g)</th>
<th>Purity (%)</th>
<th>$E_{\text{max. Bremss.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sb40</td>
<td>12</td>
<td>1.78</td>
<td>0.1350</td>
<td>99.999</td>
<td>40 MeV</td>
</tr>
<tr>
<td>Sb45</td>
<td>12</td>
<td>1.67</td>
<td>0.1261</td>
<td>99.999</td>
<td>45 MeV</td>
</tr>
<tr>
<td>Sb50</td>
<td>12</td>
<td>1.90</td>
<td>0.1440</td>
<td>99.999</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Sb55</td>
<td>12</td>
<td>1.77</td>
<td>0.1340</td>
<td>99.999</td>
<td>55 MeV</td>
</tr>
<tr>
<td>Sb60</td>
<td>12</td>
<td>1.82</td>
<td>0.1378</td>
<td>99.999</td>
<td>60 MeV</td>
</tr>
</tbody>
</table>

### Beam Condition

<table>
<thead>
<tr>
<th>Sample</th>
<th>Energy (MeV)</th>
<th>Current (mA)</th>
<th>Pulse width (µs)</th>
<th>Repetition rate (Hz)</th>
<th>Irradiation time (h)</th>
<th>Purity (%)</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>natPd</td>
<td>50</td>
<td>21±2</td>
<td>2.0</td>
<td>15</td>
<td>1.11</td>
<td>99.97</td>
<td>13.48±0.07</td>
<td>0.05±0.0025</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>21±2</td>
<td>2.0</td>
<td>15</td>
<td>2.66</td>
<td>99.97</td>
<td>14.79±0.07</td>
<td>0.05±0.0025</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>36±3</td>
<td>2.0</td>
<td>15</td>
<td>1.00</td>
<td>99.97</td>
<td>13.22±0.05</td>
<td>0.05±0.0025</td>
</tr>
<tr>
<td>natCd</td>
<td>50</td>
<td>21±2</td>
<td>2.0</td>
<td>15</td>
<td>3.94</td>
<td>99.99</td>
<td>22.91±0.08</td>
<td>0.05±0.0025</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>30±3</td>
<td>2.0</td>
<td>15</td>
<td>3.62</td>
<td>99.99</td>
<td>15.78±0.05</td>
<td>0.05±0.0025</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>36±3</td>
<td>2.0</td>
<td>15</td>
<td>1.72</td>
<td>99.99</td>
<td>24.10±0.07</td>
<td>0.05±0.0025</td>
</tr>
</tbody>
</table>
Decay scheme and Nuclear reactions leading to $^{109m,g}$Pd, $^{115m,g}$Cd isomeric pairs

<table>
<thead>
<tr>
<th>Nuclear reaction</th>
<th>Threshold energy, $E_{th}$ (MeV)</th>
<th>Half-life, $T_{1/2}$</th>
<th>Spin states, $J^\pi$</th>
<th>$\gamma$-ray energy, $E_\gamma$ (keV)</th>
<th>$\gamma$-ray intensity, $I_\gamma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{110}$Pd($\gamma,n$)$^{109}$Pd</td>
<td>8.81</td>
<td>13.70 h</td>
<td>5/2$^+$</td>
<td>88.04* 311.40 647.30</td>
<td>3.6 0.032 0.024</td>
</tr>
<tr>
<td>$^{110}$Pd($\gamma,n$)$^{109m}$Pd</td>
<td>9.00</td>
<td>4.696 m</td>
<td>11/2$^-$</td>
<td>188.99*</td>
<td>55.9</td>
</tr>
<tr>
<td>$^{116}$Cd($\gamma,n$)$^{115}$Cd</td>
<td>8.70</td>
<td>53.46 h</td>
<td>1/2$^+$</td>
<td>260.89 336.24 492.30 527.90*</td>
<td>1.94 45.90 8.03 27.45</td>
</tr>
<tr>
<td>$^{116}$Cd($\gamma,n$)$^{115m}$Cd</td>
<td>8.81</td>
<td>44.6 d</td>
<td>11/2$^-$</td>
<td>158.03 484.47 933.80* 1290.58</td>
<td>0.017 0.29 2 0.89</td>
</tr>
</tbody>
</table>
Methodology

\[ \sigma_m \] isomeric state \\
\[ \text{target nuclei} \] \\
\[ \sigma_g \] ground state \\
\[ \lambda_g \rightarrow \text{stable} \]

\[ \frac{dN_m}{dt} = Y_m - \lambda_m N_m \]

\[ \frac{dN_g}{dt} = Y_g - \lambda_g N_g + P \lambda_m N_m \]

where: \( N_m, N_g \) are the numbers of nuclei for m, g state, \( \lambda_m \) and \( \lambda_g \) are the decay constants of these states, and \( P \) is the branching ratio for the decay of metastable to ground state. \( Y_m \) and \( Y_g \) are the reaction yields.

- **Reaction Yield:**
  \[ Y = N_o \phi \sigma = \frac{C \lambda (1 - e^{-\lambda T})}{\varepsilon I \gamma F (1 - e^{-\lambda t_i}) (1 - e^{-\lambda t_d}) (1 - e^{-\lambda t_m})} \]

where: \( C \) is the net counts under the full-energy peak, \( N_o \) is the number of target nuclei, \( \varepsilon \) is the detector efficiency, \( I \gamma \) is the intensity of the gamma-ray, \( \lambda \) is the decay constant, \( F \) is correction factor, \( t_i \) is the irradiation time, \( t_d \) is the waiting time, \( t_m \) is the measuring time, \( \tau \) is the pulse width, and \( T \) is the cycle period.

- **Isomeric Ratio:**
  \[ IR = \frac{\sigma_m}{\sigma_g} = \left[ \frac{C_g}{C_m} \times \frac{\varepsilon_m I_{gm}}{\varepsilon_g I_{gg}} - \frac{P \lambda_g}{\lambda_g - \lambda_m} \right] \times \frac{A_m B_m C_m D_m}{A_g B_g C_g D_g} + \frac{P \lambda_m}{\lambda_g - \lambda_m} \]

where:

\[ A_{m(g)} = \frac{1 - e^{-\lambda_m(g) T}}{1 - e^{-\lambda_m(g) T}} e^{\lambda_m(g) (T - \tau)} \]
\[ B_{m(g)} = \frac{1 - e^{-\lambda_m(g) t_i}}{\lambda_m(g)} \]
\[ C_{m(g)} = e^{\lambda_m(g) t_w} \]
\[ D_{m(g)} = 1 - e^{-\lambda_m(g) t_c} \]
Measured isomeric yield ratios of $^{109m,g}$Pd, $^{115m,g}$Cd pairs

$^{110}$Pd$(\gamma,n)^{109m,g}$Pd

$^{116}$Cd$(\gamma,n)^{115m,g}$Cd

Measured isomeric yield ratios of $^{120m,g}$Sb, $^{122m,g}$Sb pairs

Results of Isomeric Yield Ratio Measurement

Isomeric yield ratios in the photoproduction of $^{52m,g}$Mn from natural iron using 50-, 60-, 70-MeV, and 2.5-GeV bremsstrahlung


Van Do Nguyen · Duc Khue Pham · Tien Thanh Kim · Md. Shakilur Rahman · Kyung-Sook Kim · Guinyun Kim · Hee-Seock Lee · Moo-Hyun Cho · In Soo Ko · Won Namkung · Tae-Ik Ro

Measurement of isomeric-yield ratios for the $^{197}$Au(γ,n)$^{196m,g}$Au reactions induced by bremsstrahlung


Md. Shakilur Rahman · Kyung-Sook Kim · Manwoo Lee · Guinyun Kim · Youngdo Oh · Hee-Seock Lee · Moo-Hyun Cho · In Soo Ko · Won Namkung · Van Do Nguyen · Duc Khue Pham · Tien Thanh Kim · Tae-Ik Ro

Measurement of isomeric yield ratios for $^{93}$Nb(γ,4n)$^{89m,g}$Nb and $^{nat}$Mo(γ,xn1p)$^{95m,g}$Nb reactions with 50-, 60-, and 70-MeV bremsstrahlung


Kyung Sook Kim · MD. Shakilur Rahman · Manwoo Lee · Guinyun Kim · Pham Duc Khue · Nguyen Van Do · Moo-Hyun Cho · In Soo Ko · Won Namkung · H. Naik · Tae-Ik Ro

Measurement of isomeric yield ratios in $^{nat}$In and $^{nat}$Sn with 50, 60, and 70 MeV bremsstrahlung photons


Md. Shakilur Rahman$^a$, Kyung-Sook Kim$^a$, Manwoo Lee$^a$, Guinyun Kim$^{a,*}$, Youngdo Oh$^b$, Hee-Seock Lee$^b$, Moo-Hyun Cho$^b$, In Soo Ko$^b$, Won Namkung$^b$, Nguyen Van Do$^c$, Pham Duc Khue$^c$, Kim Tien Thanh$^c$, Tae-Ik Ro$^d$
Photo-fission Reaction

Mass–yield distributions of fission products from photo-fission of natPb induced by 50–70 MeV bremsstrahlung


Haladhara Naik · Guinyun Kim · Ashok Goswami · Sarbjit Singh · Vijay Kumar Manchanda · Devesh Raj · Srinivasan Ganesan · Young Do Oh · Hee-Seock Lee · Kyung Sook Kim · Man-Woo Lee · Moo-Hyun Cho · In Soo Ko · Won Namkung

Mass–yield distribution of fission products from photo-fission of natPb induced by 2.5 GeV bremsstrahlung


Haladhara Naik1, Sarbjit Singh1, Ashok Goswami1, Vijay Kumar Manchanda1, S.V. Suryanarayana2, Devesh Raj3, Srinivasan Ganesan3, Md. Shakibur Rahman4, Kyung Sook Kim4, Man Woo Lee4, Guinyun Kim4,a, Moo-Hyun Cho5, In Soo Ko5, and Won Namkung5

Product yields for the photo-fission of 209Bi with 2.5 GeV bremsstrahlung


Haladhara Naik2, Sarbjit Singh2, Annareddy Venkat Raman Reddy2, Vijay Kumar Manchanda2, Guinyun Kim b, Kyung Sook Kim b, Man-Woo Lee b, Srinivasan Ganesan c, Devesh Raj c, Hee-Seock Lee d, Young Do Oh d, Moo-Hyun Cho d, In Soo Ko d, Won Namkung d

Measurement of photo-neutron cross-sections in 208Pb and 209Bi with 50-70 MeV bremsstrahlung

Mass-yield distributions of fission products from photo-fission of \( ^{\text{nat}}\text{Pb} \) by 50-70 MeV and 2.5-GeV bremsstrahlung

Measured yields of fission products (%) from (a) 2.5-GeV, (b) 70-MeV, (c) 60-MeV, and (d) 50-MeV bremsstrahlung induced fission of \( ^{\text{nat}}\text{Pb} \) as a function of mass number. The line indicated the fitting for measured data points.

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Energy (MeV)</th>
<th>Mean mass (mass units)</th>
<th>FWHM (mass units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{\text{nat}}\text{Pb} )</td>
<td>50</td>
<td>102.34</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>102.25</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>102.03</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>94.0±0.5</td>
<td>55.0±2.0</td>
</tr>
</tbody>
</table>
Mass-yield distributions of fission products from photo-fission of $^{209}$Bi induced by 50-70 MeV and 2.5-GeV bremsstrahlung.

<table>
<thead>
<tr>
<th>Fissioning nuclei</th>
<th>Energy (MeV)</th>
<th>Mean mass (mass units)</th>
<th>FWHM (mass units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{209}$Bi</td>
<td>28-40</td>
<td>103.5</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>103.1</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>102.7</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>102.5</td>
<td>23.0</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>$100.4 \pm 1.4$</td>
<td>$34.8 \pm 0.7$</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>$100.8 \pm 1.8$</td>
<td>$35.0 \pm 1.0$</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>$98.5 \pm 1.0$</td>
<td>$40.0 \pm 1.0$</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>$95.0 \pm 0.5$</td>
<td>$51.0 \pm 2.0$</td>
</tr>
</tbody>
</table>
The FWHM and the mean mass of the mass-yield distributions for the photo-fission of $^{\text{nat}}\text{Pb}$ and $^{209}\text{Bi}$
Determination of Yields for Fission Products

- From the observed number of γ-rays ($N_{\text{obs}}$) under the photo-peak of each individual fission product, their cumulative yields ($Y_R$) relative to $^{135}\text{I}$ were determined by:

\[
N_{\text{obs}}(CL / LT) = n \sigma_F(E) \Phi I_\gamma \varepsilon Y_R (1 - e^{-\lambda t_{\text{irr}}}) e^{-\lambda t_{\text{cool}}} (1 - e^{-\lambda CL}) / \lambda
\]

where $n$ is the number of target atoms $\sigma_F(E)$ is the photo-fission cross-section of the target nuclei and $\Phi$ is the integrated photon flux from the reaction threshold ($E_b$) to the end-point energy ($E_e$) for the photon flux ($\phi$) at the photon energy $E$. The $t_{\text{irr}}$ and $t_{\text{cool}}$ are the irradiation and the cooling time, and $CL$ and $LT$ are the real and the live times of counting, respectively. $\lambda$ is the decay constant of the isotope of interest and $\varepsilon$ is the detection efficiency of the γ-rays in the detector system. $I_\gamma$ is the abundance or the branching intensity of the chosen γ-rays of the reaction products.

- From the relative cumulative yields ($Y_R$) of the fission products, their relative mass-chain yields ($Y_A$) were determined by:

\[
Y_A = Y_R / FCY, \quad FCY = \frac{EOF^a(Z)}{\sqrt{2\pi\sigma_z^2}} \int_{-\infty}^{Z+0.5} \exp[-(Z - Z_P)^2 / 2\sigma_z^2] dZ
\]

where $Z_P$ is the most probable charge and $\sigma_z$ is the width parameter of an isobaric yield distribution. $EOF^a(Z)$ is the even-odd effect with $a(Z) = +1$ for even $Z$ nuclides and -1 for odd-$Z$ nuclides.
Fig. 1. Yields of Fission Products (%) for bremsstrahlung-induced fission of $^{232}$Th
Bremsstrahlung-induced fission of $^{238}$U

Bremsstrahlung-induced fission of $^{232}$Th

[Fig. 2] Yields of fission products (%) as a function of mass number in (a) 10-MeV, (b) 40-MeV, and (c) 70-MeV bremsstrahlung-induced fission of $^{238}$U and in (d) 10-MeV, (e) 40-MeV, and (f) 70-MeV bremsstrahlung-induced fission of $^{232}$Th.
[Fig. 3] Yields of fission products (%) as a function of mass number in the neutron-induced fission of $^{238}\text{U}$ at (a) 7.35-MeV, (b) 12.45-MeV, and (c) 19.15-MeV excitation energies and in the neutron-induced fission of $^{232}\text{Th}$ at (d) 7.61-MeV, (e) 12.61-MeV, and (f) 19.41-MeV excitation energies.
From Figs. 1, 2, and 3 that there is a well-known third peak around the symmetric mass region in the mass-yield distribution of \(^{232}\text{Th}(\gamma,f)\) and \(^{232}\text{Th}(n,f)\) reactions, which is absent in the case of \(^{238}\text{U}(\gamma,f)\) (Fig. 2) and \(^{238}\text{U}(n,f)\) (Fig. 3). This is due to the fact that the type of potential barrier for \(^{232}\text{Th}\) differs from that for \(^{238}\text{U}\), as shown by Moller, who calculated the saddle point configurations against the mass asymmetric deformation.

From Figs. 2 and 3, the yields of fission products for \(A=133-134, 138-139, 143-144\), and their complementary products in the bremsstrahlung- and the neutron-induced fission of \(^{232}\text{Th}\) are higher than those of the other fission products. Similar observation was shown by us in the neutron-induced fission of various actinides and also in the 10-MeV bremsstrahlung-induced fission of \(^{232}\text{Th}, ^{238}\text{U}, \text{and} ^{240}\text{Pu}\).

From Figs. 2-3, the yields of fission products for \(A=133-134\) are lower than those for \(A=143-144\) in \(^{232}\text{Th}(\gamma,f)\), whereas those are reversed in \(^{232}\text{Th}(n,f), ^{238}\text{U}(n,f), \text{and} ^{238}\text{U}(\gamma,f)\).
Yield of fission products with different mass number

(a) $A=143$ in $^{232}$Th($\gamma,f$)  
$A=143$ in $^{232}$Th(n,f)

(b) $A=139$ in $^{232}$Th($\gamma,f$)  
$A=139$ in $^{232}$Th(n,f)

(c) $A=134$ in $^{232}$Th($\gamma,f$)  
$A=134$ in $^{232}$Th(n,f)

(a) $A=143$ in $^{238}$U($\gamma,f$)  
$A=143$ in $^{238}$U(n,f)

(b) $A=139$ in $^{238}$U($\gamma,f$)  
$A=139$ in $^{238}$U(n,f)

(c) $A=134$ in $^{238}$U($\gamma,f$)  
$A=134$ in $^{238}$U(n,f)
The yields of fission products for $A=133-134$ in the $^{232}\text{Th}(\gamma,f)$ reaction at lower excitation energy are lower than those in the $^{232}\text{Th}(n,f)$, $^{238}\text{U}(n,f)$, and $^{238}\text{U}(\gamma,f)$ reactions, whereas those for $A=143-144$ are reversed. The yield of fission products for $A=133-134$ increases but that of fission products for $A=143-144$ in $^{232}\text{Th}(\gamma,f)$ decreases with increasing the excitation energy.

On the other hand, the yields of fission products for $A=133-134$, $138-139$, and $143-144$ in the $^{232}\text{Th}(n,f)$, the $^{238}\text{U}(n,f)$, and the $^{238}\text{U}(\gamma,f)$ reactions decrease with increasing the excitation energy.

The increasing or the decreasing trends of fission product yields in the above fissioning systems with increasing the excitation energy are due to the different shell combinations in the complementary products, which changed with increasing the number of neutron evaporation.
Nuclear Data Measurements using MC 50 Cyclotron at KIRAMS

Proton Beam

45 MeV

1 mm

30 mm

Al Cu Cd Al Cu Cd Al Cu Cd

30 mm

42.1 MeV

HV(-3.5kV) AMP. MCA

Irradiated sample Pb bricks

MC-50 cyclotron

RT target irradiation

Low intensity irradiation

Horizontal beam

Neutron and High Intensity Irradiation

Vertical beam

Low energy

Nuclear interaction, etc.
<table>
<thead>
<tr>
<th>Projectile (MeV)</th>
<th>Target</th>
<th>Investigated radionuclides</th>
<th>Publication</th>
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<tr>
<td>Proton (35 MeV)</td>
<td>natMo</td>
<td>$^{99m}$Tc, $^{96m,g}$Tc, $^{95m}$Tc, $^{95g}$Tc</td>
<td><em>J. Korean Phys. Soc.</em>, 48 (2006) 821</td>
</tr>
<tr>
<td>Proton (35 MeV)</td>
<td>natMo</td>
<td>$^{94m}$Tc, $^{94g}$Tc, $^{93m}$Tc, $^{93g}$Tc</td>
<td><em>J. Korean Phys. Soc.</em>, 50 (2007) 1518</td>
</tr>
<tr>
<td>Proton (45 MeV)</td>
<td>natZn</td>
<td>$^{66,67}$Ga, $^{62,65,69m}$Zn, $^{61}$Cu</td>
<td><em>NIM B</em> 258 (2007) 313</td>
</tr>
<tr>
<td>Proton (45 MeV)</td>
<td>natMo</td>
<td>$^{99m,96g,96m,95m,95g}$, $^{94m,94g,93m,93g}$Tc, $^{99,93m}$Mo, $^{96,95g,90}$Nb, $^{89g}$Zr</td>
<td><em>NIM B</em> 262 (2007) 171</td>
</tr>
<tr>
<td>Proton (45 MeV)</td>
<td>natZr</td>
<td>$^{90,92m}$, $^{95g,96}$Nb, $^{88,89}$Zr, $^{86,87m,87mg,88}$Y</td>
<td><em>NIM B</em> 266 (2008) 13</td>
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<tr>
<td>Proton (45 MeV)</td>
<td>natW</td>
<td>$^{181,182m,182g,183,184g,186}$Re</td>
<td><em>NIM B</em> 266 (2008) 1021</td>
</tr>
<tr>
<td>Proton (45 MeV)</td>
<td>natCd</td>
<td>$^{107,111m,115g}$Cd, $^{108m,108g,109g,110m,110,111g,113m,114m,115m,116m}$In, $^{104g,105g,106m,110m,111g,113g}$Ag</td>
<td><em>NIM B</em> 266 (2008) 4877</td>
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<td>Proton (45 MeV)</td>
<td>natAg</td>
<td>$^{104g,105,106m}$Ag, $^{104,107}$Cd</td>
<td><em>NIM B</em> 266 (2008) 5101</td>
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<td>Proton (45 MeV)</td>
<td>natSn</td>
<td>$^{124,122,120m,118m,117}$Sb, $^{117m,113}$Sn, $^{114m,111,110}$In</td>
<td><em>NIM B</em> 267 (2009) 23</td>
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<tr>
<td>Proton (45 MeV)</td>
<td>natZr</td>
<td>$^{86g,87m,87g}$Y, $^{88,89g}$Zr, $^{90,92m}$Nb</td>
<td><em>ARI</em> 67 (2009) 1341</td>
</tr>
<tr>
<td>Proton (45 MeV)</td>
<td>natTi</td>
<td>$^{48}$V, $^{43,44m,44g,46,47,48}$Sc</td>
<td><em>ARI</em> 67 (2009) 1348</td>
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<tr>
<td>Proton (45 MeV)</td>
<td>natPd</td>
<td>$^{105g+m,106m}$Ag, $^{100,101}$Pd, $^{100g+m,101m,105g+m}$Rh</td>
<td><em>NIM B</em> 268 (2010) 2303</td>
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<tr>
<td>Proton (45 MeV)</td>
<td>natNi</td>
<td>$^{55,56,57,58m+g}$Co, $^{56,57}$Ni</td>
<td><em>NIM B</em> 269 (2011) 1140</td>
</tr>
</tbody>
</table>
Determination of beam flux

\[ \phi = \frac{\lambda C}{\epsilon \times I_\gamma \times N_d \times t \times \sigma (1 - e^{-\lambda t_m}) e^{-\lambda t_c} (1 - e^{-\lambda t_i})} \]

\[ T_{1/2} = 9.186 \text{ h} \]
\[ \mathcal{E} = \frac{CPS}{A_0 e^{-\lambda t} \times I_\gamma} \]
Reaction Rate

\[ R = \frac{\lambda C}{\varepsilon I_\gamma N Q (1 - e^{-\lambda t_m}) e^{-\lambda t_c} (1 - e^{-\lambda t_i})} \]

Cross-Sections

\[ \sigma = \frac{RQN}{\phi N d l} \]

- \( R \) = Reaction rate
- \( \lambda \) = decay constant, \( \text{s}^{-1} \)
- \( C \) = total counts of gamma-ray peak area
- \( N \) = number of target atoms, \( \text{atom} \)
- \( \varepsilon \) = peak efficiency
- \( I_\gamma \) = branching ratio of gamma-ray
- \( t_c, t_m, t_{irr} \) = cooling time, measuring time, irradiation time (s)
- \( Q \) = proton beam current, coulomb.

\[ \sigma = \frac{\lambda C}{\varepsilon I_\gamma N d \times t \times \phi (1 - e^{-\lambda t_m}) e^{-\lambda t_c} (1 - e^{-\lambda t_i})} \]
Measured Cross sections of $^{nat}\text{Fe}(p,x)$
Measured Cross sections of $^{nat}Fe(p,x)$

$^{nat}Fe(p,x)^{51}Cr$
- This work
- M. Al-Abyad (2009)
- I.F. Barchuk (1987)
- I.R. Williams (1967)
- R. Michel (1979)
- R. Michel (1997)
- TALYS

$^{nat}Fe(p,x)^{52}Mn$
- This work
- I.R. Williams (1967)
- M.C. Lagunas-Solar (1979)
- TALYS

$^{nat}Fe(p,x)^{54}Mn$
- This work
- E. Daum (1997)
- I.F. Barchuk (1987)
- I.R. Williams (1967)
- M. Al-Abyad (2009)
- R.L. Brodzinski (1971)
- R. Michel (1979)
- R. Michel (1997)
- TALYS
Measured Cross sections of $^{nat}Fe(\alpha,x)$
Measured Cross sections of $^{nat}Fe(\alpha, x)$
Measured Cross sections of $^{nat}Y(p,x)$

- $^{89}Y(p,x)^{89\text{g}}Zr$
- $^{89}Y(p,x)^{88\text{g}}Y$
- $^{89}Y(p,x)^{88\text{g}}Sr$

Data sources include:
- Blosser & Handley '55
- Albert '59
- Saha et al., '66
- Birattari et al., '73
- Mustafa et al., '88
- Levkovskij '91
- Wenrong et al., '92
- Michel et al., '97
- Uddin et al., '05
- Omar et al., '09
- Steyn et al., '10
- This work

Comparisons with theories:
- ALICE-IPPE
- TALYS
Measured Cross sections of \(^{nat}\)Y(p,x)

- \(^{89}\)Y(p,x)\(^{87}\)Y
  - Michel et al., '97
  - Uddin et al., '05
  - This work
  - ALICE-IPPE \(^{87}\)Y+\(^{87}\)Zr
  - TALYS \(^{87}\)Y+\(^{87}\)Zr

- \(^{89}\)Y(p,x)\(^{87m}\)Y
  - Saha et al., '66
  - West et al., '93
  - Michel et al., '97
  - Uddin et al., '05
  - This work
  - TALYS \(^{87m}\)Y+\(^{87}\)Zr

- \(^{89}\)Y(p,x)\(^{84}\)Rb
  - Michel et al., '97
  - Uddin et al., '05
  - This work
  - ALICE-IPPE (Total)
  - TALYS (Total)

- \(^{89}\)Y(p,x)\(^{86}\)Y
  - Michel et al., '97
  - Uddin et al., '05
  - This work
  - ALICE-IPPE \(^{86}\)Y+\(^{86}\)Zr
  - TALYS \(^{86}\)Y+\(^{86}\)Zr
Cyclotron at CYRIC, Tohoku Univ.

Deutron Beam Energy

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<tr>
<td>65 MeV</td>
<td>40 MeV</td>
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</tr>
<tr>
<td>50μA</td>
<td>100nA</td>
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http://www.cyric.tohoku.ac.jp/english/cyric/avfproe/avfproe1.html
Measured Cross sections of $^{nat}Fe(d,x)$

$^{nat}Fe(d,x)^{51}Cr$
- This work
- J.W.Clark(1969)
- TALYS

$^{nat}Fe(d,x)^{52}Mn$
- This work
- B.Kiraly(2009)
- ZhaoWenrong(1995)
- TALYS

$^{nat}Fe(d,x)^{54}Mn$
- This work
- B.Kiraly(2009)
- J.W.Clark(1969)
- ZhaoWenrong(1995)
- TALYS

$^{nat}Fe(d,x)^{56}Mn$
- This work
- J.W.Clark(1969)
- TALYS
Measured Cross sections of $^{nat}Fe(d,x)$

- $^{nat}Fe(d,x)^{55}Co$
  - Thiw work
  - B. Kiraly(2009)
  - J.W. Clark(1969)
  - Zhao Wenrong(1995)

- $^{nat}Fe(d,x)^{56}Co$
  - This work
  - B. Kiraly(2009)
  - J.W. Clark(1969)
  - M. Nakao(2006)
  - P. Jung(1991)
  - Zhao Wenrong(1995)
  - S. Takacs(1996)
  - S. Takacs(2001)

- $^{nat}Fe(d,x)^{57}Co$
  - This work
  - A. Hermanne
  - B. Kiraly(2009)
  - S. Takacs(1996)
  - Zhao Wenrong(1995)

- $^{nat}Fe(d,x)^{58}Co$
  - This work
  - B. Kiraly(2009)
  - Zhao Wenrong(1995)

Graphs showing cross sections vs. deuteron energy for different isotopes of iron.
Cyclotron at VECC, KOLKATA

Alpha Beam : 65 MeV, 1 μA
**Preliminary Results for \( \text{nat} \text{Nb}(\alpha, x) \)**

\[ \text{\( ^{93} \text{Nb}(\alpha, x) \text{\( ^{95} \text{g} \text{.Tc} \) \)}} \]

- **Graph 1:**
  - \( \text{Cross section [MeV]} \)
  - \( \text{Alpha energy [MeV]} \)
  - Data points: *This work*
  - Line: TALYS 1.2

- **Graph 2:**
  - \( \text{\( ^{93} \text{Nb}(\alpha, x) \text{\( ^{96} \text{Tc} \) \)}} \)
  - \( \text{Cross section [MeV]} \)
  - \( \text{Alpha energy [MeV]} \)
  - Data points: *This work*
  - Line: TALYS 1.2
2. Neutron Capture Cross-section Measurements at Pulsed Neutron Facility, RPI in US

15 m station: Transmission Measurement

25 m station: Transmission Measurement
Capture, Scattering and Fission

100 m station & 250 m station
Transmission Measurement
Neutron Spectra Measurements
RPI Neutron Capture Experiment

Measurement date: 2010.02.08 ~ 2010.02.15
Place: RPI Linac

Electron energy: Gd - 57 MeV, Dy - 59 MeV
Repetition rate: 225 pps
Pulse width: 18 ns
TOF at last Channel: 4200 μs
Flight path length: 25.5686 ± 0.0058 m
Monitor Detector: Ring, Westinghouse fission chamber
                         Amperex fission chamber, 15m Li glass
Capture Detector: 16-segments Gamma Detector of NaI(Tl)
Neutron Source: Tantalum
Samples: Metaric Enriched Gd Isotopes, Natural Samples (0.254 mm, 5.08 mm)
                Metaric Enriched Dy Isotopes, Natural Sample (0.508 mm), $^{238}$U (0.508 mm)

<table>
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<th>Gadolinium</th>
<th>Dysprosium</th>
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<tr>
<td>Total run Time (hours)</td>
<td>54</td>
<td>28</td>
</tr>
<tr>
<td>Sample Time (runs)</td>
<td>50</td>
<td>28</td>
</tr>
</tbody>
</table>
Neutron source : Tantalum
Repetition rate : 225 pps
Flight path : 25.5686 ± 0.0058 m
Capture Detector

2.03 cm thick B_{10}C Liner (98.4% ^{10}B)

16 segments Gamma Detector, ~ 20 liter of NaI(Tl)

Neutron Beam

Sample

Photomultiplier Tubes

Photomultiplier Tubes
Results of Gd

New Resonances of $^{154}$Gd were observed (2)

Not in ENDF/B-VII.0

Many new Resonances were observed (185)

Not in ENDF/B-VII.0

Many new Resonances were observed (185)

Capture Yield

Neutron Energy [eV]

180.4 eV

306.4 eV

$^{160}$Gd

$^{158}$Gd

$^{157}$Gd

$^{156}$Gd

$^{155}$Gd

$^{154}$Gd

Nat10mil$^{154}$Gd
Preparation for Neutron Capture Cross Section Measurement
Construction of $4\pi$ BGO Gamma Detector

Setup1: 98.25% coverage

Setup2: 98.21% coverage
FADC DAQ for $4\pi$ BGO $\gamma$-detector System

- TOF spectra (TIME) + Pulse Height spectra (Signal Shape)
- Possible for Pulse shape analysis

- It needs fast computing system
Summary and Discussion

- Reported the recent activities at Pohang neutron facility:
  - Neutron Total Cross Section Measurement
    - 12 m TOF path length
    - New DAQ system based on FADC was developed
    - Resonance parameter determination with SAMMY code
  - Neutron Activation measurements with thermal neutrons of PNF
  - Photo-nuclear Reaction Measurements with 50-70 MeV and 2.5 GeV Bremsstrahlung
  - Charged Particle Induced Reaction Cross-section Measurements
  - Preparing for neutron capture measurement