Toward New Era of Photonuclear Reactions

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**γ-ray sources: radioisotopes**

Green and Donahue, PR 135, B701 (1964)

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**Table I. Measured gamma-ray intensities.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (MeV)</th>
<th>Intensity $\times 10^{-4}$ ($\gamma$ rays/cm$^2$-sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>7.72</td>
<td>8.1 ± 0.7</td>
</tr>
<tr>
<td>Copper</td>
<td>7.91</td>
<td>14.0 ± 1.4</td>
</tr>
<tr>
<td>Chlorine</td>
<td>7.63</td>
<td>6.4 ± 0.6</td>
</tr>
<tr>
<td>Sodium</td>
<td>8.56</td>
<td>2.3 ± 0.3</td>
</tr>
<tr>
<td>Sodium</td>
<td>7.77</td>
<td>6.0 ± 0.7</td>
</tr>
<tr>
<td>Sodium</td>
<td>7.42</td>
<td>6.9 ± 0.8</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>10.83</td>
<td>0.49 ± 0.03</td>
</tr>
<tr>
<td>Nickel</td>
<td>8.31</td>
<td>0.10 ± 0.03</td>
</tr>
<tr>
<td>Nickel</td>
<td>9.00</td>
<td>19.8 ± 2.1</td>
</tr>
<tr>
<td>Nickel</td>
<td>8.53</td>
<td>9.1 ± 0.9</td>
</tr>
<tr>
<td>Chromium</td>
<td>9.72</td>
<td>2.5 ± 0.4</td>
</tr>
<tr>
<td>Chromium</td>
<td>8.88</td>
<td>6.2 ± 0.9</td>
</tr>
<tr>
<td>Iron</td>
<td>7.64</td>
<td>22.0 ± 2.8</td>
</tr>
<tr>
<td>Iron</td>
<td>9.30</td>
<td>1.9 ± 0.2</td>
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<tr>
<td>Iron</td>
<td>6.03+5.92</td>
<td>11.0 ± 1.0</td>
</tr>
<tr>
<td>Lead</td>
<td>7.38</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>Lead</td>
<td>7.78</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td>Lead</td>
<td>6.75</td>
<td>18.9 ± 2.2</td>
</tr>
<tr>
<td>Lead</td>
<td>6.41</td>
<td>12.5 ± 1.5</td>
</tr>
<tr>
<td>Manganese</td>
<td>6.61$^b$</td>
<td>33.7 ± 2.7</td>
</tr>
<tr>
<td>Manganese</td>
<td>7.16$^c$</td>
<td>19.0 ± 1.7</td>
</tr>
<tr>
<td>Manganese</td>
<td>7.88</td>
<td>4.5 ± 0.5</td>
</tr>
</tbody>
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---

**Fig. 1. Neutron counter and source arrangement.**
TABLE II. Summary of measured cross sections (millibarns).

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (MeV)</th>
<th>Ta$^{181}$</th>
<th>Li$^7$</th>
<th>Targets</th>
<th>Li$^6$</th>
<th>C$^{12}$</th>
<th>B$^{10}$</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>7.72</td>
<td>4.1±0.4</td>
<td>0.06±0.01</td>
<td>1.13±0.12</td>
<td>1.1±0.2</td>
<td>0.97±0.13</td>
<td></td>
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<tr>
<td>Copper</td>
<td>7.91</td>
<td>10.8±1.0</td>
<td>0.07±0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorine</td>
<td>8.56</td>
<td>29±6</td>
<td>0.17±0.12</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>9.00</td>
<td>44±6</td>
<td>0.16±0.06</td>
<td>1.6±0.3</td>
<td>0.6±0.1</td>
<td>0.11±0.01</td>
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<tr>
<td>Nitrogen</td>
<td>10.83</td>
<td>121±12</td>
<td>1.07±0.25</td>
<td></td>
<td>4±2</td>
<td>0.9±0.2</td>
<td></td>
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<td>Chromium</td>
<td>9.72</td>
<td>84±25</td>
<td>0.55±0.25</td>
<td>1.3±0.2</td>
<td>0.23±0.05</td>
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<tr>
<td>Iron</td>
<td>7.64</td>
<td>0.0±0.9</td>
<td>0.079±0.014</td>
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<td>0.23±0.05</td>
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<td>Lead</td>
<td>7.38</td>
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<td>0.068±0.035</td>
<td>1.2±0.2</td>
<td>0.3±0.3</td>
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<td>Sulphur</td>
<td>5.43</td>
<td></td>
<td></td>
<td></td>
<td>0.42±0.07</td>
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<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>6.41</td>
<td></td>
<td></td>
<td></td>
<td>0.6±0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>6.75</td>
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<td></td>
<td></td>
<td>1.3±0.2</td>
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<tr>
<td>Titanium</td>
<td>6.61$^b$</td>
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<td></td>
<td></td>
<td></td>
<td>0.32±0.04</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>7.16$^a$</td>
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<td></td>
<td>0.9±0.1</td>
<td>0.4±0.1</td>
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<tr>
<td>Zinc</td>
<td>7.88</td>
<td></td>
<td></td>
<td>1.0±0.2</td>
<td>1.2±0.2</td>
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</tr>
</tbody>
</table>

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**Fig. 2.** Energy versus cross section, Ta$^{181}$(γ,n). Boxes are data of Fuller and Weiss (Ref. 8), circles are data of Bramblett et al. (Ref. 1). The solid line is a smooth curve through the present cross-section measurements.

**Fig. 3.** Energy versus cross section, Li$^7$(γ,n). Crosses are data of Goldemberg and Katz (Ref. 3), circles are data of Romanowski and Voelker (Ref. 12).
Lecture 1: Past of Photonuclear Reactions

\(\gamma\)-ray sources: Nuclear reactions

\(^{27}\text{Al}(p, \gamma)^{28}\text{Si}, E_p = 992 \text{ keV resonance}\)

Anttila et al., NIM 147, 501 (1977)

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**Fig. 1.** Gamma-ray spectrum of the \(E_p = 992 \text{ keV}\) resonance in the \(^{27}\text{Al}(p, \gamma)^{28}\text{Si}\) reaction taken at the distance of 6 cm and at \(\theta = 55^\circ\). The prime and double-prime refer to the single-escape and double-escape peaks, respectively. B means background peak. S the sum peak of the 1779 keV and 511 keV \(\gamma\)-rays and F illustrates \(E_\gamma = 6129 \text{ keV}\) energy due to the \(^{19}\text{F}(p, \gamma)^{20}\text{O}\) reaction. The insert illustrates in more detail the intensity of the weak transitions.
### TABLE 1
Relative intensities obtained in the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction at $E_p = 992$ keV. The energy values were taken from refs. 4 and 5.

<table>
<thead>
<tr>
<th>Identification in fig. 2</th>
<th>$E_p$ (keV)</th>
<th>$E_i$ (keV)</th>
<th>$E_f$ (keV)</th>
<th>Present</th>
<th>$\text{Relative intensity (%)}$</th>
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<tr>
<td></td>
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<td></td>
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<td></td>
<td>Azuma et al.$^9$</td>
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<td>1</td>
<td>1522.3</td>
<td>7798.8</td>
<td>6276.5</td>
<td>2.8 ± 0.2</td>
<td>2.9 ± 0.5</td>
</tr>
<tr>
<td>2</td>
<td>1658.7</td>
<td>6276.5</td>
<td>4617.8</td>
<td>0.52 ± 0.05</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>3</td>
<td>1778.9</td>
<td>1778.9</td>
<td>948.1 ± 1.5</td>
<td>0.29 ± 0.03</td>
<td>948.0 ± 9.4</td>
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<tr>
<td>4</td>
<td>(1874)</td>
<td>r</td>
<td>10668</td>
<td>0.24 ± 0.02</td>
<td>?</td>
</tr>
<tr>
<td>5</td>
<td>2099.7</td>
<td>9480.4</td>
<td>7380.7</td>
<td>0.22 ± 0.03</td>
<td>6.2 ± 0.6</td>
</tr>
<tr>
<td>6</td>
<td>2267</td>
<td>r</td>
<td>10275</td>
<td>0.23 ± 0.04</td>
<td>1.1 ± 0.1</td>
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<tr>
<td>7</td>
<td>2529.3</td>
<td>9418.1</td>
<td>6888.8</td>
<td>0.22 ± 0.03</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>8</td>
<td>(2780.3)</td>
<td>r</td>
<td>9761.5</td>
<td>0.26 ± 0.03</td>
<td>9418.1</td>
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<tr>
<td>9</td>
<td>2838.9</td>
<td>4617.8</td>
<td>1778.9</td>
<td>5.5 ± 0.4</td>
<td>6.2 ± 0.6</td>
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<td>4979.1</td>
<td>0.62 ± 0.04</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>11</td>
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<td>0.70 ± 0.07</td>
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<td>12</td>
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<td>9418.1</td>
<td>0.09 ± 0.02</td>
<td>1.1 ± 0.3</td>
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<td>6.0 ± 0.3</td>
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<td>14</td>
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<td>6.3 ± 0.4</td>
</tr>
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<td>15</td>
<td>3200.2</td>
<td>4979.1</td>
<td>1778.9</td>
<td>0.24 ± 0.04</td>
<td>8.1 ± 0.8</td>
</tr>
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<td>16</td>
<td>3315.6</td>
<td>7933.4</td>
<td>4617.8</td>
<td>0.21 ± 0.04</td>
<td>0.34 ± 0.05</td>
</tr>
<tr>
<td>17</td>
<td>(3377.9)</td>
<td>r</td>
<td>9163.9</td>
<td>0.19 ± 0.05</td>
<td>0.3</td>
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<tr>
<td>18</td>
<td>3952.9</td>
<td>r</td>
<td>8588.9</td>
<td>0.19 ± 0.04</td>
<td>0.3</td>
</tr>
<tr>
<td>19</td>
<td>4497.6</td>
<td>6276.5</td>
<td>1778.9</td>
<td>4.8 ± 0.3</td>
<td>4.4 ± 0.4</td>
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<td>4608.4</td>
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<td>7933.4</td>
<td>4.5 ± 0.4</td>
<td>3.6 ± 0.4</td>
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<td>r</td>
<td>7998.8</td>
<td>8.8 ± 0.5</td>
<td>8.1 ± 0.8</td>
</tr>
<tr>
<td>22</td>
<td>4900.3</td>
<td>9418.1</td>
<td>4617.8</td>
<td>0.31 ± 0.04</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>23</td>
<td>5099.7</td>
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<td>1778.9</td>
<td>0.10 ± 0.04</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>24</td>
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<td>6888.8</td>
<td>1778.9</td>
<td>0.50 ± 0.06</td>
<td>0.52 ± 0.09</td>
</tr>
<tr>
<td>25</td>
<td>5601.8</td>
<td>7380.7</td>
<td>1778.9</td>
<td>0.24 ± 0.04</td>
<td>0.1</td>
</tr>
<tr>
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<td>5653.0</td>
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<td>0.40 ± 0.04</td>
<td>0.9 ± 0.3</td>
</tr>
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<td>5663.2</td>
<td>r</td>
<td>6878.6</td>
<td>0.58 ± 0.06</td>
<td>0.89 ± 0.21</td>
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<tr>
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<td>7798.8</td>
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<td>5.9 ± 0.6</td>
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<td>0.55 ± 0.07</td>
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<td>30</td>
<td>6265.3</td>
<td>r</td>
<td>6276.5</td>
<td>2.1 ± 0.2</td>
<td>2.4 ± 0.4</td>
</tr>
<tr>
<td>31</td>
<td>6810.0</td>
<td>8588.9</td>
<td>1778.9</td>
<td>0.24 ± 0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>32</td>
<td>6878.6</td>
<td>6878.6</td>
<td>0</td>
<td>0.63 ± 0.04</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>33</td>
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<td>9418.1</td>
<td>1778.9</td>
<td>0.23 ± 0.05</td>
<td>0.32 ± 0.06</td>
</tr>
<tr>
<td>34</td>
<td>7924.0</td>
<td>r</td>
<td>4617.8</td>
<td>4.3 ± 0.4</td>
<td>4.9 ± 0.9</td>
</tr>
<tr>
<td>35</td>
<td>7933.4</td>
<td>7933.4</td>
<td>0</td>
<td>3.7 ± 0.4</td>
<td>3.8 ± 0.9</td>
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<tr>
<td>36</td>
<td>9478.5</td>
<td>9478.5</td>
<td>0</td>
<td>0.98 ± 0.10</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>37</td>
<td>10275</td>
<td>r</td>
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<td>0</td>
<td>1.1 ± 0.4</td>
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<tr>
<td>38</td>
<td>10762.9</td>
<td>r</td>
<td>1778.9</td>
<td>76.6 ± 1.5</td>
<td>77.0 ± 7.7</td>
</tr>
</tbody>
</table>
Lecture 1: Past of Photonuclear Reactions

Response of a high-resolution and high-energy spectrometer


BGO
Compton-suppression

Twin Ge crystals

$^{27}\text{Al}(p,\gamma)^{28}\text{Si}, E_p = 992 \text{ keV}$ resonance
Lecture 1: Past of Photonuclear Reactions


Table 1
Parameters of the (p, γ) reactions, energies (Eγ) and relative intensities (Iγ) of the γ-rays emitted by product nucleus [9,11,12].

<table>
<thead>
<tr>
<th>Reaction</th>
<th>E_res (keV)</th>
<th>Q value (keV)</th>
<th>E_p (keV)</th>
<th>E_γ (keV)</th>
<th>I_γ</th>
<th>Target and its thickness (µg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}$Na(p, γ)$^{24}$Mg</td>
<td>1318.1</td>
<td>11693</td>
<td>1323</td>
<td>1368.6(1)</td>
<td>1.000(2)</td>
<td>Na₂WO₄, 20</td>
</tr>
<tr>
<td>$^{23}$Na(p, γ)$^{24}$Mg</td>
<td>1416.9</td>
<td>11693</td>
<td>1422</td>
<td>11584.9(6)</td>
<td>0.960(2)</td>
<td>Na₂WO₄, 20</td>
</tr>
<tr>
<td>$^{27}$Al(p, γ)$^{28}$Si</td>
<td>767.2</td>
<td>11585</td>
<td>770</td>
<td>2754.0(1)</td>
<td>1.000(1)</td>
<td>Al, 20</td>
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<tr>
<td>$^{39}$K(p, γ)$^{40}$Ca</td>
<td>1346.6</td>
<td>8328</td>
<td>1351</td>
<td>7706.5(2)</td>
<td>0.940(14)</td>
<td>K₂SO₄, 15</td>
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<tr>
<td>$^{11}$B(p, γ)$^{12}$C</td>
<td>675</td>
<td>15957</td>
<td>676</td>
<td>5736.5(1)</td>
<td>0.965(1)</td>
<td>LiBO₂, 20</td>
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<tr>
<td>$^7$Li(p, γ)$^8$Be</td>
<td>441</td>
<td>17255</td>
<td>450</td>
<td>12137.1(3)</td>
<td>1.000(7)</td>
<td>LiBO₂, 75</td>
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</table>

Nuclear data are taken from ENSDF [13]. Q values calculated by QCalc from NNDC [14].

Response of a 2” x 2” LaBr₃(Ce) detector

$^{23}$Na(p, γ)$^{24}$Mg, $E_p = 1416.9$ keV

$^7$Li(p, γ)$^8$Be, $E_p = 441$ keV

Fig. 1. Gamma-ray spectrum emitted by $^{24}$Mg nuclei created in the $^{23}$Na(p, γ)$^{24}$Mg reaction at the 1.318 MeV resonance energy, measured by a LaBr₃ : Ce 2 in. x 2 in. scintillation detector.

Fig. 2. Gamma-ray spectrum emitted by $^8$Be nuclei created in the $^7$Li(p, γ)$^8$Be reaction, measured by a LaBr₃ : Ce 2 in. x 2 in. scintillation detector. It is compared, after normalization to the full absorption peak, to spectrum simulated using a GEANT4 code.
γ-ray sources: Bremsstrahlung

Collisional loss: Electrons lose kinetic energies in matter by colliding with atomic electrons, leading to atomic excitation and ionization.

Bremsstrahlung (Radiation loss): Electrons lose kinetic energies in matter by radiative processes.

Linear stopping power of electrons for radiation loss

\[ -\left(\frac{dE}{dx}\right)_r = \frac{NEZ(Z + 1)e^4}{137m_0^2c^4} \left(4\ln \frac{2E}{m_0c^2} - \frac{4}{3}\right) \]

Radiative losses are most important for high electron energies and for absorber materials of large atomic number.

Ratio of the specific energy losses

\[ \frac{(dE/dx)_r}{(dE/dx)_c} \approx \frac{EZ}{700} \quad E \text{ in MeV} \]
Bremsstrahlung facilities

1. Moscow State University, Nuclear Physics Institute, Moscow, Russia (microtron)
2. Joint Institute for Nuclear Research, Dubna, Russia (microtron)
3. Uzhgorod State University, Ukraine (betatron)
4. Kharkovskii Fiziko-Tekhnicheskii Institute, Kharkov, Ukraine (linear accelerator)
5. Forschungszentrum-Rossendorf (FZD), Dresden, ELBE, Germany (linear accelerator)
6. Tech. Universitaet, Darmstadt, S-DALINAC, Germany (linear accelerator)
7. Kyoto University, Kyoto, Japan (linear accelerator)
8. Pohang University of Science and Technology, Pohang, Korea (linear accelerator)
9. Bhabha Atomic Res. Centre, Trombay, India (linear accelerator)
10. Mangalore University, Mangalagangotri, Konaje, India (microtron)
Lecture 1: Past of Photonuclear Reactions

The bremsstrahlung facility at the electron accelerator ELBE
Lecture 1: Past of Photonuclear Reactions

**Yield** : convolution of the photonuclear cross section with the bremsstrahlung spectrum over the photon energies.

\[ Y(E_0) = N_R \int_{Threshold}^{E_0} \sigma(E_\gamma) K(E_0, E_\gamma) \frac{dE_\gamma}{E_\gamma}, \]

\[ E_0: \text{electron beam energy; } K(E_0, E_\gamma): \text{bremsstrahlung spectrum} \]

**Yield curve** : obtained by changing the electron beam energy in small steps

This technique requires:

1. Accurate knowledge of the bremsstrahlung spectrum for all electron energies
2. Great stability in the accelerator operation and large counting statistics to accurately measure the yield curve
3. Unfolding (differentiation) procedure of the yield curve
   - Photon Difference Method: difference of two bremsstrahlung spectra with slightly-different end-point energies
   - Penfold-Leiss Method: a set of linear equations for a given energy bin
   - Regularization Methods
     - Tikhonov’s Method, Cook’s Least Structure Method, the Second Difference Method, the Statistical Regularization Method
Lecture 1: Past of Photonuclear Reactions

Bremsstrahlung data compiled in CDFE, MSU

$^{16}\text{O}$

$^{208}\text{Pb}$
Lecture 1: Past of Photonuclear Reactions

**γ-ray sources: Positron annihilation in flight**

- **Annihilation Target 9Be**
  - Neutron detector
  - $\text{BF}_3$ counters + paraffin
  - $\gamma$-ray Beam
    - $E_\gamma = K_{e^+} + 3/2(mc^2)$

- **Converter (W, Au, Ta, Pt)**
  - $e^- \rightarrow e^+$
  - $e^-$ bremsstrahlung
  - Pair production

Lawrence Livermore National Laboratory (USA)
Lecture 1: Past of Photonuclear Reactions

Saclay (France)
Lecture 1: Past of Photonuclear Reactions

Subtracted

$e^+ - e^-$ annihilation (quasi-monochromatic)

$e^+$ bremsstrahlung (background)
Lecture 1: Past of Photonuclear Reactions

(γ,n) cross section measurements in 1960s – 1980s
LLNL (USA)
Saclay (France)

Thomas-Reiche-Kuhn sum rule (energy-weighted sum rule)

\[ \int \sigma(E) dE = 60 \frac{NZ}{A} [\text{MeV} \cdot \text{mb}] = \frac{16 \pi^3}{9} E \cdot B(E1) \uparrow \cdot \alpha \]
Compilations photoneutron cross sections

(1) ATLAS of photoneutron cross sections obtained with monoenergetic photons, S.S. Dietrich and B.L. Berman
Atomic Data and Nuclear Data Tables 38, 199-338 (1988)

(2) Handbook on photonuclear data for applications, Cross sections and spectra
IAEA TECDOC-1178 (2000)

International Nuclear Reaction Database in the format EXFOR

IAEA - https://www-nds.iaea.org/exfor/exfor.htm/
Lecture 2

Present of Photonuclear Reactions

2.1 Laser Compton-scattering $\gamma$-ray beam
2.2 Nuclear Physics ($\gamma, \gamma'$) for PDR
2.3 Nuclear Astrophysics
   a. p-process – ($\gamma$,$n$)
   b. s-process - gamma-ray strength function for ($\gamma$,$n$) and ($n$, $\gamma$)
\[ h'v = \frac{hv}{1 + hv(1 - \cos \phi) / mc^2} \]

\[ h + mc^2 = h' + \sqrt{p^2 c^2 + m^2 c^4} \]

\[ \frac{hv}{c} = \frac{h'v}{c} \cos \phi + p \cos \psi \]

\[ 0 = \frac{h'v}{c} \sin \phi - p \sin \psi \]

Lorentz factor

\[ \gamma = \frac{E_e}{mc^2} \]
Lecture 2: Present of Photonuclear Reactions

Laser Compton scattering γ-ray beam

\[ E_\gamma = \frac{4\gamma^2 \varepsilon_L}{1 + (\gamma \theta)^2 + 4\gamma \varepsilon_L/(mc^2)} \]

\[ \Delta E/E \approx \left\{ \left( \frac{2\Delta E_e}{E_e} \right)^2 + \gamma^4 (\theta^2_e + \theta^2_c) \right\}^{1/2} \]

\[ \gamma = \frac{E_e}{mc^2} \text{ (Lorentz factor)} \]

\[ \sim 2 \times 10^3 \quad E_e = 1 \text{ GeV} \]

Energy am

\[ E_\gamma / \varepsilon_L = 4\gamma^2 \sim 1.6 \times 10^7 \]

\[ \varepsilon_L \sim 1 \text{ eV} \]

\[ E_\gamma \sim 16 \text{ MeV} \]
Lecture 2: Present of Photonuclear Reactions

Realm of Nuclear Photonics

Two Phonon State

Pygmy Dipole Resonance

Giant Dipole Resonance

$(\gamma, \gamma)$

$(\gamma, n), (\gamma, 2n), (\gamma, 3n), (\gamma, p), (\gamma, \alpha)$

$\gamma$-ray strength function

Nucleosynthesis (p-process, s-process)

modified by H. Utsunomiya
“Applications” of low-lying E1 strength

PDR is / might be

... sensitive to neutron skin thickness

... sensitive to parameters of symmetry energy

... influencing reaction rates / nucleosynthesis

→ detailed understanding of the PDR mandatory
Lecture 2: Present of Photonuclear Reactions

Photon scattering ...

... using Bremsstrahlung

- Investigation of large energy region
- Excellent energy resolution: State-to-state analysis, investigation of fine structure

\[ \gamma(E_\gamma) \cdot \varepsilon(E_\gamma) \]

\[ E_0 = 9.1 \text{ MeV} \]

K. Sonnabend et al., Nucl. Instr. and Meth. A640 (2011) 6

e.g. Darmstadt High Intensity Photon Setup (DHIPS):

Courtesy by D. Savran Deniz Savran | ExtreMe Matter Institute
Lecture 2: Present of Photonuclear Reactions

Photon scattering ...

... using Laser Compton Backscattering

100% polarized

E1

M1

- Determination of parities

e.g. High Intensity γ-ray Source (HIγS):


Cortesy by D. Savran

Deniz Savran | ExtreMe Matter Institute
Lecture 2: Present of Photonuclear Reactions
Spin and Parity Determination

\[ ^{138}\text{Ba} \]


z axis: beam direction; x axis: vector of polarization

Courtesy by A. Tonchev
Lecture 2: Present of Photonuclear Reactions
Spin and Parity Determination


 Courtesy by A. Tonchev

\[ ^{138}\text{Ba} \]
PDR study by NRF (nuclear resonance fluorescence = photon scattering = (\(\gamma, \gamma'\))) measurements

1) Ideal to separate PDR (E1) and M1 resonance using linearly-polarized photons

2) Limited below neutron threshold (\(S_n\))

3) Best suited to even-even nuclei
   - \(0^+\) ground state
   - high neutron threshold (\(S_n\))

4) Determine partial strength
   - discrete (resolved) states
   - unresolved states: model-dependent
Lecture 2: Present of Photonuclear Reactions

PDR in $^{207,208}\text{Pb}$ above neutron threshold


9587 mg, 98.5%, $^{208}\text{Pb}$
3482 mg, 99.1%, $^{207}\text{Pb}$
Neutron anisotropy detector
for E1 & M1 ($\gamma,n$) cross section measurements
E1 cross sections for $^{208,207}$Pb

HFB+QRPA E1 strength plus pygmy E1 resonance in Lorentzian shape

$E_o = 7.5$ MeV, $\Gamma = 0.4$ MeV

$\sigma_o \approx 20$ mb for $^{208}$Pb

$\sigma_o \approx 15$ mb for $^{207}$Pb

TRK sum rule

0.42% for $^{208}$Pb

0.32% for $^{207}$Pb
$B(E1) \uparrow$

208Pb

Present

\[ B(E1) \uparrow = 0.82 \pm 0.09 \, e^2 \cdot fm^2 \]
\[ E = 7.51 - 8.32 \, MeV \]

(p,p') experiment

\[ B(E1) \uparrow = 0.982 \pm 0.206 \, e^2 \cdot fm^2 \]
\[ E = 7.515 - 8.430 \, MeV \]

207Pb

\[ B(E1) \uparrow = 0.88 \pm 0.17 \, e^2 \cdot fm^2 \]
\[ E = 7.02 - 8.32 \, MeV \]
M1 cross sections for $^{208,207}$Pb

M1 resonance in Lorentzian shape

$^{208}$Pb
$E_o = 8.06$ MeV, $\Gamma = 0.6$ MeV
$\sigma_o = 3.6$ mb
$B(M1)=4.2 \pm 2.3 \mu_N^2$ $E=7.51$-$8.32$ MeV

$^{207}$Pb
$E_o \approx 7.25$ MeV, $\Gamma \approx 1$ MeV
$\sigma_o \approx 3.2$ mb
$B(M1)=4.0 \pm 1.9 \mu_N^2$ $E=7.02$-$7.52$ MeV
Lecture 2: Present of Photonuclear Reactions

PDR study by \((\gamma,n)\) measurements

1) Limited above neutron threshold \((S_n)\)

2) Best suited to odd-\(A\) nuclei
   - low \(S_n\)

3) Determine partial strength
   - above \(S_n\) (complementary to \((\gamma,\gamma')\))
   - both discrete and continuum components

4) Energy resolution
   - low with \(4\pi\) neutron detector
   - high with TOF technique (future)
Nucleosynthesis of Heavy Elements
s-process, r-process and p-process

Abundances [Si=10^6]

\[ \text{A}\]
Lecture 2: Present of Photonuclear Reactions

p-nuclei

35 neutron-deficient nuclei from Se(Z=34) to Hg(Z=80)

3 \ (p, \gamma) + \beta - \text{decay}

4 \ (\gamma, n) + (\gamma, p)

(\gamma, n) + (\gamma, \alpha) + \beta - \text{decay}
Lecture 2: Present of Photonuclear Reactions

\textbf{p-process nucleosynthesis}


Photoreaction rates for gs

\[ \lambda_m(T) = \int_0^\infty cn_\gamma(E,T) \sigma_m(E) dE \]

Planck distribution

\[ n_\gamma(E,T) dE = \frac{1}{\pi^2} \frac{1}{(hc)^3} \frac{E^2}{\exp(E/kT)-1} dE \]
Stellar photoreaction rate

Photoreaction rates for a state $\mu$

$$\lambda_{mn}^\mu(T) = \int_0^\infty cn_\gamma(E,T)\sigma_{mn}^\mu(E)dE$$

Stellar photoreaction rate

$$\lambda_m^* = \frac{\sum (2j^\mu + 1)\lambda_{mn}^\mu(T)\exp(-\varepsilon_\mu/kT)}{\sum (2j^\mu + 1)\exp(-\varepsilon_\mu/kT)}$$

$$\sigma_{mn}^\mu(E_\gamma) = \pi D^2 \frac{1}{2(2j^\mu + 1)} \sum_{J\pi} T_{\gamma}(E_\gamma, J^{\pi})T_n(E, J^{\pi})$$

$$T_{\gamma}(E_\gamma, J^{\pi}) = 2\pi \varepsilon_\gamma^3 f_\gamma(E_\gamma) \uparrow$$ for E1 transition

Key quantity:
\gamma-ray strength function $f_\gamma(E_\gamma)$

$E_\gamma > S_n$ for gs

$E_\gamma < S_n$ for excited states $\mu$
Only naturally occurring isomer \(^{180}\text{Ta}^m\)

- Odd-odd Nucleus \((Z=73, N=107)\)
- Neutron deficient nucleus (classified as one of p-nuclei)
- Solar Abundance ; \(2.48 \times 10^{-6}\) (the rarest)
- Half Life > \(1.2 \times 10^{15}\) y
- \(E_x = 75\) keV
- \(J^\pi = 9^-\)

\(^{180}\text{Ta}^s\)

- Half Life = \(8.152\) h
- \(J^\pi = 1^+\)
Primary s-process flow \[ A \ X (n, \gamma) A+1 \ X (\beta^-) A+1 \ X' \]
p-process \[ ^{181} \text{Ta}(\gamma, n)^{180} \text{Ta(thermal equilibrium)}^{180} \text{Ta}^m \]
Weak branching s-process \[ ^{179} \text{Hf}^m(\beta)^{179} \text{Ta}(n, \gamma)^{180} \text{Ta}^m \]
Lecture 2: Present of Photonuclear Reactions

Nucleosynthesis of $^{180}$Ta$^m$

- **p-process** in the pre-supernova phase of massive stars or during their explosions as type- II supernovae
  
  Temperature: $1.8 \leq T[10^9K] \leq 3.0$

  Peak photon energy: $200[\text{keV}]$

  $^{181}$Ta($\gamma,n$)$^{180}$Ta(thermal equilibrium) $^{180}$Ta$^m$

- **s-process** in the Low-mass AGB star
  
  Temperature: $2.9 \leq T[10^8K] \leq 3.3$

  Typical neutron energy: $25[\text{keV}]$

  $^{179}$Hf$^m$(\beta)$^{179}$Ta(n,$\gamma$)$^{180}$Ta$^m$
Lecture 2: Present of Photonuclear Reactions

$^{181}\text{Ta}(\gamma,n)^{180}\text{Ta}$


Extra E1 $\gamma$-ray strength near Sn

Pygmy Dipole Resonance
N. Paar, D. Vretenar, E. Khan, G. Colò
Model calculation of the p-process nucleosynthesis


S. Goriely, ULB
Nuclear Level Density of $^{180}$Ta

$s$-wave neutron

$^{179}$Ta $T_{1/2}=1.82\text{y}$

$T_{1/2} > 1.2 \times 10^{15}\text{y}$

$T_{1/2}=8.152\text{h}$

$^{180}$Ta

Lecture 2: Present of Photonuclear Reactions
Lecture 2: Present of Photonuclear Reactions

Progress of the reactions

$T_{1/2} > 1.2 \times 10^{15}$ y
$T_{1/2} = 8.152$ h

$^{180}$Ta → $^{180}$Hf

Electron Capture

$^{180}$Ta → $^{180}$W

Incident $\gamma$-ray

$^{181}$Ta($\gamma$,n)$^{180}$Ta

$\sigma^m = \sigma^{\text{total}} - \sigma^{\text{gs}}$

per 1 decay of $^{180}$Ta$^{\text{gs}}$

93 keV $\gamma$-ray 4.665%
55.8 keV $K_{\alpha_1}$ 33.12%
54.6 keV $K_{\alpha_2}$ 19.20%
Experimental Set-up

Target Sample: $^{181}$Ta

$^3$He Proportional Counter $\times 20$

NaI(Tl) Scintillator

Target Sample: $^{197}$Au

Neutron Moderator; Polyethylene
Activated Ta foils on the acrylic cap

Ge Detector Set-up
Lecture 2 : Present of Photonuclear Reactions

$^{180}\text{Ta} \rightarrow ^{180}\text{Hf} ; \text{Electron Capture}$

<table>
<thead>
<tr>
<th>$E_{\text{photon}} [\text{keV}]$</th>
<th>$\text{Counts / h / 230 eV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>55.0</td>
</tr>
<tr>
<td>60.0</td>
<td>65.0</td>
</tr>
<tr>
<td>70.0</td>
<td></td>
</tr>
</tbody>
</table>

$\lambda_{\text{exp}} = 0.084$

$\lambda_{\text{nominal}} = 0.085$
Experimental results, and comparison with theoretical models


\[ ^{181}\text{Ta} (\gamma, n) ^{180}\text{Ta} \]

\[ ^{181}\text{Ta} (\gamma, n) ^{180}\text{Ta}^m \]

Systematic uncertainties 10～26%

Present work (2006)

IAEA: Lee et al. (1998)

Combinatorial NLD model

Statistical NLD model

HF model calculations by S. Goriely (ULB)
Lecture 2: Present of Photonuclear Reactions

\[ \text{\textsuperscript{179}Ta}(n, \gamma)\text{\textsuperscript{180}Ta}^m \]

for the s-process \(\text{\textsuperscript{180}Ta}^m\) production

Goko et al.

Present results
\(\sigma^m_{n\gamma} = 90 \pm 22\text{mb}\)
\(\sigma^m_{n\gamma}/\sigma^{tot}_{n\gamma} = 0.04 \pm 0.01\)
at 30 keV

Previous Predictions

\(\sigma^m: \bullet 44\text{mb} \) (Zs. Nèmeth, F.Käppeler, G.Reffo ;1992)
\(\sigma^m/\sigma^{tot}: 0.02 \sim 0.09 \) (K.Yokoi, K.Takahashi ;1983)
\(0.043 \pm 0.008 \) (Zs. Nèmeth, F.Käppeler, G.Reffo ;1992)
Radiative neutron capture - $^{A}X(n,\gamma)^{A+1}X$
Lecture 2: Present of Photonuclear Reactions

Hauser-Feshbach model cross section for $^{A}X(n,\gamma)^{A+1}X$

\[
\sigma_{n\gamma}(E) = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{T_{\gamma}(E,J,\pi) T_n(E,J,\pi)}{T_{tot}} \approx \frac{\pi}{k_n^2} \sum_{J,\pi} g_J T_{\gamma}(E,J,\pi)
\]

Total $\gamma$ transmission coefficient

\[
T_{\gamma}(E,J,\pi) = \sum_{\nu,X,\lambda} T_{X\lambda}^{\nu}(\varepsilon_{\gamma}) + \sum_{X,\lambda} \int T_{X\lambda}(\varepsilon_{\gamma}) \rho(E - \varepsilon_{\gamma}) d\varepsilon_{\gamma}
\]

\begin{align*}
X & = E, M \\
\lambda & = 1, 2, \ldots
\end{align*}

\[
T_{X\lambda}(\varepsilon_{\gamma}) = 2\pi \varepsilon_{\gamma}^{2\lambda+1} f_{X\lambda}(\varepsilon_{\gamma})
\]

$\gamma$-ray strength function

nuclear level density

\[\rho(E - \varepsilon_{\gamma})\]

neutron resonance spacing low-lying levels
(n,γ) and (γ,n) are interconnected through the γ-ray strength function and the nuclear level density in the Hauser–Feshbach model.

Radiative neutron capture

\[ ^A X(n,\gamma)^{A+1} X \]
\[ n^{+A} X \]

\[ f_{X\lambda}(\epsilon_\gamma) \downarrow = \epsilon_\gamma^{-(2\lambda+1)} \frac{\Gamma_{X\lambda}(\epsilon_\gamma)}{D_\ell} \]
\[ \epsilon_\gamma < S_n \]

\[ ^{A+1} X(\gamma,n)^A X \]

Brink Hypothesis

\[ f_{X\lambda}(\epsilon_\gamma) \uparrow \approx f_{X\lambda}(\epsilon_\gamma) \downarrow \]

Photoneutron emission

\[ \epsilon_\gamma > S_n \]
γ-ray Strength Function Method


Indirect determination of \((n, \gamma)\) cross sections for unstable nuclei
based on a unified understanding of \((\gamma, n)\) and \((n, \gamma)\) reactions
through the \(\gamma\)-ray strength function

The best understanding of the \(\gamma\) SF with PDR and M1 resonance
is obtained by integrating

- \((\gamma, n)\) data
- \((\gamma, \gamma')\) NRF data
- Particle-\(\gamma\) coin. data, Oslo Method
- Existing \((n, \gamma)\) data
Applications of the $\gamma$-ray Strength Function Method

1. Nuclear Astrophysics

s-process branch-point nuclei: unstable nuclei along the line of $\beta$-stability


$^{63}$Ni, $^{79}$Se, $^{81}$Kr, $^{85}$Kr, $^{95}$Zr, $^{147}$Nd, $^{151}$Sm, $^{153}$Gd, $^{185}$W

2. Nuclear Data for Nuclear Engineering
Lecture 2: Present of Photonuclear Reactions

Applications

- Present (©,n) measurements
- Existing (n,©) data
- (n,©) c.s. to be deduced

- LLFP (long lived fission products)
  - nuclear waste
- Astrophysical significance

7  Sn
   | 115 | 116 | 117 | 118 | 119 | 120 | 121 27 h | 122 | 123 129 d | 124 |

3  Pd
   | 104 | 105 | 106 | 107 6.5 10^6 y | 108 |

5  Zr
   | 89 3.27 d | 90 | 91 | 92 1.53 10^6 y | 94 64 d | 95 | 96 |

4  Se
   | 75 120 d | 76 | 77 | 78 2.95 10^3 y | 80 |

H. Utsunomiya et al., PRC80 (2009)
H.U. et al., PRC82 (2010)
H.U. et al., PRL100(2008)
PRC81 (2010)
F. Kitatani, Ph.D. thesis, to be published
Lecture 2: Present of Photonuclear Reactions

H.U. et al., PRC88 (2013)

In collaboration with Univ. Oslo etc.

5

In collaboration with ELI-NP etc.

7
Structure of $\gamma$-ray strength function

Extra strengths

$S_n$

GDR

PDR, M1

6 – 10 MeV

E1 strength of the low-energy tail of GDR
Experimental determination of \( \gamma \)-ray strength function

Statistical model calculation of \( A^{-1}X(n, \gamma)^{AX} \) cross sections with experimental \( \gamma \)SF

\[ \varepsilon_\gamma > S_n \]

\( \gamma, \gamma' \) NRF data

Particle-\( \gamma \) coin. data

(Oslo Method)

GDR

PDR, M1
Lecture 2: Present of Photonuclear Reactions

Theoretical extrapolation of \( \gamma \)-ray strength function

\[ \gamma, n \]

Statistical model calculation of \( A^{+1}X(n, \gamma)A^{+2}X \) cross sections with experimentally-constrained \( \gamma \)SF

1. \( \varepsilon_\gamma > S_n \) (\( \gamma, n \)) data

2. \( \varepsilon_\gamma < S_n \)
Extrapolation by microscopic model

3. \textbf{Justification of } \( \gamma \)SF by reproducing known \( (n, \gamma) \) cross sections in the Hauser-Feshbach model calculation

PDR, M1

GDR

\[ \gamma, n \]

known \( (n, \gamma) \)
HFB+QRPA E1 strength supplemented with a pygmy E1 resonance in Gaussian shape

\[ E_o \approx 8.5 \text{ MeV}, \quad \Gamma \approx 2.0 \text{ MeV}, \quad \sigma_o \approx 7 \text{ mb} \]

\[ \sim 1\% \text{ of TRK sum rule (E1 strength)} \]
\textbf{\(\gamma SF\) for Sn isotopes}

\textit{(\(\gamma, n\)) data}
H. Utsunomiya et al., PRC84 (2011)

\textit{Oslo data}
\((3\text{He}, \alpha\gamma), (3\text{He}, 3\text{He}' \gamma)\)
Toft et al., PRC 81 (2010); PRC 83 (2011)
Lecture 2: Present of Photonuclear Reactions

$(n,\gamma)$ CS for Sn isotopes

![Graphs showing $(n,\gamma)$ cross-sections for Sn isotopes](image_url)
Lecture 2: Present of Photonuclear Reactions

$(n,\gamma)$ CS for unstable Sn isotopes

$^{121}\text{Sn}[T_{1/2}=27 \text{ h}]$

$^{123}\text{Sn}[T_{1/2}=129 \text{ d}]$

Uncertainties:

- $^{121}\text{Sn}(n,\gamma)^{122}\text{Sn}$
  - Uncertainties: 30-40%
- $^{123}\text{Sn}(n,\gamma)^{124}\text{Sn}$
  - Uncertainties: a factor of $\sim 2$
Lecture 2: Present of Photonuclear Reactions

Mo isotopes

(γ,n) data
H. Utsunomiya et al., PRC 88 (2013)

Oslo data
(3He, αγ), (3He, 3He′γ)
M. Guttormsen et al., PRC71 (2005)

(γ,γ′) data
G. Rusev et al., PRC77 (2008)
Lecture 2: Present of Photonuclear Reactions

$(n,\gamma)$ CS for Stable Mo isotopes

$(n,\gamma)$ CS for Unstable Mo isotopes

$^{93}\text{Mo}$

$T_{1/2}=4000$ yr

$^{99}\text{Mo}$

$T_{1/2}=2.75$ d
2.3 Nuclear Astrophysics (continued)
   c. reciprocity theorem – photodisintegration of D, $^9$Be, $^{16}$O

2.4 Evaluated Nuclear Data Library – ENDF, JEFF, JENDL, RIPL

3. ELI-NP project
   3.1 ELI-NP vs HIGS and NewSUBARU
   3.2 p-process – rare isotopes
   3.3 Precision Era of Nuclear Physics
      a. PDR above neutron threshold
      b. GDR – ($\gamma, \gamma$), ($\gamma, n$) ($\gamma, 2n$), ($\gamma, 3n$) cross sections
   3.4 Special topic
      Photoreactions on isomers – laser-gamma combined experiment
Nucleosynthesis of light nuclei

Reciprocity Theorem

\[ \frac{\sigma(b \rightarrow a)}{(2I_A + 1)(2i_a + 1)p_a^2} = \frac{\sigma(a \rightarrow b)}{(2I_B + 1)(2i_b + 1)p_b^2} \]

B + b → A + a − Q \quad \text{Q value}

Neutron Channel

\( a = n, \quad b = \gamma \quad p_\gamma = \hbar k = \frac{E_\gamma}{c} \quad p_n^2 = 2\mu E_n \quad 2j_b + 1 \rightarrow 2 \)

Equivalency between \((n, \gamma)\) and \((\gamma, n)\)
Examples

Big Bang Nucleosynthesis: \( p(n,\gamma)D \) vs \( D(\gamma,n)p \)
Examples

Big Bang Nucleosynthesis: \( p(n, \gamma)D \) vs \( D(\gamma, n)p \)

Examples

9Be  Supernova Nucleosynthesis
\[ \alpha \alpha \rightleftharpoons ^8\text{Be}(n,\gamma)^9\text{Be} \text{ vs } ^9\text{Be}(\gamma,n)^8\text{Be} \]

Neutrino-Driven Wind

Type II Supernova
Examples

\[ ^{9}\text{Be} \quad \text{Supernova Nucleosynthesis} \]

\[ \alpha \alpha \rightleftharpoons ^{8}\text{Be}(n,\gamma)^{9}\text{Be} \quad \text{vs} \quad ^{9}\text{Be}(\gamma,n)^{8}\text{Be} \]

H. Utsunomiya et al. PRC 63, 018801 (2001)
K. Sumiyoshi et al. NPA709, 467 (2002)
Examples

Supernova Nucleosynthesis

\[ \alpha + \alpha \leftrightarrow ^{8}\text{Be}(n,\gamma)^{9}\text{Be} \quad \text{vs} \quad ^{9}\text{Be}(\gamma,n)^{8}\text{Be} \]

C.W. Arnold et al. PRC 85, 044605 (2012)

A new measurement has been done by Konan University and CNS, University of Tokyo etc. at the NewSUBARU synchrotron radiation facility and data reduction is in progress.
Application

\[ ^{16}\text{O}(\gamma, \alpha)^{12}\text{C} \]

Reciprocal advantage: a factor of 100
Application

$^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$

Claudio Ugalde, The University of Chicago

Bubble Chamber

Superheated Target for Astrophysics Research (STAR)

Optical Readout TPC

Moshe Gai, U. Conn. and Yale

Lecture 3: Present and Future of Photonuclear Reactions
Evaluated Nuclear Data Library

- ENDF (USA)
  http://t2.lanl.gov/nis/data/endf/index.html
- JEFF (Europe)
  http://www.oecd-nea.org/dbforms/data/eva/evatapes/jeff_32/
- JENDL (Japan)
  http://wwwندc.jaea.go.jp/jendl/j40/J40_J.html

Reference Input Parameter Library (RIPL-3)

https://www-nds.iaea.org/RIPL-3/
Lecture 3: Present and Future of Photonuclear Reactions

ELI-NP (Europe)
(Extreme Light Infrastructure- Nuclear Physics)
Magurele-Bucharest, Romania
Approved by the European Commission in 2012
First Experiments in 2018

\[ E_\gamma = 0.2 - 19 \text{ MeV} \]
\[ I_\gamma \geq 10^{11} \text{ (s}^{-1} \text{ mm}^{-2} \text{ mrad}^{-2} \text{ 0.1}\%^{-1})} \]
\[ \Delta E/E \leq 0.5\% \]
HIGS (USA)
(High Intensity Gamma-Ray Source)

Duke Free Electron Laser Laboratory

\[ E_\gamma = 1\, \text{ - } 100\, \text{MeV} \]
\[ I_\gamma > 10^8\, \text{s}^{-1}\, \text{cm}^{-2}\, \text{on target} \]
\[ \Delta E/E > 1\% \]
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AIST Electron Accelerator Facility

General-purpose Storage Ring TERAS
- レーザー逆コンプトン光
- 偏光アンジュレータ光
- 放射光

400MeV Electron Linear Acc. TELL

Stroge Ring NIJI-IV
- VUV–IR自由電子レーザー

S-band small linear acc.
- レーザーコンプトン散乱
- 準単色ps–fs X線
- コヒーレントテラヘルツ波

Small Storage Ring NIJI-II
- SRプロセス

Pulsed slow positron beam line
- ナノメートル~原子レベル空孔計測
AIST: National Institute for Advanced Industrial Science and Technology
TERAS (Tsukuba Electron Ring for Acceleration and Storage) closed in April 2012
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NewSUBARU (Japan)

0.55 – 1.5 GeV storage ring

$E_\gamma = 0.5 - 76$ MeV
$I_\gamma = 10^6 - 10^7$ s$^{-1}$
(3 – 6 mm dia.)
$\Delta E/E > 2\%$
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Experimental Hutch GACKO
(Gamma Collaboration Hutch of Konan University)

Table-top Lasers
I. Physics and Experiments with a $4\pi$ Neutron Detector

**Physics**

Rare isotope measurements for the $p$-process nucleosynthesis

$p$-nuclei are very rare.
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• Highest intensity and monochromatic $\gamma$-ray beam
• 1mg samples of rare isotopes

Production vs Destruction

$^{181}$Ta($\gamma$,n)$^{180}$Ta
$^{139}$La($\gamma$,n)$^{138}$La
measured!

$^{180}$Ta($\gamma$,n)$^{179}$Ta
$^{138}$La($\gamma$,n)$^{137}$La
Not so ever

Day 1 Experiment #1

$^{180}\text{Ta}(\gamma,n)$ & $^{138}\text{La}(\gamma,n)$ measurement

20 $^3\text{He}$ proportional counters embedded in polyethylene moderator
Triple-ring configuration
1$^{\text{st}}$ ring of 4 counters
2$^{\text{nd}}$ ring of 8 counters
3$^{\text{rd}}$ ring of 8 counters

4$\pi$ Neutron Detector
A $^{180}\text{Ta}$ sample with **rather low enrichment** may contain a large amount of $^{181}\text{Ta}$.

$$S_n(^{181}\text{Ta}: 7576.8 \text{ keV}) - S_n(^{180}\text{Ta}: 6641.2 \text{ keV}) = 935.6 \text{ keV}$$

Similarly,

$$S_n(^{139}\text{La}: 8778 \text{ keV}) - S_n(^{138}\text{La}: 7495 \text{ keV}) = 1283 \text{ keV}$$

We have to be careful about the amount of chemical impurities of $^{180}\text{Ta}$ and $^{138}\text{La}$ samples as well.
Rare isotopes to be studied

35 p-nuclei
Neutron-deficient isotopes
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Realm of Nuclear Photonics

- Two Phonon State
- Pygmy Dipole Resonance
- Giant Dipole Resonance

γ-ray strength function

Nucleosynthesis (p-process, s-process)

modified by H. Utsunomiya
Resonances above $S_n$

Threshold Photoneutron Technique
Bremsstrahlung + n-TOF

$^{207}\text{Pb}(\gamma,n)$

$^{208}\text{Pb}(\gamma,n)$

C.D. Berman et al., PRL25, 1302 (1970)
R.J. Baglan et al., PRC3, 2475 (1971)
$^{57}\text{Fe}(\gamma,n)$

$^{53}\text{Cr}(\gamma,n)$
Day 1 Experiment #2

PDR and M1 resonance in $^{207}\text{Pb}$

- $^{207}\text{Pb}(\gamma,n)$ measurement

Liquid Scintillation and LaBr$_3$(Ce) Detector Array
Exclusive neutron decays of GDR in $^{159}$Tb
in collaboration with Vladimir Varlamov

- $^{159}$Tb($\gamma$,xn) x = 1, 2, 1g/cm$^2$
- $S_n = 8.133$ MeV
- $S_{2n} = 14.911$ MeV

Neutron multiplicity sorting with a multi-stop TDC with a time range 512 ns

$E_\gamma$(max) = 19 MeV
Production of long-lived Isomers by 2 x 10PW lasers at E7

Laser acceleration of heavy ions that undergo nuclear excitations induced by electrons.

$^{189}$Os: $9/2^-$, 30.8 keV, 5.81h

$^{176}$Lu: 1-, 123 keV, 3.66h
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Experimental setup for Laser acceleration of Fe ions

Private communication with Dr. Nishiuchi of JAEA-KIZU
Acceleration mechanism
(Target Normal Sheath Acceleration)

Extension of the classical case of plasma expansion into vacuum driven by ambipolar electric field

\[
\text{Boltzmann dist. for electron}
\]
\[
n_e = n_{e0} \exp\left(\frac{e\Phi}{T_e}\right)
\]

Poission eq.
\[
\varepsilon_0 \frac{\partial^2 \Phi}{\partial^2 x} = e(n_e - n_p)
\]

Target \(\sim \mu\text{m}\), \(\lambda_D < 1\mu\text{m}\)

Proton energy at shock front
\[
E_i \propto f(t_{acc}, l_{acc}) \times T_e
\]

Mora, PRL 90, 185002 (2003), Mora, PRE 72, 056401 (2005)
Murakami and Basko, PoP 13 012105 (2006)
Nishiuchi PLA 357 339 (2006)
Passoni and Lontano LPB 22 163 (2004),
Passoni and Lontano PRL 101 115001 (2008),
Day 1 Experiment #4-2

**Photoexcitation of long-lived isomers at E8**

\[ ^{189}\text{Os}: 9/2^-, 30.8 \text{ keV}, 5.81 \text{h} \]
\[ ^{176}\text{Lu}: 1^-, 123 \text{ keV}, 3.66 \text{h} \]

We can confirm photo-excitation of isomers by detecting neutrons.
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Summary

• Following pioneering developments at HIGS, AIST, and NewSUBARU, ELI-NP will open up a new era of nuclear science with intense gamma and laser photon beams.

• Please join photon physics at different facilities worldwide.

*Imagination is more important than knowledge.*

– A. Einstein