Photon-induced reactions: an overview

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Physikzentrum Bad Honnef

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Contents

• Photon sources and experimental approaches
  – Bremsstrahlung photons vs. Laser Compton Backscattered photons
  – (Activation method vs. in-beam technique)

• Recent results – an overview

• Other techniques
  – Tagged photons
  – Virtual photons
Photon sources

Bremsstrahlung facilities - principles

• Production by stopping of electron beam with energy $E_0$
• Continuous-energy photon spectrum with max. energy $E_0$

![Graph showing photon spectrum with peak at $E_0 = 9950$ keV]
Bremsstrahlung facilities - examples

- **DHIPS @ S-DALINAC, Darmstadt, Germany**

- Energies up to 10 MeV
- Photon intensities:
  - @ T1: $10^6$ keV$^{-1}$s$^{-1}$cm$^{-2}$
  - @ T0: $3 \cdot 10^8$ keV$^{-1}$s$^{-1}$cm$^{-2}$

Photon sources

Bremsstrahlung facilities - examples

- ELBE @ HZ Dresden-Rossendorf, Germany

Feb 7th, 2012

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**Photon sources**

**Laser Compton Backscattered (LCB) photons - principles**

![Diagram showing laser beam (eV), Compton scattering, and gamma-ray (MeV) interactions](image)

\[
E_\gamma = \frac{\hbar \omega \left(1 - \beta \cdot \cos \theta_i\right)}{1 - \beta \cdot \cos \theta_f + \frac{\hbar \omega}{E_{\text{electron}}} \left(1 - \cos \theta_{\text{photon}}\right)}
\]

- **Example:** \(E_{\text{laser}} = 3.3 \text{ eV}, E_{\text{electron}} = 450 \text{ MeV} (\gamma = 882)\)
  \(\rightarrow E_\gamma = 10 \text{ MeV}\)

- Compton scattering preserves polarization
  \(\rightarrow (\text{quasi-}) \text{monoenergetic 100\% linearly polarized high-energy photon beam}\)
Photon sources

LCB photons - examples

• TERAS @ AIST, Tsukuba, Japan

Photon sources

LCB photons - examples

• HI$\gamma$S @ DFELL, Durham, NC, USA

Experimental approaches

Activation method

1. Produce unstable nuclei in particle- or photon-induced nuclear reaction, e.g. \((\alpha, \gamma)\), \((p, n)\), \((n, \gamma)\), or \((\gamma, n)\)

2. Determine reaction yield \(Y\) offline using \(\gamma\) spectroscopy or alternative methods, e.g. accelerator mass spectrometry

• Advantages:
  – Measurement of weak \(\gamma\) branchings (e.g. \(^{185}\text{W}\): \(T_{1/2} = 75\) d, \(I_\gamma(125\) keV) \(\approx 10^{-4}\))
  – Usage of naturally composed targets (e.g. \(^{196}\text{Hg}, \text{^{198}Hg}, \text{^{199m}Hg}, \text{^{200}Hg}\))
  – Activate targets simultaneously (e.g. Zr, Re, Ir, and Au)

• Restrictions:
  – Appropriate lifetime of product nucleus
  – Appropriate \(\gamma\) transitions in decay of product nucleus
  – Limited to stable (or very long-lived) nuclei
Experimental approaches

In-beam technique

• Measure reaction product(s) with efficient detector array

• Advantages:
  – Generally applicable
  – Energy- and time-resolved measurements

• Restrictions:
  – Highly-enriched target material
  – Contaminations of target material
  – Natural and beam-induced background
  – Lower sensitivity
Recent results – an overview

„Gamow window“ of (γ,n) reactions

- **Planck distribution:**
  \[ n_γ^{\text{Planck}} \, dE = \frac{1}{\pi^2 (\hbar c)^3} \cdot \frac{E^2}{\exp(E / kT) - 1} \cdot dE \]

- **σ(E)** with typical threshold behaviour

- **Reaction rate:**
  \[ \lambda(T) = \int c \cdot n_γ^{\text{Planck}} \cdot \sigma(E) \cdot dE \]
Recent results – an overview

Approximate Planck spectrum by bremsstrahlung spectra

→ Determine ground-state reaction rates at typical $p$-process temperatures ($T_9 \approx 2 - 3$)
Recent results – an overview

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Recent results – an overview

DHIPS @ S-DALINAC, Darmstadt, Germany

Recent results – an overview

ELBE @ HZ Dresden-Rossendorf, Germany

$^{144}\text{Sm}(\gamma,n)$: experiment vs. theory

$^{144}\text{Sm}(\gamma,x)$: experiment vs. theory

Recent results – an overview

TERAS @ AIST, Tsukuba, Japan

$^{91, 92, 94, 96}$Zr($\gamma$,n): experiment vs. theory

Recent results – an overview

HIγS @ DFELL, Durham, NC, USA

- $^{96}$Zr(γ,n): activation of naturally composed targets

→ Enhancement of cross section also observed
Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany

(\gamma,\gamma'x) - experiments at NEPTUN tagger

Other techniques: Tagged photons

Photon energy: $E_\gamma = E_0 - E_e$
Energy range: $6\text{ MeV} \leq E_\gamma \leq 20\text{ MeV}$
Energy resolution: $\Delta E = 25\text{ keV @ 10 MeV}$
Energy window: $\approx 2$ to $3\text{ MeV}$
Photon intensity: $\approx 10^3\text{ keV}^{-1}\text{s}^{-1}\text{cm}^{-2}$
Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany
Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany
Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany

- DE
- SE
- FEP

$\text{FWHM} \approx 50 \text{ keV}$

$\approx 1250 \text{ keV}$
Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany

Other techniques: Tagged photons

NEPTUN @ S-DALINAC, Darmstadt, Germany

- 13 liquid scintillator neutron detectors (pulse shape discrimination)
- 4 additional $^{10}\text{B}$ loaded liquid scintillator detectors (discrimination by $^{10}\text{B}(n,\alpha)^7\text{Li}$)
- angular momentum (granularity) and energy of neutrons (TOF) → distinguish between decay to ground and excited states

Coulomb dissociation in inverse kinematics @ LAND/R3B

- CD cross section of Pb(⁹³Mo,⁹²Mo+n)Pb yields cross section of ⁹³Mo(γ,n)⁹²Mo
- Kinematically complete measurement needed
- Detection of all reaction products with energy information
Other techniques: Virtual photons

Coulomb dissociation in inverse kinematics @ LAND/R³B

![Graph showing the number of virtual photons vs. energy. The graph has a logarithmic scale on the y-axis and a linear scale on the x-axis. Three curves are plotted: E2 (dashed black), E1 (solid black), and M1 (dotted red). The x-axis represents energy in MeV, ranging from 0 to 25, and the y-axis represents the number of virtual photons, ranging from 10 to 10^4.]

O. Ershova, PhD thesis, Goethe-University Frankfurt
Other techniques: Virtual photons

Coulomb dissociation in inverse kinematics @ LAND/R³B

O. Ershova, PhD thesis, Goethe-University Frankfurt
Coulomb dissociation in inverse kinematics @ LAND/R$^3$B

Other techniques: Virtual photons

- Separation of neutrons and heavy fragments
- Identification of incoming particles
- Measurement of emitted photons
- Measurement of neutrons
- Measurement of heavy fragments

O. Ershova, PhD thesis, Goethe-University Frankfurt
Other techniques: Virtual photons

Comparison to results with real photons

- $^{100}\text{Mo}(\gamma,\text{n})$ measured & analysed at TU Darmstadt:
  results approve theoretical predictions

- $^{92}\text{Mo}(\gamma,\text{n})$ and $^{100}\text{Mo}(\gamma,\text{n})$ measured & analysed at Helmholtzzentrum Dresden-Rossendorf:
  - $^{100}\text{Mo}(\gamma,\text{n})$: results approve theoretical predictions
  - $^{92}\text{Mo}(\gamma,\text{n})$: disentangle contribution of $^{92}\text{Mo}(\gamma,\text{p})$, energy dependence of cross sections correctly predicted
Comparison to results with real photons

\[ Y_{\text{act}}(^{92}\text{Mo}(\gamma,\chi)) \frac{\Phi_\gamma(7.288 \text{ MeV})}{\Phi_\gamma(7.288 \text{ MeV})} \]

\[ ^{92}\text{Mo}(\gamma,p) \]

\[ ^{92}\text{Mo}(\gamma,n) \]

\[ ^{92}\text{Mo}(\gamma,\alpha) \]

Other techniques: Virtual photons

Comparison to results with real photons

<table>
<thead>
<tr>
<th>$^{100}\text{Mo}(\gamma,n)$</th>
<th>$^{100}\text{Mo}$ 1n</th>
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<tbody>
<tr>
<td>$\sigma_{CE}$, mb</td>
<td>$\Delta_{stat}$, %</td>
</tr>
<tr>
<td>This work</td>
<td>799</td>
</tr>
<tr>
<td>Beil et al.</td>
<td>997</td>
</tr>
</tbody>
</table>

| $\sigma_{This\ work}/\sigma_{Beil}$ | $0.8 \pm 0.1$ |
| $\sigma_{Erhard}/\sigma_{Beil}$     | $0.89 \pm 0.09$ |

• scaling factor compared to H. Beil et al. agrees within uncertainties for real and virtual photons


O. Ershova, PhD thesis, Goethe-University Frankfurt
Summary & Outlook

- Different photon sources offer a variety of experimental approaches
  - Activation with bremsstrahlung
  - In-beam with LCB photons
  - High-resolution studies with tagged photons
  - Study of unstable isotopes with CD in inverse kinematics

- New high-intense and high-resolution photon sources under development → ELI-NP @ Bucharest, Romania
- Extension of LAND/R$^3$B setup to measure ratios of $(\gamma,\alpha)/(\gamma,n)$ and $(\gamma,p)/(\gamma,n)$ reaction rates
- Determine $(n,\gamma)$ cross section from data on $(\gamma,n)$ reaction
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