Nuclear Photonics: Basic facts, opportunities, and limitations

Norbert Pietralla, TU Darmstadt
Nuclear Photonics: An attempt of a definition

„Nuclear Photonics is the cross-disciplinary field of Physics and Engineering which addresses controlled photo-nuclear reactions with artificial γ-ray beams and their applications.“

„controlled“
• excitation / manipulation of single nuclear quantum states / groups of states

„artificial gamma-ray beams“
• usage of artificially shaped γ-ray beams w.r.t. spectral intensity profile

„cross-disciplinary“
• integrates techniques from nuclear physics, quantum optics, accelerator science

Very boldly: “Nuclear Photonics is a newly emerging field of science.”
Outline

• Basic facts on Photonuclear Reactions
  • Size of photonuclear cross sections
  • Gamma-ray beam – target interaction
  • Examples
    • Selective excitation of nuclear quantum states
    • Applications in Nuclear Resonance Fluorescence

• Manipulation of spectral intensity profile
  • Nuclear Self-Absorption
  • Examples

• Limitations

• Conclusion
Photonuclear Reactions

What happens?
Elastic Scattering: Nuclear Thomson

Klein-Nishina:

\[ \frac{d\sigma_{\text{pol}}}{d\Omega}(\theta, \phi) = \frac{1}{2} r_0^2 \left( \frac{E'_\gamma}{E_\gamma} \right)^2 \left[ \frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2 \sin^2 \theta \cos^2 \phi \right] \]

\[ r_0 = \frac{\alpha \hbar c}{M c^2} \]

typical Compton cross section: \( 40 \text{ mb} \) (per electron)

typical Nuclear-Thompson cross section (A=50): \( 4 \text{ pb} \)

10 orders of magnitude smaller, because \( M_{A=50} / m_e = 10^5 \)

→ focus here on inelastic scattering
Inelastic scattering: Resonance Scattering
Photonuclear Reactions

Absorption → Separation threshold → ~ 8 MeV

\[ ^A_X \rightarrow ^{A'}_{Y} \beta \]

\[ \gamma \rightarrow \gamma' \]

Nuclear Resonance Fluorescence (NRF)
Photoactivation
Photodesintegration (-activation)
Photofission
Photonuclear reactions in the continuum

- (semi-)continuous-energy ejectiles
- energy-resolution obtained from incident $\gamma$-ray beam
- physics cases:
  - fine structure in the continuum
  - continuum-decay modes
  - multipole decomposition of resonances
- examples

S. Henshaw et al. (HI$\gamma$S)

Beene et al.
Krasnahorkay, Ponomarev

Oct. 17th, 2016 | Nuclear Photonics 2016, Monterey | “Nuclear Photonics: Basic Facts” | Prof. Dr. h. c. Norbert Pietralla | IKP, TU-Darmstadt
Nuclear Resonance Fluorescence (NRF)

\[ \Gamma = \Gamma_0 + \sum_{f>0} \Gamma_f \]

NRF cross section

- Breit-Wigner absorption resonance curve for isolated resonance
  - radioactive decay law and Fourier transform: \( \Psi(t) \rightarrow \Psi(E) \)

\[
\sigma_a(E) = \frac{\pi \lambda^2}{2} \frac{2J + 1}{(E - E_r)^2 + (\Gamma/2)^2} \frac{\Gamma_0 \Gamma}{\Gamma_0 \Gamma + (\Gamma/2)^2} = \frac{\sigma_0}{1 + (E - E_r)^2/\Gamma^2} \sim \frac{\Gamma_0}{\Gamma}
\]

- On resonance \((E = E_r)\) cross sections are very large.

\[
\rightarrow \quad \sigma_0 \cong 200 \text{ b} \quad \text{(for } \Gamma_0 = \Gamma, \quad E = 5 \text{ MeV)}
\]

- Irrespective of multipolarity!
- However, resonances are very narrow \((\Gamma_0)\)
NRF cross section

- Photonuclear excitation widths $\Gamma_0$ depend on nuclear wave functions
  
  \[ \Gamma_0 = c_\lambda \left( \frac{E_\gamma}{\hbar c} \right)^{2\lambda+1} |\langle \Psi_f \| \hat{T}_{\pi\lambda} \| \Psi_i \rangle|^2 \]

- with typical widths $\Gamma_0$ for photonuclear excitations
  (use Weisskopf estimate for $A=50$ and use $E=5$ MeV)
  - $E1$ (use 1 mW.u.): $0.1$ eV
  - $M1$: $2.6$ eV
  - $E2$: $30$ meV
  - $M2$: $0.6$ meV
  - $E3$: $4$ µeV

- much more narrow than photon beam profile

- → Integrated cross section
Thermal motion of target nuclei lead to Gaussian Doppler-broadening of resonance (typical Doppler width $\Delta \approx \text{few eV} > \Gamma$)

$$\sigma_a^D(E') = \frac{\pi}{2} \sigma_0 \frac{\Gamma}{\Delta} e^{-\left(\frac{E-E_F}{\Delta}\right)^2}$$

Energy-integrated absorption cross section:

$$I_a = \int \sigma_a^D(E) \, dE = \frac{\pi}{2} \sigma_0 \Gamma \sim \Gamma_0$$

Elastic-scattering cross section $\sim \Gamma_0^2/\Gamma$
Example: M1 and E2 NRF on $^{156}\text{Gd}$

Excitation of Scissors Mode: M1

Excitation of rotational state on top of Scissors Mode: E2

First E2 NRF in deformed nucleus

T.Beck et al., to be submitted soon
Beam – Target Interaction: Self Absorption

Evolution of Photon Flux in Target

Absorption line

„Spectral shaping“

→ Nuclear Photonics
Absorption Density Profile

Evolution of NRF intensity in Target

![Evolution of NRF intensity in Target](image-url)
Absorption Processes

Absorption lines only a few eV wide!

- **Resonant absorption**
  - only at resonance energies
  - depends on $\Gamma_0$

- **Atomic attenuation**
  - several processes
  - contributes at each energy
  - independent of $\Gamma_0$

$$\sigma_a \propto \Gamma_0 \cdot e^{-\left(\frac{E - E_r}{\Delta}\right)^2}$$
Use scatterer made of absorber material as „high-resolution detector“.  

**Principle of Measurement and Self Absorption**

1. F. R. Metzger, *Prog. in Nucl. Phys.* 7 (1959) 53

Self Absorption: Decrease of Scattered Photons because of Resonant Absorption

\[
R(G_0) = \frac{N_{woA} - f \cdot N_{wa}}{N_{woA}}
\]

\[
f = \frac{N_{std}^{woA}}{N_{std}^{wa}}
\]
Self Absorption Measurement on $^6$Li
(Ch. Romig, TU Darmstadt, PhD thesis, 2014)

- scatterer: 5 g Li$_2$CO$_3$ (enriched to 95% in $^6$Li)
- calibration target: 4.2 g $^{11}$B (sandwiched)
- absorber: 10 g Li$_2$CO$_3$ (enriched to 95% in $^6$Li)
- endpoint energy: 7.1 MeV
- 7 days w/o absorber
- 8 days w/ absorber

\[ R = 0.5178 \pm 0.0015 \]
(0.3% relative uncertainty)
\[ \rightarrow \Gamma_0 \]

Ch. Romig, TU Darmstadt, 2014
Determination of Ground-State Transition Width and Branching Ratio to the Ground State

- calculate $R$ as function of $\Gamma_0$
- self absorption $R_{\text{exp}}$ determined experimentally
- comparison of experiment and calculation gives ground-state transition width $\Gamma_0$
- NRF measurement gives $\Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$
- thus total width $\Gamma$ and branching ratio $\Gamma_0/\Gamma$ to ground state can be determined
Precision Measurements on $\Gamma_0$
Measurements on Branching Ratio $\Gamma_0/\Gamma$

Direct determination of ground-state transition widths of low-lying dipole states in $^{140}$Ce with the self-absorption technique


Branching and Fragmentation of Dipole Strength in $^{181}$Ta in the Region of the Scissors Mode

C. T. Angell, R. Hujima, and T. Shizume
Quantum Beam Science Center, Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1184, Japan
B. Ludwig and B. J. Quinter
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 4 March 2016; revised manuscript received 3 August 2016; published 26 September 2016)

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>$R(n_a)$</th>
<th>$\langle I_{cs} \rangle^*$</th>
<th>$\langle b_0 I_{cs} \rangle^*$</th>
<th>$\langle b_0 \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.28</td>
<td>0.32 ± 0.07</td>
<td>12 ± 3</td>
<td>2.9 ± 0.3</td>
<td>0.25 ± 0.10</td>
</tr>
<tr>
<td>2.75</td>
<td>0.14 ± 0.07</td>
<td>4 ± 2</td>
<td>1.8 ± 0.1</td>
<td>0.5 ± 0.7</td>
</tr>
</tbody>
</table>

Oct. 17th, 2016 | Nuclear Photonics 2016, Monterey | “Nuclear Photonics: Basic Facts” | Prof. Dr. h. c. Norbert Pietralla | IKP, TU-Darmstadt | 21
Polarization and Angular Distribution
here: Energy Splitting of $^{20}$Ne Parity Doublet
Energy Splitting of $^{20}$Ne Parity Doublet

HIγS data

Shaping of Absorption Profile
Limitations
w.r.t. atomic quantum optics

• available $\gamma$-ray beams are not coherent
• cross sections are much smaller
• level lifetimes are smaller
• $\rightarrow$ double-photon excitation very difficult
  • assume $\tau \approx 1$ fs $\rightarrow$ useful $\gamma$-bunch length: $\sim 0.3$ $\mu$m
  • corresponds to $10^{-3}$ o for a 3 GHz – accelerator
  • half-value thickness: $\sim 5$ cm $\Rightarrow$ $\sim 1$ nucleus / b
  • necessary flux for double-$\gamma$ excitation: $\sim 1$ $\gamma$ / (eV b fs) = $10^{39}$ $\gamma$ / (eV cm$^2$ s)

• spectral shaping of $\gamma$-ray flux by absorption $\rightarrow$ loss of intensity
Conclusions

“Nuclear Photonics is an emerging field of science.”

“Nuclear Photonics is the cross-disciplinary field of Physics and Engineering which addresses \textit{controlled} photo-nuclear reactions with artificial $\gamma$-ray beams and their applications.”

\begin{itemize}
\item \textit{controlled}\\
\begin{itemize}
\item excitation / manipulation of single nuclear quantum states / groups of states
\end{itemize}
\end{itemize}

\begin{itemize}
\item \textit{artificial gamma-ray beams}\\
\begin{itemize}
\item usage of artificially shaped $\gamma$-ray beams w.r.t. spectral intensity profile
\end{itemize}
\end{itemize}

\begin{itemize}
\item \textit{cross-disciplinary}\\
\begin{itemize}
\item integrates techniques from nuclear physics, quantum optics, accelerator science
\end{itemize}
\end{itemize}
Thank you very much!

\[ \gamma \text{ at } 10^5 - 10^7 \frac{\gamma}{(\text{eV s})} \text{ at CERN - ERL} \]
S-DALINAC at TU Darmstadt

Source
- Electron Source
- 130 MeV Electron LINAC

Photon Experiments
1. 10 MeV Injector: Photon Scattering / Photofission
2. < 30 MeV Tagger: Photodesintegration / Photon Scattering

Thanks to
- State of Hesse
- TU Darmstadt
- DFG
S-DALINAC at TU Darmstadt

Recirculating superconducting LINAC
Niobium cavities,
LHe cooled @ 2 K,
3 GHz cw e-beams,
< 130 MeV, ≤ 60 µA
Darmstadt Low-Energy Photon Scattering Site at S-DALINAC

K. Sonnabend et al., NIM A (2011).

Diagram:
- Electrons
- Bremsstrahlung
- $E_\gamma < 10$ MeV

$\gamma$-detectors
Radiator target
Target

$\text{Cu}< 10$ MeV

Oct.17th, 2016 | Nuclear Photonics 2016, Monterey | “Nuclear Photonics: Basic Facts” | Prof. Dr. Dr. h. c. Norbert Pietralla | IKP, TU-Darmstadt | 33
Parity quantum number $\pi$ for J=1 states

Elastic scattering distribution not isotropic about incident polarization plane.
No intensity along oscillating dipole vector
Azimuthal rotation by 90° for M1 and E1 distributions
Observable only for linearly polarized beam

$W(\theta, \phi) = 1 + \frac{1}{2} [P_2(\cos \theta) + \frac{1}{2} \pi_1 \cos(2\phi) P_2^{(2)}(\cos \theta)]$

CERN - ERL
1,000 x more flux
10 x higher energy resolution
great discovery potential

"pygmy resonance": all E1!


established international community
(not only NRF!)
Parity Violation in Nuclear Structure?

parity violation (PV) effect postulated in 1956 and experimentally verified in 1957 by Wu et al.

various theoretical and experimental attempts but impact of weak interaction on nuclear structure not well tested, yet

parity non conservation in nuclear excitation could be tested with circularly photon beams [1]

\[ A_{RL}^{a} = \frac{\sigma_{R}^{a} - \sigma_{L}^{a}}{\sigma_{R}^{a} + \sigma_{L}^{a}} \sim \frac{2R}{E_{\pi} - E_{-\pi}} \langle \phi_{-\pi} | V_{PNC} | \phi_{\pi} \rangle \]

<table>
<thead>
<tr>
<th>Transition</th>
<th>[E_f]</th>
<th>[E_f]</th>
<th>[R_N/\Delta E]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{14}\text{C} )</td>
<td>(0(^{-}), 1) \rightarrow (2(^{-}), 1)</td>
<td>7340</td>
<td>7010</td>
</tr>
<tr>
<td>(^{14}\text{N} )</td>
<td>(1(^{+}), 0) \rightarrow (1(^{+}), 0)</td>
<td>6203</td>
<td>5691</td>
</tr>
<tr>
<td></td>
<td>(1(^{+}), 0) \rightarrow (0(^{+}), 1)</td>
<td>8624</td>
<td>8776</td>
</tr>
<tr>
<td></td>
<td>(1(^{+}), 0) \rightarrow (2(^{-}), 1)</td>
<td>9509</td>
<td>9172</td>
</tr>
<tr>
<td>(^{15}\text{O} )</td>
<td>((1(^{-}), (1)(^{-}))</td>
<td>11025</td>
<td>10938</td>
</tr>
<tr>
<td>(^{16}\text{O} )</td>
<td>(0(^{+}), 0) \rightarrow (2(^{-}), 0)</td>
<td>8872</td>
<td>6917</td>
</tr>
<tr>
<td></td>
<td>(0(^{+}), 0) \rightarrow (2(^{+}), 1)</td>
<td>91520</td>
<td>95 ± 0.7</td>
</tr>
<tr>
<td>(^{18}\text{F} )</td>
<td>(1(^{+}), 0) \rightarrow (1(^{-}), 0 + 1)</td>
<td>5605</td>
<td>5603</td>
</tr>
<tr>
<td>(^{20}\text{Ne} )</td>
<td>(0(^{+}), 0) \rightarrow (1(^{-}), 0)</td>
<td>11270</td>
<td>11262</td>
</tr>
</tbody>
</table>

\(^{20}\text{Ne}\) Parity Doublet

\[ \begin{align*}
\Delta E & \quad 1^- \quad 11270 \ (5) \quad T=1 \\
1^+ \quad 11262.3\ (19) & \quad \text{isobaric analogs} \\
\pi(d_{5/2}) & \quad \pi(d_{5/2}^{1}) \nu(d_{5/2}^{3}) \\
\pi(p_{3/2}) \nu(d_{5/2}^{3}) & \quad 2^+ \quad 3^+ \quad 4^+ \quad \text{gs} \\
^{20}\text{F, } T_\epsilon = 1
\end{align*} \]

- doublet is isobaric analog of simple shell model states
- high nuclear enhancement factor [1]:
  - overlapping wavefunctions
  - small energy splitting (large uncertainty)
- feasibility of measurement of PV effect on \(^{20}\text{Ne}\)?

\[ |R_N/\Delta E| = (670 \pm 7000) \quad \Delta E = (7.7 \pm 5.3) \text{ keV} \]
Experiment on $^{20}\text{Ne}$ at HI$\gamma$S

- beam energy: 11.26 MeV ($\Delta E \approx 350 \text{ keV}$)
- 4 h with circular polarized photons (isotropic emission $\rightarrow$ reference point)
- 20 h with linear polarized photons (separation of $1^+$ and $1^-$ state)
Scientific Opportunities at High-Intensity

Outline

• Photonuclear Reactions
• Nuclear Resonance Fluorescence
• Some Previous Achievements

• Intensity Frontier (instrumental challenge) → „Discovery Frontier“
  (scientific opportunities)

  • „Availability Frontier“ (NRF on rare isotopes)
  • „Sensitivity Frontier“ (weak channels: strong physics)
  • „Precision Frontier“ (high count rates, new methods)

• Conclusion
Application: $^6$Li as Benchmark for \textit{ab-initio} Nuclear Structure Theory

Isospin Excitations of Nucleons and Nuclei

Nucleon

- $\Delta S=1$, $\Delta T=1$
- $S=3/2$, $T=3/2$
- $S=1/2$, $T=1/2$

Deuteron

- $\Delta S=1$, $\Delta T=1$
- $S=0$, $T=1$
- $S=1$, $T=0$