NUCLEAR PHOTONICS – Opportunities for photonuclear reactions at the ELI-NP facility

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NUCLEAR PHOTONICS –
Opportunities for photonuclear reactions at the ELI-NP facility

- principle of photon induced reactions
- Extreme Light Infrastructure: ELI-NP
- physics cases
Photonuclear Reactions

- Photodissociation
- Nuclear Resonance Fluorescence (NRF)

Symbols:
- $\gamma$
- $S_n$ or $S_p$
- $n$ or $p$ or $f$
- $\beta$
- $A'Y$
- $AX$
Photons in the universe
Photons in the universe

[Diagram showing the spectrum of photons from radio waves to gamma rays, with labels for wavelength and energy in nanometers and electron volts, respectively.]

NASA/CXC/SAO/MPE
Photonuclear Reactions

• pure EM interaction
• spin selectivity (mainly E1, M1, E2 transitions)
• strength selectivity

• **For \( E_\gamma < S_n \) and \( S_p \):**
  derivation of excitation energies, spins, parities, decay energies, level widths, lifetimes, decay branchings, multipole mixing ratios, absolute transition strengths

completely model independently
NRF using bremsstrahlung

- "white" photon spectrum
- wide energy region examined
- Background at low energies

NRF using monoenergetic photons

Laser Compton Backscattering (LCB)

- "monoenergetic" photon spectrum
- tunable energy
- polarized beam

Examples:
- HIGS at TUNL (USA)
- NewSUBARU (Japan)

→ Nuclear Photonics

H.R. Weller et al., PPNP 62 (2009) 257
NRF using monoenergetic photons

Parity determination by measuring asymmetries

\[ ^{52}\text{Cr} \]

\[ 1^+ \]

\[ 1^- \]

\( E_\gamma = 7.89 \text{ MeV} \)

J. Beller et al., PLB 741 (2015) 128

Krishichayan et al., PRC 91 (2015) 044328
NRF using monoenergetic photons

$^{52}\text{Cr}$

Asymmetry vs. $E_\gamma (\text{keV})$

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The Extreme Light Infrastructure – Nuclear Physics

- High power laser system, 2 x 10 PW maximum power
  Thales Optronique SA and SC Thales System Romania

- High intensity gamma beam system GBS, 0-20 MeV beam from laser Compton backscattering
  European Consortium EuroGammaS led by INFN Rome, subcontractors include STFC (UK)

- Eight experimental areas for laser, gamma, gamma&laser

Total investment 2013-2018: > 300 M€ (230 M£) (mainly European Regional Development Fund)
Civil construction

33000 m² total:

- experimental areas
- guest house
- office spaces
The photon beam at ELI-NP

- very high intensity $> 10^4 \gamma/(s\cdot eV)$ (HIGS: $10^2 \gamma/(s\cdot eV)$)
- narrow bandwidth down to 0.5% (HIGS: 3%)
- small beam diameter in mm range (HIGS: cm range)
- high degree of polarization $> 99%$ (HIGS: $> 99%$)
- low duty factor of 100 Hz (HIGS: MHz)
ELIADE: ELI-NP Array of DEtectors

- 8 segmented HPGe Clover detectors @ 90° and 135°, \( \varepsilon_{\text{total}} \approx 6\% \) @ 1.3 MeV
- Anti-Compton shields
- 4 LaBr_3 detectors @ 90° or 4 additional HPGe Clover

C. Petcu
Discovery frontiers for NRF at ELI-NP

Availability frontier
(access to rare isotopes)

Sensitivity frontier
(weak channels)

Precision frontier
(high statistics)
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Physics cases at ELI-NP: Examples

• constraints on **neutrinoless double-beta decay** matrix elements: A novel decay channel of the scissors mode
Constraints on neutrinoless double-beta decay matrix elements: Decay channels of the scissors mode

D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl Phys. 70 (2013) 210
Branching ratios of the $1^+$ scissors mode are sensitive to parameters in certain nuclear structure models (e.g., IBM-2 Hamiltonian) → constrain nuclear matrix element in $0\nu\beta\beta$ transition rate

\[
\lambda_{0\nu\beta\beta} = G_{0\nu} |M^{(0\nu)}|^2 \left( \frac{\langle m_\nu \rangle}{m_e} \right)^2
\]

(see talks by Ben Kay, Stuart Szwec, Jonathan Entwisle)
ELI-NP:  
- narrow bandwidth allows selective excitation and detection of weak decay channels
- polarization allows to distinguish $1^+$ and $1^-$ states
Physics cases at ELI-NP: Examples

• constraints on neutrinoless double-beta decay matrix elements: A novel decay channel of the scissors mode

• parity violation in nuclear excitations: The case of $^{20}$Ne
Parity violation in nuclear excitations: The case of $^{20}\text{Ne}$

Study level mixing in $1^+/1^-$ parity doublets

$\rightarrow$ constrain weak meson-nucleon coupling

$^{20}\text{Ne} \rightarrow$

$1^+$ 11.259 MeV

$V_{\text{PNC}}$ parity non-conserving interaction (about 1 eV)

$1^-$ 11.255 MeV
Parity violation in nuclear excitations

**ELI-NP:**

- nearly 100% polarized $\gamma$ beam
- thick $^{20}\text{Ne}$ absorber in front of target removes photons to excite broad $1^+$ state, because $\sigma(1^+) \approx 30 \cdot \sigma(1^-)$
- only $1^-$ state of doublet is excited by remaining photons
- measure M1 admixture to E1 excitation by analyzing NRF events in detector perpendicular to beam axis
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• an access to the equation of state and to neutron-rich matter: Investigation of the Pygmy Dipole Resonance
An access to the equation of state and to neutron-rich matter: The Pygmy Dipole Resonance

D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl Phys. 70 (2013) 210
An access to the equation of state and to neutron-rich matter: The Pygmy Dipole Resonance

Neutron skin oscillates against neutron/proton core
→ electric dipole mode (E1) around 5-10 MeV
→ impact on nucleosynthesis, EOS, neutron skin
(see talk by Dan Watts)

ELI-NP:
• narrow bandwidth allows single state excitation
  → measure, e.g., branching ratios to excited states
• high intensity and small beam diameter
  → study E1 distribution in rare isotopes

D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl Phys. 70 (2013) 210
Physics cases at ELI-NP: Examples

- constraints on neutrinoless double-beta decay matrix elements: A novel decay channel of the scissors mode
- parity violation in nuclear excitations: The case of $^{20}$Ne
- an access to the equation of state and to neutron-rich matter: Investigation of the Pygmy Dipole Resonance
- proton-neutron symmetry breaking: Rotational $2^+$ states of the nuclear scissors mode
- the origin of matter: Studies of the photoresponse of low-abundant $p$ nuclei
- photons and radioactive isotopes: Electric and magnetic dipole response of unstable nuclei
Applications of photonics at ELI-NP

HEU Grand Challenge
detection of shielded material

Medical Imaging
low density & isotope specific

Waste Imaging & Assay
non-invasive content certification

Courtesy: Chris Barty (LLNL)
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