Photo-Nuclear Physics with PERLe

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Nuclear Photonics

Photonuclear reactions

Conference photo
*Nuclear Photonics 2018*
Brasov, Romania
Generic ERL-based Light Source

from: Chris Tennant, USPAS 2011 online
ERL’s make unprecedented γ-ray beams possible:
- high flux [+ (1–3) orders of magn.],
- high energy resolution [~0.1%]

or Compton-back scattering of external laser
Outline

• Photonuclear reactions with MeV-range $\gamma$ rays

• Motivation from astrophysics and particle physics

• Examples for recent achievements

• Concluding remarks
Photonuclear Reactions

What happens?

\[ \gamma \]

0.1 – 100 MeV

PERLe: \( 4\gamma^2E_{ph} \)
\[ \sim 0.2 – 5 \text{ MeV} \]
Photonuclear Reactions

Absorption → Separation threshold → γ' → β → A'Y

Nuclear Resonance Fluorescence (NRF)
Photoactivation
Photodisintegration (-activation)
Photofission

~ 8 MeV

gs → A X → γ
Nuclear Physics with photon beams

Pure EM-interaction
- (nuclear-)model independent
- “small“ cross sections, intense beams

Minimum projectile mass
- min. angular momentum transfer,
  spin-selective: low-spin modes [E1,M1,E2,(E3?)]

Polarisation
- “Parity Physics“, channel selectivity

Narrow Bandwidth (at 4th generation LCB source)
- Explore specific excitation energy
  “Selective Manipulation of Nuclear States“:
Astrophysical Motivation
Multi-Messenger Observation of N-Star Merger

LIGO/VIRGO – collaboration, Fermi Satellite
Neutron-Star Merger in the Visible Spectrum

A star changes colour in 4 days! „Kilonova“

Light curve of neutron-star mergers due to synthesized rare-earth nuclei
Neutron-Star Mergers

Neutron-star merger:
Cosmic heavy-element nucleosynthesis

Rapid neutron-capture process and fission cycling

Nuclear dynamics govern GW signal
Cosmic Nucleosynthesis

Nuclear Chart

E1 strength: photodisintegration
M1 strength: neutrino reactions

Identified
Known half-life
r-process waiting point
Motivation from Astrophysics and Particle Physics

• Nuclear Equation of State (EoS) determines properties of neutron stars (e.g. radius) and dynamics of n-star mergers incl. GW signal.
• Constrains on density-dependence of symmetry-energy of EoS from nuclear dipole-polarizability, i.e., inversely energy-weighted E1 excitation strength from photonuclear reactions

• Fission-cycling in n-star mergers determines resulting abundance distribution
• Energy-resolved studies of photo-induced fission resonances of long-lived trans-uranium actinides

• Calibration of spin-response of neutrino-detectors and detectors for Dark-Matter searches from photonuclear reactions

• etc.
Examples of Recent Achievements
High Intensity $\gamma$-Ray Source (HlgS)

H.R. Weller, V.N. Litvinenko
Duke University, Durham, NC, U.S.A.

Compton Backscattering of Intra-cavity Laser Light

2 – 60 MeV

$E_\gamma = \frac{4\gamma^2E_{ph}}{(1 + r + \gamma^2\theta^2)}$; $r = \frac{4\gamma E_{ph}}{mc^2}$; $E_{ph} = \frac{2\gamma^2hc}{\lambda_w(1 + K_w^2/2)}$; $\gamma = \frac{E_\gamma}{mc^2}$;

nearly monochromatic, tunable, completely polarized
Looking at the Target

11B Target
5.0(2) MeV γ-ray
beam

beam monitor
Pb
Ge

5.02 MeV
3/2−
1/2−
3/2−

First NRF at HIGS 5/15/01

Count Rate (a.u.)

0 1 2 3 4 5 6
Gamma Energy (MeV)

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3/2− → gs

3/2− → 1/2−

3 h beam

SEP

DEP
Photonuclear Reactions for EoS

Valence-shell dependence of the pygmy dipole resonance: $E1$ strength difference in $^{50,54}\text{Cr}$

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Evidence for shell-dependence of nuclear neutron skin

$^{54}\text{Cr}(\gamma,\gamma')$

@ HI\gamma$S$

Photon flux in arb. units
perpendicular polarized plane

Counts per keV

Energy (MeV)

Percentage exhaust of TRK

Neutron number

$\Delta R_p$ (fm)

$\delta \Delta R_p / \delta N$(fm)

Neutron number

RMF calculations
slope upto s.c.
slope above s.c.
Nuclear Structure for Neutrino Studies

Deep Underground Neutrino Experiment

DUNE LAr – detector for cosmic $\nu$’s

$\nu + \text{Ar} \rightarrow \nu' + \text{Ar}^*$


→ total low-energy neutrino cross section
E2 decay strength of the Scissors mode

\[ B(E2; 1^+_{ScM} \rightarrow 2^+_1) = 0.037(19) \text{ W.u.} \]

\[ \delta = -0.07(1)_{\text{stat}}(2)_{\text{syst}} \]
Motivation for Nuclear Photonics @ PERLe

- Photons provide a sensitive probe for nuclear structure
- Properties of nuclear isotopes as a function of mass (neutron number)
- Low-energy frontier of Quantum Chromo-Dynamics
- Photonuclear reactions impact the structure and dynamics of stars
- Formation of chemical elements in the Universe
- Nuclei as detector material for neutrino experiments and searches beyond the Standard Model

→ Nuclear photonics
Physics with Photon Beams

- **Nuclear Structure Physics**
  - Nuclear single particle structure
  - Collective nuclear structures
  - Photofission

- **Particle-Physics Metrology**
  - Neutrino detectors
  - Nuclear matrix elements for $\beta\beta$-decay

- **Nuclear Astrophysics**
  - Capture / desintegration reactions
  - Nuclear synthesis

- **Applications**
  - Radiotomography of fuel rods
  - Cultural heritage, etc.

*Thank you very much!*