Sectoral Operational Programme „Increase of Economic Competitiveness” “Investments for Your Future”

Extreme Light Infrastructure – Nuclear Physics (ELI-NP)
Project co-financed by the European Regional Development Fund

Highlights of the experimental program with brilliant gamma beams at ELI-NP

Dimiter L. Balabanski

Carpathian Summer School of Physics
July 1st, 2016
Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

Mission: Nuclear Physics studies with high-intensity lasers and brilliant γ beams
Photonuclear Reactions

Absorption

\[ A_X \rightarrow gs \]

\[ \gamma \]

\[ \gamma' \]

\[ \beta \]

Separation threshold

\[ \sim 8\ MeV \]

\[ A'_Y \]

Nuclear Resonance Fluorescence (NRF)
Photoactivation
Photodesintegration (-activation)
Photofission
Electromagnetic dipole response of nuclei

Nuclear structure
• Modes of excitation below the GDR

Impact on nucleosynthesis
• Gamow window for photo–induced reactions in explosive stellar events

Understanding exotic nuclei
• E1 strength will be shifted to lower energies in neutron rich system

see talks of Dan Filipescu and Virgil Baran
Part I:

NRF experiments at ELI-NP
ELIADE array

γγ coincidences
angular distributions
polarization measurements
Y-ray spectroscopy

Tests of 5 Tigress-type Clovers and electronics are underway

• 8 segmented clover HPGe detectors @ 90° and 135°, $\varepsilon_{\text{total}} \approx 6%$
• Anti-Compton shields (back-catchers)
• 4 LaBr$_3$ detectors @ 90°

Calin A. Ur
Gabriel Suliman
Luigi Caponni
Cristian Petcu
Gabriel Turturica
Abdullah Coban

In collaboration with TU Darmstadt and U. Koeln
Energy deposition in 3 segments
NRF experiments

HlyS @ Duke U.
- bandwidth – few%
- spectral density – $10^2$ ph/s/eV

ELI-NP
- bandwidth – 0.3%
- spectral density – $10^4$ ph/s/eV
ELIADE physics cases

- Self-absorption measurements ($\Gamma_0/\Gamma_i$)
- Low-energy dipole response (e.g. Actinides)
- Dipole response and parity measurements for weakly-bound nuclei
- Investigation of the Pigmy Dipole Resonance
- Rotational $2^+$ states of the scissor mode
- Constraints on the $0\nu\beta\beta$-decay matrix elements of the scissors mode decay channel: $^{150}$Sm

Availability frontier: $p$-nuclei and actinides
Sensitivity frontier: week channels
Precision frontier: high statistics
While the TDR did not explicitly state a preference for a day-one experiment, the reviewers suggested:

“The opportunity to study quadrupole-octupole excitations and the recently reported enhanced magnetic dipole excitation in actinides, including long-lived unstable isotopes, due to the high luminosity leading to small beam spots and the use of polarized gamma beams at ELI-NP is unique. It is proposed as the day-one experiment.”
Part II:

Gamma above threshold experiments at ELI-NP
Gamma above neutron threshold experiments

ELIGANT-GN array
30 LaBr$_3$ or CeBr$_3$
20 $^7$Li glasses
30 Lq. Scint.

Tests of detectors and electronics are underway

ELIGANT-THN array
30 $^3$He counters

Dan Filipescu
Dan Ghita
Tudor Glodariu
Jasmeet Kaur
Ioana Gheorghe
Gheorghe Ciocan

in collaboration with U. Milano and INFN-Milano, Konan U. (and RCNP, U. Osaka)
E7 experimental area
RCNP Osaka vs. ELI-NP experiments

**RCNP**

High-resolution \((p,p')\) measurement at 0° and forward angles  
A. Tamii, NIM A605, 326 (2009)

**ELI-NP**

High-resolution \((\gamma,\gamma') + (\gamma,n)\) measurement

**advantages:** polarized (>99%) \(\gamma\) beam  
simultaneous \((\gamma,\gamma') + (\gamma,n)\) measurement

---

\[
\alpha_n = \frac{\sigma_{2s-2p} \cdot \frac{\hbar c}{e^2}}{2\pi^2 \cdot \frac{\sigma_{2s}(E_x)}{E_x^2}} \cdot \frac{\hbar c}{2\pi^2 e^2} = 20.1 \pm 0.6 \text{ fm}^3/\text{e}^2
\]

A. Tamii, PRL 107, 062502 (2011)
Day ONE:

studies of GDR and PDR decay ($^{90}$Zr, $^{208}$Pb)

- combine with information from ($\gamma$,n) experiments
- combine with information from ($\gamma$,\gamma') experiments (e.g. polarization)
- $\gamma$-decay to gs and excited states as a function of excitation energy
Neutron stars, equation of state and dipole polarizability @ELI-NP

- Neutron stars (NS) properties depend sensitively on the equation of state (EOS) of nuclear matter.
- EOS can affect many NS properties: mass-radius relationship, moment of inertia, cooling rates, Urca process, ...
- It has been suggested that the slope (L) of the symmetry energy term of the EOS is closely related to the dipole polarizability $\alpha_d$ through the neutron skin thickness [1,2,3].

**FIG. 1.**
Dipole polarizability $\alpha_d$ versus dipole polarization $Z - R_p$ for $^{208}$Pb.

**FIG. 2.**
Total and Pygmy contributions to neutron skin $\Delta R_{np}$ for $^{208}$Pb.

**FIG. 3.**
Neutron skin of $^{208}$Pb against slope of the symmetry energy. The linear fit is $\Delta R_{np} = 0.101 + 0.00147L$. PRL 106, 252501 (2011).

---

**ELI-NP:** experimental photo-nuclear reaction facility
- The dipole polarizability is obtained from the photo-absorption cross section:

$$\alpha_d = \frac{\hbar c}{2\pi^2} \int_{0}^{\omega} \frac{\sigma_{\text{abs}}(\omega)}{\omega} d\omega = \frac{8\pi}{9} \int_{0}^{\omega} dB(E1) / \omega$$

- Strongly dependent on the low-energy strength, e.g., Pygmy resonance (see also FIG. 2).
- ELI-NP will provide (accurate and unambiguous) measures of E1 strength below and above the neutron threshold.
- Model independent results: pure electromagnetic excitation process.

P-PROCESS NUCLEOSYNTHESIS FOR $^{180}$Ta AND MEASUREMENTS OF THE PHOTO-NEUTRON CROSS SECTION

$^{180}$Ta characteristics
- Lowest natural abundance (0.012%)
- Short-lived ($T_{1/2} = 8.15$ h) $J^\pi = 1^+$ ground state ($^{180}$Ta$^g$)
- Very long-lived ($T_{1/2} > 10^{15}$ yr) $J^\pi = 9^-$ isomeric state ($^{180}$Ta$^m$)
- $^{181}$Ta($\gamma$,n)$^{180}$Ta and $^{180}$Ta($\gamma$,n)$^{179}$Ta photo-disintegration reactions

Transversal section of the ELIGANT - TNH High Efficiency 4π Thermal Neutron Detector
- 20 cylindrical $^3$He proportional counters
- 60% detection efficiency
- low amount of $^{180}$Ta target (1mg/cm$^2$) to be used.

- Correct prediction of the $^{180}$Ta$^m$ yield highly requires both $^{181}$Ta($\gamma$,n)$^{180}$Ta and $^{180}$Ta($\gamma$,n)$^{179}$Ta cross section measurements.
- The measurements for the ($\gamma$,n) cross sections related to the p nuclides destruction requires gamma ray beam three orders of magnitude higher than the existing ones.
- Measurements of the $^{180}$Ta($\gamma$,n)$^{179}$Ta reaction are foreseen in the Day 1 experiment at ELI NP facility by using the maximum available gamma ray energy of 19 MeV.
Part III:

Charge-particle reactions at ELI-NP
(γ,α) and (γ,p) reactions for nuclear astrophysics

- The $^{16}$O(γ,α)$^{12}$C reaction
- The $^{24}$Mg(γ,α)$^{20}$Ne reaction
- The $^{22}$Ne(γ,α)$^{18}$O reaction
- The $^{19}$F(γ,p)$^{18}$O reaction
- The $^{21}$Ne(γ,α)$^{17}$O reaction

Instrumentation:

(i) ELISSA: Large-area Si SD array
(ii) ELI-eTPC

Best illustration of the anthropic principle: Observations in the Universe must be compatible with the conscious life that observes them.
eTPC for ELI-NP

- **Gas Electron Multiplier (GEM) structures:**
  - developed at CERN → F. Sauli, NIM A386 (1997) 531
  - electric fields ~40 kV/cm, electron charge gain factors ~10³
  - several GEM foils can be stacked together
Active target TPC with electronic readout (eTPC):

- for simple track topologies 3-coordinate planar readout will suffice:
  - $u$-$v$-$w$ strip arrays for hit disambiguation in 2D (“virtual pads”)
  - $z$-coordinate from timing information
  - need $O(10^3)$ channels $\Rightarrow$ moderate cost of electronics
- advantages: more freedom in gas mixture selection and more compact design w.r.t. TPC with optical readout (PMT + CCD)
Demonstrator detector

- Results for single alpha tracks (5.5 MeV from $^{222}$Rn gas decays):

**Step 1:** Raw data waveforms

**Step 2:** Clustering

**Step 3:** 2D and 3D reconstruction
Mini-eTPC detector

• Assembling Mini-eTPC detector:

Drift cage

Drift cage + triple-GEM stack
Mini-eTPC detector

- Test beam at 9 MV Tandem, Magurele, Romania:
  - 15 MeV $\alpha$-particle beam
nuclear astrophysics with ELISSA

ELISSA:

- 3 rings of 12 position sensitive X3 silicon-strip detectors by Micron
- 2 end cap detectors from 4 QQQ3 segmented detectors by Micron
- 320 channels readout with GET electronics

$^7\text{Li}(\gamma,\text{t})\alpha$

- reaction could still be a game changer in resolving the “Li problem”
- experimental measurements below 1.5 MeV are 30 yrs. old and disagree with theoretical predications
- higher energy measurements can restrict the extrapolation to astrophysically important energies

C. Matei et al., exp. at H$\gamma$S approved by the 2016 PAC
Testing X3 and QQQ3 detectors for low-energy threshold and energy resolution
Why charge-particle reactions (courtesy Yi Xu)

<table>
<thead>
<tr>
<th>Element</th>
<th>Reaction Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn</td>
<td>$^{91}$Nb($\gamma$,p)</td>
</tr>
<tr>
<td>La</td>
<td>$^{92}$Mo($\gamma$,p)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{97}$Tc($\gamma$,p)</td>
</tr>
<tr>
<td>Sm</td>
<td>$^{96}$Ru($\gamma$,p)</td>
</tr>
<tr>
<td>Eu</td>
<td>$^{101}$Rh($\gamma$,p)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{142}$Nd($\gamma$,p)</td>
</tr>
<tr>
<td>Sm</td>
<td>$^{144}$Sm($\gamma$,p)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{146}$Sm($\gamma$,a)</td>
</tr>
<tr>
<td>Sm</td>
<td>$^{147}$Sm($\gamma$,a)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{148}$Sm($\gamma$,a)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{145}$Gd($\gamma$,p)</td>
</tr>
<tr>
<td>Eu</td>
<td>$^{150}$Gd($\gamma$,a)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{152}$Gd($\gamma$,a)</td>
</tr>
<tr>
<td>Gd</td>
<td>$^{154}$Dy($\gamma$,a)</td>
</tr>
</tbody>
</table>

[Graph showing abundances and isotopic distribution]
Part III:

Photofission at ELI-NP
Photofission

tests for a BIC, 8 Si DSSD, THGEM detectors, electronics are ongoing
tenders for support infrastructure are in preparation

1. Studies in the 2\textsuperscript{nd} and 3\textsuperscript{rd} minimum of the fission barrier:
   transmission resonances
2. Rare fission modes: ternary fission, Pb radioactivity
3. Structure of neutron-rich nuclei: the $A \approx 100$ Sr-Zr and rare-earth neutron-rich deformed regions

Instrumentation:

- **ELI-BIC**: an array of Bragg ICs coupled to Si DSSD based $\Delta E$-$E$ detectors
- **ELITHGEM**: a 4$\pi$ THGEM detector
- **ELI IGISOL** beam line

D.L.B.
Paul Constantin
Deepika Choudhury
Jasmeet Kaur
Bo Mei
Phan Viet Cuong
Le Tuan Anh
Sevda Coban
Mihai Merisanu

in collaboration with MTA Atomki Debrecen, GSI, IPN Orsay, CSNSM Orsay, INP VAST Hanoi and Akdeniz U. Antalya
Studies of the 2\textsuperscript{nd} and 3\textsuperscript{rd} minimum

remember talk of Deepika Choudhury

schematic description of the occurrence of transmission resonances

P.G. Thirolf et al., EPJ Web of Conferences 38, 08001 (2012)
This set-up will be used in two types of experiments:

• Studies of the properties of the fission fragments (angular, energy, mass and charge distributions) on/off the fission resonances,

• Identification of the ternary fission particles and study their correlation with the properties of the fission fragments defined above.
ELITHGEM-(DSSD-CsI) array

This set-up will be used in two types of experiments:

• Measurement of cross-sections and fission fragment angular distributions as a function of the photon energy and mapping of fission resonances,

• Measurement of cross-sections and angular distributions of ternary (alpha) particles as a function of the photon energy by using polarized photons; absorbers will be used for stopping the fission fragments. Mapping of highly deformed states will be done.
ELITHGEM array

ten targets along the beam axis

technical design and tests at MTA ATOMKI, Debrecen

5° angular resolution
ALTO, ARIEL, etc.

\[ \gamma \text{-beam spectrum at the IP (without collimator)} \]
\[ \sim 10^{11} \frac{\gamma}{s} \]
Fragment Yields at the IGISOL-4 facility at JYFL
segmented anode
DC electrodes
target assembly
RF carpets
Laval nozzles
beam extraction
Part V:

Applications at ELI-NP
GOAL:
Build a laboratory for spectroscopy with spin polarized slow positron beam of high intensity

METHOD:
$(\gamma, e^+ e^-)$ reaction of $\gamma$-beam of $I_\gamma = 2.4 \times 10^{10} \text{s}^{-1}$ and $E_\gamma < 3.5 \text{MeV}$ with circular polarization incident on W-converter

Fig. Gamma Beam Timing
Beam formation

L - length limited to 300 mm

Converter/Moderator Assembly

γ-beam

Extraction grid

Solenoid

Electrostatic focusing from PULSTAR Nuclear Reactor e+ source

Adiabatic Magnetic Guidance to the Positron Laboratory Hall
Moderated positrons are emitted normal to the surface with $E_+ = 3$ eV. Reflection with 60% survival.
Table: The absolute $\gamma$-to-slow positron conversion efficiency, $\Gamma$, at selected values for the CMA height, $h$, and foil thickness, $d$, for CMA width $b=16$ mm and length $L=300$ mm, and $\gamma$-beam intensity profile with $D_\gamma=6.1$ mm, as obtained by GEANT4 simulation.

<table>
<thead>
<tr>
<th>$d$ (mm)</th>
<th>$h$ (mm)</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td></td>
<td>7.4x10^{-5}</td>
<td>7.6x10^{-5}</td>
<td>7.5x10^{-5}</td>
<td>7.3x10^{-5}</td>
</tr>
<tr>
<td>0.07</td>
<td></td>
<td>7.5x10^{-5}</td>
<td>7.7x10^{-5}</td>
<td>7.6x10^{-5}</td>
<td>7.5x10^{-5}</td>
</tr>
<tr>
<td>0.08</td>
<td></td>
<td>7.8x10^{-5}</td>
<td>8.2x10^{-5}</td>
<td>8.1x10^{-5}</td>
<td>7.6x10^{-5}</td>
</tr>
<tr>
<td>0.09</td>
<td></td>
<td>7.4x10^{-5}</td>
<td>7.4x10^{-5}</td>
<td>7.2x10^{-5}</td>
<td>7.0x10^{-5}</td>
</tr>
</tbody>
</table>

Efficiency $e^+_s/\gamma = 8.2\times10^{-5}$

Slow positrons = $1.6\times10^6$ s$^{-1}$
Nuclear Resonance Fluorescence

Energy [keV]

Flux of gamma-rays

Tunable

incident photon

scattered photon

electron

243 Am

0^+ 0

237 Np

0^+ 0

239 Pu

1/2^+ 0

7/2^- 0

235 U

1862 2003

Absorption

11/2^- 0

Emission

2040 1815

Absorption

2454 2423

Emission

2143

1733

938 861 870

1053 933

1123

0
Two tomography tables with biaxial movement and rotation
Various collimators with collimation holes between 0.2 mm and 5 mm.

High volume detector for pencil-beam
2D detector for cone-beam: CCD based gamma-ray camera or 2D flat panel
The European initiative for Extreme Light Infrastructure laboratories in Romania (ELI-NP), will shortly provide tunable energy γ-rays from inverse Compton scattering of laser light on a high-energy electron beam. This will allow Nuclear Resonance Fluorescence studies of isotope-specific trace element distributions to be performed with unprecedented sensitivity. It is planned to use this powerful tool for cultural heritage object studies.
Medical radioisotopes

Wen Luo et al., Appl. Phys. B 122, 8 (2016)

Dana Niculae (IFIN-HH)
Wen Luo
Mariana Bobeica
D.L.B.
Radioisotopes for medical use

• New approaches and methods for producing radioisotopes urgently needed

• Mo-99 and other medical isotopes used globally for diagnostic medical imaging and radiotherapy

• $^{195m}$Pt: In chemotherapy of tumors it can be used to exclude ”non responding” patients from unnecessary chemotherapy and optimizing the dose of all chemotherapy
Thank you!