Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

Progress of ELI-NP and photofission

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NUSTAR meeting, GSI Darmstadt
February 26th- March 2nd, 2018
the world’s first international laser research infrastructure

“The CERN of Laser Research”

a distributed research infrastructure based

initially on 3 facilities in CZ, HU and RO

Total budget: 1 B€, e.g. 350 M€ for ELI-RO

ELI–ALPS, Szeged, HU
Attosecond Laser Science
new regimes of time resolution

ELI–Beamlines, Prague, CZ
High–Energy Beam Facility
development and application of ultra–short pulses of high–energy particles and radiation

ELI–NP, Magurele, RO
Nuclear Physics Facility with ultra–intense laser and brilliant gamma beams (up to 19 MeV)
novel photonuclear studies

ELI 4, to be decided
Ultra–High–Field Science
direct physics of the unprecedented laser field strength
Mission: Nuclear Physics studies with high-intensity lasers and brilliant γ beams

- 2 x 10 PW synchronizable lasers
- 0.2 – 20 MeV 0.5% bw 95% polarized γ beam
1.5m thick, 150,000 ton “optical table”

1000 springs + vibration dampers
250 J in 25fs
1 pulse/min
Contrast
1:10^7 @ 5ps
1:10^9 @ 10ps
1:10^{14} @ 100ps

Station E4
2 x 0.1 PW/10 Hz

Station E5
2 x 1 PW/1 Hz

Stations E1 and E6
2 x 10 PW/min
10 PW lasers will enable unique experiments from Day-1

**Strong-field QED**

**Nuclear Physics with Lasers**

Extreme light intensity \((10^{23} \text{ W/cm}^2)\)

- Extreme electric fields \((10^{15} \text{ V/m})\)
  - 10 PW laser + solid target
  - Ultra-intense PW \(\gamma\)-source
  - "Day-0"

- 10 PW laser + 10 GeV LWFA electron beam
  - Radiation reaction, Breit-Wheeler pairs

- Extreme light pressures (Tbar)
  - Radiation Pressure Acceleration of dense 10 MeV/A ion beams
  - Neutron-rich nuclei
  - Ultra-intense neutron source
  - Nuclear reactions in plasmas

Day-1 experiments reviewed by ELI-NP International Scientific Advisory Board
Extreme light pressure will be used at ELI-NP to accelerate solid density ion bunches to GeV energies

- Light pressure $>10^{13}$ atm for $5 \times 10^{22}$ W/cm$^2$ intensity
- Pressure accelerates ultrathin solid foil as a whole ("light-sail")
- Good fraction of laser energy can be converted to GeV ions
Laser System Implementation Schedule

2017

Thales Laser System Implementation

10PW Laser Beam Transport System Impl.

2018

100 TW June

1 PW Sept

2019

10 PW June

Commissioning Exp.
Nuclear processes in plasmas

Nuclear (de-)excitations in plasmas

- Observed in cold targets at $10^{-8}$ rates in $^{197}$Au, $^{189}$Os, and $^{193}$Ir.
- Never observed in plasmas.

Nuclear lifetimes in plasmas

- Significant changes of nuclear lifetimes are predicted in hot and dense plasmas.

- Transition energies and lifetimes for specific nuclear states:
  - $17/2^+$: 3.53 ns, 2429.80 keV
  - $21/2^+$: 6.85 h, 2424.95 keV
  - $13/2^+$: 46 ps, 2161.90 keV
  - $5/2^+$: 0 keV

- Lifetime vs. temperature for direct and two-step deexcitation.
Gamma Beam System

low-energy accelerator section:
0.2-3.5 MeV
factory acceptance in Dec. 2015

high-energy accelerator section:
3.0-19.5 MeV

$E_{\gamma} \sim 4\gamma^2 E_L$
Gamma Beam System – Layout

- **e⁻ beam dump**
- **Interaction Point High Energy**
- **e⁻ beam dump**
- **Interaction Point Low Energy**
- **Photogun multi-bunch**
- **γ beam coll&diag**
- **γ beam coll&diag**
- **γ beam coll&diag**
- **e⁻ beam dump**

**Low-Energy Stage:**
- γ rays up to 3.5 MeV

**High-Energy Stage:**
- γ rays up to 19.5 MeV

**Master clock synchronization @ < 0.5 ps**
what to remember

- beam size: 1 mm at 10 m away from collimator
- energy spread: 50 keV at $E_\gamma=10$ MeV
- time structure: micropulses at 16 ns
- photons/pulse: $10^5$
- photons/macro-pulse: $32 \times 10^5 = 3 \times 10^6$
- photons/s: $3 \times 10^8$
Nuclear Resonance Fluorescence (NRF) – A. Zilges group, N. Pietralla group, D. Savran, W. Verner

Giant/Pigmy Resonances (GANT) – A. Zilges group, N. Pietralla group, D. Savran, R. Schwengner

Photodisintegration ($\gamma$,n), ($\gamma$,p), ($\gamma$,\alpha) – N. Pietralla group, T. Aumann

Photofission ($\gamma$,ff) – J. Enders, P. Thirolf, Ch. Scheidenberger

Applications (positron beams) – Ch. Hugenschmidt
ELIADE array
in collaboration with U. Koeln and TU Darmstadt

NRF experiment at ELI-NP

- detector tests are ongoing
- array design is at a final stage
- day-one experiments are under discussion

γγ coincidences
angular distributions
polarization measurements

• 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
Day-zero: Photoactivation of $^{180}$Ta (ISAB recommendation)


$^\text{a}$Fixed by the onset of the activation.
Day-one: Separation of the parity doublet in $^{20}$Ne (ISAB recommendation)

**Advantages at ELI-NP**
- Large volume Clover detector array
- Higher brilliance of the $\gamma$ beam
- Narrow band-width: 0.3% vs 3% at Hi$\gamma$S
- Simultaneous measurement of polarization with ELIADE and within each Clover detector

Day ONE:

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

- combine with information from $(\gamma,n)$ experiments
- combine with information from $(\gamma,\gamma^\prime)$ 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: Neutron skin of $^{208}$Pb.
- Fig. 2: Dipole polarizability $\alpha_d$ vs. $R_N-R_P$ fm.
- Fig. 3: Neutron skin of $^{208}$Pb against slope of the symmetry energy. The linear fit is $\Delta E_{sym} = 0.101 + 0.00147L$.

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

$$\alpha_d = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma_{abs}}{\omega} d\omega = \frac{8\pi}{9} \int_0^\infty dE/\omega$$

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

RCNP Osaka vs. ELI-NP experiments

**RCNP**
High-resolution $(p,p')$ measurement at $0^\circ$ and forward angles
A. Tamii, NIM A605, 326 (2009)

**ELI-NP**
High-resolution $(\gamma,\gamma') + (\gamma,n)$ measurement

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

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A. Tamii, PRL 107, 062502 (2011)
(γ,n) cross-section experiment at ELI-NP

ELIGANT-TN
Day-zero: Measurement of the $^9\text{Be}(\gamma,n)$ cross section (ISAB recommendation)

![Graph showing $^9\text{Be}(\gamma,n)$ cross section data]

<table>
<thead>
<tr>
<th>$B(E1) \downarrow$</th>
<th>Ref.</th>
</tr>
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<tbody>
<tr>
<td>$(e^2 \text{ fm}^2)$</td>
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<tr>
<td>0.107 ± 0.007</td>
<td>Utsunomiya et al. [5]</td>
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<tr>
<td>0.104 ± 0.002</td>
<td>Sumiyoshi et al. [37]</td>
</tr>
<tr>
<td>0.136 ± 0.002</td>
<td>Arnold et al. [6]</td>
</tr>
<tr>
<td>0.111 ± 0.004</td>
<td>Present</td>
</tr>
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A case where ELI-NP will have a say at Day-Zero!
The mini-eTPC detector with 256-channel readout was built and successfully tested in-beam at the IFIN Tandem in 2016.

flagship experiment: $^{16}\text{O}(\gamma,\alpha)^{12}\text{C}$

in collaboration with U. Warsaw
mini-TPC event recognition


Bihałowicz J S 2015 AIP Conf. Proc. 1645 301
nuclear astrophysics with ELISSA

ELISSA: in collaboration with INFN LNS Catania

- 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

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

- 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 in March 2017
addressing the Li-problem and theoretical aspects
using SIDAR array from ORNL
two lamp-shades of YY1: 300, 500, 1000 μm
clean alpha-triton coincidence
proposed by ELI-NP together w/: ORNL, Rutgers U, INFN-LNS, York U, Aarhus U, U Michigan
DSSD testing at ELI-NP
Experimental approach for study of fission barrier
Observation and study of transmission resonances

\[ E \]

\[ \beta \]

\[ P \]

Note: Nuclear structure correlations influence the fission probability

Investigation of Transmission Resonances as function of energy

- mapping the fission barrier
- study of SD and HD states in these min
- fine str. in the isomeric shelf


see also ELI-NP White Book: contributions of P. Thirolf and D. Habs
Photofission experiments at ELI-NP

ELI-BIC

Array of Bragg ICs coupled to Si DSSD based $\Delta$E-E detectors

BIC prototype tested with sources and in-beam

in collaboration with ATOMKI
Feasibility test of dE-E detector with AMR-33 ($^{239}$Pu + $^{241}$Am + $^{244}$Cm)

**Conclusion:** The designed dE-E array is effective for the α detection.
RA4 Timeline of Instrument Implementation

**Gamma Beam Delivery & Diagnostics**
- Beam pipes/vacuum
- Beam Dumps/Mobile shielding
- Attenuator system for beam energy
- Detectors & electronics for d(g,n)
- CCD cameras, optics
- Detector & electronics for Compton
- Integration & testing

**ELTHGEM**
- THGEM detectors
- Vacuum system
- Gas system
- Integration & tests

**ELISSA**
- QO3 end-cap detectors
- Front-end electronics & cables
- SSD testing station
- Experimental reaction chamber
- Integration & tests

**ELIAD**
- LabR3 detectors
- Single-to-differential conversion & transport
- Electronics for single-diff conversion
- Mechanical structure

**ELIAC**
- Gas-flow system
- ELTPC drift cage (internal structure)
- ELTPC vacuum chamber
- GEM detectors
- Integration & tests

**ELIBIC**
- Front-end electronics
- Gas system
- Vacuum system
- Digitizers
- Integration & tests

**Medical applications**
- Solid target gamma beam irradiation system
- Measurement station (HPGe detector)
- Target Body and Target Materials
- Integration & tests

**ELIGANT**
- Gamma Mechanical Structure
- Neutron Mechanical Structure

**Position production**
- Pipes and Chambers
- HPGe detectors
- Ne-22 source
- DAQ electronics
- Vacuum and Control
- Power Supplies (e+ transport)
- PAGS

**Industrial applications**
- Positioning systems for S&L objects
- Detectors & collimators
- Integration & tests

ALTO, ARIEL, etc

**ELI-NP**

- E-linac
- Laser Compton back-scattering
- $^{238}\text{U}$ Target
- Ion Source
- Mass Separator
- RIB User

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**Graphs:**
- Cross section vs. photon energy (MeV)
- Energy spectrum vs. photon energy (MeV)
Simulations related to the cryogenic stopping cell (CSC) are finalized.
- Gas flow simulations to study the properties of the supersonic jets through the nozzles are ongoing.
- An extension (E9) along the high-energy gamma beamline is under construction.
- A project to connect the ELI experimental building with the Reactor hall has been prepared.
IGISOL facility at ELI-NP

Studies of gas-flow dynamics funded by the Romanian Science Agency

Work in collaboration with GSI, Darmstadt and University of Giessen

P. Constantin et al, NIM B 378, 78 (2016), ibid (2016) submitted
IGISOL beamline:
Exotic Neutron-Rich Isotopes

- Energy range up to 19.5MeV covers the GDR:
- RIB via photofission in a actinide thick target
- Production of exotic neutron-rich fission fragments
- Refractory elements: light region Zr-Mo-Rh and heavy rare-earths region around Ce

U-238 target:
- thick because $\sigma(\gamma,f)\sim 1b$
- sliced in many thin foils: refractory, fast extraction
- tilted foils:
  1. avoid hitting neighboring foils
  2. increase $\gamma$ pathlength w/o increasing thickness

IGISOL beam line:
(collaboration with GSI/Giessen)
1. Cryogenic Stopping Cell (orthogonal extraction)
2. RFQ
3. MR-ToF mass spectrometer

A $\beta$-decay measurement station:
(collaboration with IPN Orsay)
tape station, HPGe detectors

T. Dickel et al., NIM B 376 (2016) 216
CSC Simulations: Fragment Slowing Down in the Gas Cell

Geant4: He, T=70K, p=300mbar ($\rho=0.206\text{mg/cm}^3$) $\rightarrow >95\%$ of fragments stop in 11.3cm $\rightarrow$ width~24cm

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ [mg/cm$^3$]</td>
<td>0.053</td>
<td>0.120</td>
<td>0.206</td>
</tr>
<tr>
<td>p [mbar]</td>
<td>100</td>
<td>200</td>
<td>306</td>
</tr>
<tr>
<td>T [K]</td>
<td>90</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>$L_{\text{max}}$ [cm]</td>
<td>43.7</td>
<td>19.4</td>
<td>11.3</td>
</tr>
</tbody>
</table>

CSC width [cm]: 90 40 24

$\rho \cdot L_{\text{max}} = 2.33\text{mg/cm}^2$
CSC Simulations: Space Charge (I)

Divide CSC in 1x1x1 cm³ cells: 24x24x100 for ρ=0.21 mg/cm³, 40x40x100 for ρ=0.12 mg/cm³, 90x90x100 for ρ=0.05 mg/cm³; Cumulate dE/dx deposited in 1s of beam and divide by Wᵢ=41 eV.

\[ \rho=0.05 \text{ mg/cm}^3 \]
\[ \rho=0.12 \text{ mg/cm}^3 \]
\[ \rho=0.21 \text{ mg/cm}^3 \]

\[ \sim 700 \text{ cells} \]

\[ \sim 2\% \text{ stop in saturated region} \]
\[ \sim 10\% \text{ stop in “dead region”} \]
\[ \sim 5\% \text{ ions not stopped} \]

extraction efficiency < 85%
CSC Simulations: Space Charge (II)

Q is not the best parameter.

\[ V_{\text{ind}} = d^2 \sqrt{\frac{eQ}{4\varepsilon\mu}} \]

d = distance between parallel electrodes
\( \varepsilon = \) electrical permittivity
\( \mu(T,p) = \) ion mobility
Universal threshold at \( V_{\text{ind}}/V \approx 1-2 \).
Field saturation sets in for \( V_{\text{ind}}/V > 1 \).

Supported by theoretical calculations:
S. Palestini et al., NIM A 421 (1999) 75

However, for our CSC: \( Q(r,\phi,z) \) inhomogeneous! → moving to SIMION!
CSC Simulations: Space Charge (III)

Heavy ions trajectory: (1) stopping segment: ultra-fast (~50 ns), high KE (>20 MeV), high charge (>30+)
(2) electric drift segment: slow (~several ms), low KE (~2 keV), low charge (1-2+)

SIMION 8.1 simulation in 3 steps:
1) solves the Poisson equation:
\[ \varepsilon \nabla^2 \Phi(x, y) = -e \tau Q(x, y) \]
with Q(x,y) from Geant4 and DC extraction time: \( \tau_i = 1.32/E \) (+7ms along carpet)
2) drifts 4000 photofission fragments from Geant4 thru \( \Phi(x,y) \)
3) obtain extraction efficiency \( \varepsilon \) and time \( \tau \). Reiterate until <10% variation: \( \varepsilon = 50-85\%, \tau \sim 10\text{ms} \)

NB! IF \( \tau < 9.5\text{ms} \): PULSED REGIME!
Conservative “day-one”: beam $5 \cdot 10^{10} \, \gamma/s$, target release eff. 25%, CSC extraction eff. 50% → $\sim 10^7$ photofissions/s and $\sim (0.8-2) \cdot 10^6$ extracted ions/s

Optimal estimate: beam $10^{12} \, \gamma/s$, twice CSC extraction eff. → expect $\sim 2$ orders of magnitude more!
Gas jet properties and gas system design with COMSOL

Nozzles (number, diameter, length), gas recirculation system (outlet number, diameter, location, mass flow) and cryogenic system (power) study w.r.t. the properties of the supersonic gas jets.

COMSOL modules: Computational Fluid Dynamics, Heat Transfer, Particle Tracing

\[
M = \frac{v}{\sqrt{\gamma RT}}
\]

results from Alex & Mihai

cylindrical 0.3mm
\[ T_{\text{min}} = 24 K \]

\[ v_{\text{max}} = 668 m/s \]

cylindrical 0.3mm
\[ M_{\text{max}} = 2.37 \]

de Laval 0.3mm
\[ M_{\text{max}} = 2.15 \]
\[ M_{\text{in}} = 2.4 \]
Current developments

Design of the main CSC components:
- target system
- gas recirculation and purification system
- cryogenic system
- electrode system (RF carpets) for ion drift

A CSC demonstrator to test these systems:
- visualize and optimize gas flow
- test offline & online ion extraction
Summary

• the instrumentation of the ELI-NP GBS experimental program is been implemented according to the project timeline;
• the physics cases, which will be addressed, have been prepared within a broad scientific community;
• commissioning and day-one experiments are currently under discussion;
• the ELI-NP GBS is expected to provide beam to the users in 2020.
Thank you!