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Nuclear Physics with the ELI-NP high power laser systems

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ELI-NP - The Physics Rationale

How to facilitate the ultraintense ion, electron, neutron, and $\gamma-$beam bursts for nuclear physics

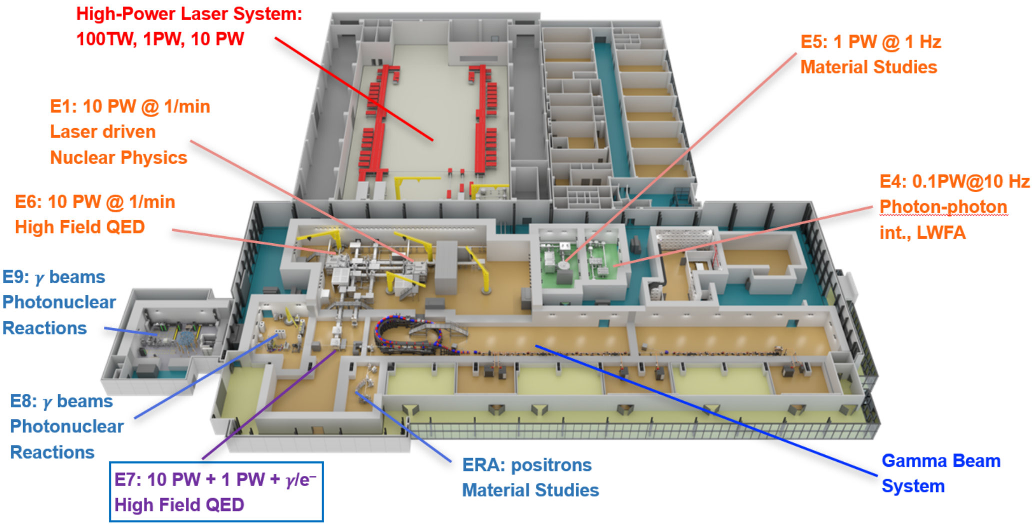
- At ELI-NP 10 PW (& 1 PW) HPLS's manipulations of nucleons in hot keV plasma, measurement of cross-sections in astrophysical conditions
- Evaluate the onset of multi-step absorption processes induced by ultrashort beam bursts
- Evaluate the possibility of reactions on short-lived excited states
- Evaluate new concepts enabled by laser-driven accelerator systems for applied physics

Remember: High-Power Laser-driven accelerator systems are technologically diametral opposed to DC- and RF accelerators:

Low momentum - High Intensity // Low repetition rate - Low overall yield

- Nuclear Physics with an HPLS at ELI-NP: E1 (10 PW)
  - The extreme entropy conditions with flagship 10 PW: $I_{\mathrm{Las}} \sim 10^{23}$ Wcm^{-2}
  - Nuclear reactions induced by ions in plasma can proceed and lead to non-linear effects (Warm Dense Matter, coherent acceleration, change in stopping power, & fusion technology (NIF, +30 laser-based fusion startups worldwide)
  - Ultraintense neutron source will allow one-neutron- and maybe even two-neutron-capture processes
    - 10^{11} n_N srad^{-1} in a few ns
  - Ultraintense source for hard X-rays ('$\gamma-$rays')
  - Nuclear reactions in plasma

The ELI-NP facility



ELI-NP Overview

ELI-NP Programs for NP: Laser-driven ion source

- Development of a high-intensity short-pulsed laser-driven ion sources for nuclear physics and applications
- Achieving highest laser-driven energies for acceleration
- Creating Warm Dense Matter (WDM) & stellar entropies
- Fast neutrons, but also cold feasible using ultra-compact, moderator in the few cm-length, pulse duration $\sim$ µs
- Program for laser-driven ion acceleration at ELI-NP
- Collective acceleration (Veksler V.I CERN Symp. on High Energy Accelerators and Pion Physics, pg 80-83 (1956))
- Inaugural studies of laser-driven oncology with highest intensity beams probing the FLASH-effect, p-beams, C-beams

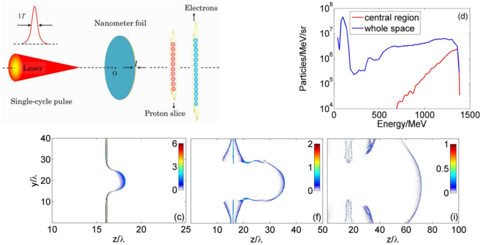


FIG. 3. Single-cycle acceleration. Transverse electric field (top row), electron density $\frac{n_e}{n_c}$ (middle row), and proton density $\frac{n_i}{n_c}$ (bottom row), in the (z, y) plane at times $t = 20T$ (left column), $t = 40T$ (middle column), $t = 80T$ (right column) for a foil of $n_e = 480n_c$, and $l = 50$ nm irradiated by CP laser pulses at $a_0 = 200$ ($\tau = 1T$).

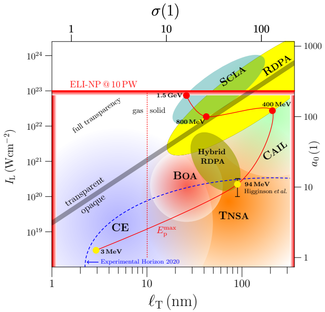
Zhou M.L. *et al.* PoP **23** 043112 (2016)

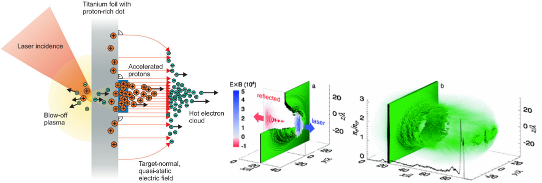
Laser-driven Nuclear Physics, Scaling Laws: TNSA & Collective Ion acceleration *via* RPA

- Strong function of ℓ_T and I_L and dimensionless laser parameter a_0,

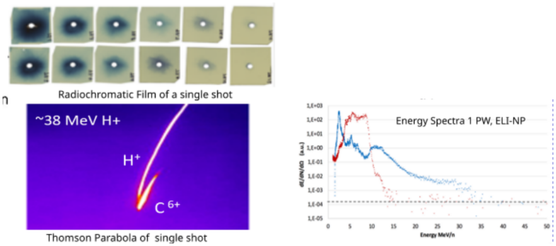
$$a_0 = \sqrt{\frac{I_0 \lambda^2}{1.37 \times 10^{18}\,\mathrm{Wcm}^{-2} (\mu\mathrm{m}/\lambda)^2}} > 30$$

- TNSA well investigated, Maxwell-Boltzmann E_p distribution, ~ 100 MeV, Higginson *et al.* Nat. Comm. **9**, 724 (2018)
- Radiation Pressure Acceleration: collective! "mono-energetic" acceleration of GeV protons
- Very efficient $>$ 50% coupling of E_{laser} to E_p





TNSA Schlenvoigt *et al.*, Adv Sol St Las (2010) & RPA Esirkepov *et al.*, PRL **92**, 175003 (2004)



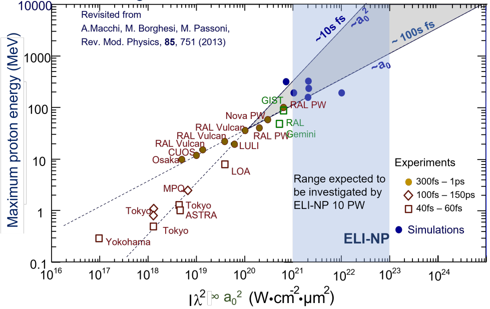
TNSA @ ELI-NP 1 PW Doria, D., M. Cernaianu *et al.* tbp

ELI-NP, Commissioning of 10 PW HPLS (E1 (solid, Spring ’23) and E6 (gas, Autumn ’23))

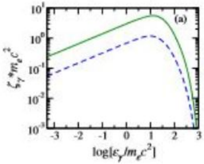
Approved Flagship Experiments at ELI-NP

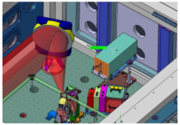
- 1st: TNSA Scaling Law & RPA
- First shot of 10 PW on target 13/04/2023
- TNSA & RPA hybrid regime $E_\mathrm{p} \gtrsim 200$ MeV

TNSA scaling law and state-of –the-art

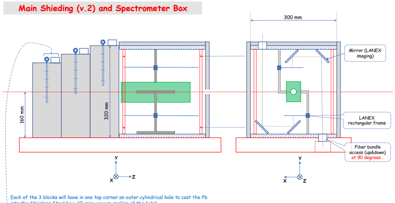


- 2nd: Gamma-ray Flash, proofing focal intensity
- Laser-to-$\gamma -$conversion=10%-40% $\rightarrow$ 4 PW in photon energy by Radiation Reaction and not by bremsstrahlung



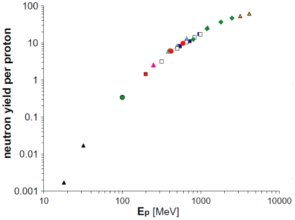


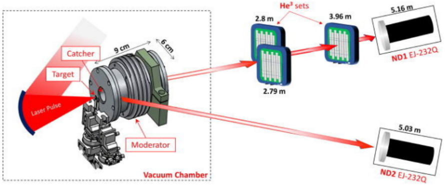
Left: Simulation of $\gamma -$Flash distribution Capdessus *et al.*, PRL, **110**, 215003 (2013); Right: E1 Setup; Below: Gamma & Inverse Compton Spectrometer at E1



ELI-NP Programs for NP: Laser-driven neutron source (LDNS)

- Development of a high-intensity short-pulsed laser-driven neutron source
- Low-energy nuclear reaction on $^{7}\mathrm{Li}$, pitcher-catcher or proton-induced fission of heavy metal target (*e.g.* Pb)
- : Current record for LDNS: 2.3 $\times$ 10^{10} $N_n sr^{-1}$ for $I_{\mathrm{Las}} = 10^{19}$ Wcm^{-2} Yogo, A *et al.* PRX **13** 011011 (2023), also $N_n \propto I^4_{\mathrm{Las}}$
- Photonuclear (γ,n) reaction, (QED-effects based
- Fast neutrons, but also cold feasible using ultra-compact, moderator in the few cm-length, pulse duration $\sim$ μs
- Programs using LDNS at ELI-NP
- Spatially and temporal confined neutron-source with $t^{\mathrm{fast}}_{\mathrm{pulse}} \sim 1$ ns, $t^{\mathrm{slow}}_{\mathrm{pulse}} \sim 10$ μs, and $\varnothing \sim 100$ μm
- Radiography by a bright source of laser-driven thermal neutrons and X-rays Yogo A. *et al.* 2021 Appl. Phys. Express **14** 106001 (2021)
- Epithermal and thermal neutrons *via* compact moderators for *e.g.* immunotherapy supported BNCT (3 patents (K. Spohr)





Left: Neutron yield for E_p & Right: Compact neutron moderator for LDNS R. Mirfayzi *et al.*, APL,**111**, 4, 044101 (2017)

Neutron capture with an HPLS-driven neutron source, MPIK theory

- Hill, P. & Wu, X *Exploring laser-driven neutron sources for neutron capture cascades and the production of neutron-rich isotopes*, PRC **103** 014602 (2022)
  - Max-Planck Institut Heidelberg (MPIK), long-standing theoretical support of laser-nuclear physics
  - Theoretical evaluation of neutron capture cascades *via* laser-driven pulsed neutron sources
  - Survey of 95 elements with $3 \leq Z \leq 100$
  - For specific Z the heaviest isotope with $t_{1/2} > 1$ hr considered
  - Neutron per pulse: $N_{\mathrm{p}} = 10^{10}$ n/pl to 10^{12} n/pl, feasible at ELI-NP Horny, V. *et al.* Sci. Rep. **12** 19767 (2022)
  - ENDF-B-VIII.0 neutron library for calculations
    - 1 D model, damping of the incident neutron beam, & and loss of by transmutation and radioactive decay, dimensions: $25\ \mu\mathrm{m}^2 \times 100\ \mu\mathrm{m}$
    - Both Single- and multi-neutron pulses scenarios calculated (N_{pl})
    - $50\,\mathrm{keV} \leq E_{\mathrm{n}} \leq 10\,\mathrm{MeV}$ are considered
- Identified candidates of astrophysical interest
  - s-process branching point nuclei: $^{126}_{51}\mathrm{Sb}$, $^{176}_{71}\mathrm{Lu}$, & $^{187}_{75}\mathrm{Re}$
  - r-process waiting point nuclei: Lu, Re, Os, Tm, Ir, & Au
- Diagnostics: $\gamma-$spectroscopy after irradiation

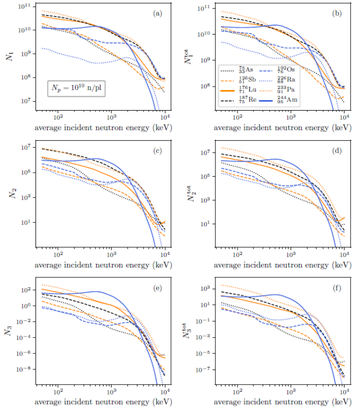
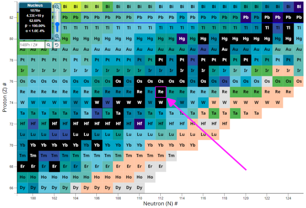


FIG. 6. N_i after 10^4 neutron pulses (at time $10^4 T_{\mathrm{del}}$) and total produced amount of neutron-enriched isotopes N_i^{tot} as functions of the average incident neutron energy. A neutron beam with $N_p = 10^{10}$ n/pl and a repetition rate of $f_{\mathrm{rep}} = 1$ Hz is assumed. The seed nuclides $^{75}_{33}\mathrm{As}$ (black dotted curve), $^{126}_{51}\mathrm{Sb}$ (orange dashed curve), $^{176}_{71}\mathrm{Lu}$ (orange solid curve), $^{187}_{75}\mathrm{Re}$ (black dashed curve), $^{192}_{76}\mathrm{Os}$ (blue dashed curve), $^{226}_{88}\mathrm{Ra}$ (blue dotted curve), $^{233}_{91}\mathrm{Pa}$ (orange dotted curve), and $^{244}_{95}\mathrm{Am}$ (blue solid curve) are considered.

Multiple $N-$capture 10^{10} n/pl $\sim 10^{17}\ \mathrm{N_n cm^{-2} s^{-1}}$ @ 1 Hz for 10^4 pulses Hill & Wu ibid, High yield for ≈ 3 hr @ 1 Hz

Neutron capture with an HPLS-driven neutron source, MPIK theory implementation

- For $E_{\mathrm{n}} \approx 100$ keV 1% to 10% of isotopes can be neutron enriched
  - Subsequent accumulation of neutron-enriched nuclei during the successive neutron pulses
  - Favourable, nonlinear (!) increase of $N^{\mathrm{tot}} \propto (N_{\mathrm{pl}})^{\mathrm{i}}$
  - ${}^{187}_{75}\mathrm{Re}$ ideal case, with $t_{1/2}({}^{187}_{75}\mathrm{Re}) = 4 \times 10^{10}$ yr and $t_{1/2}({}^{188}_{75}\mathrm{Re}) = 17.0$ hr and $t_{1/2}({}^{189}_{75}\mathrm{Re}) = 24.3$ hr
- 1 PW station E5 runs @ 1 Hz with ribbon target
  - $E_{\mathrm{p}}^{\mathrm{max}}$ 25 MeV, variation 10%
  - $E_{\mathrm{Las}} = 20$ J with $\tau_{\mathrm{Las}} = 24$ fs, (04/11/2022)
  - M. Cernaianu tbp
- Challenge: Develop a neutron source with:
  - ps - ns pulse length (fast neutrons) in the sub-mm^3 dimension
  - Alternatively, extreme bright thermal neutron source in µs regime: 10^{21} $\mathrm{N_n cm^{-2} s^{-1}}$ (peak value only!)
  - Commissioning run results induce optimism for 1N capture, but 2N long-range
  - ${}^{189}_{75}\mathrm{Re}$ has weak $\gamma-$fingerprint $\sim$ 15% per decay
- Evaluation for 10 PW system, lower rep. rate but higher neutron flux $\rightarrow$ similar 2$N-$caption yield to 1 PW



Above: s-process nuclei ${}^{187}_{75}\mathrm{Re}$; Below: Setup of ribbon target at E1 target station, courtesy M. Cernaianu

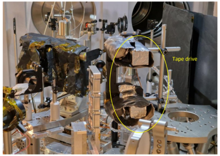


Fig. 1 - The tape drive system set up in the C1 chamber of the E5 1 PW experimental area of ELI-NP

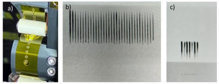
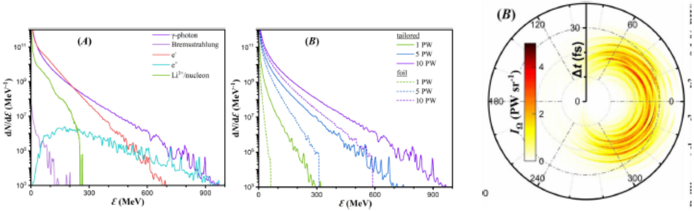


Fig. 2 - a) Sequence of shots on the tape with 2 J laser energy. b) proton traces on the image plate obtained with 33 consecutive shots for 2 J laser energy delivered at 1 Hz. c) proton traces of 7 shots delivered at 20 J and 1 Hz

ELI-NP Programs for NP: Laser-driven $\gamma-$source

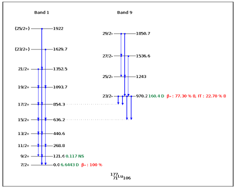
- Harvesting the intense production of $\gamma-$radiation
- for 10 PW conversions $\kappa_\gamma \approx 30\,\%$ and $\propto 1/n_{e^-} \longrightarrow$ thin, Li, Be, C (as foam) targets, Hadjisolomou P., Jeong T.M., & Bulanov S.V., Sci. Rep., 12 **(1)**, 17143 (2022)
- Multiphoton Compton scattering, supersedes bremsstrahlung yield @ 10 PW: Breit-Wheeler $e^- e^+$ pair-production?
- Programs using the $\gamma-$flash at ELI-NP
- Synchrotron radiation induced by high-intensity laser-fields (Scanning thickness of appropriate target materials)
- Radiography by a bright source of X-rays and neutrons Yogo *et al.* Appl. Phys. Express **14** 106001 (2021)
- Multi-photon excitation of isotopes?



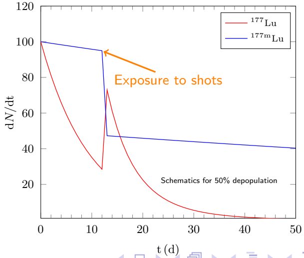
PIC-EPOCH Yield estimations and radial distribution for $\gamma-$flash Hadjisolomou P. *et al.*, ibid

Depopulation of isomers *via* an ultra intense $\gamma-$flash, ^{177}Lu

- Radioactive $^{177}_{71}\mathrm{Lu}$ with $t_{1/2}(^{177}\mathrm{Lu}) = 6.65$ d has long-lived isomer at 970 keV with $t_{1/2}(^{177\mathrm{m}}\mathrm{Lu}) = 160.44$ d
  - $^{177\mathrm{m}}\mathrm{Lu}$ can be used for energy storage ('Isomer based Nuclear Battery')
  - $^{177\mathrm{m}}\mathrm{Lu}$ is a nuisance in medical applications (prostrate cancer treatment PLUVICTO)
  - $\rightarrow$ Depopulation mechanism would be of great societarian and medical benefit
    - Only few induced isomer depopulations have been experimentally achieved so far Belic, D. *et al.*, PRL **83** (1999) for $^{180\mathrm{m}}\mathrm{Ta}$
  - Depopulation of $^{177\mathrm{m}}\mathrm{Lu}$ will be indicated by the enhancement of $^{177}\mathrm{Lu}$ after irradiation
    - $^{177}\mathrm{Lu}-$decay and $^{177\mathrm{m}}\mathrm{Lu}$-decay have distinguishable $\gamma-$ray pattern
    - Timely HPGe measurements to confirm depopulation because of long-lived $^{177}\mathrm{Lu}$
  - Experiment runs parasitic with Laser-to-γ campaign
  - Estimations: $\lesssim 10^4\ \mathrm{N}_\gamma \mathrm{eV}^{-1} \rightarrow > 50$ d campaign at 10 PW with $f_{\max} = 1\ \mathrm{min}^{-1}$
  - Peeler-regime: Plasma-surface wave on tape target by Phukov, A. *et al.* $> 10^7\ \mathrm{N}_\gamma\ \mathrm{eV}^{-1}$ and brilliance of $\approx 10^{23}\ \mathrm{N}_\gamma\ \mathrm{s}^{-1}\ \mathrm{mm}^{-2}\ \mathrm{mrad}^2$ 0 1% BW Shen X.F, Pukhov A., & Qiao B. PRX **11** 041002 (2021)

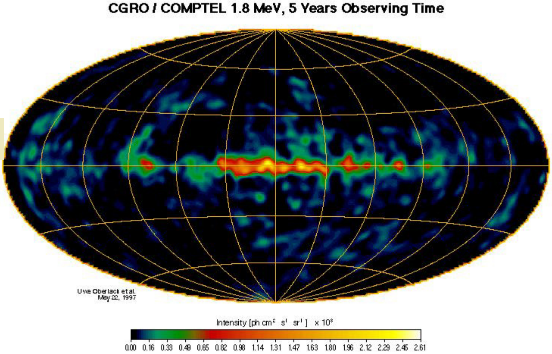


Low-energy decay scheme of $^{177}_{71}\mathrm{Lu}$; Below: Schematics of depopulation process signature



- Cosmogenic ^{26}Al, $t_{1/2}(^{26}\mathrm{Al}_{\mathrm{g.s.}}) = 7.17 \times 10^5$ a, **most important isotope** in nuclear astrophysics (star formation, astrophysical clock).
- Production of $^{26}_{13}\mathrm{Al}_{\mathrm{g.s.}}$ ^{26m}Al isomer, $t_{1/2} = 6.35$ s with ~ 100 A-kA currents of laser accelerated protons with $E_{\mathrm{Thresh.}} \geq 4.97$ MeV:

$$^{26}_{12}\mathrm{Mg}\,(\mathrm{p,n}) \begin{cases} ^{26}_{13}\mathrm{Al}_{\mathrm{g.s.}} \xrightarrow{t_{1/2}=7.17\times10^5\ \mathrm{a}} {}^{26}_{12}\mathrm{Mg} + \gamma_{(1809\ \mathrm{keV})} & \text{2^{nd} order forbidden } \beta^+ \\ ^{26m}_{13}\mathrm{Al} \xrightarrow{t_{1/2}=6.35\ \mathrm{s}} {}^{26}_{12}\mathrm{Mg}_{\mathrm{g.s.}} & \text{superallowed } \beta^+. \end{cases}$$

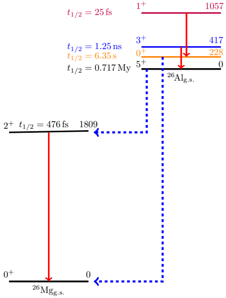


Mahoney, W. *et al.*, Astrophys. J., **286**, 578 (1984)

Fig. – ^{26}Al in the Universe

Cosmost in the laboratory: Decay studies of ^{26}Al isomers with an ultra intense $\gamma-$flash

- Production and decay of cosmogenic $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ with $t_{1/2} = 0.72\,$My is of paramount astrophysical interest (high abundance, astronomical clock)
  - Dramatic reduction of effective lifetime τ_{eff} in very hot ($\sim$ GK) by *via* coupling of the 5^+ g.s. and the 0^+ first excited state at 228 keV *via* with interlinking higher-lying states Gupta, S.S. & Meyer, B.S. PRC **64** 025805 (2001)
  - Production and decay studies with HPLS feasible since ultrashort p-production beam pulses mimick astrophysical entropies Spohr, K.M., Doria, D., & Meyer, B.S. Galaxies **7** 4 (2019)
- Possibility of achieving a coupling of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ with super-allowed β^+ decay at 228 keV with $t_{1/2}(^{26\mathrm{m}}\mathrm{Al}) = 6.35\,$s *via* intermediate states at 10 PW?
  - Few targets of $^{26}\mathrm{Al}_{\mathrm{g.s.}}$ in existence, $\approx 5 \times 10^{18}$ isotopes, on extended target backing $> 20\,\mathrm{cm}^2$ or in solution in veils
  - Simulations: Yield from photoabsorption $\sigma_\lambda = \frac{\lambda_\gamma^2}{2\pi} \frac{1}{(1+\alpha_{\mathrm{tot}})} \frac{2I'+1}{2I+1}$ of $\gamma-$flash
  - $\Sigma\sigma_\lambda^{\mathrm{i}}$ factor 10 to 100 below detection limit for 10 PW
  - But: Decay studies of (γ,n), (γ,p), $(\gamma,\ldots)$ feasible
  - Non-linear $\propto I_\gamma^2$ effects may occur, fs-pulses are NOT in balance & transient ($\tau_{\mathrm{pl}} \sim t_{1/2}$) of interlinking transitions
  - Improvements of $\gamma-$flash modeling, Peeler-regime (), (resonant multi-pulse ionization, ReMPI), leading to pencil-like $\gamma-$beam with $\theta \sim 1/\gamma$ Tomassini, P. *et al.* Plasma Phys. Control. Fusion **62** 014010 (2020)



Low-energy decay scheme of ^{26}Al

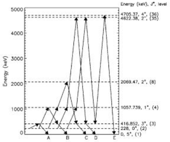


FIG. 2. The dominant pathways at (A) $T_9=0.2$, (B) $T_9=0.6$, (C) $T_9=1.3$, (D) $T_9=3.0$, and (E) $T_9=5.0$ in the internal equilibration of ^{26}Al. At low temperatures, the dominant pathways must take spin jumps larger than unity. At higher temperatures, large energy transitions are possible. This allows strongly favored spin jumps of unity in the dominant pathway, thereby dramatically increasing the effective equilibration rates. Levels are denoted by the format, energy in keV, spin parity, and (level number) on the right-hand side of the energy-level diagram.

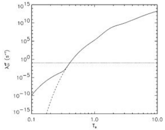


FIG. 1. The effective transition rate λ_{21}^{eff} for ^{26}Al as a function of temperature. The solid line gives the result of the full calculation. The dashed line gives the rate when the direct transitions between levels 2 and 3 are disabled. For reference, the dotted line gives the β^+-decay rate of the 0^+ metastable state. For $T_9 \lesssim 0.4$, the metastable state has no chance of equilibrating with the ground state before β decaying.

Nuclear Reaction in Plasma: Nuclear Excitation by Electron Capture in ^{93}Mo?

- Isomers such as $^{93}\mathrm{Mo}$ can store MeV energy per atom $\rightarrow$ highest human-made energy densities of GJ kg^{-1}
- Stored energy could be released by keV photon radiation (E_{trig}) in a controllable manner!, provided by plasma or directly by photons (small σ_{p}), so far ONLY few experiments in literature Belic *et al.* PRL 83 (**25**) 5242 (1999) on $^{180\mathrm{m}_2}\mathrm{Ta}$ and Chiara on $^{93\mathrm{m}}\mathrm{Mo}$ (Chiara *et al.*, Nature 554 216 (2018))
- Nuclear Excitation by Electron Capture (NEEC): A free electron is captured into an atomic vacancy and excites the nucleus to a higher-energy state: $E_{\mathrm{T}} = E_{\mathrm{I}} + E_{\mathrm{kin}}(e^-) + E_{\mathrm{b}}$
- Ideal candidate for *prima faci* studies of NEEC in laser-induced plasma: $^{93}\mathrm{Mo}$
  - $^{93\mathrm{m}}\mathrm{Mo}$ production: $^{93}\mathrm{Nb(p,n)}^{93\mathrm{m}}\mathrm{Mo}$ with $E_{\mathrm{p}} \sim 5 - 10\,\mathrm{MeV}$ ($E_{\mathrm{tr}} \sim 3.3$ MeV) and subsequent exposure to keV-plasma.
    - Only possible at a High Power Laser System (HPLS) such as ELI-NP
    - Trigger: $E_{\mathrm{trig}} \sim 5$ keV $\rightarrow$ 500 fold energy amplification!
  - High energy of 2.425 MeV, $\gamma-$decay sequence allows unambiguous identification
  - NEEC process with high probability claimed to be observed! Argonne National Lab (ANL) tandem accelerator with GAMMASPHERE, Chiara (ibid), but heavily disputed!
- Other isomers of interest for ELI-NP:
  - $^{242\mathrm{m}}\mathrm{Am}$, $E^{\mathrm{m}} = 49$ keV, $t_{1/2} = 141$ y
  - $^{178\mathrm{m}_2}\mathrm{Hf}$, $E^{\mathrm{m}_2} = 2.5$ MeV, $t_{1/2} = 31$ y, pure: 1.3 TJ kg^{-1}, 3 targets known to exist, access heavily restricted

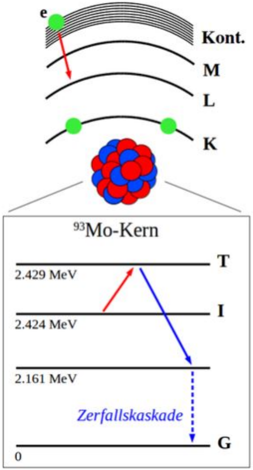


Fig. – NEEC-schematics for $^{93\mathrm{m}}\mathrm{Mo}$

ANL experiment: Depopulation of the 2.4 MeV isomer in $^{93}\mathrm{Mo}$

- Chiara and experienced team of the Argonne National Laboratory, using GAMMASPHERE with 92 Compton-suppressed high-purity germanium detectors, highest efficient $\gamma-$Spectrometer worldwide
- Using standard fusion evaporation experiment Chiara *et al.* (ibid), reaction $^{7}\mathrm{Li}(^{90}\mathrm{Zr},\ \mathrm{p}, 3\mathrm{n})^{93\mathrm{m}}\mathrm{Mo}$ @ $E(^{90}\mathrm{Zr}) = 840\,\mathrm{MeV}$ using the Argonne Tandem Linac Accelerator System
  - $^{93\mathrm{m}}\mathrm{Mo}$ is highly ionized and moves with $v/c \sim 5\%$
- $I(^{90}\mathrm{Zr}) \sim 6 \times 10^{8}\,\mathrm{ions\,s^{-1}}$, few weeks experiment
- Lithium target: complicated fabrication and careful handling

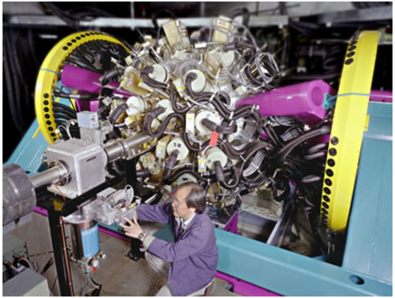


Fig. – GAMMASPHERE at ANL

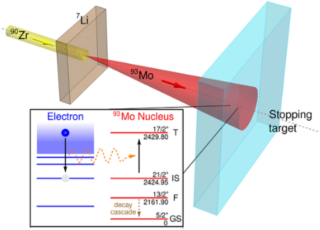


Fig. – Target Schematics in Chiara *et al.* (ibid) taken from Wu *et al.* PRL 122 **21** 212501 (2019)

*

Depopulation of the 2.4 MeV isomer in ^{93}Mo

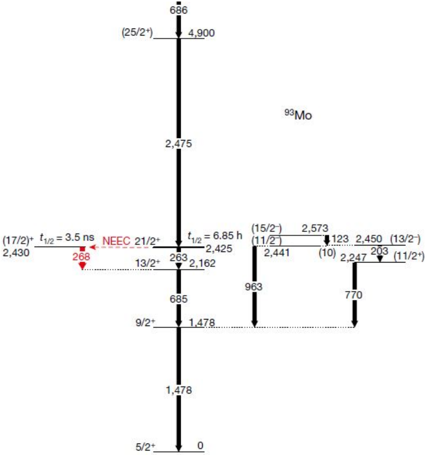
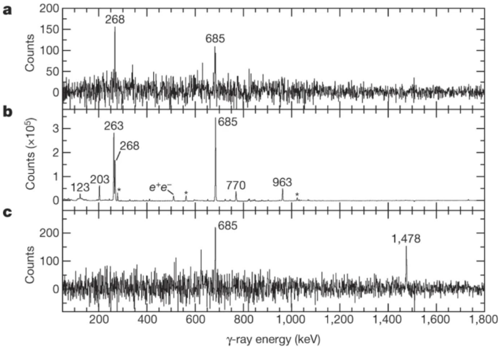


Fig. – ^{93}Mo Relevant lower level scheme

Figure 2: Spectra demonstrating the signature of NEEC in ^{93}Mo.



No correction for the Doppler effect has been applied. **a**, Spectrum obtained with a double gate on the Doppler-shifted 2,475-keV and unshifted 1,478-keV γ-rays. **b**, Spectrum obtained with a single gate on the unshifted 1,478-keV line. **c**, Spectrum obtained with a double gate on the Doppler-shifted 2,475-keV and unshifted 268-keV γ-rays. Peaks of ^{93}Mo shown in Fig. 1 are labelled with their energies in kiloelectronvolts. Additional known ^{93}Mo transitions, not shown in Fig. 1, are marked with asterisks in **b**. The label 'e^+e^-' indicates the 511-keV electron–positron annihilation peak. We note that transitions located above the isomer are too spread out in energy by the Doppler effect to be visible in these spectra.

Fig. – Coincidence Spectra

Depopulation of the 2.4 MeV isomer in ^{93}Mo

- Experimental evidence suggest 268 keV in 'decay path' **instead** of normal $^{93\mathrm{m}}\mathrm{Mo}$ decay route including 263 keV attributed to NEEC.
- High NEEC probability claimed: $P_{\mathrm{NEEC}} = 0.010(3)$
- NEEC condition is attributed to the high rel. velocity $v/c \sim 5\%$ of the recoils fulfilling the NEEC requirement for the **bound** e^- in the $^{7}\mathrm{Li}$-target

but a controversy starts!

- NEEC explanation strongly disputed by Max Planck Institut für Kernphysik, (MPIK) Heidelberg, $P^{\mathrm{theo}}_{\mathrm{NEEC}} \sim 10^{-11}$. Wu *et al.* PRL 122 (**21**) 212501, (2019).
- (Even) Letter to Nature: Guo *et al.* *'Possible overestimation of isomer depletion due to contamination'* Nature (Matters Arising) 594 7861, E1-E2 (2021), citing Misinterpretation of prompt-Compton background
- Rzadkiewicz, J. *et al.* PRL **127** (4) 042501 (2021) & Gargiulo, S. *et al.* PRL **128** (21) 212502 (2022)

  ... and then the experimental tsunami

- Gou *et al.*, 'Isomer Depletion with an Isomer Beam', PRL 128 (**24**), 242502 (2022) (cited as Gou *et al.*)
  - $^{12}\mathrm{C}(^{86}\mathrm{Kr}, 5\mathrm{n})^{93\mathrm{m}}\mathrm{Mo}$ with $E = 559$ MeV and transport isomer by secondary beamline to minimize background and associated artifacts.
  - NO isomer depletion consistent with $P_{\mathrm{NEEC}} = 0.010(3)$ detected, but consistent with very low $P^{theo}_{\mathrm{NEEC}}(\mathrm{MPIK})$

The NEEC controversy, NO confirmation of Chiara *et al.* by Gou *et al.*

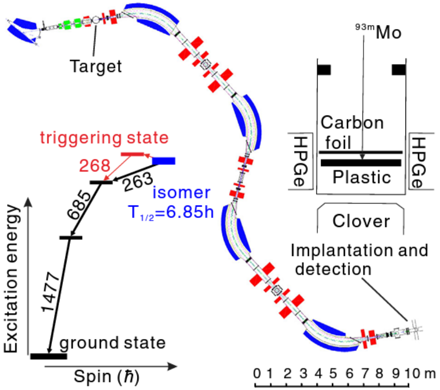


FIG. 1. Experimental setup in the present Letter. The secondary beam line RIBLL is shown with the corresponding distance scale. ^{93m}Mo residues were produced at the primary target position and transported to the end of RIBLL to study the isomer depletion. In the lower left area, the isomer depletion of ^{93}Mo is sketched together with the spontaneous decay of the long-lived isomer. The setup for implantation and detection is shown in the upper right area.

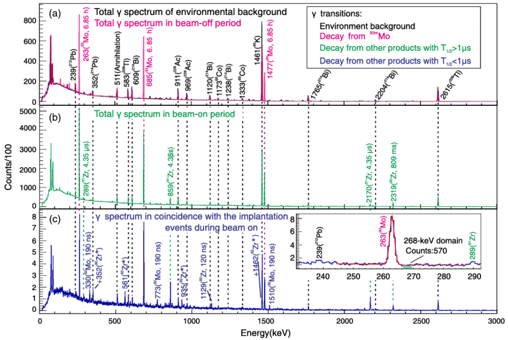


FIG. 2. Spectra acquired by germanium detectors in this measurement. (a) The γ spectra of decay events (in purple) and environmental background (in black). (b) The total γ spectrum recorded by the germanium detectors during the collection of products. (c) The γ spectrum in coincidence with implantation events. The detailed spectrum for the 263- and 268-keV transitions is shown in the inset and fitted by a combination of Gaussian and linear functions. The half-lives of the known isomers are marked for corresponding γ peaks, and the lines assigned to an unidentified isomer of ^{92}Zr are marked with asterisks. Two γ rays with nearly the same energy of 352 keV were identified to originate from ^{214}Pb and ^{92}Zr, respectively. The 352-keV line in (a) and (b) is attributed to ^{214}Pb, and in (c) this line has two components corresponding to ^{214}Pb and ^{92}Zr.

Fig. – γ-Spectra by Gou *et al.* (2022)

ELI-NP campaign, solving the ^{93}Mo conundrum

ELI-NP has provides the possibility to create $^{93\mathrm{m}}\mathrm{Mo}$ *via* MeV proton beam bursts $^{93}\mathrm{Nb(p,n)}^{93\mathrm{m}}\mathrm{Mo}$ and subsequent exposure to ns-long keV-plasma. A campaign has already started and will proceed with a beamtime at the 1 PW system at the CLPU in Salamanca Spain (Autumn 2023). As HPLS systems can provide keV-plasma in coincidence with the isotope production, there grant the unique opportunity to solve the current NEEC conundrum

- Three Tier systems (A,B,C) adopted for the investigation of $^{93\mathrm{m}}$Mo representing different experimental configurations
- Use of $^{45}\mathrm{Sc(p,n)}^{45}\mathrm{Ti}$as an isomeric reference ('spy') reaction to allow a deduction of the yield changes, indicating a potential depopulation in $^{93\mathrm{m}}\mathrm{Mo}$, Yield ratio $R = Y(^{93\mathrm{m}}\mathrm{Mo})/Y(\{^{45}\mathrm{Ti})$ measured for Tiers B & C
  - Tier-A
    - 6 hr of proton burst to produce $^{93\mathrm{m}}\mathrm{Mo}$ (and $^{45}\mathrm{Ti}$), thin plastic target to maximize proton production.
  - Tier-B
    - 2 hr to 8 hr with laser-induced hard X-rays rays to test the depopulation of $^{93\mathrm{m}}\mathrm{Mo}$ *via* the intermediate 4.85 keV state.
    - Bremsstrahlungs target: 4 mm thick Ta, long-term: X-ray production by multiple Compton-scattering and ReMPI Tomassini, P. (ibid)
  - Tier-C
    - 6 hr exposure to direct laser radiation to induce hot keVl plasma for NEEC.
    - Theoretical benchmark, Gunst, L. *et al.* PRL **112** 082501 (2014)

Schematics of the Three Tier systems adopted for ^{93m}Mo campaign

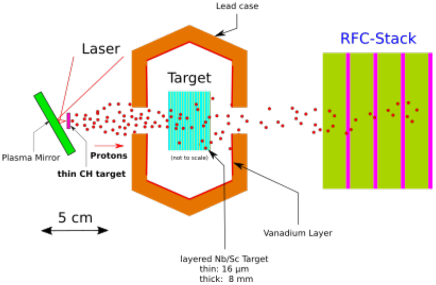


Fig. – Tier-A configuration for isomer production.

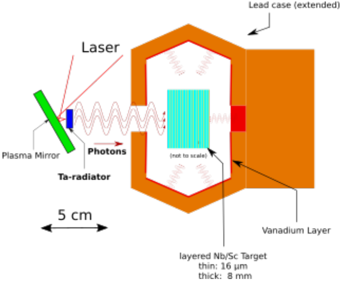


Fig. – Tier-B configuration for depopulation by X-rays. Hohlraum canvas in orange

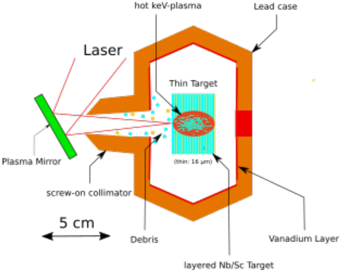
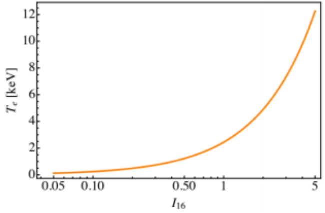
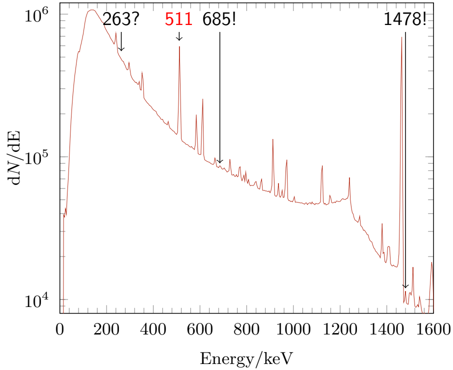


Fig. – Tier-C configuration, NEEC investigation by direct laser irradiation with $I \sim 1 \times 10^{16}$ Wcm^{-2}.

Plasma evaluation and first results of the ELI-NP ^{93m}Mo campaign



$T_{e-} = f(I_{16})$ for ^{93}No Wu, Y. private communication (2019)



- We can achieve keV plasma with the 1 PW and 10 PW system
- Plasma duration extends into ns

Summed up (single) spectra from the ELIADE array on shot, 1/11/2022 (no coincidence condition), 1478 keV evidences the production of ^{93m}Mo

- ^{93}Mo successfully produced
- together with ^{45}Ti from 'spy' reaction (511 keV)

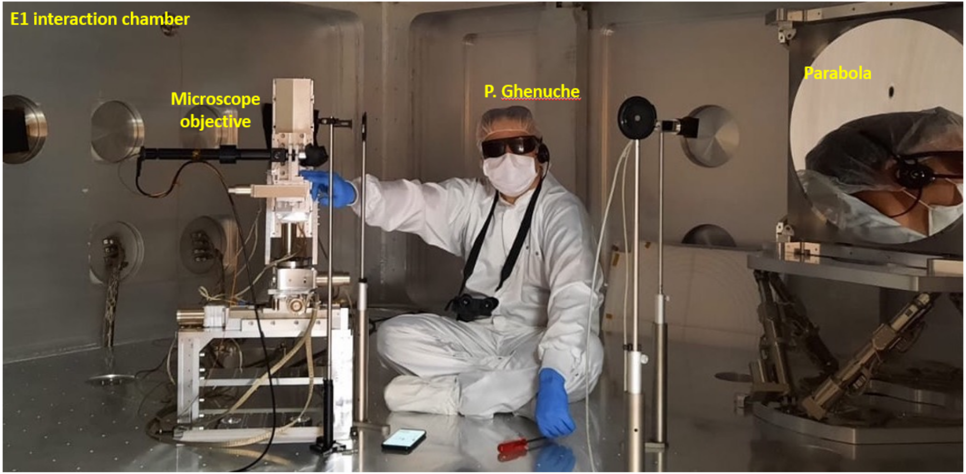
ELI-NP, Impressions of the 10 PW HPLS commissioning at E1

E1 commissioning setup Sept. 2022

ELI-NP, Impressions of the 10 PW HPLS commissioning at E1

10 PW E1 experimental area commissioning (from 26 Sept 2022)

Laser beam alignment and focal spot check

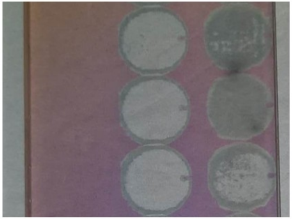


E1 commissioning setup Sept. 2022

ELI-NP, Impressions of the 10 PW HPLS commissioning. We did it!

Interior of the interaction chamber. The picture shows clearly the several diagnostics and optics used to perform the experiment.

Target holder after the shot.

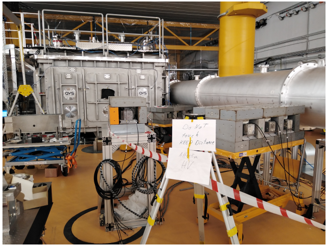


Damages left on plasma mirror by the interaction with the high-power laser beam.

E1 before and after FIRST 10 PW shots 13/04/2023

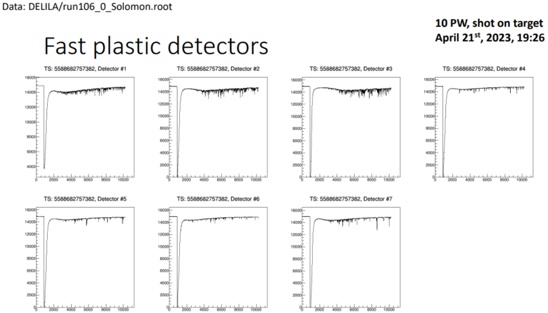
Control room of the 10 PW experimental area: scientists are recording during the countdown of the first 10 PW shot coming soon on screen.

ELI-NP, Very very raw spectra from the 10 PW HPLS commissioning. We did it!

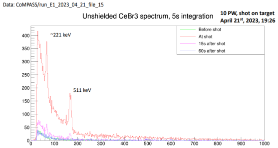


Frontview of 10 PW setup at E1 with plastic detectors 13/04/2023

Backview of 10 PW setup at E1 with plastic detectors 13/04/2023



Spectra of E232 plastic scintillators, γ—flash & neutron-bump? (analysis ongoing)



Spectrum of $CeBr_3$, 511 keV very likely from $^{27}\mathrm{Al}(\gamma, \mathrm{n})^{26}\mathrm{Al}$

Summary & Outlook

ELI-NP has successfully established and started laser-driven nuclear physics research on its unique 10 PW HPLS beamline. With data still being analyzed, we have indications that I_{las} values around the highest human-made intensities have been reached by us, which are the first step to achieving the highest human-made flashes of proton, neutron, and $\gamma - -$beam bursts.

The research foresees:

- Research into nuclear physics with laser-accelerated ions (protons) reaching 100's of MeV reaching extreme entropy conditions with flagship 10 PW: $I_{\mathrm{Las}} \sim 10^{23}$ Wcm^{-2}leading to (Warm Dense Matter, coherent acceleration, entropy conditions resembling astrophysical scenarios)
    - Exploring the possibility of triggered decay of $^{26\mathrm{m}}\mathrm{Al}$ thus informing astrophysical theory in GK -like entropies.
- Development of ultraintense neutron source 1×10^{11} n_N srad^{-1} in a few ns
    - 1 *N* and -maybe 2 *N* capture processes ($^{187}\mathrm{Re}$)
- Ultraintense source for hard X-rays ('$\gamma-$rays')
    - Photon/Multiphoton maybe (non-linear effects $\propto I_\gamma^2$?) to induce a population of excited states in *e.g.* $^{177}\mathrm{Lu}$,
- Nuclear reactions in plasma
    - Program on informing the highly-publicized and hotly debated research on the NEEC conundrum on $^{93}\mathrm{Mo}$.
- The dawn of the exciting field of nuclear physics in laser-generated plasma

Thanks

EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2014-2020

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme "Investing in Sustainable Development"

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

eli nuclear physics

Thank you !

www.eli-np.ro

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