Nuclear astrophysics at ELI-NP

or «conditions created by one Extremely hot Infrastructure for Nuclear astrophysics»

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with material from N.V. Zamfir, I.I. Ursu, P. Thirolfs, ELI-NP workshops participants et al.

IFIN-HH Bucharest-Magurele

11th Russbach School on Nuclear Astrophysics
9-15 March 2014 Russbach (Austria)
Summary

1. Nuclear physics for astrophysics (NPA)
   - Direct measurements
   - Indirect methods – radioactive nuclear beam
2. ELI-NP in Bucharest – presentation
3. ELI-NP: RIB production
4. ELI-NP: stellar plasmas
Nuclear Physics for Astrophysics

NPA: study in the lab nuclear reactions that happen(ed) in the stars – which are cold

- Low energies => low cross sections: nb, pb, ... fb!
- exotic partners (unstable)

a) Direct measurements: very low rates (=> *w* stable beams so far)
   - high intensities
   - high detection efficiency
   - selectivity
   - reduced background

b) Indirect methods – *with stable beams* and radioactive beams
   A. Coulomb dissociation
   B. Transfer reactions (ANC method)
   C. Breakup of loosely bound nuclei
   D. Spectroscopy of resonances: β-decay, β-delayed proton decay, transfer reactions, resonant elastic scatt., etc
      - Decay spectroscopy
      - Any spectroscopy ...
   E. Trojan Horse Method
   - ...

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Two big problems:
1. Reactions in stars involve(d) radioactive nuclei ⇒ use RNB
2. Very small energies and very small cross sections ⇒ indirect methods
Superconducting FRagment Separator at FAIR

Beam intensity improvement: $10^2$ to $10^5$
MARS spectrograph

- $^{26}$Mg primary beam from K500 at 16 MeV/u.
- Produce $^{26}$Al beam with $^{26}$Mg(p,n) reaction.
- Refocus Beam in detector chamber on $\text{CD}_2$ target.
- Separation by production mechanism:
  - Fusion-evaporation: $3 \times 10^6$ pps, 67% $^{26}$Al gs
  - Transfer (charge exchange (p,n)): $3 \times 10^5$ pps, 67% $^{26m}$Al
Motivation: cosmic production of $^{26}\text{Al}$, $^{26}\text{mAl}$

Galactic images with Comptel and Integral

- Satellites detect 1.8 MeV gamma ray from $^{26}\text{gAl}$ $\beta$-decay.
- Lifetime of $^{26}\text{gAl}$ is $7.2 \times 10^5$ yrs. For $^{26}\text{mAl}$ is 6.2 sec.
- Gives evidence of ongoing Nucleosynthesis in stars in the galaxy.
- Want to understand production and destruction of nuclei like $^{26}\text{Al}$ in stars – maybe $^{26}\text{mAl} (0^+)$ is important?
Destruction of $^{26}_{\text{Al}}$

- Satellites detect less 1.8 MeV $\gamma$-rays than expected.
- In astrophysical environment ($0.1 \text{ GK} < T < 0.4 \text{ GK} \rightarrow 100 \text{ keV} < E_{\text{CM}} < 600 \text{ keV}$) $^{26}_{\text{Al}}$ can also be destroyed by $^{26}_{\text{Al}}(p,\gamma)$.
- Try to investigate levels of interest for $^{26}_{\text{mAl}}(p,\gamma)$ and $^{26}_{\text{gAl}}(p,\gamma)$ by studying IAS states in $^{27}_{\text{Al}}$ with $^{26}_{\text{Al}}(d,p)$ reaction.

Figure: C.M. Deibel et al. PRC 80
Extreme Light Infrastructure - Nuclear Physics ELI – NP
Bucharest-Magurele, Romania

Project leader: Nicolae-Victor Zamfir
Bucharest-Magurele, Romania
Extreme Light Infrastructure

2006 – ELI on ESFRI Roadmap

ELI-PP 2007-2010 (FP7)
   ELI-Beamlines (Czech Republic)
   ELI-Attoseconds (Hungary)
   ELI-Nuclear Physics (Romania)

Project Approved by the European Competitiveness Council (December 2009)

ELI-DC (Delivery Consortium): April 2010

Bucharest: June 2013 – civil constr start
Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

- A chance for Romania to have the most powerful laser system and the most brilliant gamma beams in the world at the level of 2015 for 280 MEuro from EU Structural Funds.

ELI will be an European Research Infrastructure for high-level research on ultra-high intensity lasers and laser-matter interaction.

ELI will have 4 pillars:
- ELI – Attoseconds in Szeged (Hungary)
- ELI – Beamlines in Prague (Czech Republic)
- ELI – Nuclear Physics in Magurele (Romania)
- ELI – High Fields (to be decided in 2012)

ELI-NP 20 PW Laser
Two synchronized arms of 10 PW (200 J / 20 fs) with:
- 0.02 Hz repetition rate
- OPCPA Front-End
- Ti:Sapphire amplification

ELI-NP Research
- Understanding laser-driven acceleration mechanism
- Exotic nuclei and astrophysics studies
- Vacuum properties and particle creation in laser-gamma beams interactions
- Materials under extreme irradiation
- Management of Nuclear Materials
- Industrial tomography
- Brilliant positron and neutron sources for materials/processes characterization

ELI-NP γ-beams
- Max. γ energy: 19 MeV
- Total flux: $10^{13}$ photons/sec
- Bandwidth: 0.1%

Production method:
- light photons (10 J laser) scattered on high energy electrons (600 MeV linear accelerator)
Bucharest – Magurele Physics Institutes
Bucharest-Magurele
National Physics Institutes
ELI-NP “Start-up” Activities

- **February-April 2010**
  Scientific case “White Book” (100 scientists, 30 institutions) approved by ELI-NP International Scientific Advisory Board (www.eli-np.ro)

- **August 2010**: Feasibility Study: 293 Meuro
  - Buildings: 60 M€
  - Lasers: 60 M€
  - Gamma Beam: 60 M€
  - Beam Transport: 20 M€
  - Exp. equipments: 30 M€

- **August 2011 – March 2012**: Technical Design

- **January 2012**: Submission of the application to the E.C.

- **July 2012**: Government Decision approving the construction of ELI-NP

- **September 2012**: Approval of the application by the E.C.

- **June 14, 2013**: Foundation stone ceremony

- **March 2014**: all components contracted, work started
“Extreme Light”:

- **two 10 PW APOLLON-type lasers**

- **brilliant γ beam, up to 20 MeV, BW: 0.1% produced by Compton scattering of a laser beam on a 700 MeV electron beam**
ELI-NP
Main buildings

- Lasers
- Gamma
- experiments
- Laboratories
Chirped Pulse Amplification (CPA)

Idea: to stretch (and chirp) a fs pulse from an oscillator (up to 10,000 times), increase the energy by linear amplification, and thereafter recompress the pulse to the original pulse duration and shape.

During amplification, the laser intensity is significantly decreased in order:
- to avoid the damage of the optical components of the amplifiers;
- to reduce the temporal and spatial profile distortion by non-linear optical effects during the pulse propagation.
ELI-NP Next Steps

- January 2012: Submission of the Application to DG-Regio
- July 2012: Romanian Government Approval
- August 2012: Tender Procedures start

- November 2012- end 2014: Civil Construction
- July 2015 : Lasers and Gamma Beam – Phase 1
- December 2016 : Lasers and Gamma beam Phase 2
- 2013-2015: TDR for experiments
- 2016-2018: experimental set-ups
- 2018: beginning of operation
ELI – Nuclear Physics Research

• Nuclear Physics experiments to characterize laser – target interact.
• Photonuclear reactions – most brilliant γ-beam, good resol.
• Exotic Nuclear Physics and Astrophysics - complementary to other NP large facilities (FAIR, SPIRAL2, EURISOL).
• Applications based on high intensity laser and very brilliant γ beams. Complementary to the other pillars

ELI - Nuclear Physics
in ‘Nuclear Physics Long Range Plan in Europe’ as a major facility
Nuclear Astrophysics: RIB production & ELI-NP
Target Normal Sheath Acceleration (TNSA)

Primary radiations
Electrons are expelled from the target due to the ponderomotive force
Heavy ions are accelerated in the field created by the electrons

\[ E \sim I_{\text{laser}}^{1/2} \]

Secondary radiations
- electrons bremsstrahlung
- gamma rays, neutrons

Radiation Pressure Acceleration RPA

Electrons and ions accelerated at solid state densities $10^{24} \text{e cm}^{-3}$ (Classical beam densities $10^8 \text{e cm}^{-3}$)

$E \sim I_{\text{laser}}$
motivation:
- exploit ultra-dense laser-accelerated ion beams for novel nuclear reaction mechanism: “fission-fusion”
- produce extremely n-rich species towards N=126
- expected production range:

- waiting point N=126: bottleneck for nucleosynthesis of actinides
- last region of r process ‘close’ to stability

Production of Extremely Neutron-Rich Isotopes

LoI: P. Thirolf et al. (LMU Munich)
Exp. Scheme for “Fission-Fusion”

Production target

- CD₂: 520 nm
- \(^{232}\text{Th}: 560 \text{ nm}

< 1 mm

Reaction target

- CH₂: \(~70 \mu\text{m}\)
- \(^{232}\text{Th}: \sim5 \text{ mm}\)
- Fission fragments
- Fusion products

conventional stopping:

- high-power, high-contrast laser: 150-300 J, \(~32 \text{ fs}\) (8.5-17 PW)
- 1.2 \cdot 10^{23} \text{ W/cm}^2
- focal diam. \(~3 \mu\text{m}\)

collective stopping:

- Peter G. Thirolf, LMU München

Towards N=126 Waiting Point

- r process path:
  - known isotopes ~15 neutrons away from r-process path (Z ≈ 70)

- visions:
  - test predictions: r process branch to long-lived (~ 10^9 a) superheavies (Z ≥ 110)
    → search in nature?
  - improve formation predictions for U, Th
  - recycling of fission fragments in r-process loops?

- measure:
  - masses, lifetimes, structure
  - lifetime measurements:
    already with ~ 10 pps

- measure:
  - key nuclei

Peter G. Thirolf, LMU München

Nuclear Astrophysics - Indirect methods

1. with RIBs: Steps at ELI-NP

- RNB production: mechanism → study production w. spectrometer(s), w. gas-filled separator ?!
- RNB separation – momentum achromat + velocity filter ?!
- Secondary beam preparation – Filters?! Reacceleration?! 
- Secondary reaction – target station 
- Detection – complex array(s): gas, Si, γ, PID, position sensitive, ... 
- Extract NS information - difficult theory calc: structure and reactions 
- (Normalization) - may need absolute values from elsewhere 
- NA interpretation - theory support again! 
- Comparison with direct measurements/ normalization – develop strong program of direct measurements at the 3 MV tandemron

L. Trache, ELI-NP workshop, Bucharest, June 25-26, 2013
ISOL (currently)  
In-Flight (currently)  
ISOL (future)  
In-Flight (future)
2. Laser-induced “stellar plasma”?! 

• Short-lived plasmas w conditions similar to stellar plasmas?!  
  – Characterization  
  – Nuclear astrophysics: capture reactions on excited states – very imp for quantitative descr of stellar nucleosynthesis, but out of the range of our current experimental possibilities. Can we...?!!  
  – How?! What setups?!  
  **CETAL** – 1 PW laser to work in 2014, in Bucharest!!!
Topics so far ...

- NA proposals
  - NA in the neutron channel (Utsunomyia)
  - NA with gamma-ray beams (Ugalde et al.)
  - NA with $\gamma$-ray beams and OTPC (M. Gai et al)
  - Study on n-rich in the r-proc path (P. Thirolfs, Habs, ...)
  - ($\gamma$, $\gamma'n$) reactions (K. Sonnabend et al)
  - Active target TPC (C. Mazzocchi, M. Pfuetzner e.a.)
  - Laser induced reactions (A Bonasera, Anzalone, L. T., ...)
  - Indirect reactions with RIBs (Catania group, LT, etc)
  - ...

Conclusions: Expected Impact of ELI-NP

European laboratory to consistently investigate a very broad range of science domains, from new fields of fundamental physics, new nuclear physics and astrophysics topics, to applications in material science, life sciences and nuclear materials management.

- World-class research infrastructure (+200 positions of researchers)
- Education – high-level training in science and engineering
- Increasing employment opportunities in research, decreasing brain drain
- Knowledge and technology transfer as a primary objective, collaboration with the local for-profit sector (contractual research); significant expectations of International Patents
- Positive direct and indirect effects on the local and regional economic environment – opportunities for frontier research for companies, stimulating effects on high-tech industries

Time past and time future
What might have been and what has been
Point to one end, which is always present
T.S. Eliot: Burnt Norton (I), Four Quartets (1943)
Status right now (March 2014):

• ELI-NP activities going on:
  Civil construction
  Lasers
  Gamma-ray source – to be signed next week!
  TDR (Techn Design Report) under preparation for experiments and equipment

• ELI-NP workshops:
  – April 2-4 experiments with lasers
  – April 16-17 experiments with gamma-ray beam
Thank you!
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Carpathian Summer School of Physics
Sinaia, Romania, July 13-26, 2014

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Thank you!