Nuclear Physics Experiments with High Power Laser Systems

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Outline of Talk

1. Introduction
   - Nuclear physics, brief overview of status & theory
   - Accelerators: the drivers of nuclear physics research
   - Accelerators: towards laser-plasma acceleration

2. Nuclear physics with lasers
   - History of laser-driven nuclear research
     - Photonuclear cross section measurements
     - Cross section measurements to inform nuclear technology
     - Production of $^{99m}$Tc for medical use
   - Day-1 experiments @ ELI-NP
     - Layout and current status
     - Inaugural (Day-1) nuclear experiments with solid targets
     - E1 set-up for Day-1 experiments & core instrumentation
   - Future nuclear experiments @ ELI-NP
     - Fission fusion & neutron production experiments
     - Isomer depopulation of $^{93}$Mo
     - Cosmos in the Laboratory, the isotope $^{26}$Al
     - Neutron skin of $^{208}$Pb with the $\gamma$–Beam at ELI-NP

3. Summary & Outlook
Introduction
Nuclear physics, brief overview of status

- Study of the properties of the nuclei formed by a certain amount of protons, \( Z \) and neutrons, \( N \) (isotope) and bound together by the strong nuclear force to a quantum mechanical system of \( A = N + Z \) nucleons
  - Identifying isotopes and elements, their masses \( m \), spins \( I \), magnetic moments \( \mu \), excitation levels \( E_i \) and associated \( \gamma \) decay, shapes (spherical, prolate, oblate, pear-shaped), magic numbers, abundances in the Universe, ...
  - Measuring radioactive decay, \( \alpha, \beta, \gamma, \) SF, ...
  - Applications with societarian benefit (medical physics, energy)
  - Informing nuclear astrophysics (creation of elements, \( r \)-process, \( s \)-process), astrophysics (neutron stars), atomic & particle physics

+ \( \sim 3500 \) known isotopes
+ Potentially \( \sim 6000! \) more
+ Only 252 stable (black)
+ \( \sim 40 \) very long lived
+ \( 10^{-21} \) s < \( \tau \) < \( 10^{15} \) s
+ \( \sim 180000 \) nuclear levels
+ Heaviest: \( ^{294}_{118} \text{Og} \) (oganesson)
Nuclear physics, brief overview on theory

- Nuclear force, potential has no central potential $V$ that can be used in the describing Hamiltonian $\hat{T} + \hat{V} = \hat{H} \psi = E \psi$, very different to atomic physics!
  - Approximations on $\hat{V}$, self-consistent fields
  - Single particle like interaction with average $\hat{V}$ Shell Model, leading to magic numbers, 2, 8, 20, 28, 50, 82, 126 (strong $\mathbf{L} \cdot \mathbf{S}$-coupling)
  - But, also collective effects leading to deformed nuclei
  - Unified Nuclear Energy Density Functional (UNEDF)

- Light nuclei (red): nucleon-nucleon, three nucleon forces
- Medium nuclei (green): Interacting Shell Model
- Heavy nuclei (blue): Self consistent Mean Field Theory
- 50 million core hours
- Largest theoretical collaboration in the history of nuclear physics
Lasers in nuclear physics, the quest for control

Current high power laser systems allow nuclear physics experiments, indirectly via the creation of laser-induced radiation. A direct manipulation of nuclear states needs $I > 10^{25} \text{ Wcm}^{-2}$

- For $I_0 \sim 10^{23} \text{ Wcm}^{-2}$ indirect interaction via laser induced radiation
  - Resonant coupling of electric and nuclear transitions (10 PW ELI-NP)
- Theory: $I_0 > 10^{25} \text{ Wcm}^{-2}$ onset of direct interaction of laser fields with nuclei
  - As laser (EM) – nuclear matrix elements become of significant amplitude.
- Modify or even control the nuclear dynamics and processes
- Nuclear quantum optics, the ability to ‘play’ with nuclear transitions in the keV-regime in the same way as with atomic transitions in the eV-regime with a laser, leading to many applications

Amplification and full fine-tuned control  Energy generation, failures in control  Full ‘nuclear’ control?
Accelerators: the drivers of nuclear physics research

Progress in our understanding of nuclear and astrophysical phenomena as well in the application of nuclear reactions for medical purposes has ALWAYS been driven by accelerator technologies as those provide the short-lived nuclei via dedicated nuclear reactions.

An accelerator is an sophisticated transformer with the aim to amplify energies and connected intensities into a desired regime. Accelerators use electromagnetic fields to propel single charged particles individually to very high speeds and energies bundling them in beams. Laser Plasma based acceleration techniques are a disruptive technology and as such potential 'Game-Changers' in this fields, as they provide acceleration of collective bunches of ions (Veksler, 1956).

Traditional DC- and RF-based accelerators:

- Worldwide ∼30000 in operation
- LHC CERN, 13 TeV, RHIC Brookhaven, Tevatron Illinois
- Electrostatic (DC)
  - 1930s: Van de-Graff, Cockroft-Walton
- Electrodynamic
  - Betatrons (electron)
  - Linear accelerators
  - RF-based: Synchrotrons, cyclotrons, storage rings
Accelerators: towards laser-plasma acceleration

The development of laser-plasma based accelerators was enabled by the invention of the Chirped Pulse Amplification (CPA) by Strickland and Mourou, Physics Nobel Laureates 2018

Disruptive technology that led to an increase of 5-6 orders of magnitude for the laser intensity $I_0$ as it allows to exploit the innermost structure and high electromagnetic fields via the disturbance of an atom to create plasma. At such high intensities, laser plasma can induce particle acceleration and the production of MeV $\gamma$ radiation, thus indirectly triggering high-energy processes such as nuclear fusion and fission or particle acceleration.
Ion acceleration regimes, collective acceleration via RPA

- Strong function of $\ell_T$ and $I_L$ and dimensionless laser parameter $a_0$,

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

- TNSA well investigated, Maxwell-Boltzmann $E_p$ distribution, currently:

  $\sim 100$ MeV, Higginson et al. Nat. Comm. 9, 724 (2018)

- Radiation Pressure Acceleration promises mono-energetic "GeV protons

- Possibility of polarized protons (see Poster Anna Hützen)

TNSA

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Esirkepov et al., PRL 92, 175003 (2004)
"You have a non mono-energetic beam with a repetition rate of 1 Hz and an aperture of 30°. What kind of 'beam' is that?"

A fast one!

Fast transposes into high intensity of incoming particle beams in MA - GA regime, onset of QED effects that will induce coherent betatron radiation and alter nuclear processes, reaction cross-section and yields and induce the emergence of new reaction processes (NEEC). Collective effects of nuclear de-excitation may appear and novel applications for nuclear medicine and transmutation will become accessible. The quest to explore new acceleration regimes may lead to TeV proton beams.

- Lower overall yield for comparable experiment duration
- Development of radiation hardened detector systems necessary
+ Highest temporal production intensities & yields
+ Production and Irradiation times in the time spans of nuclear decays (isomers & even prompt decay), time resolution
+ Production (via ion acceleration) and probing with X-ray flux of nuclear system can be done in coincidence in-situ!
+ Astrophysical entropy conditions in the laboratory
Comparison: electromagnetic vs laser plasma acceleration

High Intensity/Low Repetition rate ↔ Low Intensity/High Repetition rate

- Challenge: Diametrically opposed acceleration characteristics:

<table>
<thead>
<tr>
<th>Accelerator System</th>
<th>$t_{\text{pulse}}$</th>
<th>$\frac{dN_p}{dt}$ (1/s)</th>
<th>$f_{\text{rep}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>conv. electrostatic</td>
<td>$&gt; \mu$s - DC</td>
<td>$&lt; 10^{15}$</td>
<td>kHz-MHz</td>
</tr>
<tr>
<td>Laser plasma driven</td>
<td>30 – 50 fs</td>
<td>$\sim 10^{25}$</td>
<td>mHz-10 Hz</td>
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- 1 10 PW shot per minute, 1 Hz at 1 PW, 10 Hz at 100 TW
- Overall yield will be $10^3$–$10^6$ orders of magnitude less

The future is bright!

Currently worldwide: 65 1 PW to 10 PW systems build or commissioned. Asia and Europe leading the way.

Abbildung – PW laser systems 2019
Nuclear physics with lasers
History of laser-driven nuclear research

- Nuclear physics in plasma
- Isotope/isomer production with ultra-intense accelerated electron/ion and radiation beams, reaction studies
- Applied (medical) and fundamental (astrophysics) experiments

- First acceleration of ions (protons) with NOVA laser 1996
- First nuclear transmutation created by a laser, K. W. D. Ledingham, founding father of laser-induced nuclear physics,

- Photonuclear cross sections measurements $\sigma^{\text{int}}$

- Production of isotopes for medical research.
  - First time high power laser research ADDED new data to nuclear physics database.
Nuclear Experiments: Primary & secondary target

- Primary target = production of ion beam or radiation
- Secondary target = Reaction production target

Abbildung – Primary & secondary target arrangements in a laser plasma nuclear experiment
30 TW, \( f=10 \text{ Hz} \) Lasersystem: IOQ Jena.

Laser-accelerated electrons \(\rightarrow\) Bremsstrahlung \((kT = 3.0 \text{ MeV})\).

Bremsstrahlung induces nuclear reaction, \((\gamma, n)\), \((\gamma, p)\), \((\gamma, \alpha)\), ….

Measurement of \(\sigma_{\text{int}}(\gamma, p)\) for 6 different isotopes which are present in nuclear power plants.

**Abbildung** – Schematics of experiment

**Abbildung** – Activity measured with Ge-Detector
Production of $^{99m}$Tc for medical use

- $^{99m}$Tc **most important isomer** for medical treatments worldwide, $\sim$ 50 m treatments per year!
- Supply has declined dramatically from 2017 onwards,
- Production: $^{100}$Mo ($\gamma$, n) $^{99}$Mo $^{\beta^-}$ $^{t_1/2=66}$ $^{99m}$Tc, **first time with a laser** $\sim$ 50 kBq
  - Treatment dose: $\sim$ 500 MBq
  - for more on medical isotope production see talk P. Ghenuce

Abbildung – Decay-Scheme

Abbildung – Identification of $^{99m}$Tc
Day-1 experiments @ ELI-NP
Abbildung – The ELI facility
The 10 PW target station E1 & E6 at ELI-NP

Abbildung – Overview of E1 & E6
Inaugural (Day-1) nuclear experiments with solid targets

Core rationale

Harvesting nuclear/quantum electrodynamic (QED) effects emerging at the high fields \( (E \sim 10^{15} \text{ Vm}^{-1}) \) provided by the high laser light intensities \( I_L \sim 10^{23} \text{ Wcm}^{-2} \) in laser-matter interaction with the 10 PW): \( E_{\text{laser}} \sim 250 \text{ J}, \ t_{\text{pulse}} \sim 25 \text{ fs} \)

- Efficient proton/ion acceleration \( E_{\text{p}}^{\text{max}} \gg 200 \text{ MeV} \) with high yield; Radiation Pressure Acceleration (RPA): \( (10^{13} / (25 \text{ fs})) \).

- Macroscopic (!) ion-sheet acceleration (bulky bunches, Pancake-like beams) with quasi-solid density and with quasi-monoenergetic energies of 100’s of MeV \( \rightarrow \) hitherto unachievable intensities of nuclear reaction products (kA-MA beam bursts). Changes in nuclear stopping (Bethe - Bloch formula)

- Ultra-intense \( \gamma \)-source Onset of QED ’Radiation Reaction’; large conversion efficiency for laser-to-\( \gamma \) \( (E_{\text{Laser}} \rightarrow E_{\gamma}) \), predicted 20% to 50% for \( I_L > 10^{23} \text{ Wcm}^{-2} \)

- Understanding the partitioning of the laser pulse energy \( E_{\text{Laser}} \) between ion and \( e^- \) acceleration & \( \gamma \) production to evaluate the quality and quantity of the laser induced beams
  - Partitioning: \( E_{\text{Laser}} = f(I_L) \), hence \( t_{\text{pulse}}, \ \varnothing_{\text{beam}}, I_{\text{reflected}}, \) the target’s thickness \( \ell_T \) crucial
  - Influence of unavoidable prepulse! (Spontaneous Emission)
  - Emergence and influence of RPA is a strong function of \( \ell_T \)
**Inaugural nuclear physics experiments (solid targets)**

**Challenges**
- High intensity - low momentum (Pancake-bursts, rather than beam), time-integrated intensity and yield more than $10^{-3}$ smaller than DC–RF systems
- Processes in the fs-regime, faster than electronics"domain
- All optical detection using scintillators (Lanex Screens), optical fibres and cameras, all-at oncemasurements, no event-by-event base
- Reproducibility of conditions & Fail-safe operation of optics (Plasma Mirror)

**Unique chances of the new technology**
- Nuclear reactions with high temporal intensity and possible high efficiency & mixed beam acceleration
- Non-linear, intensity dependent effects
- Real plasma conditions, coupling of atomic, plasma and nuclear states
- Mixed beams (by using mixed targets, see Poster Aurelia Ionescu)

**Strategy**
- Day-1 experiments: Fixed set-up, only variation $E_{\text{Laser}}$ and $\ell_T$
- Target wheel: 20 thin solid targets (Starform) and supported by plastic stocks to reduce Electromagnetic Pulse (Emp)
- Targets: Plastics down to $\sim 10$ nm, as well as Al and Fe $\sim 100$ nm $< \ell_T < \text{few} \ \mu\text{m}$. Mixed targets = Mixed beams!
TNSA vs RPA regime, thickness & projected energies

- Source for proton distribution at the TNSA and RPA interface with $E_p^{\text{max}} \sim 100$ MeV: Higginson et al., Nature Communications 9, 724 (2018)
  - $E = 210(40)$ J, $t_{\text{pulse}} = 0.9(1)$ ps, 30% on focal spot $I \sim 3(2) \times 10^{20}$ Wcm$^{-2}$
  - underpinned by EPOCH calculations
- Optimal thickness for $E_p^{\text{max}}$ and laser-to-proton energy efficiency (=12%) for $d_{\text{target}} \sim 100$ nm
- Onset and influence of RPA will be a strong function of $I$ for short pulses $t_{\text{pulse}} \sim 40$ fs
- Onset of RIT for ultra-thin targets

Abbildung – a) TNSA/RPA regimes for 900 fs (red) 40 fs pulse (blue), dotted=maximum $d_{\text{target}}$ for RIT onset, dashed=optimal $d_{\text{target}}$ for plastic
EPOCH (PIC2D) simulations for 10 PW at ELI-NP

Abbildung – EPOCH Simulations in the hybrid TNSA/RPA regime, Sangwan et al. to be published
Laser-to-\(\gamma\) conversion, theoretical rationale QED

**Rationale:**
Harvesting of QED to create ultra-intense x-ray source for nuclear investigations

QED enhances the efficiency of the laser-to-\(\gamma\) conversion, as new forms of regimes emerge, e.g. betatron radiation, new wave-forms (cnoidal waves)

- \(I > 10^{22} \text{ Wcm}^{-2}\), \(E\) repartitioning between ions, \(e^-\) and \(\gamma\) radiation changes dramatically favouring laser-to-\(\gamma\) conversion for increasing \(I\) and \(a_0\)
- Expectations: \(\varepsilon_{\gamma} \sim 3\%\) for 1 PW, \(\varepsilon_{\gamma} \sim 32\%\) for 10 PW \(\sim 3\) PW of \(\gamma\)
  - Capdessus *et al.*, PRL, 110, 215003 (2013)
  - Gordon *et al.*, to be published
- The atomic mass \(m_i\) of the production target is a crucial parameter as for \(I > 10^{22} \text{ Wcm}^{-2}\) \((m_i/m_e)\) strongly affects the \(E\) repartitioning between the ions, \(e^-\) and \(\gamma\) radiation
- Predicted \(\gamma\) intensity peaks at \(E_{\gamma} \sim 10\) MeV, highest yields expected in backward direction for heavy ion (HI) target
Laser - to - $\gamma$ conversion, expected $\gamma$ spectra

Capdessus et al., PRL, 110, 215003 (2013)
Sangwan et al., to be published (EPOCH with Radiation Reaction and preplasma models relating to ELI-NP)

Abbildung – Angular distribution of $\gamma$ radiation with respect to laser propagation, blue=proton, green=HI

Abbildung – Energy distribution of $\gamma$ radiation in the PW regime, blue=proton, green=HI
Laser-to-\(\gamma\) conversion, \(E\) partitioning

\[\begin{align*}
\text{\(\gamma\) Radiation} & \quad \text{Electron Acceleration} \\
\text{Ion Acceleration} & \quad \text{Total Conversion}
\end{align*}\]

Abbildung – Laser energy partition between \(\gamma\), \(e^-\) and ions, Capdessus et al., PRL, 110, 215003 (2013)
E1 set-up for Day-1 experiments & core instrumentation

Abbildung – Planned E1 set-up with Thomson Parabola or $\gamma$-Compton Spectrometer/Electron Spectrometer
Thomson Parabola for $E_p > 200$ MeV

- Established, robust instrument for ion separation according to their charge-to-mass ratio & deriving energy distribution
- Static electromagnetic field forces ions on a parabolic curve
- Small entry pinhole ($\Omega = 0.2 \text{ mrad}$) to suppress background
- Optical readout from Lanex
- for details see Poster Lucian Tudor

 Ion Deflect.
Electron & Positron Spectrometer / γ–Compton

- Forward Compton Gamma Spectrometer’ (FCGS) (5 MeV to 50 MeV) and the ‘Electron-positron’ pair spectrometer (5 MeV to 100 MeV with 10-15% resolution)
- A 2.5 cm Li-converter at FCGS which converts γ into electrons
- Magnets: 20 mm × 55 mm; B=0.55 T
- Optical readout from Lanex

Upper and Lower Lanex

Main Shieding (v.2) and Spectrometer Box

Cross Sections
Further detectors concepts & optics instrumentation

- Standard radiochromatic film stacks with absorbers of varying thickness (established methodology)
- Specific reactions triggered by laser accelerated protons or $\gamma$ radiation which lead to the population of short-lived nuclear isomeric states $\tau \sim \mu$s to ms. So yield measurements allow a pulse-by-pulse online (active) characterization of proton and/or $\gamma$ spectra
- Development of an additions compact scintillator detector for 1 MeV to 20 MeV $\gamma$ detection
- Passive activation methodology via the creation of longer lived ($\sim$ few hrs) isomers (from protons and $\gamma$) which allow an integral evaluation of achieved nuclear yields after e.g. 20 to 100 shots.
- Optics: $1\omega, 2\omega$ probe to evaluate electron density $n_e$ (for details see Poster of Domenico Doria)
- Optics: Interferometry, shadowgraphy
- For details see K.A. Tanaka et al., accepted for publication, Mat. Rad. Extr. (2019)
Exhaustive programme, experiments 10 PW starting 2021 (1 PW 2020)

Exploiting QED with a standard experimental set-up to characterise laser induced particle and radiation beams achievable for $I > 10^{22} \text{ Wcm}^{-2}$ for future studies of nuclear systems in a novel kind of nuclear experimentation:

- Proton acceleration 200 MeV protons at high yields
- Dense bulk acceleration of heavy ions, Highest man-made ion beam densities, leading to high intensities and yields of reaction products, hitherto not achievable in research laboratories
- Laser $\rightarrow \gamma$ conversion, Establishing strong and intense $\gamma$ source for future exploitation in nuclear experiments

Design of detectors, implementation and arrangement of detectors is driven by state-of-the-art current knowledge, all-optical

With the crucial parameters, the interplay of production and acceleration regimes is a strong function, amongst others, of $\ell_T$

Challenges are the EMP, targetry and fail-safe operation of optics (plasma mirror)
Fission fusion & neutron production experiments

- Understanding the r-process by measuring the properties of heavy nuclear around the $N = 126$ waiting point created by fission fusion reactions and neutron capture reactions on heavy targets (see following talk by J. Fuchs)
- Merger of neutron star binaries is the main source for the heavier r-process branch
- Quenching of shells to explain abundance
- Currently only very limited knowledge, supporting campaigns at SPIRAL II and FAIR
- Needs additional mass separator & ion trap installed at huge costs

**Abbildung** – Astrophysical nucleosynthesis: thermonuclear fusion (orange), s-process path (red vector) and the r-process generating heavy nuclei (red pathway)
Fission fusion & neutron production experiments

Abbildung – Target arrangement for fission-fusion with ELI-NP using fissile $^{232}$Th

Isomer depopulation of $^{93}$Mo

- Nuclear isomers ($t_{1/2} > 10^{-9}$ s) hold the key for the development of nuclear batteries and form a potential pathway to achieve nuclear lasing.
- $^{93}$Mo prominent case for isomer de-population via NEEC (Nuclear Excitation by Electron Capture) proposed 1976.
  - Demonstrated via standard fusion evaporation experiment Chiara et al. Nature (554), 216 (2018), reaction $^7\text{Li}(^{90}\text{Zr}, p, 3n)^{93m}\text{Mo} @ E(^{90}\text{Zr}) = 840$ MeV
  - $^{93m}\text{Mo}$ is highly ionised and moves with $v/c \sim 5\%$
- High power laser measurement $^{93}\text{Nb}(p, n)^{93m}\text{Mo} @ E_p \sim 5 - 15$ MeV & X-ray pulse

Abbildung – Level scheme

Abbildung – NEEC Schematics
Optimal plasma and laser parameters for Isomer depopulation of $^{93}\text{Mo}$ are already achievable at 1 PW laser facilities existing today, Gunst et al. arXiv 1804.03694v2 (2018).

If plasma tuned correctly $\sigma_{\text{NEEC}}^{\text{hot}}/\sigma_{\text{Photoabsorption}} \sim 10^{11-12}$, mainly due to long $t_{\text{plasma}}$.

*Abbildung* – $\lambda_{\text{NEEC}}$ for optimal conditions at $I \sim 10^{18}\text{Wcm}^{-2}$
Cosmos in the Laboratory, the isotope $^{26}\text{Al}$

- VULCAN Petawatt system (PW), Rutherford Appleton Laboratory (Oxfordshire), $E_{\text{pulse max}} \sim 2.5 \text{ kJ}$, $I \sim 10^{21} \text{ Wcm}^{-2}$, $\lambda = 1054 \text{ nm}$, $\leq 15$ pulses/day.
- Two beams available: Proton production & X-ray pulse, adjustable time delay between beams $\sim 1$ ns to 4 ns.

**Advantages**

- Protons not mono-energetic, Maxwellian distribution, with $kT \sim 1 - 3 \text{ MeV}$.
- Fluctuation between pulses, reproducibility!
- Electromagnetic Pulse (EMP) saturates standard detectors. Difficulty to measure any prompt particle or gamma radiation.
- Stability of targets which are more complex as those in low intensity experiments.
- Multi-A to kA of protons, in $\sim 100 \text{ ps}$-time scales $\rightarrow$ highest man-made intensities & plasma generation!
- Short duration of reaction driving pulse leads to a manifold of new fundamental and applied possibilities.
- Coinciding X-ray pulse, $E \sim 100 \text{ J}$, $\sim 10 \text{ ps}$ duration with $kT \sim 3 - 6 \text{ MeV}$, resulting in hotter & denser plasma.
Cosmos in the laboratory, VULCAN at RAL

Abbildung – Compressor & Target-Chamber

Abbildung – VULCAN proton and X-ray (inlet) spectra

\[ \frac{dN}{dE_p}(1) \]

\[ E_{tr.} = 7.6(3) \text{ MeV} \]

\[ kT_{exp.} = 3.9(3) \text{ MeV} \]
Cosmos in the laboratory, $^{26\text{m}}\text{Al}$ in the Universe

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

$$^{26}\text{Mg} (p, n) \left\{^{26}\text{Al}_{\text{g.s.}} \xrightarrow{t_{1/2}=7.17 \times 10^5 \text{a}} ^{26}\text{Mg} + \gamma(1809 \text{keV}) \right\}$$

$$^{26\text{m}}\text{Al} \xrightarrow{t_{1/2}=6.35 \text{s}} ^{26}\text{Mg}_{\text{g.s.}}$$

2nd order forbidden $\beta^+$
superallowed $\beta^+$.


Abbildung – $^{26}\text{Al}$ in the Universe
Cosmos in the laboratory, production and decay of $^{26m}\text{Al}$


$t_{1/2} = 1.25\text{ ns}$
$t_{1/2} = 6.35\text{ s}$
$t_{1/2} = 0.72\text{ Ma}$

E2-transition

Level scheme for $^{26}\text{Al}$

$\sigma^{\text{int}}$ for $4.97 \leq E_p \leq 5.80\text{ MeV}$

Abbildung – Cross sections for $^{26}\text{Al}$

Norman et al.: 5.0-14.8 MeV in 0.3 MeV bins
Skelton et al.: 4.97-5.80 MeV in 0.002 MeV bins
Cosmos in the laboratory, theory of $^{26}$Al-decay in plasma


Abbildung – Dominant pathways for $^{26}$Al

Abbildung – Enhancement of $\lambda_{\text{eff}}$ with $T_9$

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 equilibrium of $^{26}$Al. At low temperatures, the dominant pathways must take sp jumps larger than unity. At higher temperatures, large energy transitions are possible. This allows strongly favored spin jumps at 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 $\lambda_{\text{eff}}^{26}$ 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 $\beta^+$-decay rate of the $0^+$ metastable state. For $T_9 \leq 0.4$, the metastable state has no chance of equilibrating with the ground state before $\beta$ decaying.

Abbildung – Enhancement of $\lambda_{\text{eff}}(^{26}\text{Al}) = f(T_9)$
Cosmos in the laboratory, RAL-experimental set-up

p-Beam
E $\sim 300 \text{ J}$
$\sim 16 \text{ ps}$
Gold
13 mm

X-ray-Beam
E $\sim 100 \text{ J}$
Tantalum
d=11 mm

Target

2 cm gap

Target
(Cross Section)

Magnetic toroid

Nal Detectors
close geometry
space constraints

Spohr, K. M. et al., ALPA book-chapter, published April 2018
Cosmos in the laboratory, identification $^{26m}$Al

- Per 300 J proton pulse on Au primary production target, $A \sim 300 - 500$ kBq of $^{26m}$Al, thick target $d_{\text{thick}} = 1 \text{ mg} \cdot \text{cm}^{-2}$, $N_p \sim 10^{10-11}$.
- Full confirmation of VULCAN results & identification of the prompt 417 keV transition with a dedicated Tandem-ALTO experiment at the IPN-Orsay.
- With coinciding X-ray pulse ($E \sim 100$ J) $\rightarrow$ substantial enhancement of $^{26m}$Al yield $Y_{228}$.
- Labaune C. et al., Nat. Commun. 4, 2506 (2013) $^{11}$B(p, α)$^8$Be + 8.59 MeV.

Abbildung – Delayed activity at VULCAN

Abbildung – Delayed activity at ALTO
Cosmos in the laboratory, findings so far for $^{26}$Al

- We accomplished first step towards an astrophysical lab, as guided by theory.

- All three lowest lying-states, $^{26}$Al_{g.s.}, $^{26m}$Al and $^{26}$Al_{417 keV} are produced with substantial yields $Y_{^{26}$Al} \sim 10^{6-7}$ and corresponding densities $\rho = 10^7-8$ cm$^{-3}$ via reaction driving proton pulses with ($N_p \sim 10^{10-11}$).

- Ultra-short reaction driving proton pulse due to short distance of 13 mm and hence short ToF for protons between production target (Au) and target (MgO). Duration only $\sim 100$ ps (ToF & SRIM calculations). Hence,

  - $\sim 100$ ps $-$ 500 ps: $Y_{228} \sim Y_{417} > Y_{g.s.}$.
  - $\sim 500$ ps $-$ few ns: $Y_{228} \gg Y_{417} \sim Y_{g.s.}$.
  - $\sim$ few ns: $Y_{228} \sim Y_{g.s.} \gg Y_{417}$.
  - $\sim$ few s: $Y_{228} \sim Y_{g.s.}$ & $Y_{417} = 0$.

- The first 100 ps around the beam impact are most special, as *i.e.*

  $$t_{1/2}(^{26}$Al_{g.s.})/t_{1/2}(^{26}$Al_{417}) \sim 10^{17}.$$

- Population distribution *mimics* high temperatures during the ps-ns time spans after the reaction driving pulse. *E.g.*

  $$Y_{417}/Y_{g.s.} \propto e^{-417 \text{ keV}/kT} \propto e^{-4.8 \times 10^9 K/T_9}.$$

- Population inversion between the 417 keV state and the ground-state can be assumed for $t \sim$ few 100s ps. Both states are connected via an E2 transition.
Neutron skin of $^{208}\text{Pb}$ with the $\gamma-$Beam at ELI-NP

Abbildunng – $^{208}\text{Pb}$, a nuclear ‘orange’, mini neutron star
Neutron skin of $^{208}\text{Pb}$ with the $\gamma-$Beam at ELI-NP

- Initiated by discussions with W. Nazarewicz, MSU & Chief Scientist at FRIB, formerly Scientific Director of the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory & Visiting Professor at UWS & Glasgow Uni.

- Neutron-rich $^{208}\text{Pb}$ has the highest $N/Z$ ratio of any known stable isotope at 1.537. Neutrons hence form a skin around its core. Its thickness $r_{\text{skin}}$ is of uppermost importance for theory,

$$r_{\text{skin}} = r_{\text{n}}^{\text{rms}} - r_{\text{p}}^{\text{rms}},$$

with $r_{\text{p}}^{\text{rms}} = 5.45$ fm being rather well known.

- Neutron skin of $^{208}\text{Pb}$ is purest form of neutron “only” matter in Earth-bound laboratories.
  - Dedicated “Lead Radius Experiment” (PREX) at Jefferson Lab, USA.

- Precision measurement of neutron skin thickness allows to deduct the neutron Equation of State (EOS) and to benchmark most modern theories in the framework of the UNEDF theory.
  - UNEDF (Universal Nuclear Energy Density Functional), collaborative theoretical effort to use state-of-the-art energy density functionals to establish, with error estimates(!), the combinations of protons and neutrons which can form nuclei.
Sketch of possible $\gamma$-beam system at ELI-NP, tbd

Abbildung – Gamma Beam facility at ELI-NP
Neutron skin of $^{208}\text{Pb}$ & neutron EOS


from: http://www.unedf.org
Neutron skin of $^{208}$Pb & dipole polarizability

Measurement of $r_{\text{skin}}(^{208}\text{Pb})$ with the $\gamma$–beam at ELI-NP

- With the $\gamma$–beam at ELI-NP $\alpha_D$ could be precisely measured with photoabsorption. $E_{\gamma}^{\text{max}} \leq 19.5\text{ MeV}$ is just about right.
- UNEDF will improve substantially if $\Delta r_{\text{skin}}/r_{\text{skin}} \leq 0.5\% \rightarrow \Delta r_{\text{skin}} \sim 0.001\text{ fm}$!

Abbildung – Photoabsorption cross section for $^{208}\text{Pb}$
The neutron skin of $^{208}$Pb with the $\gamma$–beam at ELI-NP

- Measurement of $\alpha_D$ with ELI-NP could supplement and potentially even succumb e.g. PREX measurements.
  - With the projected $\gamma$-beam features at ELI-NP $\rightarrow$ smallest value for $\Delta r_{\text{skin}}$.
  - Minimisation of $\Delta r_{\text{skin}}$ is as essential as value for $r_{\text{skin}}$ itself.
- Currently value via Coloumb excitation measurements induced by proton scattering:
  \[ \alpha_D = 20.1(6) \text{ fm}^3 \]
  from which the authors derived a value of,
  \[ r_{\text{skin}} = 0.165 \pm (0.009)_{\text{exp}} \pm (0.013)_{\text{the}} \pm (0.021)_{\text{est}} \text{ fm}. \]
  This equates to a high uncertainty of $\sim 26\%$ in the worst case scenario. Moreover, the biggest contribution to the uncertainty comes from a model dependent estimation of the symmetry energy at saturation density, Tamii, A. et al., Eur. Phys. J. A50, 28 (2014).
- In addition: Measurement will allow to address newest theoretical work by Reinhard, P. & Nazarewicz W., Phys. Rev. C87, 014324 (2013) which questions the interpretation of low-energy dipole excitations to be interpreted as collective “Pygmy” resonances, but should be understood in the frame of rapidly varying particle-hole excitations.
Summary & Outlook
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- Laser driven nuclear physics heralds a new era in nuclear experimentation allowing insights into nuclear astrophysics and applied technologies which were hitherto unthinkable.

- Laser driven nuclear physics has matured in the last decade and informs state-of-the-art nuclear physics research. It is a truly multidisciplinary field.

- Challenge to theory at the interface of atomic and nuclear physics, informing e.g. UNEDF.

- There is a huge potential for nuclear physics due to the shortness of particle pulses.

- Interaction of electrons with nuclei may show new unexpected new regimes in plasma and the emergence of new reaction channels such as NEEC.

- Mimicking of population distributions in nuclei at high MK-GK temperatures. Unexpected scenarios may arise which can be technologically exploited (population inversion).

- High intensity laser research need auxiliary measurements to characterise targets with Tandem & IGISOL systems.

- Huge challenge in making subsequent laser pulse more reproducible.

- Electro-magnetic pulse (EMP) problematic, saturating electronics, handicapping prompt measurements.

- Target assemblies totally different to low intensity experiments.

- Need to find new detector systems and materials (LaBr$_3$).
Final Remark
The future of ELI-NP is as bright and intense as its pulses. 😊 ELI-NP will become a world-leading centre for e.g. astrophysical & applied research, initiating a paradigm shift on the way we conduct nuclear physics experiments. World-leading research will be undertaken and new phenomena at the interface of atomic and nuclear physics will be discovered. You can take part in these developments with sound experimental campaigns, based on your knowledge & vision to promote physics with laser driven high intensity accelerators.

Thank you for your attention!