Studies of exotic proton-rich nuclei

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ATLAS User Meeting 15th-16th May 2014

With thanks to the FMA/GAMMASPHERE Collaboration:

Argonne National Laboratory
University of Edinburgh
University of Maryland
Physics motivation

Explosive astrophysics

- Stellar proton-capture cross sections (rp-process)
  - Precise level energies (sub keV)
  - Level spins and parities
  - Lifetimes (~fs)

Structure effects near N=Z

- Isospin symmetry (interplay of T=0 and T=1 states)
- Shape coexistence –
  - deformed shell gaps at N(=Z) = 34,36
  - Coulomb/Triplet energy differences
- np-pairing correlations

Nuclear Structure Working Group, ATLAS User Meeting 15th May 2014
Physics motivation

\[^{100}\text{Sn} \text{ region}\]

Landscape of proton emitters

- Highly-deformed fast proton emitters
- Heavy proton emitters

Nuclear Structure Working Group, ATLAS User Meeting 15th May 2014

Figures courtesy of D. Seweryniak
Astrophysics with gamma-rays

Recent highlights:

$^{30}\text{P}(p,\gamma)^{31}\text{S}$ (Doherty et al., PRL 108, 262502, 2012)

(ONe Novae) (Doherty et al., PRC 89, 045804, 2014)

$^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ (Lotay et al., PRL 102, 162502, 2009)

(Wolf-Rayet, AGB stars, Classical Novae)

More to come, e.g.:

$^{26}\text{Al}$ Cosmic gamma-ray emitter, $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ (GAMMASPHERE)

$^{34}\text{Ar}/^{34}\text{Cl}$ mirror system, classical novae (GRETINA + FMA)

Pushing to heavier (more exotic) nuclei means lower cross sections!

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High intensity beams
Doppler correction
Solid angle (FMA)
Parity

Published

$\gamma$ emitters

Figure courtesy of D. Seweryniak
Exotic nuclei close to N=Z

- Recoil-beta-tagging technique allied to mass-separator for the first time

- Fast (superallowed) β decays provide tag for in-beam gamma rays

- New digital DAQ for GAMMASPHERE and FMA (focal plane + 2x160 channel DSSD)

- New results for $^{62}$Ga (N=Z) using new system (H.M. David et al., PLB 726, 665, 2013)
Exotic nuclei close to N=Z

Upcoming:

$^{78}$Y using GRETINA + Digital FMA (+ Digital DSSD)

Isomeric state ($T_{1/2} \sim 6$ s) \rightarrow
tagging requires additional mass selection - FMA

GREtina - Polarization sensitivity (e.g. 5$^-$ or 6$^+$)
- Increased FMA transmission by factor of $\sim 4$
- Improved $\beta$ detection with digital DAQ for DSSD

High Ge rates
Doppler correction
Polarization
FMA transmission

$\beta$ hit patterns in 160x160 DSSD for analogue (left) and digital (right)

Nuclei in \(^{100}\text{Sn}\) region

Multiple projects ongoing –

- Core-excited states in \(^{101}\text{Sn}\) (on the books)

  Single-particle states observed in \(^{101}\text{Sn}\)
  \(\beta p\) recoil-decay-tagging with GS+FMA
  (Seweryniak et al., PRL 99, 022504, 2007)

  Ordering of \(v_g 7/2 \) and \(v_d 5/2\) remains uncertain
  Should reveal info on \(2^+\) state in \(^{100}\text{Sn}\)

- In-beam spectroscopy of \(^{105}\text{Te}\)

  Alpha emitter with \(T_{1/2} \approx 0.5 \mu\text{s}\)
  Help resolve order of \(v_g 7/2 \) and \(v_d 5/2\) states in \(^{101}\text{Sn}\)
  \(^{106}\text{Te}\) studied with RITU (PRC 72, 041303(R), 2005)
Nuclei in $^{100}$Sn region

- **Superallowed alpha-decay chain**
  $^{112}$Ba -> $^{108}$Xe -> $^{104}$Te -> $^{100}$Sn

Search for ultrafast alpha decays (10s-100s ns) using digital FMA (trace analysis)

- **$^{100}$In (pn 2BMEs at $^{100}$Sn)**
  In-beam spectroscopy of $^{100}$In using $\beta^+$ tag
  3n channel -> charged-particle veto detector

**Very** high Ge rates
Doppler correction
Transmission efficiency - AGFA
Proton emitters

- More than half of known proton emitters discovered at ATLAS (incl. first highly-deformed p emitters $^{131}\text{Eu}$ and $^{141}\text{Ho}$ and heaviest known proton emitter $^{185}\text{Bi}$)

**Highly-deformed fast proton emitters**
Search hampered by
- small cross sections
- short lifetimes (< tof)

High efficiency and shortened flight path with AGFA may allow access to (e.g.)
$^{125}\text{Pm}$, $^{139}\text{Eu}$, $^{139}\text{Ho}$ (odd Z even N)
$^{116}\text{La}$, $^{120}\text{Pr}$, $^{134}\text{Pr}$ (odd Z odd N)

**Heavy proton emitters**
Many expected heavier than $^{185}\text{Bi}$ (e.g. $^{188,189}\text{At}$, $^{194,195}\text{Fr}$, $^{200,201}\text{Ac}$)
Could be accessible with ATLAS intensity upgrades and AGFA

-> *Plus, exciting opportunities using in-flight radioactive beams from AIRIS + AGFA separator!*
Summary

Many ongoing projects at ATLAS studying exotic proton-rich nuclei
To carry out successful future experiments...

- **High beam intensities (recent ATLAS upgrades)**
  (stellar proton-capture reactions, heavy proton emitters)

- **High Ge rates (Digital GS, GRETINA)**
  (up to 40 kHz for $^{101}\text{Sn}$, $^{105}\text{Te}$, $^{78}\text{Y}$)

- **Large solid angle acceptance for FMA (factor ~4 increase with GRETINA cf GS)**
  ($^{101}\text{Sn}$, tagging e.g. $^{78}\text{Y}$, $^{100}\text{In}$, proton-resonances)

- **Excellent Doppler correction for high-energy gammas (GRETINA)**
  (esp. $^{100}\text{Sn}$ region)

- **Sensitivity to polarization (recently demonstrated with GRETINA)**
  (characterization of states in N=Z nuclei, proton resonances)

- **Increased separator transmission and reduced TOF (AGFA)**
  ($^{105}\text{Te}$, fast proton emitters)

- **Improved tagging at focal plane (new Si-box, digital DSSD)**
  (e.g. $^{78}\text{Y}$, $^{100}\text{In}$)

- **PLUS opportunities with radioactive proton-rich beams with AIRIS...**
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Thank you!
Table 1: Comparison between GRETINA+FMA and DGS+FMA configurations.

<table>
<thead>
<tr>
<th></th>
<th>$^{62}$Ga study</th>
<th>$^{78}$Y: GRETINA + FMA</th>
<th>$^{78}$Y: DGS + FMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSSD total implantation rate</td>
<td>1500 Hz</td>
<td>3000 Hz</td>
<td>9400 Hz</td>
</tr>
<tr>
<td>DSSD recoil implantation rate</td>
<td>120 Hz</td>
<td>750 Hz</td>
<td>750 Hz</td>
</tr>
<tr>
<td>Per-pixel recoil rate</td>
<td>1 every 150\textsuperscript{a} s</td>
<td>1 every 24\textsuperscript{a} s</td>
<td>1 every 24\textsuperscript{a} s</td>
</tr>
<tr>
<td>Beam current</td>
<td>12 pnA</td>
<td>26 pnA</td>
<td>75 pnA</td>
</tr>
<tr>
<td>Total Ge rates (per crystal)</td>
<td>4000 Hz</td>
<td>22000 Hz</td>
<td>25000 Hz</td>
</tr>
<tr>
<td>Triggered Ge rates (total)</td>
<td>9000\textsuperscript{b} Hz</td>
<td>21800\textsuperscript{b} Hz</td>
<td></td>
</tr>
<tr>
<td>Estimated resolution (1 MeV)</td>
<td>$\sim$4 keV</td>
<td>$\sim$9 keV</td>
<td></td>
</tr>
<tr>
<td>Gamma-ray efficiency (1 MeV)</td>
<td>6-7%</td>
<td>9%</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}Assuming $\sim$70\% of the 25600 DSSD pixels are illuminated.

\textsuperscript{b}Assuming an average of 4 gamma rays per recoil and 2 per scattered beam ion (the DSSD serves as the trigger for data acquisition).
Large-area high-resolution micro-channel plate detector
L. Afansieva, B. Digiovine, J. Greene, B. Nardi, B. Zabransky, D.S.

- Large area to cover the whole focal plane - 4 cmX12 cm (focal plane 2cm X10 cm)
- High rate capability (100 kHz)
- Three micro channel plates for large multiplication/efficiency
- Resistive layer readout in one dimension for position

Resistive readout
3 mcp’s
foil
e
E,B
magnet
HI from FMA

Photonis Inc., USA

Permanent magnets to limit diffusion of electrons to achieve better position resolution
New Micro-Channel Plate Detector
Position resolution test

- Pu-Cm alpha source
- Aluminized mylar foil
- Slits 6/4/2/1/2/4/6 mm
- PAs+shaping amps

Position resolution better than 1 mm!
Efficiency > 99%
Digital MCP

- CREMAT PA + GREtINA digitizer

![Graphs showing data analysis results for CREMAT PA + GREtINA digitizer.](Slide courtesy of D. Seweryniak)
MCP next steps

- Carbon foil
  - Thin
  - Large area, no supporting grid
  - Magnesium oxide layer
- In-beam test with heavy ions
- High-rate test
  - Fast electronics
    - FAST amp + FERA (analog)
    - Fast shaping + (CREMAT amp) + GRETINA digitizer (digital)
The case of $^{105}\text{Te} - \text{FMA vs AGFA comparison}$

$^{54}\text{Fe}(^{54}\text{Fe},3n)^{105}\text{Te}$ reaction
Beam energy 190 MeV (based on $^{101}\text{Sn},^{109}\text{Xe}$)
Total fusion cross section 200 mb (HIVAP)
3n channel cross section $\sim 10$ nb (FMA experiment)

**Maximum beam current (limited by GS)**
Gamma ray multiplicity 20
Average GS photo-peak efficiency 15%
Raw P/T 25% (need to include Compton scattered events)
Ge count rate at 50 pnA - 40 kHz (maximum for digital GS)

**Recoil rates**
FMA efficiency 5%
AGFA efficiency 50%
AGFA recoil rate at 50 pnA 175 kHz
FMA recoil rate at 50 pnA 17.5 kHz
Need to add scattered beam

**DSSD radiation damage**
5 days at 50 pnA amounts to $2 \times 10^7$ (resolution is not critical)

**Bottom line**
5 times more $^{105}\text{Te}$ events with AGFA
(additional x2 due to shorter TOF and DDAQ)