Studies of exotic proton-rich nuclei

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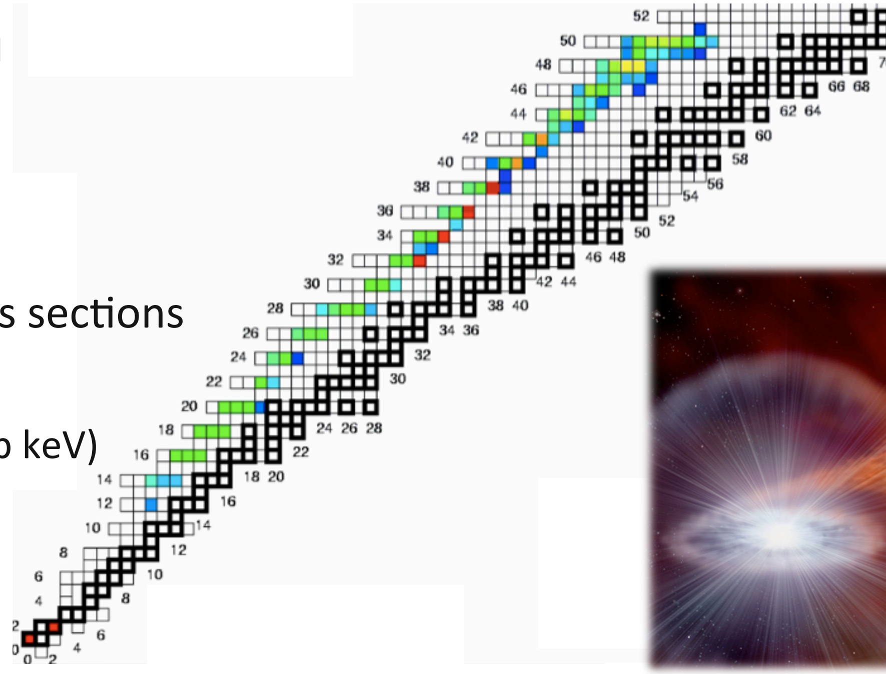
With thanks to the FMA/GAMMASPHERE Collaboration:

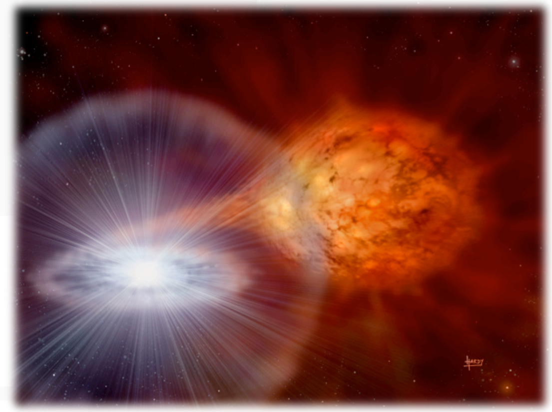
Argonne National Laboratory
University of Edinburgh
University of Maryland

Physics motivation

Explosive astrophysics

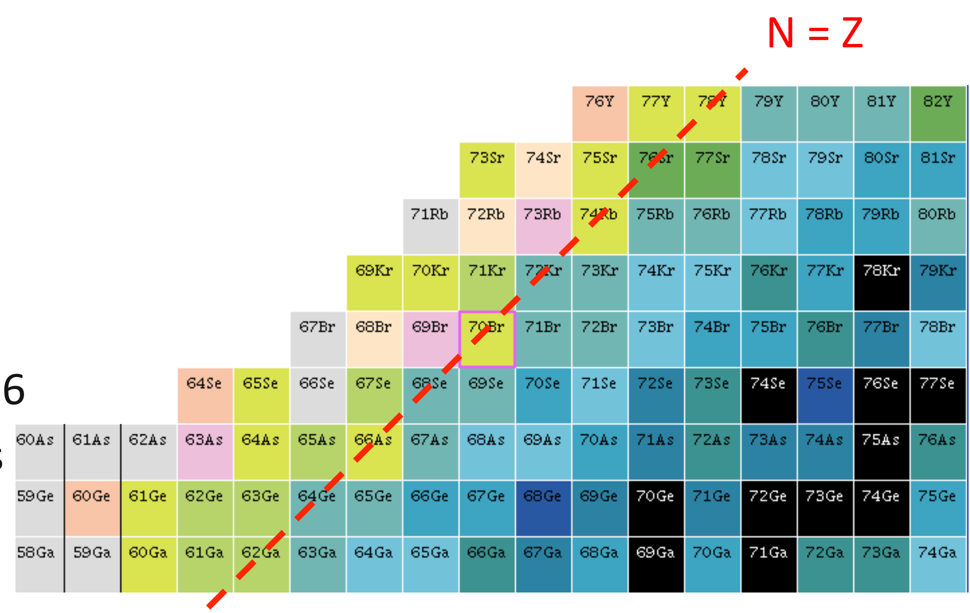
- Stellar proton-capture cross sections (rp-process)
  - Precise level energies (sub keV)
  - Level spins and parities
  - Lifetimes (~fs)





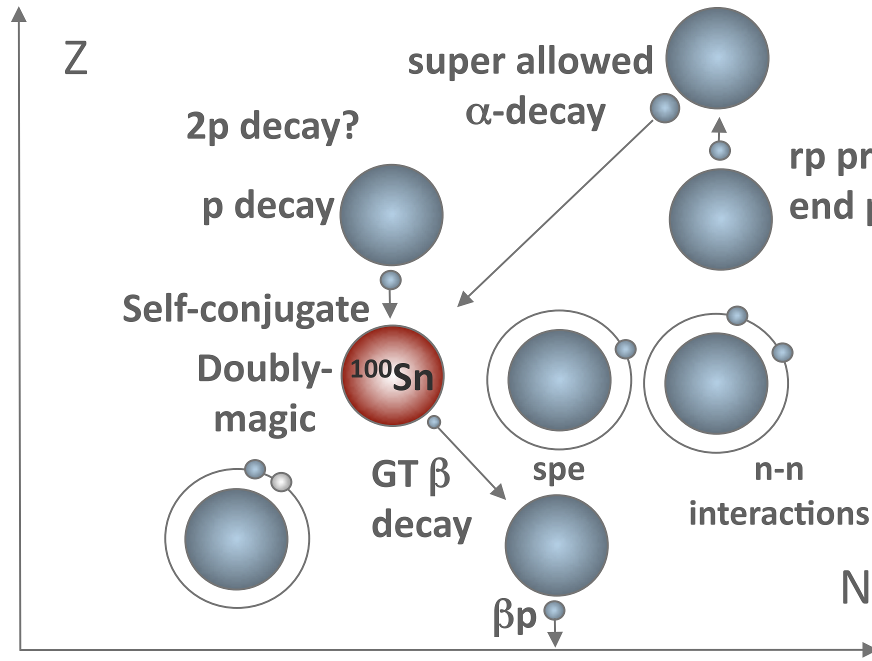
Structure effects near N=Z

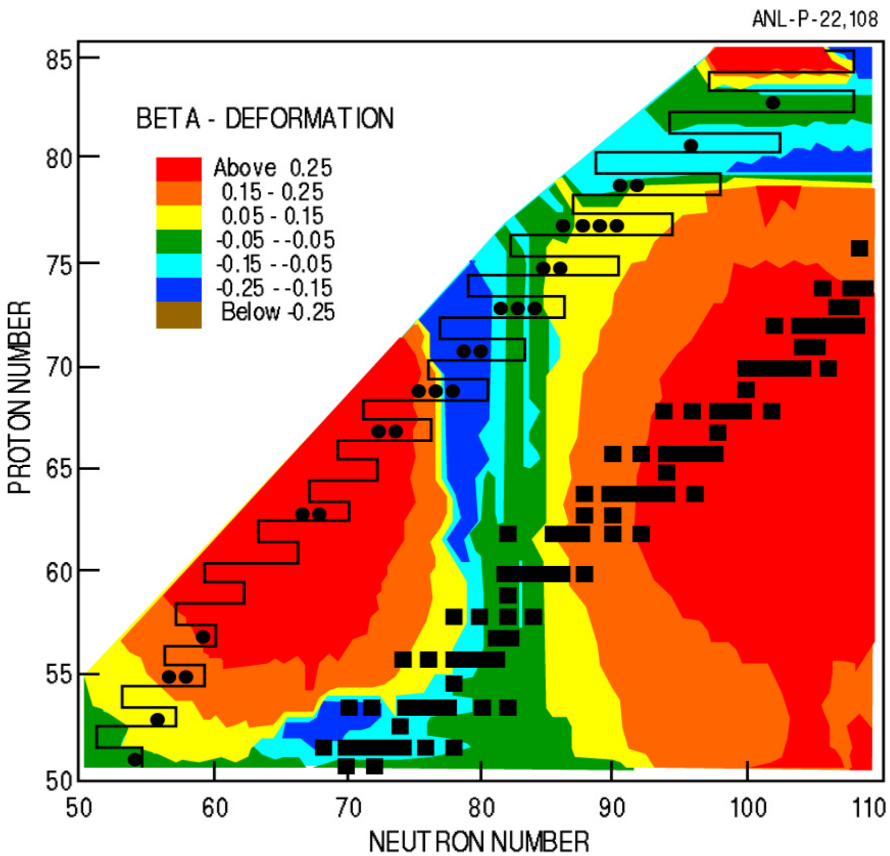
- Isospin symmetry
  (interplay of T=0 and T=1 states)
- Shape coexistence –
  - deformed shell gaps at N(=Z) = 34,36
  - Coulomb/Triplet energy differences
- np-pairing correlations



Physics motivation

^{100}Sn region →





← **Landscape of proton emitters**

- Highly-deformed fast proton emitters
- Heavy proton emitters

Astrophysics with gamma-rays

Recent highlights:

^{30}P(p,γ)^{31}S (Doherty *et al.*, PRL **108**, 262502, 2012)

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

^{26g}Al(p,γ)^{27}Si (Lotay *et al.*, PRL **102**, 162502, 2009)

(Wolf-Rayet, AGB stars,

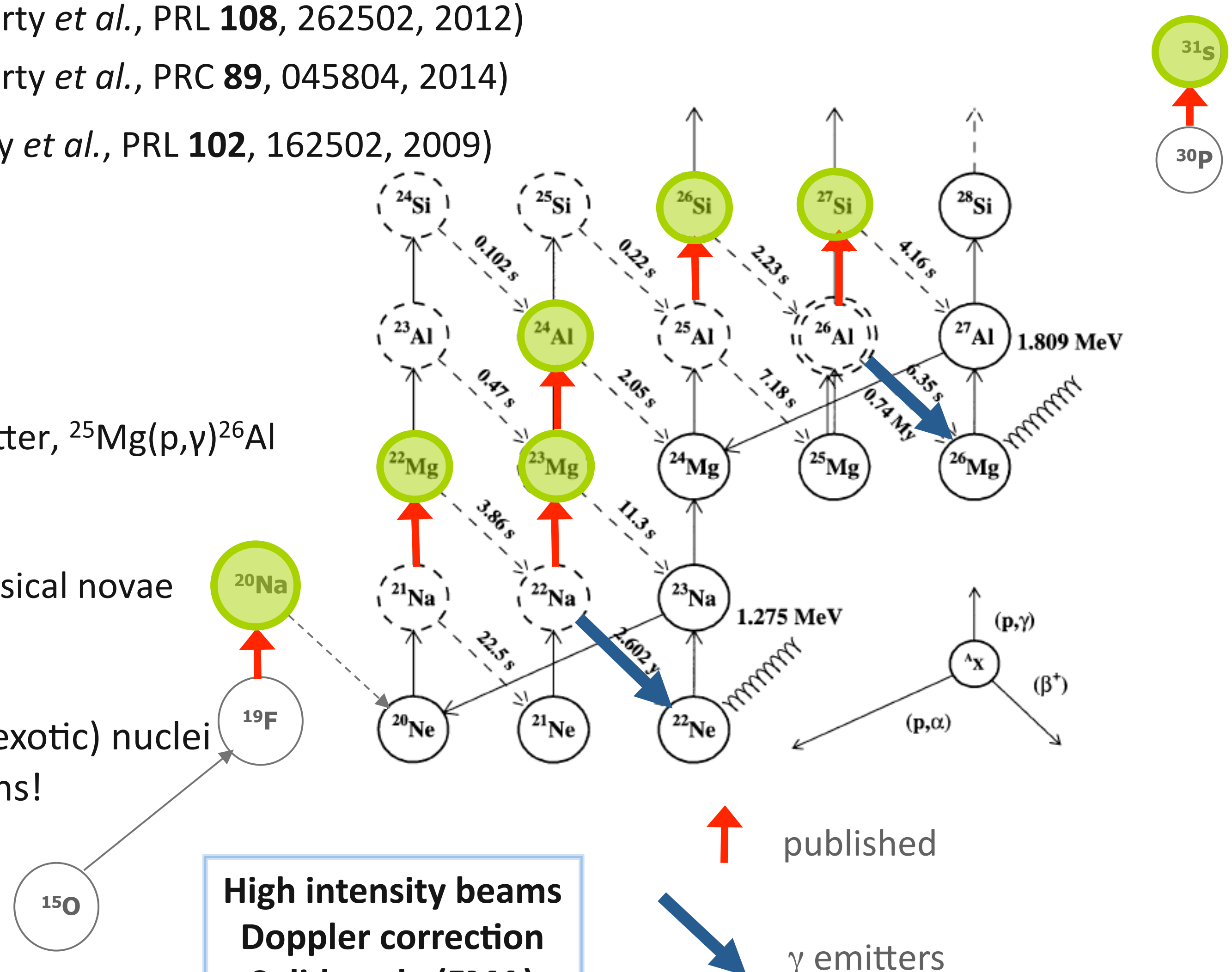
Classical Novae)

More to come, e.g.:

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

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

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

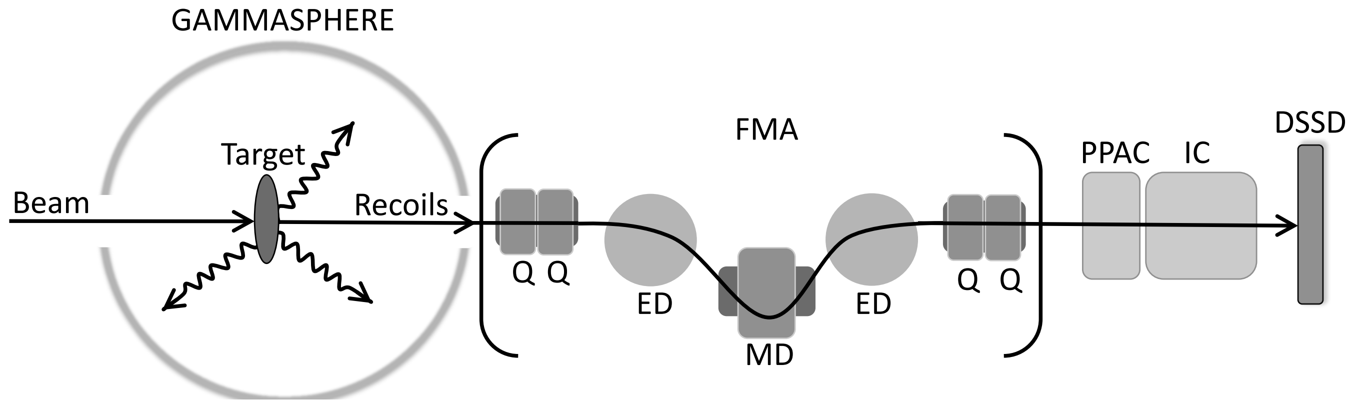


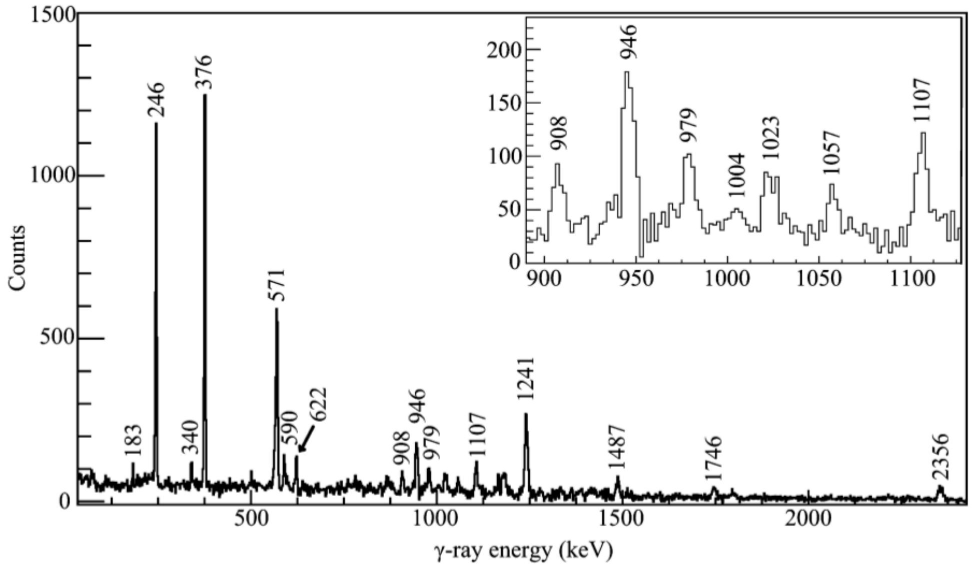
High intensity beams
Doppler correction
Solid angle (FMA)
Parity

Figure courtesy of D. Seweryniak

Exotic nuclei close to N=Z

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





^{62}Ga singles spectrum

- 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)

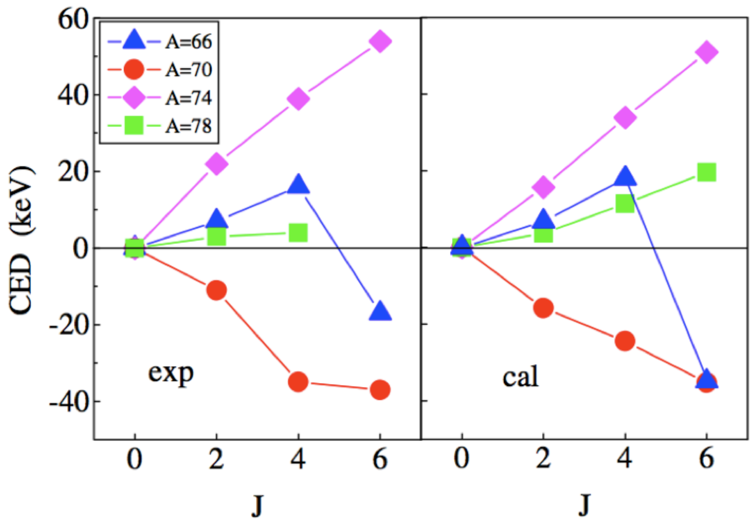
Exotic nuclei close to N=Z

Upcoming:

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

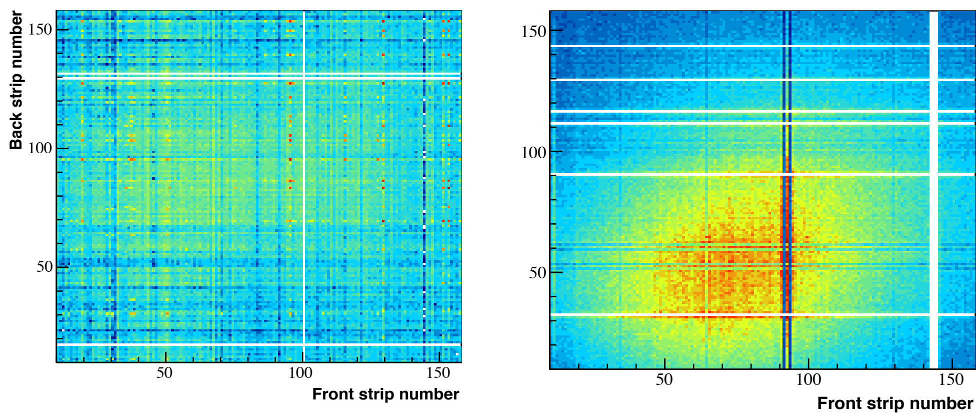
Isomeric state ($T_{1/2}$ ~ 6 s) –>
tagging requires additional mass selection - FMA

GRETINA - Polarization sensitivity (e.g. 5^- or 6^+)
- Increased FMA transmission by factor of ~4
- Improved β detection with digital DAQ for DSSD



Experimental and calculated CEDs for A = 66, 70, 74 and 78 [1]

High Ge rates
Doppler correction
Polarization
FMA transmission

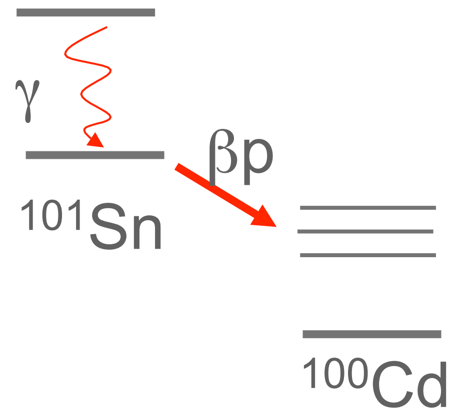


β hit patterns in 160x160 DSSD for analogue (left) and digital (right)

[1] Kaneko *et al.*, PRL **109**, 092504, 2012

Nuclei in ^{100}Sn region

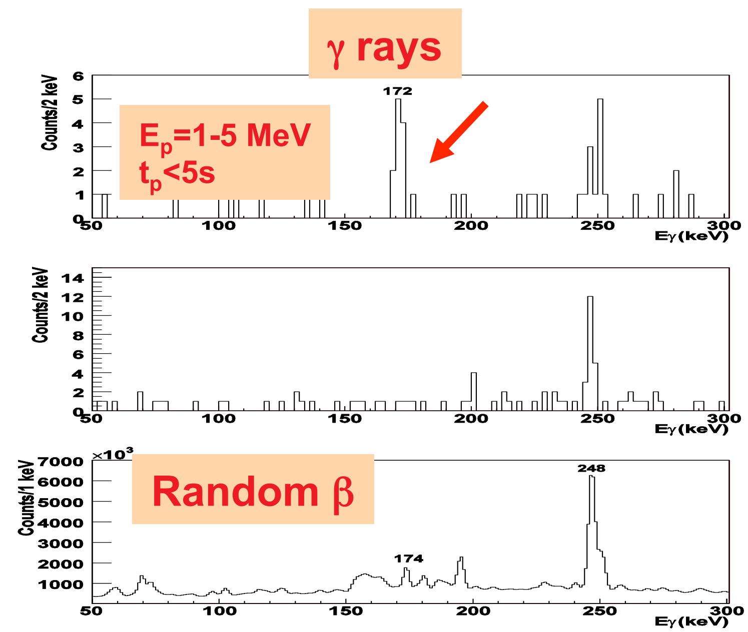
Multiple projects ongoing –



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

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

  Ordering of $\nu g_{7/2}$ and $\nu d_{5/2}$ remains uncertain
  Should reveal info on 2^{+} state in ^{100}Sn



- **In-beam spectroscopy of ^{105}Te**

Alpha emitter with $T_{1/2}$~0.5 µs
Help resolve order of of $\nu g_{7/2}$ and $\nu d_{5/2}$ states in ^{101}Sn
^{106}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)**

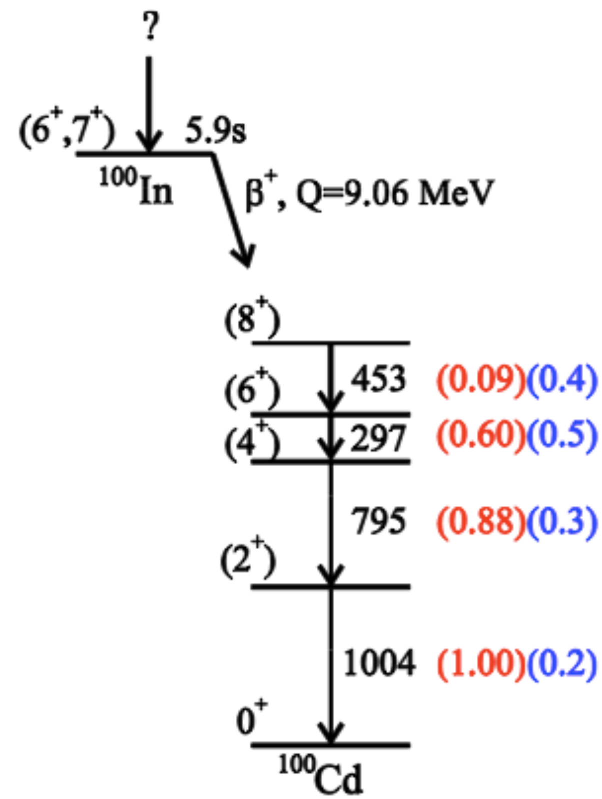
In-beam spectroscopy of ^{100}In using βγ tag

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}Eu and ^{141}Ho and
  heaviest known proton emitter ^{185}Bi)

High beam intensities
High transmission efficiency
(AGFA)

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}Pm, ^{139}Eu, ^{139}Ho (odd Z even N)

^{116}La, ^{120}Pr, ^{134}Pr (odd Z odd N)

Heavy proton emitters

Many expected heavier than ^{185}Bi (e.g. ^{188,189}At, ^{194,195}Fr, ^{200,201}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}Sn, ^{105}Te, ^{78}Y)
- **Large solid angle acceptance for FMA (factor ~4 increase with GRETINA cf GS)**
  (^{101}Sn, tagging e.g. ^{78}Y, ^{100}In, proton-resonances)
- **Excellent Doppler correction for high-energy gammas (GRETINA)**
  (esp. ^{100}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}Te, fast proton emitters)
- **Improved tagging at focal plane (new Si-box, digital DSSD)**
  (e.g. ^{78}Y, ^{100}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.

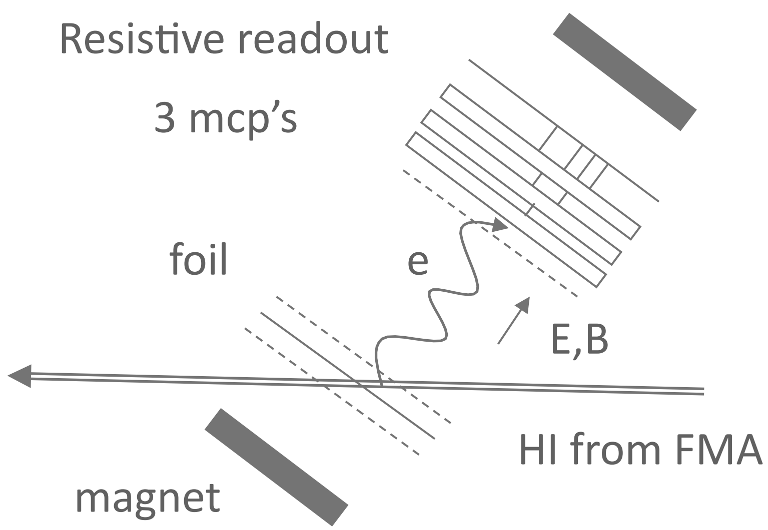
	^{62}Ga study	^{78}Y: GRETINA + FMA	^{78}Y: DGS + FMA
DSSD total implantation rate	1500 Hz	3000 Hz	9400 Hz
DSSD recoil implantation rate	120 Hz	750 Hz	750 Hz
Per-pixel recoil rate	1 every 150[a] s	1 every 24[a] s	1 every 24[a] s
Beam current	12 pnA	26 pnA	75 pnA
Total Ge rates (per crystal)	4000 Hz	22000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

[a]Assuming ~70% of the 25600 DSSD pixels are illuminated.
[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



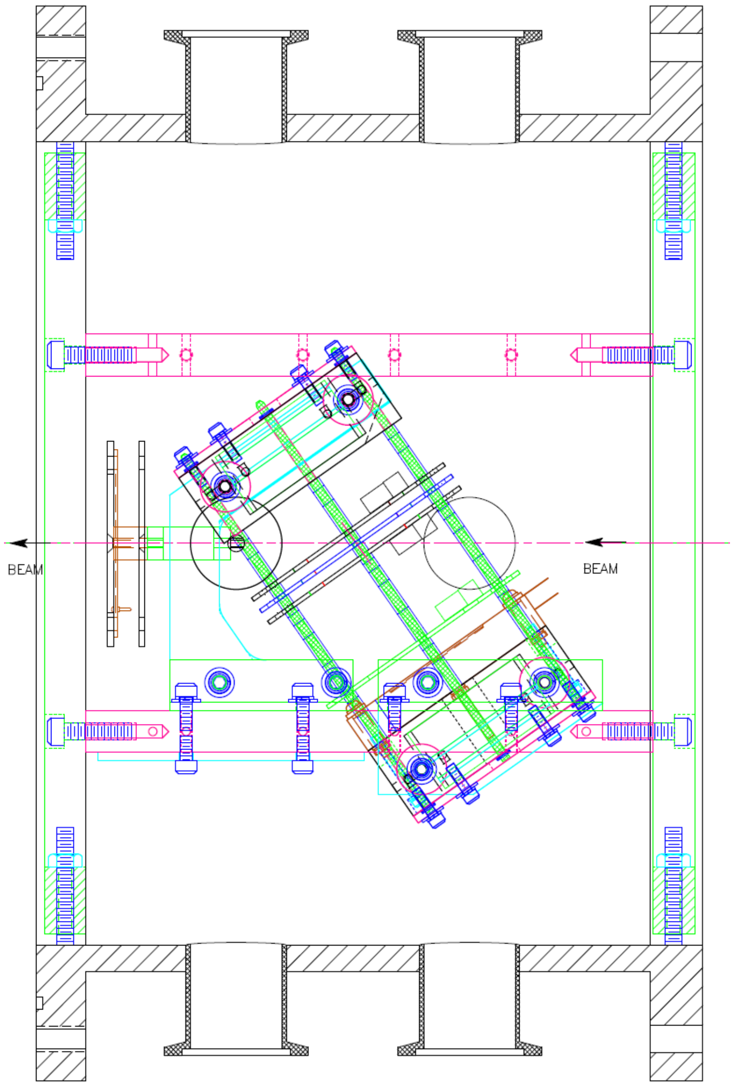
Photonis Inc., USA

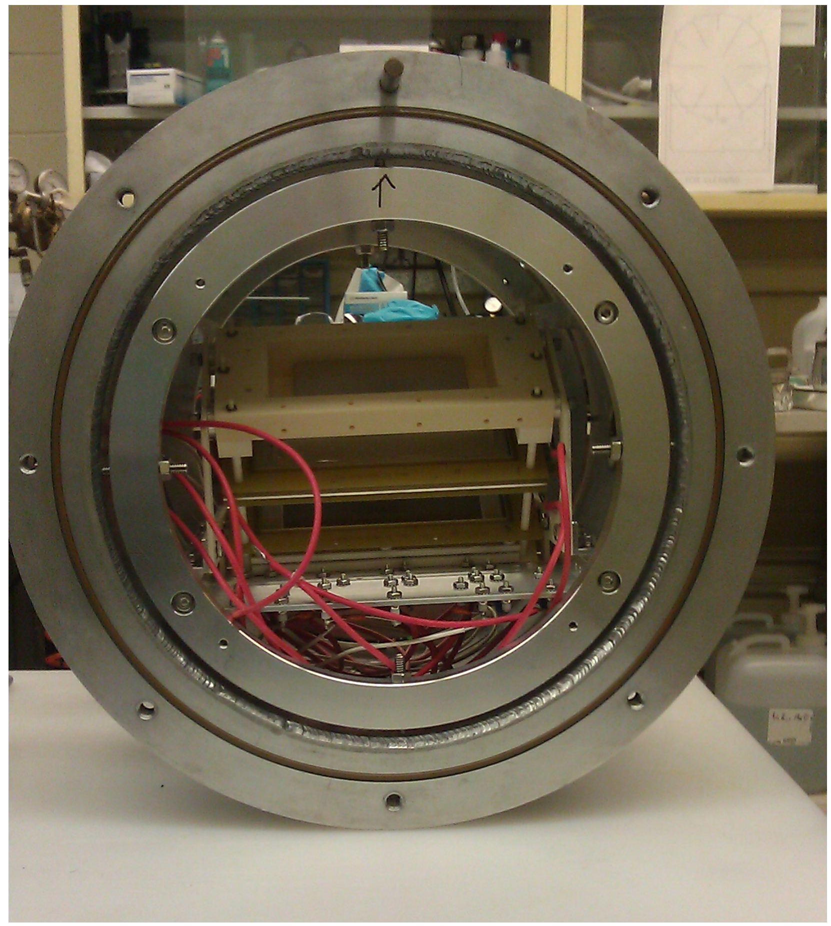
Permanent magnets to limit diffusion of electrons to achieve better position resolution

D.Shapira et al., Nucl. Instr. and Meth. in Phys. Res. A 454 (2000) 409

Slide courtesy of D. Seweryniak

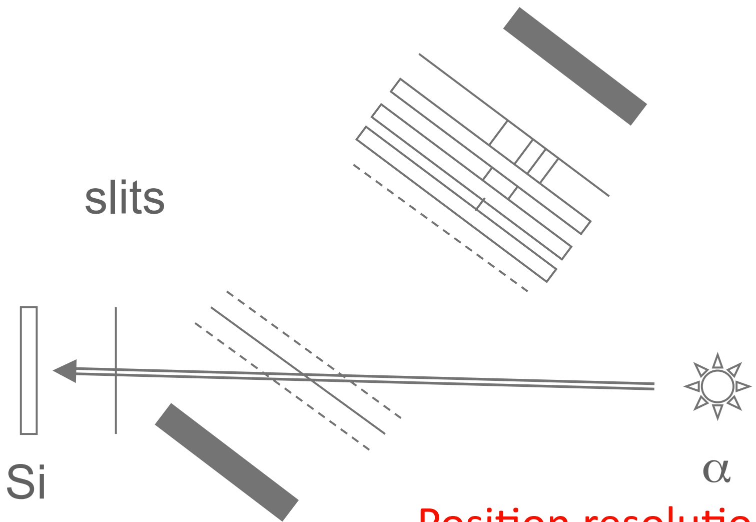
New Micro-Channel Plate Detector





Slide courtesy of D. Seweryniak

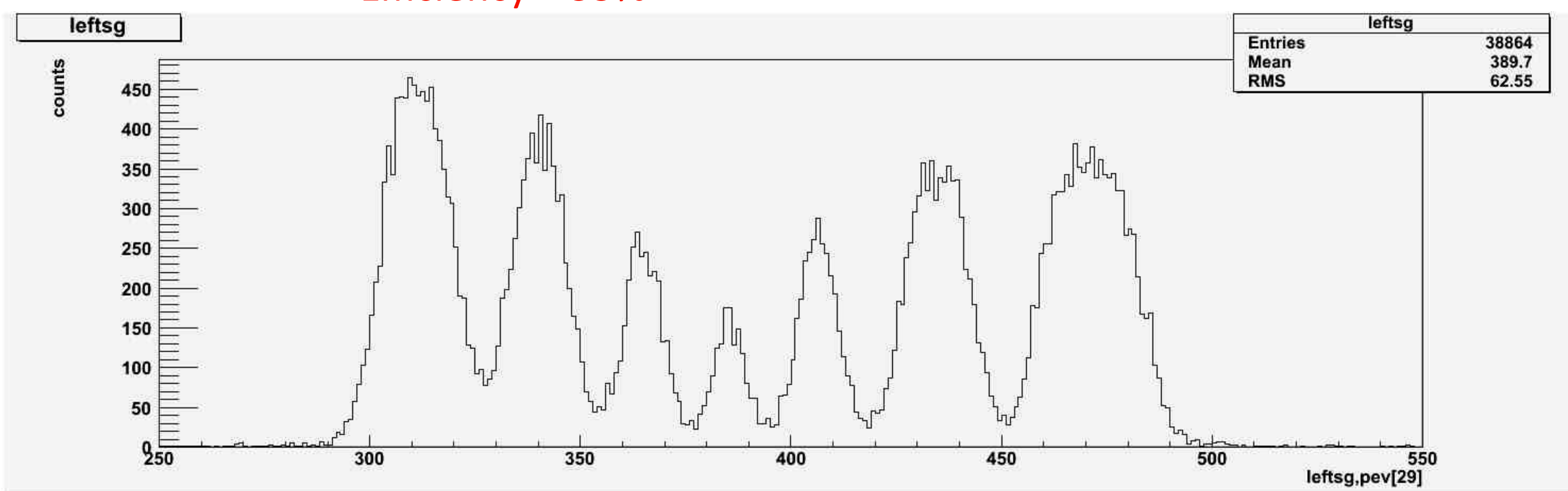
Position resolution test



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

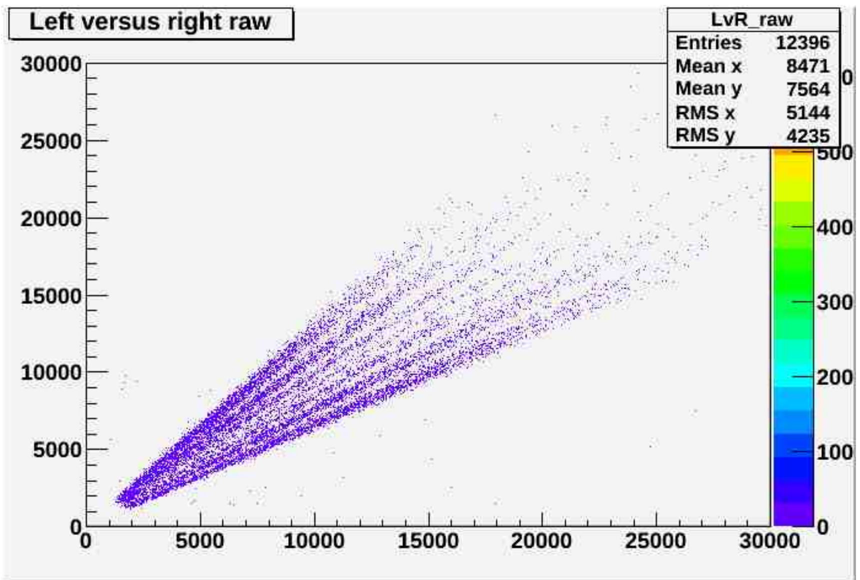
Position resolution better than 1 mm!

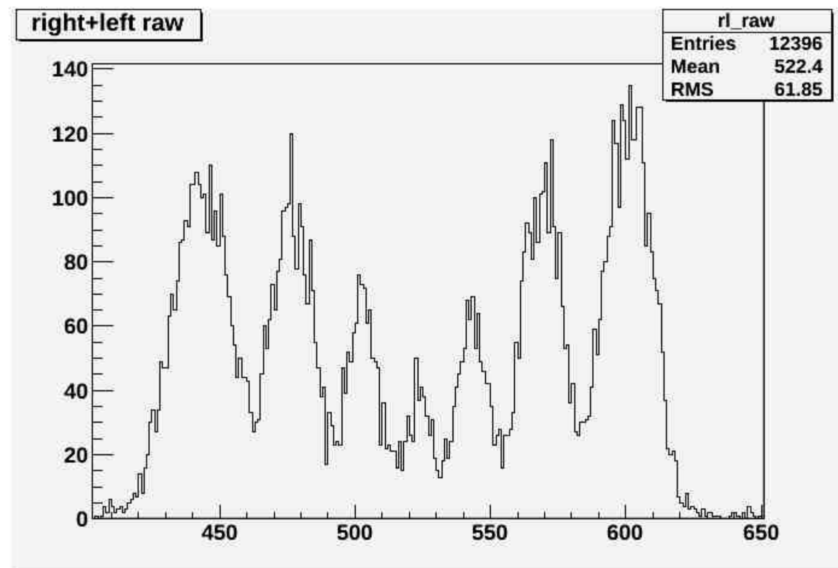
Efficiency > 99%



Digital MCP

- CREMAT PA + GRETINA digitizer





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)

Slide courtesy of D. Seweryniak

The case of ^{105}Te – FMA vs AGFA comparison

^{54}Fe(^{54}Fe,3n)^{105}Te reaction
Beam energy 190 MeV (based on ^{101}Sn, ^{109}Xe)
Total fusion cross section 200 mb (HIVAP)
3n channel cross section ~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 2x10^7 (resolution is not critical)

Bottom line

5 times more ^{105}Te events with AGFA
(additional x2 due to shorter TOF and DDAQ)