Towards Next-Generation In-Beam Gamma-Ray Spectroscopy at the RIBF with HYPATIA

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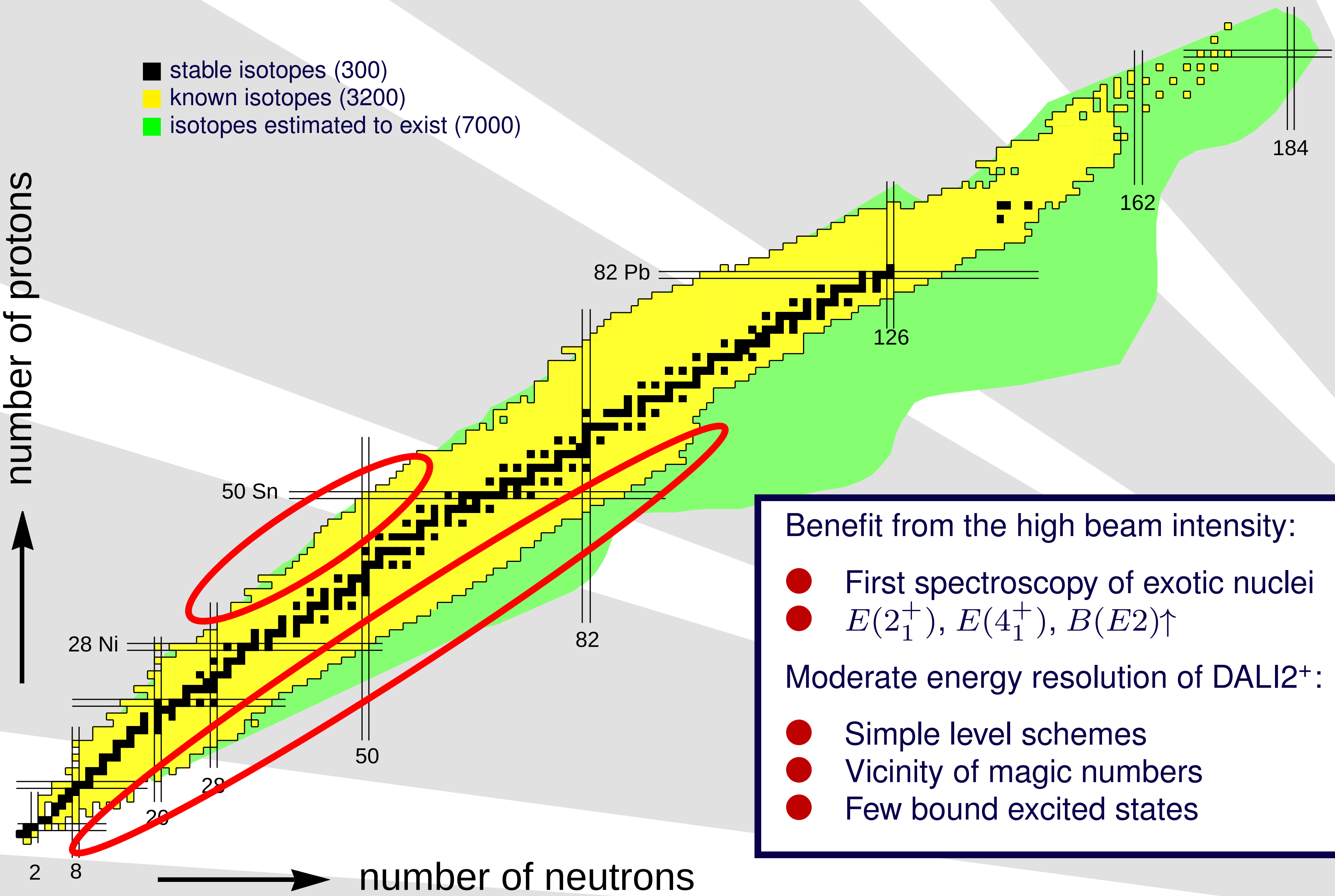
Introductory Comments

- In-beam γ-ray spectroscopy of exotic nuclei with fast beams is a powerful tool for nuclear structure and reaction studies
- We can assume that 2 pμA ^{238}U at 345 MeV/nucleon become available after RIBF upgrade
- DALI2$^+$
  - High scientific production
  - Outdated detector technology, but very affordable
- GRETA, a 4π Ge tracking array in the US
  - 60 Mio USD project, fully funded
  - 30 quads, 25 available from 2025
- Focus not only on better energy resolution but also other quantities for a broad physics program
  - We want **high efficiency, high P/T, excellent timing, high flexibility, easy maintenance**
    - Produce cleanest possible spectra
  - Cost effective solution

In-Beam γ-Ray Spectroscopy at the RIBF



Benefit from the high beam intensity:

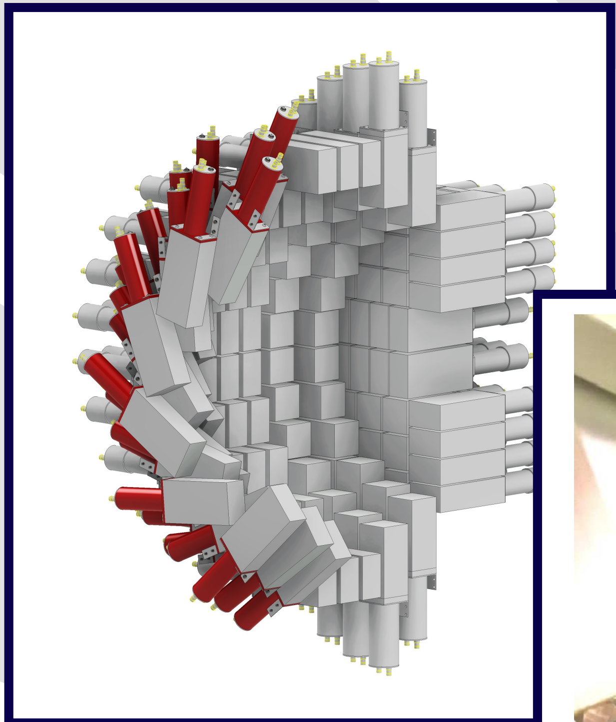
- First spectroscopy of exotic nuclei
- $E(2^+_1)$, $E(4^+_1)$, $B(E2)\uparrow$

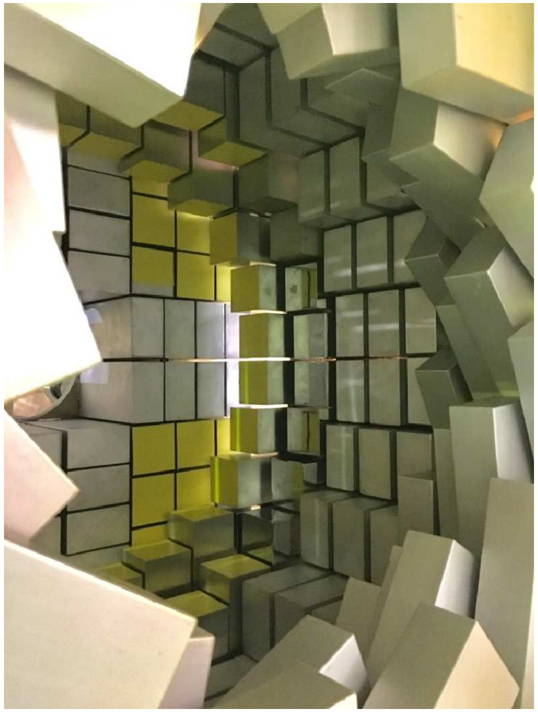
Moderate energy resolution of DALI2$^+$:

- Simple level schemes
- Vicinity of magic numbers
- Few bound excited states

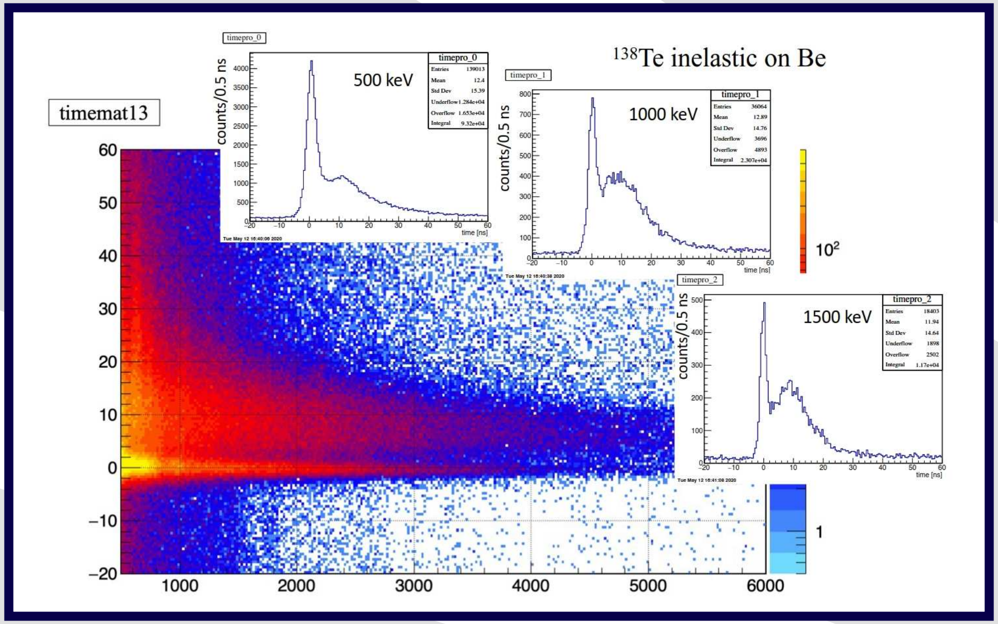
DALI2^{+} (From Fall 2023)

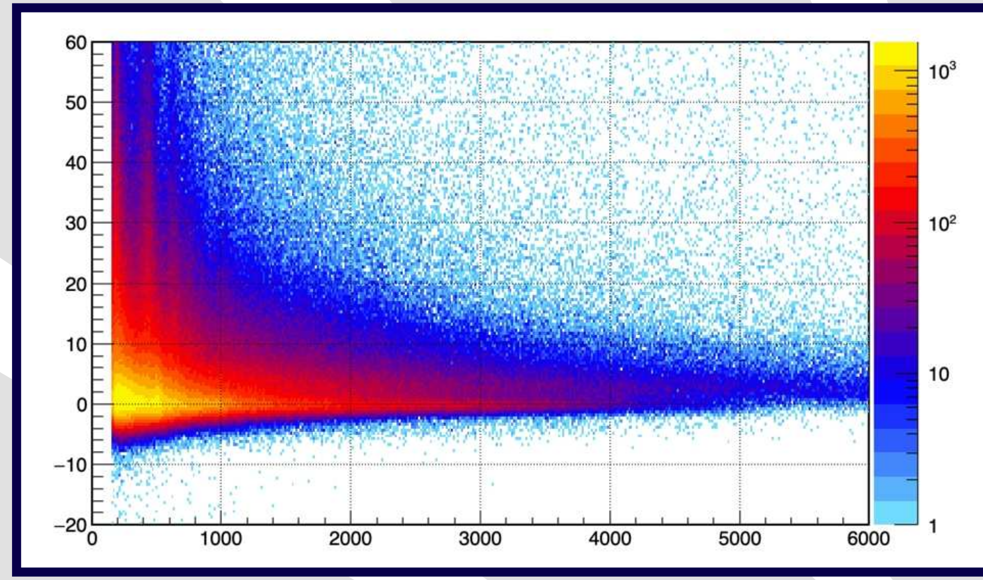
- 226 NaI(Tl) detectors
  - In Collaboration with ATOMKI and HKU
- 46 Scionix (red)
- 92 Saint-Gobain $\rightarrow$
  - 10 from ATOMKI
- 88 DALI1-type $\rightarrow$
  - 10 from ATOMKI
  - 70 from HKU
- Performance of 1 MeV γ-ray:
  - 7 % intrinsic energy resolution (FHWM)
  - 9 % energy resolution @ 100 MeV/nucleon
  - 35 % FEP efficiency with add-back
- Scientific production: 104 peer-reviewed publications
  - 2 Nature, 28 PRL, 27 PLB, 42 PRC, 7 others
  - Expect $\approx$ 130 publications in total
  - $\approx$ 20 publications at "old" facility





^{9}Be(^{138}Te,^{137}Te+γ) with DALI2^{+}
The Benefit of Good Time Resolution





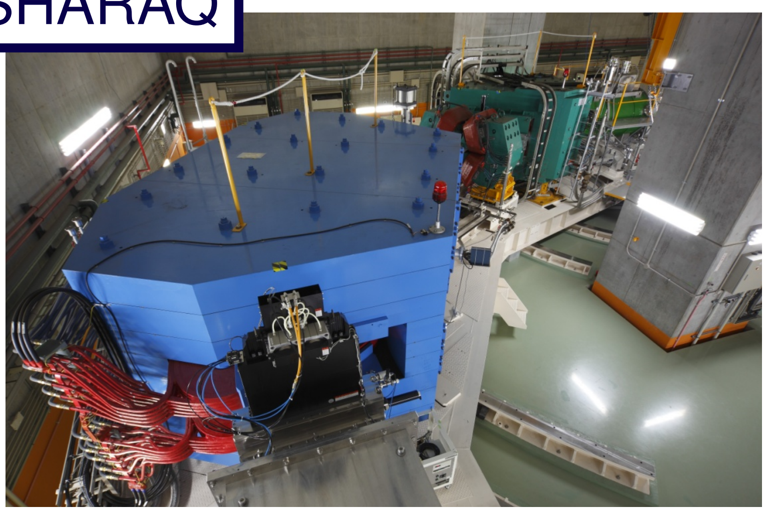
- In-beam γ-ray spectroscopy with fast beams always has background
  - Inelastic scattering on H as well as (p,pn) and (p,2p) has similar background
- “Good” γ rays from ejectile up to neutron-separation energy (2.5 MeV for ^{137}Te) in c.m. system
- Huge background time delayed by several ns
  - Cannot resolve with Ge detectors (14 ns FWHM at 1.33 MeV)
  - Background free spectroscopy with fast scintillators

Where to Measure with Fast Beams?
The Three Magnetic Spectrometers of RIBF

ZeroDegree

- Inelastic scattering, knockout, quasi-free scattering $A > 100$
- Simultaneous mass, isomer spectroscopy/tagging

SHARAQ



- Inelastic scattering at reduced velocities

SAMURAI

- Inelastic scattering, knockout, quasi-free scattering $A < 100$
- Invariant mass spectroscopy

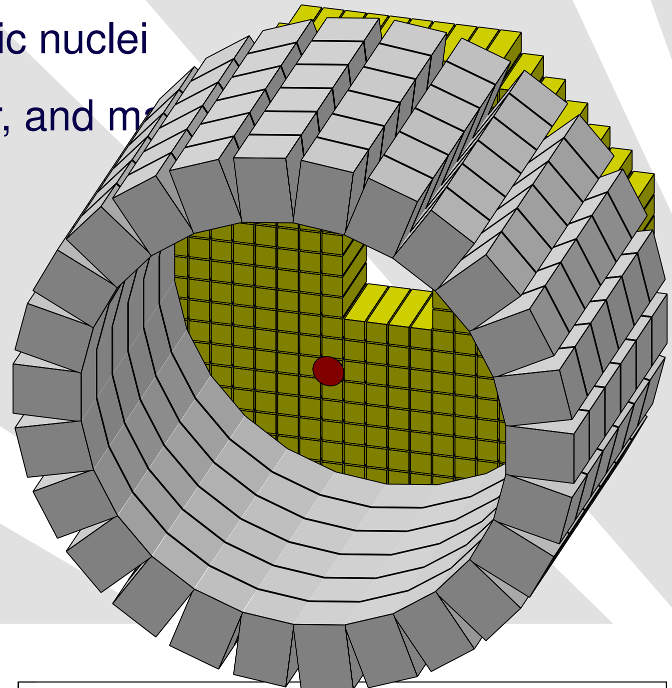
Concept

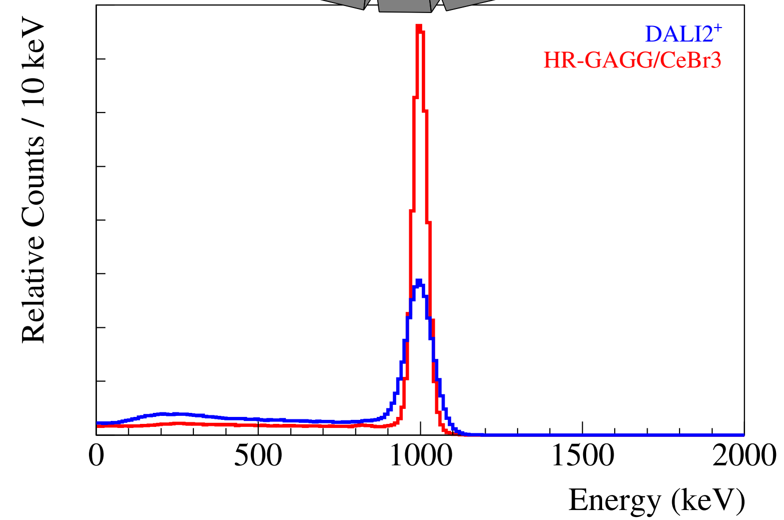
The Next Step: HYPATIA
Transition to High-Resolution Scintillators

- HYPATIA: HYbrid Photon detector Array To Investigate Atomic nuclei
  - Named after first known female philosopher, astronomer, and mathematician

The Next Step: HYPATIA Transition to High-Resolution Scintillators

- HYPATIA: HYbrid Photon detector Array To Investigate Atomic nuclei
  - Named after first known female philosopher, astronomer, and m
- Around 1000 scintillators
  - 384 HR-GAGG crystals for forward wall $25 \times 25 \times 100$ mm^3
  - 624 CeBr crystals in annular arrangement 2×2 in common Al housing, $30 \times 30 \times 80$ mm^3
  - In collaboration with York, HKU, Beijing Normal, ATOMKI, LPC Caen, CNS, ...
  - Other collaborators are highly welcome
- Performance goals (for 1 MeV γ-ray):
  - 4.5 and 3.5 % intrinsic energy resolution (FHWM)
  - $\leqslant$ 5 % energy resolution @ 100 MeV/nucleon (FWH
  - > 50 % FEP efficiency with add-back
  - $\geqslant$ 0.7 P/T
  - 1.5 and 0.5 ns time resolution (FWHM)
- Compatible with LH2 targets STRASSE and MINOS
- Suitable for combination with Ge tracking
- Gradual replacement of DALI2$^+$





Performance Comparison for Fast Beams

Parameter	HYPATIA	DALI2$^+$	GRETINA[1]	GRETA
Energy Resolution /% (FWHM)	5–6[2]	10	2	2
Time Resolution /ns (FWHM)	0.5–1.5	3	14	14
Efficiency at 1 MeV/ %	52	36	7	36
P/T %	0.72	0.54	0.4	0.51
Initial costs / Mio USD	7–9	1.5–2	12?	60?
Operation costs / year/ Mio USD	0.1	0.05	0.3	1.3[3]
Maintenance effort, manpower	low	low	high	high
Flexibility to change configuration	high	high	fixed radius	fixed radius
Time to change location	1 week	1–2 weeks	months	months
Analysis effort	low	low	high	high

- Energy resolution depends on target thickness. Around 1.5–2 % for GRETA for thin targets

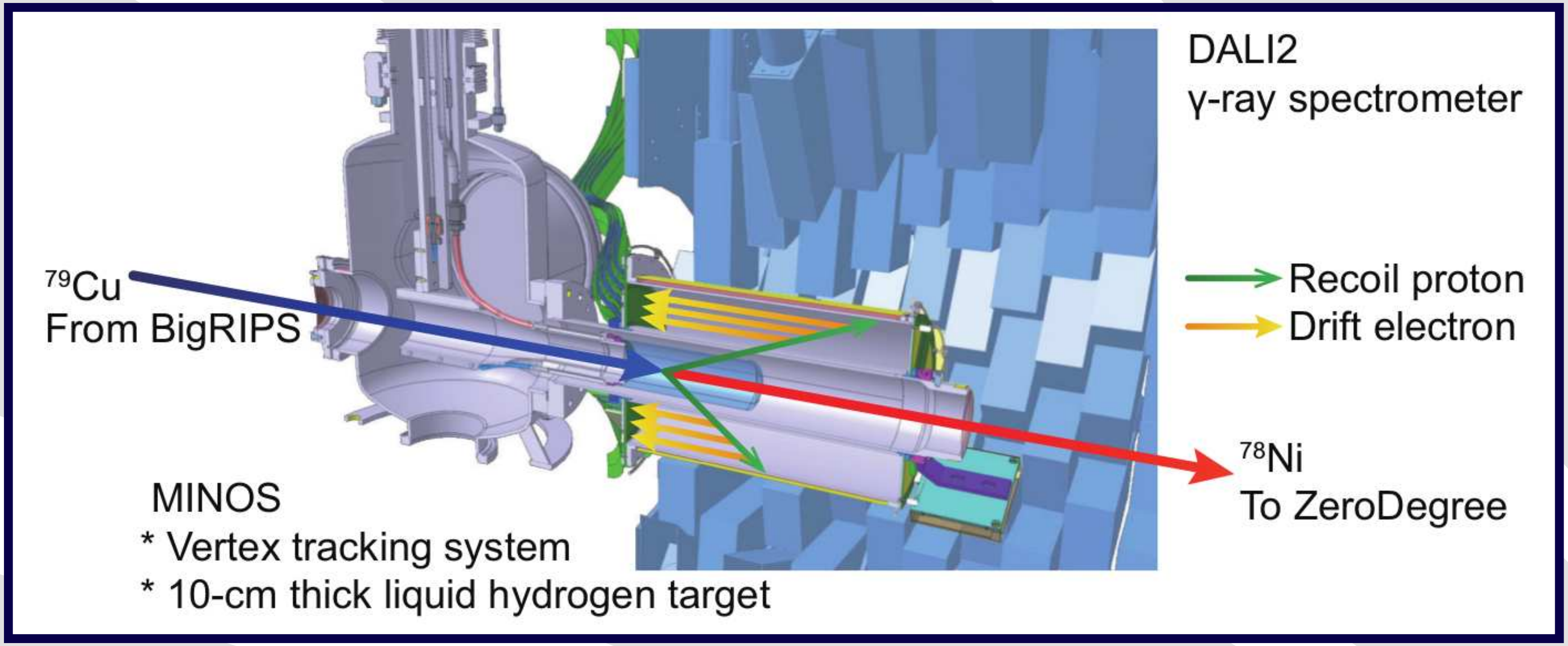
[1] 7 Quads

[2] Can be reduced to ≈4.5 % if detector-target distance increased

[3] AGATA collaboration estimates operation costs 10.000 euro / crystal/year

Physics Opportunities

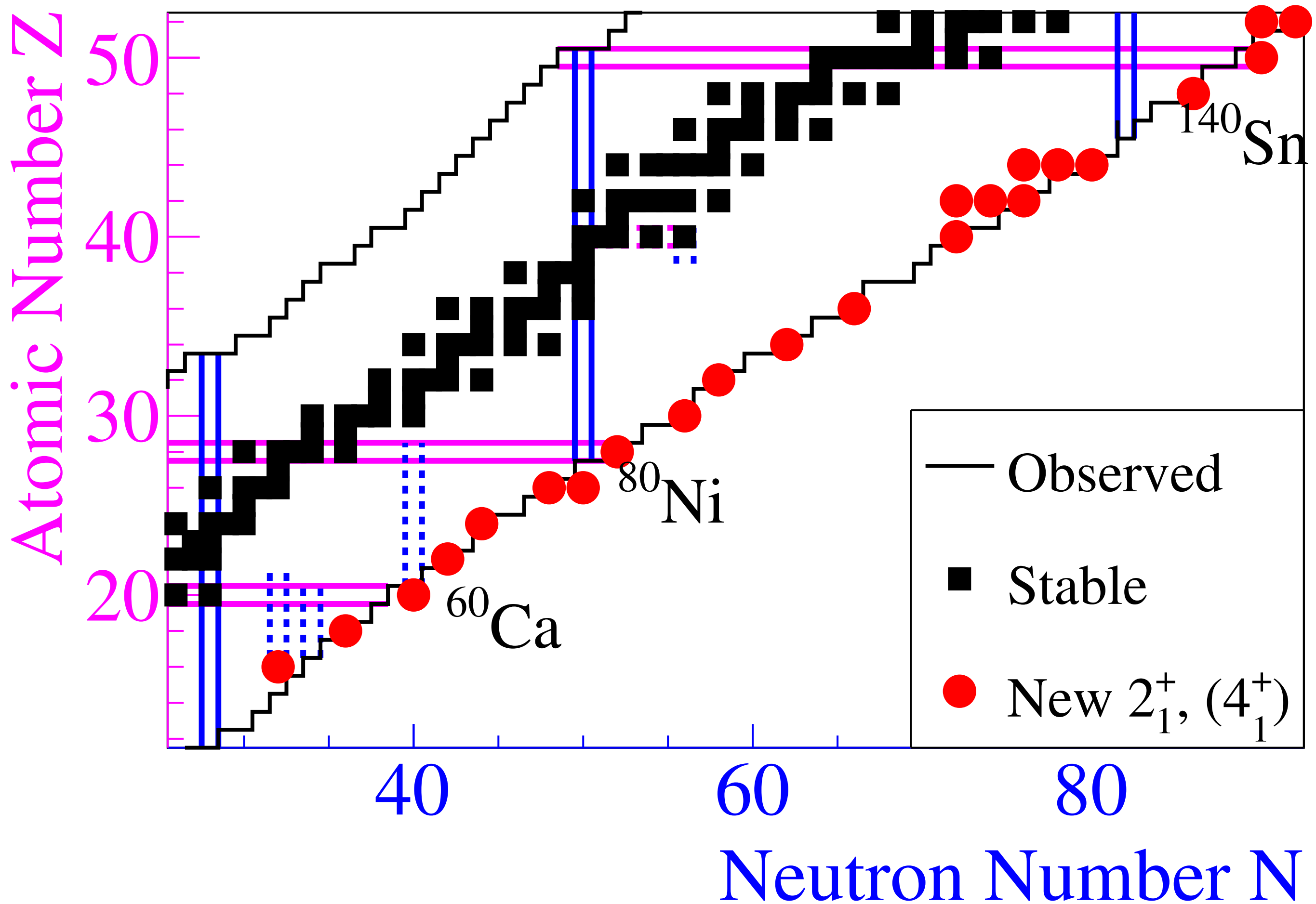
In-Beam Gamma-Ray Spectroscopy With a Liquid Hydrogen Target



- MINOS, **M**ag**I**c **N**umbers **O**ff **S**tability
  - up to 1 g/cm^2 (150 mm) liquid hydrogen target, velocity $\beta \approx 0.6$
  - Position sensitive TPC, vertex position reconstruction with $\approx$5 mm (FWHM)
  - Higher resolution, higher luminosity, "cleaner" probe than solid targets
  - Resurgance of quasi-free scattering $(p, 2p)$ (p, pn) as spectroscopic tool
- DALI2$^+$
  - 226 NaI(Tl) detectors, large solid angle coverage
  - 10 % resolution 35 % efficiency at 1 MeV

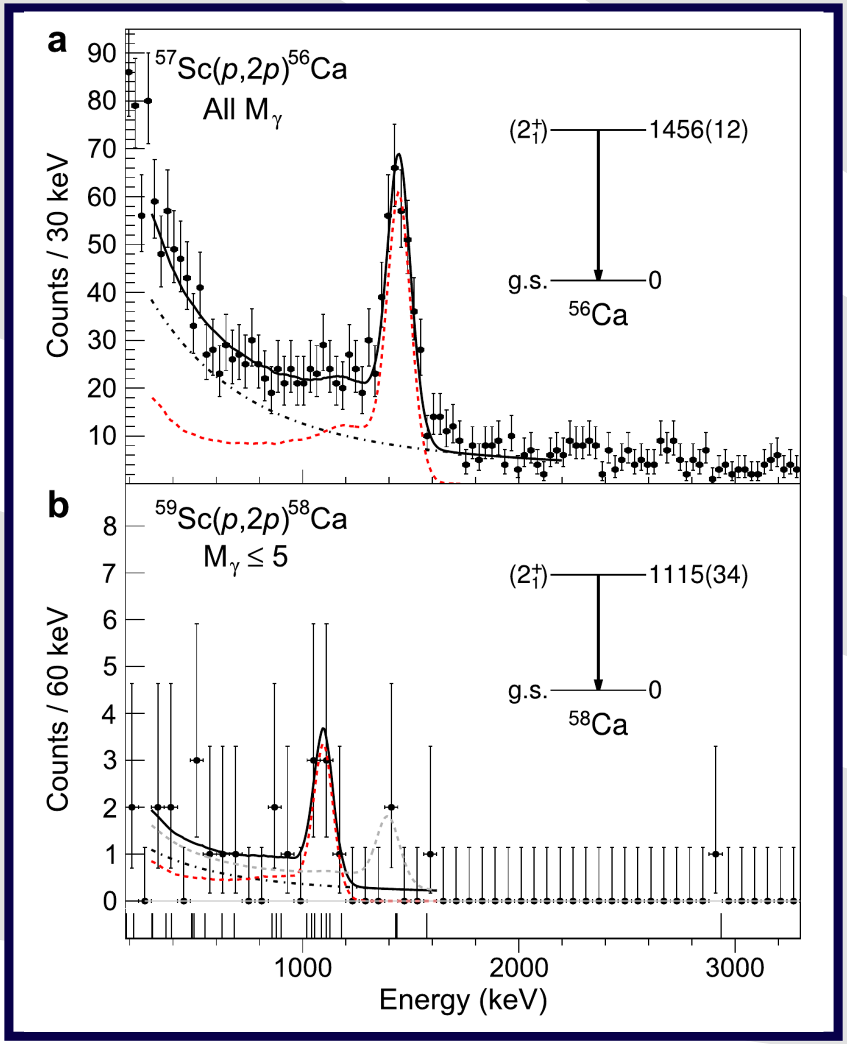
MINOS: A. Obertelli *et al.*, EPJA 50, 8 (2014), DALI2$^+$: S. Takeuchi *et al.*, NIMA 763, 596 (2014).

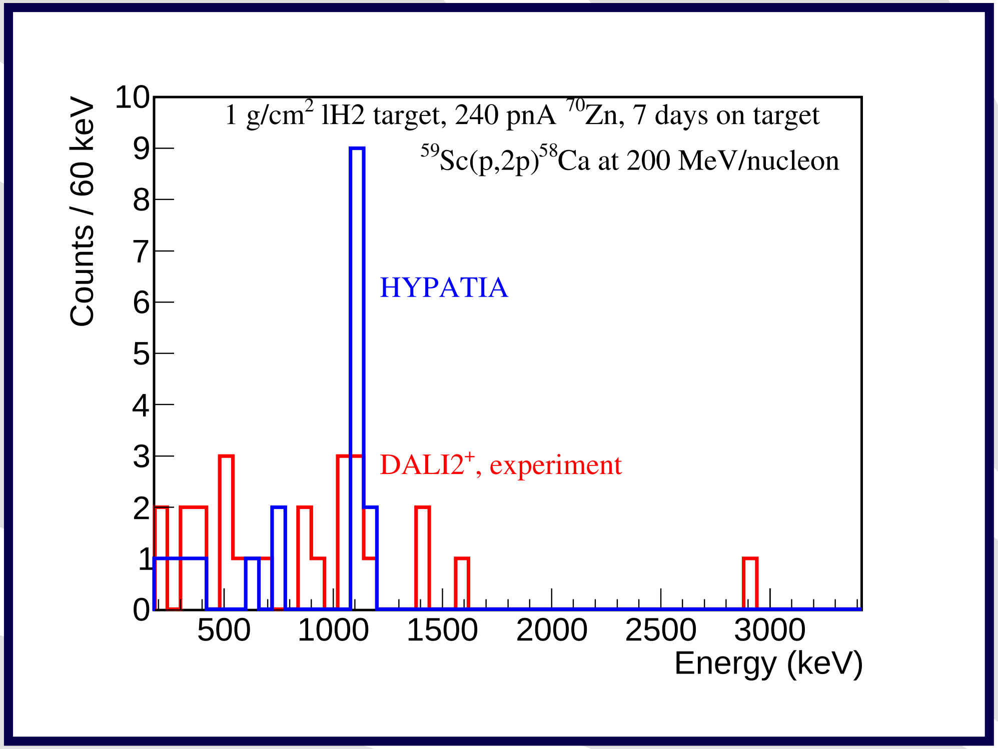
SEASTAR IV, V, VI: "The Final Frontier"



- 2 pμA ^{238}U @ 345MeV/nucleon (160 kW), ≈30 days beam time

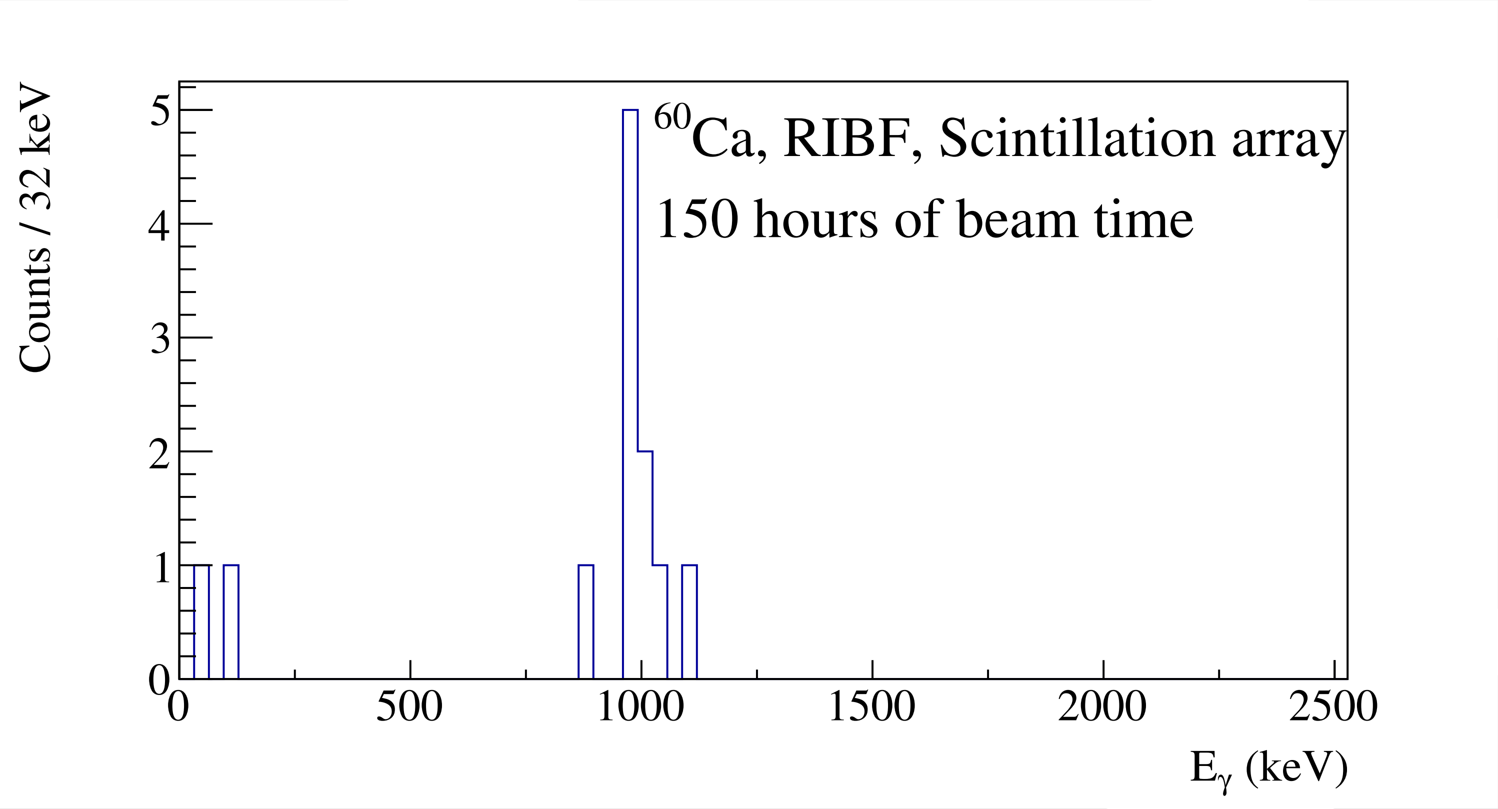
In-Beam γ-Ray Spectroscopy at the Isospin Limit





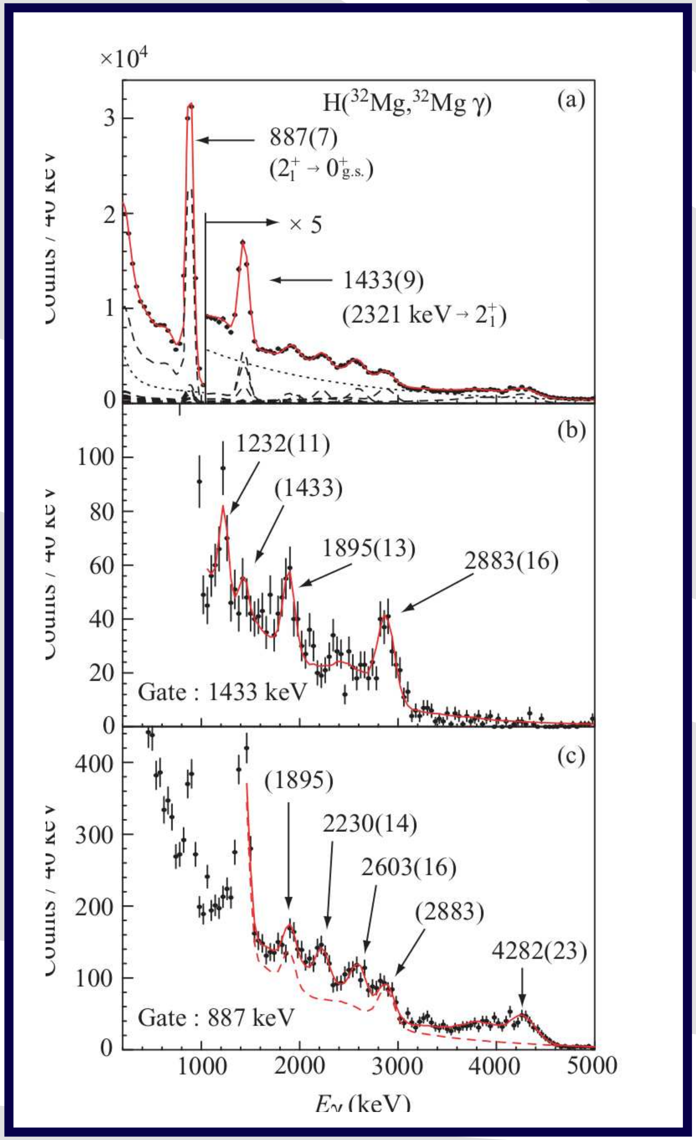
S. Chen *et al.*, PLB 843, 138025 (2023).

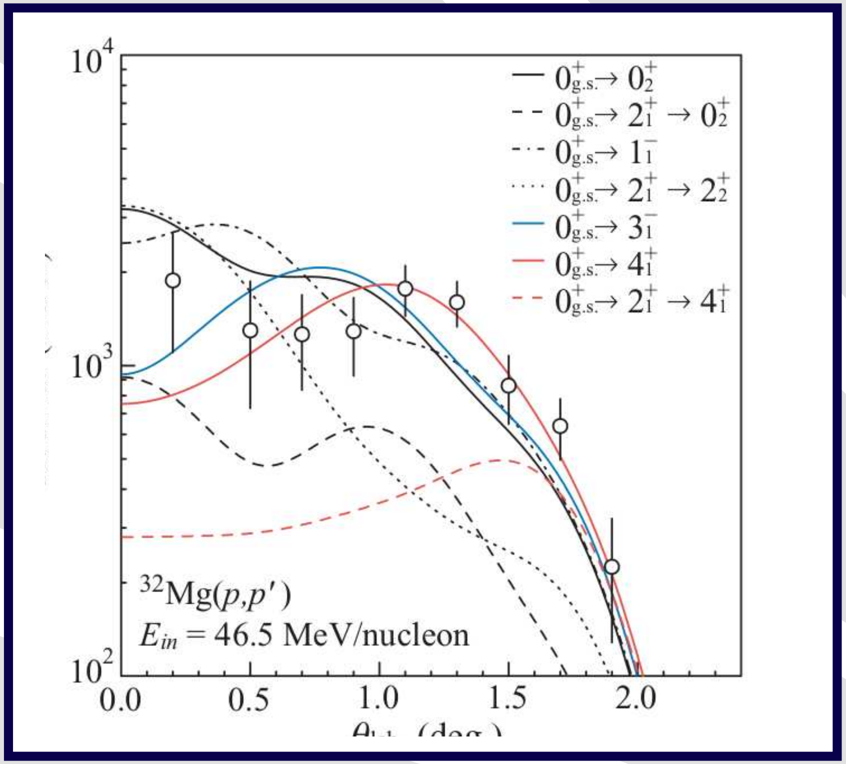
In-Beam γ-Ray Spectroscopy at the Isospin Limit



- 2 pμA primary beam of ^{238}U
- 0.11 pps of ^{61}Sc, from LISE++ including user cross section
- 150 mm lH2 target + 50 % transmission
- Cross section to 2^+ state from ^{57}Sc(p,2p)^{56}Ca reaction

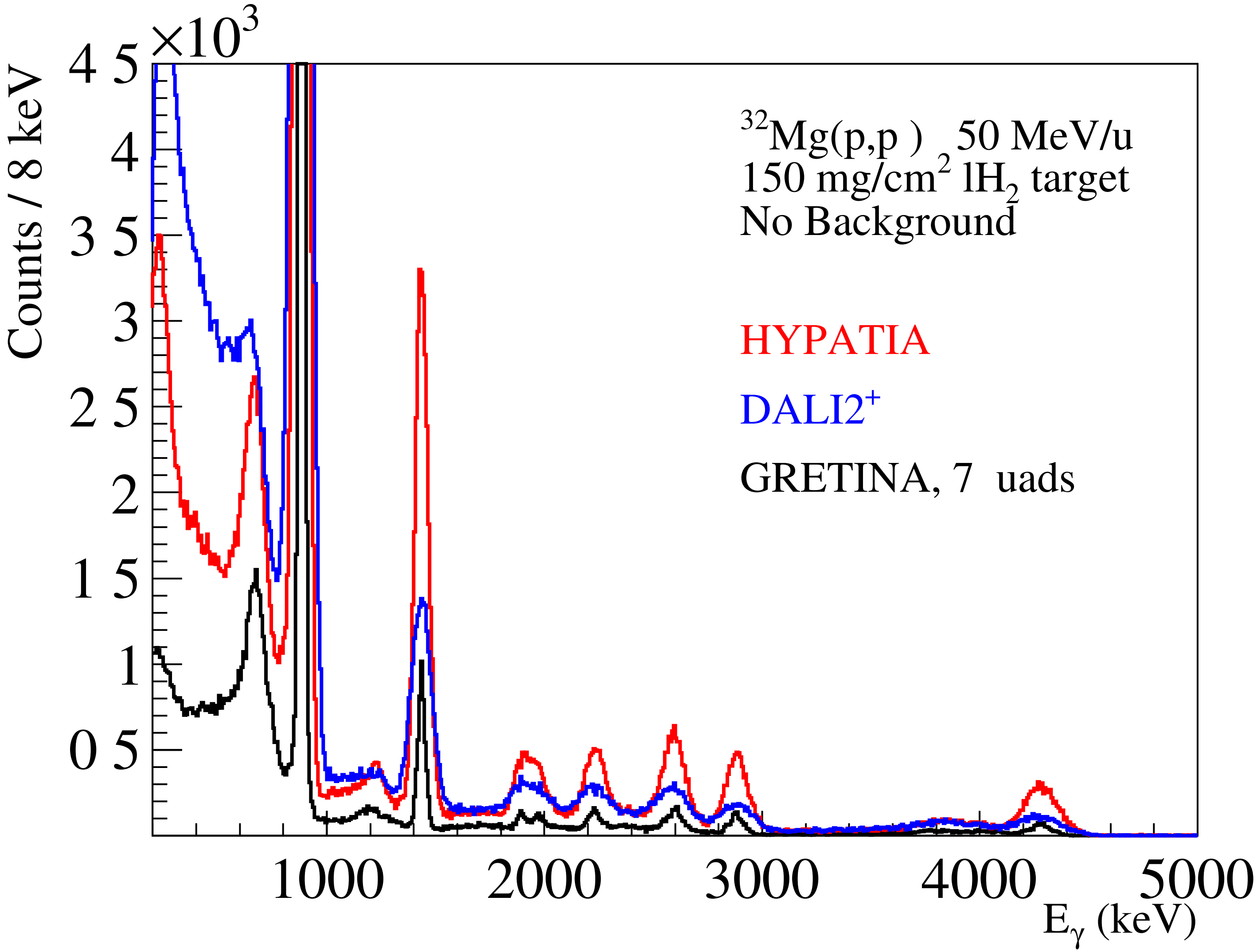
Inelastic Scattering on Liquid Hydrogen at 50 MeV/nucleon





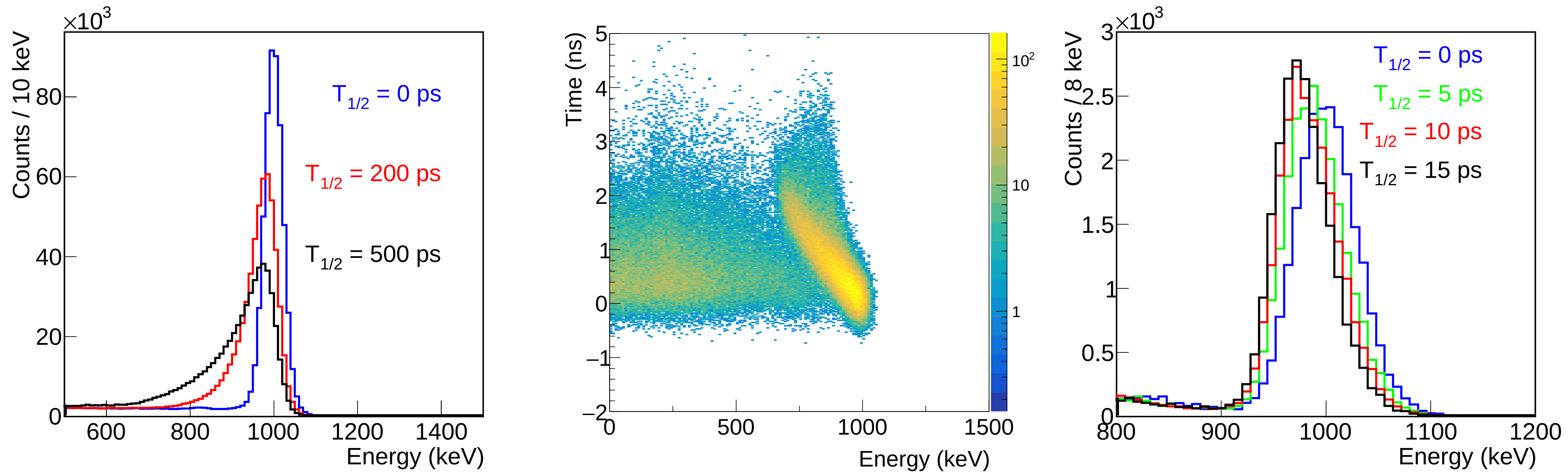
S. Takeuchi *et al.*, PRC 79, 054319 (2009).

Inelastic Scattering on Liquid Hydrogen at 50 MeV/nucleon



Cross sections from S Takeuchi et al , PRC 79, 054319 (2009)

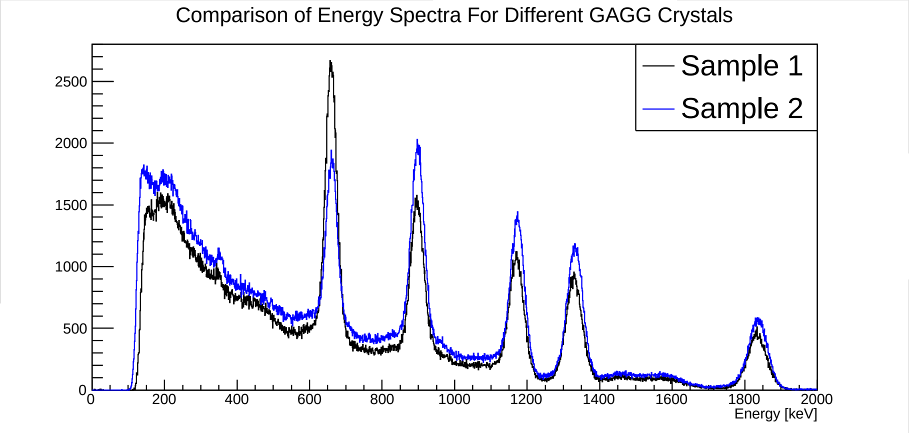
Lifetime Measurements With HYPATIA

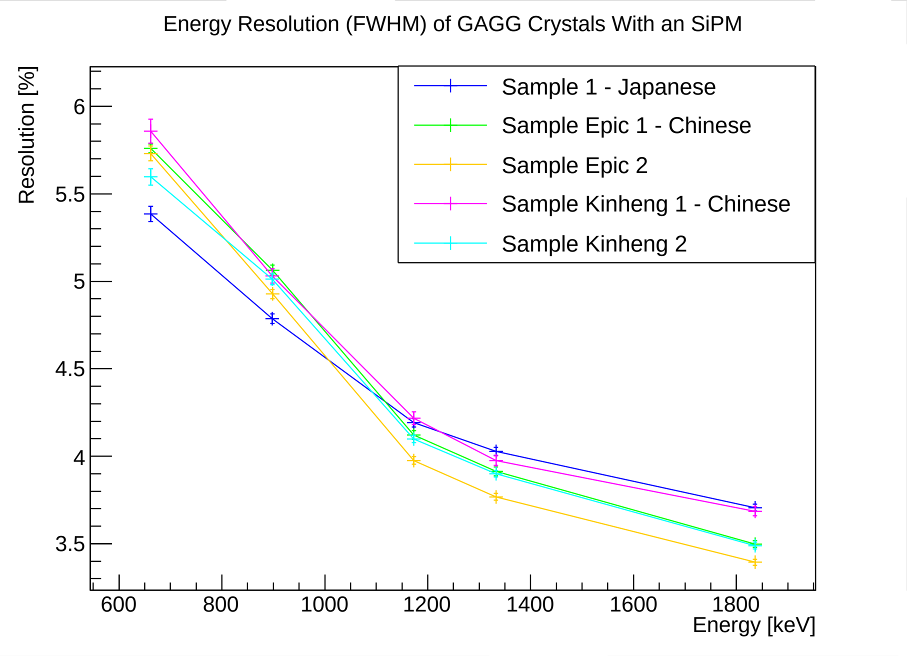


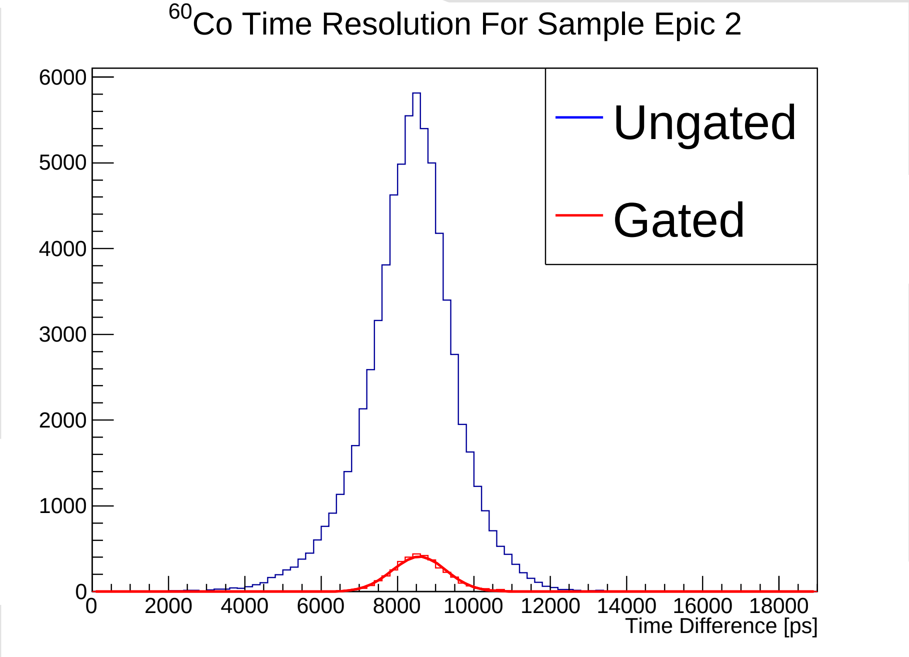
- Can measure different lifetime ranges simultaneously
- Short lifetimes with forward wall HR-GAGG (shown is ^{79}Cu on 700 mg/cm^2 Be)
- Long lifetimes with CeBr3 barrel
- Direct lifetime measurements from excellent $CeBr_3$ time resolution
  - Time relative to fast plastic scintillator (no γ–γ necessary)

Status and First In-Beam Tests

Status, HR-GAGG Crystals



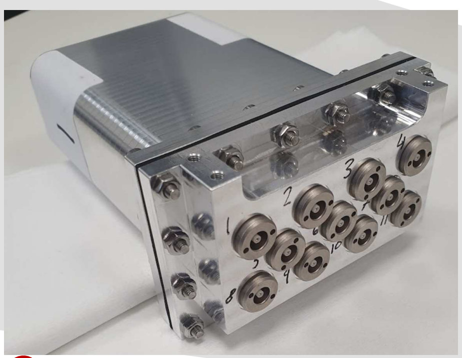




- Sample sizes of $25\times25\times75\text{mm}^3$
  - Front to match size of HAMAMATSU S13361-6050AE-04
- Comparable time and energy resolution for C&A, EPIC, Kinheng, CETG crystals
  - ≈4.5 % at 1 MeV (FWHM)
  - 1.6–1.7 ns for ^{60}Co (FWHM)

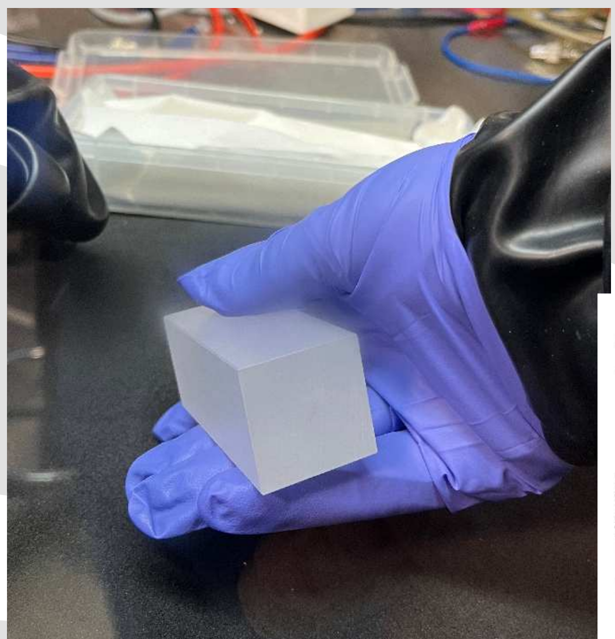
Status, CeBr3 Crystals

- 4 x Hellma Crystals (30 x 30 x 80 mm^3)
- 6 mm quartz window
- 4 x S14 (4x4) Hamamatsu SiPMs
- TMP37FT9Z Temperature sensor
- Wrapped and packaged by Scionix



- 1 x Hellma Crystals (30 x 30 x 80 mm ^{3})
- 1 x Epic Crystal (28 x 28 x 80 mm ^{3})
- 4x4 Hamamatsu S14 array - 1 mm quartz
- TMP37FT9Z Temperature sensor
- Wrapped and packaged in York

- γRIBF-UK:
  - 72 $CeBr_3$ crystals – 18 quad modules
  - Funded with 850k £ (160,000 k¥) for equipment, 3000k £ (5,550,000 k¥) total amount of grant
  - $\approx$ 4.5 % resolution at 662 keV
  - Wrap and package ourselves
    - comparison to commercial product from Scionix



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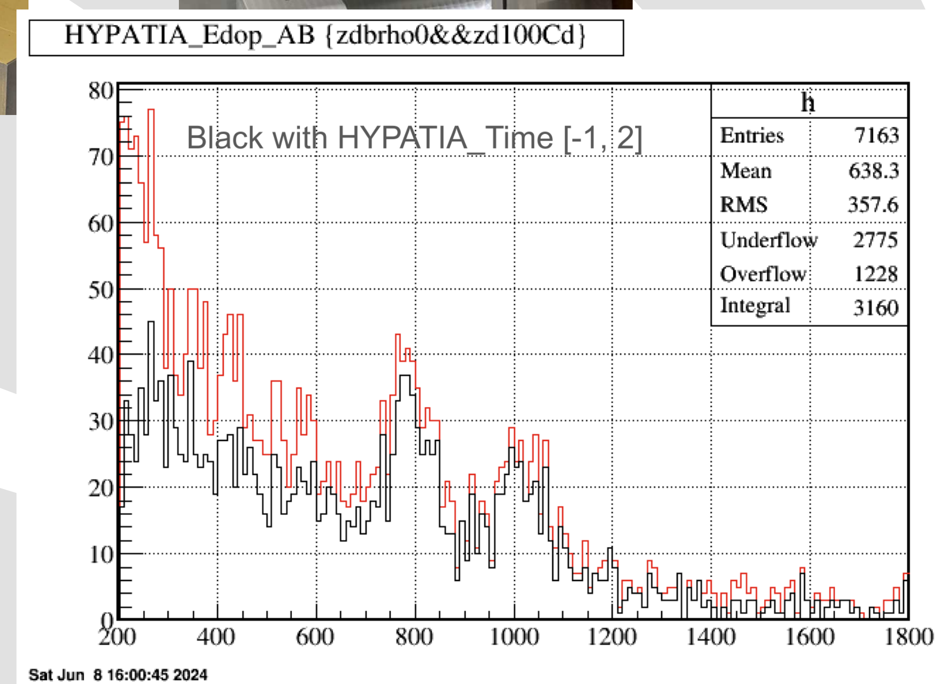
In-Beam Tests During NP2112-RIBF211 (June 2024)



- 2 x 2 HR-GAGG Crystals (25 x 25 x 75 mm^3)
- 4 x S13 (4x4) Hamamatsu SIPMs
- In-house developed power supply
- Temperature compensated

- Proton-rich nuclei around ^{100}Sn at 210 MeV/nucleon on 34 mm LH_2 target
- Two 2$\times$2 clusters of HR-GAGG, one 2$\times$2 $CeBr_3$, one 1$\times$2 $CeBr_3$
- Replacement of 4 DALI2$^+$ crystals

Summary

Summary

- Cannot compete with FRIB and GRETA+HRS for highest energy resolution in-beam γ spectroscopy with thin targets
  - But I don't think we have to
  - Focus on obtaining clean spectra
    - Excellent time resolution and superior P/T critical
- HYPATIA Project's construction proposal (NP2412-RIBF244) was rated "S" in last NP-PAC meeting
  - Anticipate to have array ready in 2031
  - Total costs are estimated to be around 7–9 Mio USD
- Partially funded
- First $CeBr_3$ and HR-GAGG prototype crystals delivered and tested
  - Time and energy resolution meet requirements
  - First in-beam tests performed

Thank You!

Backup Slides

γRIBF-UK: Scintillator-Based High-Resolution γ-Ray Spectrometer at RIBF

- 72 $CeBr_3$ crystals – 18 quad modules
- Readout out with SiPMs strategically placed along the crystal to increase position sensitivity
- Electronics
- Simulation effort
- Mechanical design support for the whole array
- Funded with 850k £ (160,000 k¥) for equipment, 3000k £ (5,550,000 k¥) total amount of grant

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