Recent Results from GRETINA and the Status of GRETA

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17th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics – CGS17

July 18, 2023

Outline

- Recent Physics Campaigns of GRETINA
  - GRETINA campaigns with fast beams
  - First Experiments at FRIB
- Status of GRETA
  - Overview of GRETA systems
  - Project status
  - Transition from GRETINA to GRETA
- Summary and Outlook

GRETINA

Gamma-Ray Energy Tracking In-beam Nuclear Array

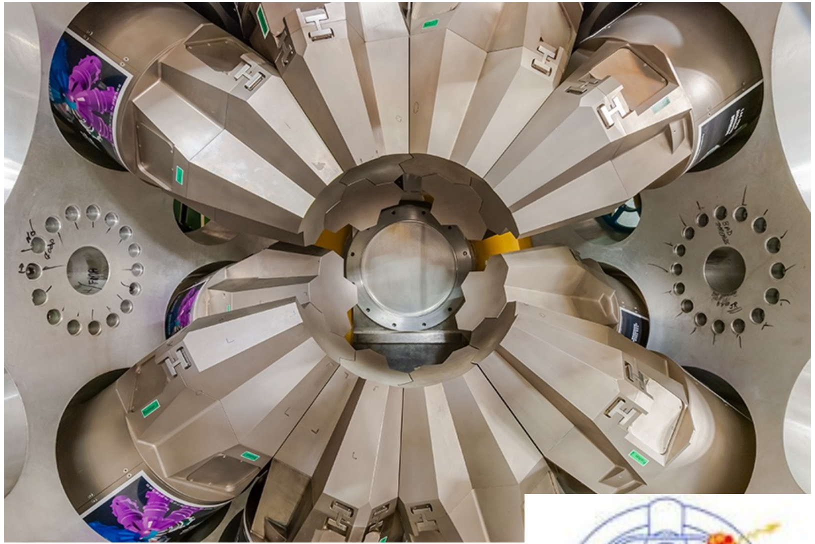
Between 2003 and 2011, the US low-energy nuclear physics community constructed GRETINA, a 1π tracking detector employing the same segmented detector and signal decomposition technology as GRETA.

GRETINA was a $20M project funded by US DOE-Nuclear Physics Office

- Covered ~¼ of a sphere with 7 Quad Detector Modules

GRETINA science operations at MSU and ANL have demonstrated the technology and scientific impact of a γ-ray tracking array.

Added Quad Detector Modules – total of 12 (+ 1 spare)

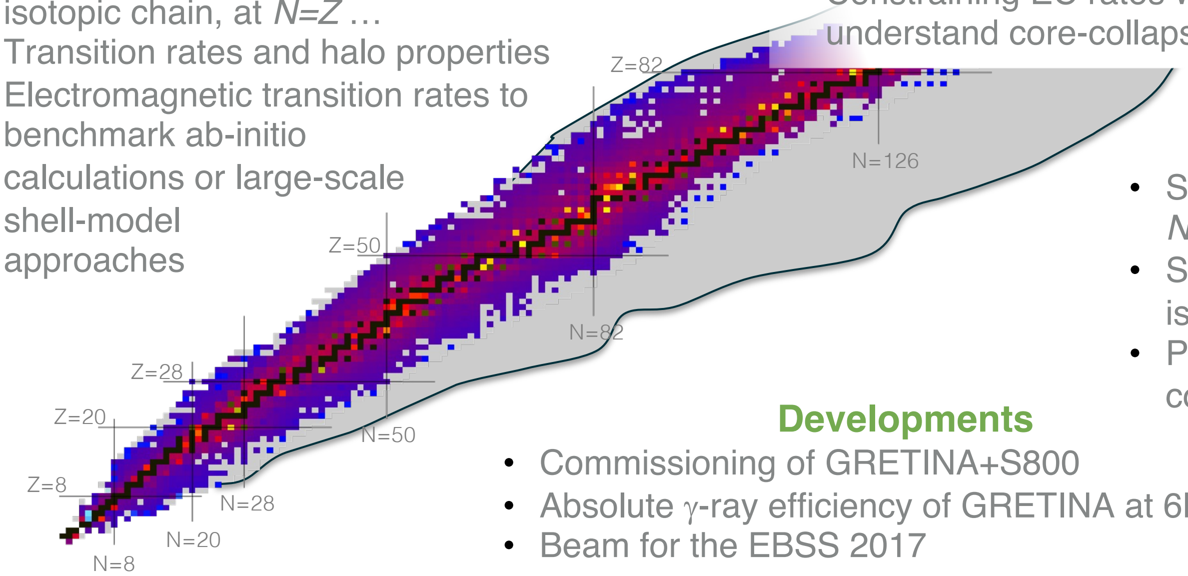


History of GRETINA at NSCL

62 Experiments in 3 Campaigns

Collectivity

- Shape coexistence in *N*=20, 28, 40 Island of Inversion
- Shape changes and collectivity along the Ni isotopic chain, at *N*=*Z* …
- Transition rates and halo properties
- Electromagnetic transition rates to benchmark ab-initio calculations or large-scale shell-model approaches



Nuclear Astrophysics

- Precise energy measurements of resonances important for (p,γ) captures in the rp process
- Angle integrated measurement of (d,n) and (d,p) transfer reactions +mirror symmetry to constrain p capture rates for nucleosynthesis processes
- Constraining EC rates with (t,^{3}He+γ) CEX reactions to understand core-collapse supernovae

Nuclear Shell Evolution

- Single-particle structure at *N=20*, *N*=28, *N*=40 from direct reactions
- Shell evolution along the Ca, Ni, Zn, … isotopic chains from direct reactions
- Probing core excitations and shell-model cores with different methods

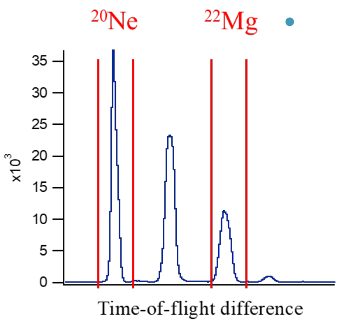
Developments

- Commissioning of GRETINA+S800
- Absolute γ-ray efficiency of GRETINA at 6MeV
- Beam for the EBSS 2017

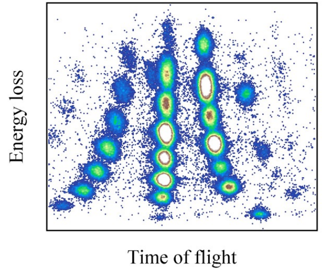
The Experimental Setup at NSCL and FRIB

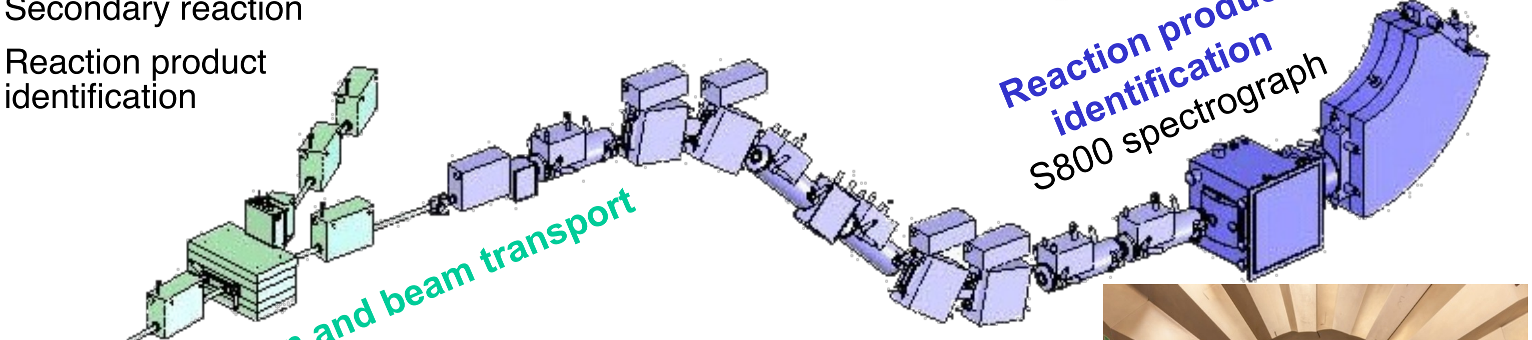
GRETINA + S800 (+ LH_2 target, + LENDA, …)

- Identification and beam transport
  - Stopped beam experiments
  - Fast beam experiments
    - Secondary reaction
    - Reaction product identification



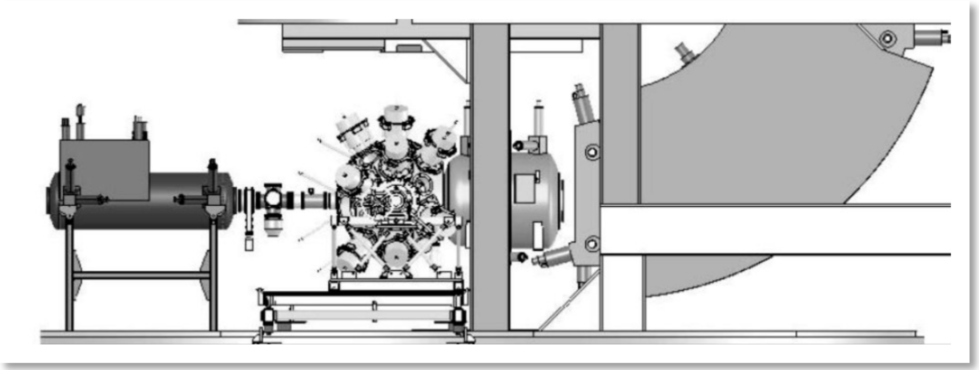
Reactions induced by ^{20}Ne

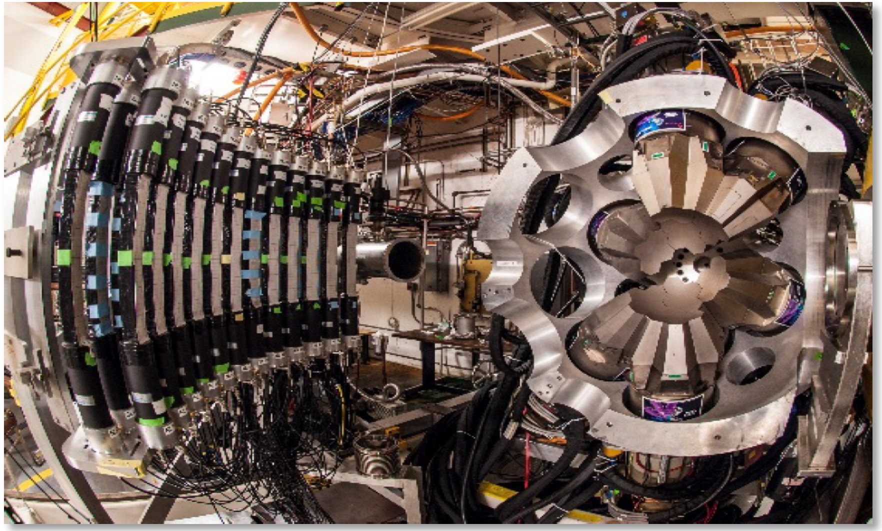


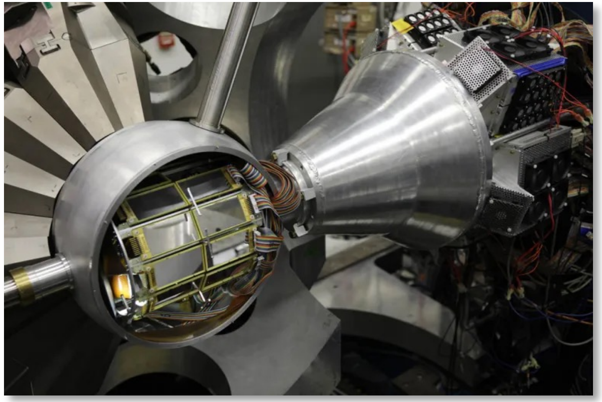


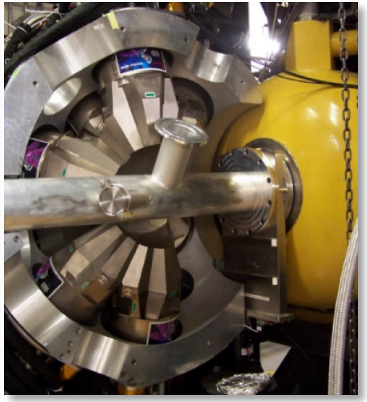
The Experimental Setup at NSCL and FRIB

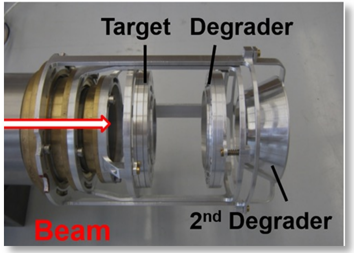
GRETINA + S800 (+ LH_2 target, + LENDA, …)









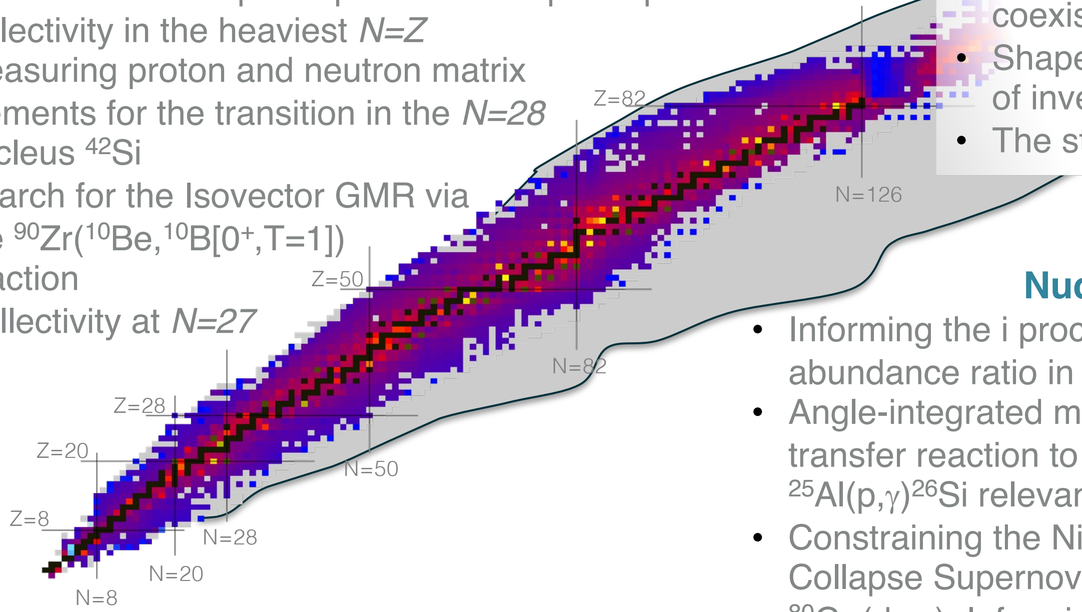


First GRETINA @ FRIB Campaign

14 Experiments Approved in 2 FRIB PACs

Collectivity

- Quadrupole Collectivity at the Boundaries of the *N*=40 Island of Inversion
- Evolution and isospin-dependence of quadrupole collectivity in the heaviest *N=Z*
- Measuring proton and neutron matrix elements for the transition in the *N=28* nucleus ^{42}Si
- Search for the Isovector GMR via the ^{90}Zr(^{10}Be,^{10}B[0^+,T=1]) reaction
- Collectivity at *N=27*



Nuclear Shell Evolution

- Single-neutron structure at the heart of the *N=28* island of inversion
- Halo formation in neutron-rich carbon isotopes
- Understanding shape and configuration coexistence at *N=28*
- Shape coexistence at the heart of the *N=40* island of inversion
- The structure of light tin isotopes

Nuclear Astrophysics

- Informing the i process: constraining the As/Ge abundance ratio in a metal poor star via ^{75}Ga(d,pγ)^{76}Ga
- Angle-integrated measurement of the d(^{25}Al,nγ)^{26}Si transfer reaction to probe resonance strengths in ^{25}Al(p,γ)^{26}Si relevant for ^{26}Al production in classical novae
- Constraining the Ni-Cu cycle in X-ray bursts and Core Collapse Supernovae: Spectroscopy of ^{60}Zn
- ^{80}Ge(d,pγ): Informing weak r-process neutron capture

FRIB Experiments to Date

6 Experiments Have Taken Beam So Far

- Shape coexistence in neutron-rich Cr isotopes
  - The *N=40* Island of Inversion
- Nuclear structure toward ^{100}Sn
  - One-neutron knockout to figure out level orderings
- The curious case of $^{40,42}Si$
  - Competing configurations in the *N*=28 Island of Inversion
  - Measuring proton and neutron matrix elements for the $0^+_{gs} \rightarrow 2^+_1$ transition in the deformed neutron-rich N=28 nucleus
- Evolution and isospin-dependence of quadrupole collectivity in the heaviest N=Z systems
- Constraining the Ni-Cu cycle
  - Spectroscopy of ^{60}Zn

Led by FRIB, U. Surrey and FSU (Gade, Tostevin, Weidenhoever et al.)
with LBNL, LLNL, and Ursinus College

Shell Evolution at *N*=28

Testing Model Descriptions of ^{42}Si

- Motivation – theory has been unable to describe ^{42}Si and different models disagree with each other
- Approach – measure ^{44}S(-2p)^{42}Si reaction
- Initial beam time did not go to plan – had to move to Plan B, namely ^{42}S(-2p)^{40}Si reaction

PHYSICAL REVIEW LETTERS **122,** 222501 (2019)

Is the Structure of ^{42}Si Understood?

A. Gade,[1,2] B. A. Brown,[1,2] J. A. Tostevin,[3] D. Bazin,[1,2] P. C. Bender,[1,*] C. M. Campbell,[4] H. L. Crawford,[4] B. Elman,[1,2] K. W. Kemper,[5] B. Longfellow,[1,2] E. Lunderberg,[1,2] D. Rhodes,[1,2] and D. Weisshaar[1]

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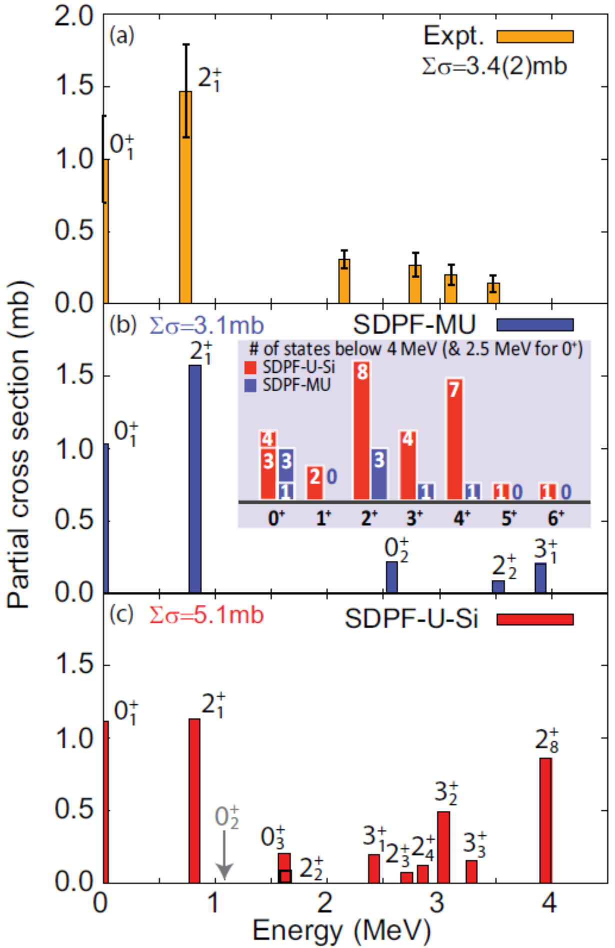
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, California 94720, USA*
[5]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*



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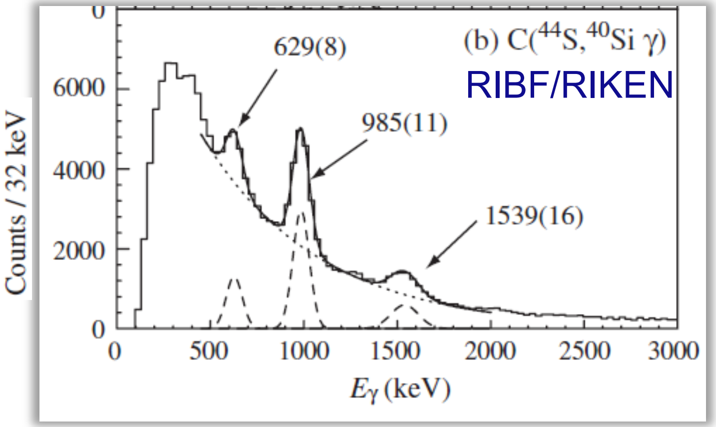
- Motivation – theory has been unable to describe ^{42}Si and different models disagree with each other
- Approach – measure $^{44}S(-2p)^{42}Si$ reaction
- Initial beam time did not go to plan – had to move to Plan B, namely $^{42}S(-2p)^{40}Si$ reaction
- Very rich data set
  - Interesting discrepancy between two different shell-model effective interactions and IM-SRG
  - Similar to the case of ^{42}Si where obviously the drivers of shell evolution are not understood

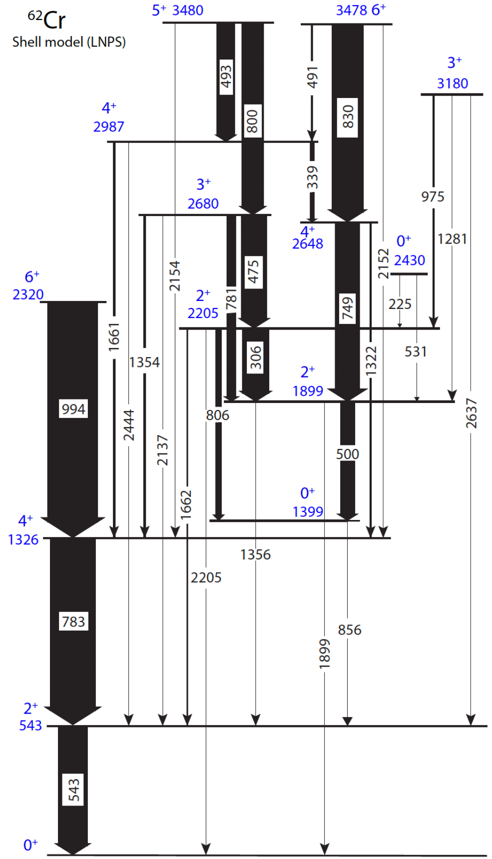


Led by FRIB and UNC (Gade, Janssens et al.) with ANL, LBNL, LLNL, and MSU

Shape Coexistence in the N=40 Island of Inversion

Identifying the Excited 0^+ Band-head in ^{62}Cr

- Longitudinal momentum distributions of ^{62}Cr in ^{9}Be(^{64}Fe,^{62}Cr+γ) are sensitive to the final state total angular momenta
- 4^+_1 and 6^+_1 states prove approach



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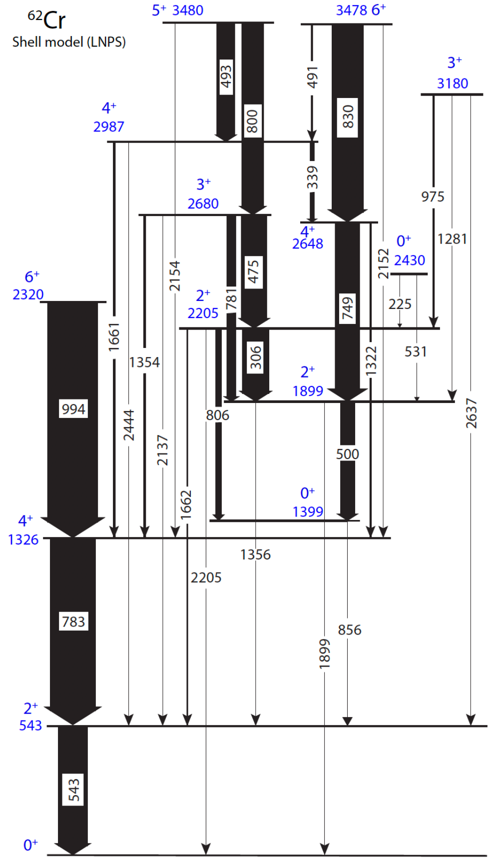
- 4^+_1 and 6^+_1 states prove approach; second 0^+ located



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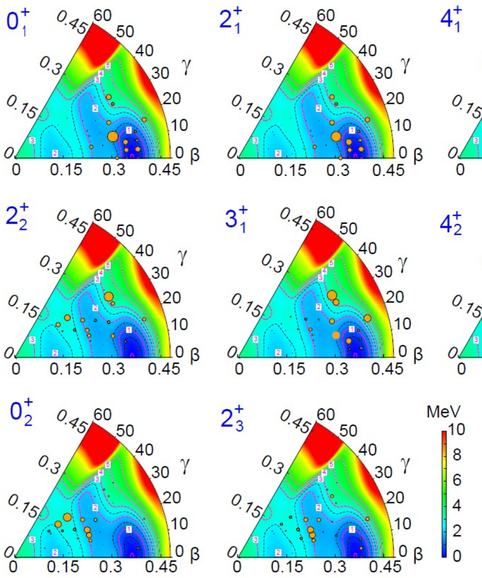
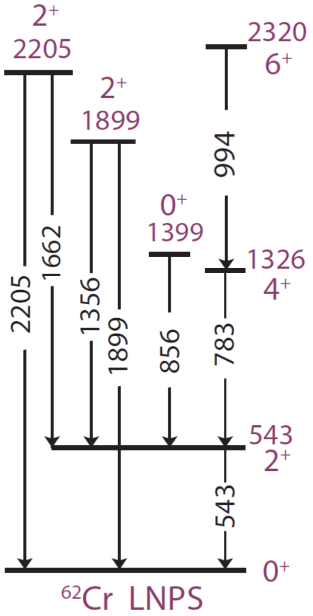
Shape Coexistence in the *N*=40 Island of Inversion

Identifying the Excited 0^+ Band-head in ^{62}Cr

- LNPS shell model effective interaction describes well the proposed level scheme
- DNO-SM study shows that triaxiality degree of freedom is important for γ band on top of the 2^+_2 and the band on top of 0^+_2



Theory:
Dao and Nowacki, PRC **105**, 054314 (2022).



Led by U. Tenn. (Jones et al.) and FRIB with LBNL, LLNL, ORNL, and Rutgers.

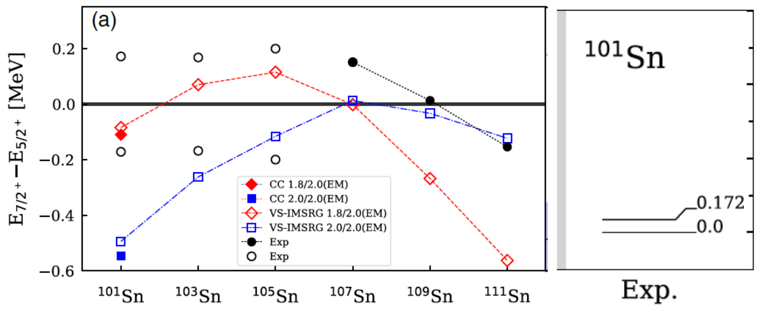
Shell Evolution Towards ^{101}Sn

The Structure of Light Sn Isotopes

The energy splitting between the ground and first excited states in the light, odd-mass tin isotopes is small, between 151 keV (^{107}Sn) and

200 keV (^{105}Sn). It is expected that the order of these states in ^{101}Sn will be switched, with respect to $^{103, 105, 107}$Sn.

One way to make spin and parity assignments for these states is to measure the momentum distributions in coincidence with γ rays depopulating the first excited state following a knockout reaction → allows to distinguish the involved *g* and *d* neutron orbitals.

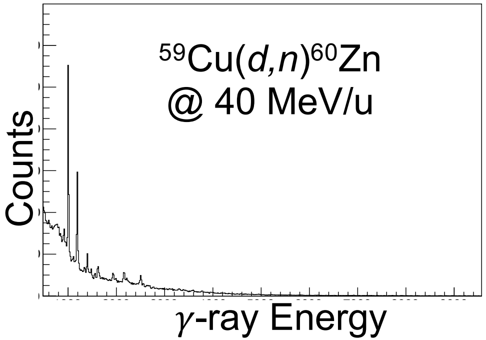


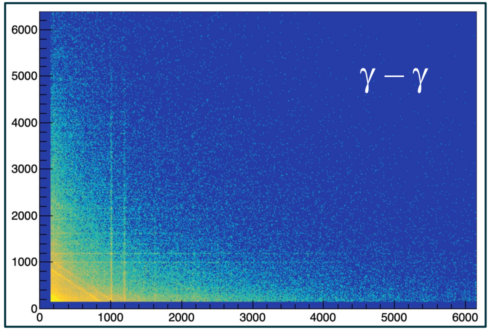
Spectroscopy of ^{60}Zn

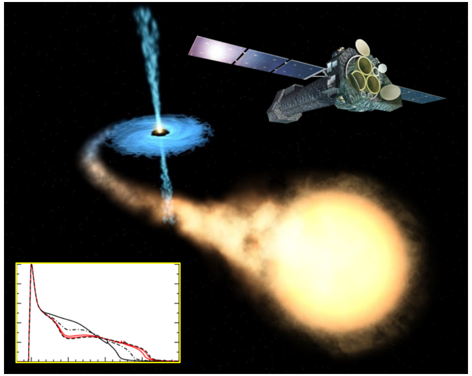
Constraining the Ni-Cu cycle in X-ray bursts and Core Collapse Supernovae

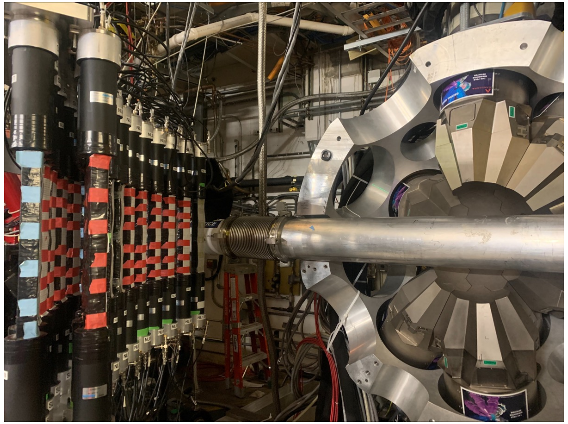
The ^{59}Cu(p,g) reaction is expected to strongly influence the shape of X-ray burst light curves.

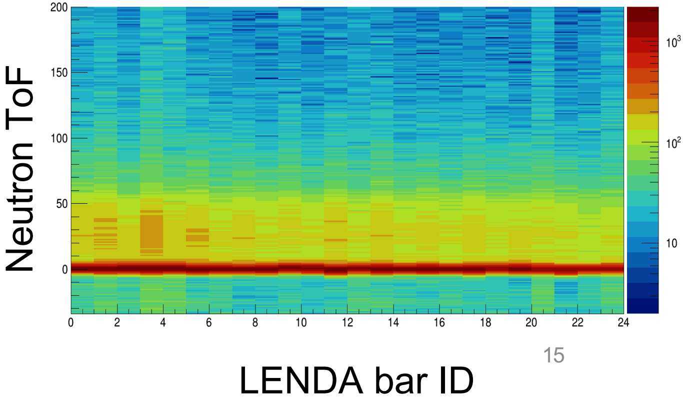
This process was studied via (d,n) transfer at FRIB using GRETINA, LENDA and the S800 spectrometer.











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The Case for GRETA

The GRETA Physics Case Mirrors that of FRIB

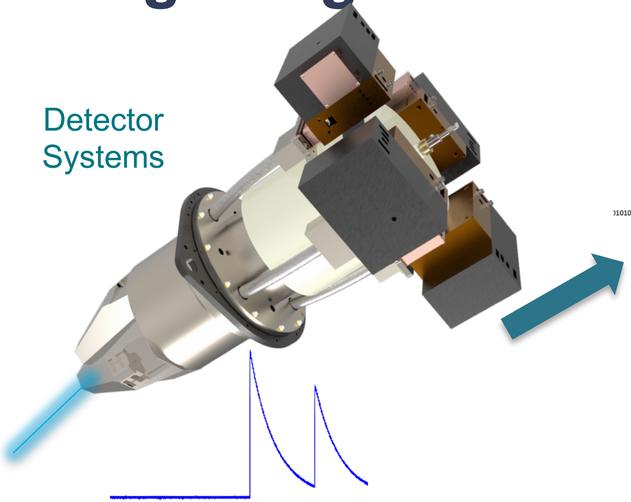
Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Intellectual challenges from NRC Decadal Study 2013			
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?
1. Shell structure ✓ 2. Superheavies ✓ 3. Skins ✓ 4. Pairing 5. Symmetries ✓ 6. Equation of state 13. Limits of stability ✓ 14. Weakly bound nuclei ✓ 15. Mass surface ✓	1. Shell structure ✓ 6. Equation of state 7. r-Process ✓ 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 13. Limits of stability ✓ 15. Mass surface 16. rp-Process 17. Weak interactions ✓	12. Atomic electric dipole moment ✓ 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship ✓

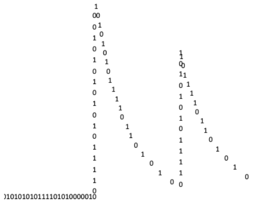
✓ indicate topics where GRETA will be used.

17 Benchmark programs introduced by the NSAC Rare-Isotope beam task force (2007).

Integrating the Subsystems of GRETA

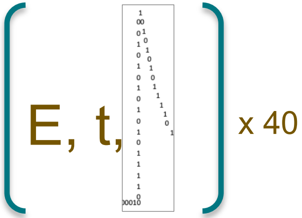
Detector Systems





- Continuous 100MHz digitization of **40** preamplifier signals **per crystal**

Electronics Systems



- FPGA-based energy filters, event selection in response to physics triggers

Integrating the Subsystems of GRETA

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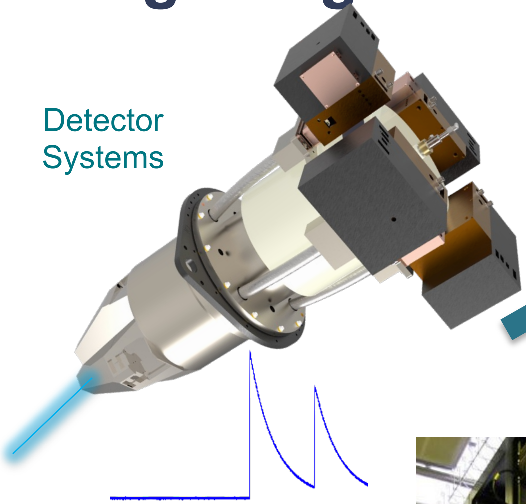

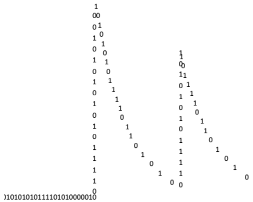

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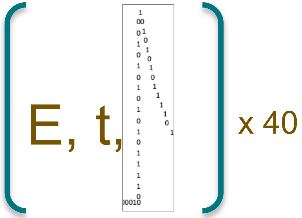

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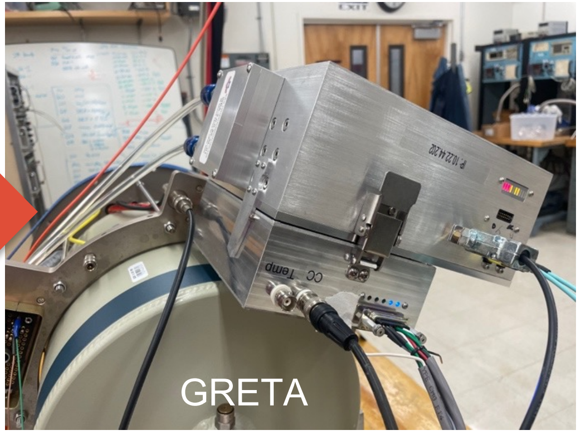

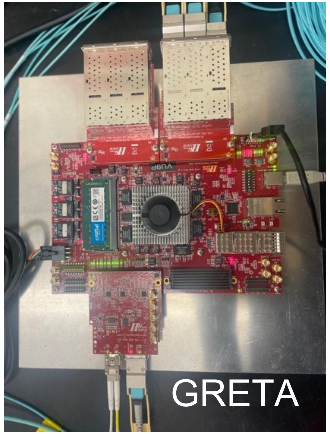

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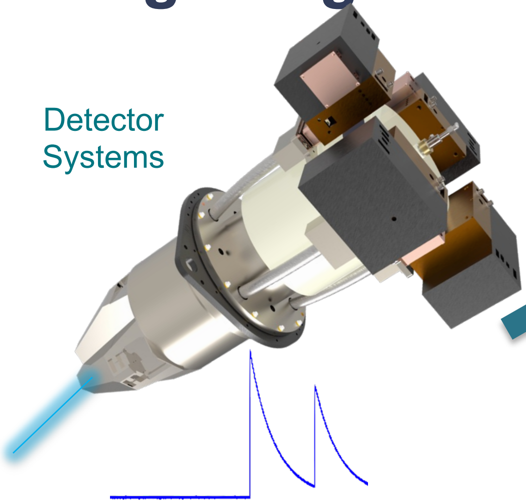

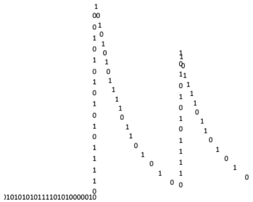

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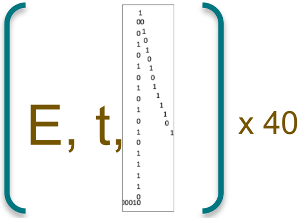

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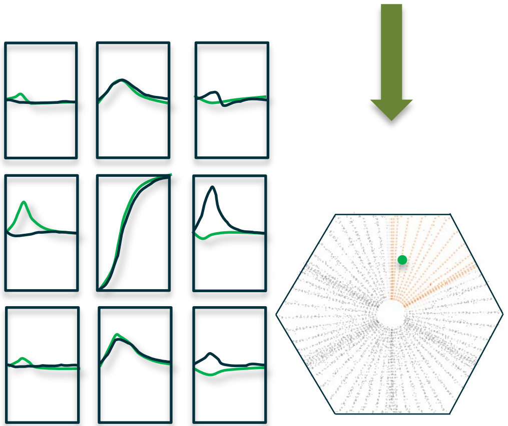

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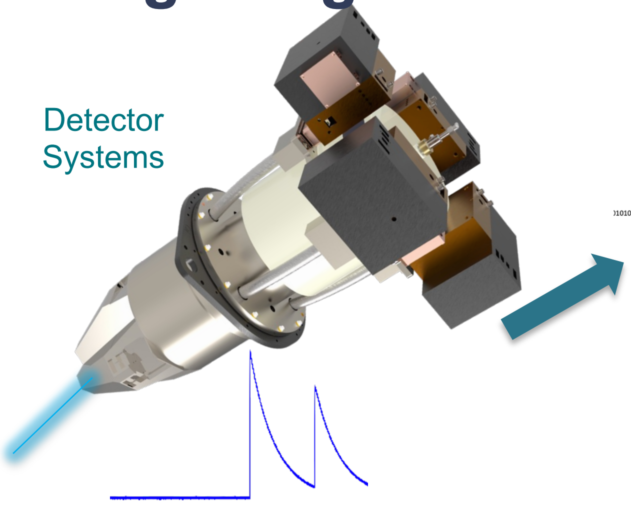

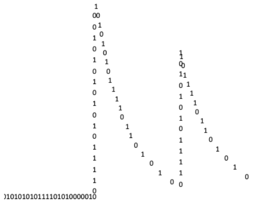

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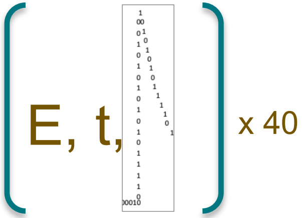

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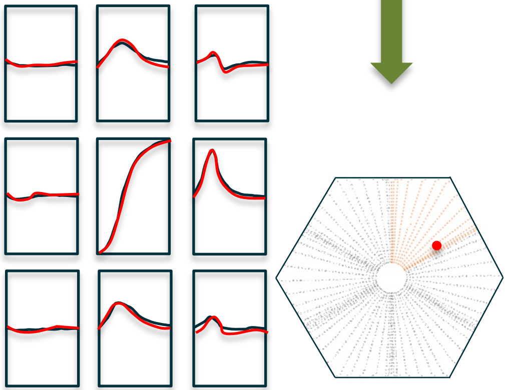

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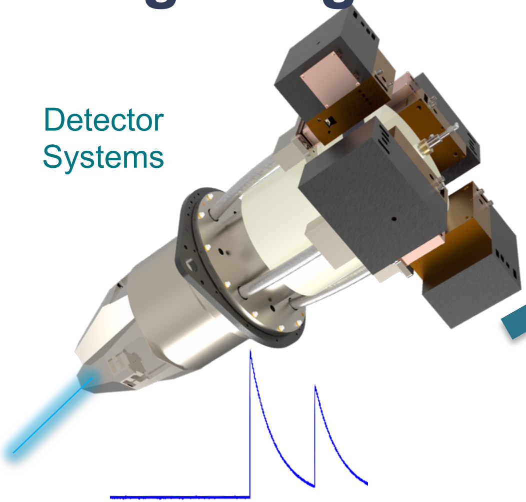

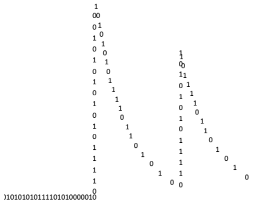

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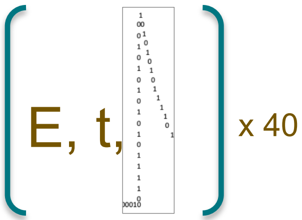

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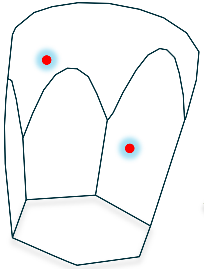
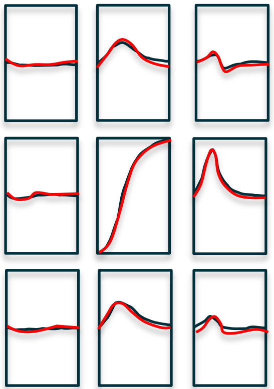
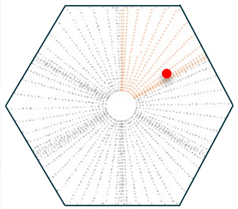
Computing Systems



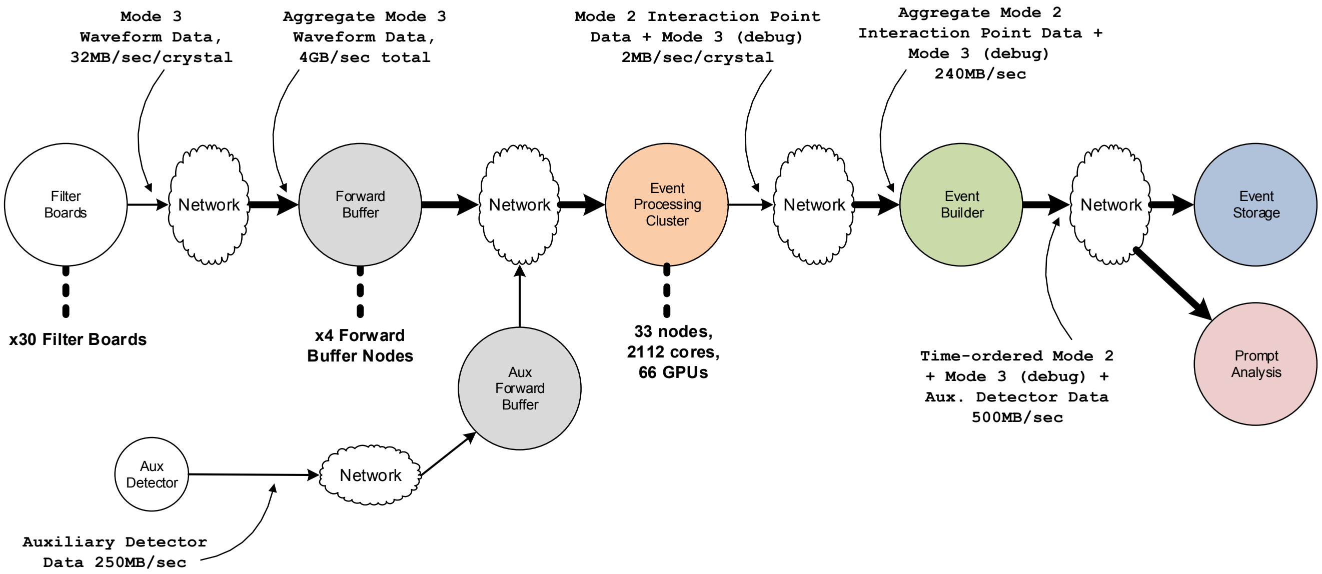
$$\left[E,\ t,\ (x,\ y,\ z)_{crystal}\right]_n$$





GRETA Computing Systems

Pipeline-Based Network Architecture Enables Cutting-Edge Performance



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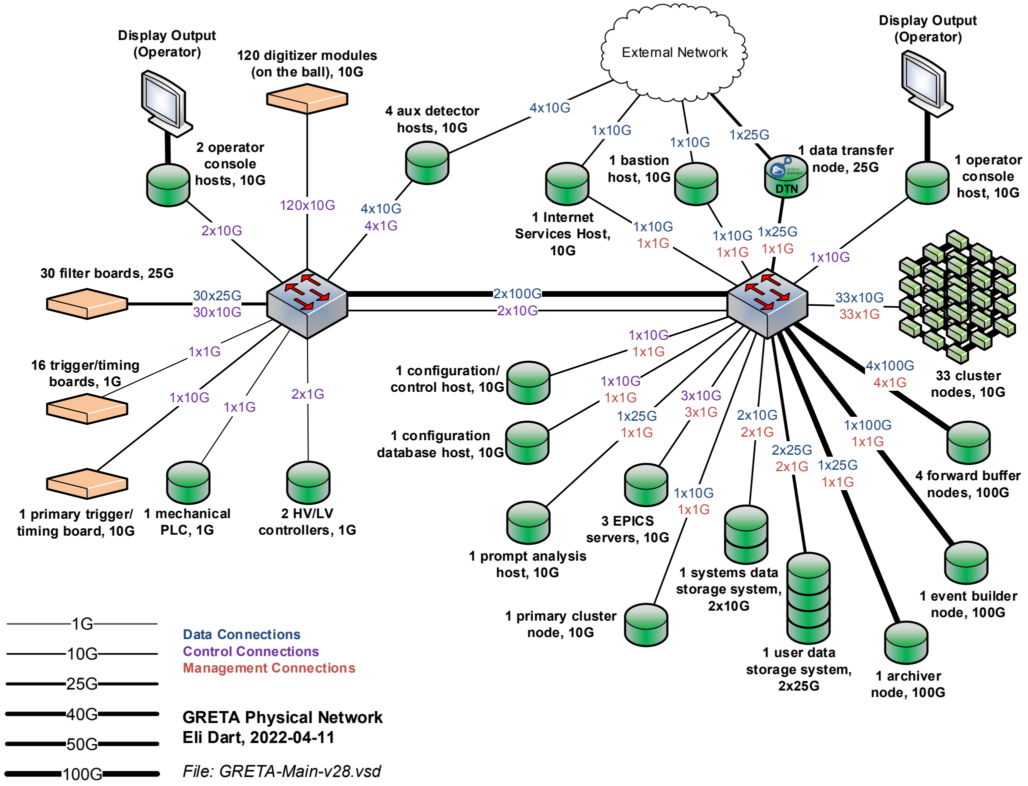
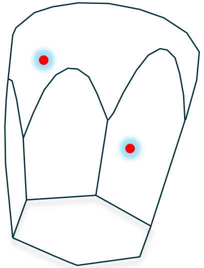


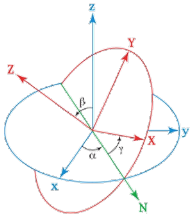
- 300TB full SSD storage array improves ability to sort online, move data quickly off the cache to the DTN
- High-performance computing cluster enables in-line compression and will support 500k signal decomposition calculations per second

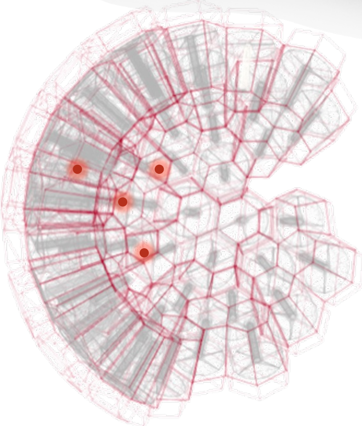
Integrating the Subsystems of GRETA

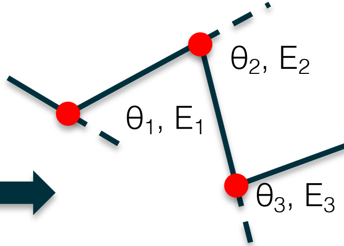


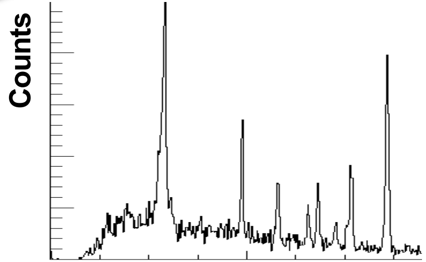
$\left[E,\ t,\ (x,\ y,\ z)_{crystal}\right]_n$

Mechanical Systems





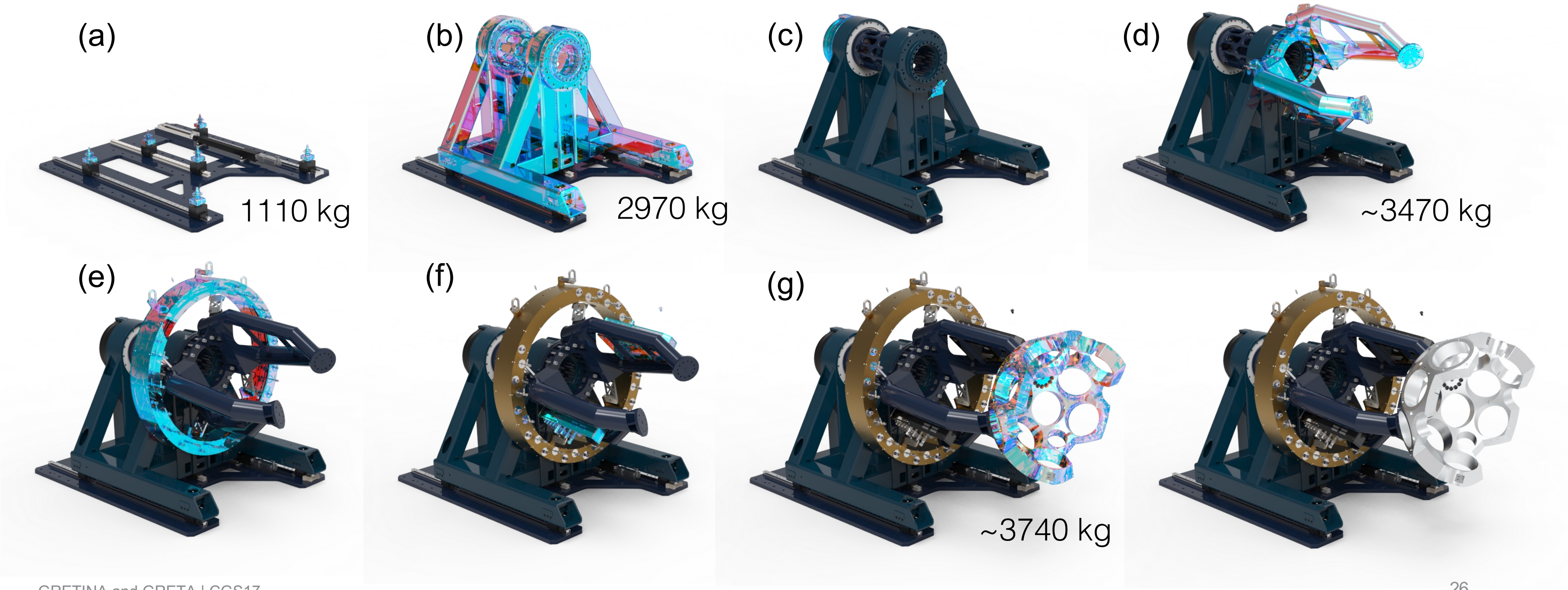




- Detectors located absolutely in space to +/- 0.4 mm

GRETA Mechanical Systems

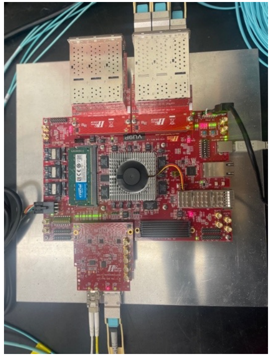
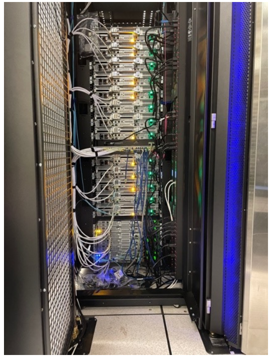
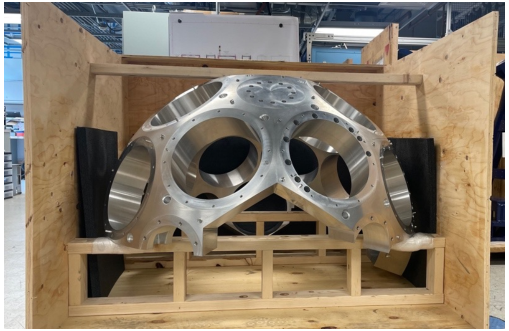
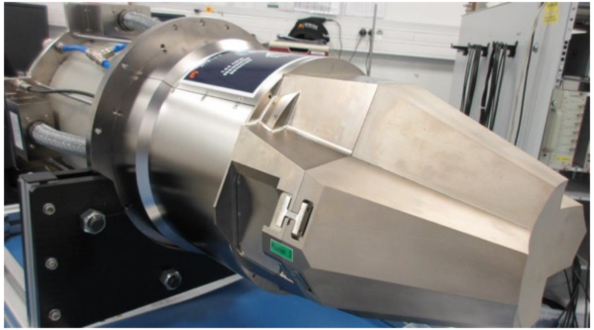
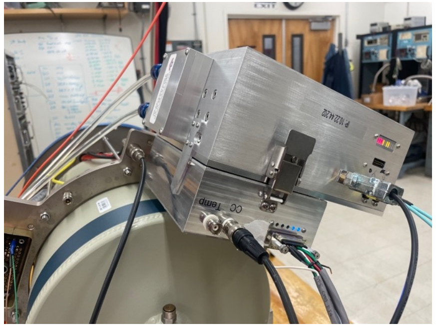
Motor-driven Translation + Rotation, LN and Two Closed-Loop Cooling Systems



Technical Progress

16/18 Detectors, 95% Complete Mechanical, Integration Starting Now



Beginning of GRETA Operations at FRIB

GRETA will be Delivered to FRIB in CY2025

System Assembly & Test Complete
6/2024

CD-4A EF
10/2024

Shipment to FRIB
1/2025

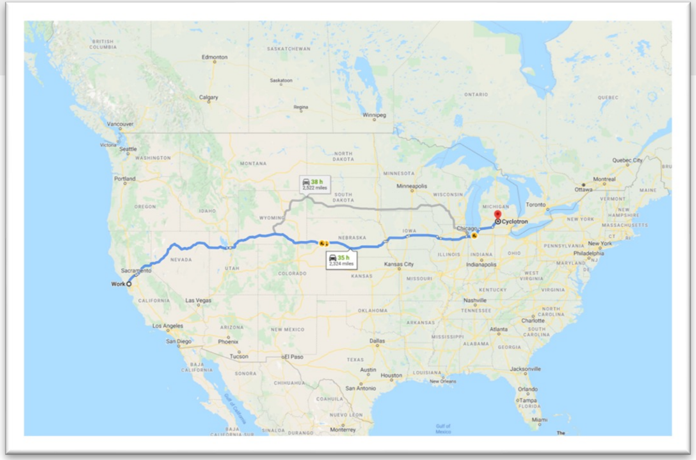
2024 | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | **2025**

GRETA Pre-Operations

- **Technical Training at LBNL** — 6/2024 - 9/2024

GRETA Pre-Operations

- **Technical Training at LBNL** — 10/2024 - 10/2024
- **Disassembly and Packing at LBNL** — 10/2024 - 12/2024
- **Shipment Final Preparations** — 12/2024 - 1/2025



Summary

- GRETINA has completed a total of 6 scientific campaigns at NSCL and ATLAS; the 7^{th} campaign, and the first FRIB campaign is ongoing
- With over 100 publications since the start of operations 12 years ago, the scientific impact of GRETINA is unquestionable
- GRETA builds on the success of GRETINA with updated electronics and computing systems to enhance performance, and a full 120 HPGe crystals covering ~80% of the 4π solid angle
- GRETA is planned for delivery to FRIB in 2025 for first operations after integration with the GRETINA Quad detector modules

Thank You

And a special thanks to A. Gade and G. Lotay for sharing material from their experiments!