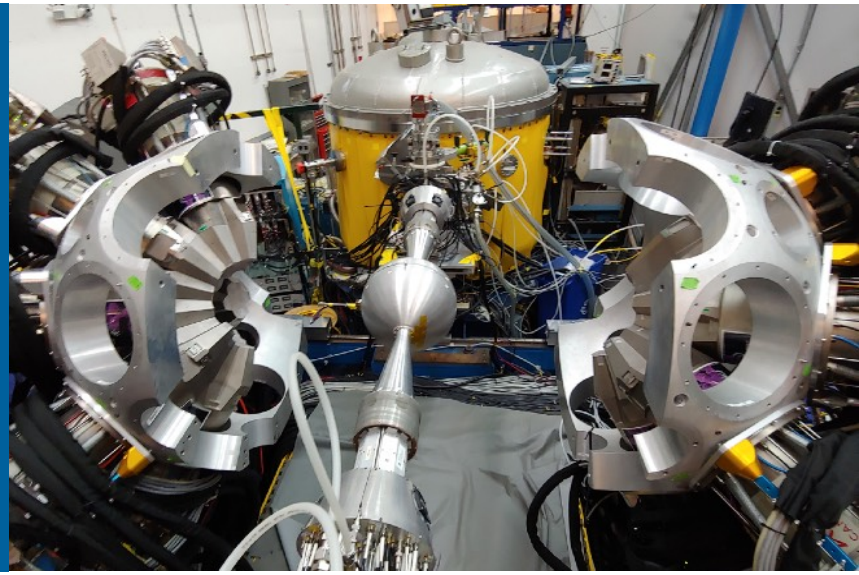
NUSTAR 2020 WORKSHOP

Argonne NATIONAL LABORATORY

RECENT RESULTS FROM GAMMASPHERE AND GRETINA AT ANL



SANNA STOLZE
Physics Division
Argonne National Laboratory

GRETINA

March 6, 2020
Darmstadt, Germany

TALK OUTLINE

GAMMASPHERE AND GRETINA

ARGONNE ACCELERATOR FACILITY

- ATLAS
- CARIBU
- RAISOR

RECENT GAMMASPEHERE HIGHLIGHTS

- 254NO
- BETA-DECAY EXPERIMENTS

RECENT GRETINA HIGHLIGHTS

- COULOMB EXCITATION OF STABLE AND CARIBU BEAMS
- EXPERIMENTS WITH FMA-GRETINA
- EXPERIMENTS WITH GODDESS-GRETINA

GAMMASPHERE

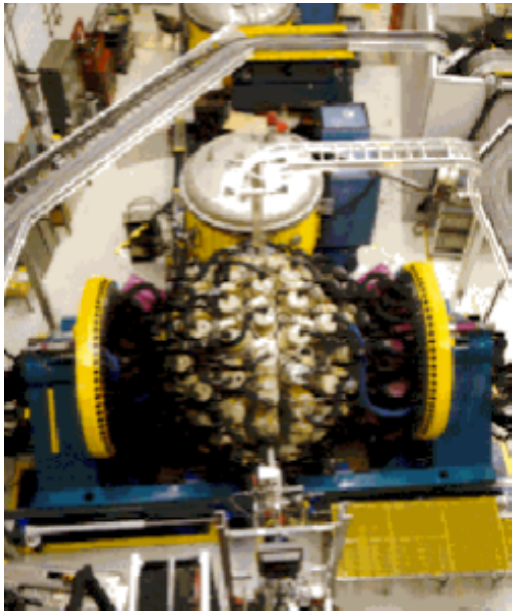
110 HPGe detectors

Has been delivering science since 1997

Major repair work ongoing to keep detectors operational

- Pre amps, HV filters, FETs, transistor resets, vacuum ports

Experiments with FMA or AGFA and/or with several auxiliary detectors



GRETINA

Gamma-Ray Energy Tracking In-Beam Nuclear Array

Constructed 2003-2010: $20M funded by US DOE-Nuclear Physics Office

Optimized for rare isotope science utilizing either fragmented (~100 MeV/A), or (re)accelerated (~5 MeV/A) beams.

Science Campaigns

NSCL: April 2012 – June 2013
7 quad modules at S800 target

ATLAS: July 2013 – June 2015
Up to 8 quad modules

NSCL: July 2015 – June 2017
Up to 10 quad modules

ATLAS: July 2017 – March 2019
11 modules Placed at FMA target position.

NSCL: April 2019 – October 2020
12 modules

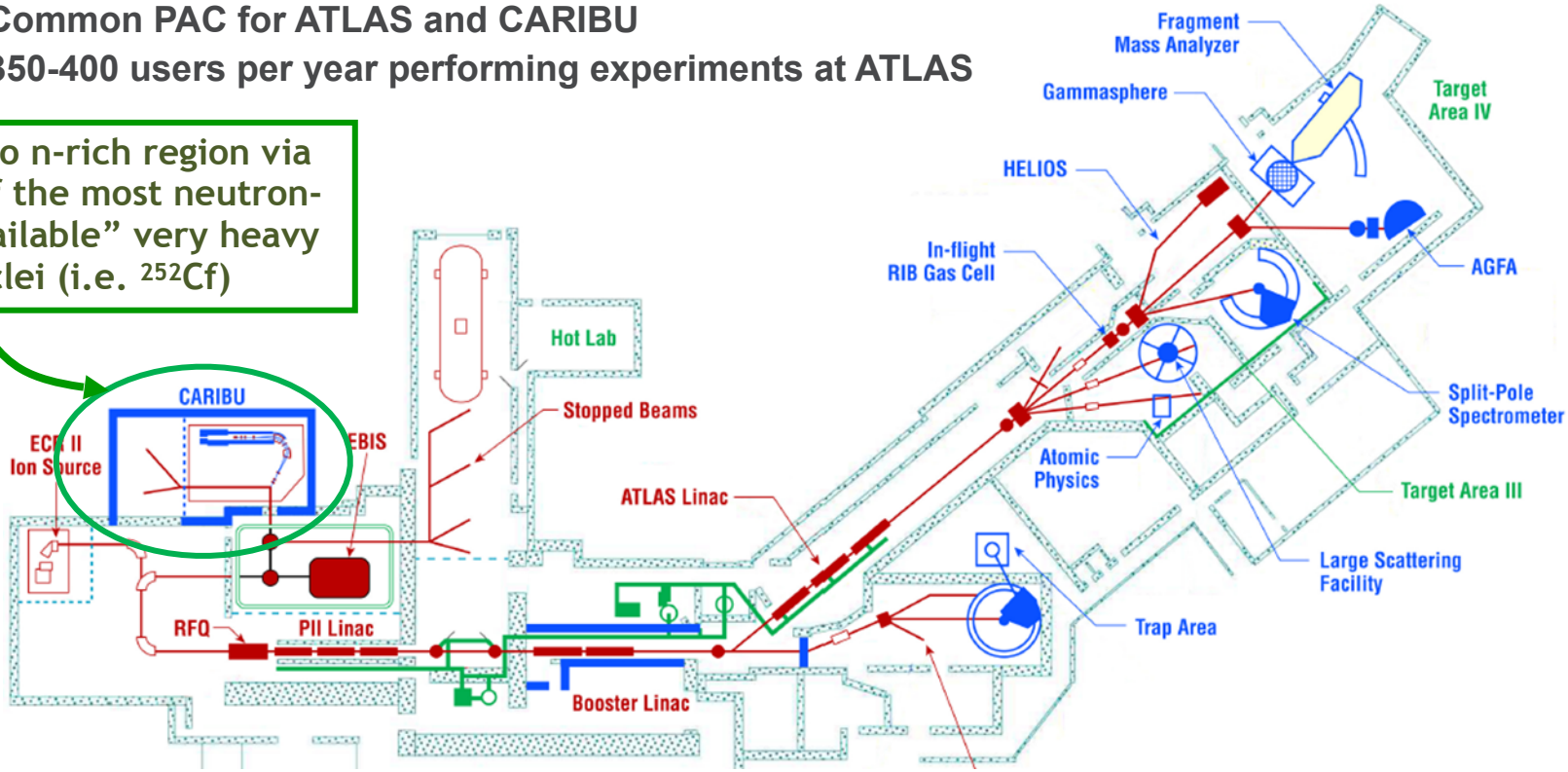
ATLAS: November 2020 - 2021

Upgrade to GRETA at NSCL ~2022

ATLAS/CARIBU FACILITY

- Stable beams at high intensity and energy up to 10-20 MeV/u
- Light in-flight radioactive beams
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- CARIBU beams
  - *heavy n-rich from Cf fission, no chemical limitations, low intensity, ATLAS beam quality, energies up to 15 MeV/u*
- State-of-the-art instrumentation for Coulomb barrier and low-energy experiments
- Operating 5000-6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone) at about 95% efficiency
  - Common PAC for ATLAS and CARIBU
  - 350-400 users per year performing experiments at ATLAS

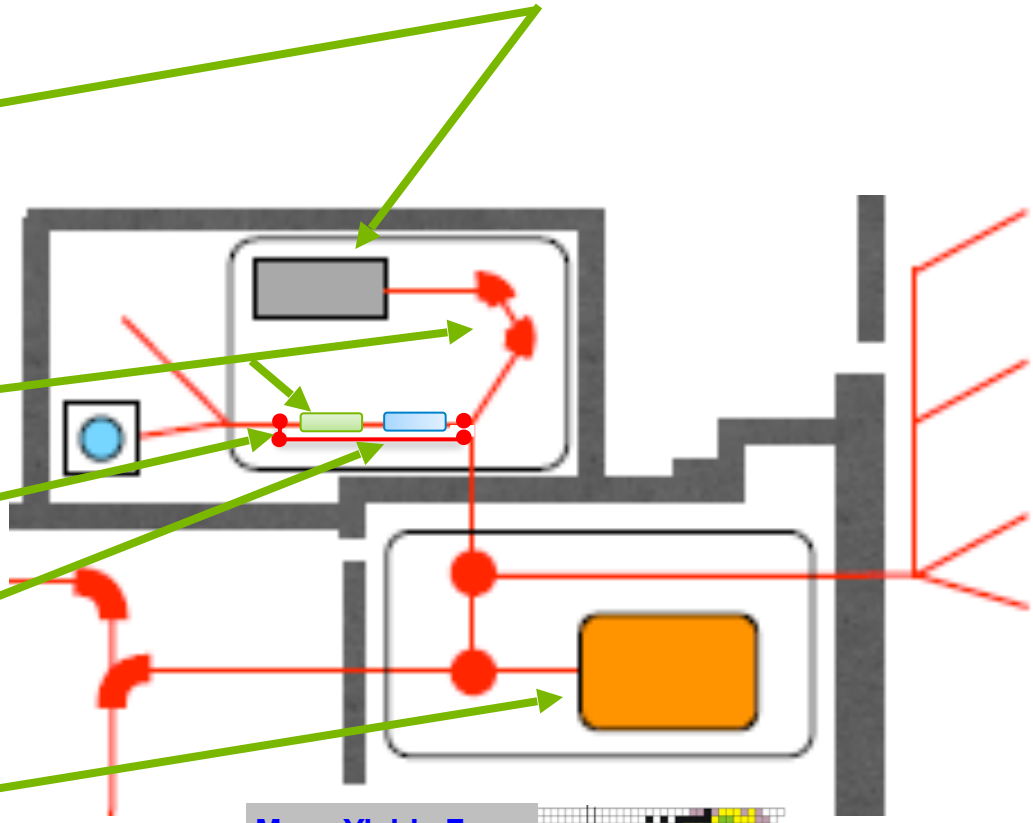
Access to n-rich region via fission of the most neutron-rich "available" very heavy nuclei (i.e. ^{252}Cf)

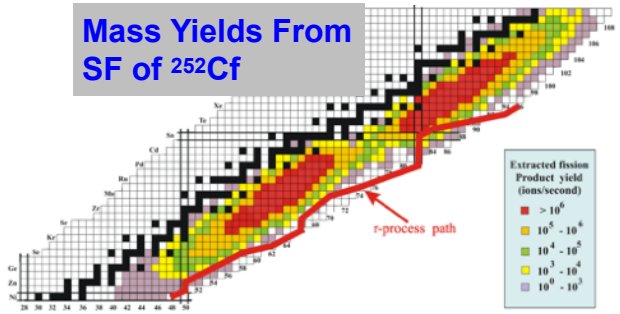


NEUTRON-RICH BEAM SOURCE FOR ATLAS: CARIBU "FRONT END" LAYOUT

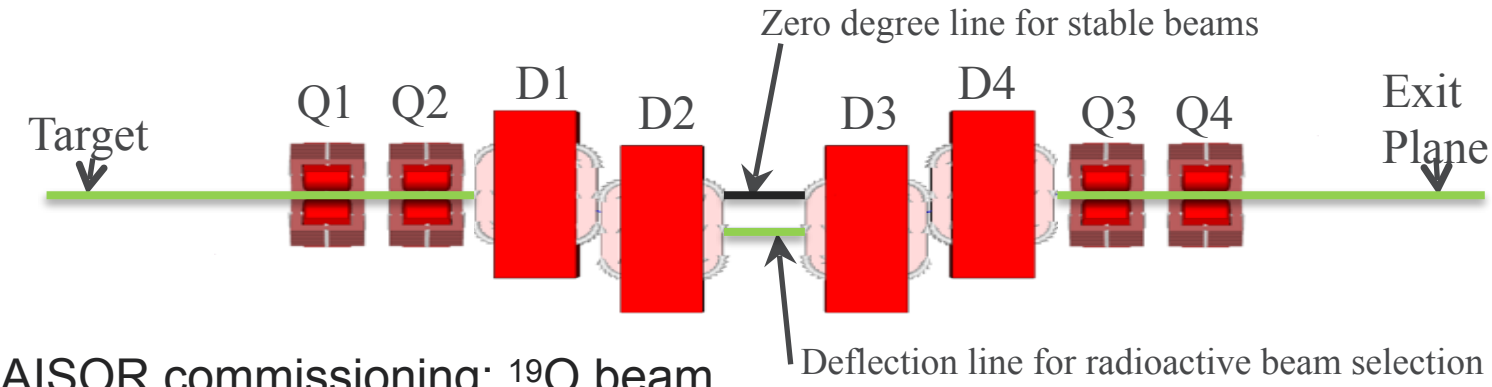
Main components of CARIBU

- **PRODUCTION**: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator and MR-TOF
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics

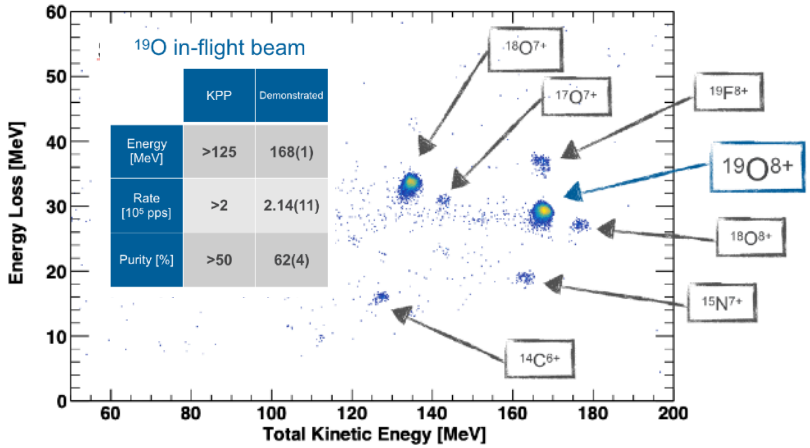




RAISOR – IN-FLIGHT RIB PRODUCTION



- RAISOR commissioning: ^{19}O beam



- Successful commissioning completed in Summer 2018 & closeout conducted in Fall of 2018
- Production of ^{19}O with specified characteristics
  - Production method: ^{18}O [10 MeV/u] + D
  - Measured at both separator exit & at a target station
- x2 – x4 improvement in ^{19}O production & purity over previous facility

- RAISOR serves the experimental areas down stream from the ATLAS section of the linac while maintaining stable beam operations – GRETINA, GAMMASPHERE
- For stable beam operations, the dipoles are turned off and the beam follows its normal trajectory.
- For radioactive beams, all beams are deflected and the selection is done in the middle plane on the deflection line away from the main line. The selected beam is then deflected back to the main ATLAS line at AIRIS exit

HIGHLIGHTS FROM RECENT GAMMASPHERE EXPERIMENTS

- GAMMASPHERE AND AGFA
- BETA-DECAY WITH CARIBU BEAMS

GAMMASPHERE

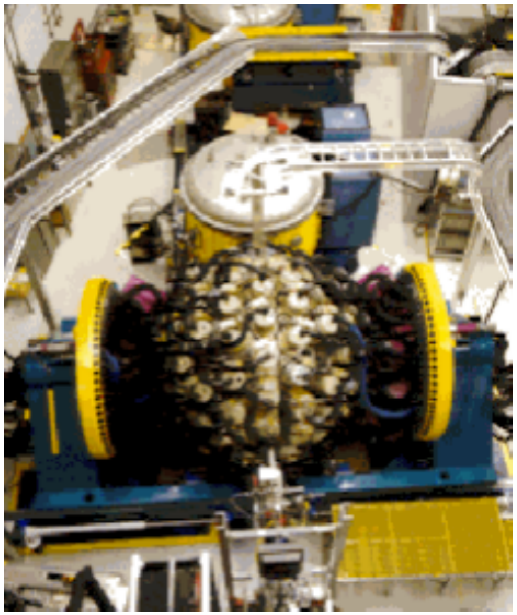
- **Commissioning of the Argonne Gas Filled Separator**
  D. Seweryniak, ANL
- **Towards Complete Spectroscopy of ^{254}No**
  R. Clark, LBNL
- **In-beam Spectroscopy of ^{255}Lr: Information on a Shell Gap at *Z*=114 for Super-Heavy Elements**
  A. Korichi, Orsay
- **Rotation of the ^{254}Rf nucleus at the Fission Limit**
  D. Seweryniak, ANL
- **Quasi-particle structure of Odd-A Transfermium Nuclei: Spectroscopy of ^{251}Md and ^{253}No**
  R. Clark, LBNL
- **Synthesis of heavy and super-heavy neutron-rich nuclei in multinucleon transfer reactions at 0°**
  Z. Favier, Saclay
- **Chiral Wobbling in 135Pr**
  Garg et. al.
- **Investigation of Wobbling Motion in the A~190 Region**
  Garg et. al.
- **Investigation of large odd-even shape staggering in 188Bi and of deformed configurations in 188Po, 189Bi**
  A. N. Andreyev
- **Commissioning of a Dedicated Decay Station at Gammasphere**
  F. Kondev et. al.
- **Decay spectroscopy of fission products near A ~ 100 using Gammasphere and HEART for improving antineutrino spectra predictions**
  P.Copp et. al.

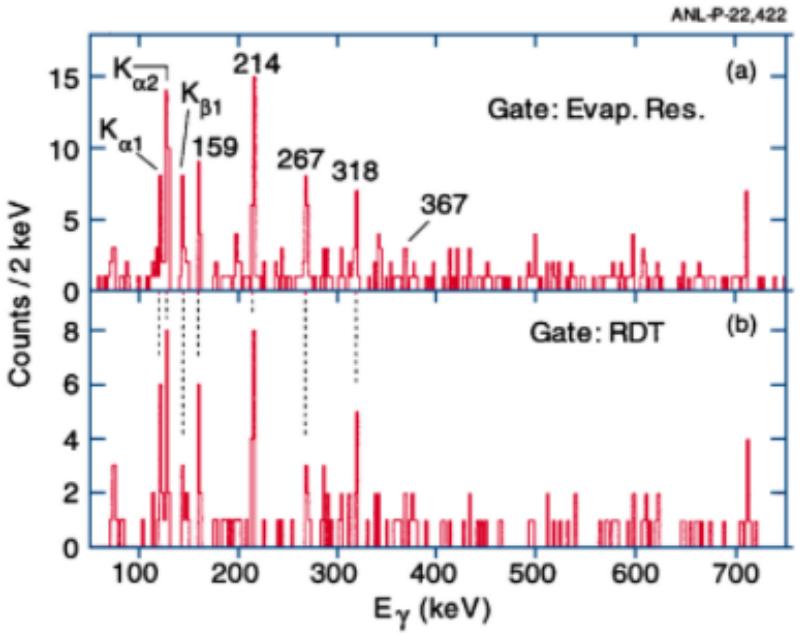
^{254}No: THE BEGINNING

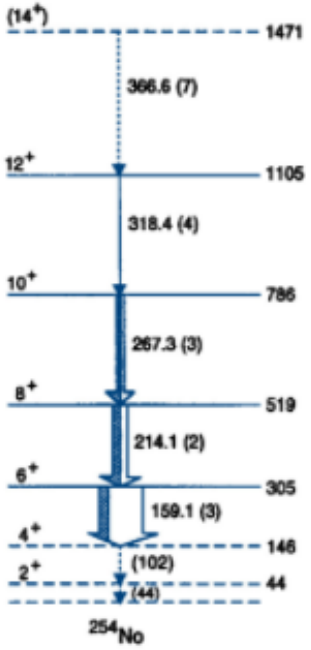
VOLUME 82, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1999

Ground-State Band and Deformation of the $Z = 102$ Isotope ^{254}No

P. Reiter,[1] T. L. Khoo,[1] C. J. Lister,[1] D. Seweryniak,[1] I. Ahmad,[1] M. Alcorta,[1] M. P. Carpenter,[1]
J. A. Cizewski,[1,3] C. N. Davids,[1] G. Gervais,[1] J. P. Greene,[1] W. F. Henning,[1] R. V. F. Janssens,[1]
T. Lauritsen,[1] S. Siem,[1,8] A. A. Sonzogni,[1] D. Sullivan,[1] J. Uusitalo,[1] I. Wiedenhöver,[1] N. Amzal,[2]
P. A. Butler,[2] A. J. Chewter,[2] K. Y. Ding,[3] N. Fotiades,[3] J. D. Fox,[4] P. T. Greenlees,[2] R.-D. Herzberg,[2]
G. D. Jones,[2] W. Korten,[5] M. Leino,[6] and K. Vetter[7]







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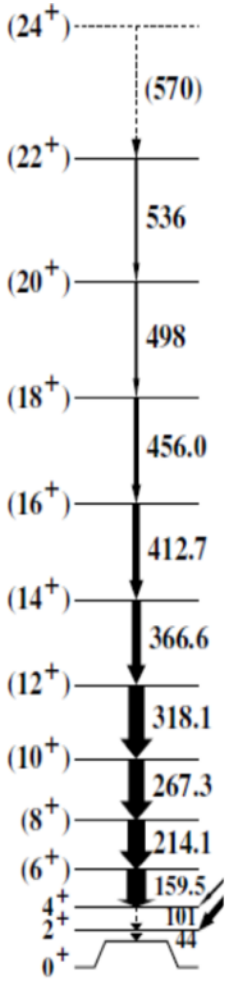
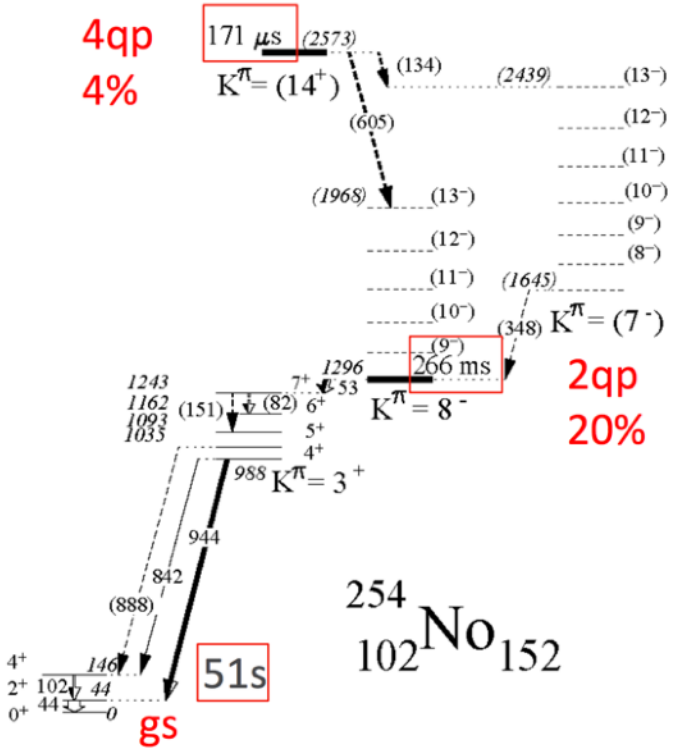
STRUCTURE OF ^{254}No



S. Eeckhaudt et al.,
Eur. Phys. J. A 26, 227 (2005)

β_2=0.26
Higher multipoles important
β_6 opens N=152 gap



$^{254}_{102}No_{152}$

S.K. Tandel et al.,
PRL 97, 082502(2006)

Benchmark case
Largest cross section (2 μb)

The very first trans-fermium nucleus ever studied in-beam (Gammasphere/FMA)

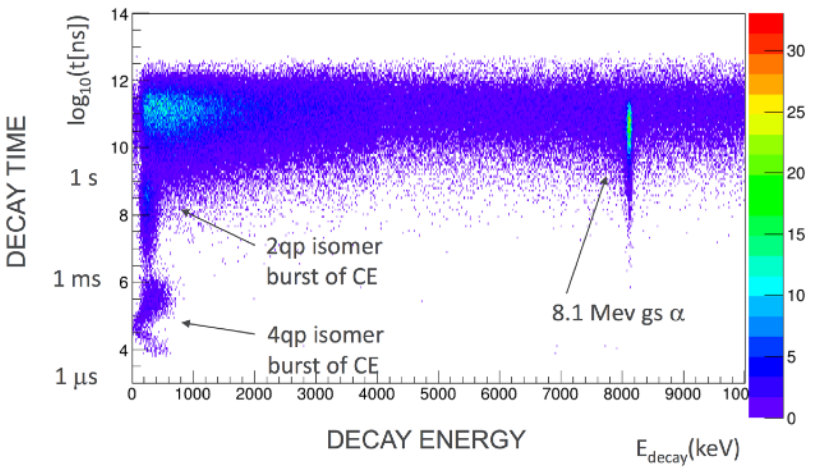
Despite many experiments contradictory level schemes and uncertain isomer configuration assignments

High-spin states – backbending
Rotational bands feeding isomers

Promising attempt to observe rotational bands in the most fissile nucleus ^{254}Rf (2nb)

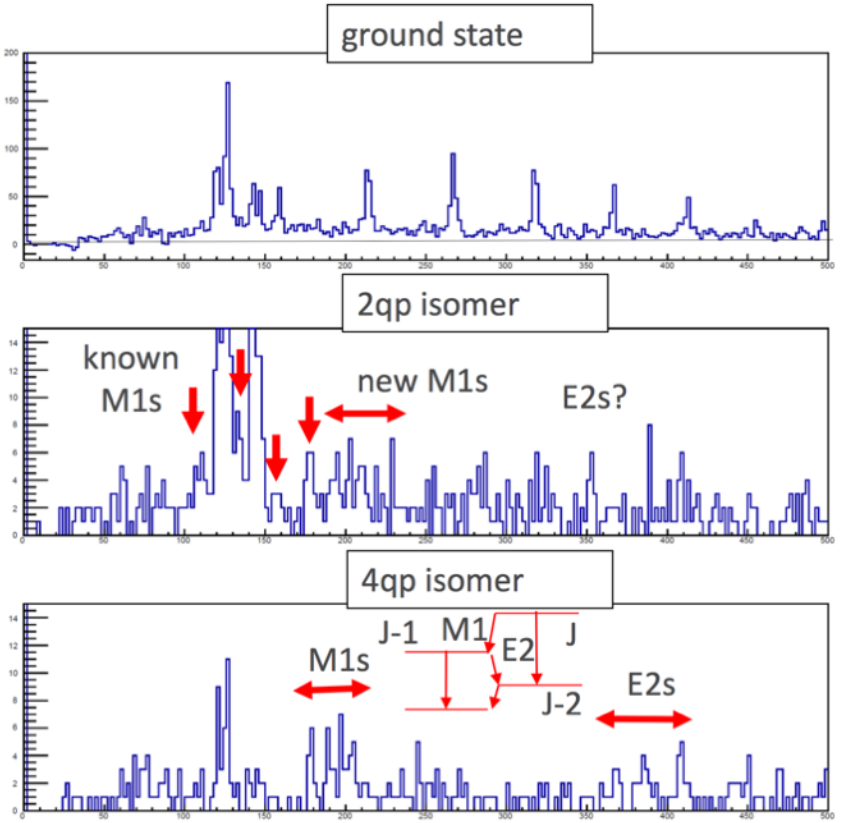
RESULTS OF ^{254}No EXPERIMENT

α-decay spectrum



- ~44,000 gs ^{254}No alpha decays (2000 in 1999 experiment)
- 10x higher separator efficiency
- 2x count Ge count rate (digital daq)

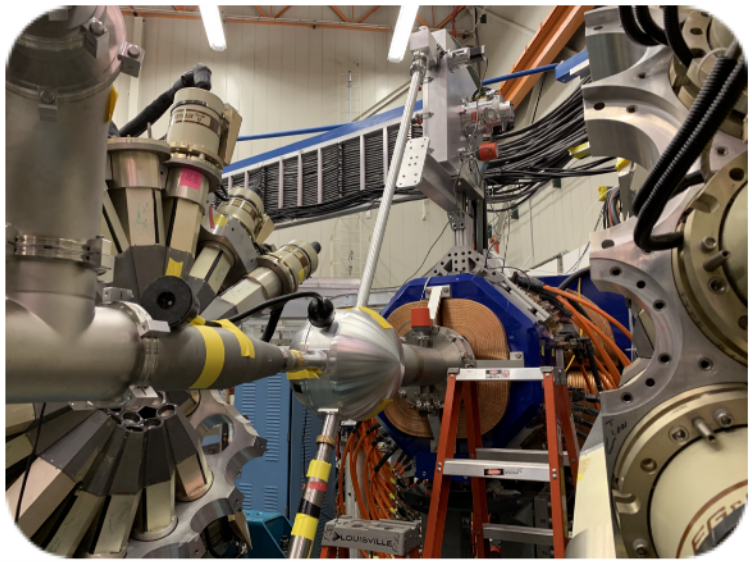
Gammasphere spectra

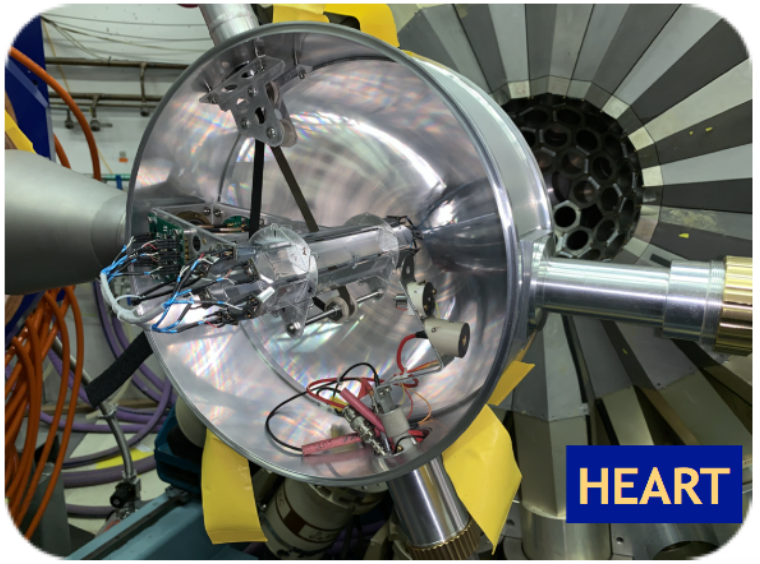


T. Huang, Ch. Morse et al., data analysis in progress

β-DECAY STATION FOR GAMMASPHERE

Funded from both DOE-NP and NNSA NA-22 via FOA





Tape Station Components

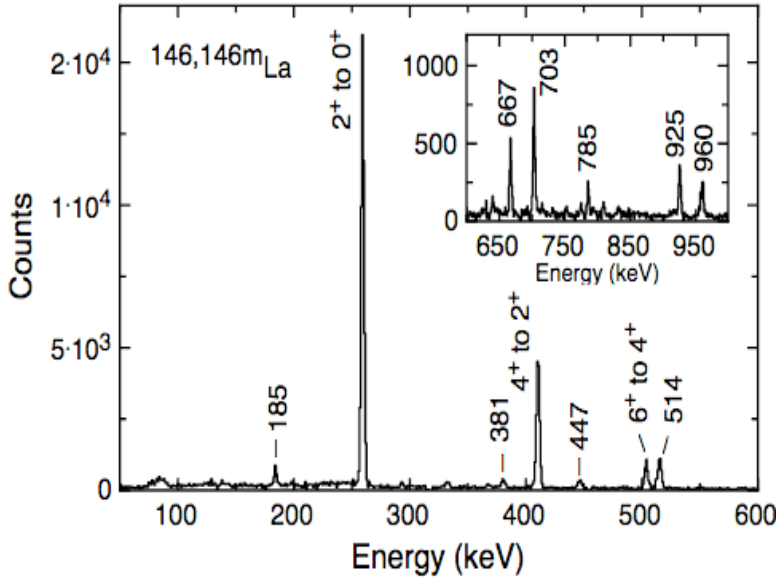
- Moving Tape Station – LSU (S. Marley, E. Zganjar and G. Morgan)
- Target Chamber – Wash U. (W. Reviol and D. Sarantities)
- **HE**xagonal **AR**ray for **T**riggering (HEART) – An array of six plastic scintillators (200 mm x 20 mm x 2 mm) for β-particle detection

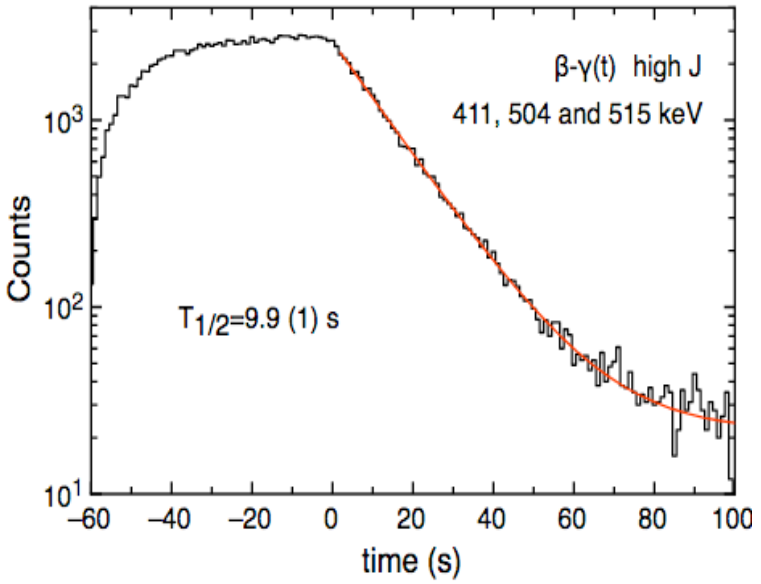
Commissioned December 2018 – ^{144,146}La decay

ANL Key Personal – F.G. Kondev (PI), **P. Copp**, J. Wu, M. P. Carpenter

SELECTED RESULTS FROM GS β-DECAY

Results from Commissioning Experiment

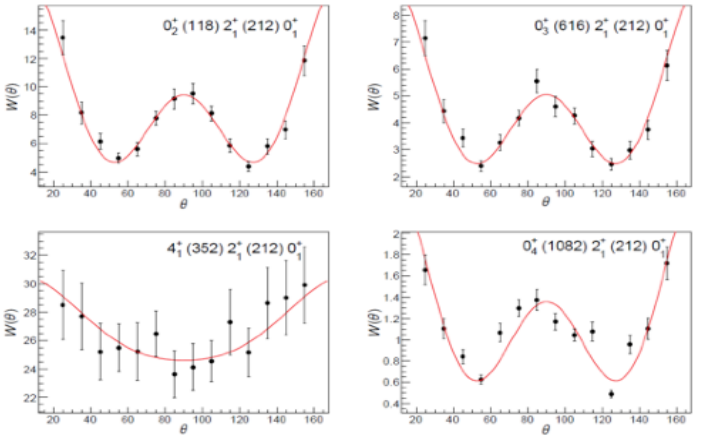




^{100}Y decay measured in Gammasphere

- ^{100}Y implanted from CARIBU implanted at GS target position.
- Angular correlations without corrections identify 0^+ states.

J. Wu *et al*., to be published.



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HIGHLIGHTS FROM THE SECOND GRETINA CAMPAIGN AT ATLAS

- COULOMB EXCITATION OF STABLE AND CARIBU BEAMS
- EXPERIMENTS WITH FMA-GRETINA
- EXPERIMENTS WITH GODDESS-GRETINA

STUDIES WITH STABLE AND CARIBU BEAMS WITH GRETINA AND CHICO II

Shape coexistence in the neutron-rich germanium isotopes ^{72}Ge and ^{76}Ge
R.V. F. Janssens *et. al.*

Angular Distribution Measurements of Target-Like Products of N=126 Neutron-Rich Isotopes
S. Zhu *et. al.*

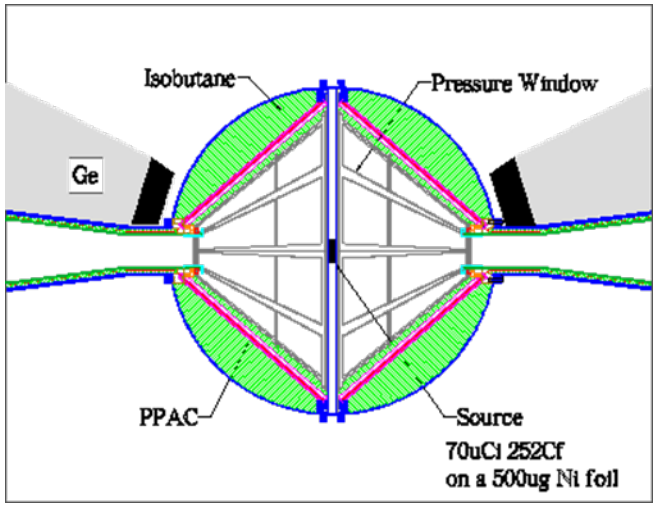
Shape Coexistence in ^{64}Ni?
R.V. F. Janssens *et. al.*

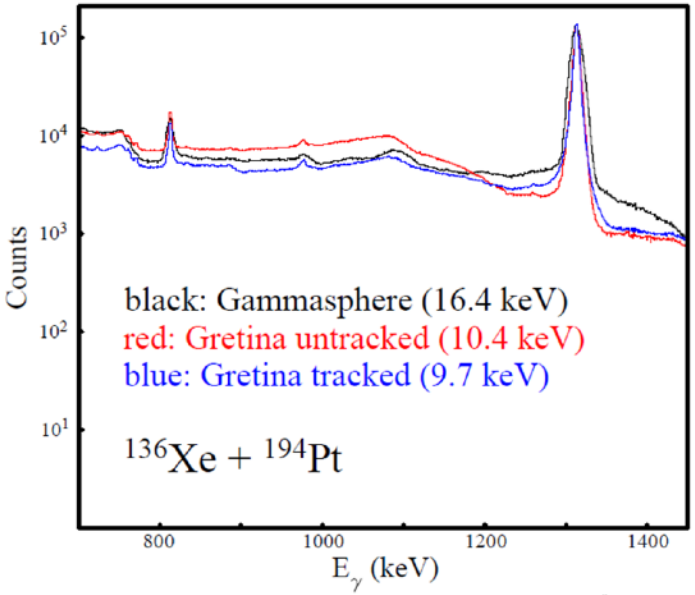
Properties of high-lying 0^+ states in ^{70}Zn
J. Li *et al.*

Octupole Strength of Condensing Octupole Phonons in ^{240}Pu
S. Zhu *et. al*.

Shape Evolution and Coexistence in the Mo-Ru Region: A Request for Additional Beam Time with the New EBIS
J. M. Allmond *et. al.*

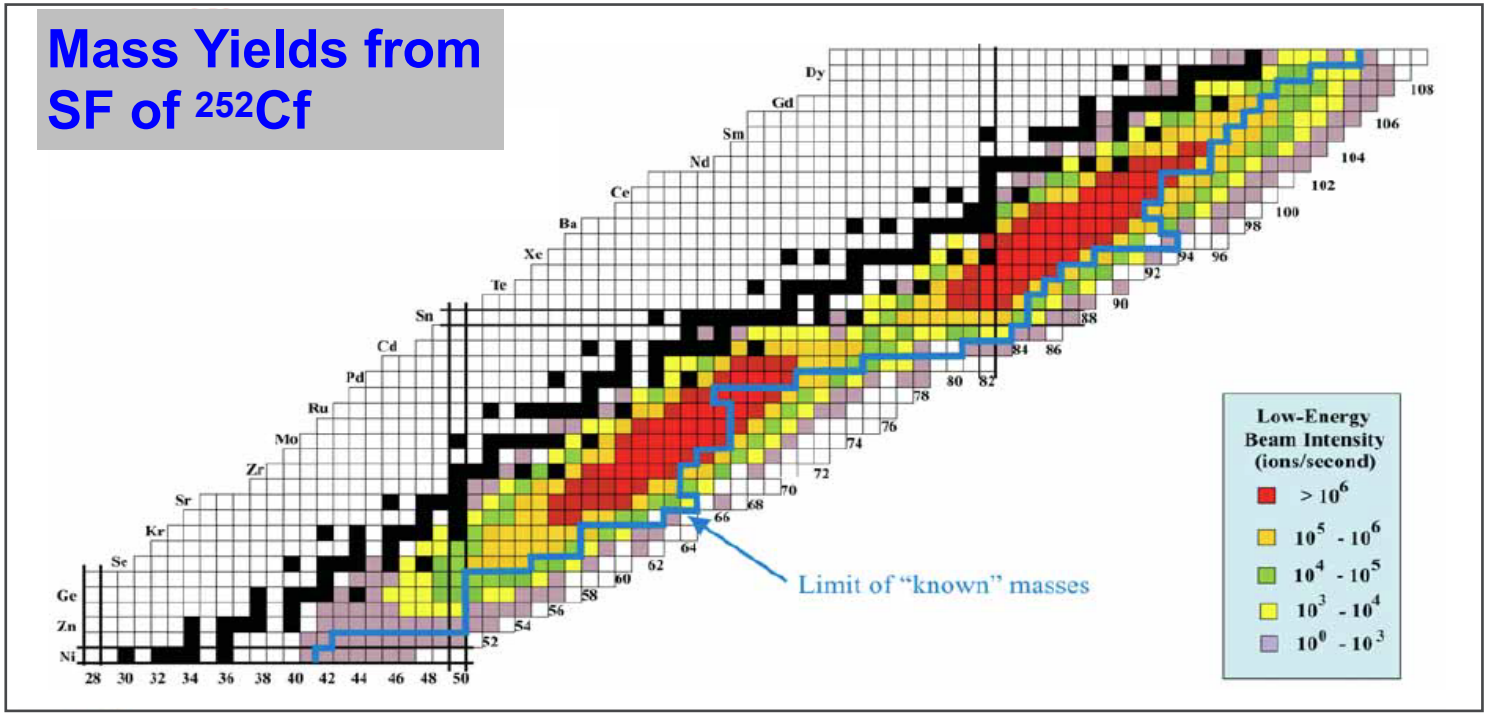
Octupole Correlations in neutron-rich Ba nuclei: Coulomb Excitation of odd-A ^{143}Ba and ^{145}La
A. O. Macchiavalli *et. al*.





C.Y. Wu and J. Henderson (LLNL)

COULOMB EXCITATION WITH CARIBU BEAMS

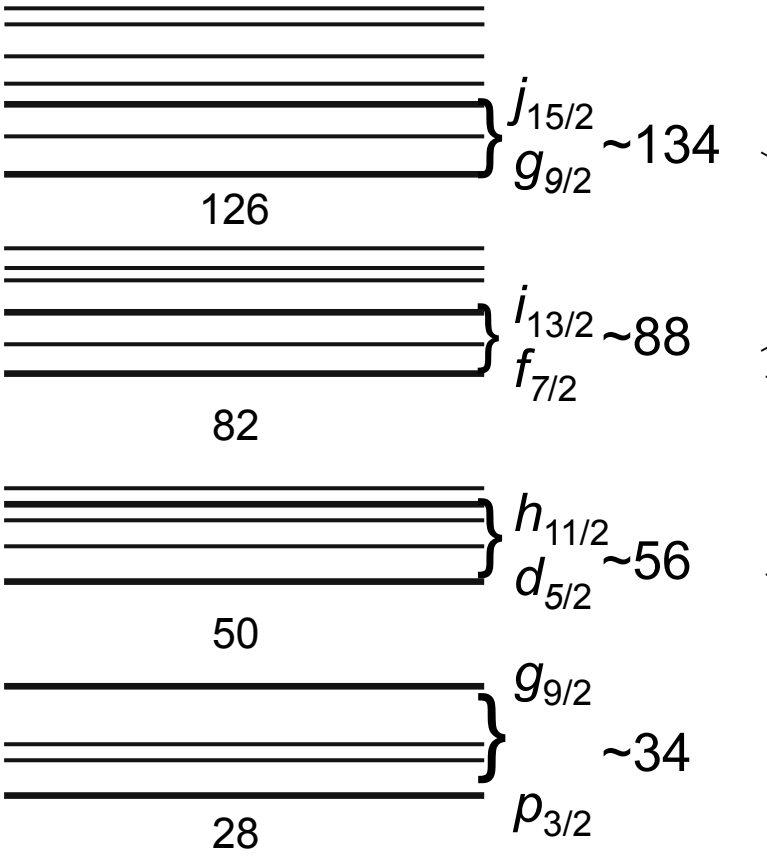


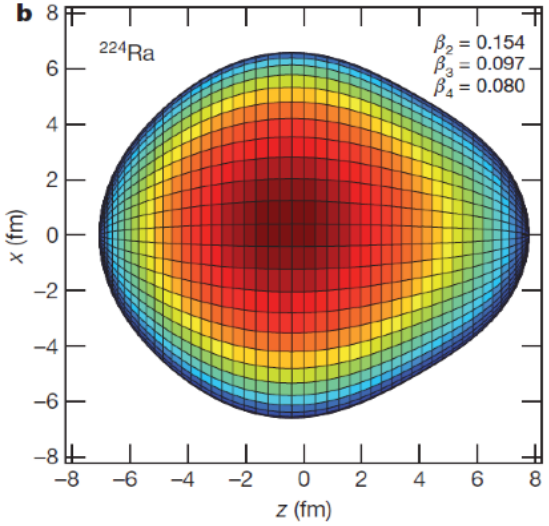
- Sr-Zr-Mo region – nuclei with most deformed ground states, triaxility
- Xe-Ba-Ce region – one of only a few regions exhibiting enhanced octupole collectivity.

Coulomb excitation experiments performed in first GRETINA campaign at ATLAS include ^{145}Ba, ^{104}Mo, ^{106}Mo, ^{110}Ru … most are only possible at ATLAS

OCTUPOLE DEFORMATION IN ATOMIC NUCLEI

Long-range interactions between single particle states with $\Delta j = \Delta l = 3$;





Previous GRETINA campaign:

- ^{144}Ba- ^{146}Ba CARIBU re-accelerated beam
- Coulomb excitation using 3000-10000 ions/sec with CHICO II coupled to GRETINA

Results

- ^{146}Ba: B(E3;3-⟶0+) = 48^{+21}_{-29} W.u.
- ^{144}Ba: B(E3;3-⟶0+) = 48^{+25}_{-34} W.u.
- These results are consistent with stable octupole deformation.

B. Bucher, S. Zhu *et al.*, Phys. Rev. Lett. **116**, 112503 (2016)
B. Bucher, S. Zhu *et al.*, Phys. Rev. Lett. **118**, 152504 (2017)

COULOMB EXCITATION OF NEUTRON-RICH ^{143}Ba

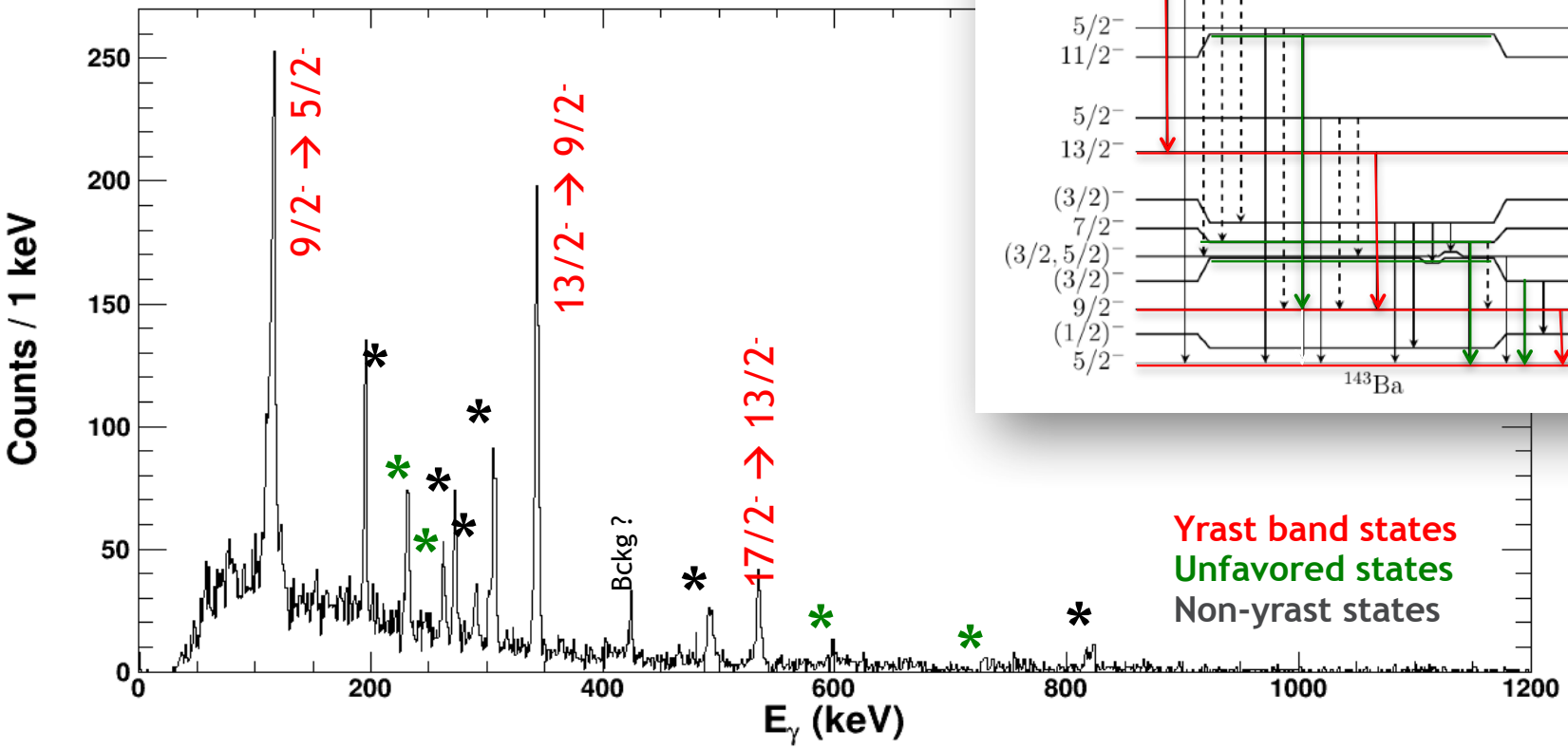
A. O. Macchiavelli *et al.*,

- Single-particle coupling to Quadrupole and Octupole collective modes
- Recent IBMF calculations [*Nomura et. al. PRC 97, 024317 (2017)*] suggest weak collectivity in both degrees of freedom

CHICOII and CARIBU

~3000 pps ^{143}Ba at 630 MeV on 2mg/cm^2 ^{208}Pb

Doppler-reconstructed GRETINA spectrum

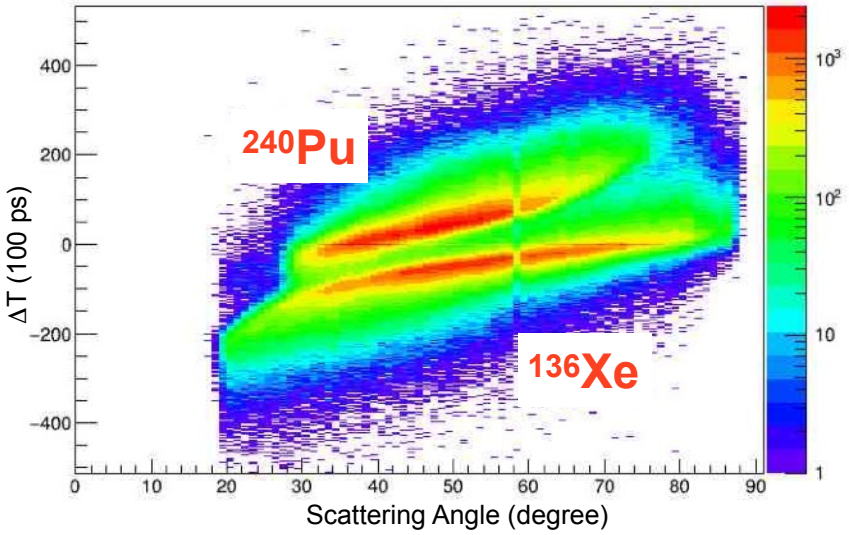


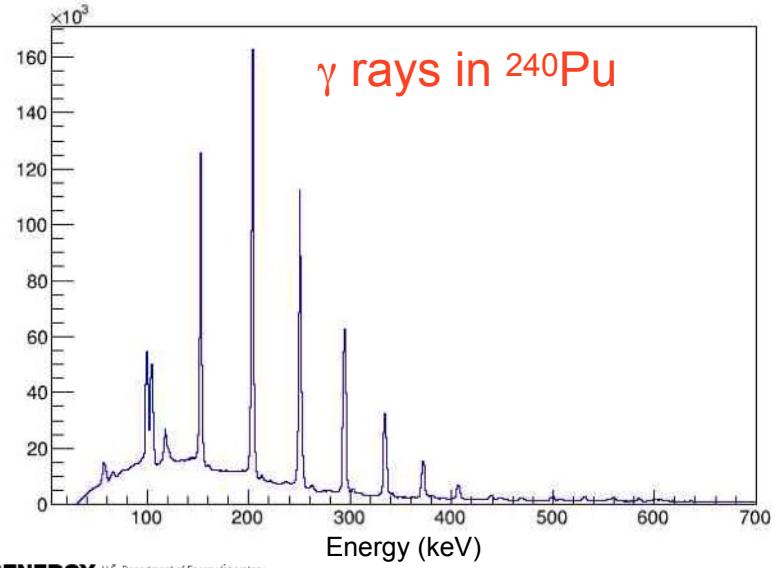
Observed transitions

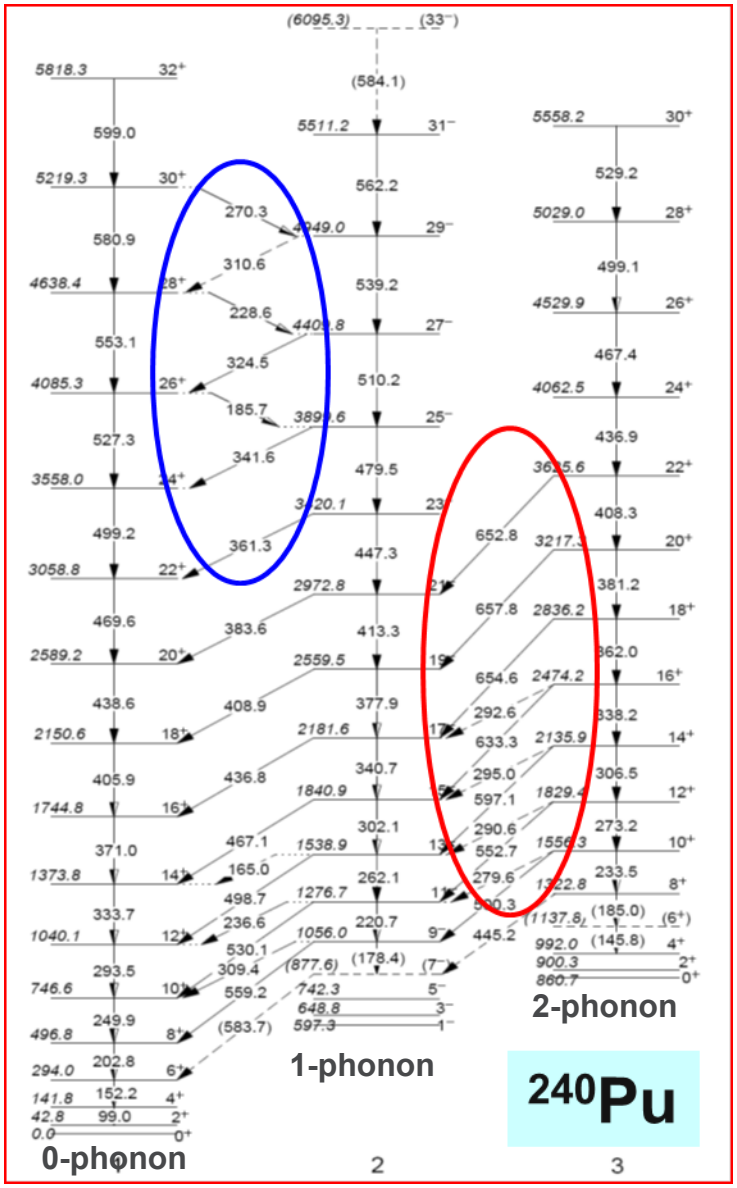
DOUBLE-OCTUPOLE PHONON BANDS IN ^{240}Pu

S. Zhu et al.

Coulomb Excitation Measurements







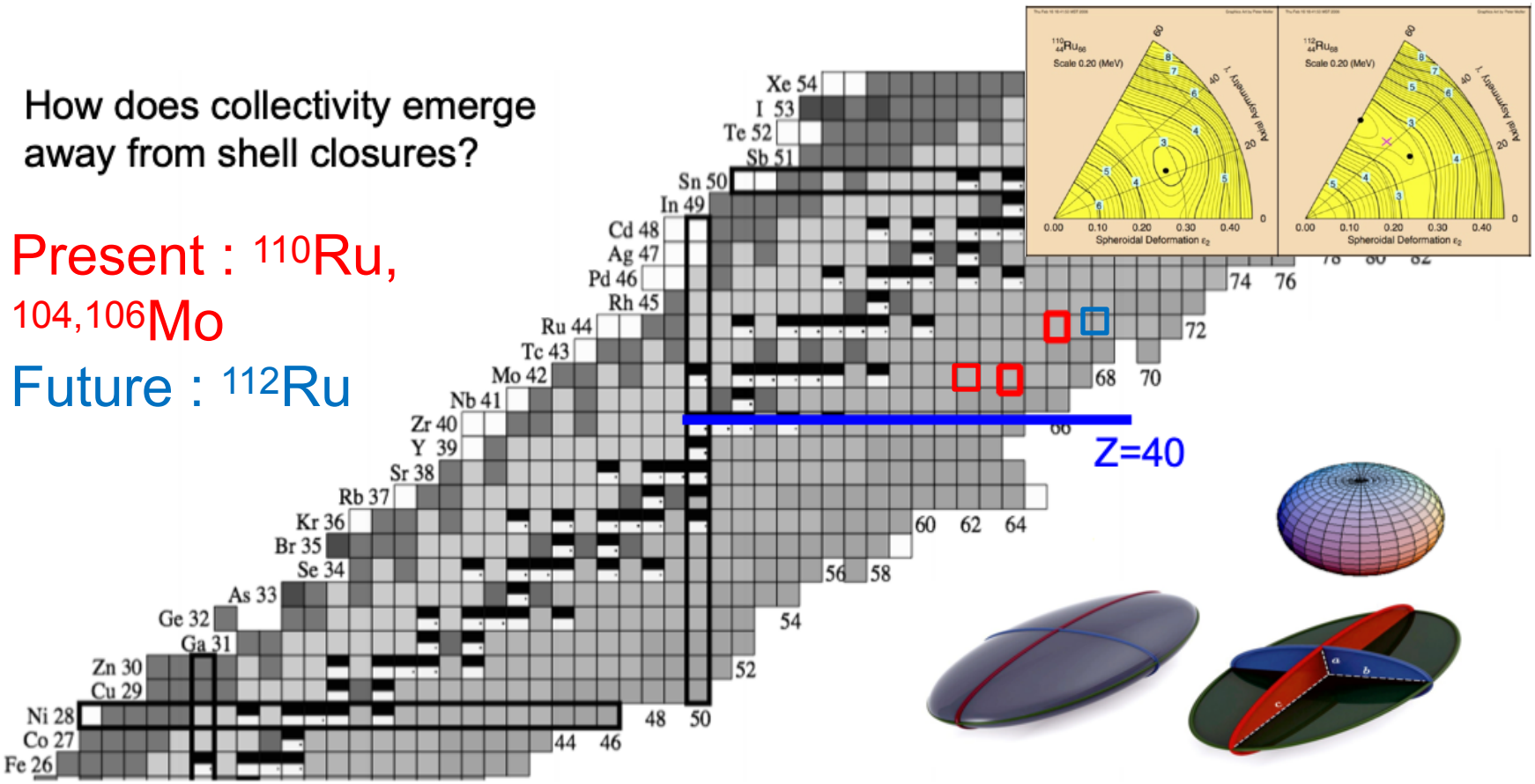
COULOMB EXCITATION OF NEUTRON-RICH Ru/Mo

M. Almond, D. Doherty *et al.*

How does collectivity emerge away from shell closures?

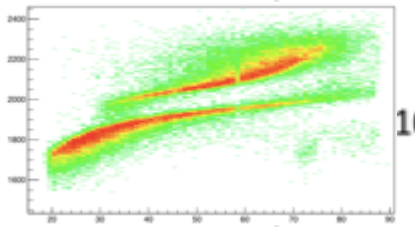
Present : ^{110}Ru, ^{104,106}Mo

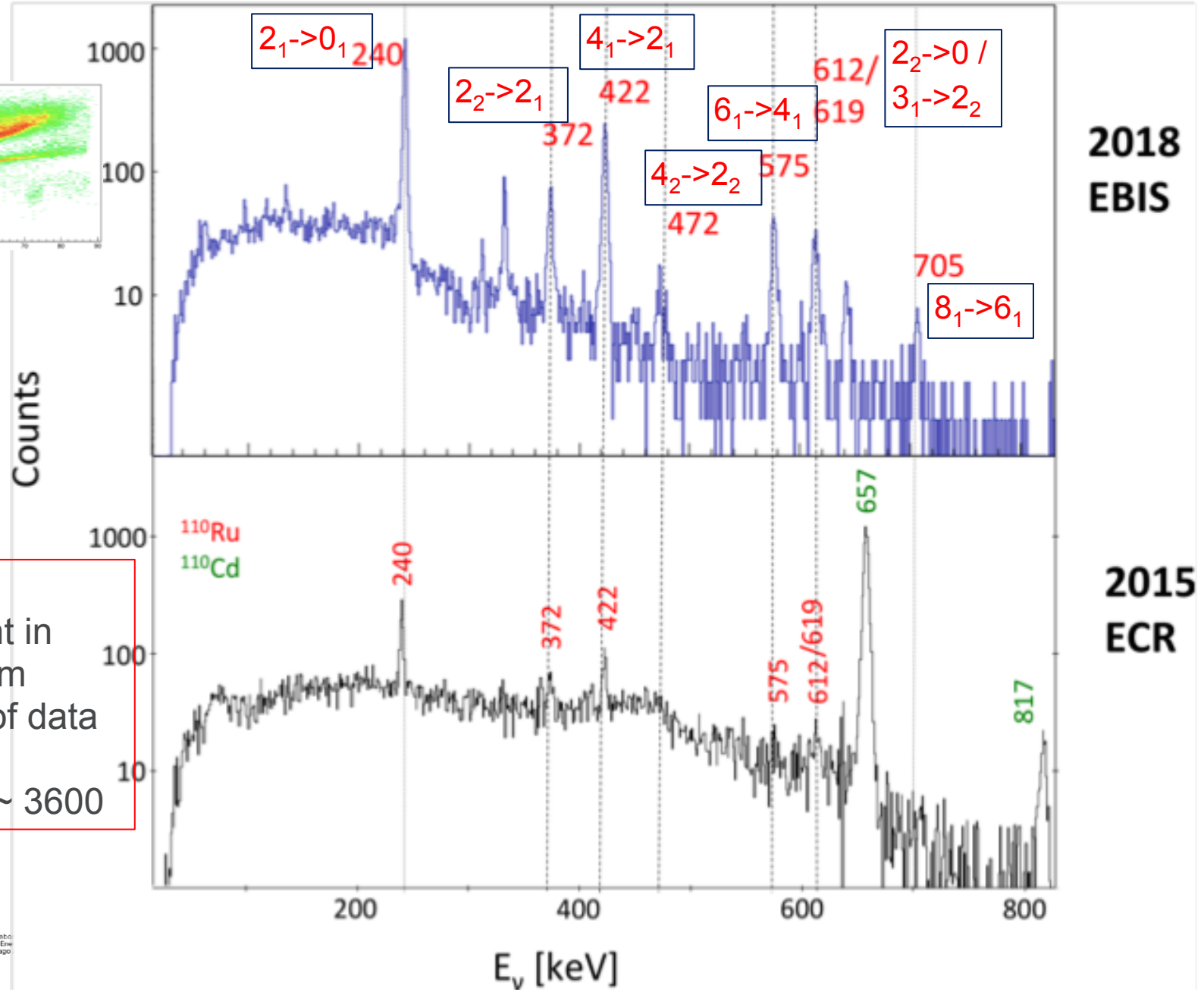
Future : ^{112}Ru



Are the neutron-rich refractory isotopes **triaxially** deformed or **oblate** close to their ground state?

EBIS (2018) VS ECR(2015)

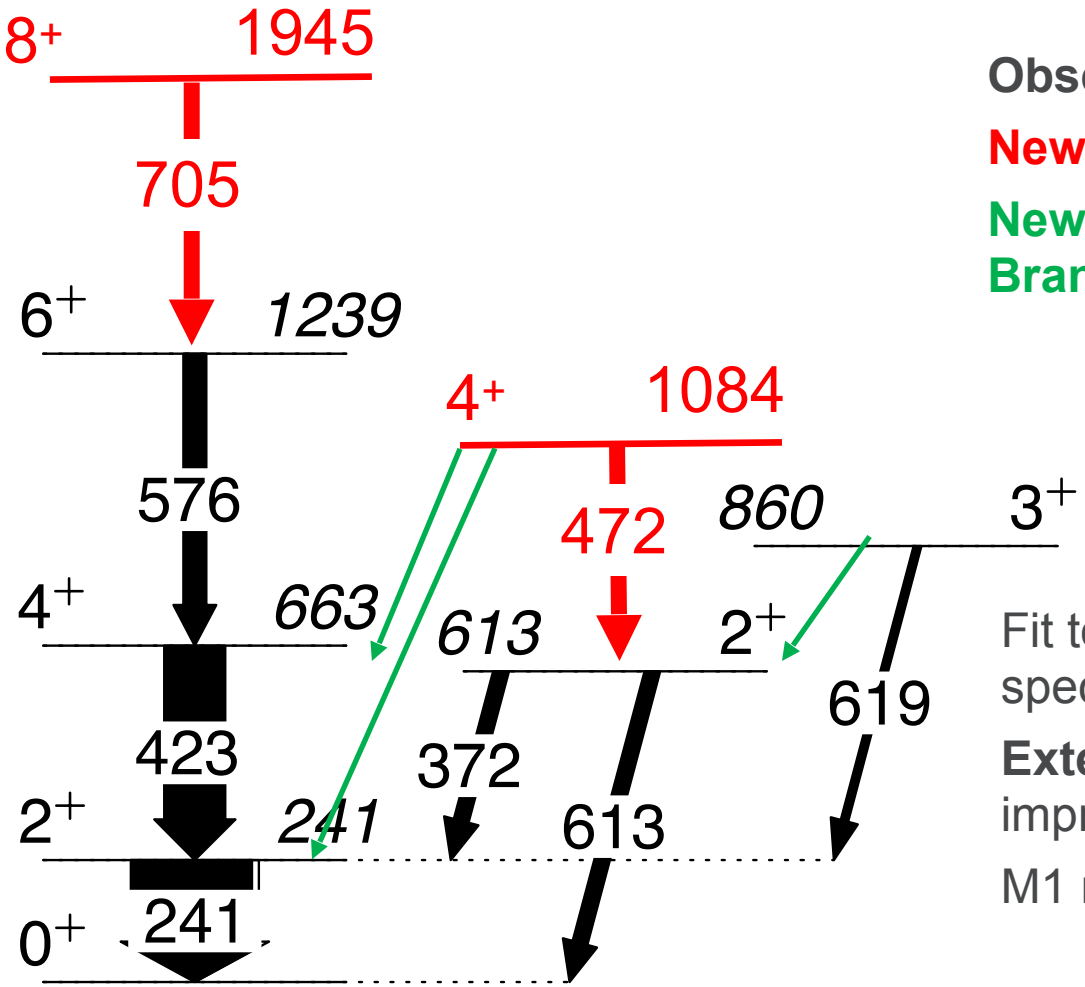




Factor ~2.5 improvement in statistics from ~60 hours of data

e.g. A(240) ~ 3600

NEW INFORMATION ON ^{110}RU COULEX



Observed in previous study

New information from Coulex

New information from beta decay. Branching and mixing ratios

GOSIA Re-analysis

Fit to gamma-ray yields and known spectroscopic data

Extended set of matrix elements, with improved precision

M1 matrix elements to be added

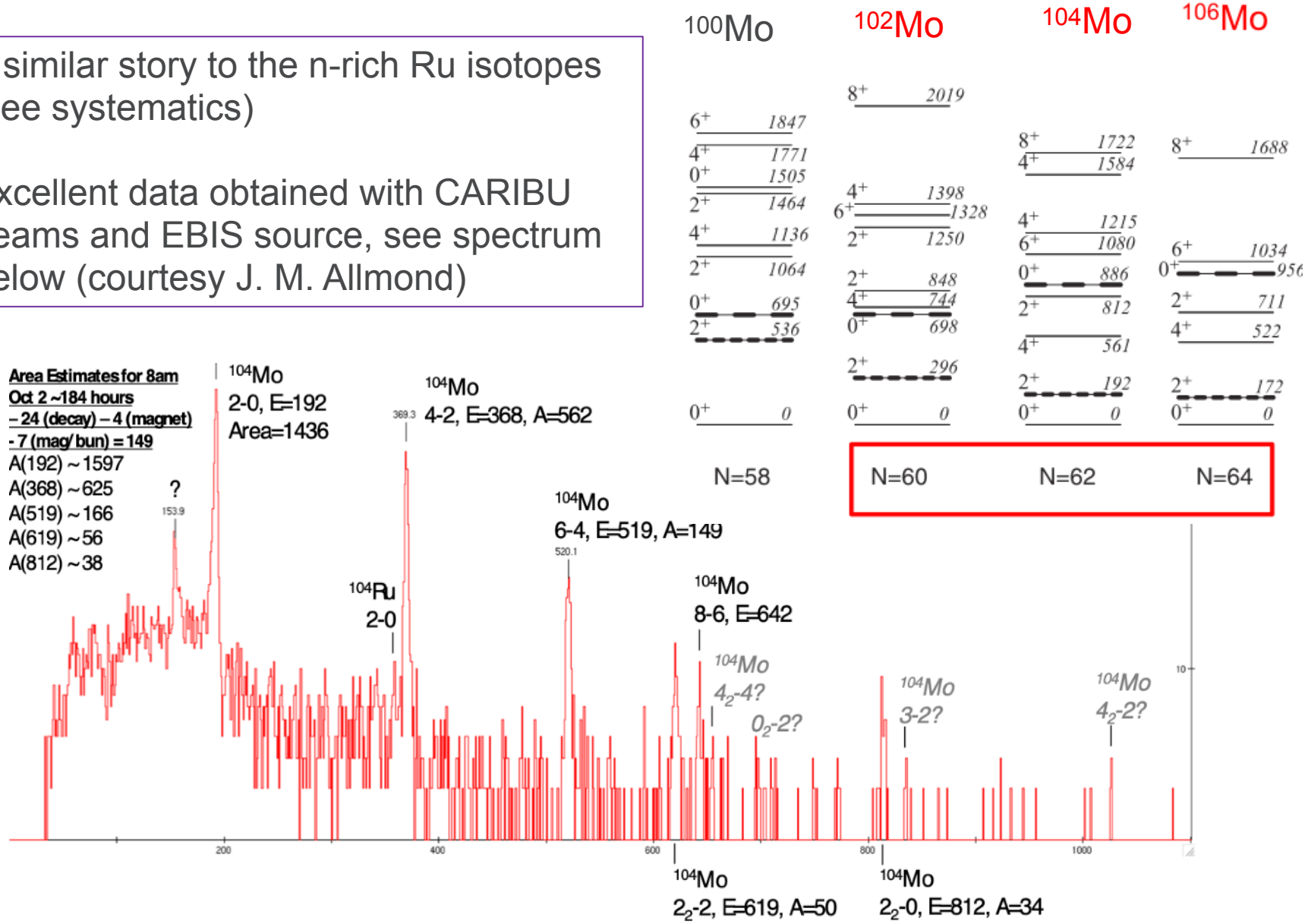
Quadrupole Sum Rules yield γ = 29(6)°,

Previous work: D. T. Doherty, J. M. Allmond et al., Phys. Lett. **B766** (2017) 334

NEW RESULTS ON ^{104,106}Mo

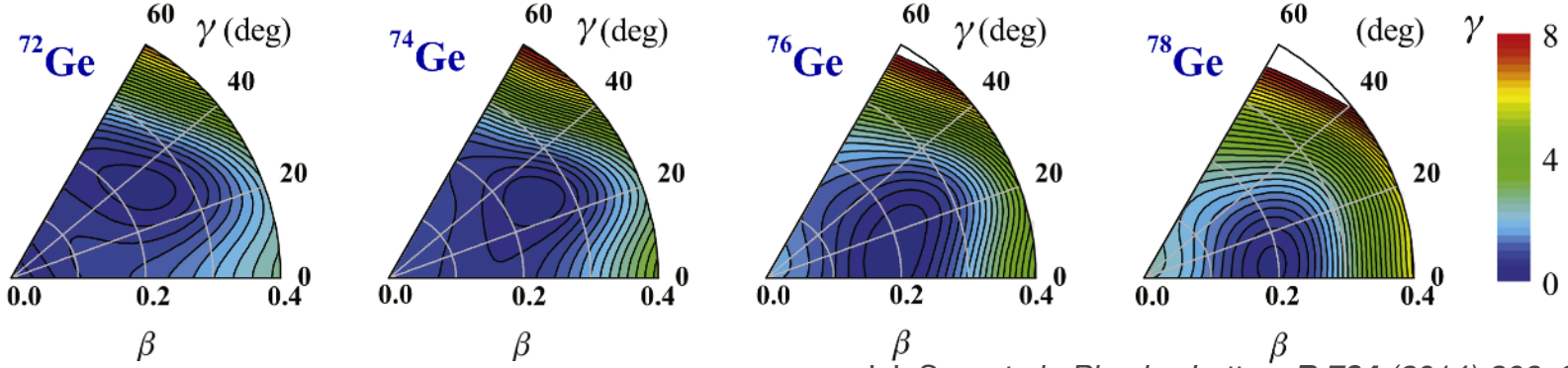
A similar story to the n-rich Ru isotopes (see systematics)

Excellent data obtained with CARIBU beams and EBIS source, see spectrum below (courtesy J. M. Allmond)



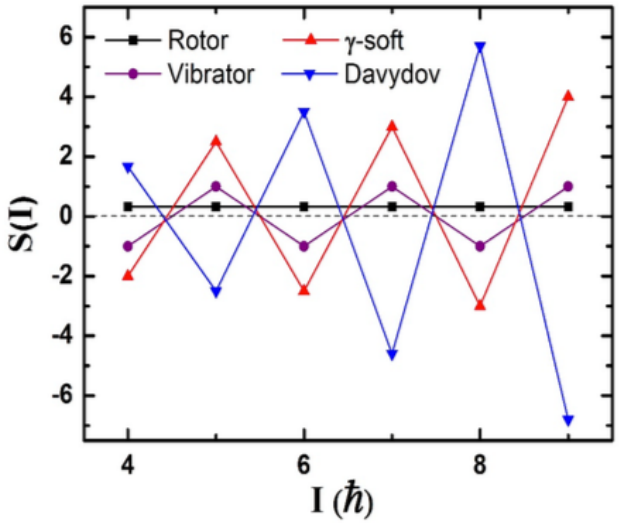
TRIAXIALITY IN GE ISOTOPES

Triaxiality plays a role in structure of Ge isotopes

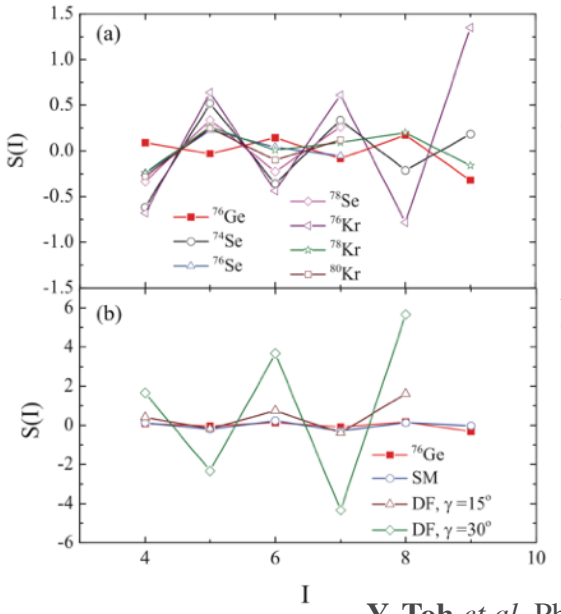


J.J. Sun *et al.* *Physics Letters* ***B 734*** *(2014) 308–313*

$$S(I) = \frac{[E(I) - E(I-1)] - [E(I-1) - E(I-2)]}{E(2_1^+)}$$



E. A. McCutchan et al., Phys. Rev. C76 (2007) 024306



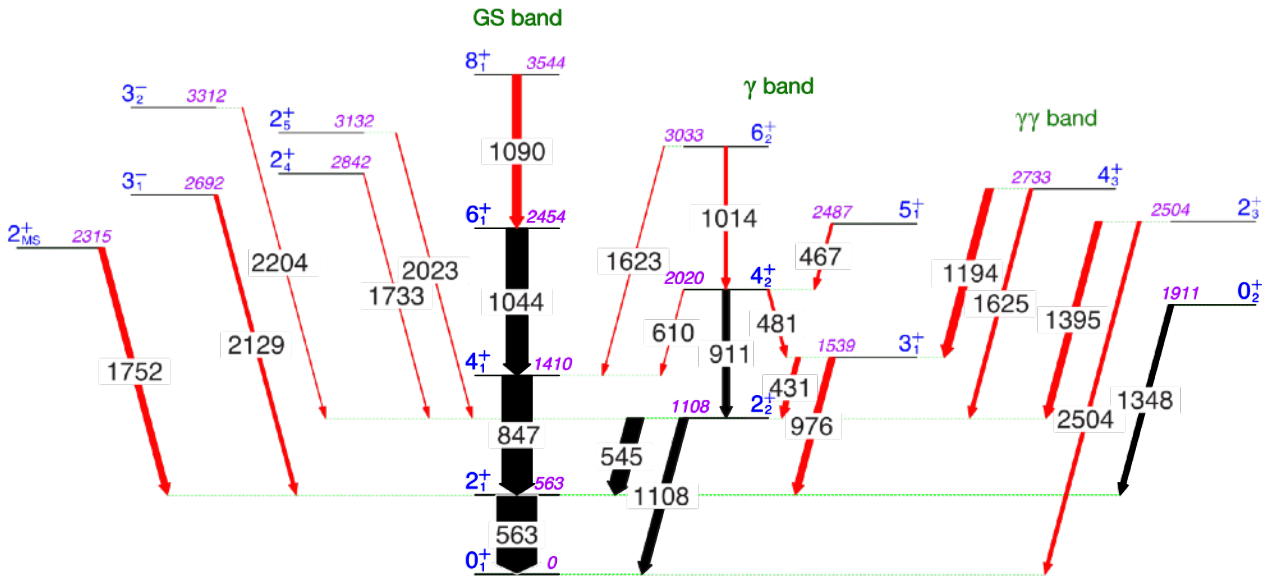
Energy Staggering for the γ bands provide evidence of triaxiality

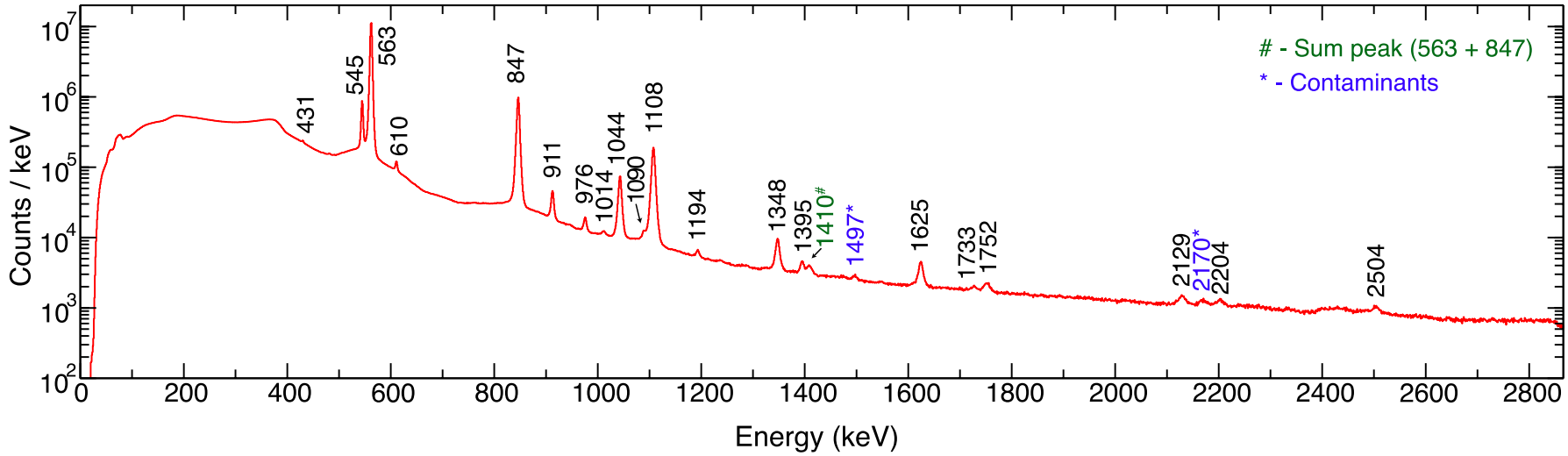
Are energies alone sufficient to answer the question of RIGID triaxiality in ^{76}Ge?

Y. Toh *et al*. Phys. Rev. C**87**, 041304(R) (2013)

^{76}Ge COULOMB EXCITATION GRETINA/CHICO II

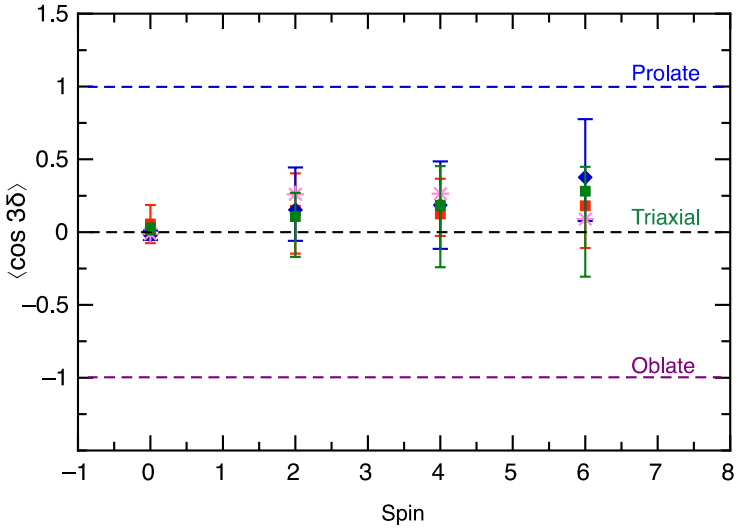
A.D. Ayangaekaa, R.V.F. Janssens et al.



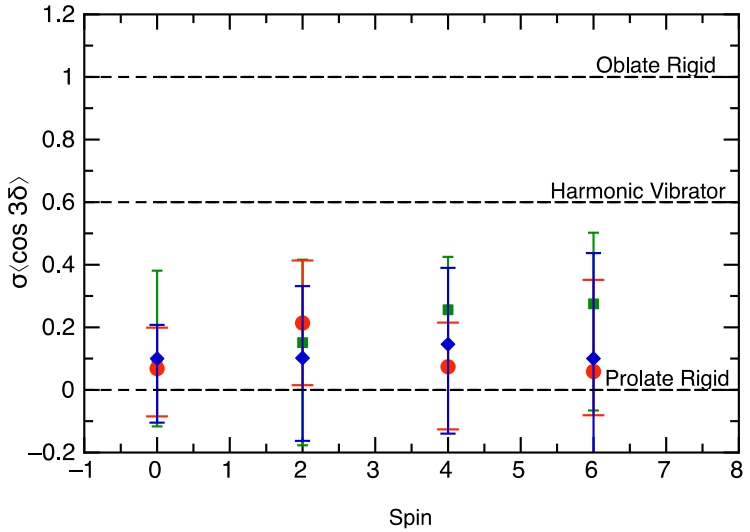


MATRIX ELEMENTS FROM GOSIA ANALYSIS

⟨cos 3δ⟩



σ⟨cos 3δ⟩



- The expectation values of the asymmetry of the intrinsic frame E2 properties of the ground-state band.
- Four independent values of ⟨cos 3δ⟩ are shown for each state; one from the third-order (red) and three from the fifth-order invariant.
- Statistical fluctuation or variance of the asymmetry deformation for the ground-state band.
- Three independent measure of σ⟨cos 3δ⟩ for each state are shown. This provide a test of convergence.

Similar results are obtained for the gamma-band in ^{76}Ge

A. D. Ayangeakaa *et. al.*, PRL 123, 102501 (2019)

FMA – GRETINA EXPERIMENTS

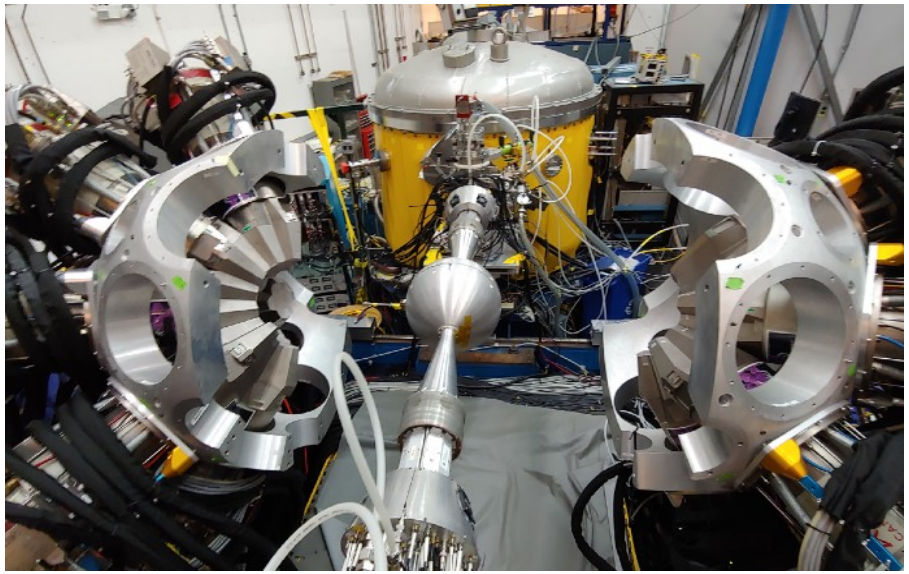
Integration of the digital FMA DAQ with the GRETINA DAQ
D. Seweryniak *et. al.*

Core excitations and single-neutron states in ^{101}Sn
D. Seweryniak *et. al.*

Mirror-energy differences in the A=93, T=1/2 mirror pair ^{93}Ag-^{93}Pd
D. Seweryniak *et. al*

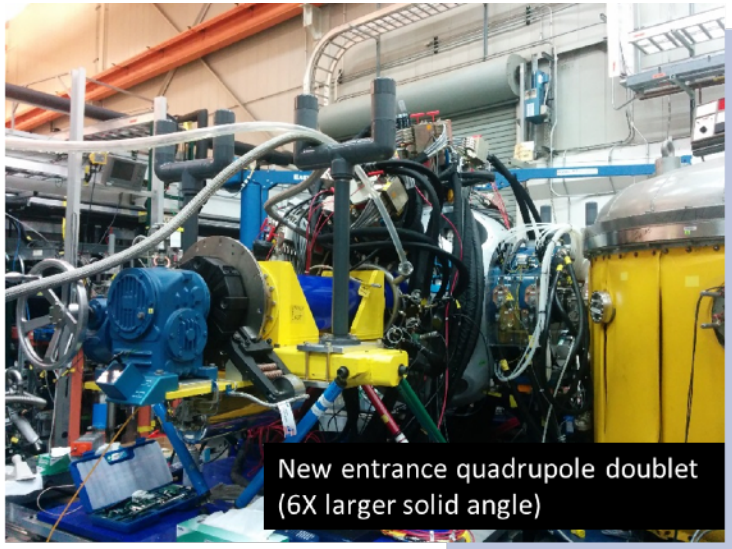
First Study of ^{38}S at High Excitation via Fusion Evaporation
C. R. Hoffman *et al.*

The importance of the ^{33}Cl(p,γ)^{34}Ar reaction in explosive binary systems : Spectroscopy of ^{34}Ar with GRETINA
G. Lotay *et. al*.

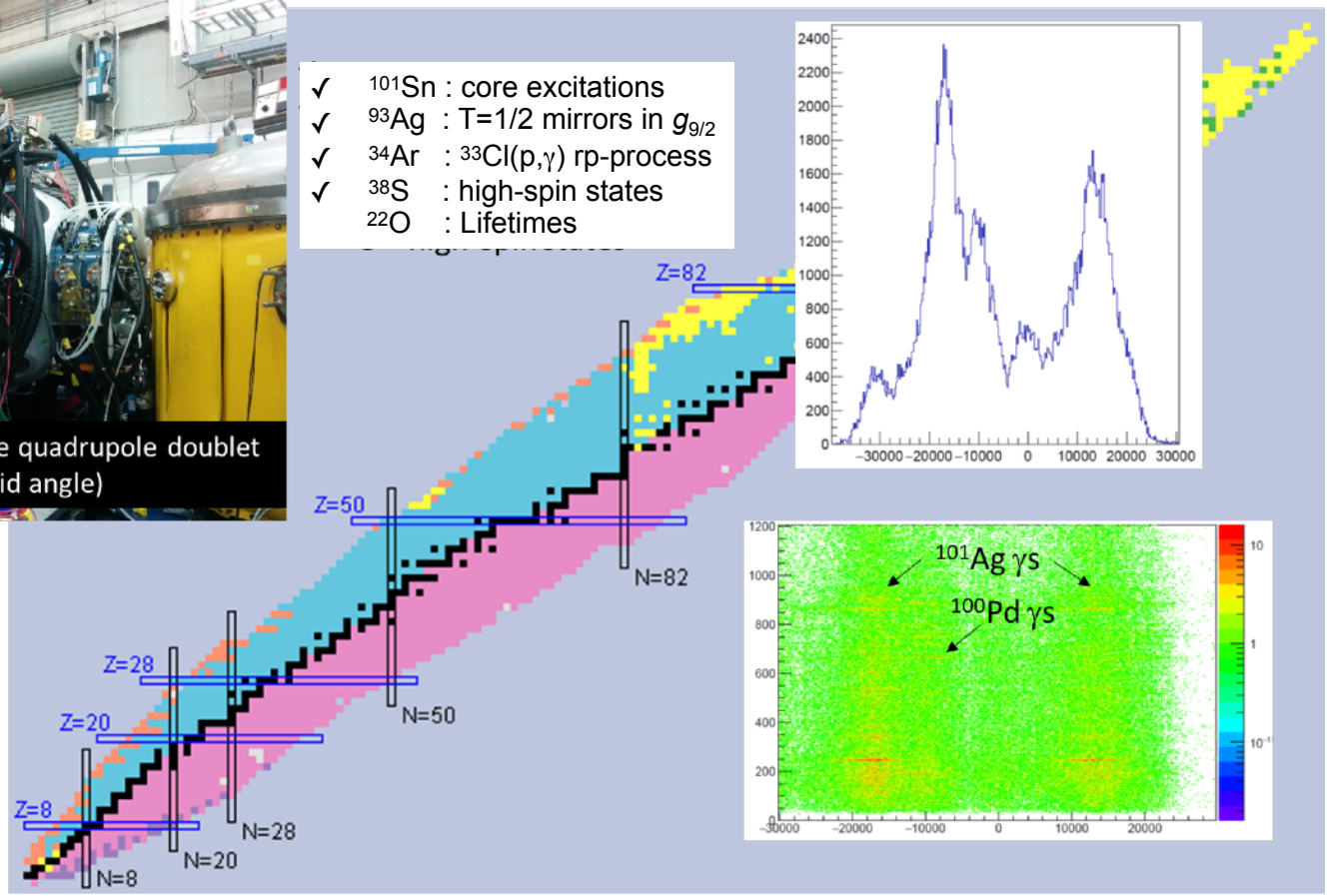


- Gammasphere target position ***90 cm*** from 1st quad (2msr)
- GRETINA target position ***30 cm*** from 1st quad (12msr)

GRETINA/FMA EXPERIMENTS



- ✓ ^{101}Sn : core excitations
- ✓ ^{93}Ag : T=1/2 mirrors in $g_{9/2}$
- ✓ ^{34}Ar : ^{33}Cl(p,γ) rp-process
- ✓ ^{38}S : high-spin states
- ^{22}O : Lifetimes



- High Ge singles γ rates
- High data rates
- Mass tagging
- ΔE tagging
- Recoil-decay tagging

Courtesy by D. Seweryniak

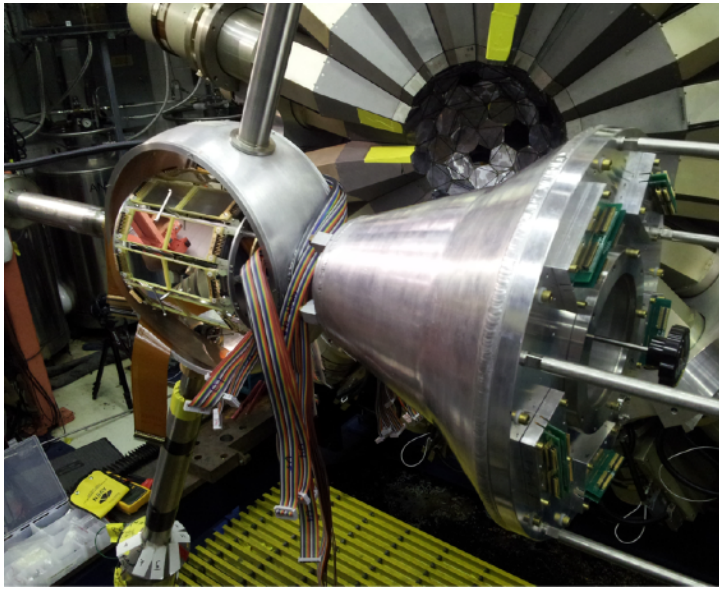
GRETINA – GODDESS EXPERIMENTS

Measurements of (d,pγ) on neutron-rich Xe and Te with CARIBU beams (CARIBU)
S. Pain *et. al.*

Constraining the ^{30}P(p,γ)^{31}S reaction using ^{30}P(d,pγ)^{31}P with GODDESS (In-flight-RAISOR)
S. Pain *et. al.*

Determining the E1/M1 polarization of the Low-energy Enhancement in the gamma-ray Strength Function of ^{56}Fe
M.D. Jones et. al

Deducing the ^{143}Ba(n,γ) cross section via surrogate (d,pγ) with GODDESS (CARIBU) Did Not Run
J. Cizewski *et. al.*



- GODDESS is a coupling of ORRUBA with forward and backward annular strip detectors for reaction studies with γ-rays. G-rays provide resolution when used with reactions in inverse kinematics.
- ~700 channels – DAQ synched with GRETINA resulting in synchronized timestamps.
- 3 experiments were during the current installation with GRETINA
- S. Pain (ORNL), J. Cizewski (Rutgers) and A. Ratkiewicz (LLNL)

LOW-ENERGY ENHANCEMENT IN THE γSF IN ^{56}Fe

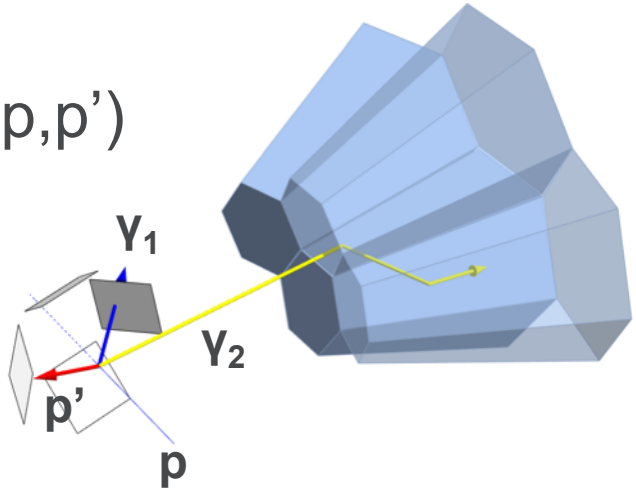
Extract γSF using a model independent method

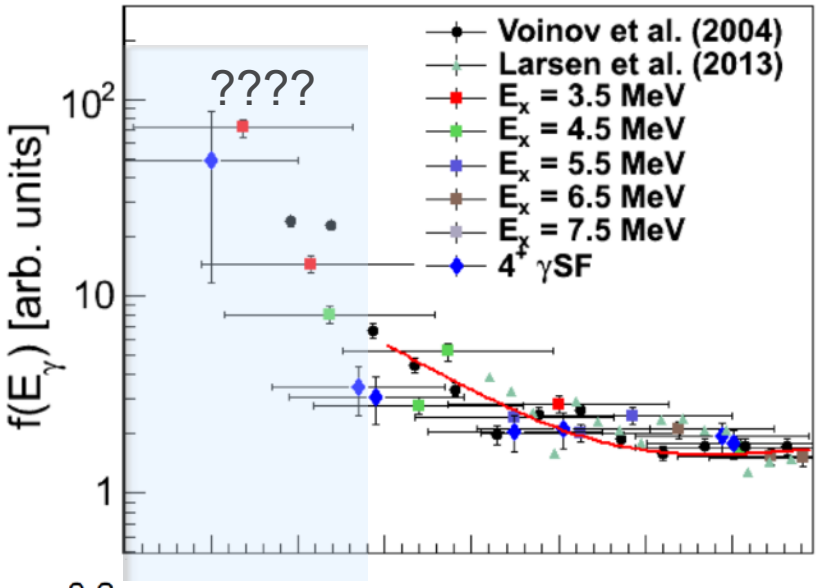
M. Wiedeking et al. PRL 108, 162503 (2012)

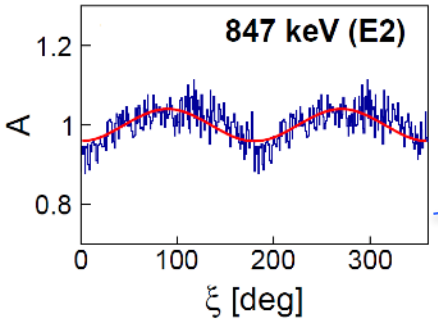
Determine M1/E1 character of the "up-bend" using GRETINA polarization sensitivity

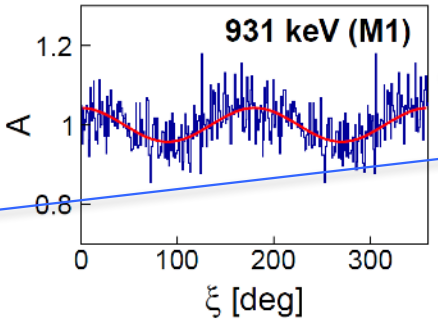
M. D. Jones et al. PRC 97, 024327 (2018) GRETINA @ ATLAS I

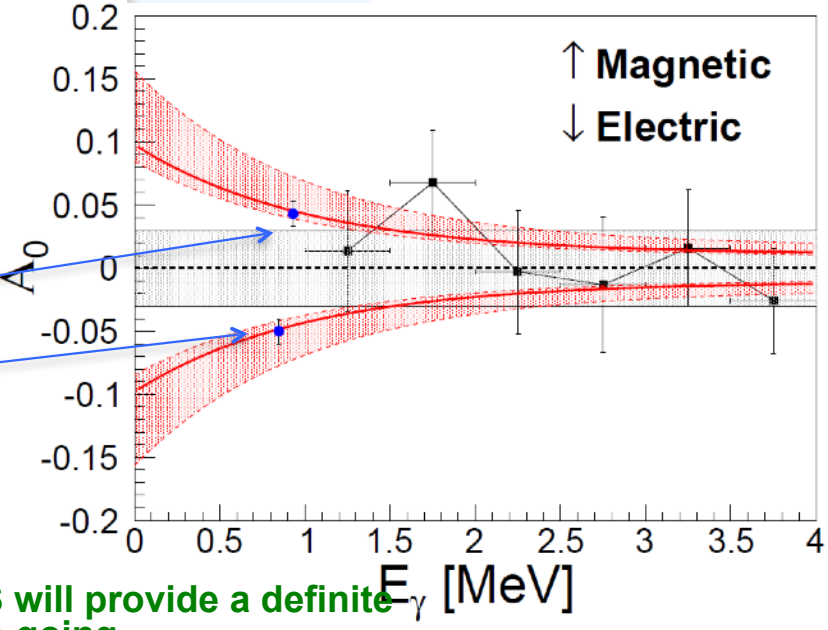
^{56}Fe(p,p')











Improved experiment with GODDESS will provide a definite answer(~ x10 statistics). Analysis on-going

SUMMARY

- Gammasphere has been successfully combined with the new AGFA separator and dedicated tape station for beta decays
- The next experiment will couple Gammasphere with Microball and FMA
- GRETINA had it's second ATLAS campaign running a program to maximize its physics reach using both stable and radioactive ions beams
- Lots of Collaborators: More than 100 scientists from more than 15 institutes.
- GRETINA will return to ATLAS in October 2020 and operate until ~2023 with current electronics and support frame – at which point detectors will become part of GRETA with new electronics and support structure.
- Thanks to M. Carpenter, S. Zhu, R.V.F. Janssens, A.O. Macchiavelli, D.T. Doherty, D. Seweryniak, and A.D. Ayangeakaa for allowing me use of their slides and presentation of their data.

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ORNL: J. M. Allmond

CHICO-II: C-Y. Wu, J. Henderson, D. Cline
LLNL and U. of Rochester

GODDESS: S. Pain, K. Chipps, A. Ratkiewicz, J. Cizewski, and many others.
ORNL, LLNL, Rutgers, Univ. TN, Univ. Notre Dame

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THANKS FOR YOUR ATTENTION!