NSAC LONG RANGE PLAN TOWN HALL MEETING ON NUCLEAR STRUCTURE, REACTIONS AND ASTROPHYSICS

Argonne NATIONAL LABORATORY | 75 1946–2021

NUCLEAR DATA NEEDS FOR NUCLEAR STRUCTURE

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U.S. DEPARTMENT OF ENERGY
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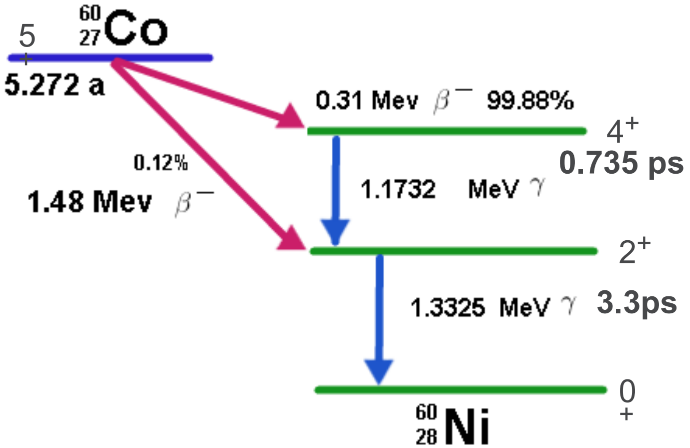
CONCLUSIONS OF 2016 WORKSHOP AT ND

Lead editors: F.G. Kondev and M. Thoennessen

- *The evaluated data should be reliable, comprehensive and up-to-date. To achieve this goal there should be continuous funding support for the existing data evaluators and an expansion of the pool of skilled nuclear structure data evaluators is imperative for succession planning.*
- *Capabilities for the compilation and evaluation of new and more complex data types should be developed.*
- *Connections to nuclear astrophysics research needs to be strengthened and expanded.*
- *Connections to theoretical databases should be established.*
- *Accessibility to the databases should be improved.*
- *Compilation of new data should be ensured by the generators of the data (US).*

WHAT IS NUCLEAR STRUCTURE



E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ	γ mult.	Final level	
0.0	ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijkl	0+	STABLE					
1332.514 *4*	ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijkl	2+	0.735 ps *21*	1332.501 *5*	100	E2	0.0	0+
2158.632 *18*	ABCDEFGHIJKLMNOPQRSTU XYZab gh jkl	2+	0.59 ps *17*	826.06 *3* 2158.57 *10*	100.0 *24* 17.6 *24*	M1+E2 (E2)	1332.514 0.0	2+ 0+
2284.80 *4*	CD FG JKLM O RST b g kl	0+	> 1.5 ps	952.4 *2* 2284.87	100	 E0	1332.514 0.0	2+ 0+
2505.753 *4*	A CDEFGHIJKLMNOPQRSTUVWXYZab de g j	4+	3.3 ps *10*	347.14 *7* 1173.228 *3* 2505.692 *5*	0.0076 *5* 100.00 *3* 2.0E-6 *4*	E2 E2(+M3) [E4]	2158.632 1332.514 0.0	2+ 2+ 0+
2626.06 *5*	CDEFGHIJKLM OP R U YZ b gh	3+	≈ 0.6 ps	120.5 *3* 467.3 *2* 1293.7 *2*	5.5 *5* 100 *5* 53 *5*	M1+E2 M1(+E2) M1+E2	2505.753 2158.632 1332.514	4+ 2+ 2+

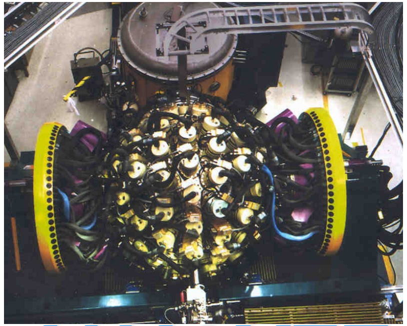
- Excitation Energy
- Spin
- Parity
- Lifetime
- Decay Modes
- Decay Branching
- Spectroscopic Factor

← Evaluated and compiled into ENDSF

Nuclear structure studies are aimed at identifying properties of nuclear states in order to determine the state's intrinsic structure and compare with theory.

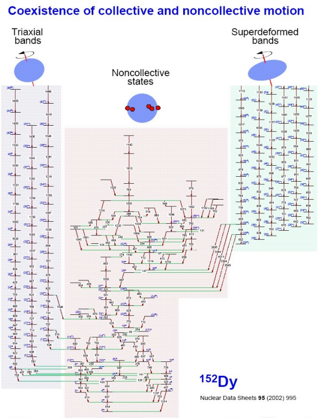
HOW DO EXPERIMENTERS INTERACT WITH ENSDF

MEASURE



ANALYZE

PLAN



PUBLISH

UPDATE

EVALUATE

LOTS OF DATA BEING GENERATED WORLD WIDE

Compton Suppressed Arrays:

- *Gammasphere – ATLAS*
- Jurosphere – *Finland*
- Ceasar – *Australia*
- GASP – *Italy*
- Bejing - China

Clover Arrays:

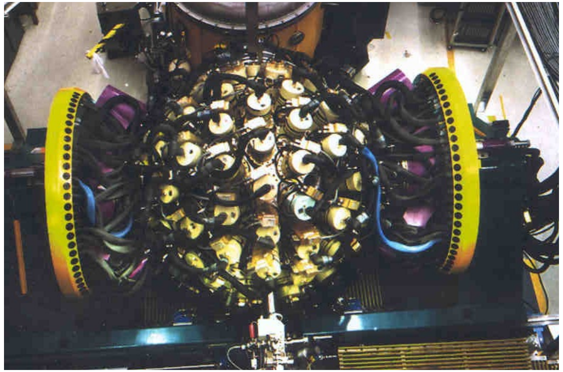
- Tigress, Griffin - *Canada*
- *Clarion – FSU*
- *FDSi – FRIB*
- *X-ARRAY - ATLAS*
- Aphrodite – *South Africa*
- EXOGAM - *France*
- INGA I & 2 - *India*
- CAGRA – *Japan*
- Lanzhou – *China*

Tracking Arrays:

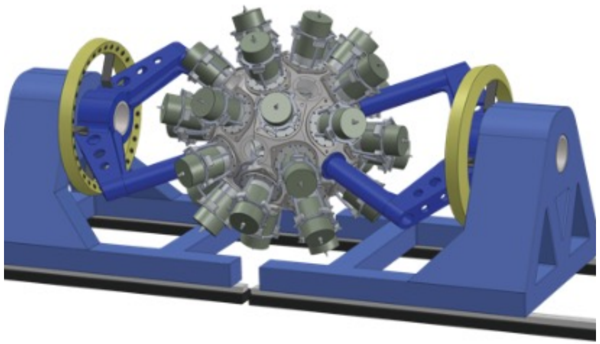
- *GRETINA/GRETA – FRIB*
- AGATA – *Europe*

Others:

- *SEGA – U.S.*



Gammasphere



GRETINA/GRETA

$_{56}$BA ISOTOPES

Neutron-Rich

No excited states identified →

149	150	151	152

139 GS SF	140 GS,EB IF,SF	141 GS,EB SF	142 GS,EB SF	143 GS,EB SF	144 G,E,GR SF,CE	145 GS,EB SF	146 G,E,GR SF,CE	147 GS,EB SF	148 GS,EB SF

130 IN HI	131 IN HI	132 NB HI	133 NB HI	134 HI	135 IN HI	136 GS DI	137	138 EB IF

← N=82

119 GS HI	120 GS HI	121 NB HI	122 GP HI	123 TS HI	124 GS,EB HI	125 EB HI	126 8π HI	127 8π,GP HI	128 GP HI	129 CS,GP HI

114	115	116	117

← No excited states identified

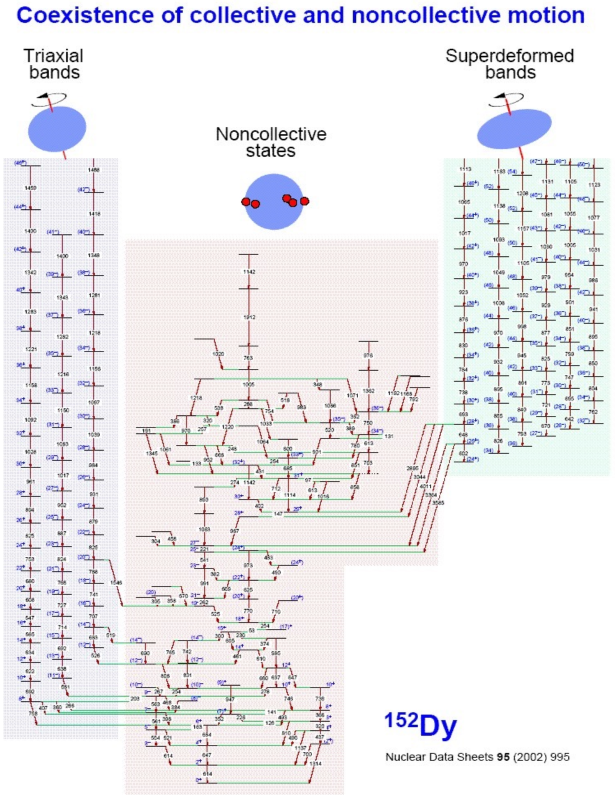
Proton-Rich

- 34 isotopes of Ba have been identified
- 8 isotopes' have no identified excited states
- 25 of 26 remaining isotopes have been examined by γ-ray arrays using prompt spectroscopy.

Symbol	Reaction
HI	HI Evaporation
CE	Coulomb Ex.
DI	Deep Inelastic
IF	Induced Fission
SF	Spont. Fission

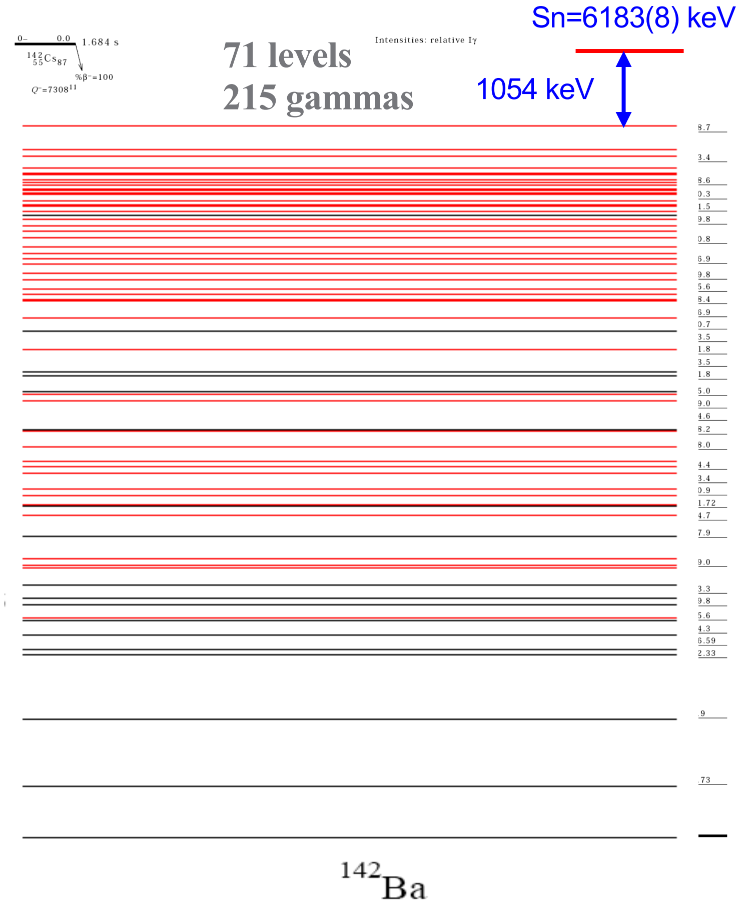
	γ-Ray Array
GS	Gammasphere
EB	Eurogam/Euroball
GR	GRETINA
NB	Nordball
CE	CEASAR
IN	INGA
TE	Tessa
GP	Gasp

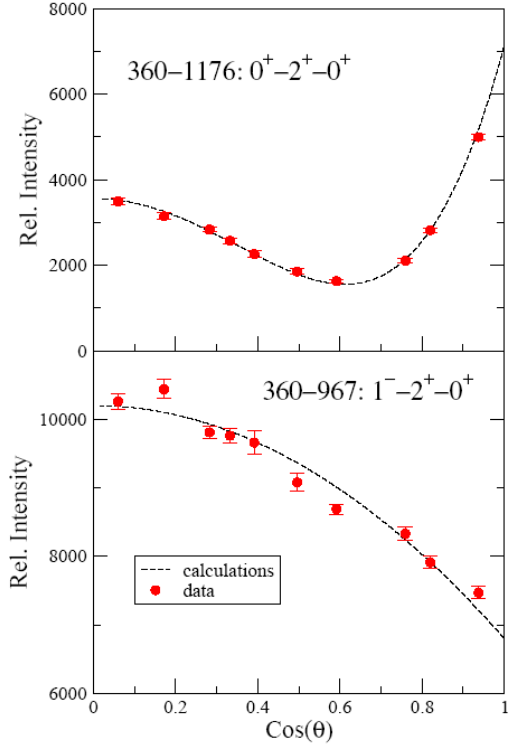
MEASURE NUCLEAR LEVELS AND PROPERTIES



- Level sequences determined by measuring de-excitation γ rays in coincidence (2-fold, 3-fold, …).
- Lifetime information is often crucial to characterize state and can be measured using RDDM or DSAM.
- Spins and parities of levels can be determined from gamma-ray angular distributions, angular correlations and polarizations.
- Coulomb excitation using RIB's are yielding new and valuable information on properties of excited states in nuclei – (NSCL, RIBF, CARIBU, REX-ISOLDE, TRIUMF).

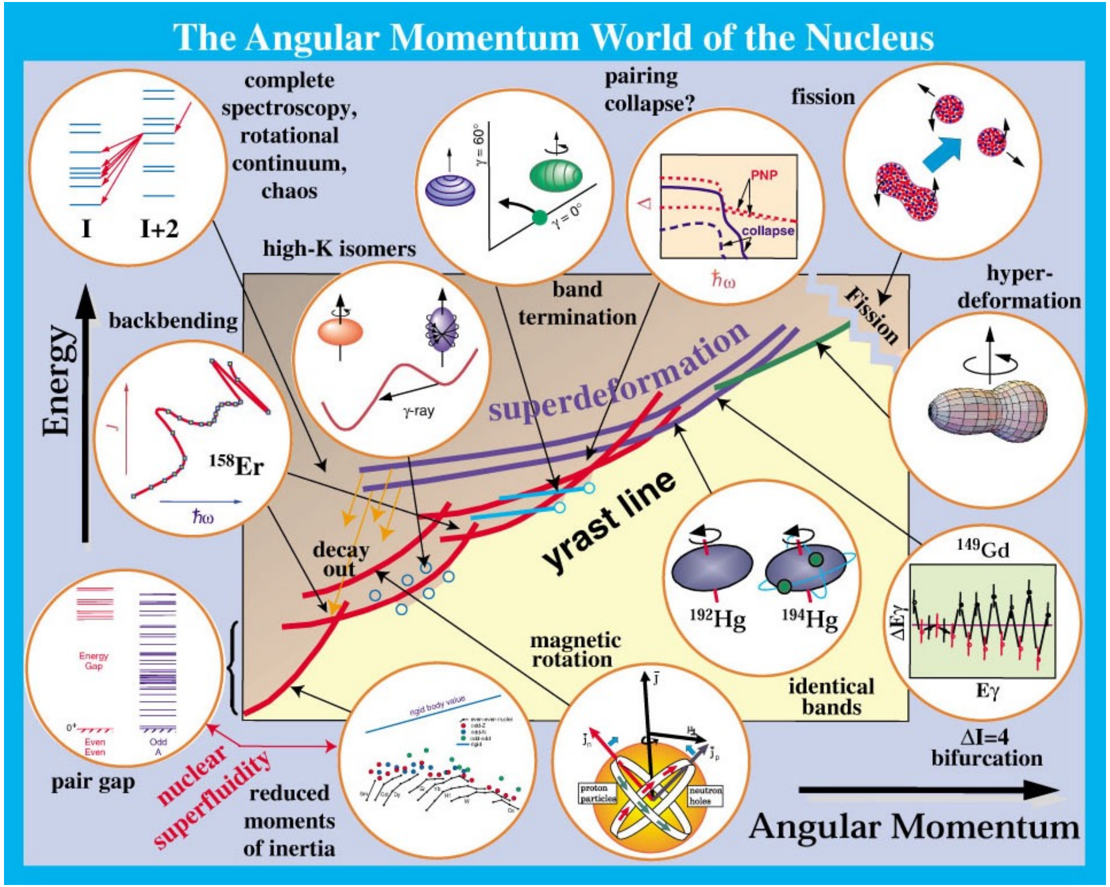
BETA DECAY STUDY OF ^{142}Ba WITH GAMMASPHERE





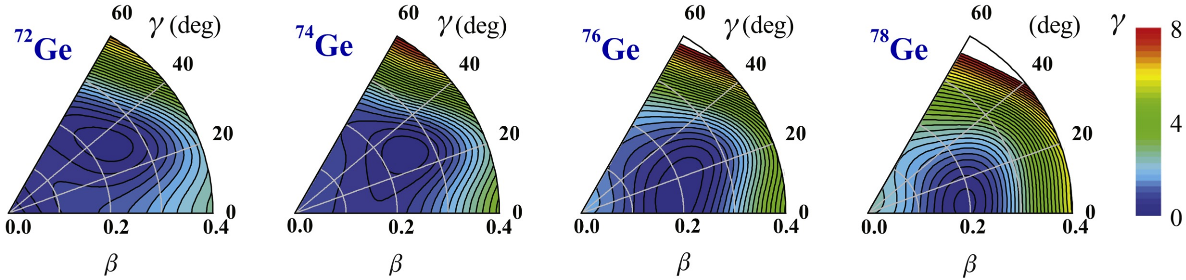
Shaofei Zhu

THE FRUITS OF OUR LABOR: UNDERSTANDING



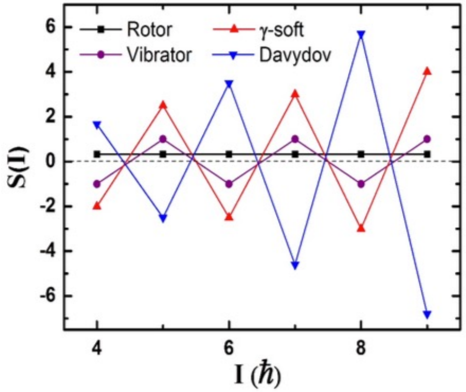
TRIAXIALITY IN GE ISOTOPES

Triaxiality plays a role in structure of Ge isotopes

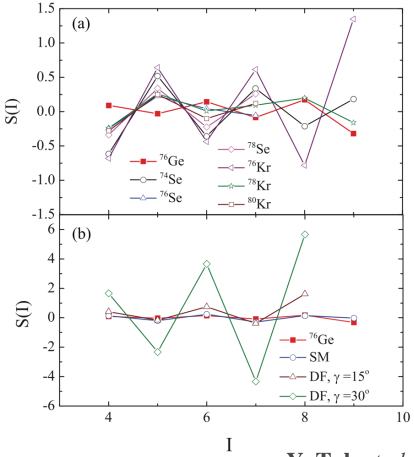


J.J. Sun *et al.* *Physics Letters **B 734** (2014) 308–313*

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



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

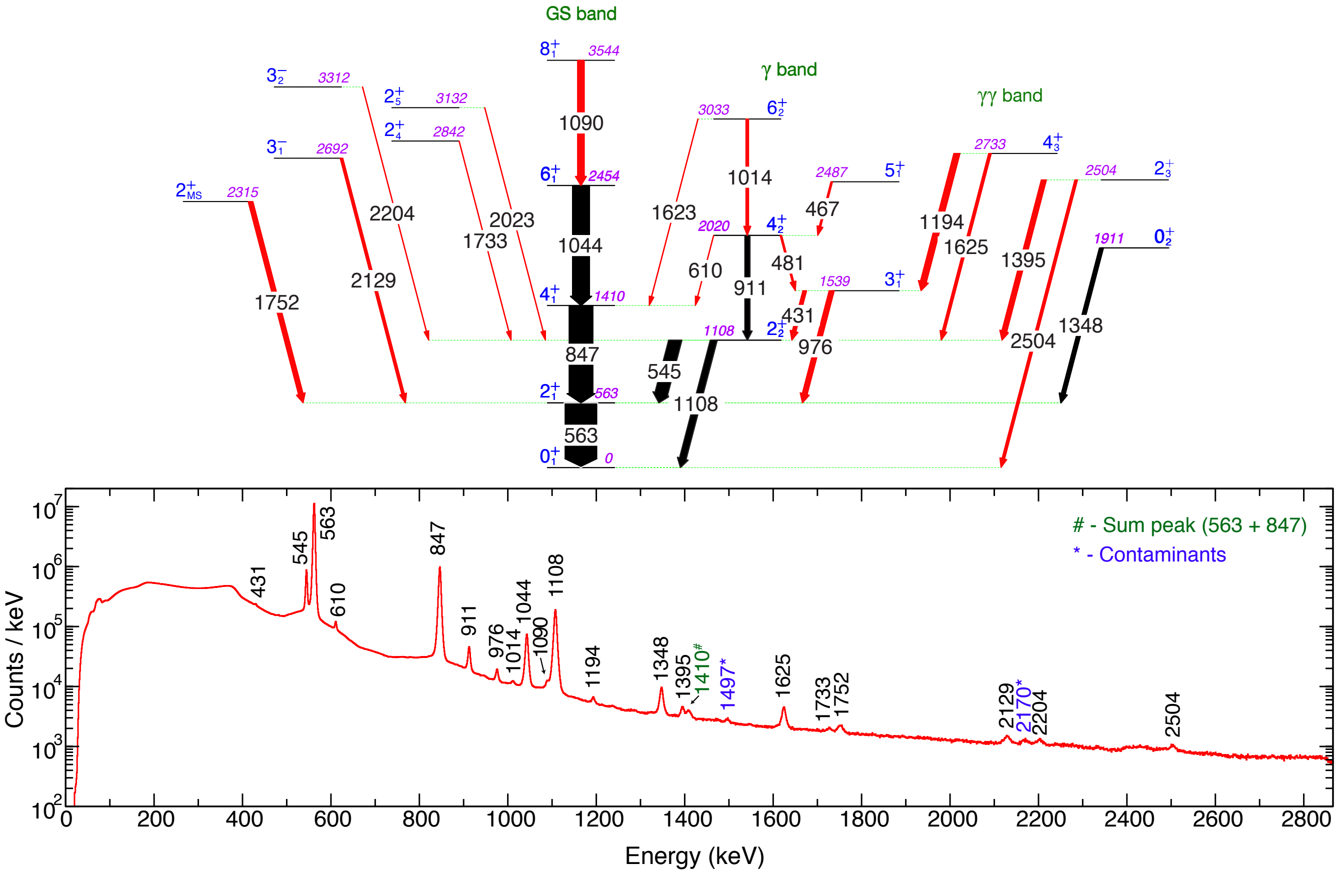


Y. Toh *et al*. Phys. Rev. C**87**, 041304(R) (2013)

Energy Staggering for the γ bands provide evidence of triaxiality

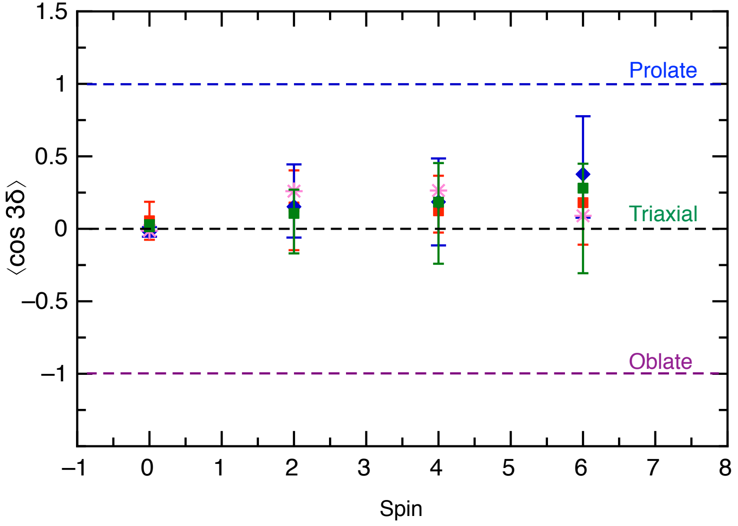
Are energies alone sufficient to answer the question of RIGID triaxiality in ^{76}Ge?

^{76}Ge COULOMB EXCITATION GRETINA/CHICO II

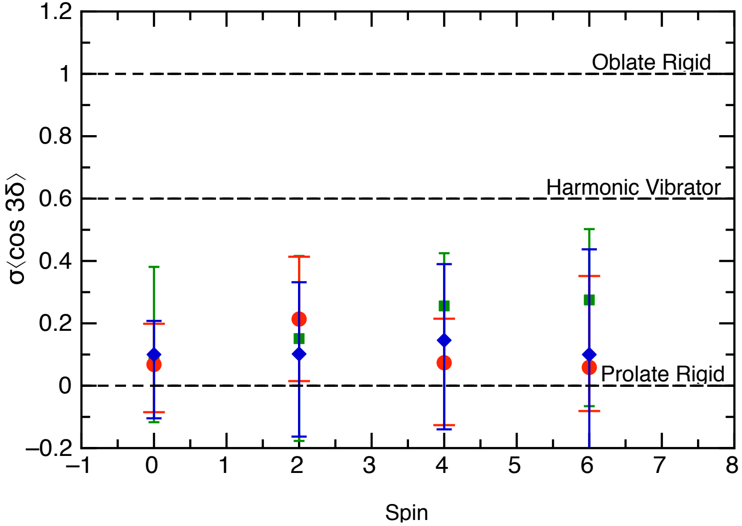


MATRIX ELEMENTS FROM GOSIA ANALYSIS

⟨cos 3δ⟩



σ⟨cos 3δ⟩



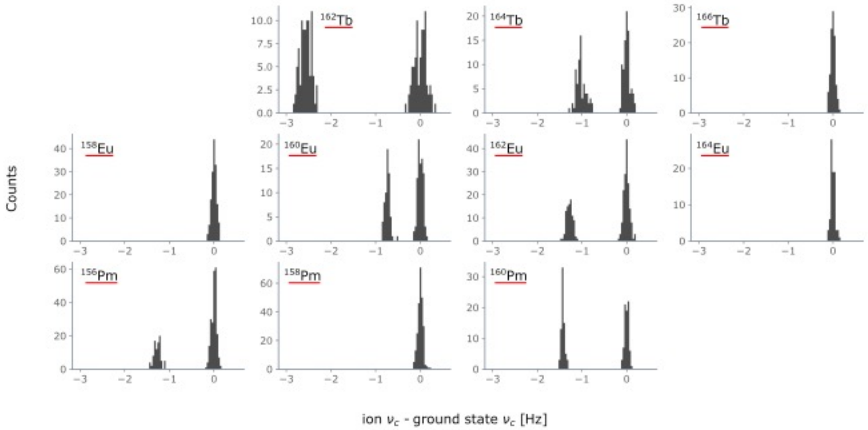
- The expectation values of the asymmetry of the intrinsic frame E2 properties of the ground-state band are determined as a function of spin and indicate a triaxial shape ⟨cos 3δ⟩ .
- Statistical fluctuation or variance of the asymmetry deformation for the ground-state band is determined σ⟨cos 3δ⟩ and indicates that ground state band exhibits a “static” triaxial shape.

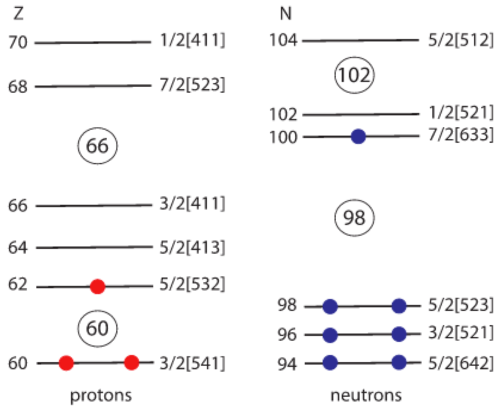
A. D. Ayangeakaa *et al.*, Phys. Rev. Lett. **123**, 102501 (2019).

IDENTIFYING ISOMERIC STATES IN NUCLEI

Penning trap identifies excitation energy of excited states

R. Orford *et al.*, PRC **102**, 011303 (2020).

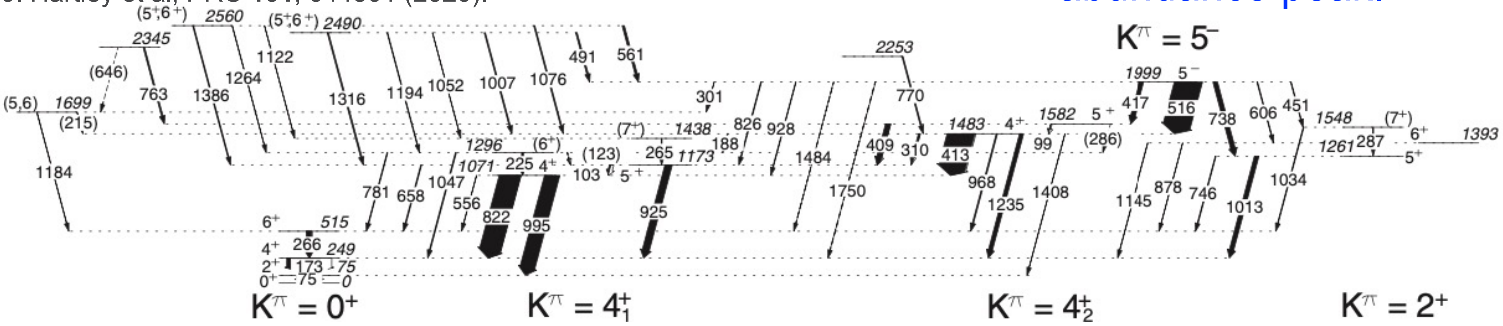




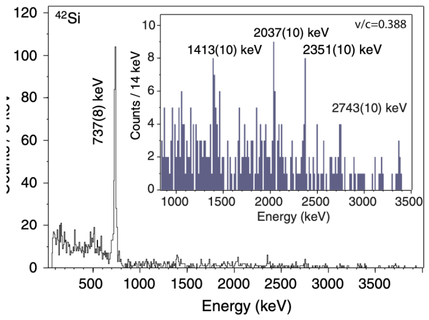
Data understood if deformed shell gap at N=98 – implications for rare-earth abundance peak.

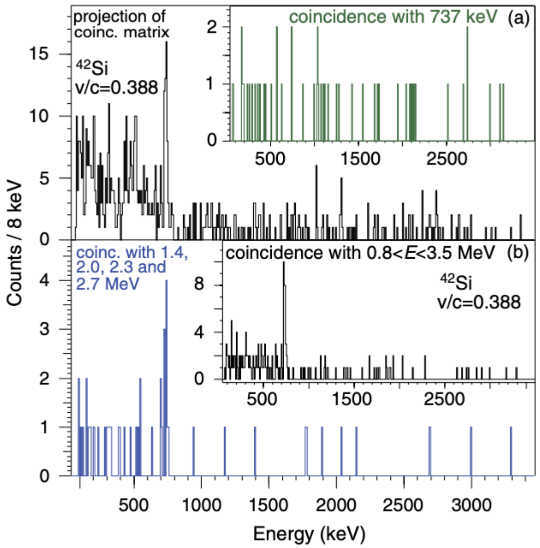
Decay of isomer in ^{160}Eu feeds high-K states in ^{160}Gd

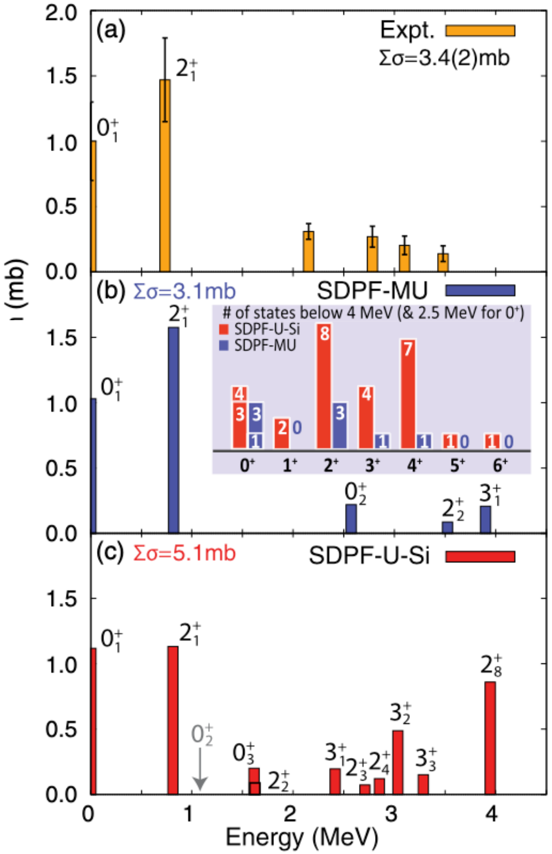
D. J. Hartley et al, PRC **101**, 044301 (2020).

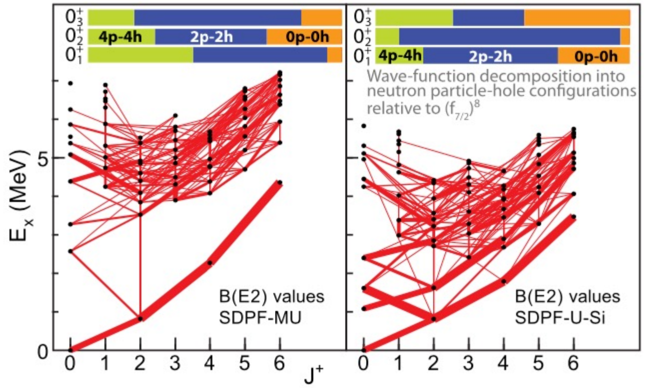


KNOCKOUT REACTIONS AT NSCL





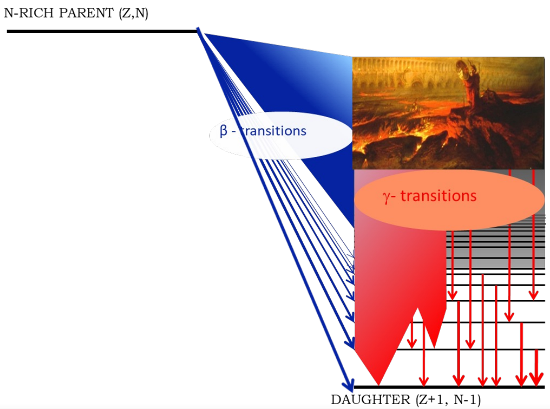


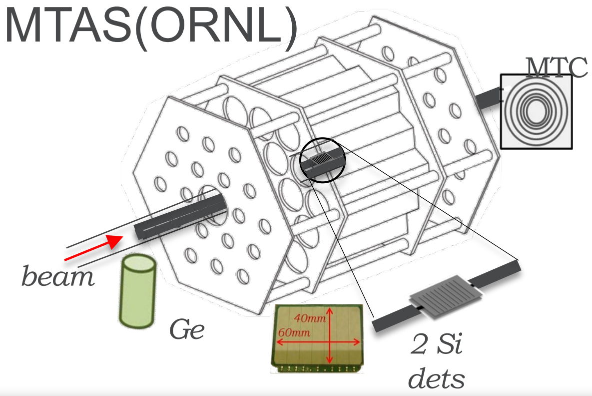


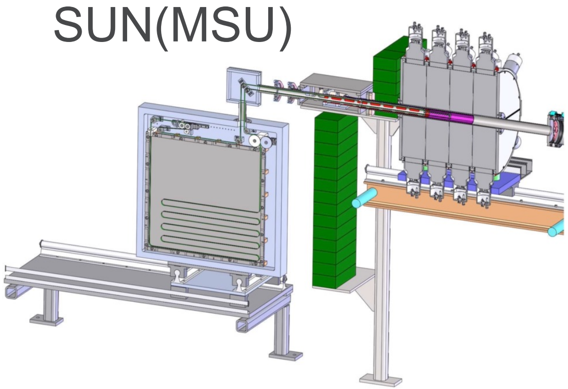
- Two shell model calculations reproduce 2^+ energy, but have vastly different predictions of higher lying states
- Identified states and γ-decay pathway, distinguish the two models.
- Neither produce the excited states in ^{40}Mg (coupling to continuum).

A. Gade *et al.*, PRL **122**, 222501 (2019)

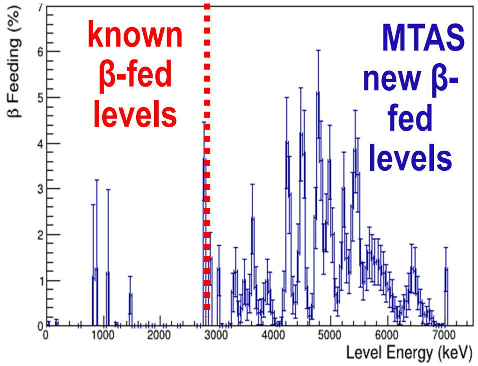
CONTINUUM MEASUREMENTS:





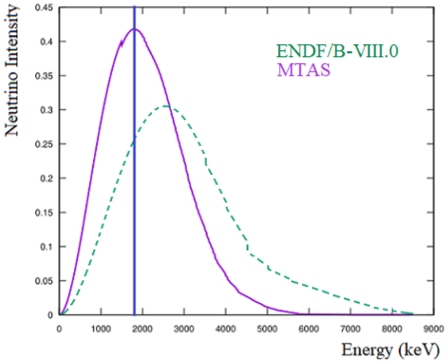


^{104}Nb β-decay ENSDF/ENDF vs MTAS



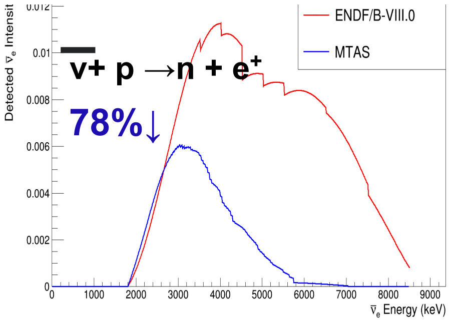
New β-feeding distribution ^{104}Nb⟶^{104}Tc

Anti-neutrino spectra ^{104}Nb β-decay



Note a shift of anti-neutrino spectra towards lower energies

^{104}Nb anti-neutrino - proton interactions

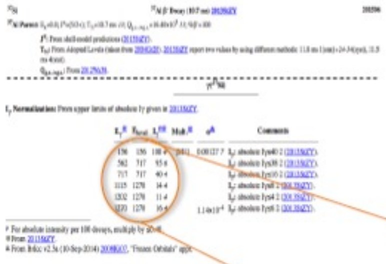


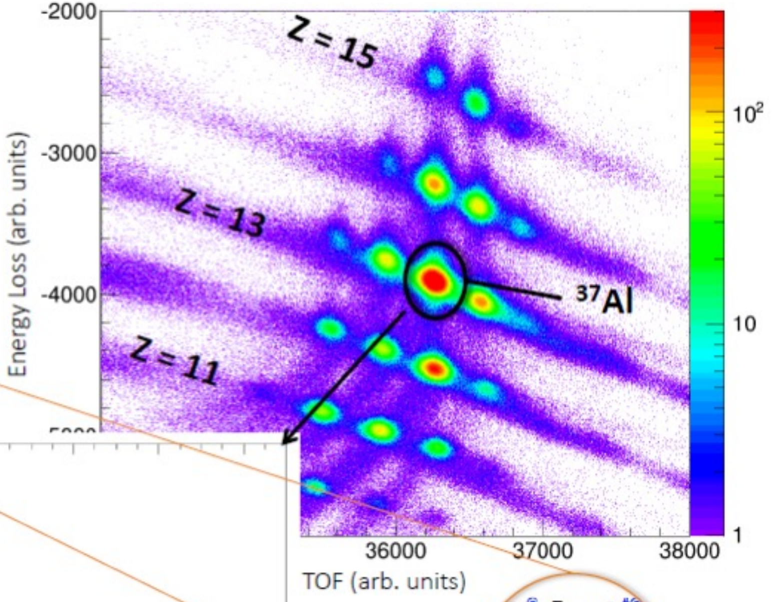
Reduction of the interacting ν-flux lowers Reactor Anti-neutrino anomaly and increases "high energy bump"

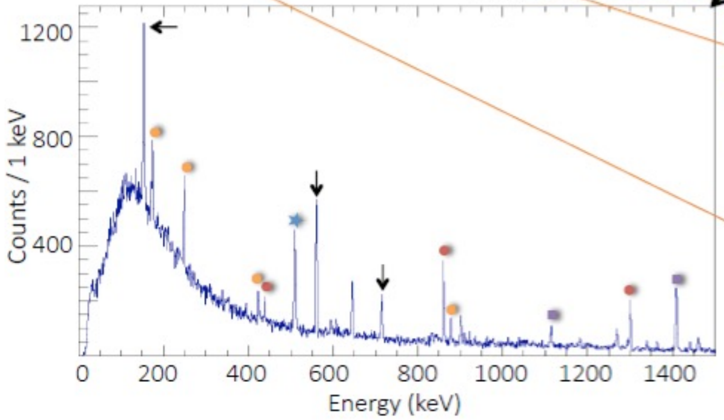
A. Laminack, C. Rasco, O. Fijałkowska *et al.*, 2022 → *PRC Letters*

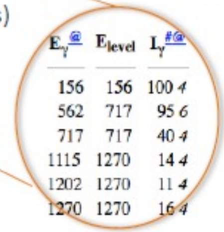
USE OF ENSDF TO VALIDATE EXP. DATA IN REAL TIME

- ENSDF data for ^{37}Si from ^{37}Al β decay









E_γ @	E_{level}	I_γ #@
156	156	100 4
562	717	95 6
717	717	40 4
1115	1270	14 4
1202	1270	11 4
1270	1270	16 4

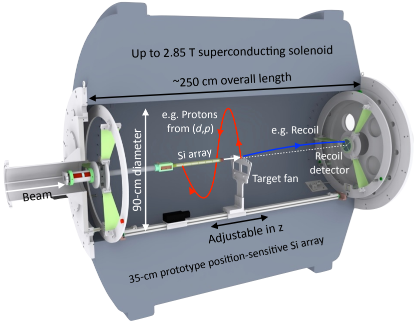
Figure 4 in 2016 WP

Taken from H. Crawford's presentation

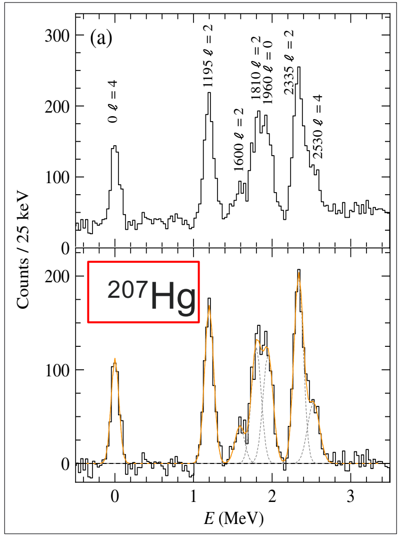
Could develop tool to use ENSDF intensities to calculate expected spectrum.

NUCLEAR STRUCTURE FROM DIRECT REACTIONS

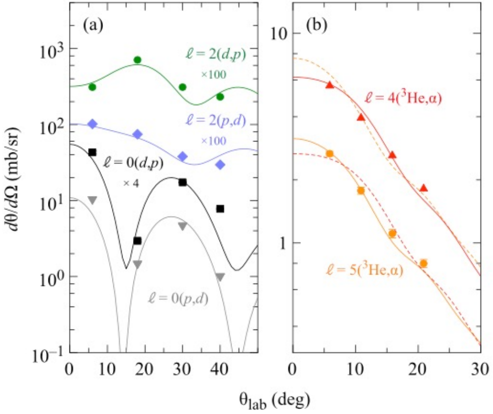
Solenoidal Spectrometers



HELIOS, SOLARIS, ISS

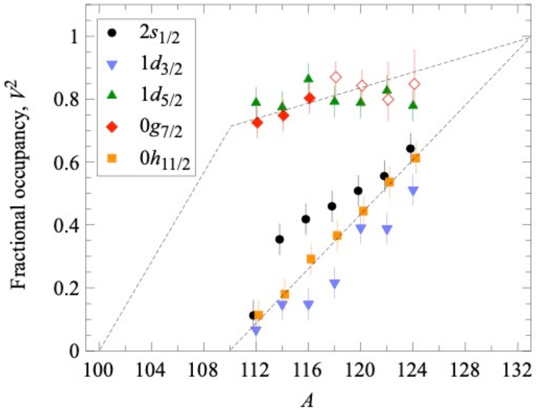


T. L. Tang et al., Phys. Rev. Lett. **124**, 062502 (**2020**)



Coupling Gretina with Goddess

- ATLAS – 5 MeV/A
- FRIB – 200 MeV/A



S. V. Szwec et al.,, Phys. Rev. C **104**, 054308 (2021).

Repurposed Magnetic Spectrographs at:

- FSU(Yale)
- Notre Dame(ORNL)
- TUNL

COMMENTS FROM B. KAY

- Cross Sections are the most important nuclear data from reactions – what is measured.
- Spectroscopic factors inform us about nuclear structure – while simple in concept, there are a wealth of subtleties.
- Much of what has been done in the field of transfer-reactions studies was recorded as spectroscopic factors and figures with angular distributions (cross sections)
  - Spectroscopic factors cannot be reanalyzed (models improve)
  - Figures can be poor quality and complex (hard to recover the cross sections)
- A mechanism should be established to encourage cross-section results to be made along with the publications *e.g., as* supplemental material.
- ENSDF format upgrade should allow for cross-section angular distributions could be entered into ENSDF.

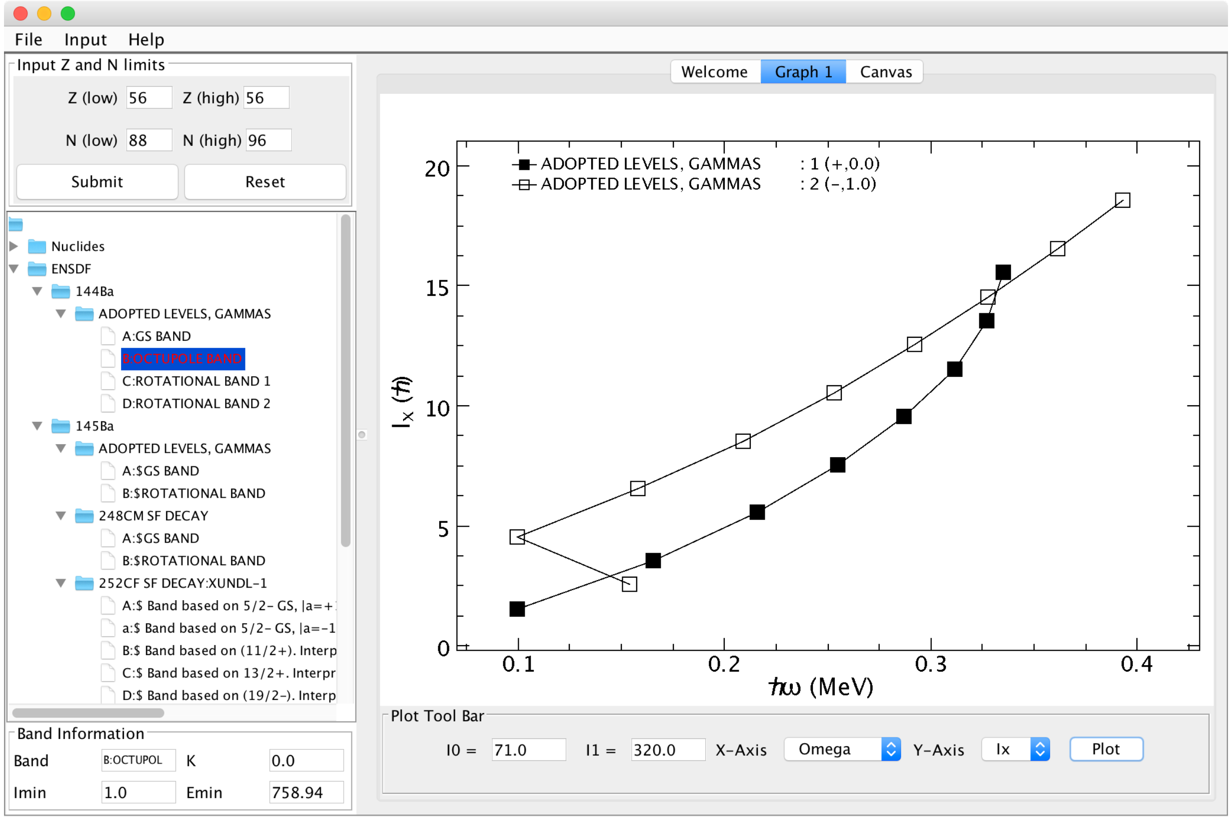
WHAT IS NEEDED (2016)?

- NP facilities continue to generate new-information on excited states in nuclei – input for ENSDF.
- Needs from USNDP are two-fold :
  - Evaluation of this data by USNDP in a timely way by Evaluators who are well versed in how data are taken and final level scheme's are deduced. Many of the evaluators have a strong background in γ-ray spectroscopy. ***Contributor***
  - Access of the data in pre and post evaluated stage (XUNDL and ENSDF)***. End User***

WHAT IS DESIRED?

- New tools to access both XUNDL and ENSDF in real-time in order to calculate and display quantities in our quest to understand our data and its significance to nuclear structure.

TOOL TO EXTRACT BAND INFORMATION FROM ENSDF



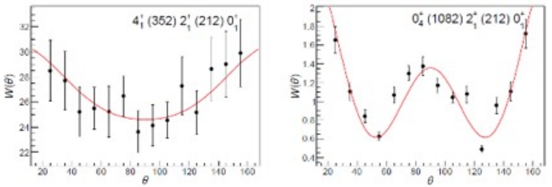
This tool illustrates the potential of harvesting the information in ENSDF/XUNDL

β-DECAY FACTORY AT CARIBU

Gammasphere Decay Station

- β–γ coincidences for proper feeding intensities
- γ–γ, γ–γ–γ for level structure determination and spin assignments from angular correlations
- Reduced summing and crystal to crystal scattering (in contrast to X-Array)
- Calorimetry provides information on excitation energy on event-by-event basis (Ge + BGO)
- Gammasphere electronics upgrade provides 3 copies of Ge central contact @ 4, 8 and 20 MeV full range

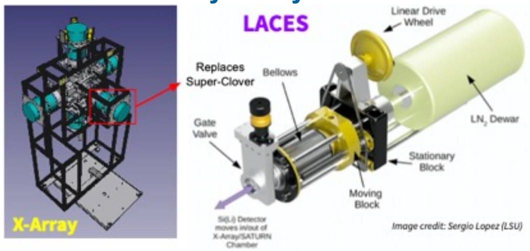
γ ray angular correlations following ^{100}Y beta decay with Gammasphere



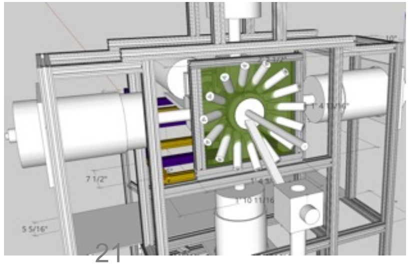
Saturn/X-Array Upgrades

- $LaBr_3$ to measure lifetimes – 2 rings, 15 1”x1” crystals each ring.
- Conversion electron measurements utilizing Laces (LSU)
- 2 BEGe detectors for low-energy gamma-ray and x-ray detection

Si(Li) detector system to couple with X-Array decay station



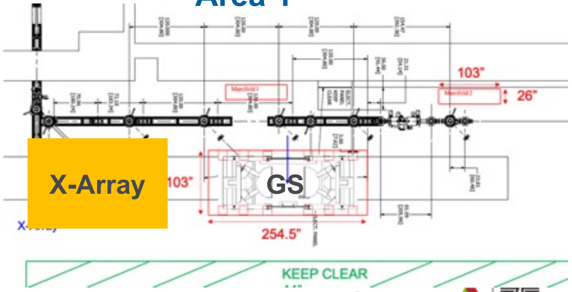
1 LaBr3 Ring @ X-Array



Beta Decay Factory

- Gammasphere upgrade project allows for relocation of device to Area 1.
- Using nuCARIBU, we estimate 2 orders of magnitude increase in implanted ions.
- Gammasphere gives multi-fold coincidences, total gamma-ray energy, angular correlations, for spin, parity, mixing rations.
- X-Array – lifetimes ($LaBr_3$), low-energy gamma detections (BEGe), conversion electron measurement (LACES).
- **Campaign of six months to measure 30-50 parent decays**

Area 1



HOW WOULD THIS MODEL OF DATA TAKING WORK?

- Generate a large amount of data on properties of excited states
  - Who would analyze it?
  - Who would evaluate it?
- Who has access to the data:
  - Data would likely be of interest to a broad community - basic and applied
  - How does one get access to the data?
- New integrated tool for data analysis:
  - More automated extraction of coincidence information for both level scheme building, angular correlation, lifetime extraction
  - Analysis tools need to be coupled to both ENSDF and XUNDL in real-time
- How can that analyzed data be evaluated and entered in ESNDF in a timely manner?

Based on Libby's talk yesterday and presentations today – USNDP is asking similar questions and engaged in providing solutions.

GETTING BACK TO STATED NEEDS FROM 2016

- *The evaluated data should be reliable, comprehensive and up-to-date. To achieve this goal there should be continuous funding support for the existing data evaluators and an expansion of the pool of skilled nuclear structure data evaluators is imperative for succession planning.* This need still exists – AI/ML techniques may help but skilled work force is key. Is this a funding issue?
- *Capabilities for the compilation and evaluation of new and more complex data types should be developed.* New database format for ENSDF should provide this capability. Examples: TAS data, cross-section angular distributions.
- *Accessibility to the databases should be improved*. USNDP will provide software to enable direct access to database information but how will that work? Can I directly download the database in order to integrate into my analysis codes?
- *Compilation of new data should be ensured by the generators of the data (US).* Group publishing results really needs to provide all relevant experimental details to enable proper evaluation of data.

SUMMARY

- NP facilities will continue to yield information on excited states in nuclei for the foreseeable future – ***World Wide Effort.*** It is important that the long-standing effort by USNDP continues to maintain both XUNDL and ENSDF.
  - FRIB providing new opportunities and new data (but more than NSCL?)
  - Tracking Arrays, GRETA and AGATA, will provide 2-3 times higher resolving power over Gammasphere (more detailed information).
- Need to incorporate our utilization of XUNDL and ENSDF in a more seamless way by developing tools and applications that give us easy access to these feature-rich databases both for analysis and real time data taking. USNDP has made great progress since 2016 here.
- This should be a community-based effort involving USNDP and end users – access to raw data, archiving of data analysis.