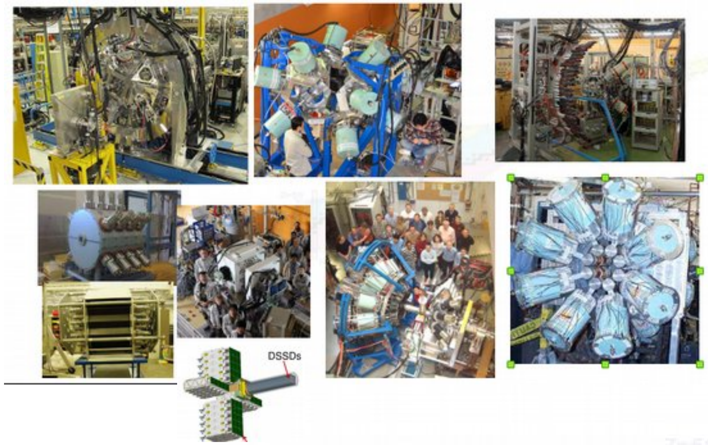
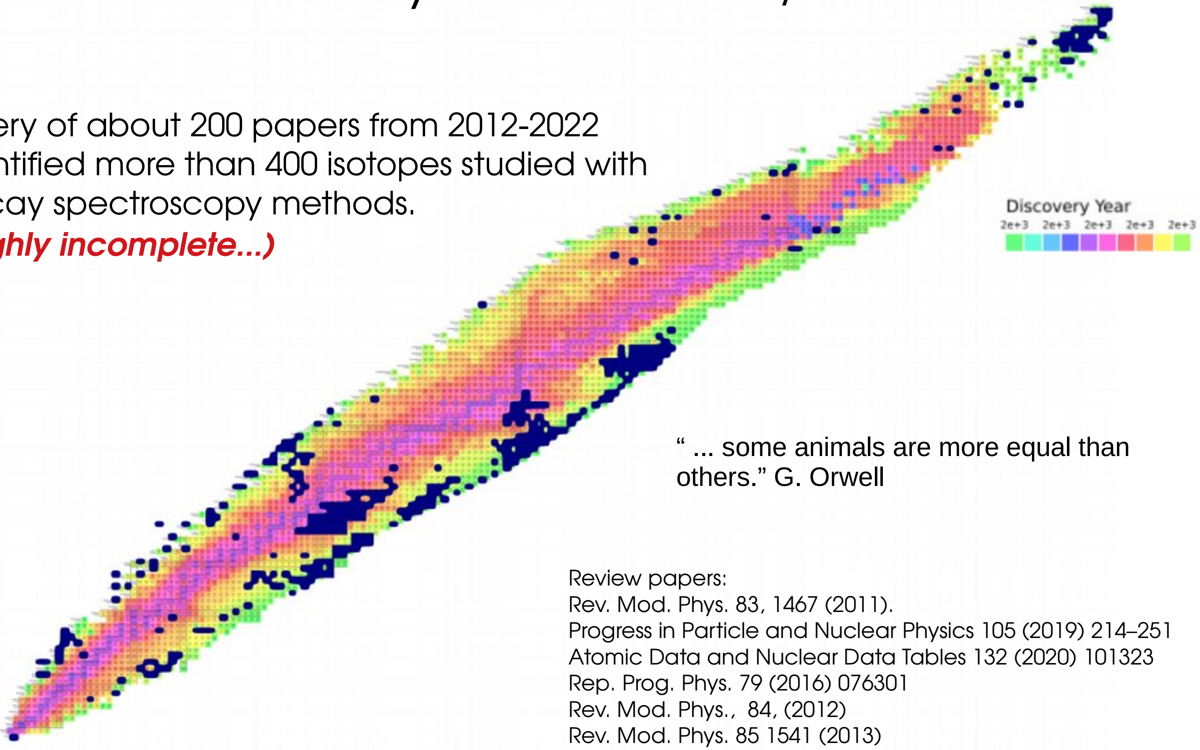
Decay spectroscopy - the Golden Age ?

Recent achievement and future prospects.

Robert Grzywacz
University of Tennessee/ORNL



Query of about 200 papers from 2012-2022 identified more than 400 isotopes studied with decay spectroscopy methods.
(Highly incomplete...)



" ... some animals are more equal than others." G. Orwell

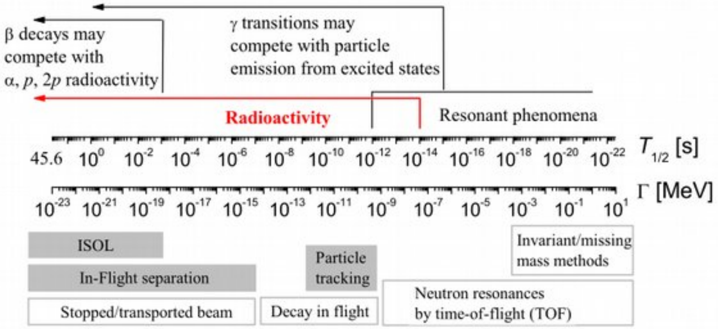
Review papers:
Rev. Mod. Phys. 83, 1467 (2011).
Progress in Particle and Nuclear Physics 105 (2019) 214–251
Atomic Data and Nuclear Data Tables 132 (2020) 101323
Rep. Prog. Phys. 79 (2016) 076301
Rev. Mod. Phys., 84, (2012)
Rev. Mod. Phys. 85 1541 (2013)
arXiv:2206.09271 (2022)

https://people.physics.anu.edu.au/~ecs103/chart/

Decay spectroscopy - relevance

Radioactive decays:

"...radiation is emitted ***spontaneously*** by a system whose nuclear and atomic degrees of freedom are ***close to equilibrium***."

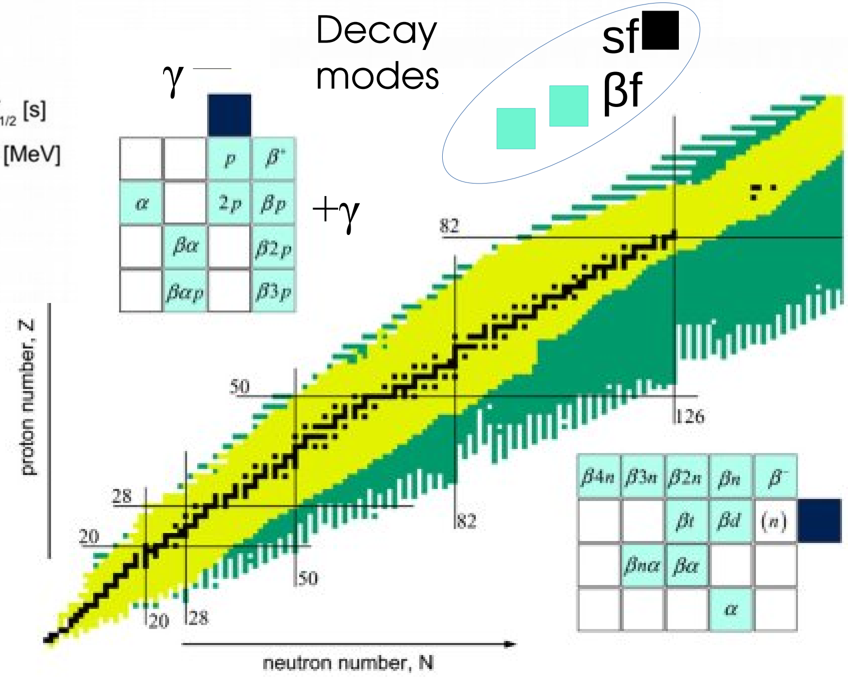


Rev. Mod. Phys., 84, (2012)

How does subatomic matter organize itself and what phenomena emerge?
How did visible matter come into being and how does it evolve?

What are the ***boundaries of existence*** in A, N and Z ?
What is the ***microscopic foundation*** of nuclear shell structure and the emergence of shapes, and how do these ***evolve across the nuclear chart***?
Are there new phenomena in ***loosely bound*** nuclear systems?

Nuclear decays are also sensitive to ***subnucleonic*** degrees of freedon (e.g. weak interactions, 3N forces)
and ***atomic*** properties (interaction with electrons).



Rev. Mod. Phys., 84, (2012)

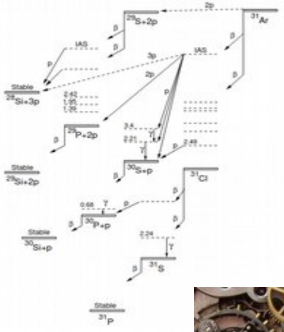
Decay spectroscopy - discover and explain

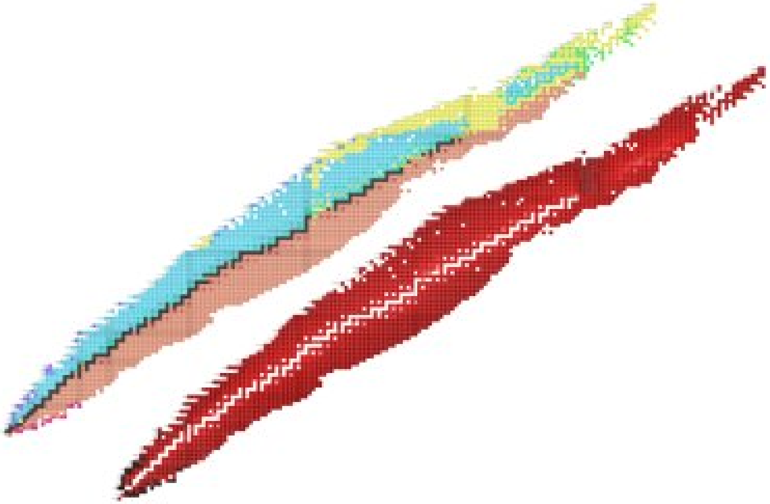
... what phenomena emerge ?

Decay measurements, first step with/after isotope/isomer identification

- Nuclear lifetime
- Primary decay mode.

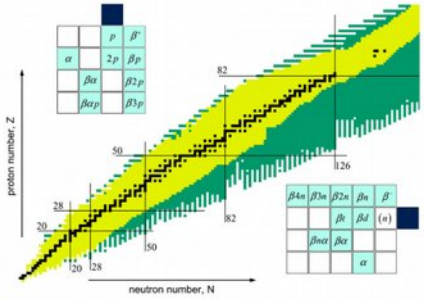
Provides ***very first test*** of nuclear models and ***sets the stage*** for future experiments.





How does subatomic matter organize itself ...

- Energy of emitted radiation
- Relative branching ratios
- Establish decay sequences
- Correlations, angular distributions



Rev. Mod. Phys., 84, (2012)

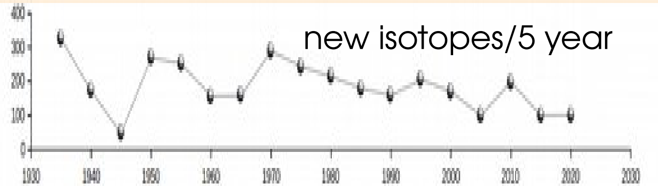
Universal !

What quantum effects influence decay properties ?

Can we extrapolate ?

Impact on other fields !

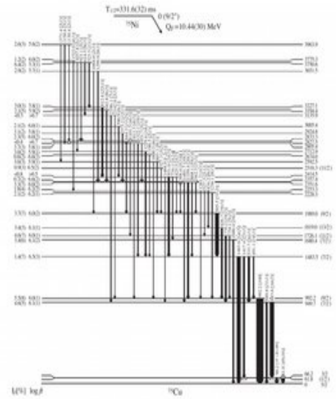
Looking back into last decade

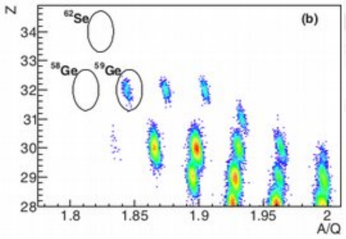


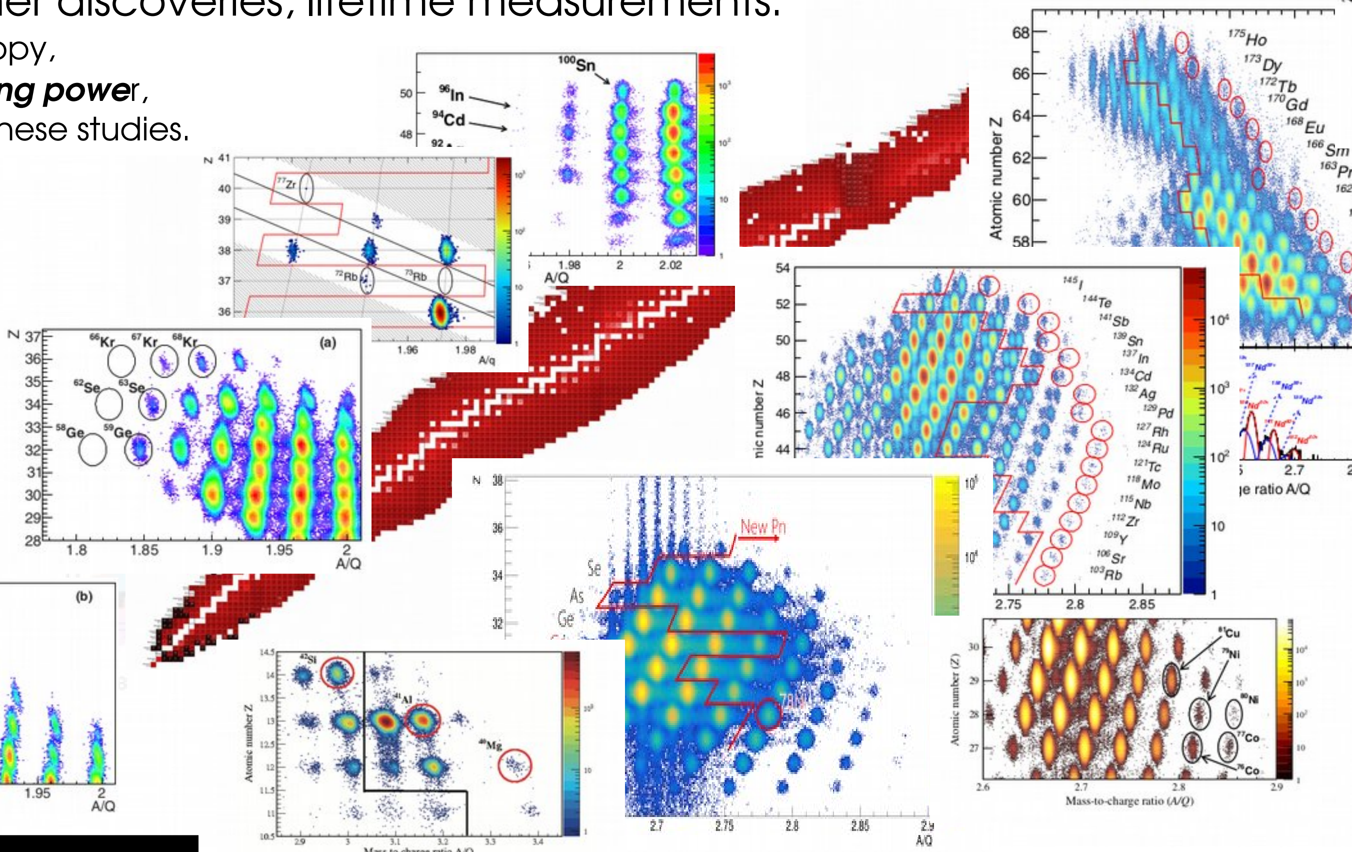
The power of the fragmentation reaction as a production method.

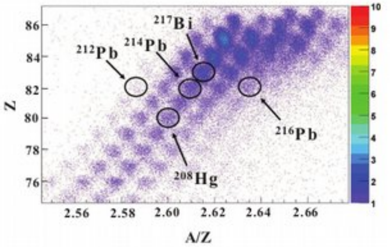
New isotope/isomer discoveries, lifetime measurements.

Gamma-ray spectroscopy,
owing to its ***high resolving powe***r,
played a major role in these studies.



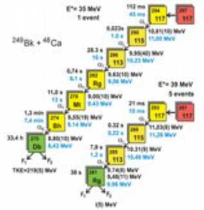
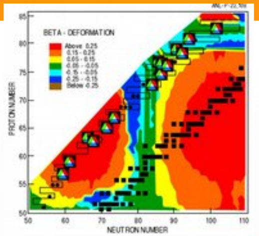


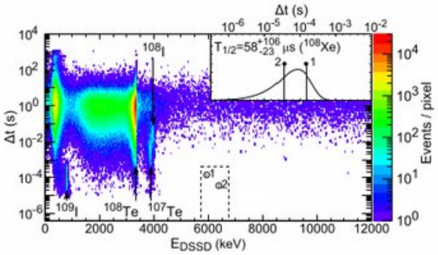


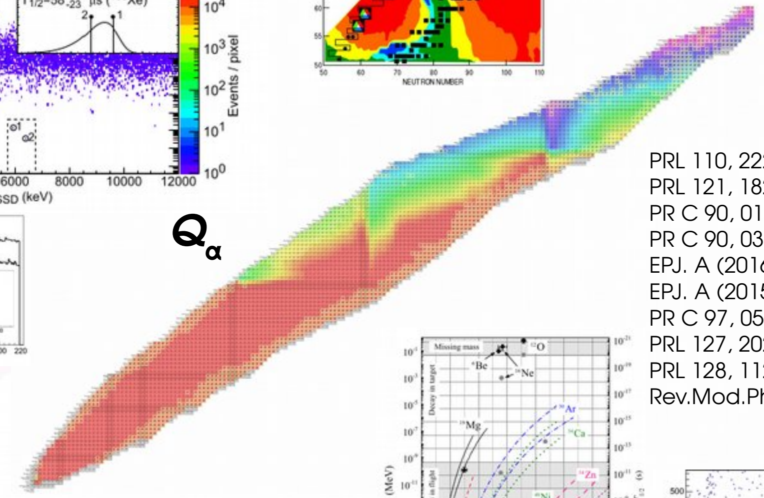


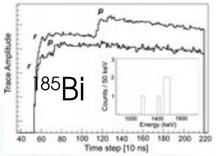
PRL 113, 032505 (2014)
PR C 90, 034317 (2014)
PR C 93, 061301(R) (2016)
PR C 95, 051601(R) (2017)
PR C 96, 034604 (2017)
PR C 100, 044311 (2019)
PR C 101, 042801(R) (2020)
PRL 114, 192501 (2015)
PRL 116, 162501 (2016)
PRL 118, 072701 (2017)
PRL 119, 192503 (2017)
....

Single step particle radioactivity







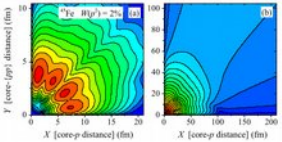
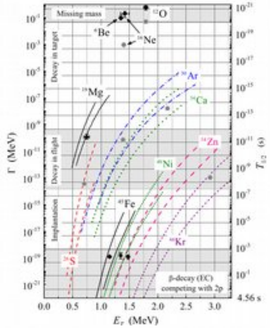
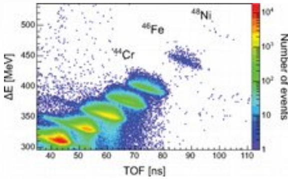
- Alpha decay

Precise Q_α and $T_{1/2}$ measurement,
Discovery ***tool*** for heavy and SHE nuclei
Alpha preformation
Superallowed alpha decay near ^{100}Sn.
Microscopic mechanism of alpha decay
Revisit the Gamow-Model ?

PRL 110, 222501 (2013).
PRL 121, 182501 (2018)
PR C 90, 014311 (2014)
PR C 90, 034317 (2014)
EPJ. A (2016) 52: 89
EPJ. A (2015) 51
PR C 97, 051301(R) (2018)
PRL 127, 202501 (2021)
PRL 128, 112501 (2022)
Rev.Mod.Phys., 84, (2012)

- Proton emission

"Spectroscopic factors" - nuclear structure at the drip-line.
3D barrier tunneling for deformed proton emitters.

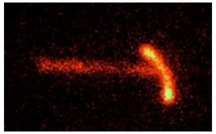
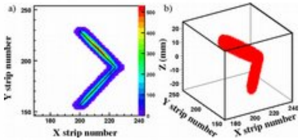




- Two-proton emission: ^{45}Fe, ^{48}Ni, ^{54}Zn, ^{67}Kr

"***nucleon-nucleon correlations***" and links to nuclear structure

- Discovery of 3p emission (^{31}K $T_{1/2}$<10 ps) PRL 123, 092502 (2019)

Can we observe ***neutron or two-neutron*** radioactivity?

Isomer spectroscopy - addiction to gambling

- Short lived isomers populated directly in the reaction surviving the transit time through electromagnetic separators (>100ns).
- Isomers populated through radioactive decays

(~1ns or longer).

Discovery tool, nuclear structure effects

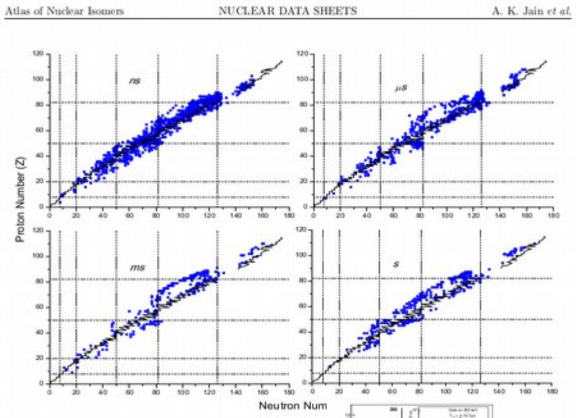
spin isomers, seniority isomers, shape isomers, K-isomers

Lifetimes. levels schemes, conversion electrons, g-factors

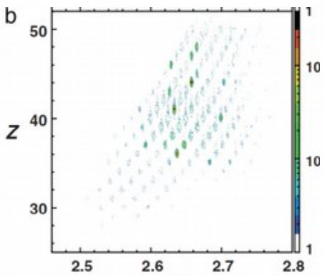
Shell evolution, nuclear shapes

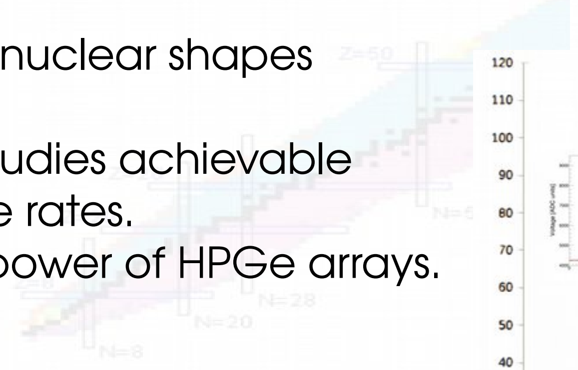
Very sensitive studies achievable with low isotope rates.

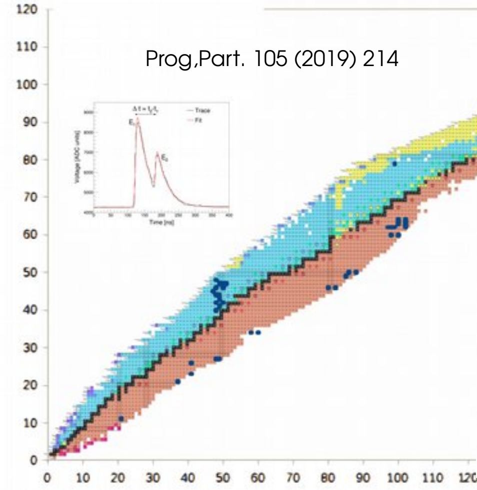
High-resolving power of HPGe arrays.



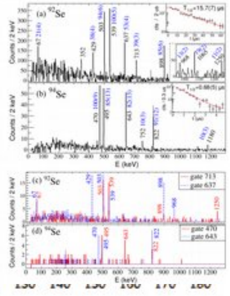
PRC 94, 064322 (2016)
PRL 113, 132502 (2014)
PRL 124, 222501 (2020)
PRC 90, 014311 (2014)
PRC 91, 064309 (2015)
PRC 92, 051305(R) (2015)
PRC 96, 034305 (2017)
PRC 96, 044311 (2017)
PRC 99, 021302(R) (2019)
PRC 100, 011302(R) (2019)
PRC 100, 024302 (2019)
PRC 100, 034309 (2019)
PRC 101, 011301(R) (2020)
PRC 103, 044307 (2021)
PRC 104, 014304 (2021)
PRC 106, 024309 (2022)

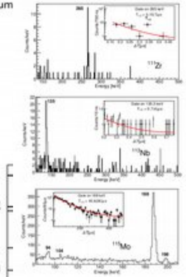


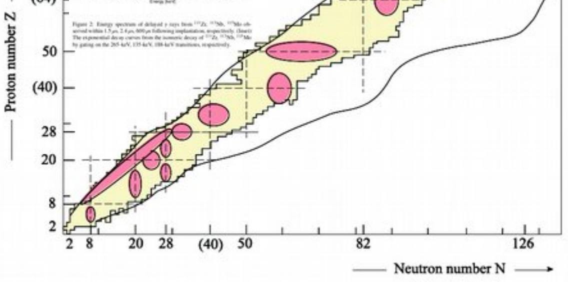




Prog,Part. 105 (2019) 214







K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011).

Beta decay: the most common decay mode

The strength distribution within Q_β determines decay properties.

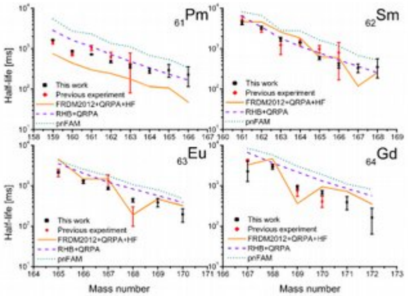
$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

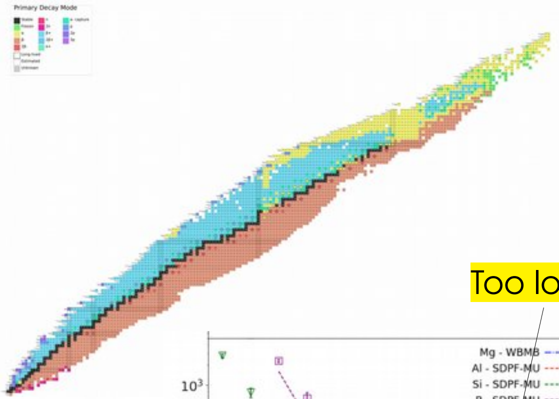
Lifetime measurements are difficult to provide feedback into nuclear models due to the distributed nature of the decay strength.

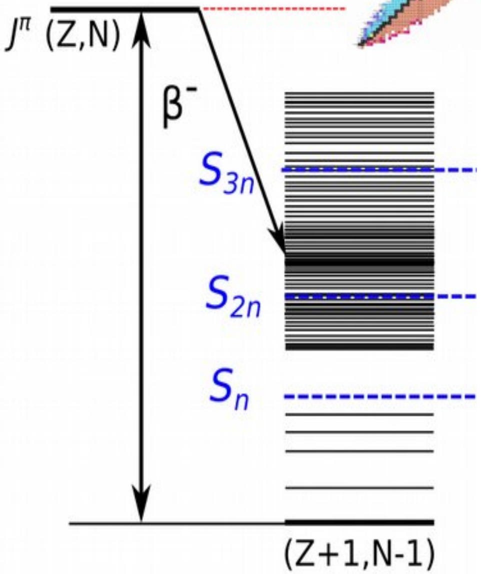
$$S_\beta(E_i) = \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle$$

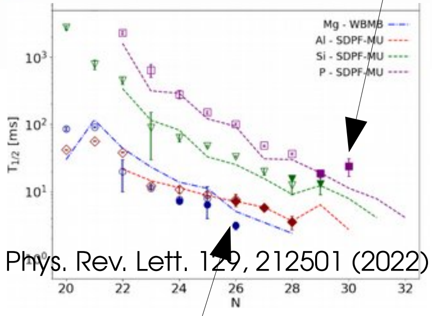
Connects strong and weak interactions
Requires the knowledge of the structure of parent and daughter.

G. G. Kiss et al 2022 ApJ 936 107



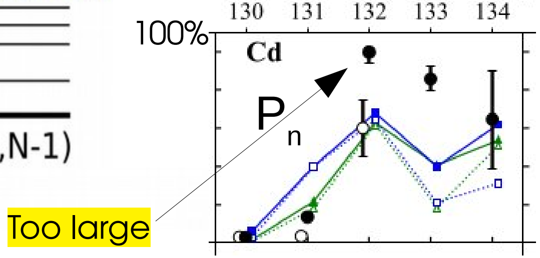






Phys. Rev. Lett. 129, 212501 (2022)

PRL 129, 172701 (2022)



Beta decay ... powerful and sophisticated (difficult)

The strength distribution within Q_β determines decay properties.

$$\frac{1}{T_{1/2}} = \sum_{E_i \ge 0}^{E_i \le Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

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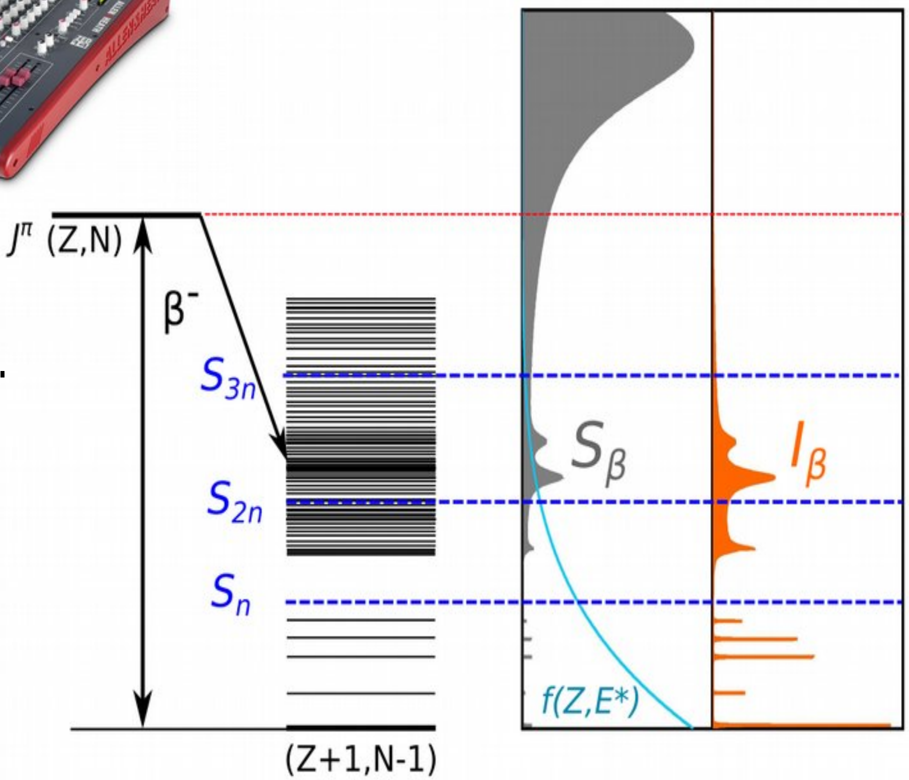
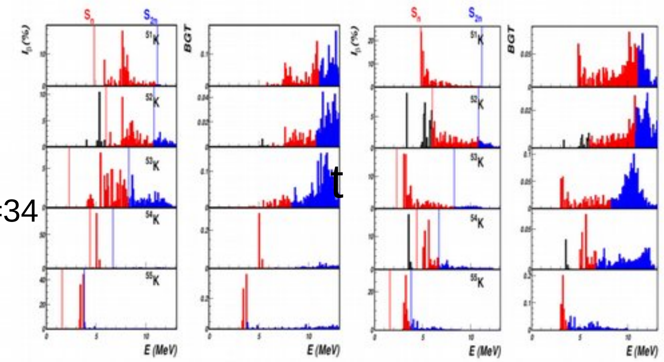
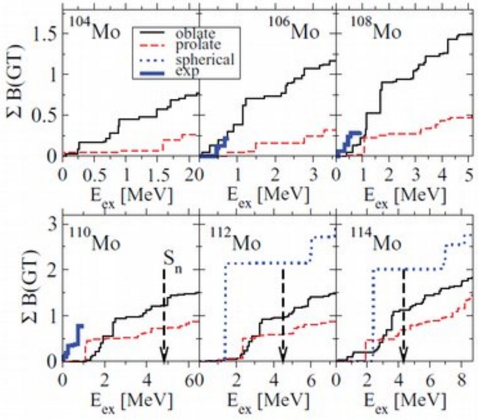


Beta-decay strenght and nuclear structure

Shell-evolution

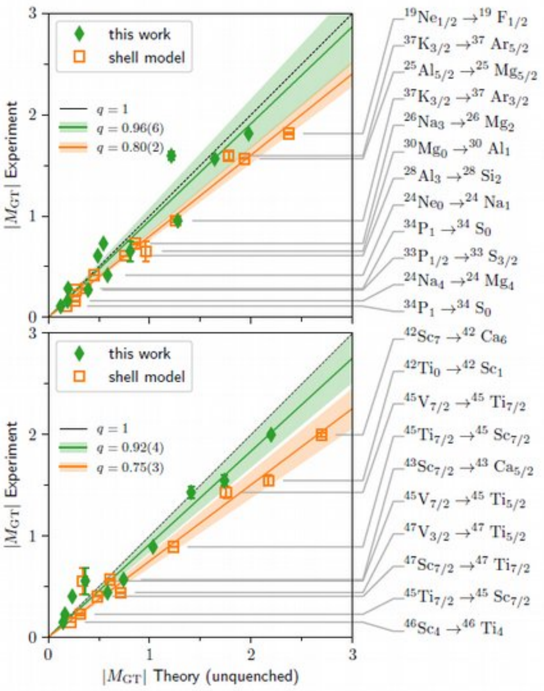


Shape



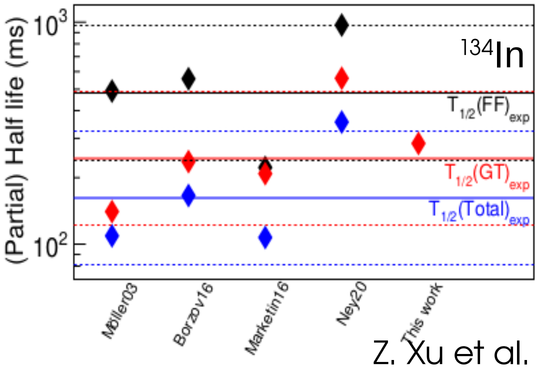
PR C 95, 024308 (2017)

GT quenching

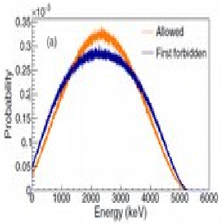


Nature Physics 15, 428–431 (2019)

Allowed vs. forbidden

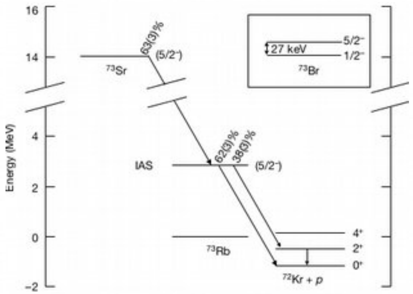


Z. Xu et al.



Phys. Rev. C 105, 054312 (2022)

Isospin mixing
Mirror symmetry breaking



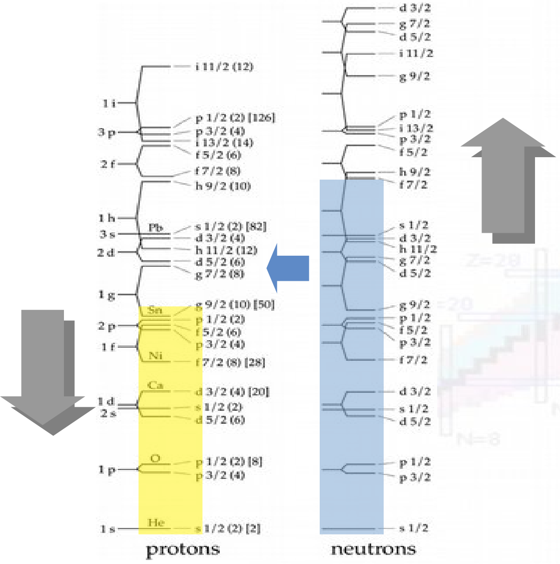
Nature 580 (2019).

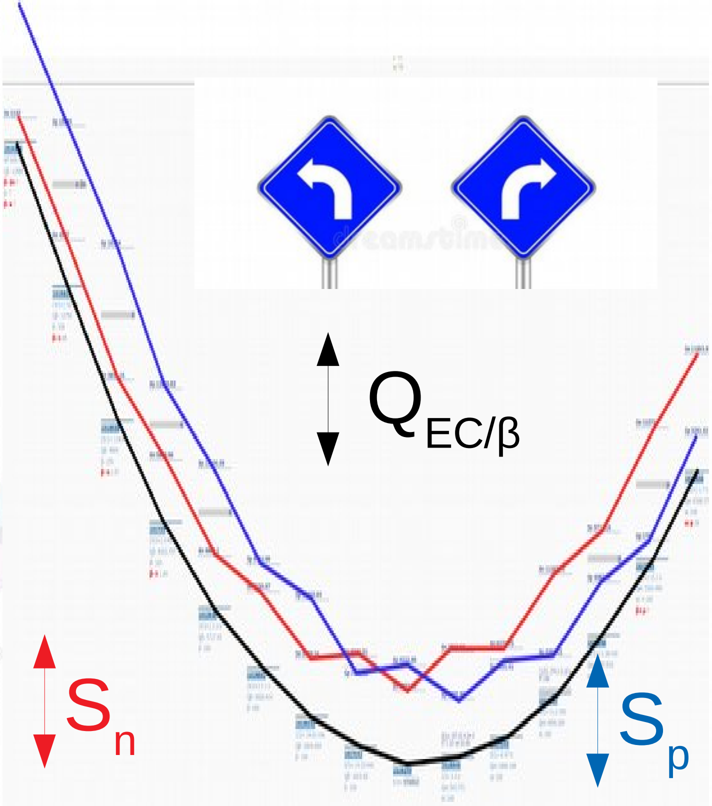
Beta decay and the shell structure

Beta decay "heats" the nucleus.

Allowed GT
forbidden (mostly FF)
N > Z

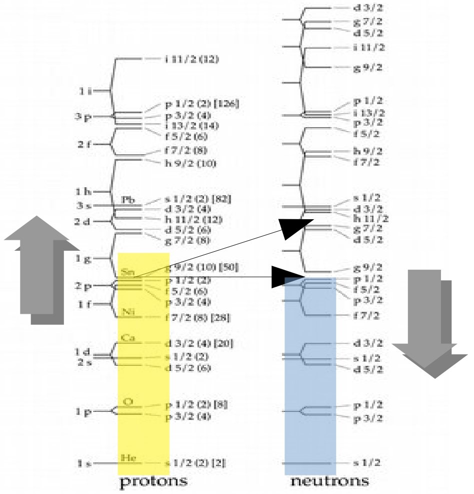
^{132}Sn





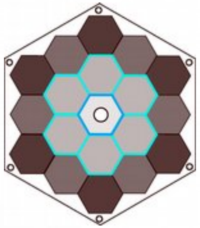
Allowed GT, FF and
Fermi decays to IAS
N ≤ Z

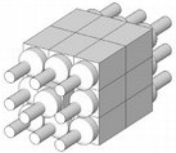
^{100}Sn

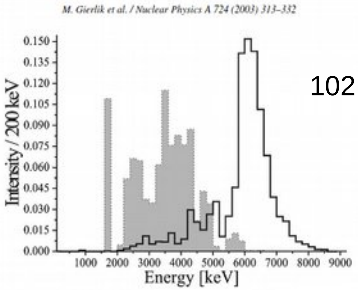


Pandemonium has been conquered by MTAS. SUN, DTAS

Total absorption gamma-ray spectroscopy (TAS)
"Synthetic" view on strength distribution !

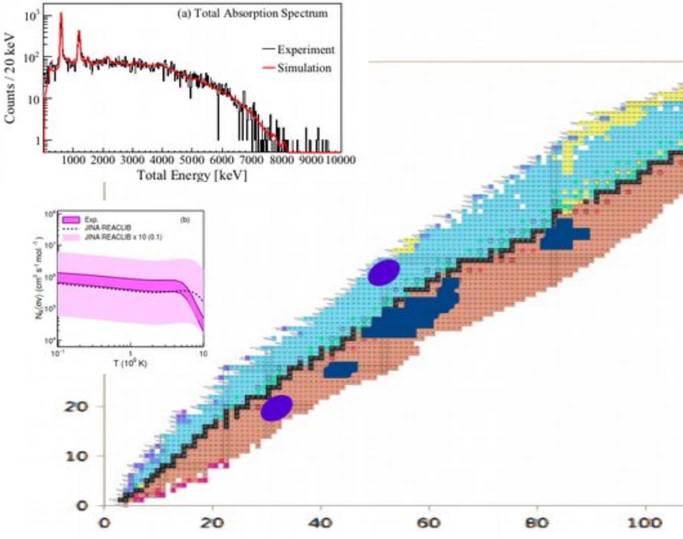


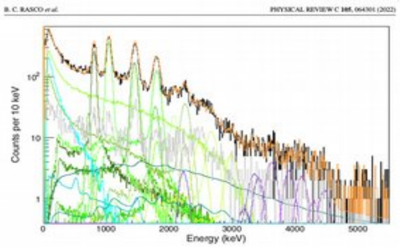


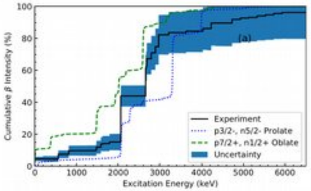


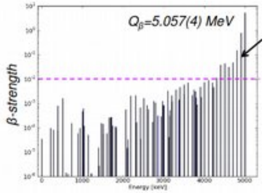
^{102}In

Modern TAS are NaI based detectors
are large and segmented
enabling g-g coincidences.
(level schemes, beta-Oslo method)
Applications: decay heat, anti-neutrino, BSM

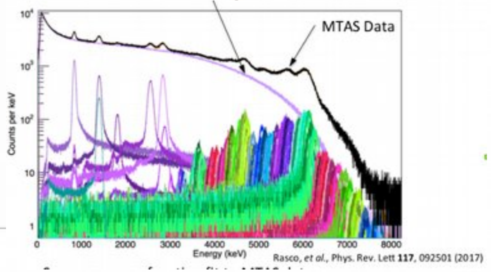




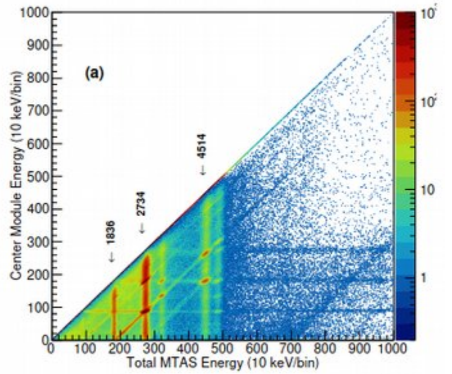




A. Fijalkowska (2015)



PRL 117, 092501 (2016)
PRL 117, 142701 (2016)
PR C 95, 054328 (2017)
PRL 119, 052503 (2017)
PR C 99, 015802 (2019)
PR C 100, 025806 (2019)
PR C 103, 035803 (2021)
PR C 106, 014306 (2022)
PR C 105, 054312 (2022)

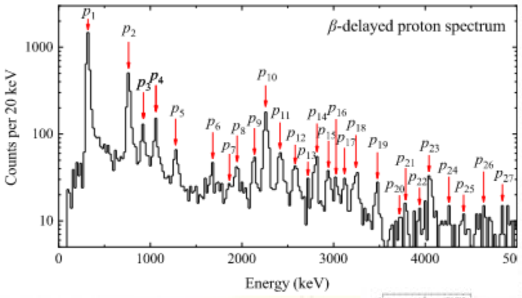


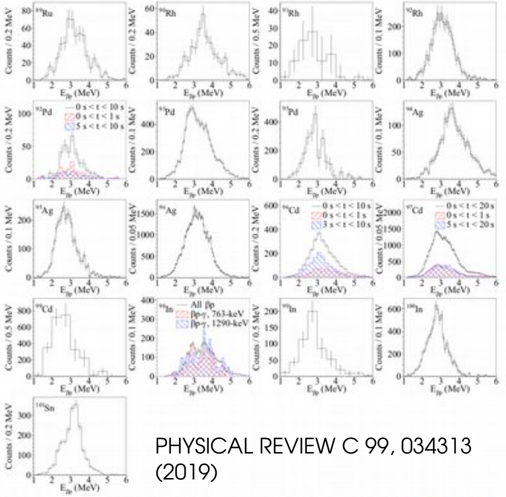
Multi-step processes - beta delayed protons

Charged particle spectroscopy
a sensitive tool for nuclear structure
Gas detectors (TPC) enable suppression
of the βp summing.

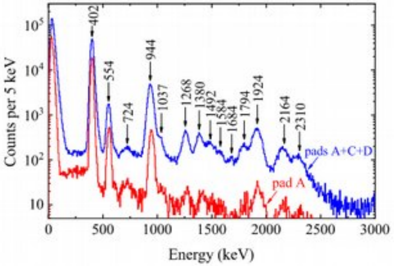
Resurgence of efforts with light nuclei
Isospin mixing, mirror symmetry
astrophysically relevant resonances
p-capture rates in novae
Proxy for reactions measurement !

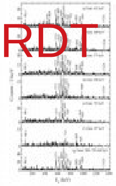
Hevy nuclei - “Pandemonium”

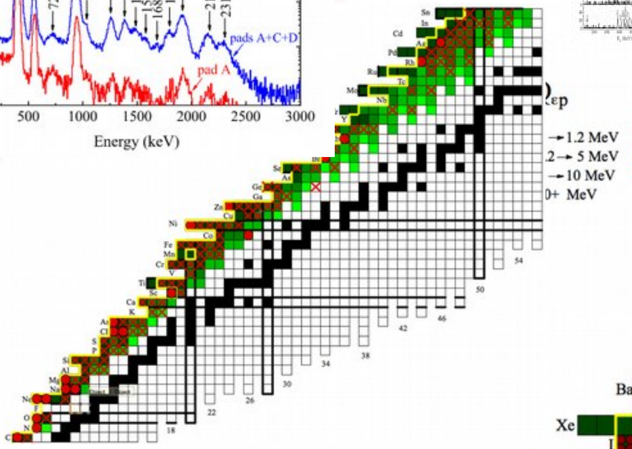


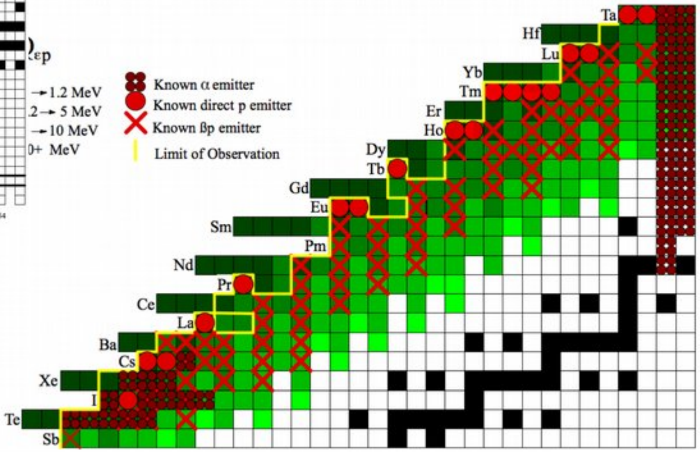


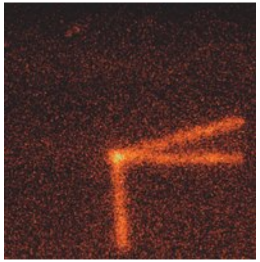
PHYSICAL REVIEW C 99, 034313 (2019)

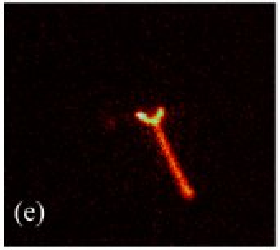












PR C 91, 064309 (2015)
PR C 93, 044336 (2016)
PR C 95, 034315 (2017)
PR C 93, 064320 (2016)
PR C 95, 024301 (2017)
PR C 99, 064312 (2019)
PR C 99, 065801 (2019)
PR C 102, 045810 (2020)

https://nucleardata.berkeley.edu/projects/beta_p.html
Atomic Data and Nuclear Data Tables 132 (2020) 101323

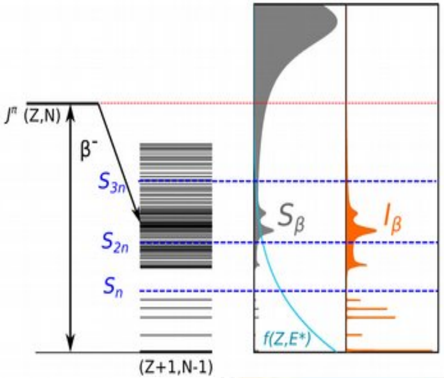
Multi-step processes - beta delayed neutrons

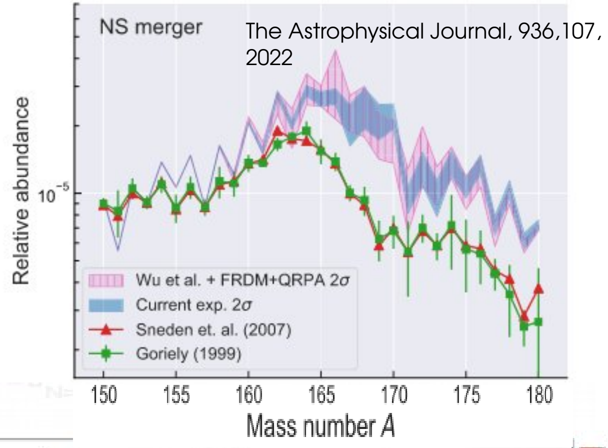
Prevalent decay mode
for ***majority*** of neutron rich nuclei
Input data for the ***r-process models.***

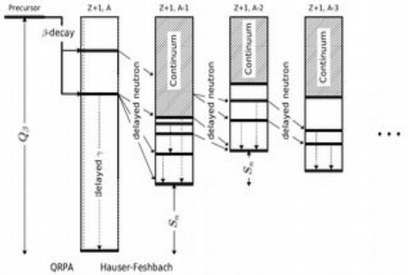
Data to ***predict*** properties of the nuclei
that we cannot ***measure*** (yet).

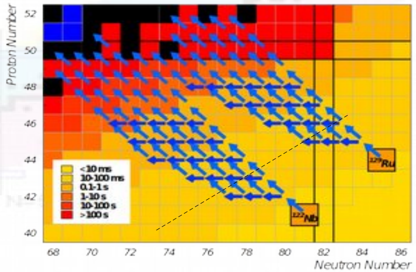
Neutron unbound ***strenght distribution***
1n/2n/gamma competition

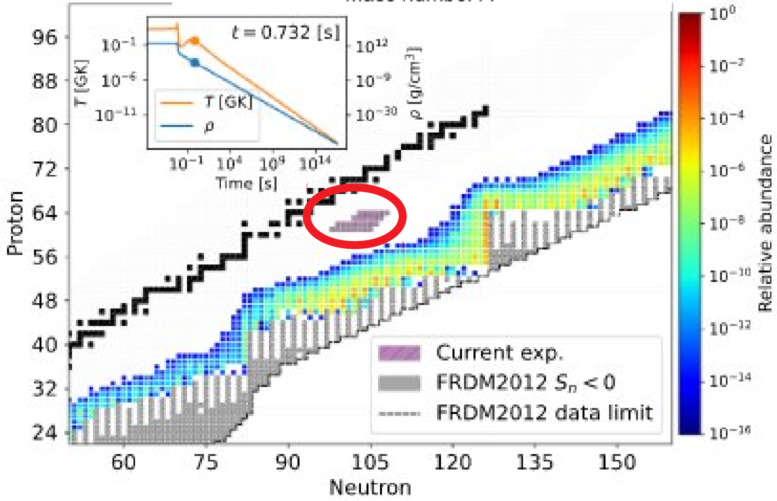
Is the statistical model always valid in
beta-delayed neutron emission ?







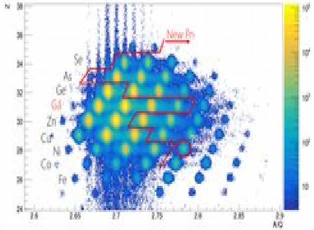


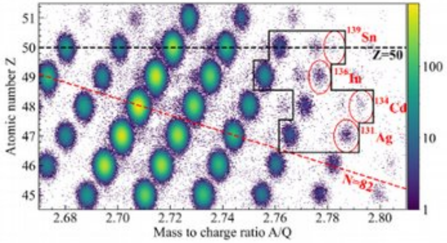


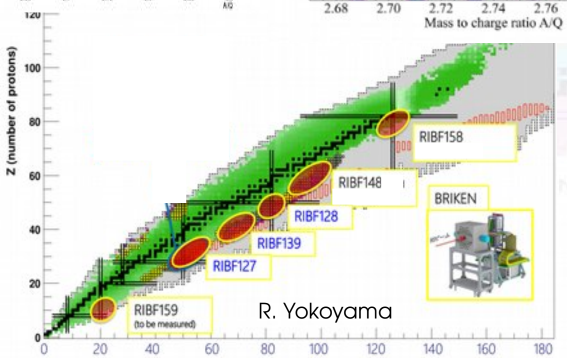
T. Kawano, P. Talou, I. Stetcu, and M. B. Chadwick, Nuclear Physics A 913, 51 (2013).
M. R. Mumpower, T. Kawano, and P. Möller, PR C 94, 064317 (2016).

Beta delayed neutrons - for the future !

Neutron counting:
P_{2n}/P_{1n} measurements
with BRIKEN array
3He based neutron counter
best know method to measure P_{xn}.





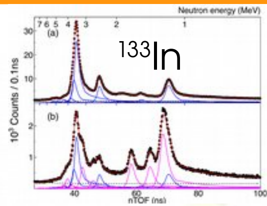


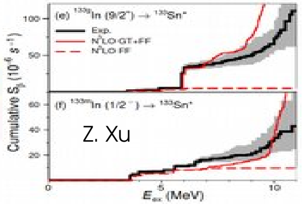
R. Yokoyama

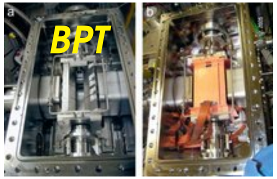
PRL 117, 092502 (2016)
PR C 99, 045805 (2019)
PR C 100, 031302(R) (2019)
NIM A 681, (2012) 94
PRL 129, 172701 (2022)

Neutron spectroscopy:
Strength distribution
Challenges for the next decade:
- β2n emission
- widths of neutron emitting states.

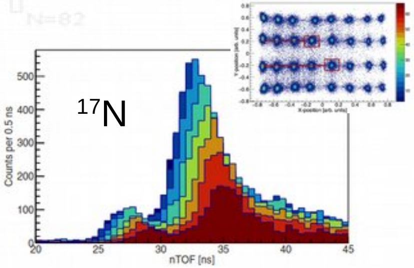
Improve resolving power
of neutron detectors.



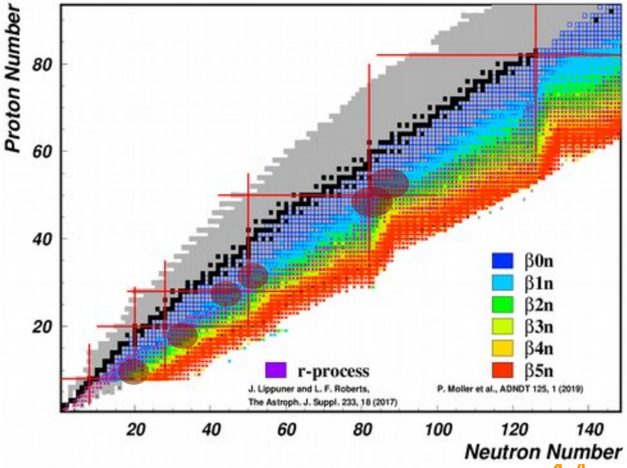




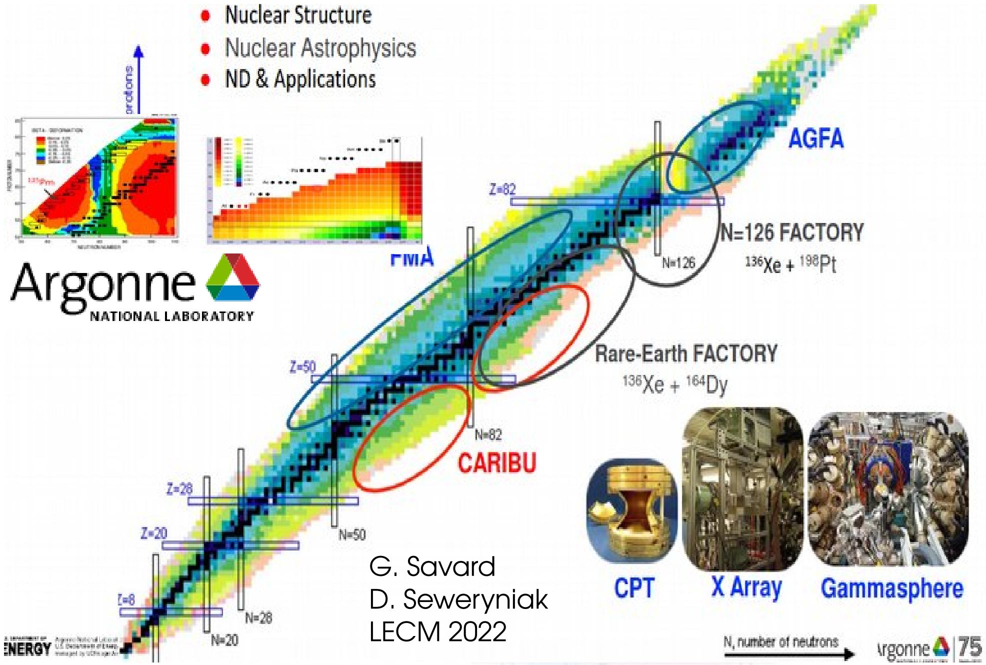
First βn experments with
neutron tracking array



PR C 106, 044320 (2022).

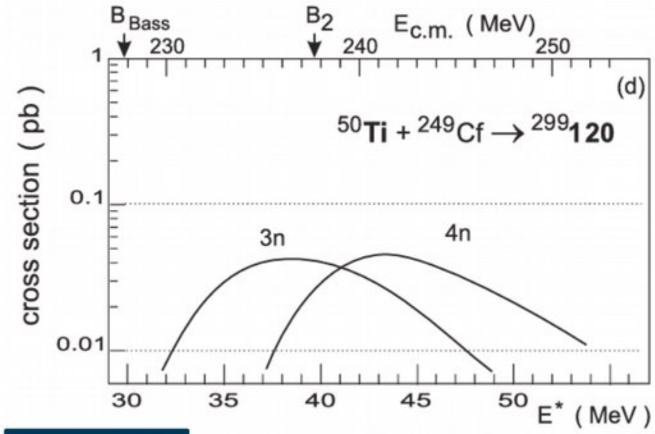


It's the beam, stupid !

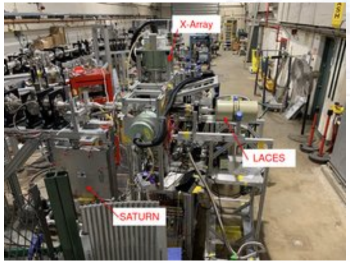


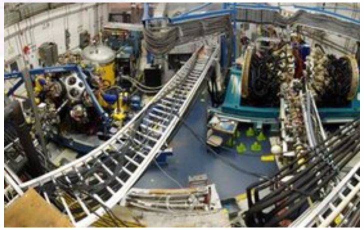
G. Savard
D. Seweryniak
LECM 2022

Uncharted territories !
Heavy and superheavy nuclei.



BERKELEY LAB





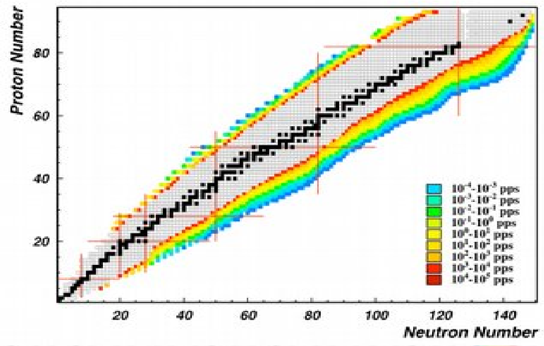
FRIB Decay Station

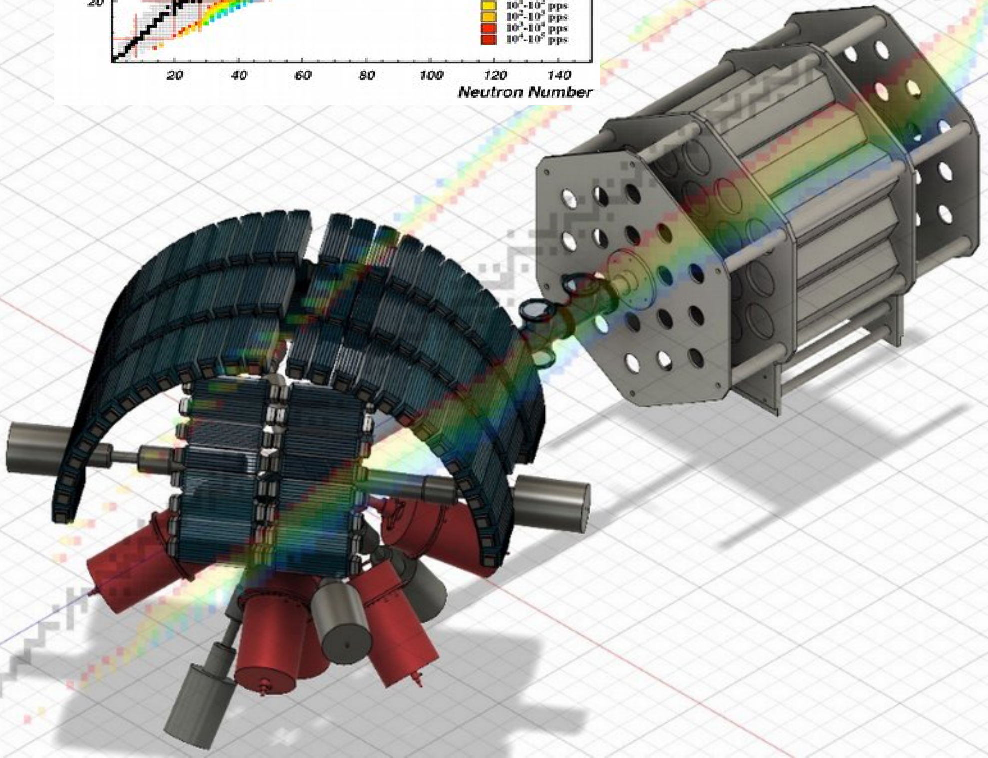
https://fds.ornl.gov/wp-content/uploads/2020/09/FDS-WP.pdf

FDS combines multiple detector systems in ***two-focal plane*** arrangement, implemented in a single experiment.
FDS enables ***efficient discrete spectroscopy, neutron counting*** and ***total absorption spectroscopy.***

FDS is designed for ***discovery science*** with nuclear decays at FRIB.
Next generation array for decay spectroscopy!

The purpose of FDSi is to utilize FRIB beams of rare isotopes as ***effectively*** as possible and ***shorten the gap between the discovery and detailed measurements.***





see FDS talk by J.M. Allmond

Hunger for discovery: FDS initiator

https://fds.ornl.gov/initiator/

Demonstrating the ***FDS principle*** with collection of the community detectors.

Featured in Physics | Editors' Suggestion | Access by University o

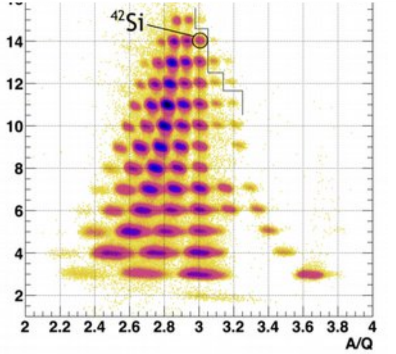
Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford *et al.*

Phys. Rev. Lett. **129**, 212501 – Published 14 November 2022

Physics

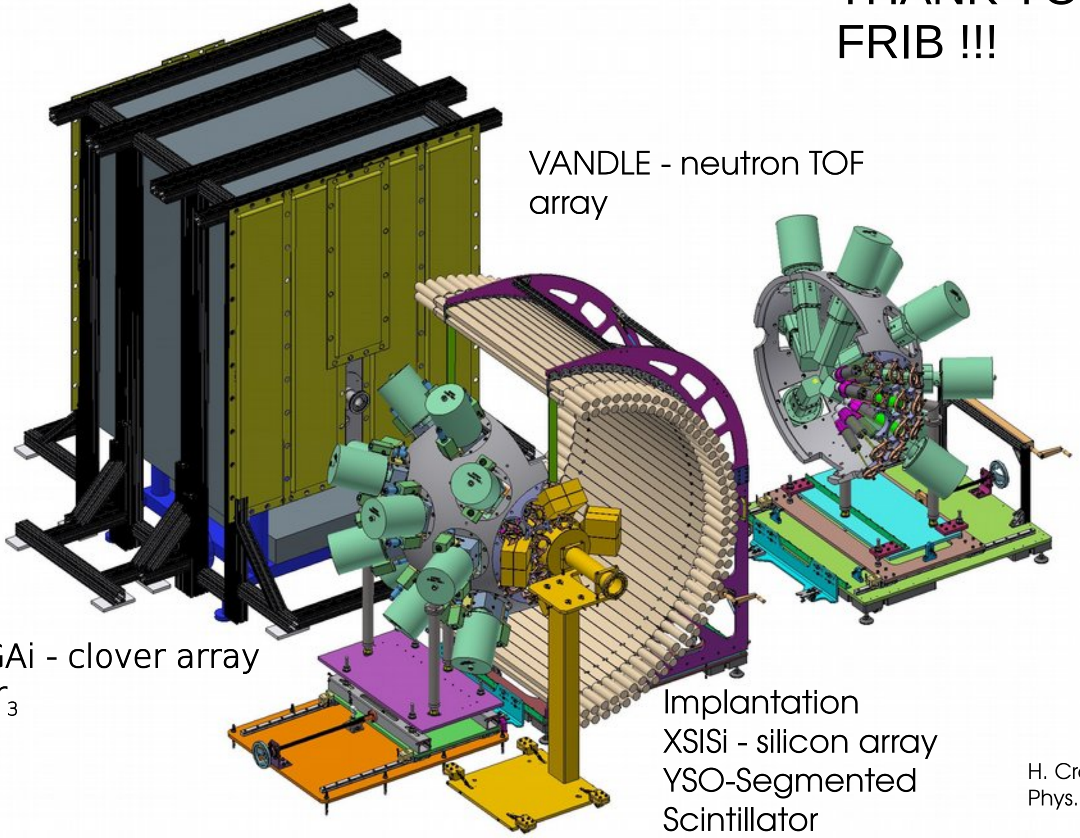
THANK YOU FRIB !!!



Hybrid Super-3Hen (neutron counter)

Modular Total Absorption Spectrometer

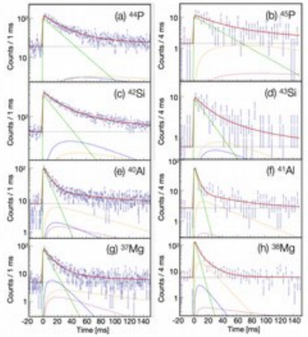
Collaborative effort of ORNL/UTK/FRIB/ANL and several universities and national labs (LBNL and LLNL)



VANDLE - neutron TOF array

DEGAi - clover array
$LaBr_3$

Implantation
XSISi - silicon array
YSO-Segmented Scintillator



H. Crawford et al.
Phys. Rev. Lett. 129, 212501 (2022)

FDSi PAC1 proposals (FRIB 10kW)

Polyphonic nature of decay spectroscopy

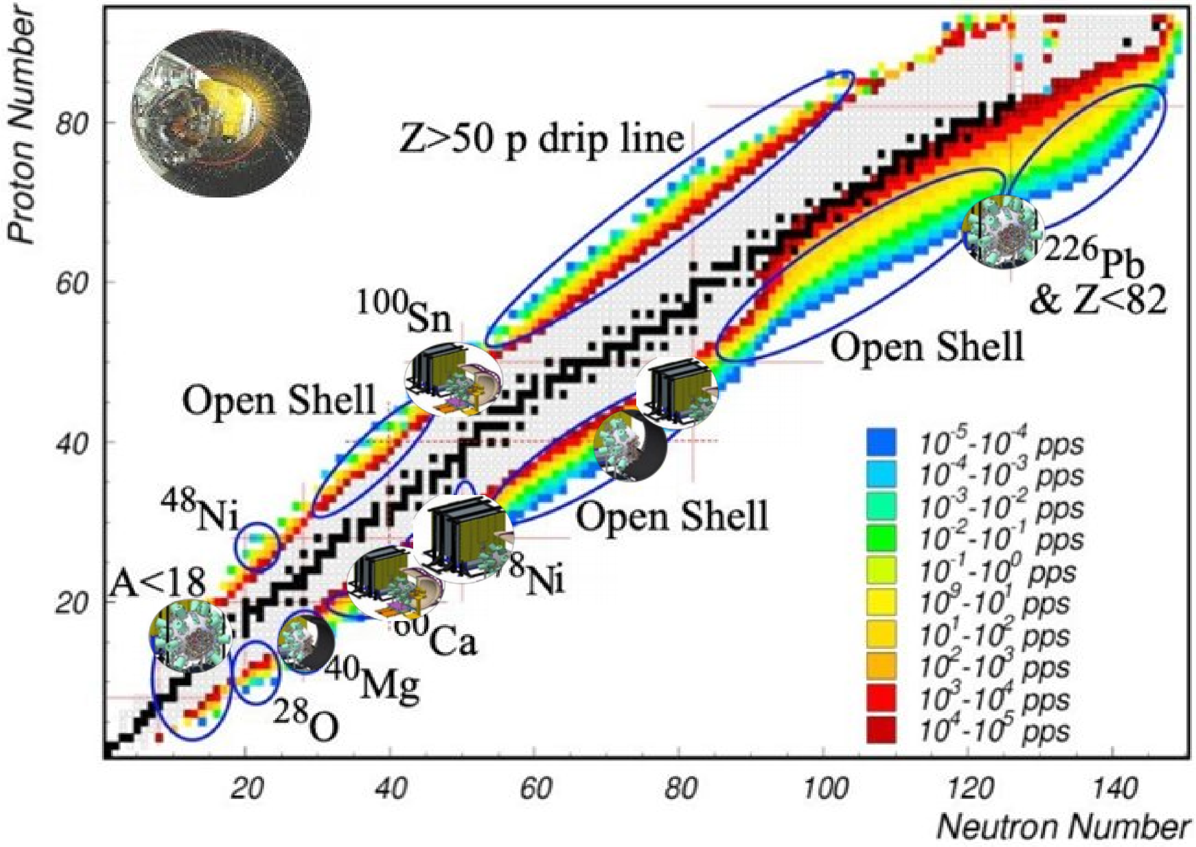
FDSi:

- Gamow-Teller quenching in ^{100}Sn
- Shape transitions and r-process in neutron rich A~100
- Shell-evolution near closed shells ^{60}Ca, ^{78}Ni, ^{226}Pb
- Island of inversion N~28
- Astrophysical resonances ^{21}Mg
- Gamma-strength function for the r-process near ^{132}Sn

OTPC:

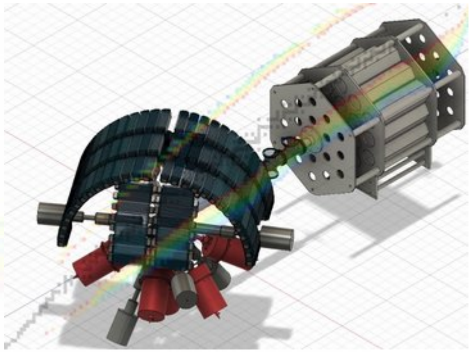
- pp-correlations in ^{48}Ni

PAC2: More to come



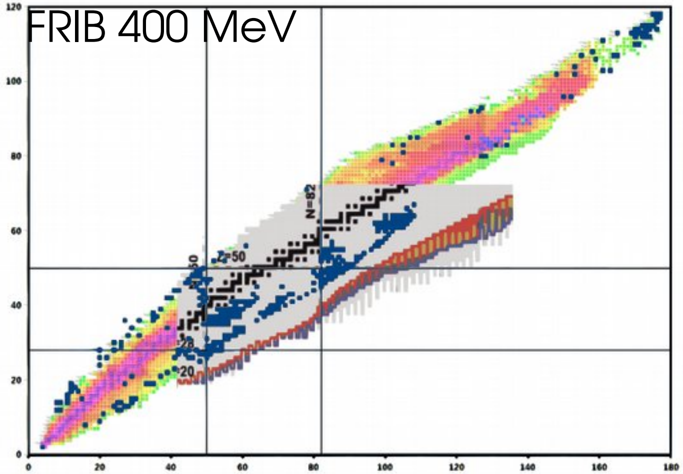
Next decade - continuation but not a sequel ?

Decay spectroscopy efforts at leading RIB facilities worldwide with ***sophisticated multi-detector*** arrays and a significant amount of ***RI beam time***, involving many institutions.
Unparallel potential in discovery: new lifetimes, decay modes, SHE.
Impacts nuclear astrophysics, particle physics, nuclear energy ...



FDS for the 400 MeV/u FRIB !

Continue the ***discoveries*** towards the outer bounds of the nuclear chart.
Deliver ***high-quality*** data and stimulate ***theory*** efforts.
Explore, ***question*** established paradigms.
Educate and train!



Prepare a foundation for the ***future*** of the field and ~2030 LRP.
What will be our physics focus, and how will we ***justify*** it?
How to maintain ***productivity*** without losing sight of new physics?

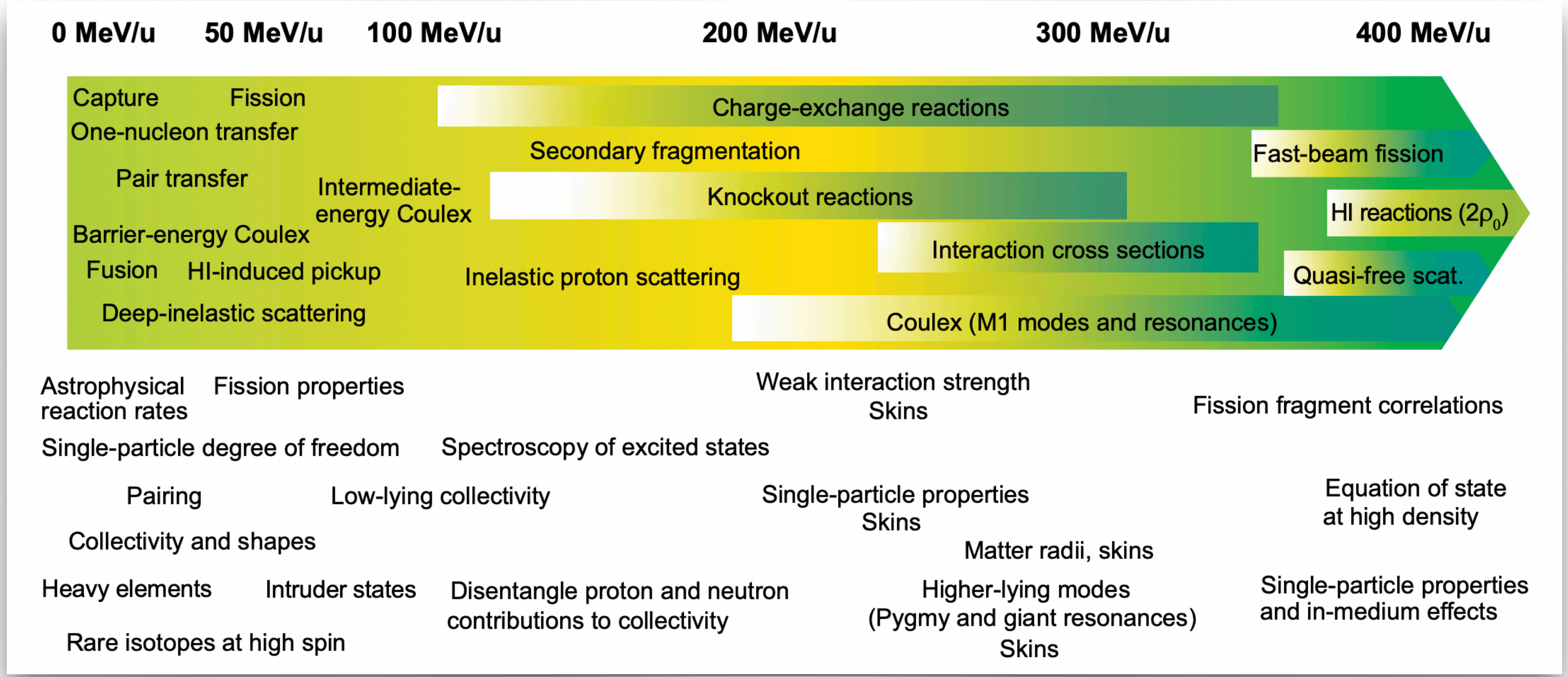
Thank you
Z. Xu, A. Macchiavelli.

Direct Reactions

LRP TOWNHALL
November 2022

CALEM R. HOFFMAN
Physicist
Argonne National Laboratory

REACTIONS LINK VARIOUS ASPECTS OF NUCLEAR SCIENCE



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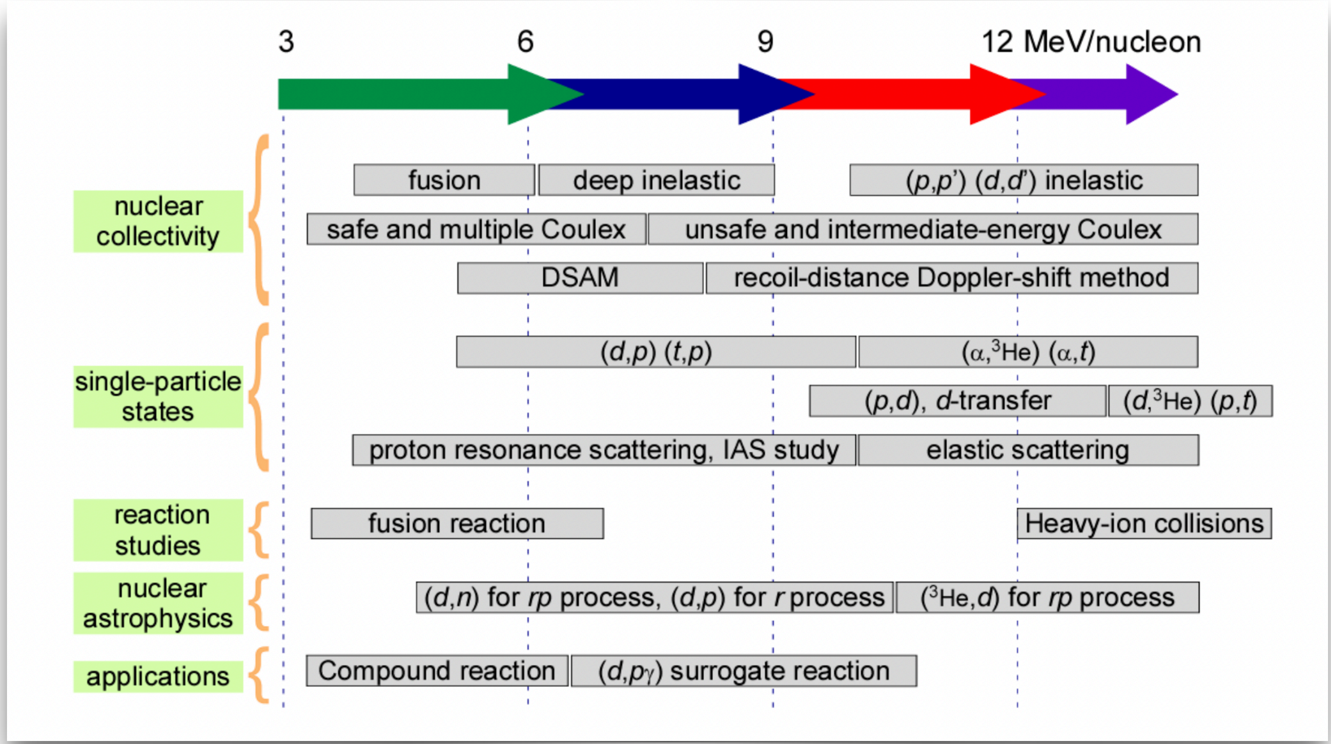
REACTIONS LINK VARIOUS ASPECTS OF NUCLEAR SCIENCE

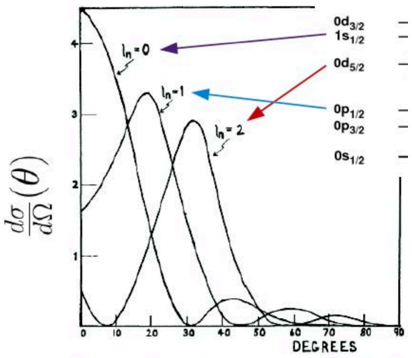


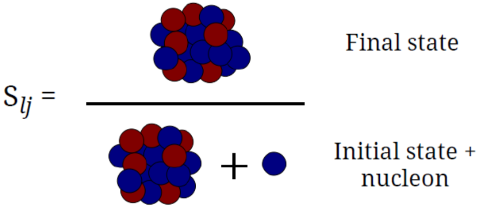
DIRECT REACTIONS

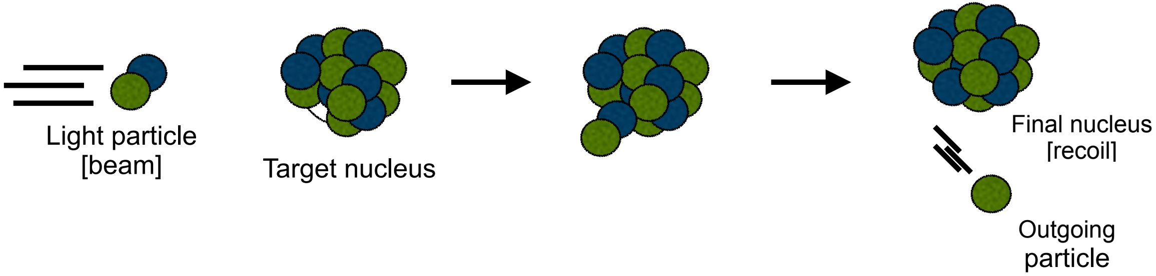
Single-nucleon transfer: (d,p), (^{3}He,d), (^{13}C,^{12}C)

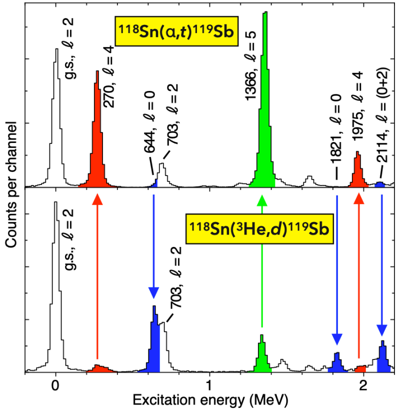
KEY POINTS

- ~few - 10's MeV/u
- Highly selective
- Direct probe of single-particle aspects
- Surrogate (p,γ) / (n,γ)
- resurgence in the RIB era
- Beam production





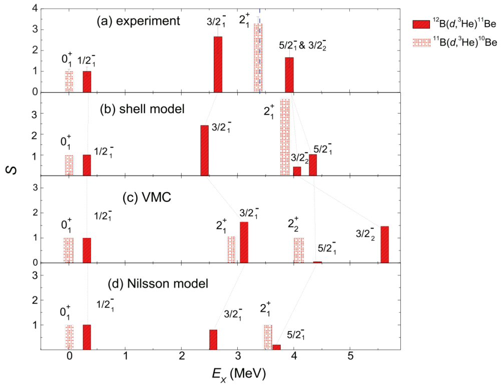


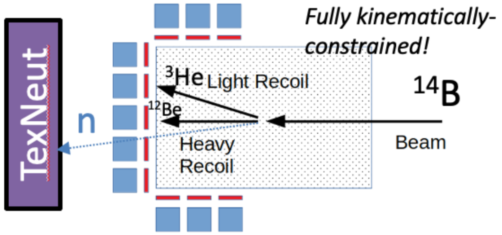


Extract: orbital angular momenta, spectroscopic overlaps, energy centroids
Deduce: nucleon occupancies, single-particle energies, two-body matrix elements

RECENT RESULTS & ONGOING WORK

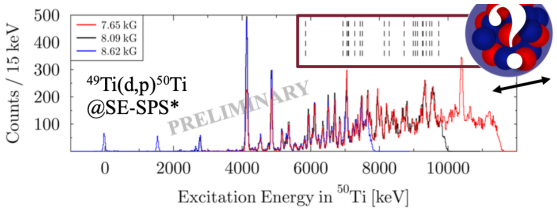
$^{11-14}$B(d,^{3}He): Rapidly evolving structure at the limits of binding

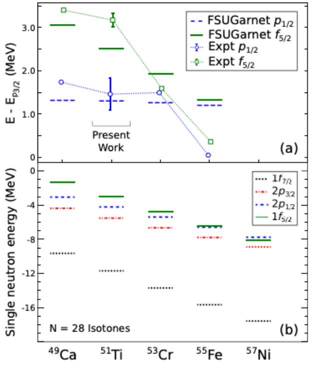




J. Chen PRC 100, 064314 (2019)
Bishop et al.,

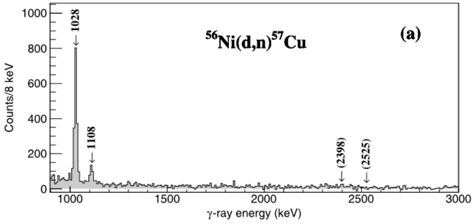
^{49,50}Ti(d,p): Complete single-particle information around N = 28

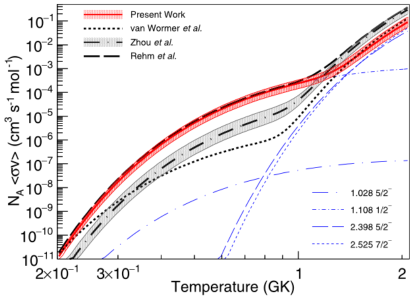




Riley PRC 103, 064309 (2021)
Spieker et al.,

Single-nucleon adding on 56Ni to inform on the (p,γ) capture rate





Kahl et al., PLB 797, 134803 (2019)

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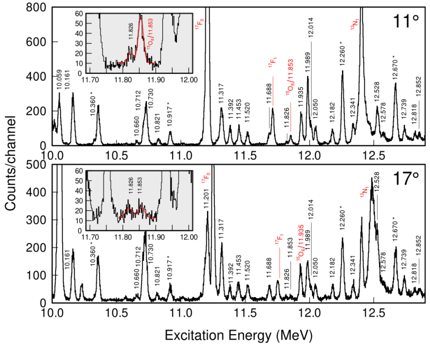
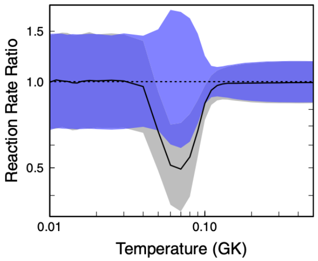
RECENT RESULTS & ONGOING WORK

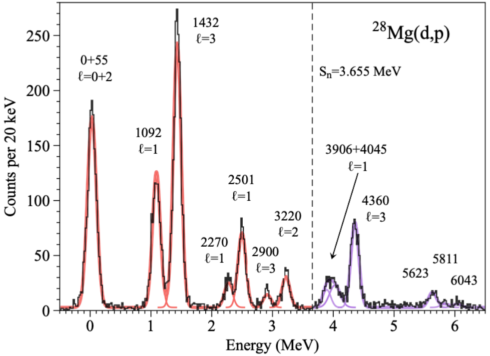
^{23}Na(^{3}He,d)^{24}Mg data to inform on the (p,γ) capture rate

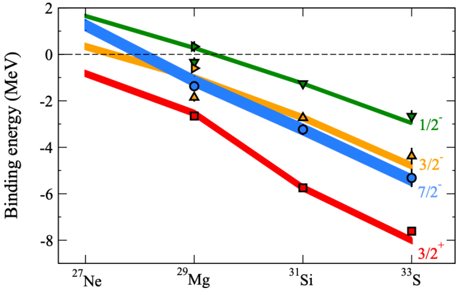




Marshall et al., PRC 104, L032801 (2021)

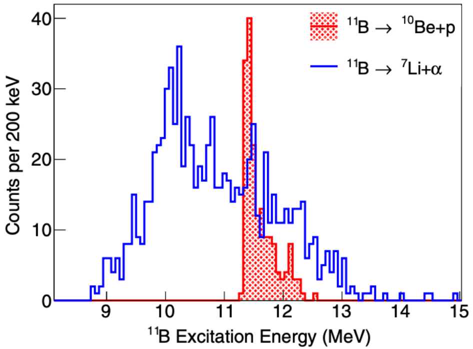
^{28}Mg(d,p)^{29}Mg: Mapping the single-particle evolution near the N=20 island of inversion





McGregor PRC 104, L051301 (2021)

Observation of a near threshold proton decay state via ^{10}Be(d,n)

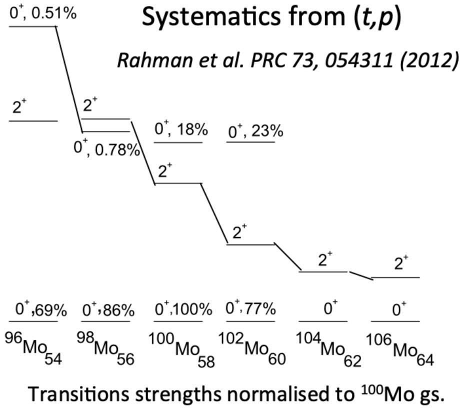


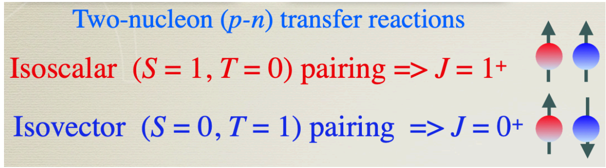
A surprisingly large branching ratio of the ^{11}Be → ^{10}Be β-delayed proton decay prompted speculations on the nature of the decay. [Ayyad et al., PRL **123**, 082501 (2019)] [Riisager et al., PLB **732**, 305 (2014)]

E. Lopez-Saavedra PRL 129, 012502 (2022)

DIRECT REACTIONS

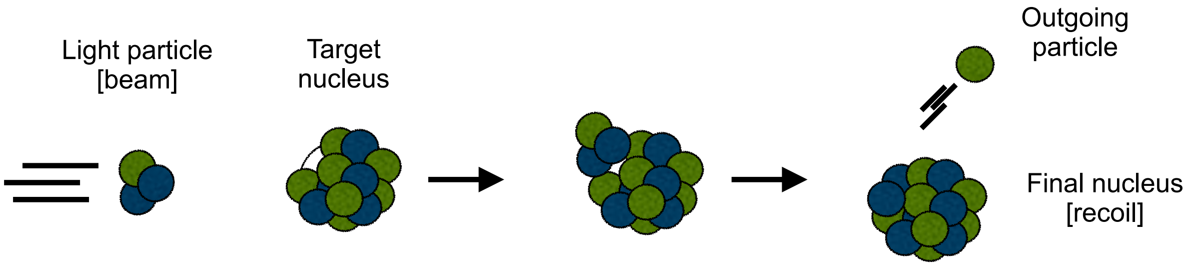
Multi-nucleon transfer e.g., (p,t), (^{3}He,p), (^{6}Li,d)

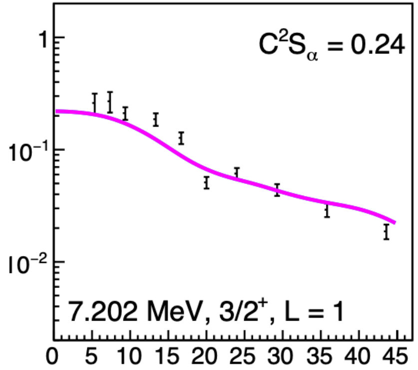




KEY POINTS

- ~few - 10's MeV/u
- selective
- Alpha-like transfer: (α,γ), (α,X)
- Sensitive to paring
- Exploratory - cluster / rotational states
- Resurgence in the RIB era



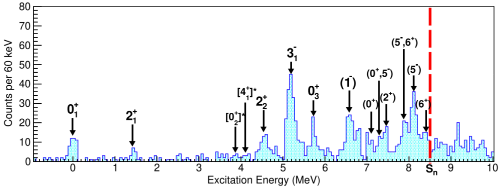


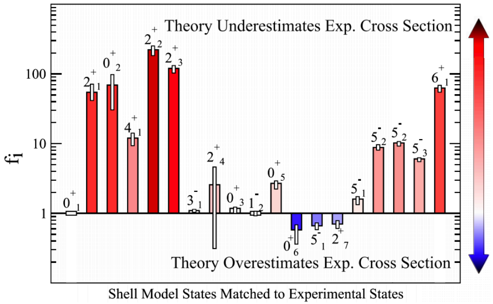
Extract: final state angular momenta, spectroscopic overlaps, resonance widths
Deduce: resonance strengths, reaction rates, pair occupancies, collectivity

Argonne NATIONAL LABORATORY

RECENT RESULTS & ONGOING WORK

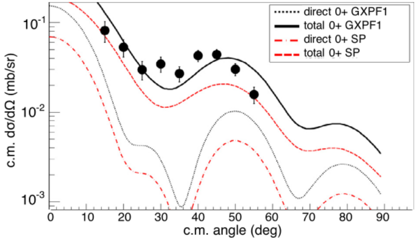
$^{26}Mg(t,p)^{28}Mg$: Pairing & configuration mixing towards N = 20

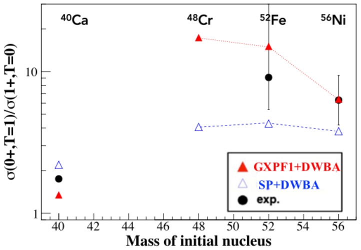




McNeel PRC 103, 064320 (2021)

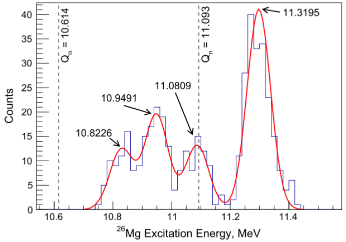
$^{52}Fe,^{56}Ni(^{3}He,p)$: No evidence for isoscalar pairing (S=1, T=0) condensate

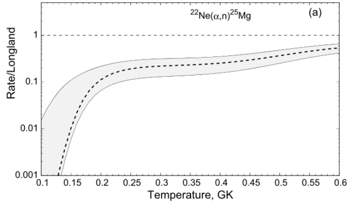


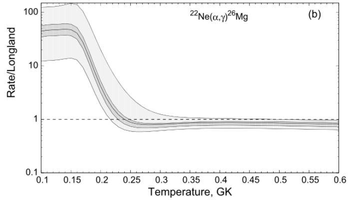


Crom PLB 829 137057 (2022)

$^{22}Ne(^{6}Li,d)$: α capture rates & the neutron flux during the s-process







Jayatisaa PLB 802, 135267 (2020)

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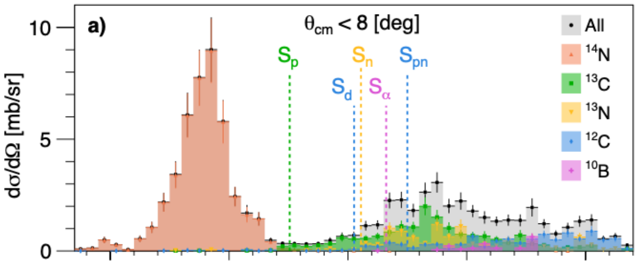
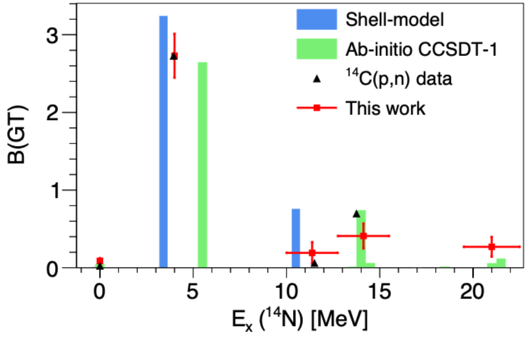
DIRECT REACTIONS

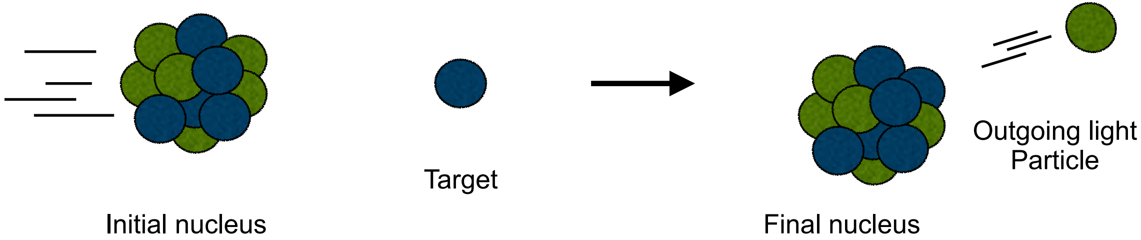
Charge-exchange:(p,n), (^{3}He,t), (d,2p [^{2}He])

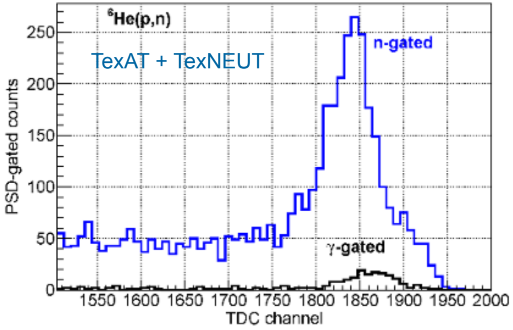
^{14}O(d,^{2}He)



S. Giraud et al. arXiv:2210.15866







E. Koshchiy et al., NIMA 957, 163398 (2020)
D.P. Scriven et al., NIMA 1010, 165492 (2021)

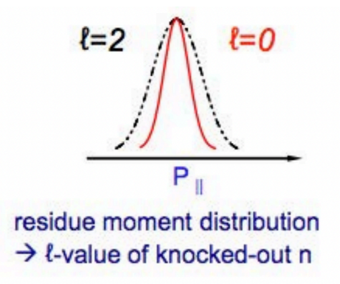
KEY POINTS

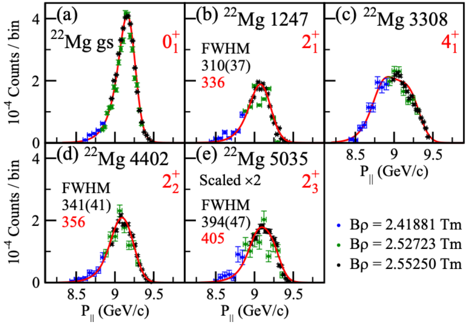
- ~5 - 400 MeV/u
- Isobaric analog states
- Gamow-Teller strengths
  - Astrophysics
  - Neutrino physics
- Radii from charge-changing σ_{cc}

Extract: angular distributions, energies of isobaric analog states
Deduce: Gamow-Teller strength distributions, level densities, g-strength functions

DIRECT REACTIONS

Single or multi-nucleon knockout: (-1p), (-2p), (-1n)
Quasi-free knockout: (p,2p), (p,pn), (p,Xp)





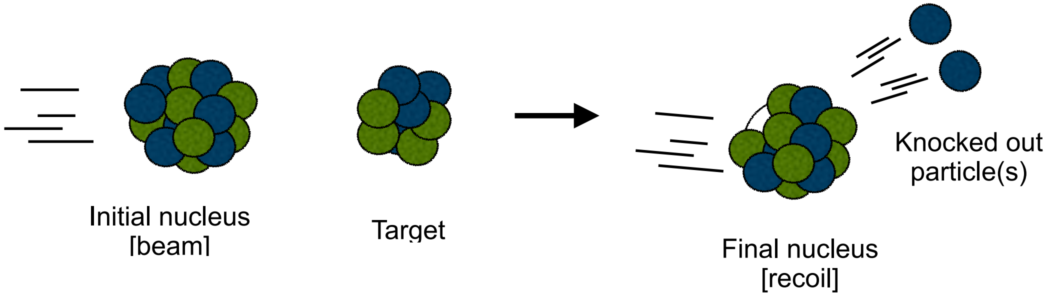
Longfellow PRC 101, 031303(R) (2020)

Theoretical cross-section

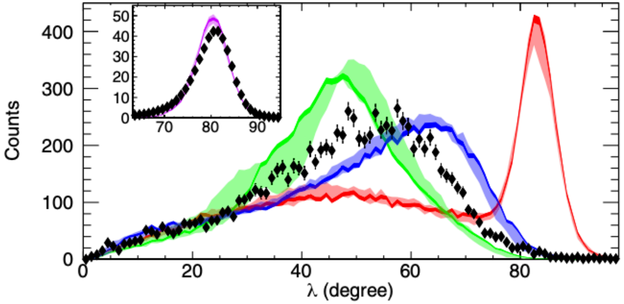
$$\sigma(j^\pi) = \left(\frac{A}{A-1}\right)^N C^2 S(j^\pi)\sigma_{sp}(j, S_N + E_x[j^\pi])$$

Reaction theory

Structure theory



(p,3p) sequential proton removal



Frotscher PRL 125, 012501 (2020)

Extract: orbital angular momenta, spectroscopic overlaps
Deduce: occupancies, single-particle energies, pairing strengths

KEY POINTS

- >50 MeV/u knockout
- >250 MeV/u quasi-free
- Highly selective: valuable in-beam spectroscopy tool
- Study of overlaps w/ established tools
- Pairing force, short/ long range correlations

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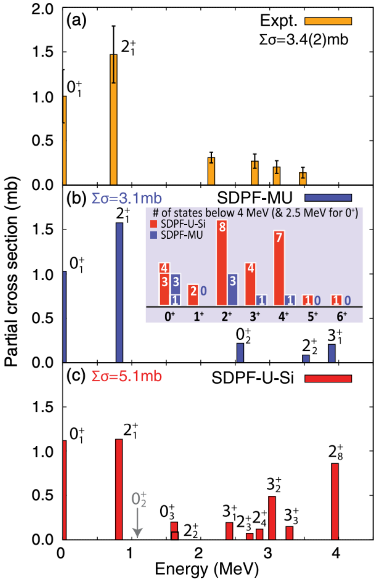
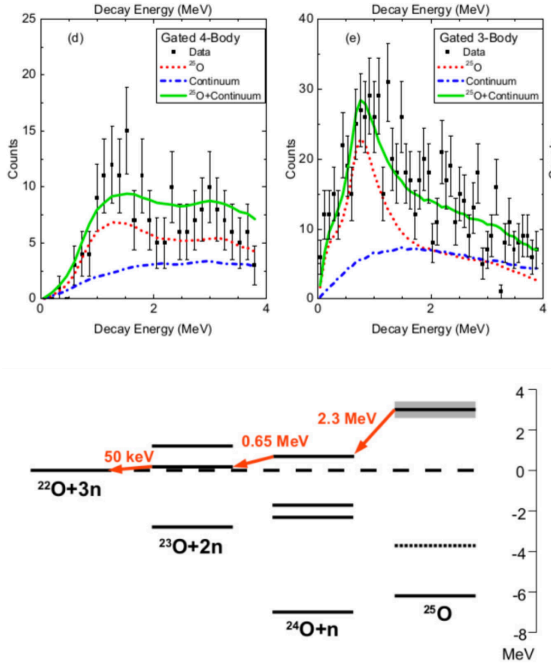
RECENT RESULTS & ONGOING WORK

Probing the key nucleus ^{42}Si in one-nucleon knockout



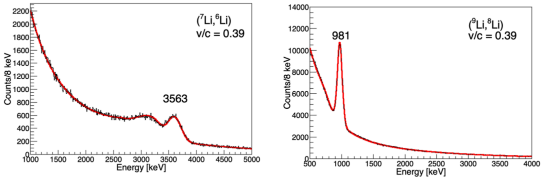
Gade et al., PRL 122, 222501 (2019)

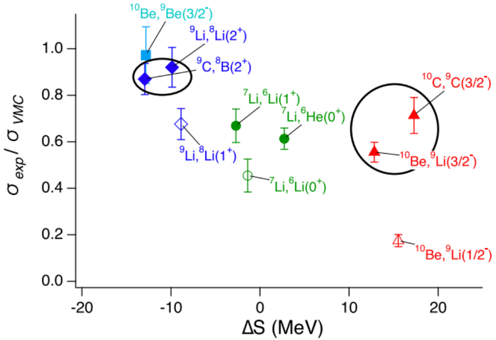
-2p knockout from ^{27}Ne to populate 3-neutron decay from ^{25}O



Sword PRC 100, 034323 (2019)

Cross sections from nucleon removal reactions in mirror systems

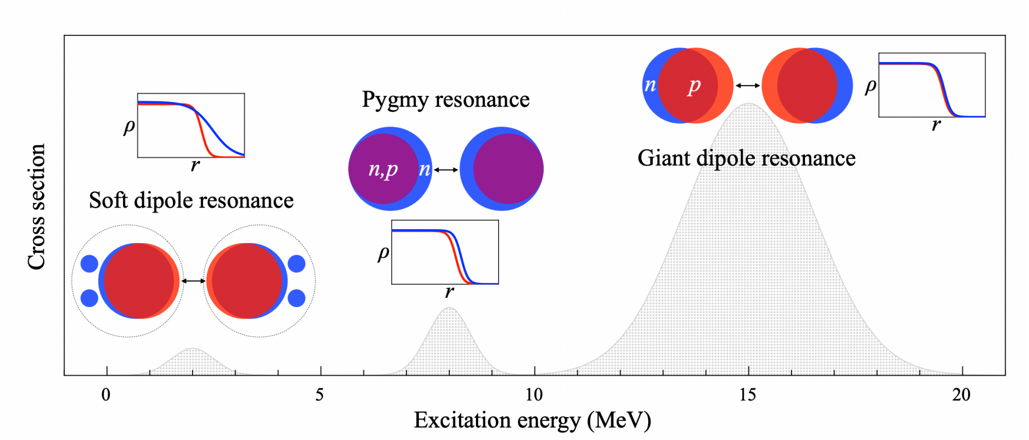


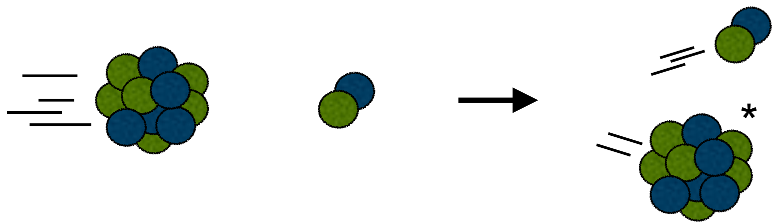


Kuchera PRC 105, 034314 (2022)

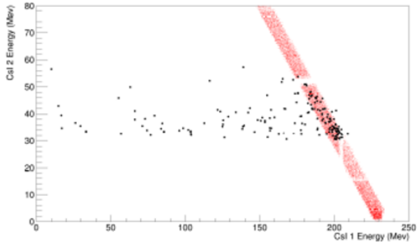
SCATTERING REACTIONS

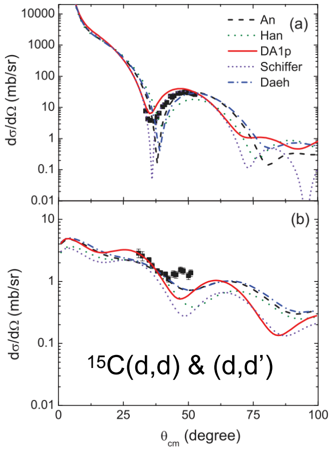
Inelastic scattering: (p,p'), (d,d'), (α,α'), (^{12}C,^{12}C')





^{12}C(α,α'α)





Chen PRC (to be pub.)

KEY POINTS

- Few to 100's of MeV/u
- Selective to probes:
  - Proton - isovector
  - Deuteron - isoscalar
- Resonance structures
- Cluster structures
- Collective features in nuclei [M_n/M_p]

Extract: Distributions, resonance strengths

Deduce: unique excitation modes, clustering prob., isoscalar / isovector modes, deformation length

REQUISITE TOOLS

KEY ROLE PLAYED BY REACTION THEORY

Importance of robust theoretical modeling

Reliance on theoretical approaches to disentangle reaction dynamics from the nuclear structure properties

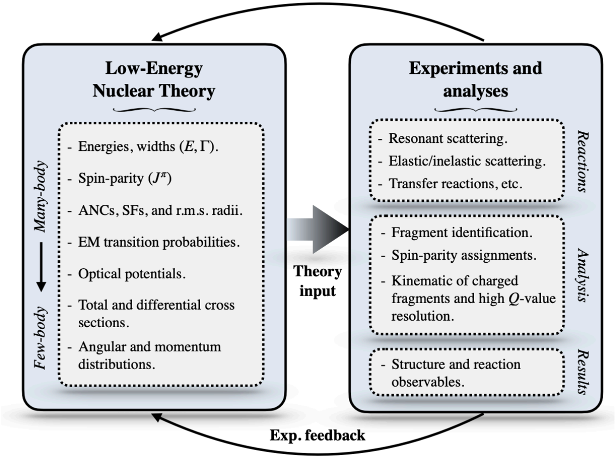
DWBA, ADWA, CC, CDCC, CRS, Glauber theory, R-Matrix, DWIA, PWIA, and many others

Continuing developments into unifying structure+reaction calculations

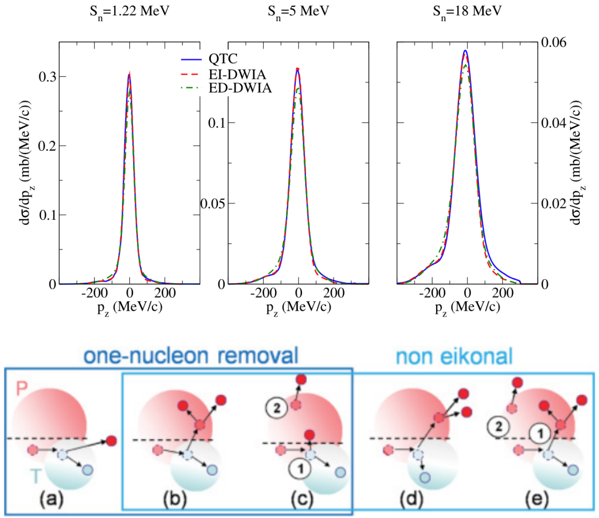
Berggren basis, Gamov Shell model, NCSM, Halo EFT, continuum-coupling, and many others

Critical that developments continue into all aspects of reaction theory:

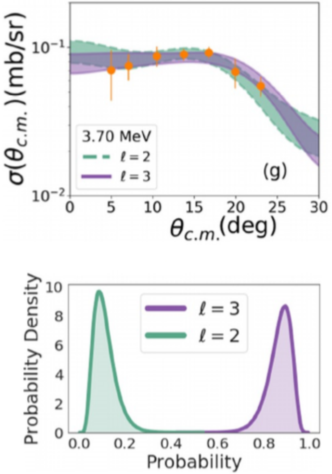
e.g., optical potential from *ab initio*, understanding quenching, global description of reactions involving near / beyond threshold states …



https://arxiv.org/abs/2211.06281



Aumann PPNP 118, 103847 (2021)



Marshall PRC 102, 024609 (2020)
[Bayesian DWBA]

STATE OF THE ART INSTRUMENTATION

Full range of experimental equipment

Active target devices: AT-TPC, TexACT, MUSIC, …

Solenoid spectrometers: HELIOS, SOLARIS, SSNAP

Multi-functional arrays: ORRUBA, HIRA, DAPPER, HYPERION, NIMROD, …

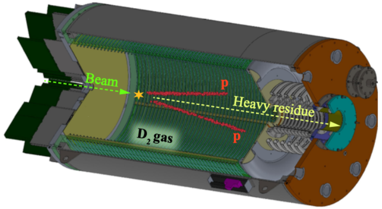
Spectrographs/Spectrometers: Split-pole, Super Enge SPS + CeBrA/SABRE, MDM, …

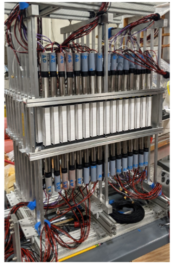
Neutron arrays: MoNA-LISA, TexNeut, LENDA, CATRiNA, VANDLE, …

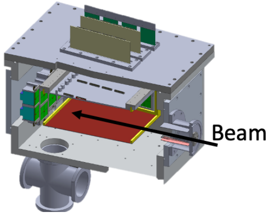
Recoil Selection: HRS, S800, SECAR, ISLA, …

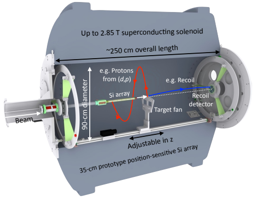
γ-ray detection: GRETA, Clarion, Gammasphere, SeGA, CAESAR, …

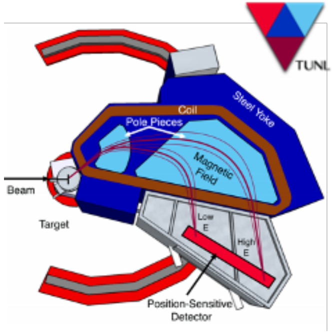
Targets: Solid (^{3}He,t), Liquid (high luminosity), Gases (JENSA), …

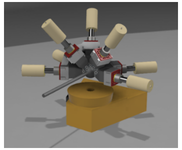


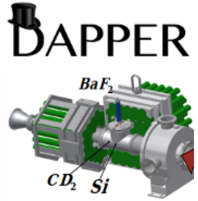


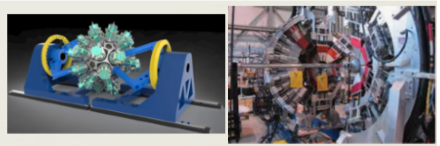












BEAMS

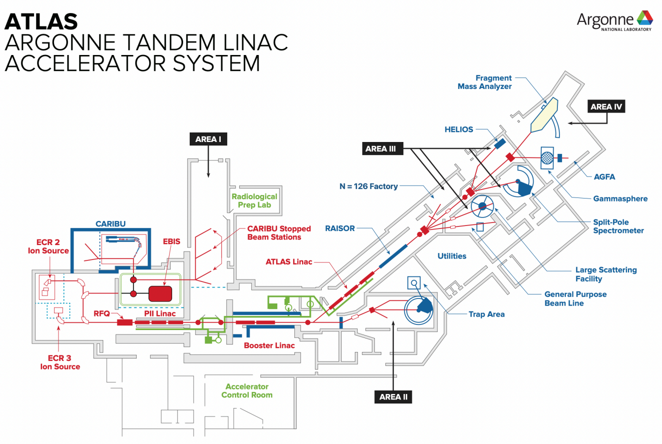
Availability of beams of interest with the requisite properties

[energies, intensities, spatial & timing structures, purities …]

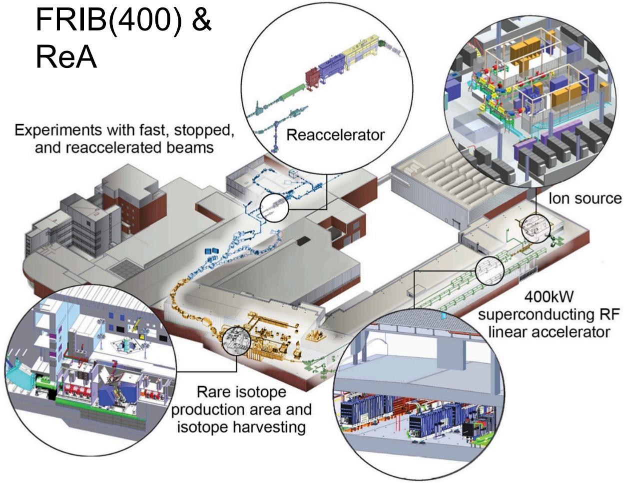
Stable beams

[both normal & inverse kinematics]

Radioactive (& isomeric) beams



FRIB(400) & ReA

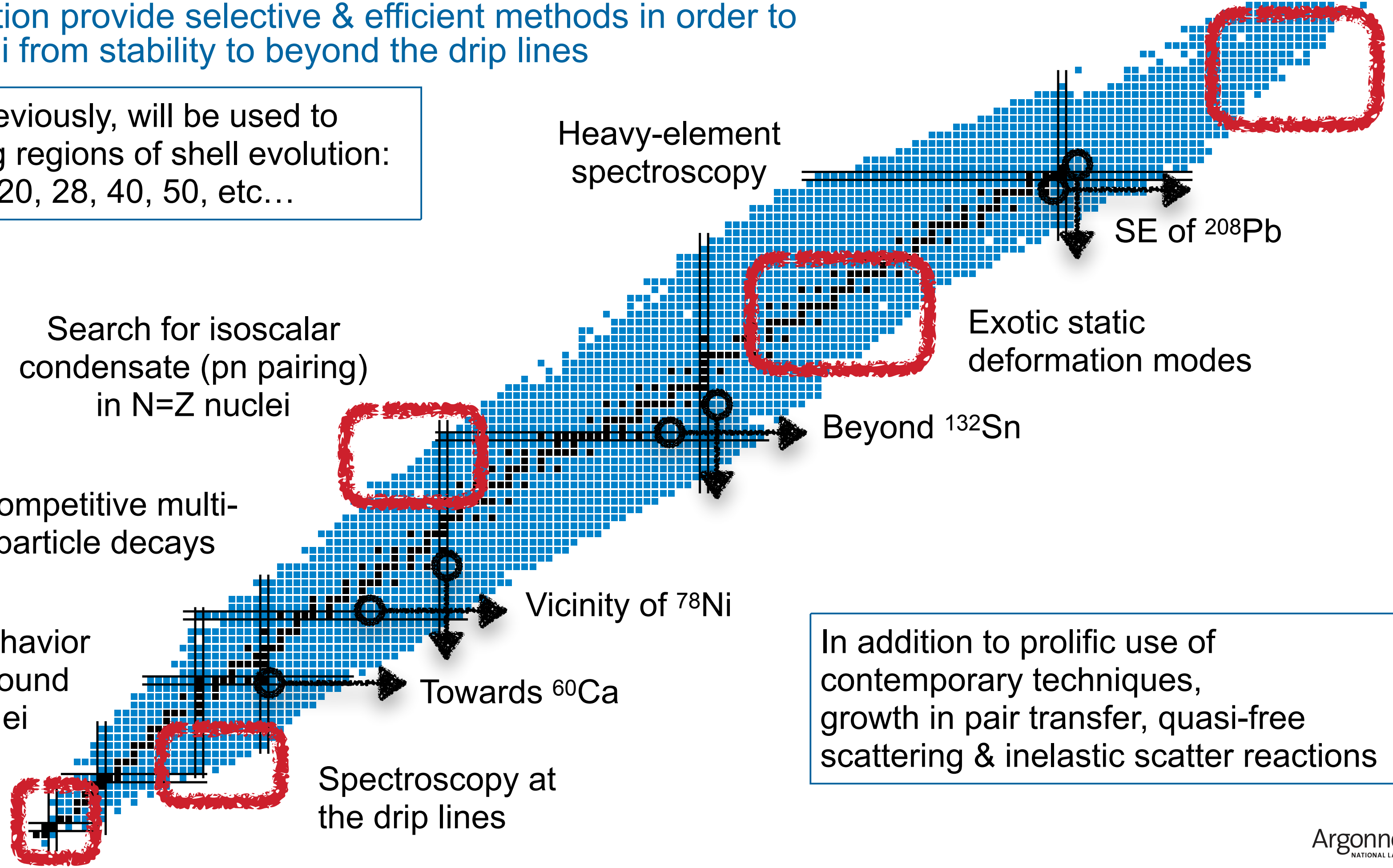


POSSIBLE FUTURE IMPACT AREAS

CHARACTERIZING EMERGENT STRUCTURES

Direct reaction provide selective & efficient methods in order to study nuclei from stability to beyond the drip lines

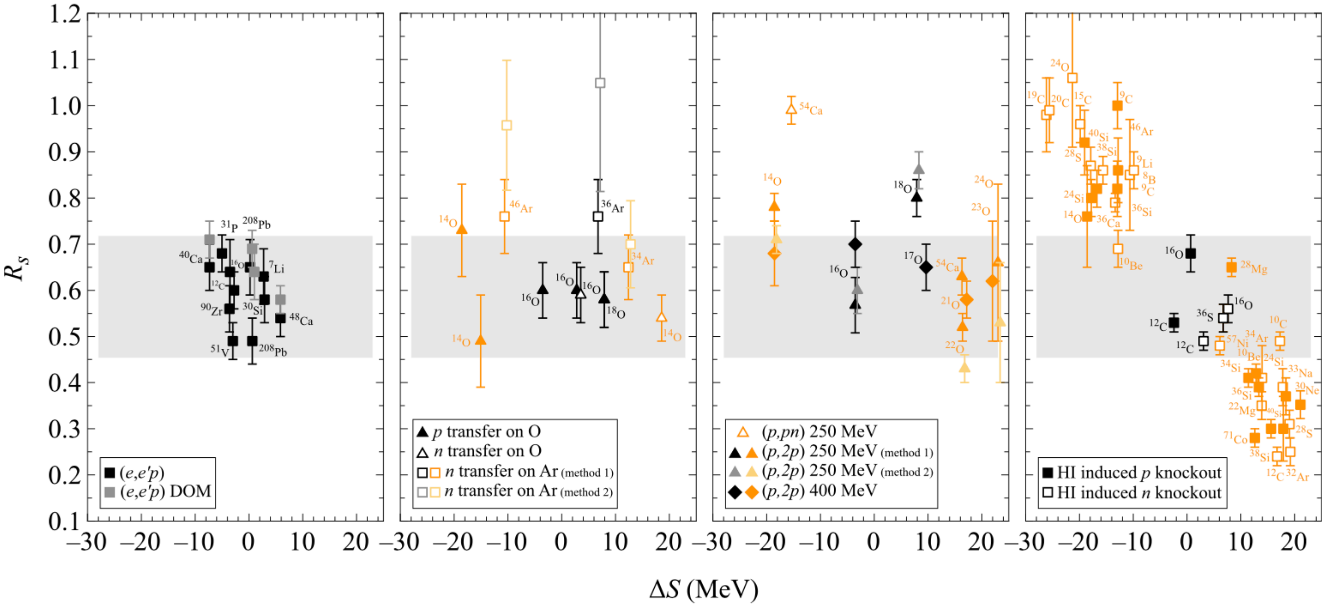
As done previously, will be used to probe along regions of shell evolution: N/Z = 6, 8, 20, 28, 40, 50, etc…



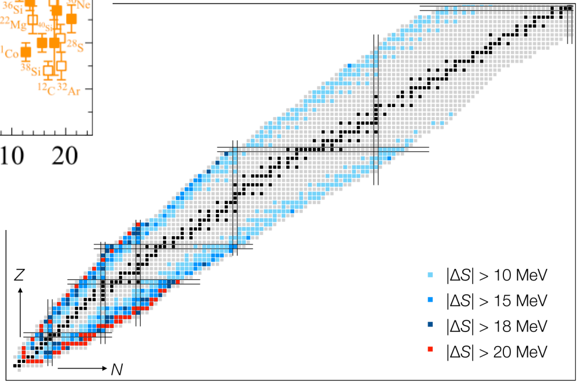
In addition to prolific use of contemporary techniques, growth in pair transfer, quasi-free scattering & inelastic scatter reactions

QUENCHING OF THE (SINGLE-PARTICLE) STRENGTH

Reduced cross sections: Knockout -vs- Transfer



Reaction data from various probes is converging (converged?)



Open challenge in direct reactions (exp & theory) - [transfer, knockout, quasi-free]
Overlaps with SRC work

Aumann PPNP 118 103847, (2021)
Tostevin PRC103, 054610 (2021)
Kay PRL (2022)

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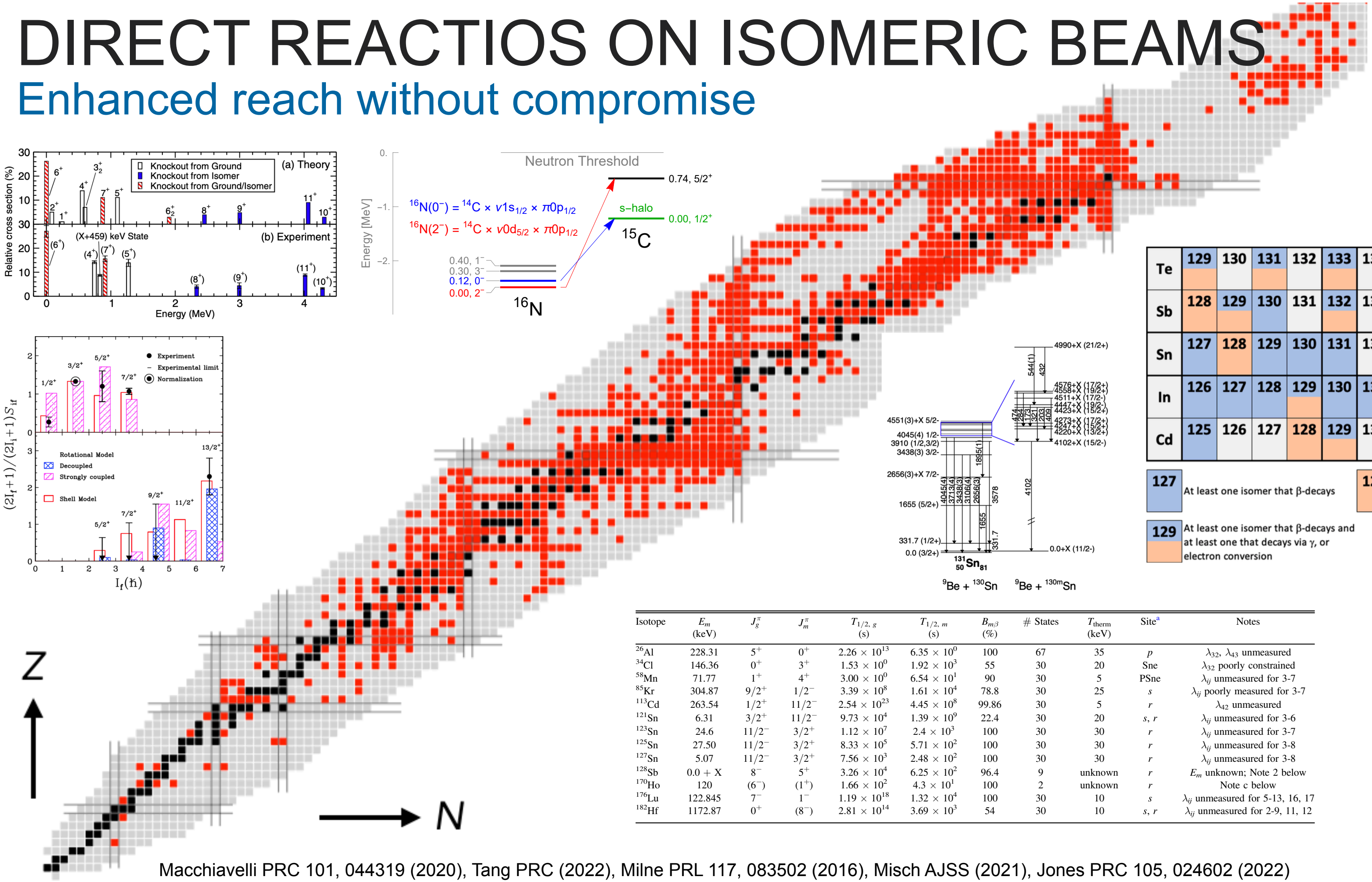
DIRECT REACTIOS ON ISOMERIC BEAMS

Enhanced reach without compromise



Te	129	130	131	132	133	134	135	136	137
Sb	128	129	130	131	132	133	134	135	136
Sn	127	128	129	130	131	132	133	134	135
In	126	127	128	129	130	131	132	133	134
Cd	125	126	127	128	129	130	131	132	133

127 At least one isomer that β-decays

128 At least one isomer that decays via or electron conversion

129 At least one isomer that β-decays and at least one that decays via γ, or electron conversion

Isotope	E_m (keV)	J_g^π	J_m^π	$T_{1/2,\,g}$ (s)	$T_{1/2,\,m}$ (s)	$B_{m\beta}$ (%)	# States	T_{therm} (keV)	Site[a]	Notes
^{26}Al	228.31	5^+	0^+	2.26×10^{13}	6.35×10^{0}	100	67	35	*p*	λ_{32}, λ_{43} unmeasured
^{34}Cl	146.36	0^+	3^+	1.53×10^{0}	1.92×10^{3}	55	30	20	Sne	λ_{32} poorly constrained
^{58}Mn	71.77	1^+	4^+	3.00×10^{0}	6.54×10^{1}	90	30	5	PSne	λ_{ij} unmeasured for 3-7
^{85}Kr	304.87	$9/2^+$	$1/2^-$	3.39×10^{8}	1.61×10^{4}	78.8	30	25	*s*	λ_{ij} poorly measured for 3-7
^{113}Cd	263.54	$1/2^+$	$11/2^-$	2.54×10^{23}	4.45×10^{8}	99.86	30	5	*r*	λ_{42} unmeasured
^{121}Sn	6.31	$3/2^+$	$11/2^-$	9.73×10^{4}	1.39×10^{9}	22.4	30	20	*s*, *r*	λ_{ij} unmeasured for 3-6
^{123}Sn	24.6	$11/2^-$	$3/2^+$	1.12×10^{7}	2.4×10^{3}	100	30	30	*r*	λ_{ij} unmeasured for 3-7
^{125}Sn	27.50	$11/2^-$	$3/2^+$	8.33×10^{5}	5.71×10^{2}	100	30	30	*r*	λ_{ij} unmeasured for 3-8
^{127}Sn	5.07	$11/2^-$	$3/2^+$	7.56×10^{3}	2.48×10^{2}	100	30	30	*r*	λ_{ij} unmeasured for 3-8
^{128}Sb	0.0 + X	8^-	5^+	3.26×10^{4}	6.25×10^{2}	96.4	9	unknown	*r*	E_m unknown; Note 2 below
^{170}Ho	120	(6^-)	(1^+)	1.66×10^{2}	4.3×10^{1}	100	2	unknown	*r*	Note c below
^{176}Lu	122.845	7^-	1^-	1.19×10^{18}	1.32×10^{4}	100	30	10	*s*	λ_{ij} unmeasured for 5-13, 16, 17
^{182}Hf	1172.87	0^+	(8^-)	2.81×10^{14}	3.69×10^{3}	54	30	10	*s*, *r*	λ_{ij} unmeasured for 2-9, 11, 12

Macchiavelli PRC 101, 044319 (2020), Tang PRC (2022), Milne PRL 117, 083502 (2016), Misch AJSS (2021), Jones PRC 105, 024602 (2022)

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IN SUMMARY

(Direct) reactions play a central role in experimental nuclear science

Robust tools, techniques & equipment have been developed for inverse kinematics

These are now in place in order to leverage the next generation of available radioactive beams

Stable beams remain vital for both precise reaction in normal kinematic reactions & to leverage advantages of inverse kinematics

A link to & continued developments from theory remain strong & are arguably as important as ever

The entirety of our success hinges on the people in our field, if the U.S. is to lead, the best must be recognized, retained & given the resources to succeed

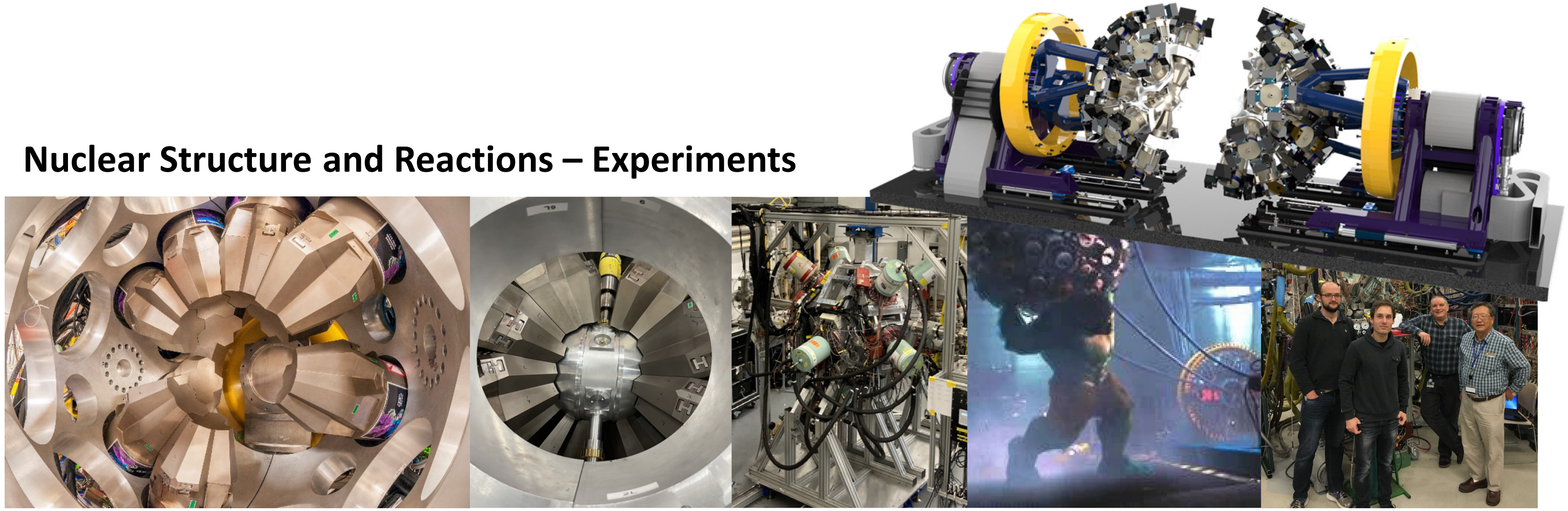
Special thanks to: A. Gade, S. Giraurd, M. Spieker, S. Almaraz, J. Bishop, P. Adsley, B. Kay and others

THE END

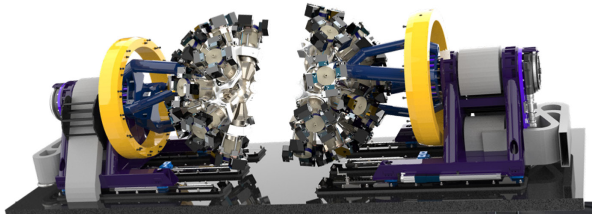
NSAC long range plan town hall meeting on nuclear structure, reactions and astrophysics at Argonne National Laboratory
November 14-16, 2022

Mark Spieker (Florida State University)

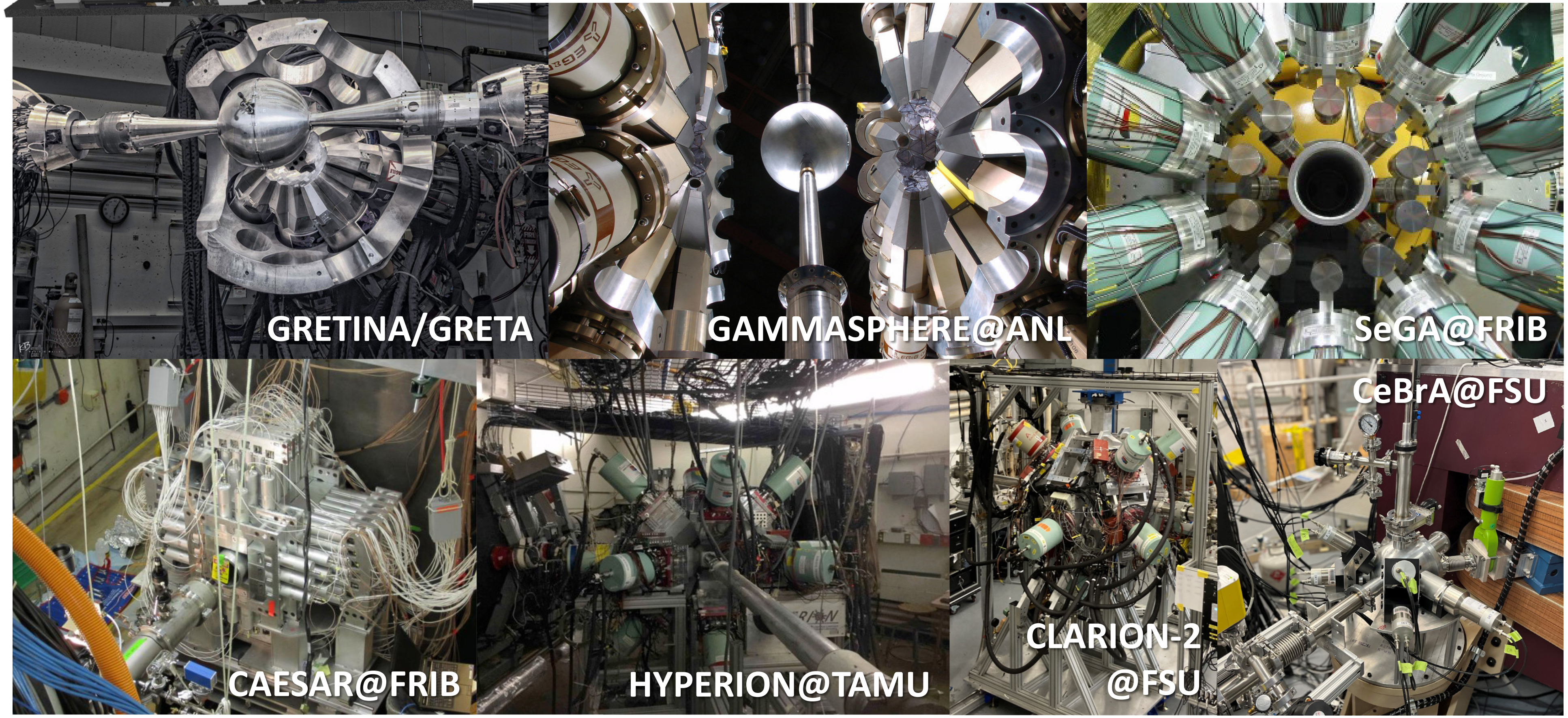
Nuclear Structure and Reactions – Experiments



Recent achievements and future prospects for in-beam gamma-ray spectroscopy



γ-ray spectrometers for in-beam γ-ray spectroscopy in the United States



+ Clover Share (at, e.g., HIgS), γ^3, …

Several arrays are available to tackle science questions at the frontiers of low-energy nuclear physics and nuclear astrophysics!

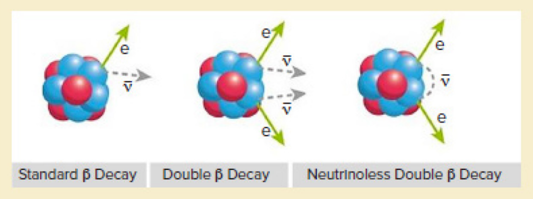
Connecting to big science ideas

(Fundamental symmetries and neutrinos)

How low-energy nuclear physics contributes. Two examples from in-beam γ-ray spectroscopy.

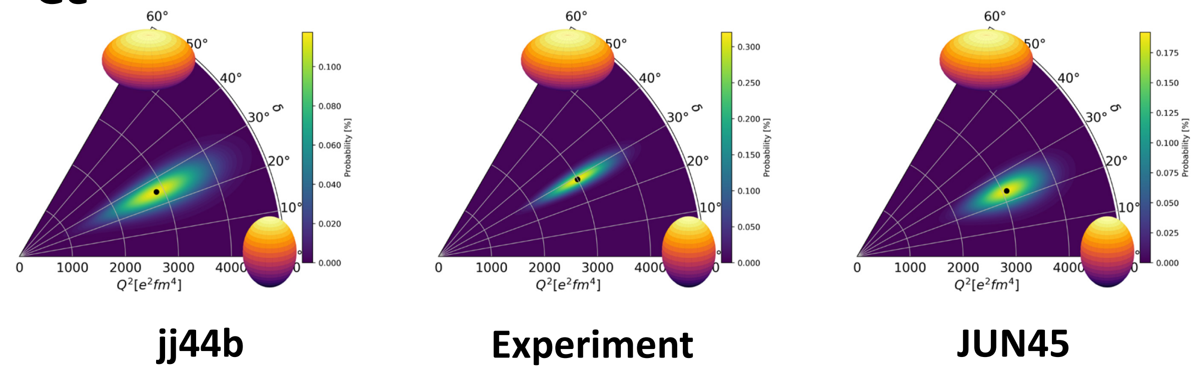
Information: A.D. Ayangeakaa (UNC) & J. Henderson (Surrey)

Neutrinoless double β decay (Sidebars 5.1 & 5.2 of 2015 NSAC LRP)



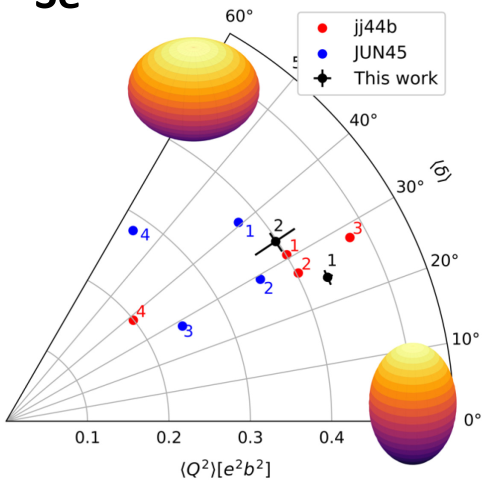
The quest to observe rare nuclear decays and to answer the question of why there is more matter than antimatter in our universe.

^{76}Ge



Experiments were performed determining the degree of triaxiality for ^{76}Ge and ^{76}Se to inform searches for the $^{76}Ge \rightarrow {}^{76}Se$ $0\nu\beta\beta$ decay searches. Detailed comparisons to configuration-interaction shell-model calculations were made. These are important steps towards constraining the $0\nu\beta\beta$ nuclear matrix element.

^{76}Se

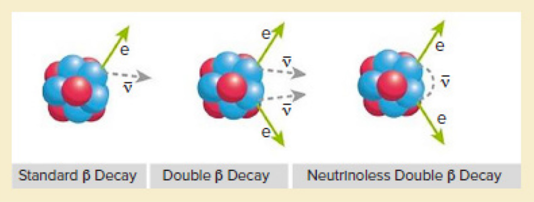


Two results are highlighted here:

1. Projectile multi-step CoulEx with GRETINA and CHICO-2 at ANL of ^{76}Ge.
   [A.D. Ayangeakaa, R.V.F. Janssens, S. Zhu, et al., PRL **123**, 102501 (2019)]
2. Sub-barrier CoulEx of ^{76}Se using the JANUS setup at ReA (NSCL/FRIB).
   [J. Henderson, C.Y. Wu, et al., PRC **99**, 054313 (2019)]

In principle, model-independent study of the quadrupole triaxial degree of freedom, based on measured E2 transition matrix elements, is possible. Detailed γ-ray spectroscopy experiments with high-resolution arrays provide the sensitivity to resolve several transitions needed for this kind of analysis.

Neutrinoless double β decay (Sidebars 5.1 & 5.2 of 2015 NSAC LRP)



The quest to observe rare nuclear decays and to answer the question of why there is more matter than antimatter in our universe.

Experiments at University of Kentucky

PHYSICAL REVIEW C **95**, 014327 (2017)

Nuclear structure of ^{76}Ge from inelastic neutron scattering measurements and shell model calculations

S. Mukhopadhyay,[1,2,*] B. P. Crider,[1] B. A. Brown,[3,4] S. F. Ashley,[1,2] A. Chakraborty,[1,2,†] A. Kumar,[1,2] M. T. McEllistrem,[1] E. E. Peters,[2] F. M. Prados-Estévez,[1,2] and S. W. Yates[1,2]

[1] *Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2] *Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

(Received 25 September 2016; revised manuscript received 4 December 2016; published 25 January 2017)

PHYSICAL REVIEW C **99**, 014313 (2019)

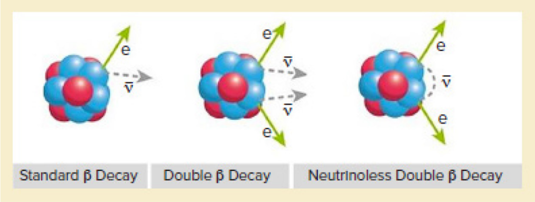
Inelastic neutron scattering studies of ^{76}Se

S. Mukhopadhyay,[1,2,*] B. P. Crider,[1,†] B. A. Brown,[3,4] A. Chakraborty,[1,2,‡] A. Kumar,[1,2,§] M. T. McEllistrem,[1] E. E. Peters,[2] F. M. Prados-Estévez,[1,2] and S. W. Yates[1,2]

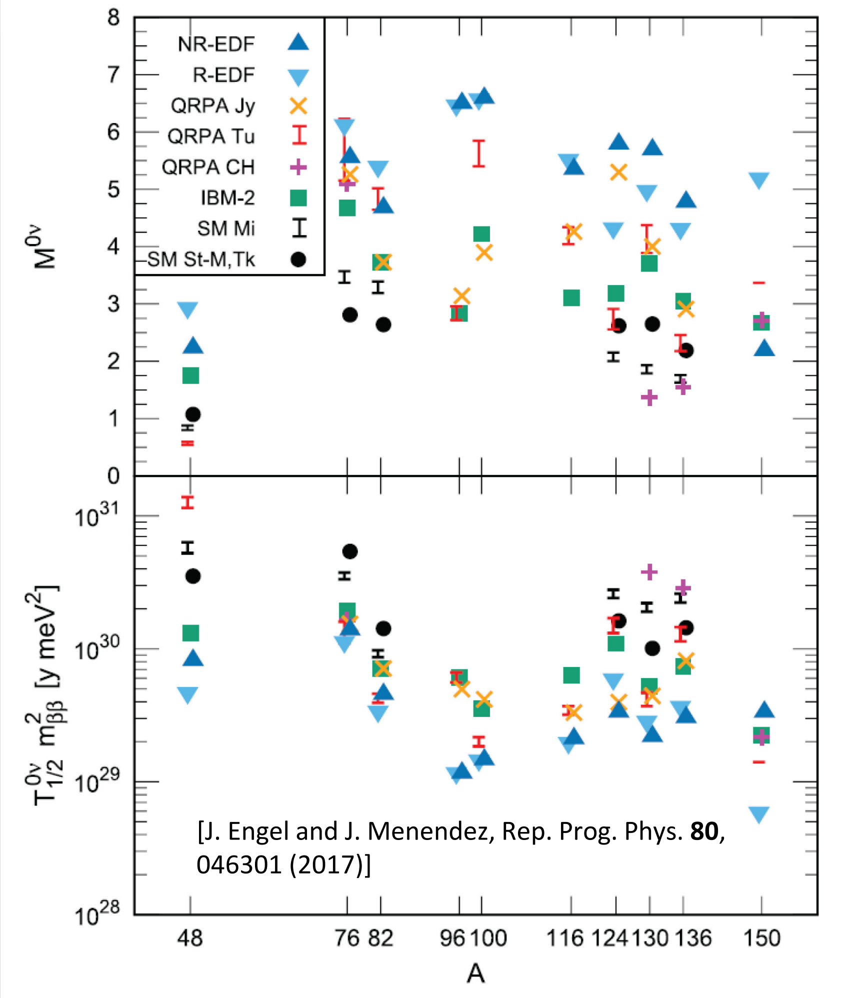
[1] *Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2] *Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

Information: S.W. Yates (UK) and B.P. Crider (MSU)

Neutrinoless double β decay (Sidebars 5.1 & 5.2 of 2015 NSAC LRP)



The quest to observe rare nuclear decays and to answer the question of why there is more matter than antimatter in our universe.

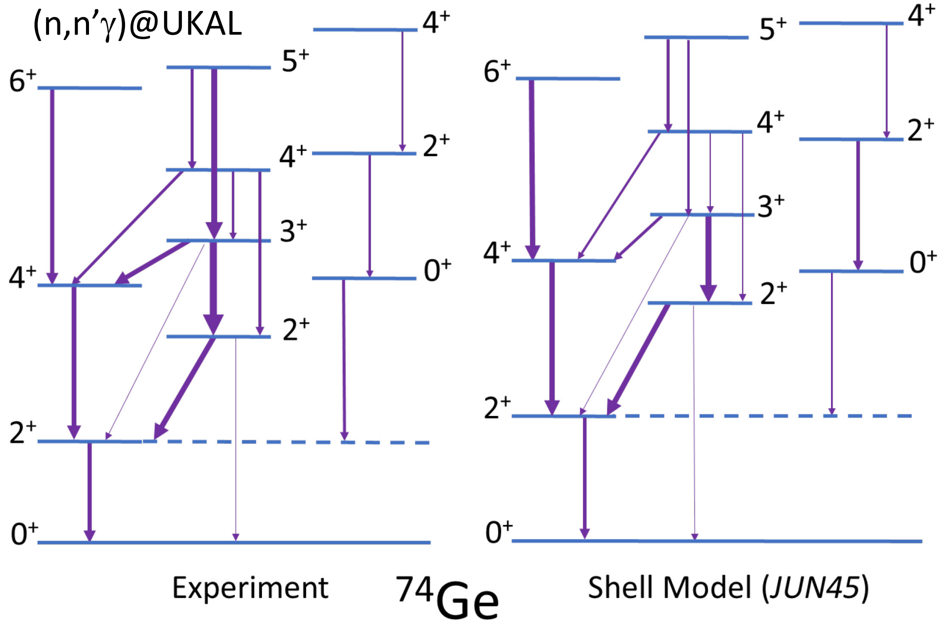


[J. Engel and J. Menendez, Rep. Prog. Phys. **80**, 046301 (2017)]

Test structure of nuclei in entire mass region and verify reliability of model predictions.

(+ANL CoulEx program).

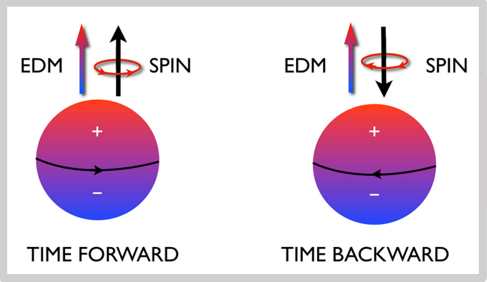
Information: S.W. Yates (UK)



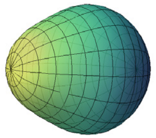
Triaxial degrees of freedom are very important in this mass region!

Information: R.V.F. Janssens & A.D. Ayangeakaa (UNC)

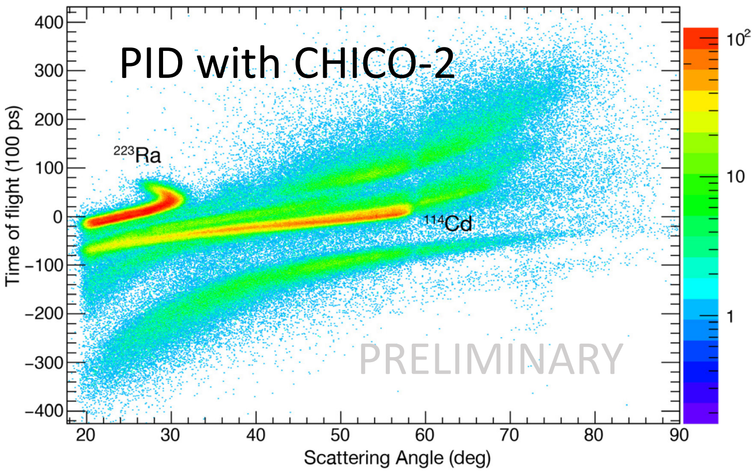
Electric Dipole Moment (Sidebar 5.2 of 2015 NSAC LRP)



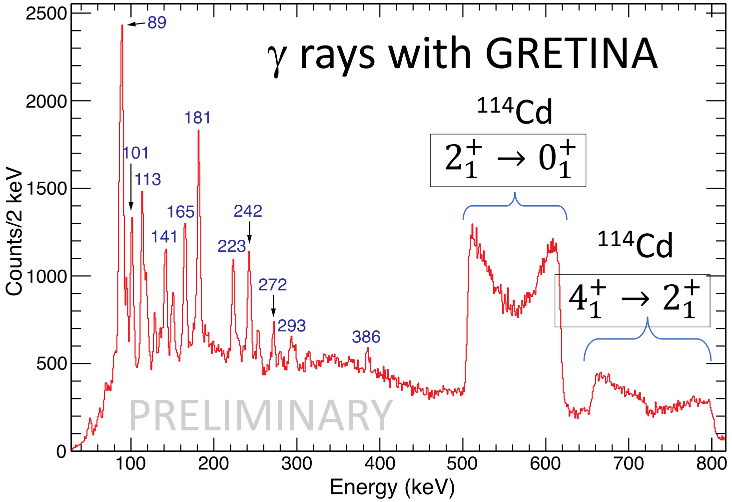
Why is there more matter than antimatter in the present universe?



Statically octupole deformed odd-A nuclei will enhance a possible experimental EDM signal by orders of magnitude! To answer whether a nucleus is statically octupole deformed, we need to measure the E3 matrix elements (amongst other observables).

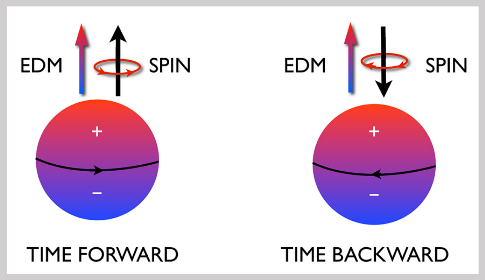


Highlighted experiment: Coulomb excitation of ^{223}Ra with GRETINA and CHICO-2 at ANL to test whether ^{223}Ra is statically octupole deformed (parity doublet ΔE=50 keV). Experiment used 400 ng $Ra(NO_3)_2$ target (70% enriched sample; dose rate of 60 mR/hr). Experiment happened during last GRETINA campaign. Analysis is ongoing.



The observation of several γ-ray transitions with energies between 100 keV and 300 keV reinforces the need to perform these studies of heavy odd-A nuclei with high-resolution γ-ray spectrometers like GRETINA/GRETA/SeGA/GAMMASPHERE. A letter of intent was submitted to FRIB PAC-1 to encourage beam developments for sub-barrier CoulEx experiments of nuclei in the A=223-229 mass region at ReA.

Electric Dipole Moment (Sidebar 5.2 of 2015 NSAC LRP)



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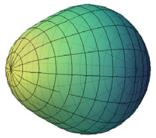

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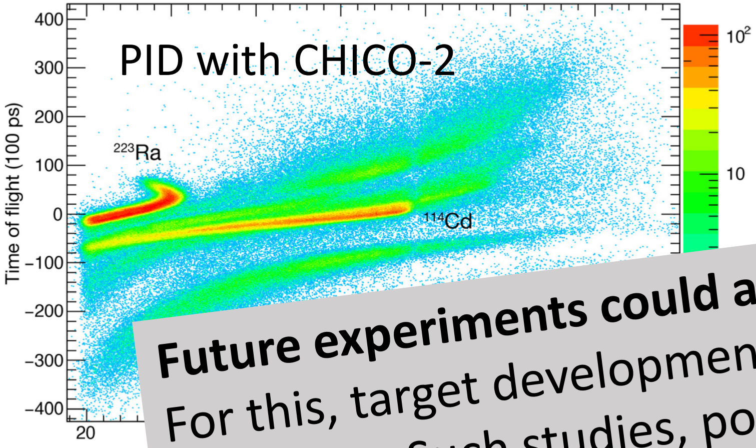
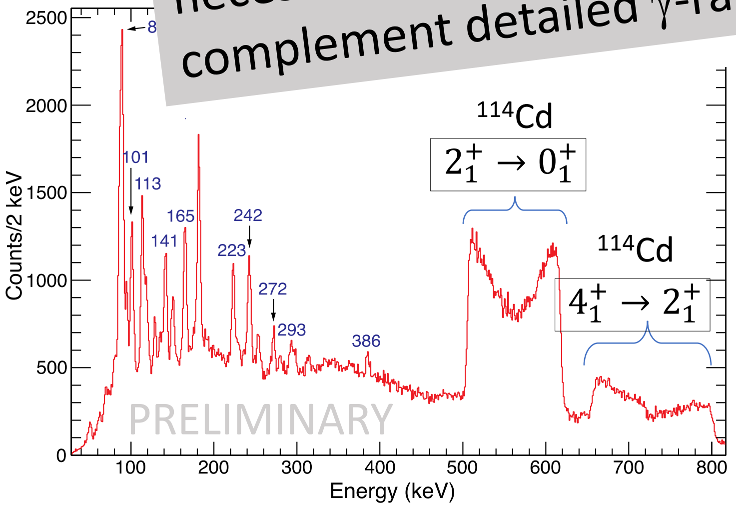
... and ... (70% ... happened during ... is ongoing.



Future experiments could also be performed at high-resolution magnetic spectrographs.

For this, target developments using highly enriched actinide isotope material will be necessary. Such studies, possibly to be performed at University laboratories, could complement detailed γ-ray spectroscopy studies at FRIB and ANL.



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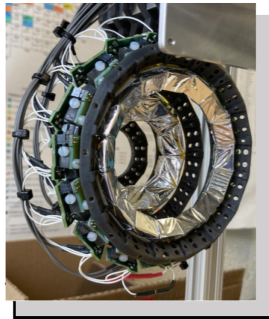
Information: R.V.F. Janssens & A.D. Ayangeakaa (UNC)

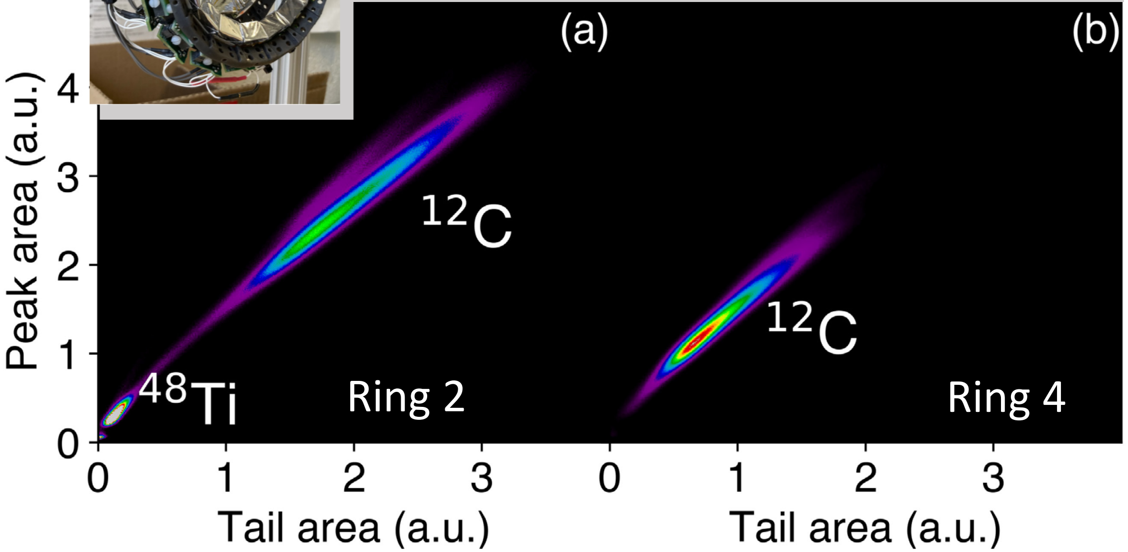
Examples of recent achievements and how they pave the way towards future experiments.

At National Laboratories and University Laboratories.

First Safe CoulEx experiments with CLARION2 at Florida State University

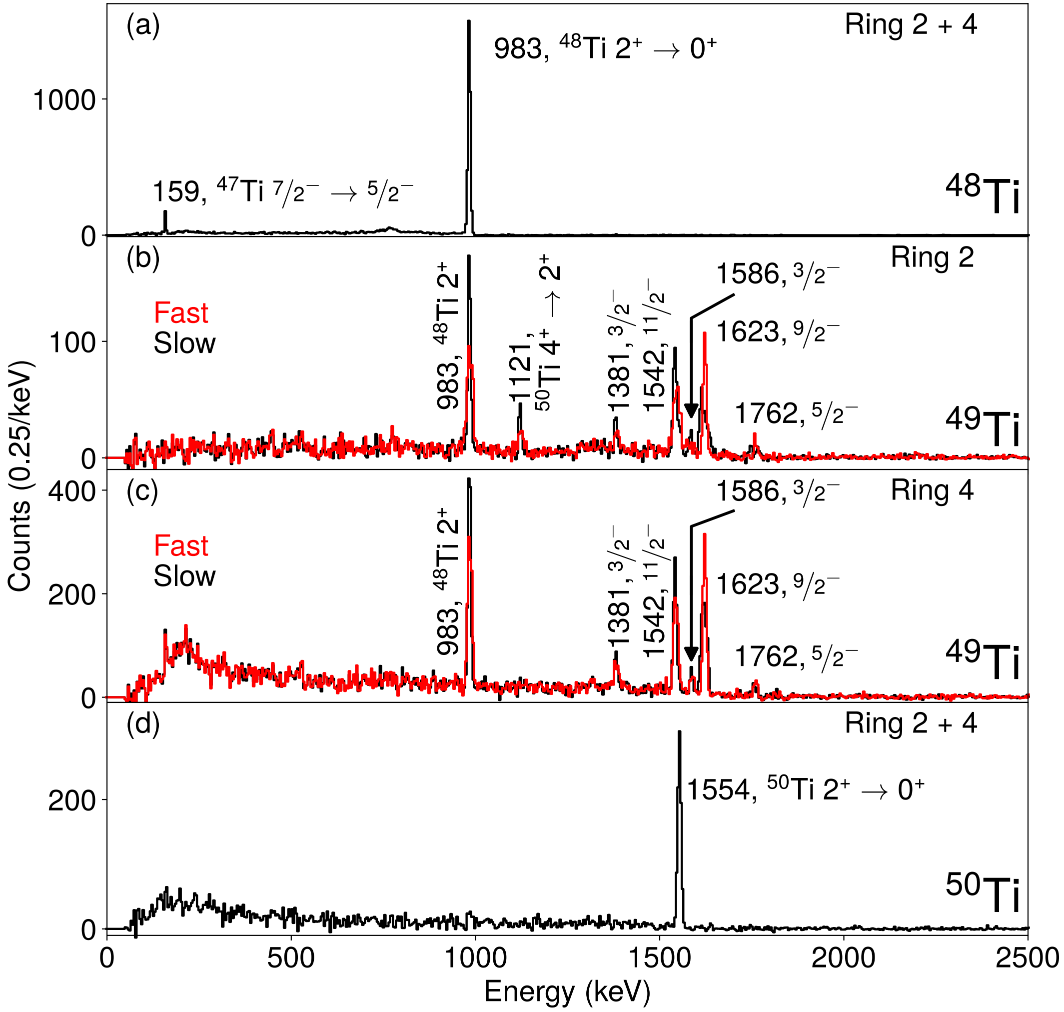


Particle Identification with GAGG:Ce



- **Safe Coulex** of ^{48,49,50}Ti at FSU John D. Fox Laboratory with TRINITY and CLARION2.
- Search for early signs of **emerging collectivity in A=50 mass region and around N=28**
  - → Effect of particle-core coupling on strength and strength fragmentation
- Compare **total quadrupole excitation** strength in odd-mass ^{49}Ti to ^{48,50}Ti neighbors to find **signature of emerging collectivity.**

[T.J. Gray, J.M. Allmond, A.E. Stuchbery, et al., PRL **124**, 032502 (2020)]

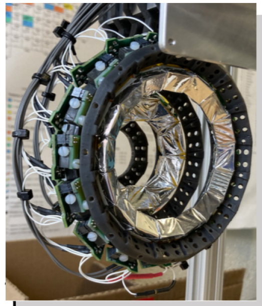


CLARION2-TRINITY:

[T.J. Gray, J.M. Allmond et al., NIM A **1041**, 167392 (2022)]

Information: T.J. Gray, J.M. Allmond (ORNL), V. Tripathi (FSU)

First Safe CoulEx experiments with CLARION2 at Florida State University



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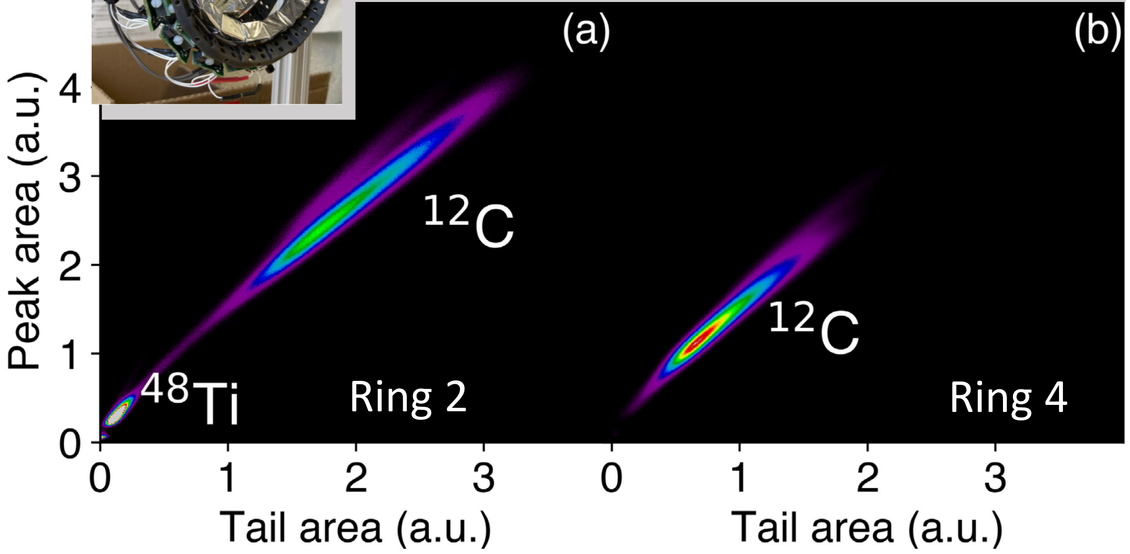

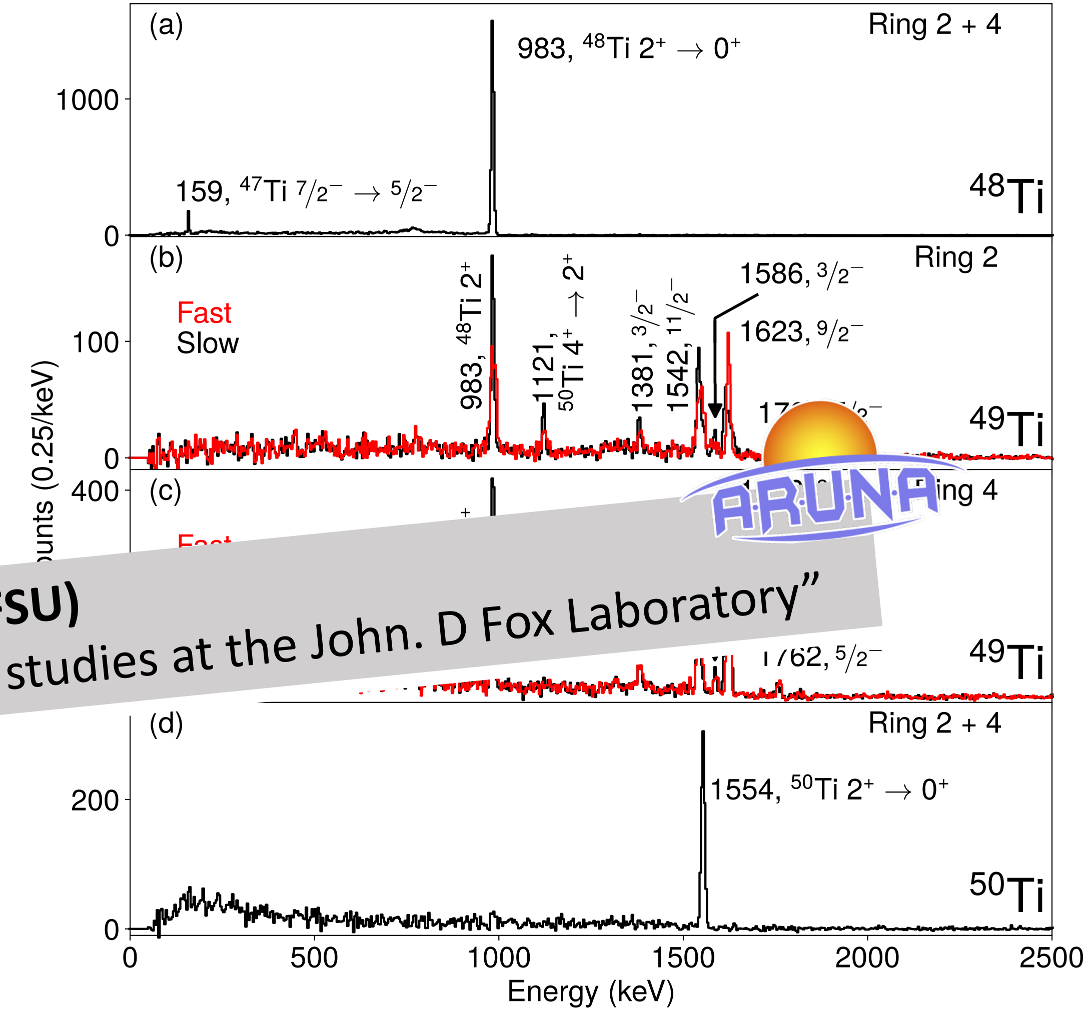

Contribution by V. Tripathi (FSU)
“Detailed γ-ray spectroscopy studies at the John. D Fox Laboratory”

- **Safe Coulex** of ^{48,49,50}Ti ... with TRINITY and CLAR...
- Search for early signs o... **...collectivity in A=50 mass region and around N=28**
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Information: T.J. Gray, J.M. Allmond (ORNL), V. Tripathi (FSU)

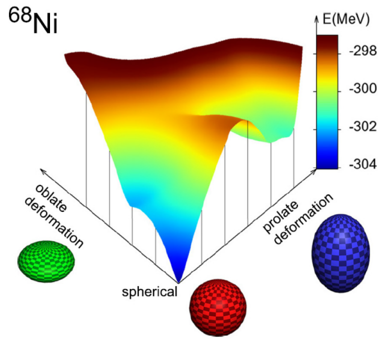
Information: B. Longfellow (MSU/FRIB/LLNL), A. Gade (MSU/FRIB)

First Simultaneous Intermediate-Energy Coulomb Excitation from Ground State and Isomer

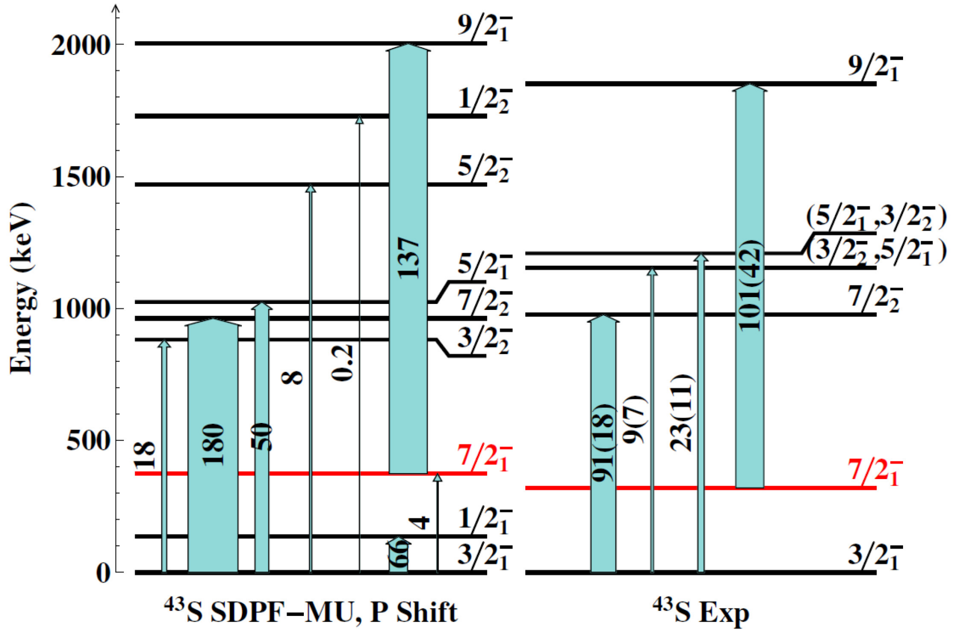
NSCL Experiment with CAESAR+S800 near N=28 Island of Inversion

- Observation of collective 1532-keV transition built on shape-coexisting $7/2^-$ isomer at 320 keV ($T_{1/2}$ = 415 ns) and other collective transitions built on $3/2^-$ ground state of ^{43}S.

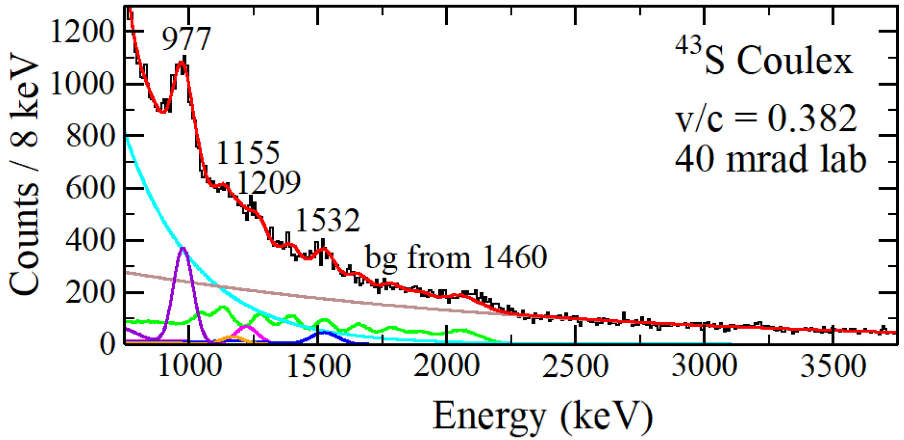
[T. Otsuka, J. Phy. G **43**, 024009 (2016)]



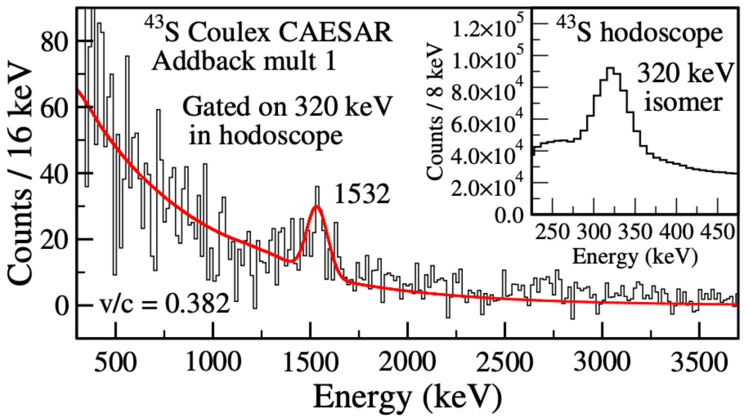
Detailed studies of shape coexistence and of the collectivity of different configurations will be possible with CAESAR, GRETINA/GRETA, the S800, and isomer beams at FRIB in even more neutron-rich nuclei!



At reaction target with CAESAR



In coincidence with isomer decay at S800 focal plane



Reference: B. Longfellow et al., PRL **125**, 232501 (2020)

Pushing for the extremes at FRIB – fast-beam in-flight γ-ray spectroscopy at μb cross sections

The power of GRETINA/GRETA & spectrometers

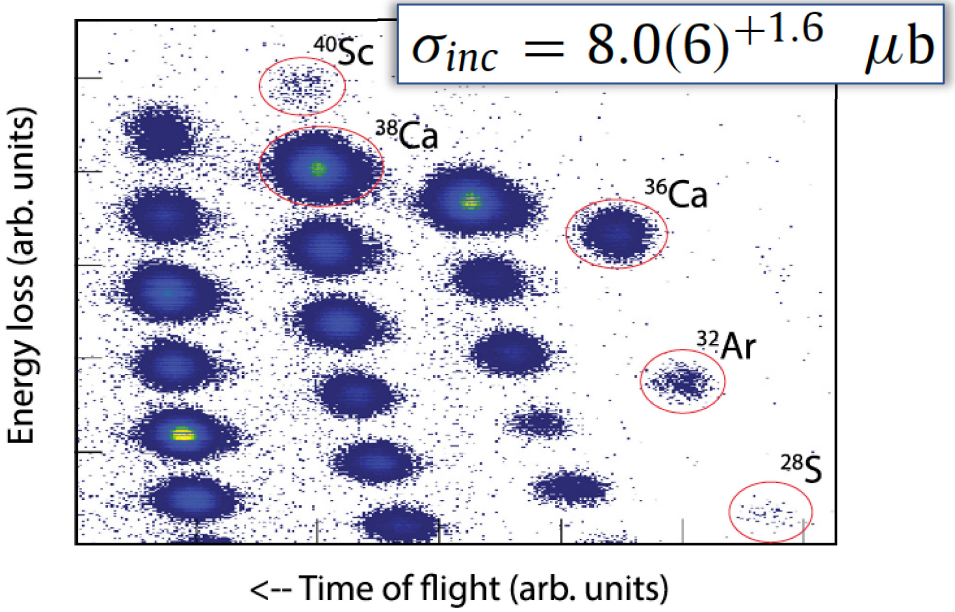
- Exotic ^{9}Be(^{38}Ca,^{40}Sc+γ)X reaction channel discovered in a ^{38}Ca+^{9}Be reaction setting
- Very clean γ-ray spectrum with only two transitions

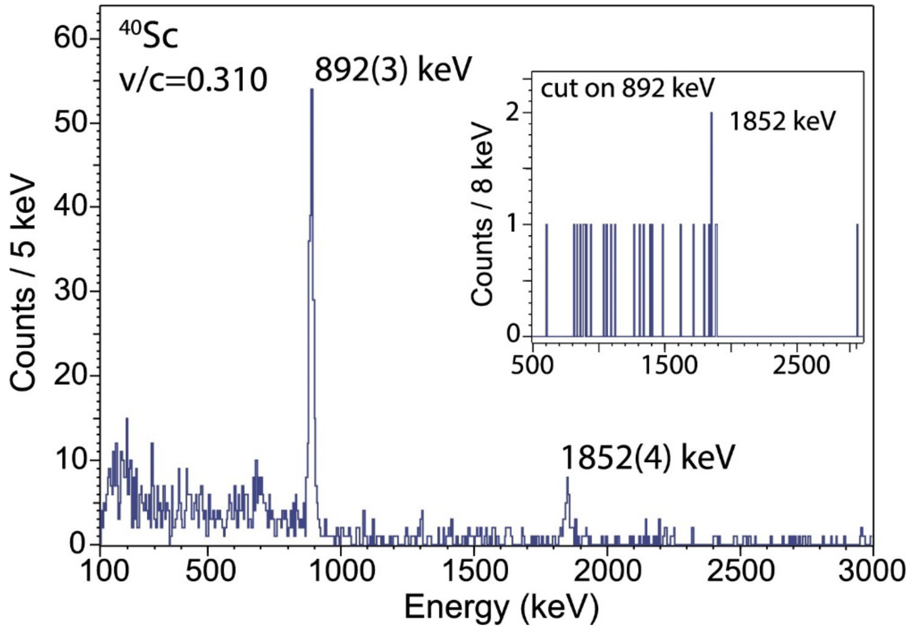
  → This was the first γ-ray spectroscopy of ^{40}Sc, the last bound Sc isotope.

This experiments proves that in-beam γ-ray spectroscopy with fast beams is possible at μb cross sections! Similar experiments can be performed by coupling GRETA/GRETINA to a fast-beam spectrometer at FRIB.

Great promise for reactions with GRETINA/GRETA at the S800 & HRS at FRIB/FRIB400.

Reference: A. Gade et al., PLB **808**, 135637 (2020)





Information: A. Gade (MSU/FRIB)

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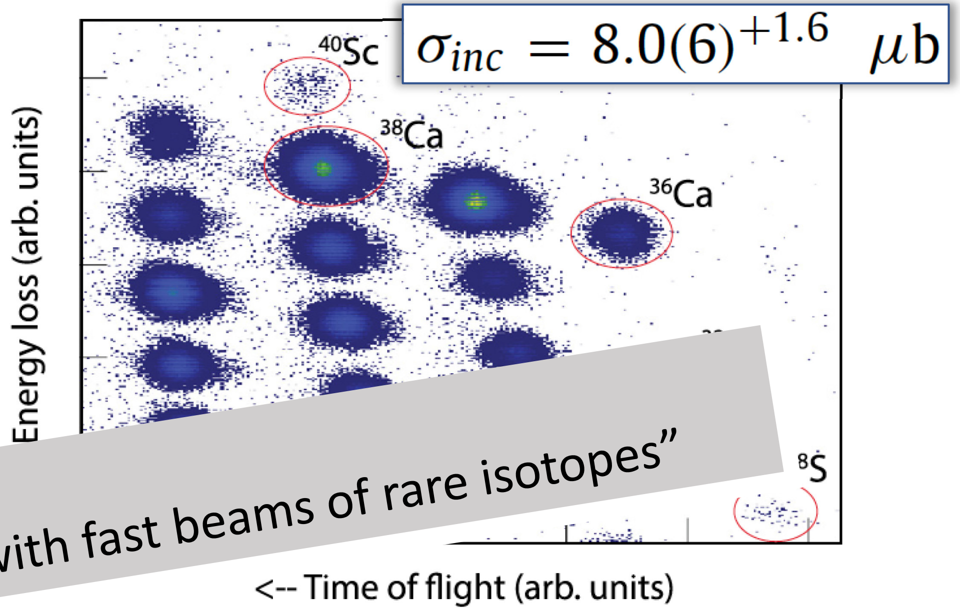
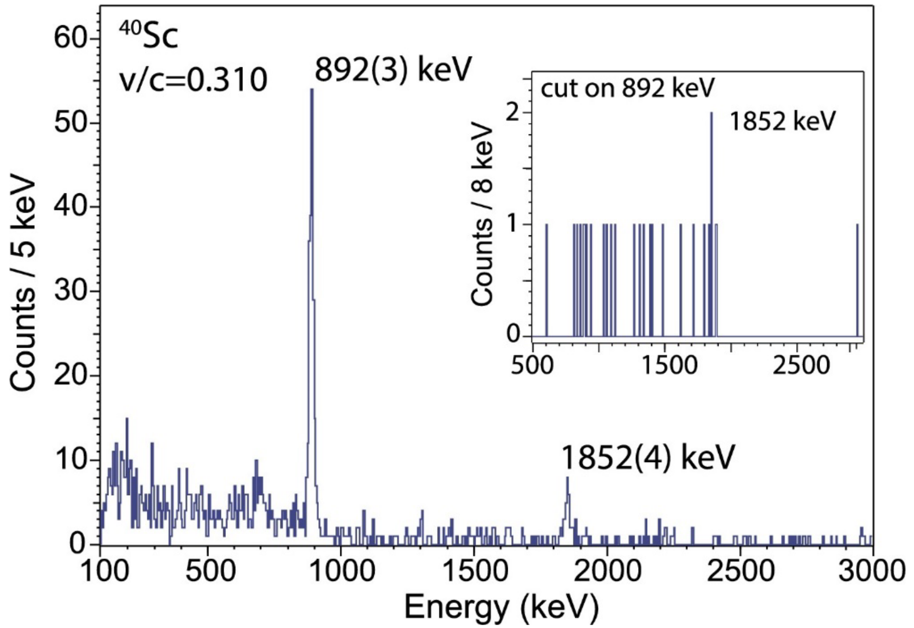
This exp… with fas… …tions! Similar experime… …ormed by coupling GRETA/GRETINA to a fast-beam spectrometer at FRIB.

Contribution by A. Gade (MSU/FRIB)
"In-beam γ-ray spectroscopy and direct reactions with fast beams of rare isotopes"





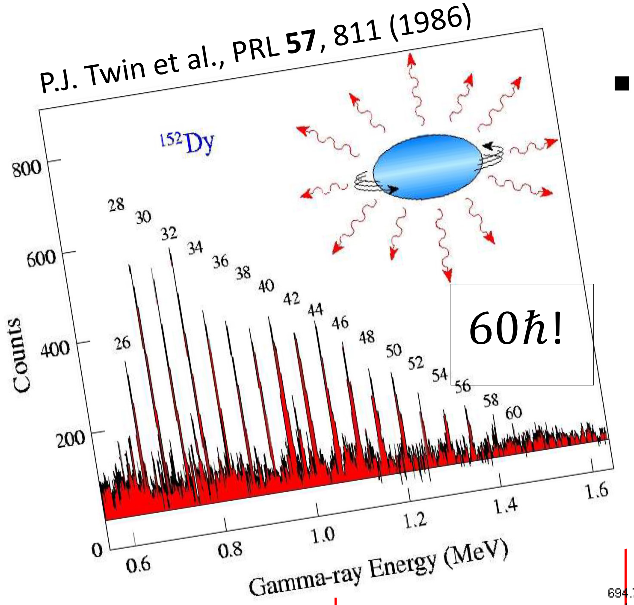
Great promise for reactions with GRETINA/GRETA at the S800 & HRS at FRIB/FRIB400.

Reference: A. Gade et al., PLB **808**, 135637 (2020)

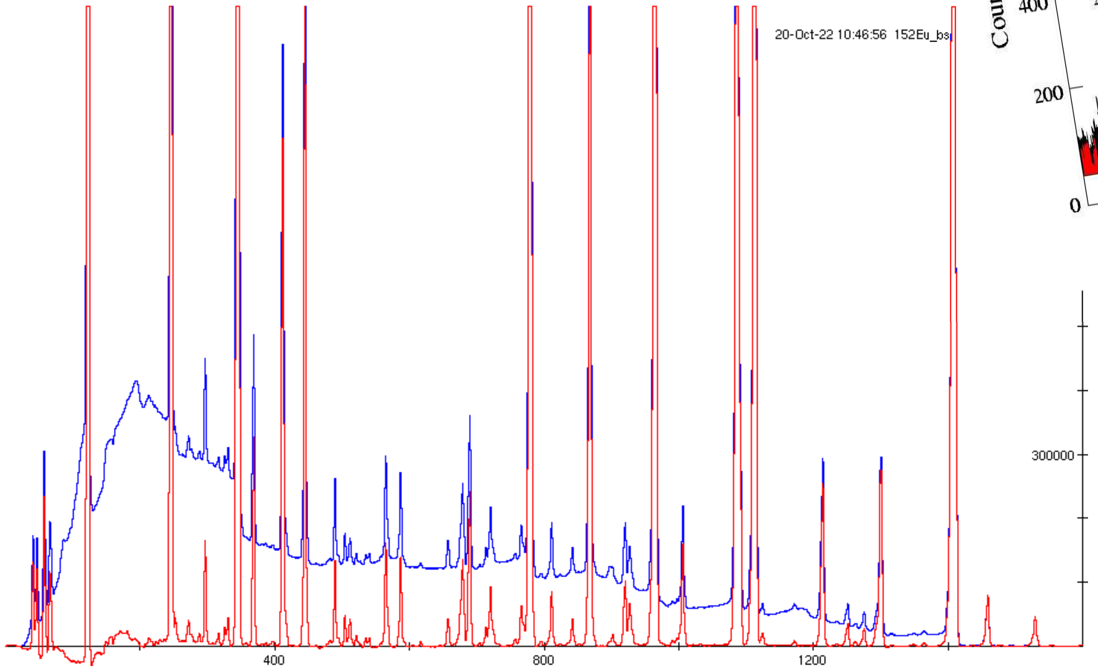
Information: A. Gade (MSU/FRIB)

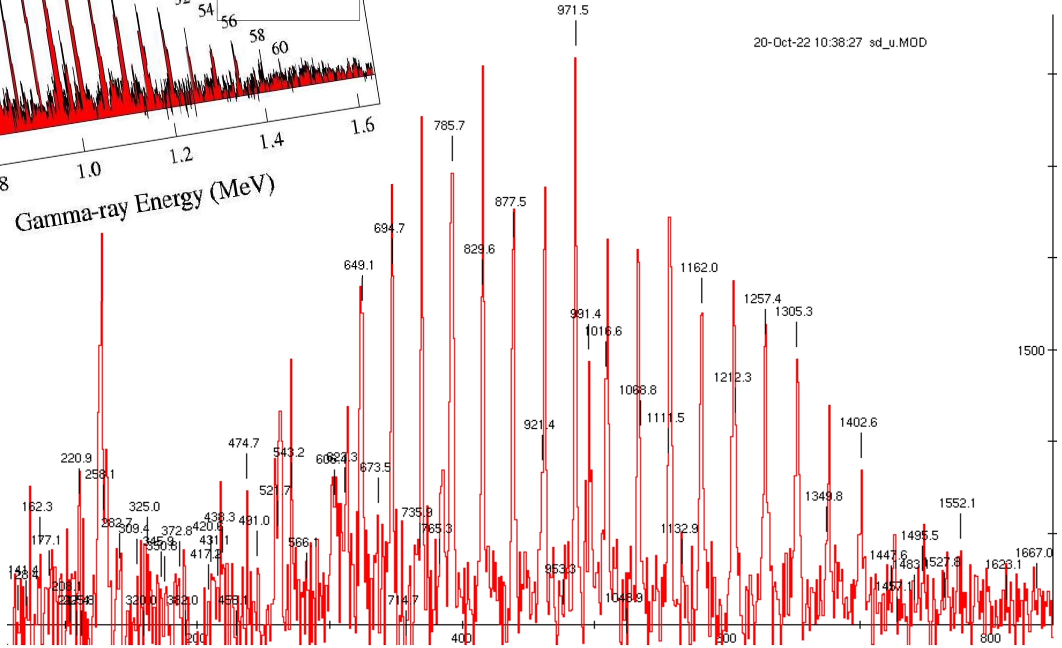
GRETINA@ANL – Response function and superdeformed rotational band in ^{152}Dy

- First extraction of a response function for a γ-ray tracking array. Happened during last GRETINA campaign at ANL. The unfolded ^{152}Eu spectrum is shown below in red.



- Superdeformed rotational band in ^{152}Dy studied with GRETINA through ^{108}Pd(^{48}Ca,4n)^{152}Dy reaction



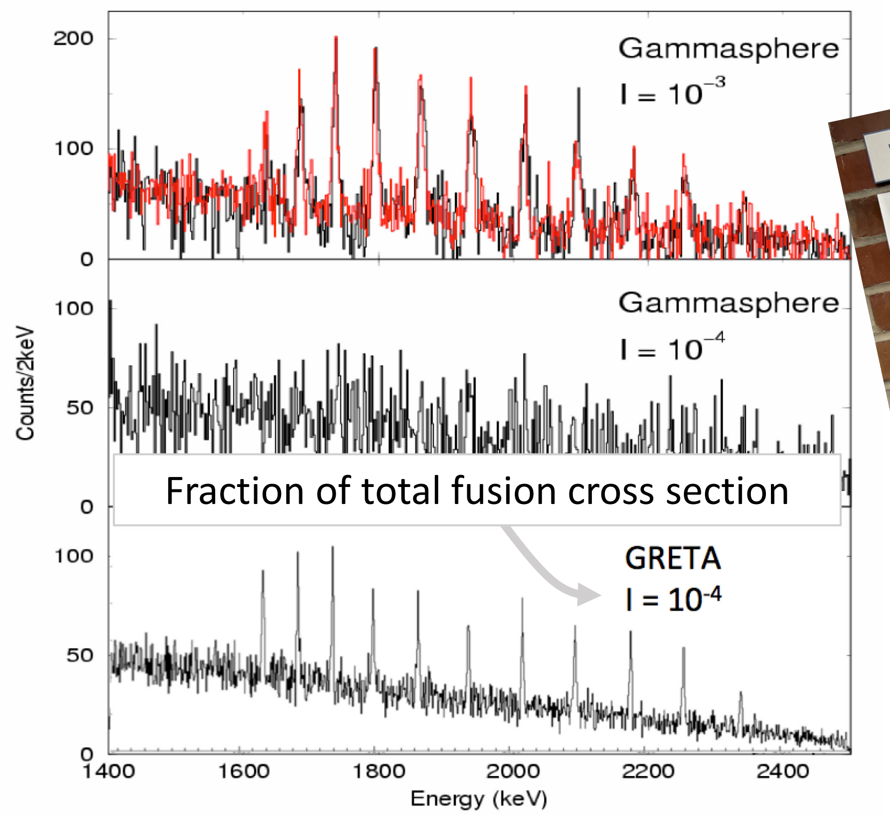


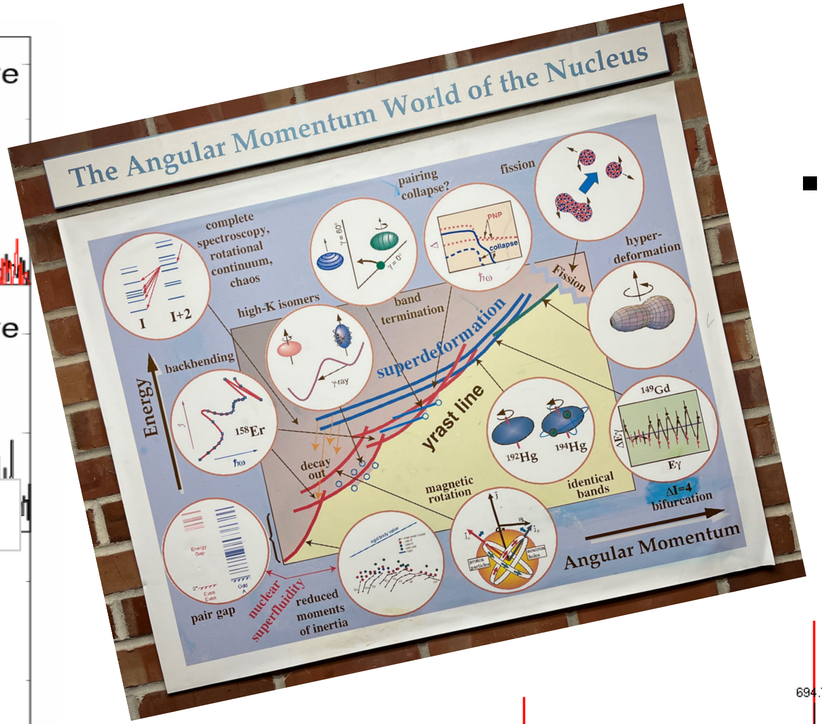
Goal: Determine the entry distribution (HK distribution), i.e., the location in the spin and energy plane from which gamma deexcitation starts, after the last particle has been evaporated.

Information: T. Lauritsen (ANL)

Example of ^{108}Cd from GRETA Final Design Report.

Pushing the limits towards previously undetectable structures





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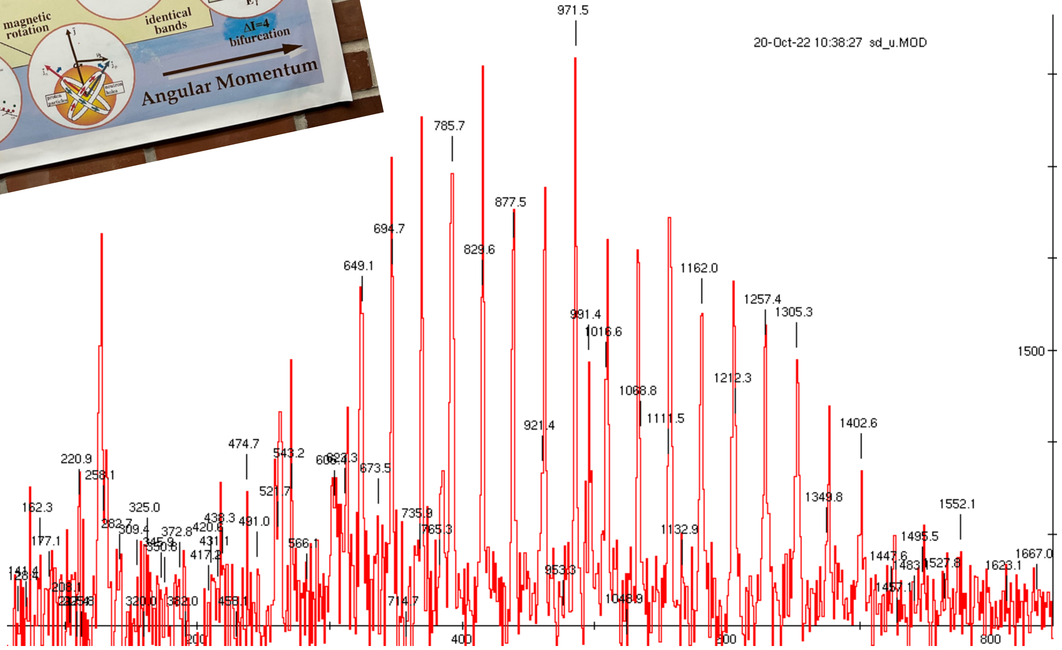


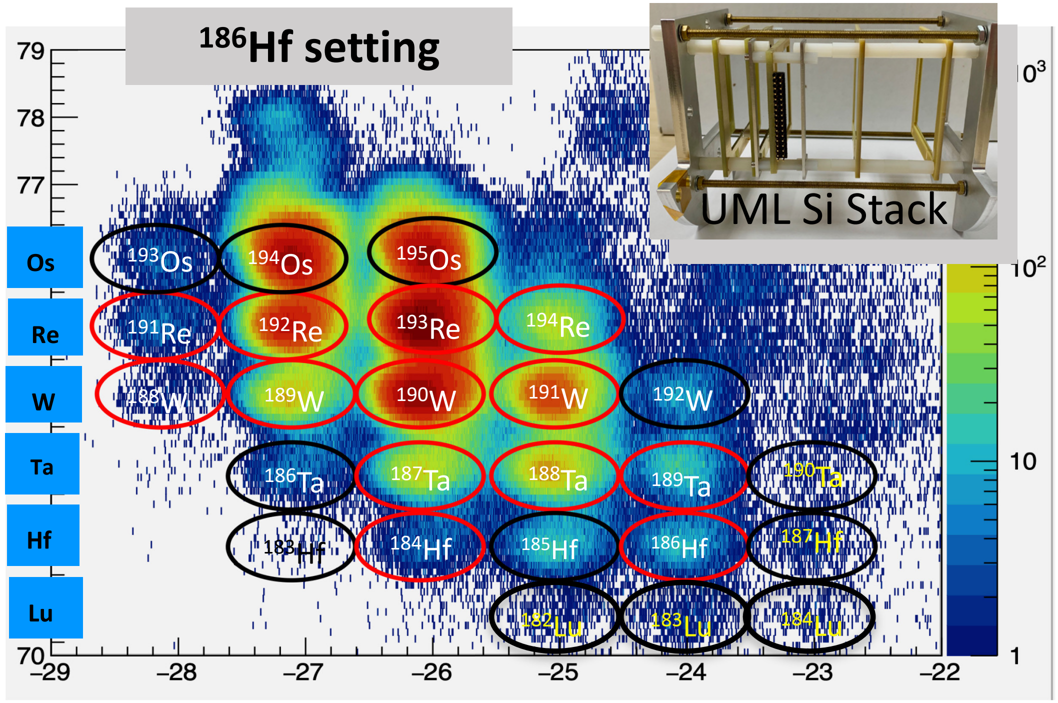
Rotational motion provides a striking example of emergent phenomena in many-body quantum systems and is a sensitive tool to study the underlying microscopic structure of atomic nuclei. GRETA will allow the study of previously undetectable rotational structures at the extremes of angular momentum due to the significant gain in resolving power.

The study at ANL during the last GRETINA campaign was critical to achieve this goal!

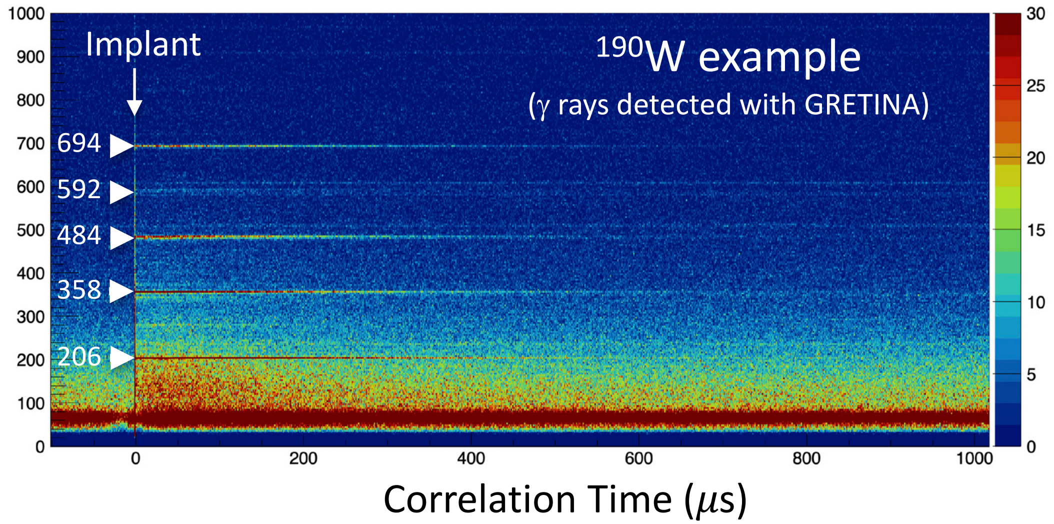
Information: T. Lauritsen (ANL)

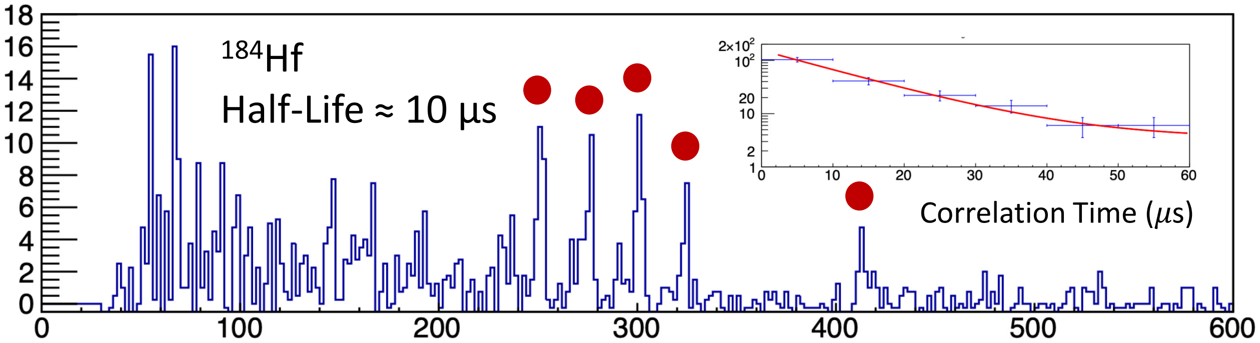
Pushing for the extremes at FRIB – First fragmentation of ^{198}Pt beam at NSCL (decay spectroscopy)

Information: A. Rogers, P. Bender, P. Chowdhury (UML)



- **First fragmentation of ^{198}Pt beam**
- Three different A1900 settings for studying nuclei south of Z=82 and west of N=126
- **Challenging particle identification accomplished**
  → UML Si stack designed in collaboration with O. Tarasov using careful LISE++ calculations to guide the design
- K-Isomers identified in neutron-rich Hf-W region
- States with angular momentum as high as 18$\hbar$ populated.
- **New neutron-rich isotopes in Hf region identified.**

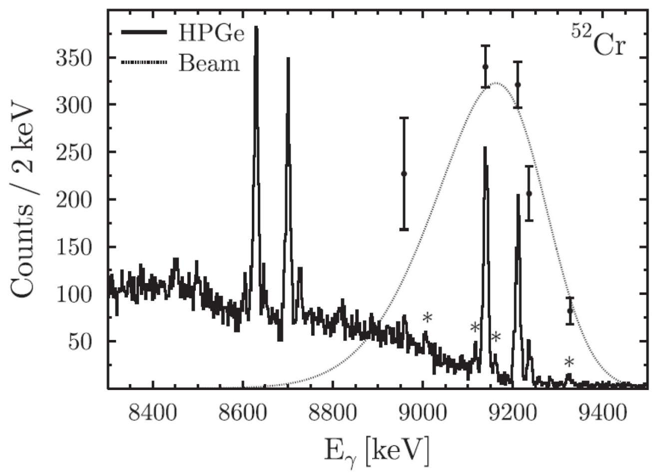


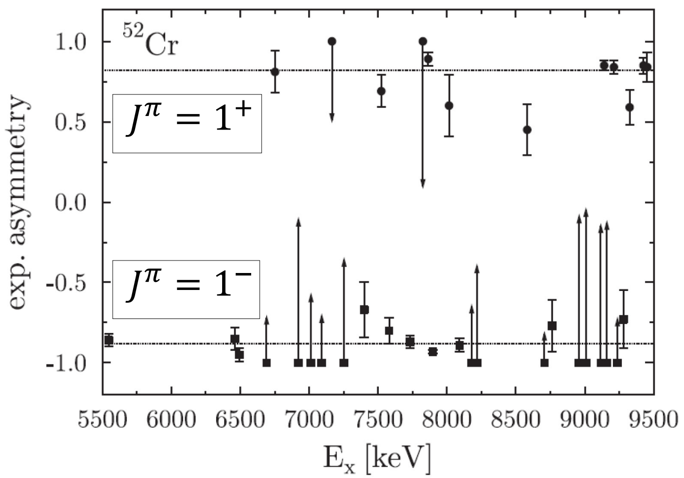


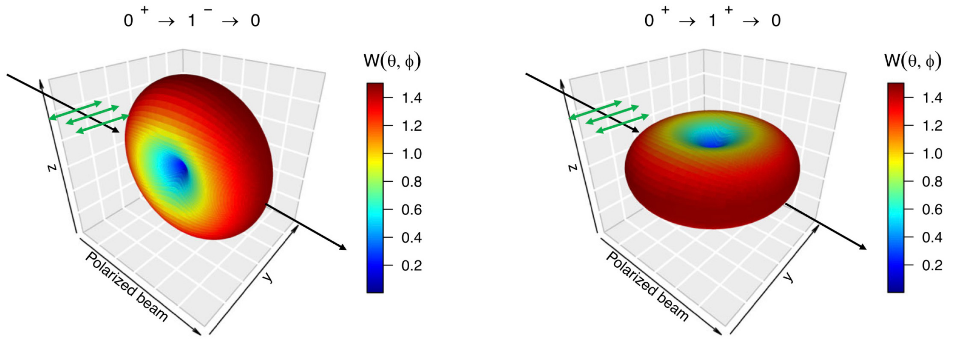
Important development for fast-beam experiments and needed as long as HRS is not available to reach heavier isotopes (S800 Bρ limit).

Studying the low-lying E1 and M1 response with quasi-monoenergetic and polarized real photons at HIgS

[Spectrum and asymmetry plot: J. Wilhelmy et al., PRC **98**, 034315 (2018)]



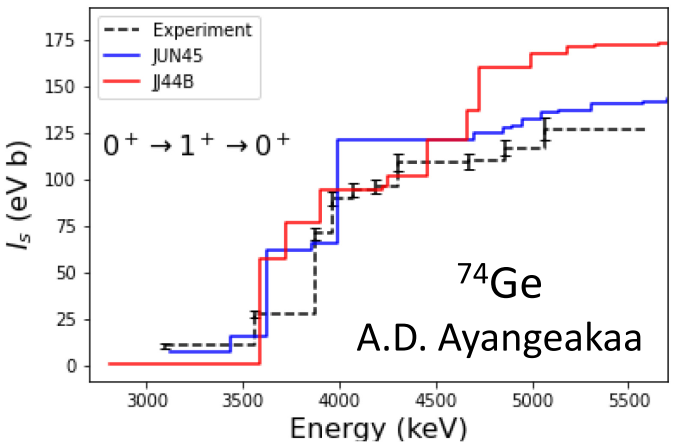




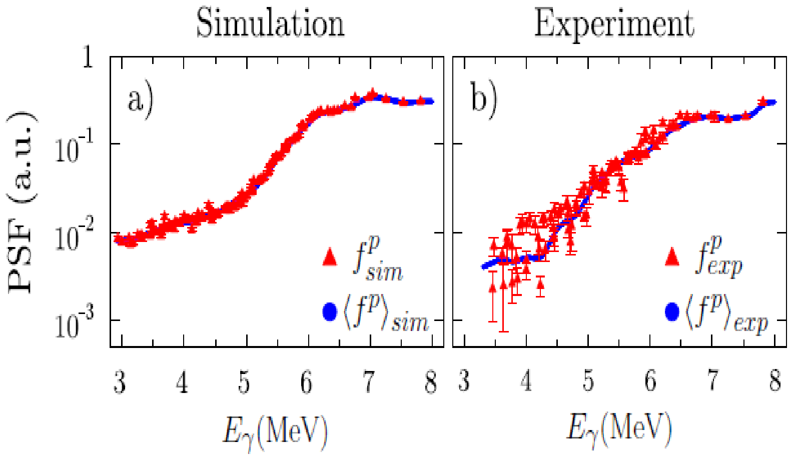
Courtesy of C. Illiadis and U. Gayer (UNC/TUNL/HIgS)

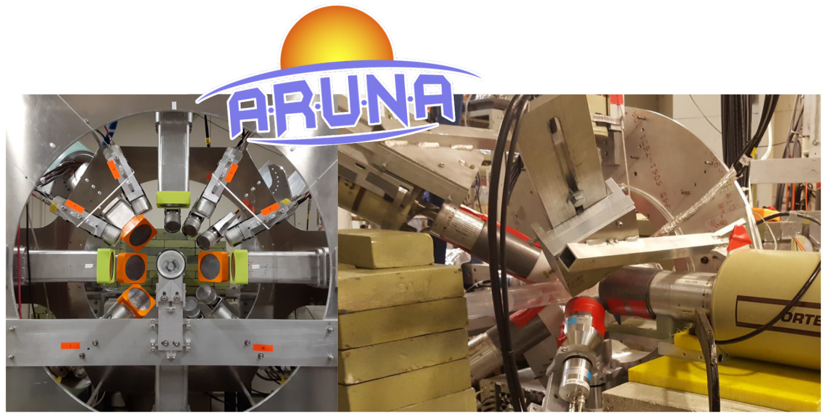
Sample results

- Further tests of shell-model predictions in mass region relevant for $0\nu\beta\beta$ decay.



- Tests of the validity of the Brink-Axel hypothesis for the low-lying dipole strengths. [J. Isaak et al., PLB **788**, 225 (2018)]



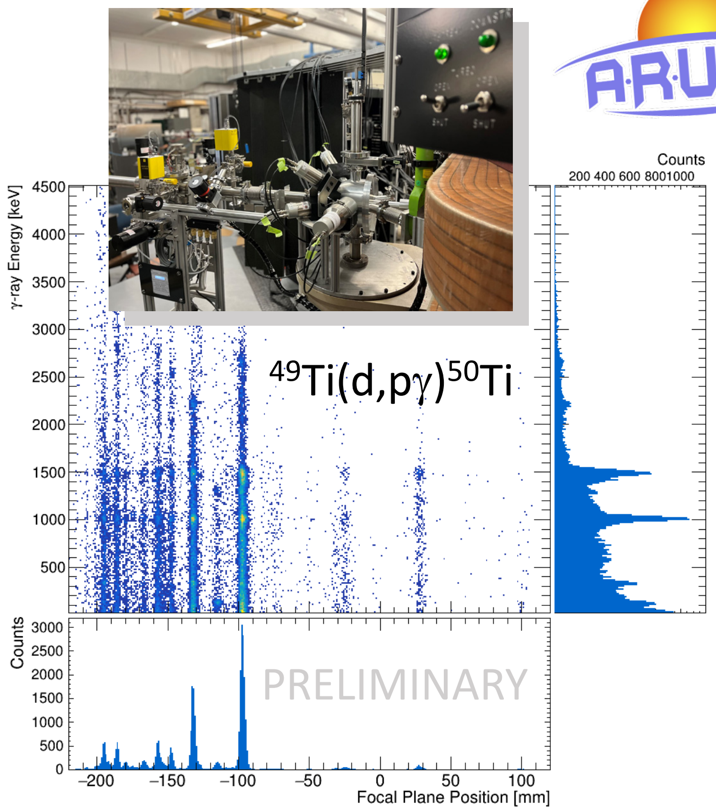


Clover Share (left) and γ^3 (right) γ-ray spectroscopy setups at HIgS (TUNL) combining HPGe with $CeBr_3$ and $LaBr_3$:Ce detectors, respectively.

[B. Löher, V. Derya et al., NIM A **723**, 136 (2013)]

Particle-γ coincidence experiments to study the low-lying E1 response at FSU and TAMU

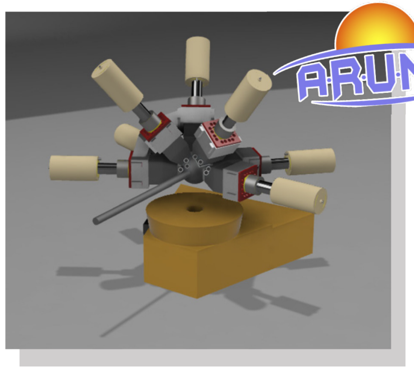
- **Coincident γ-ray detection after nucleon transfer reactions with CeBrA at FSU SE-SPS**



Probing the single-particle structure of $J^{\pi}=1^{-}$ states

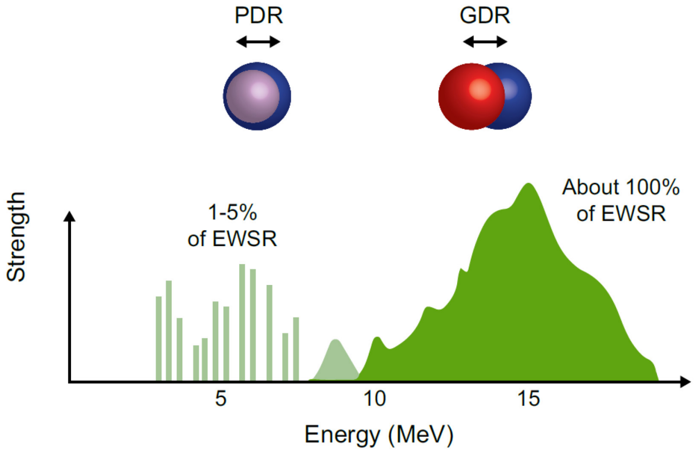
[^{208}Pb: M. Spieker, A. Heusler, et al., PRL **125**, 102503 (2020); ^{120}Sn: M. Weinert, M. Spieker, G. Potel, N. Tsoneva et al., PRL **127**, 242501 (2021)]

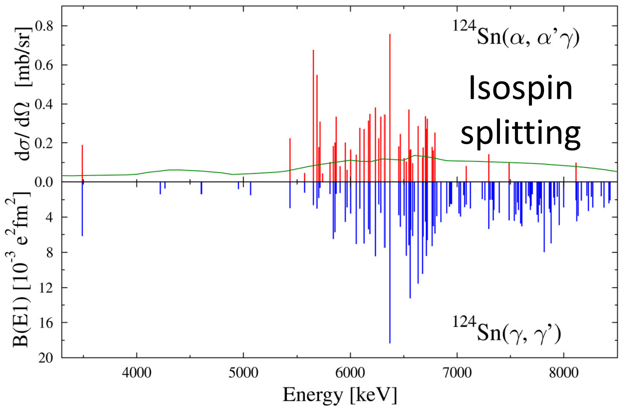
- **(α,α'γ) with MDM and HYPERION at intermediate energies at TAMU cyclotron**



Isospin structure of 1^{-} states?

[Isospin splitting in ^{124}Sn: J. Endres, E. Litvinova, et al., PRL **105** (2010) 212503; Reviews: D. Savran et al., PPNP **70**, 210 (2013) & A. Bracco et al., PPNP **106**, 360 (2019)]





Is there a unique E1 excitation mode different from the tail of the IVGDR? Does it depend on neutron excess or the neutron-skin thickness? If so, can it be used to constrain parameters of the EOS? What is the influence of this near-threshold mode on neutron capture?

Information: P. Adsley (TAMU) & M. Spieker (FSU)

Particle-γ coincidence experiments to study the low-lying E1 response at FSU and TAMU

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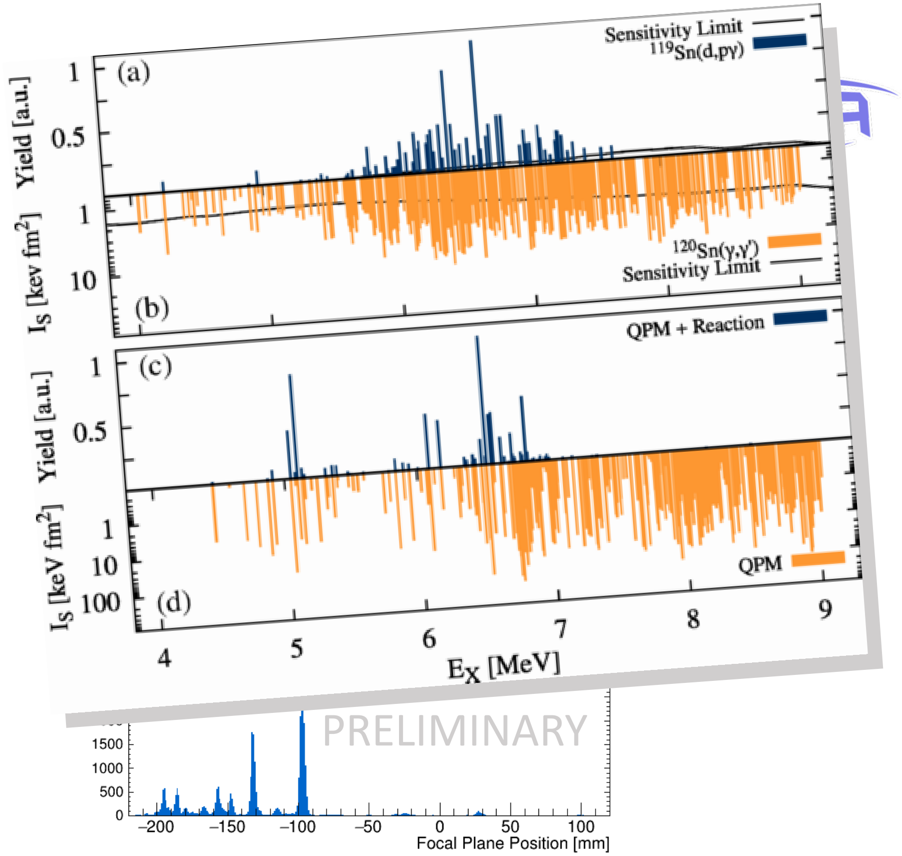
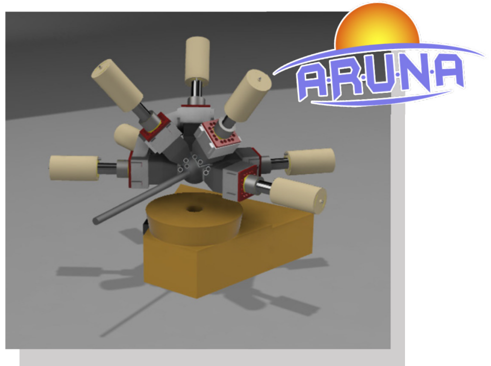


Probing the single-particle structure of $J^{\pi}=1^{-}$ states

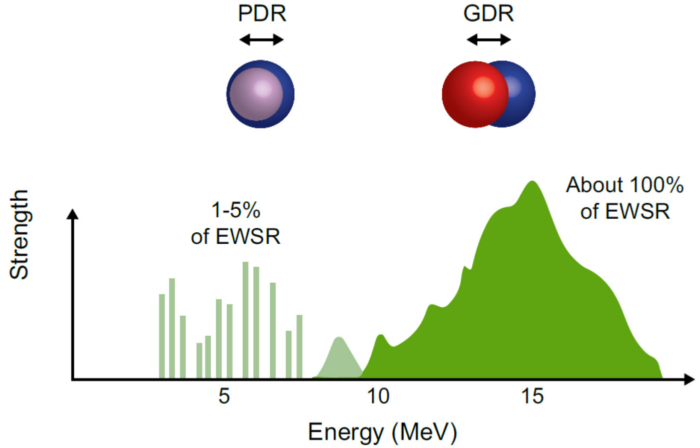
[^{208}Pb: M. Spieker, A. Heusler, et al., PRL **125**, 102503 (2020); ^{120}Sn: M. Weinert, M. Spieker, G. Potel, N. Tsoneva et al., PRL **127**, 242501 (2021)]

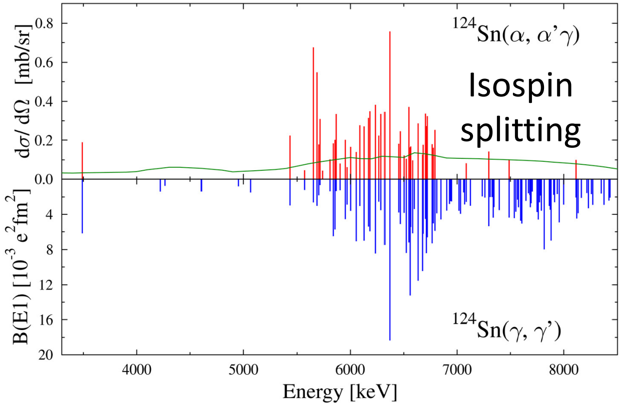
- **(α,α'γ) with MDM and HYPERION at intermediate energies at TAMU cyclotron**



Isospin structure of 1^{-} states?

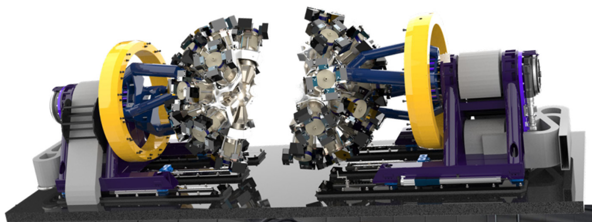
[Isospin splitting in ^{124}Sn: J. Endres, E. Litvinova, et al., PRL **105** (2010) 212503; Reviews: D. Savran et al., PPNP **70**, 210 (2013) & A. Bracco et al., PPNP **106**, 360 (2019)]



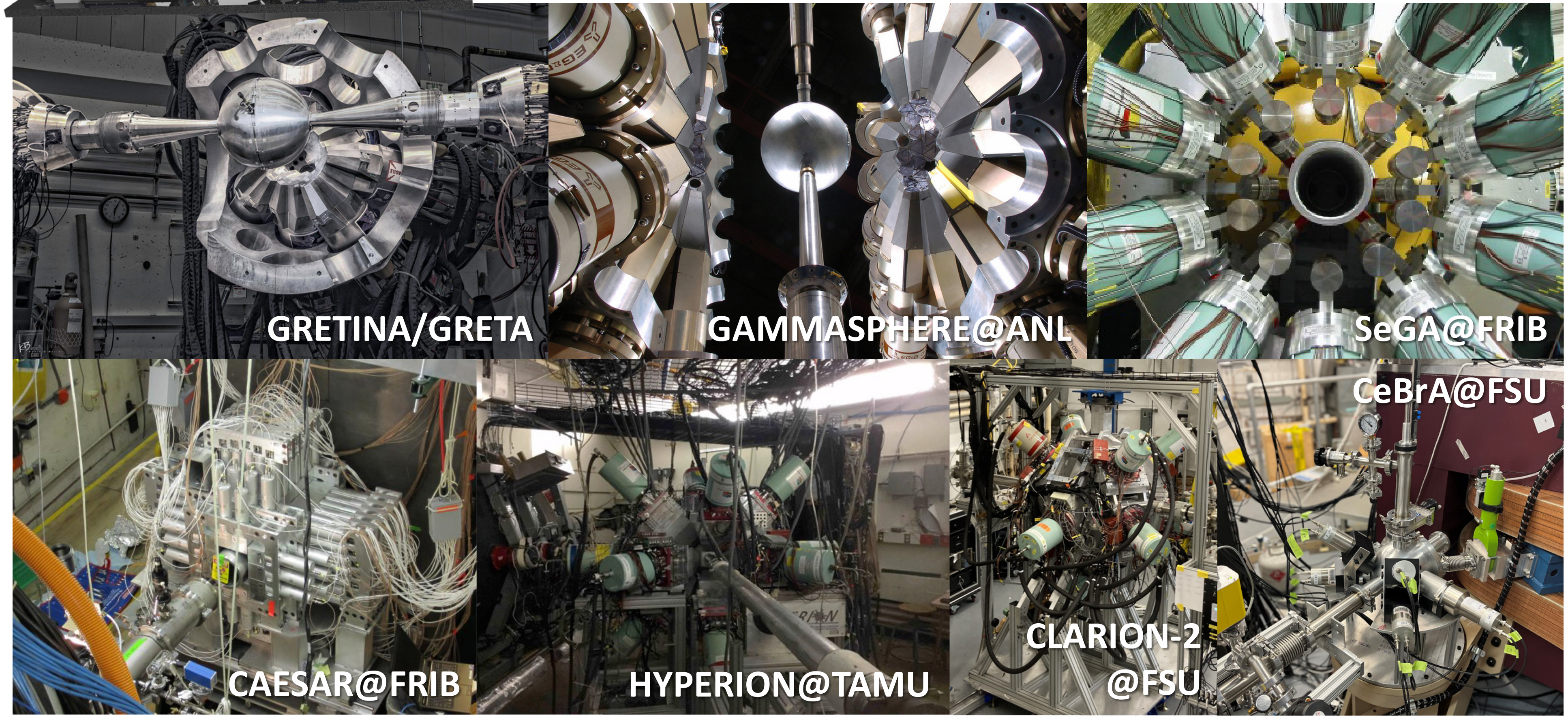


Is there a unique E1 excitation mode different from the tail of the IVGDR? Does it depend on neutron excess or the neutron-skin thickness? If so, can it be used to constrain parameters of the EOS? What is the influence of this near-threshold mode on neutron capture?

Information: P. Adsley (TAMU) & M. Spieker (FSU)



γ-ray spectrometers for in-beam γ-ray spectroscopy in the United States



+ Clover Share (at, e.g., HIgS), γ^3,…

Several arrays are available to tackle science questions at the frontiers of low-energy nuclear physics and nuclear astrophysics! The future is bright.

Solenoidal Spectrometer Programs at ATLAS and FRIB*

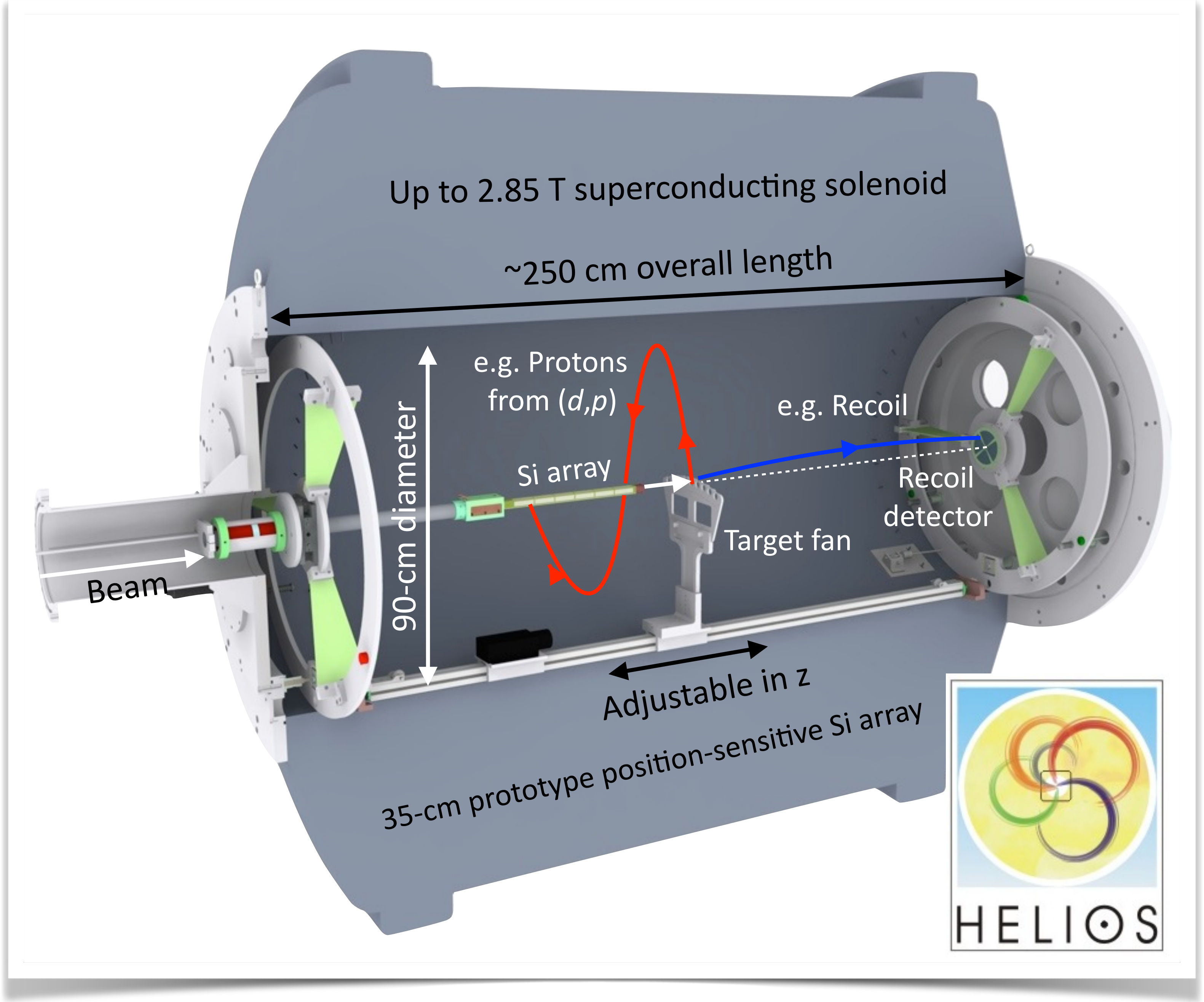
Ben Kay, Argonne National Laboratory (kay@anl.gov)
2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics

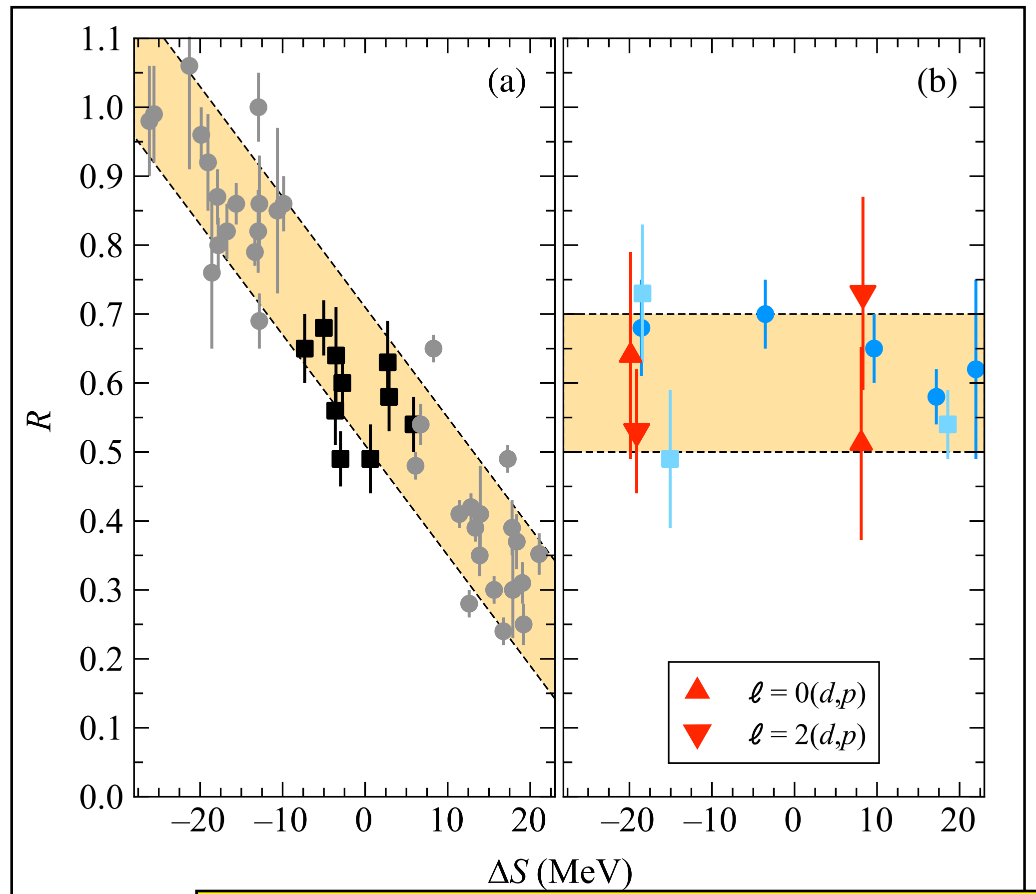
*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contracts No. DE-AC02-06CH11357

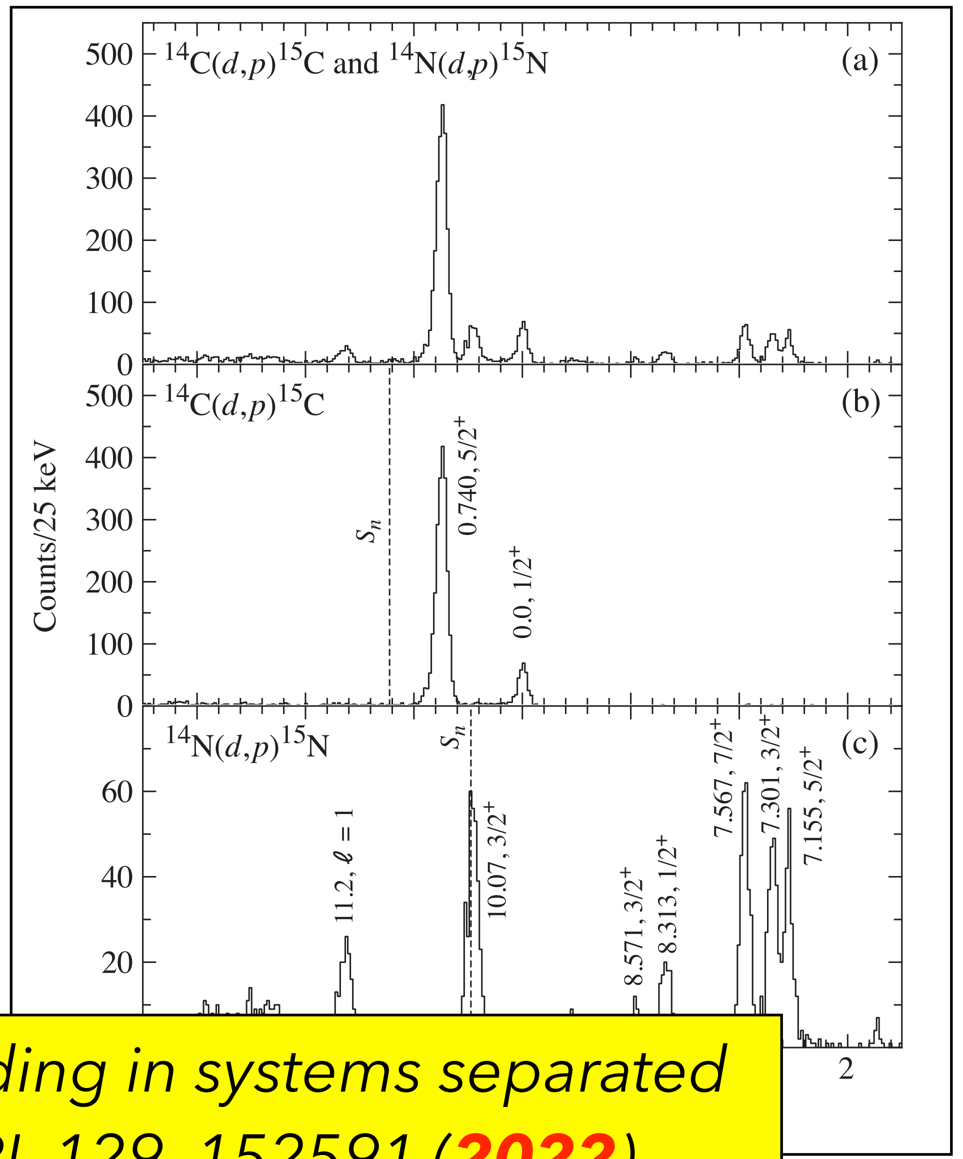
The HELIOS program

<u>*The first of kind, continuous evolution of capabilities*</u>

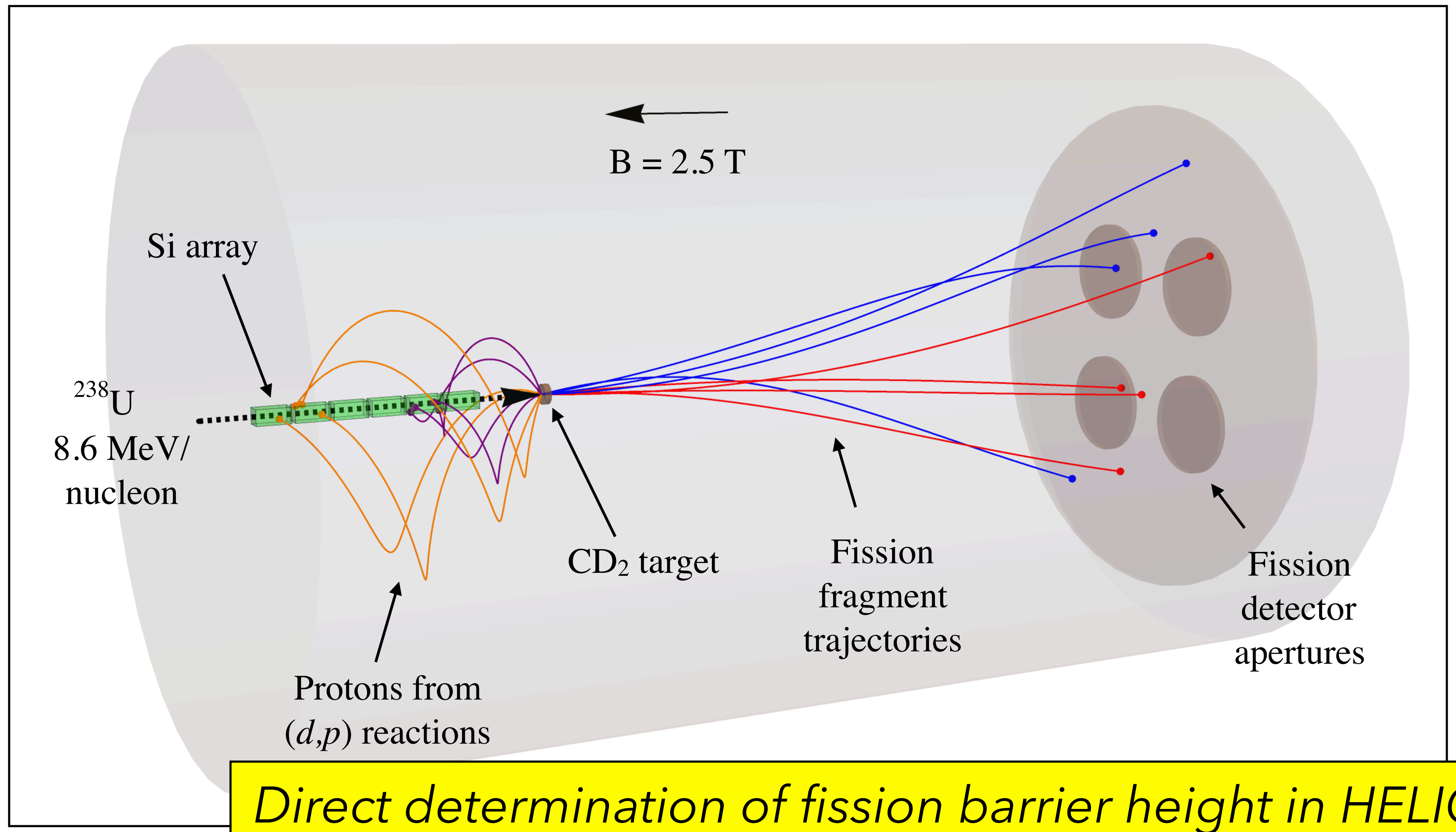
- *The "(d,p) machine" (mass 8-238), a broad class of reactions [(d,p), (d,t), (d,^{3}He), (d,a), (d,d'), (p,p'), (^{6}Li,d), (a,p), (t,p), etc.), isomeric beams (^{26}Al, ^{18}F, ^{16}N,…)*
- ***Expanding** suite of auxiliary detectors, Apollo, LSU fast-counting ionization chamber, gas-cell targets, AT-TPC, SOLSTISE, fission-fragment detectors, etc.*
- *Future: RAISOR beams (inc. isomer beams), nuCARIBU beams, large demand for stable beams, actinides, AT-TPC campaigns*

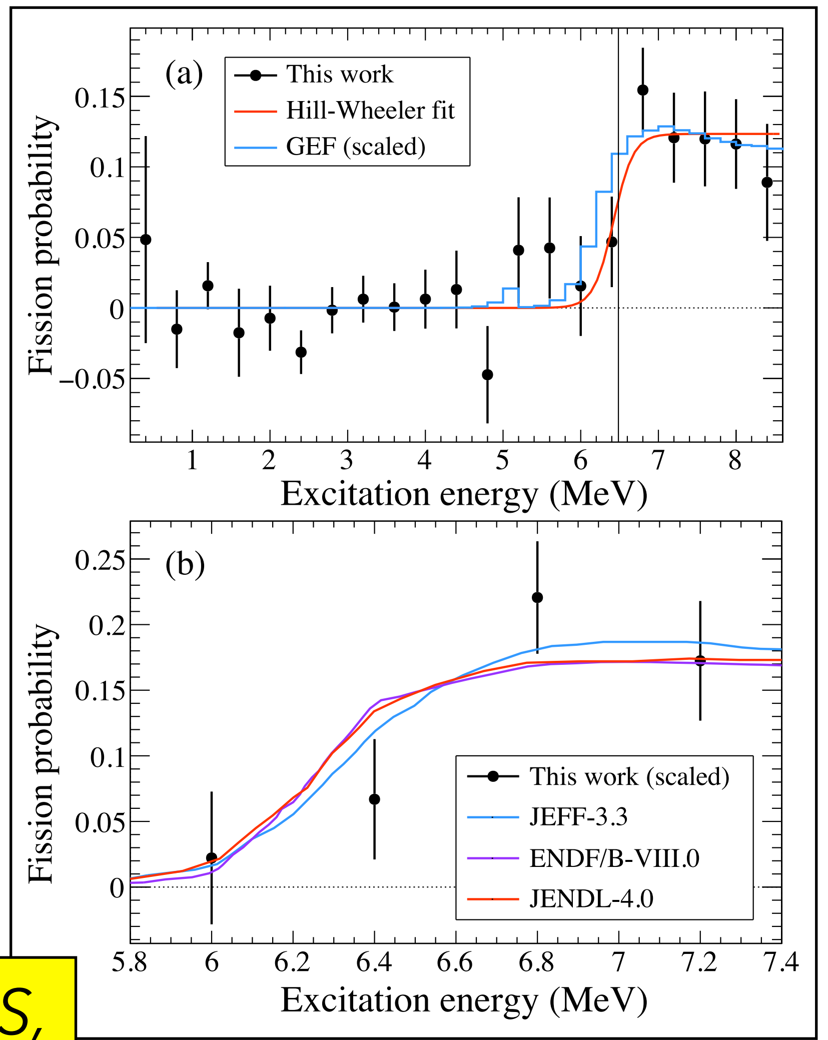






*Quenching probed via n-adding in systems separated by large ΔS, BPK et al., PRL 129, 152591 (**2022**)*





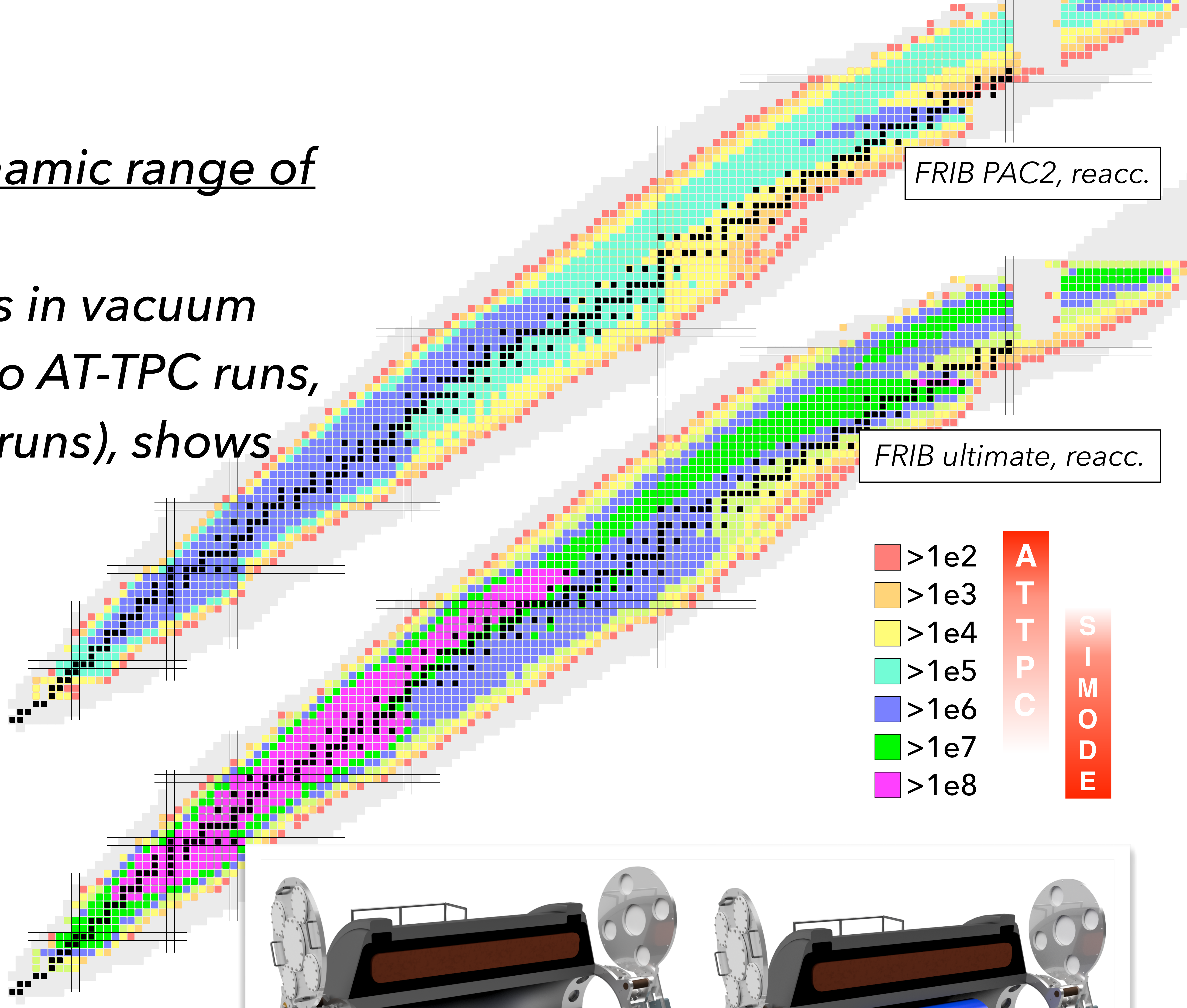
*Direct determination of fission barrier height in HELIOS, S. Bennett et al., submitted (**2022**)*

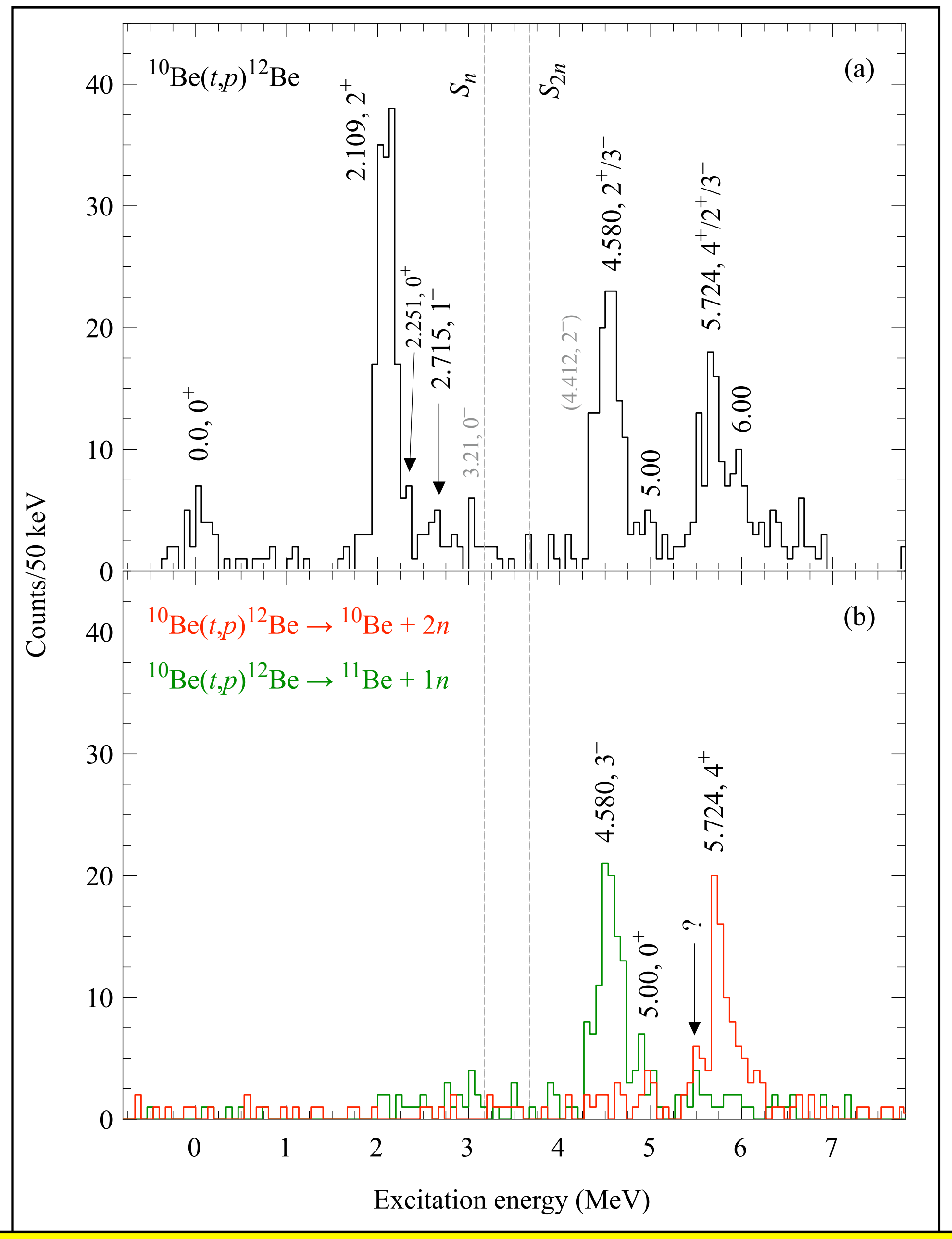
Argonne NATIONAL LABORATORY

SOLARIS at ReA

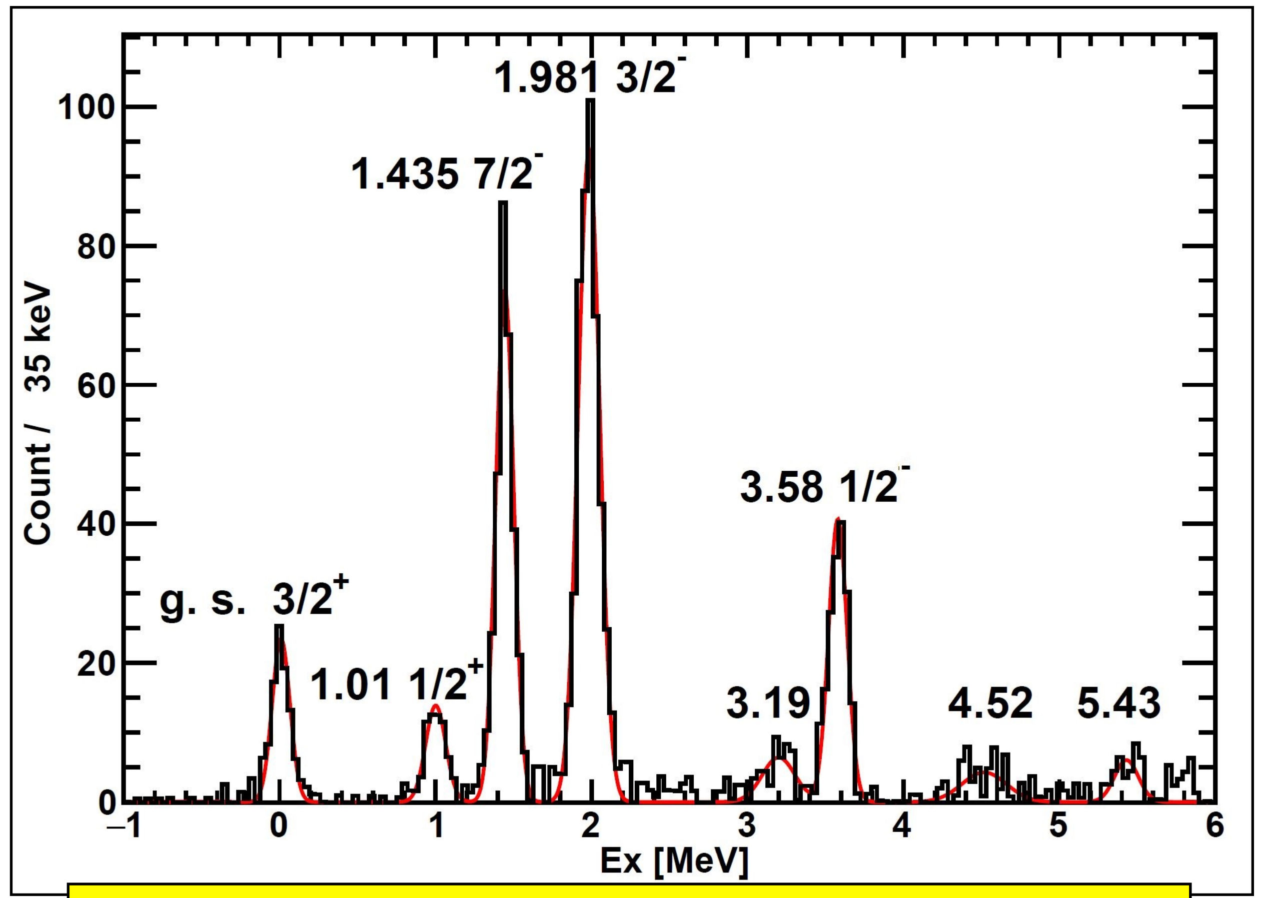
A new dual-mode device to exploit the large dynamic range of beams at ReA

- *Operates with the AT-TPC or with dual Si-arrays in vacuum*
- *Successful 2021 ReA standalone campaign (two AT-TPC runs, three Si-array-mode [using HELIOS DAQ/dets] runs), shows great potential*
- *Si-arrays under development (2023-)*

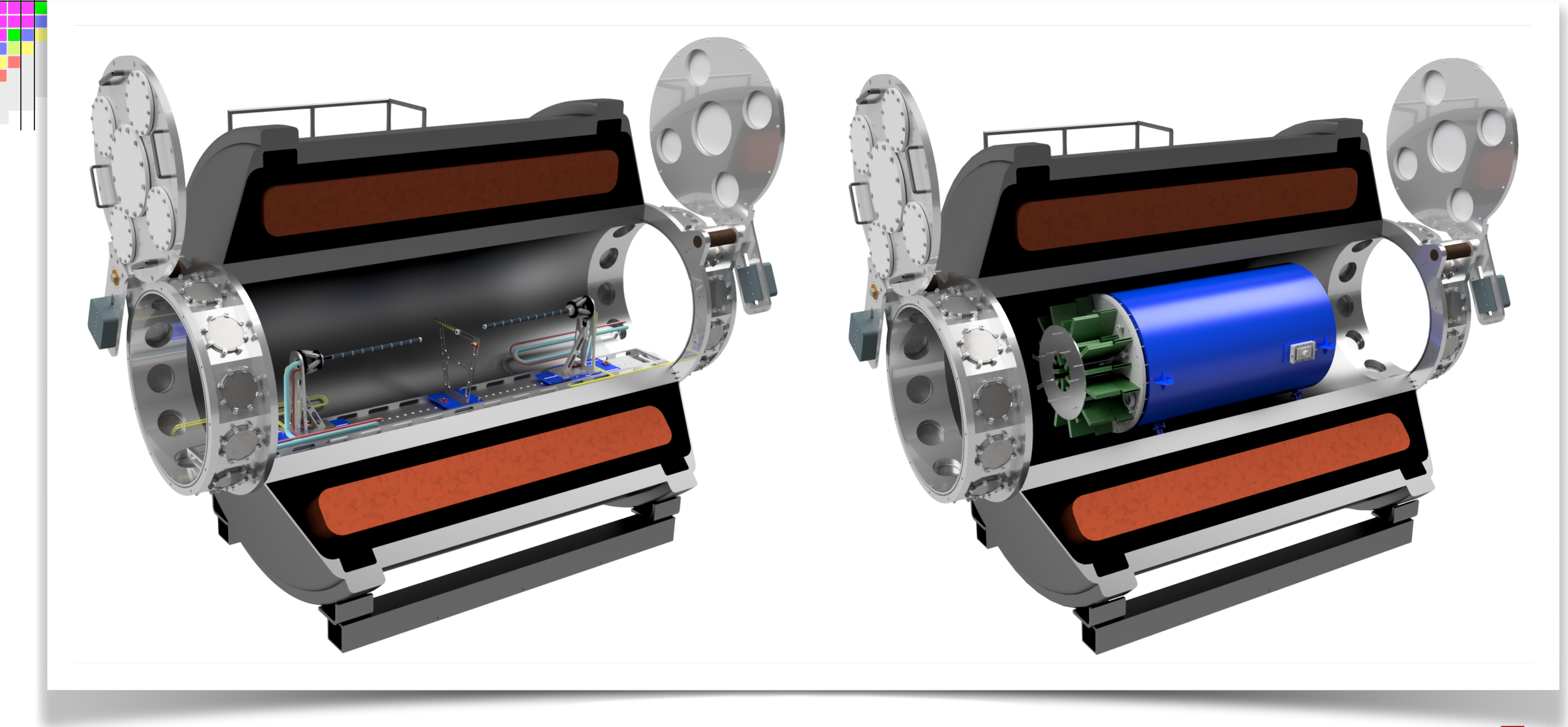




The (t,p) reaction to explore unbound states in ^{12}Be, A. Muñoz-Ramos et al., in prep. (**2022**)



The (d,p) to locate p-strength in ^{33}Si, J. Chen et al., in prep. (**2022**)



Argonne NATIONAL LABORATORY

ATLAS & FRIB solenoidal-spectrometer program

Highly complementary programs

***SOLARIS at ReA**, intense beams, best-in-class instrumentation (arrays, AT-TPC), push for higher energy, competition with the fast beam program*

Interim

08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30

***The ISOLDE Solenoidal Spectrometer**, access to ISOL beams, limited operation hours (likely ~1000 hrs for HIE-ISOLDE), chemistry dependent beams*

LS2

LS3

"The (d,p) machine" … exploiting the simple in-flight beams

Dominantly sd-shell nuclei, over 5 years led to physics program on weak-binding, bubble-nucleus arguments, etc.

Develop new techniques/ capabilities in prep. for RAISOR beams, next-generation devices

New complex reactions, gas targets, photon detection, recoil detection, new DAQ, new array

CERN, HELIOS @ ISS

First experiments with RAISOR at ATLAS

NSCL, HELIOS @ SOLARIS

***HELIOS**: **RAISOR/nuCARIBU exploitation** …*

*AT-TPC sharing …, re-vamp controls systems, **beam tracking**, gas-jet target with SOLSTISE, surrogate reactions (Apollo, upgrades for (d,p) and (d,pf) studies, develop new tritium targets*

***SOLARIS**: **PAC2 → ultimate**, dual-mode use, extends reach to the limits of ReA's potential, reactions with complex final states possible via AT-TPC, dual-arrays provide a wealth of data for the development of reaction theory, …, etc.*

Argonne NATIONAL LABORATORY

ORRUBA/GODDESS program

ATLAS (RIB/SIB)

NSCL/FRIB (fast/ReA)

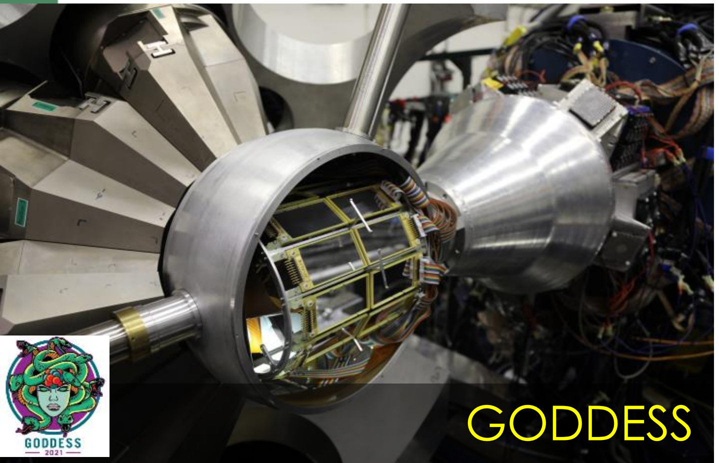
HIγS (γ-induced), …

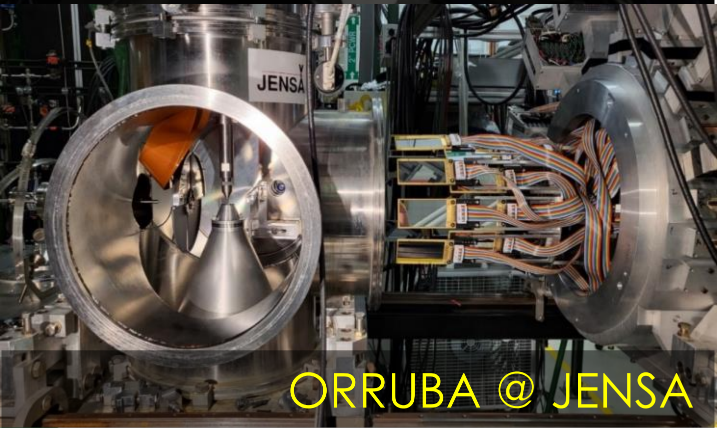
Couples to

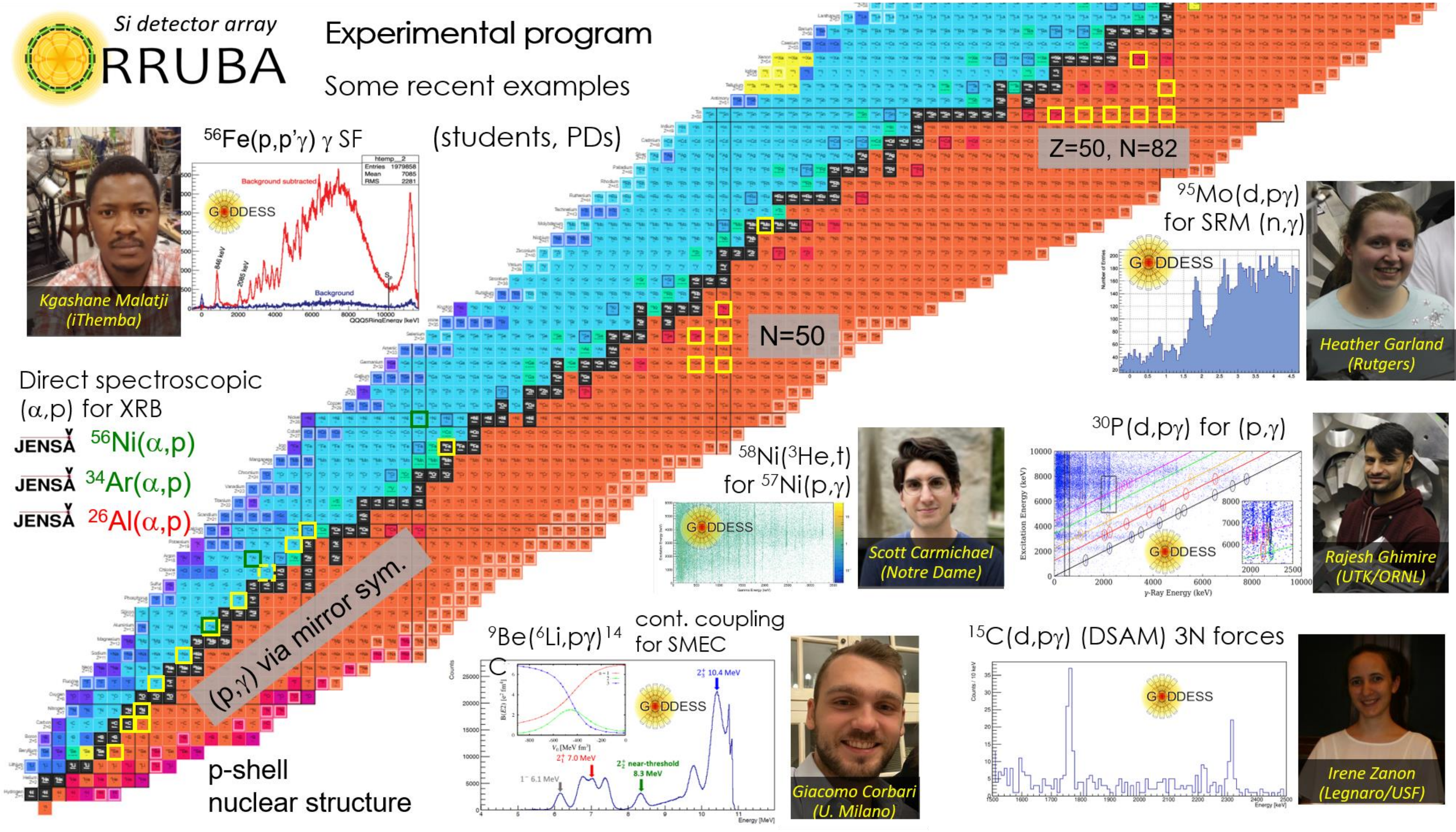
GS, GT, JENSA, S800, FMA, SECAR,…

Stripping, pickup, charge-exchange, inelastic scattering, heavier-ion induced [eg (α,p), (^{6}Li,p)]

- *Largest Si suite for RIB physics in US*
- *Designed around reaction kinematics*
- *Originally conceived as a standalone device, but increasingly coupled to other instruments*
- *Detector/FE compatibility (ANASEN, ND, …)*



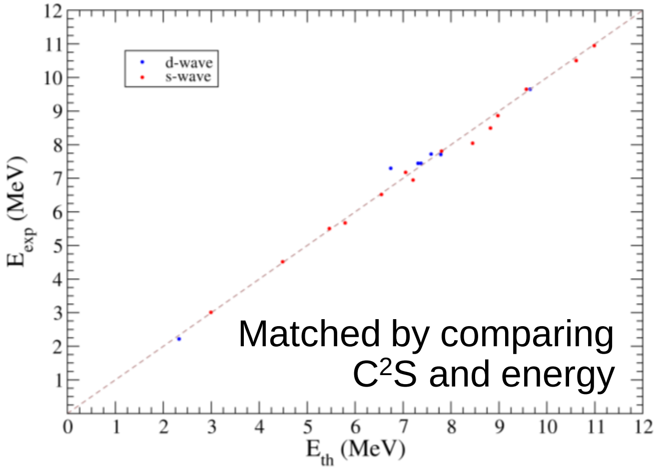


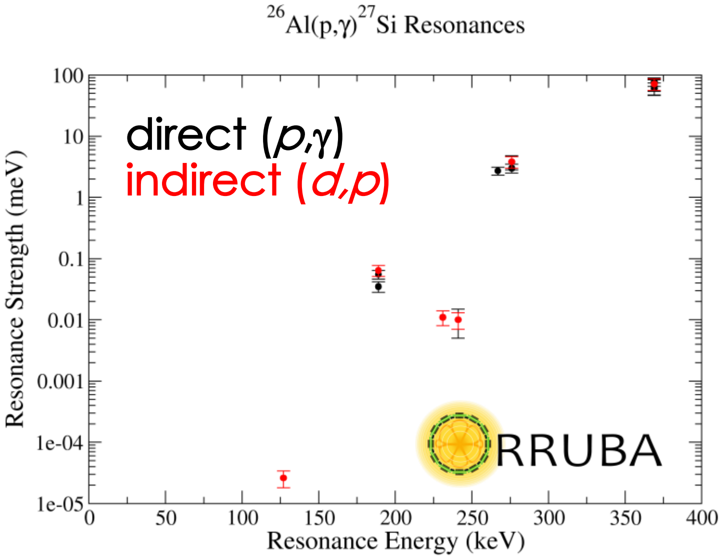


Direct reactions with RIBs (esp. at FRIB)

- Cornerstone of structure and reactions program
- Provides detailed tests of structure models (E, ℓ_p, J^π, C^2S, …)
- Can be used to determine energies and strengths of isolated resonances
  - **Guidance to the SECAR program;** *some resonances are out of reach of direct measurements*

Test of USDb in mid-sd shell

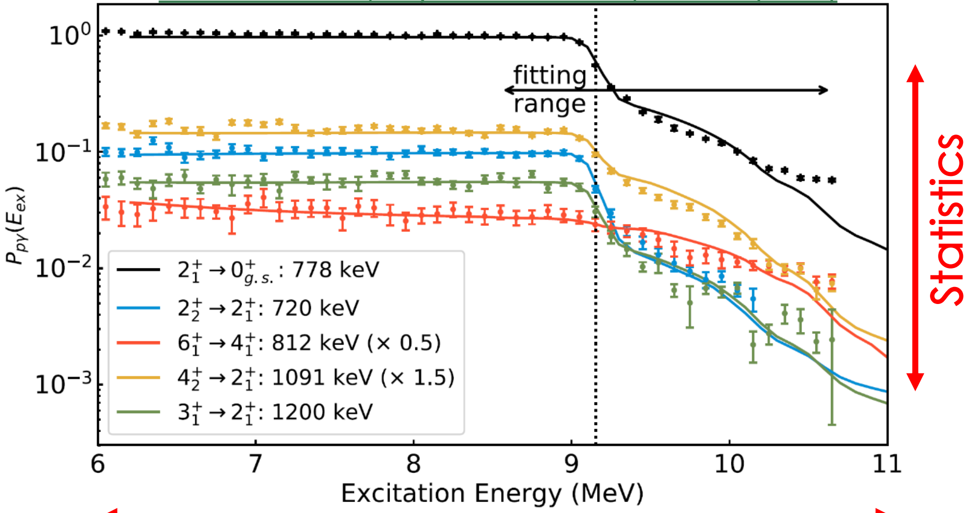




Direct reactions for determining (n,γ) cross sections

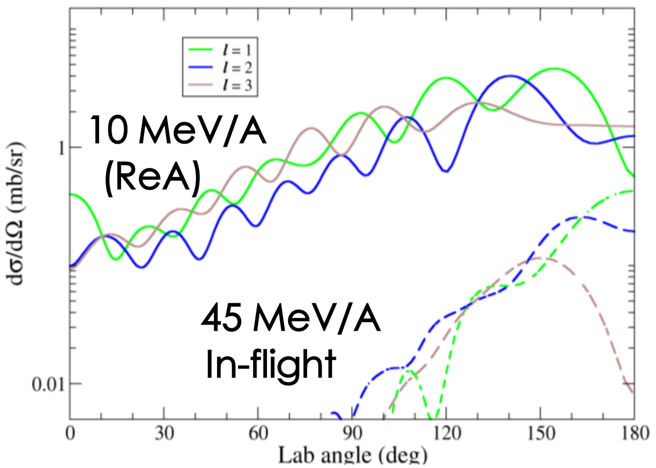
- DSD cross sections to bound states (E, ℓ_p, J^π, C^2S) eg (*d,p*)
- Decay of γ emission probabilities for unbound states (ie constraint of decay of CN)
  - eg via (d,pγ) (p,dγ) (p,p'γ) etc
- Crucial requirements
  - Beam energy (to reach states above S_n) > 10 MeV/A
  - Charged-particle resolution

Ratkiewicz et al., Phys. Rev. Lett. **122**, 052502 (2019)



Charged-particle resolution

ReA is the place to do it @FRIB

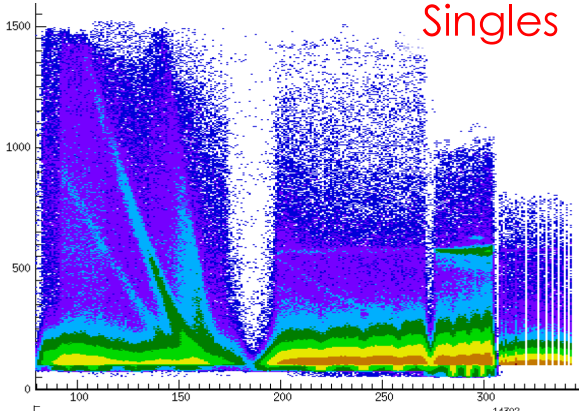


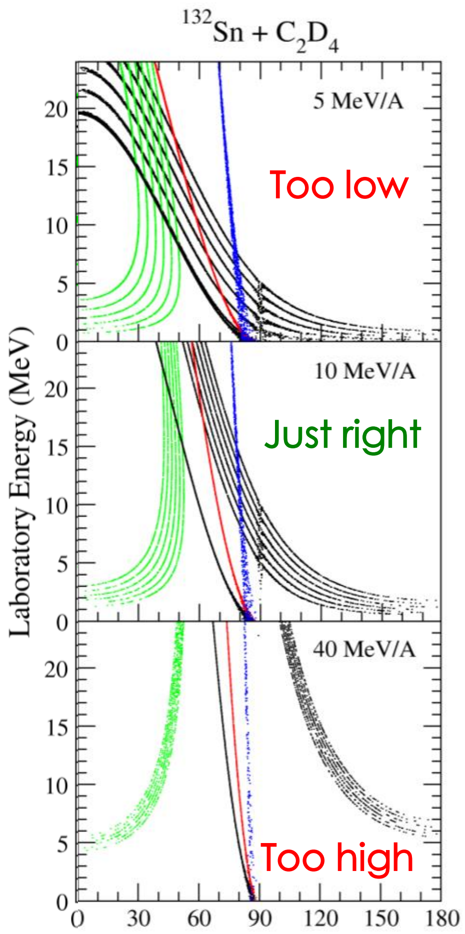
- Energy
- Emittance

VASTLY improved CP resolution vs in-flight

(ReA ~100-200 keV vs In-flight 0.5-1 MeV)

^{38}K,^{38}Ar(*d*,*p*) @ ~5 MeV/u



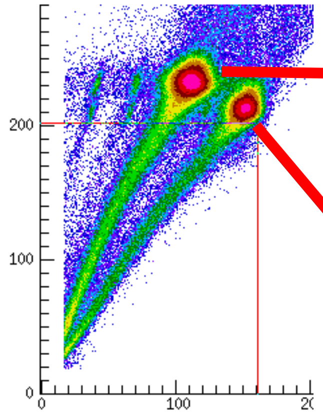


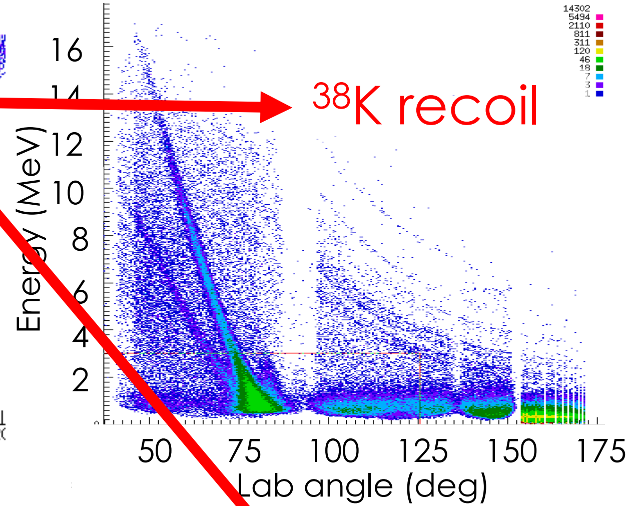
Priority Requests

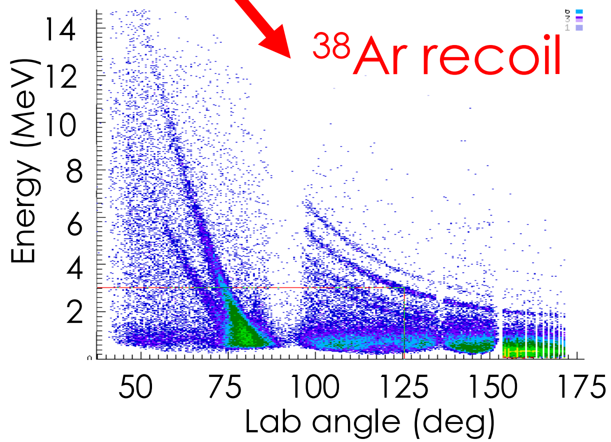
- **ReA12 upgrade** to populate above S_n, S_p

(comparatively minor investment away from world-leading facility)

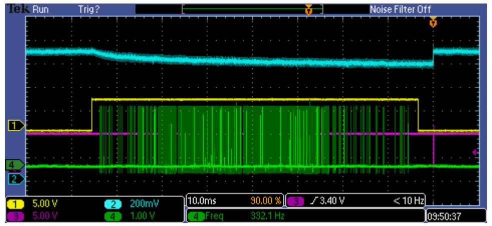
- **High-acceptance recoil separator (ISLA)**, critical for recoil detection at FRIB intensities







instantaneous beam rates = 10 – 100 x av.



ISLA

Opportunities with lifetime measurements – tracking structural evolution of exotic nuclei

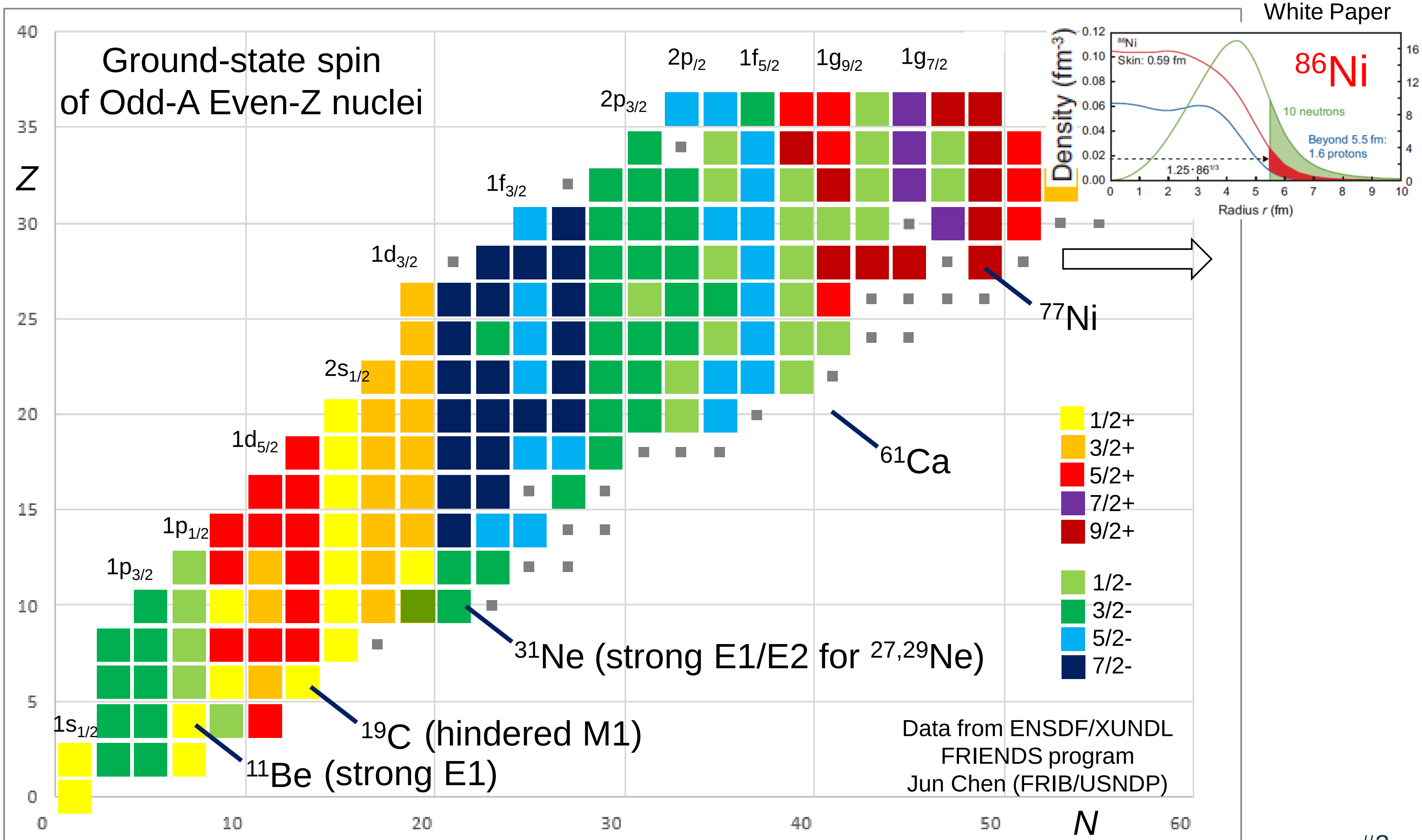
Hiro IWASAKI
(FRIB/MSU)

Work presented supported by DE-SC0020451

Unified understanding of nuclear structure and its evolution

Integrated picture of structural evolution of exotic nuclei

- New experiments toward dripline (FRIB400), toward higher spins (ReA/ISLA), with higher precision and accuracy (GRETA/HRS/model independent methods)
- Coordinated efforts with nuclear data and theory (sensitivity studies)

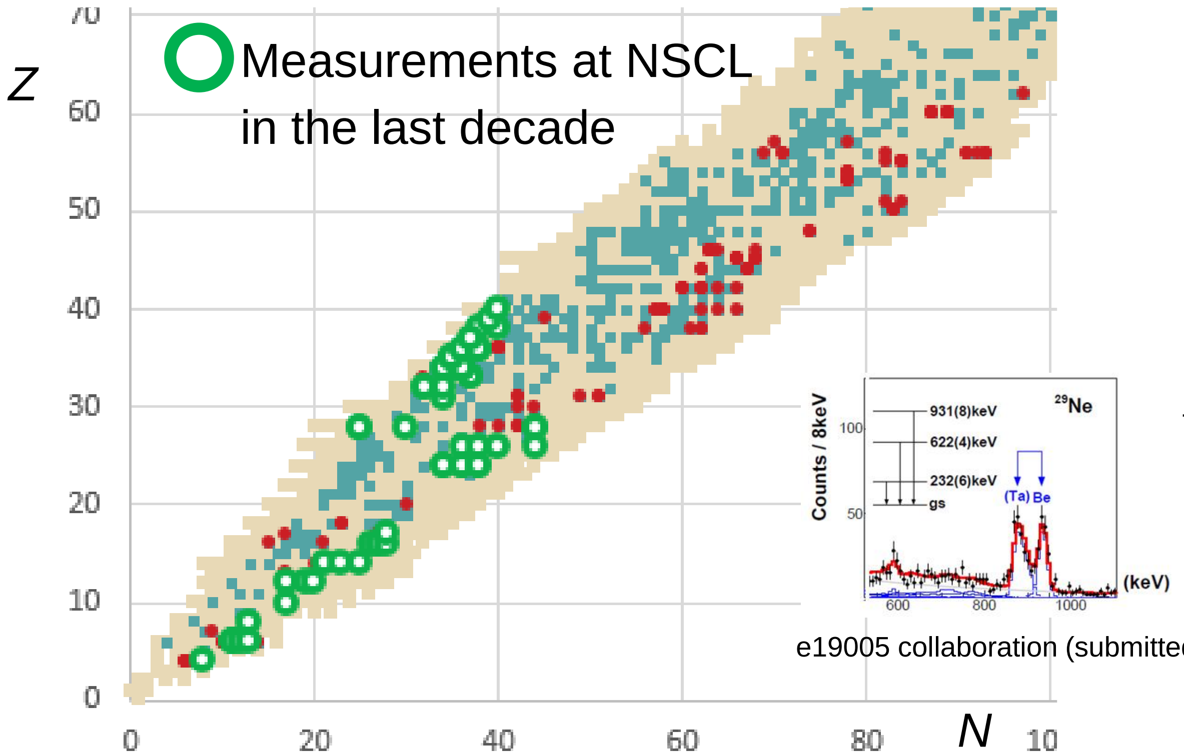


Opportunities with lifetime measurements at FRIB and FRIB400

···Known isotopes (~3000 nuclides)

···Lifetime studied in the last 20 years (~5000 levels for ~700 nuclides)

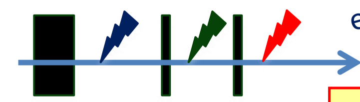
···Lifetime studied with rare isotope beams (~250 levels for ~120 nuclides)



e19005 collaboration (submitted)

TRIPLEX Plunger device

existing approach

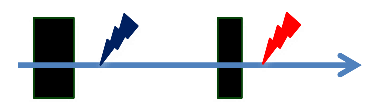


Target Degrader
2ndDegrader

$\beta \geq Z/137$

new approach

RDM + Inelastic Measurement

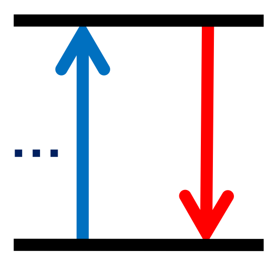


Be Target **Ta Target/ Degrader**

Collectivity B(E2)
N=Z, N=8-40
Dripline N<20

Collectivity, Spin, E/M
N<Z,
N=28-50 and beyond
Dripline N>20

Coulex, Inelastic …
Ji/Jf, βN



Lifetime
a sensitive probe for structure…
B(E2), B(M1)

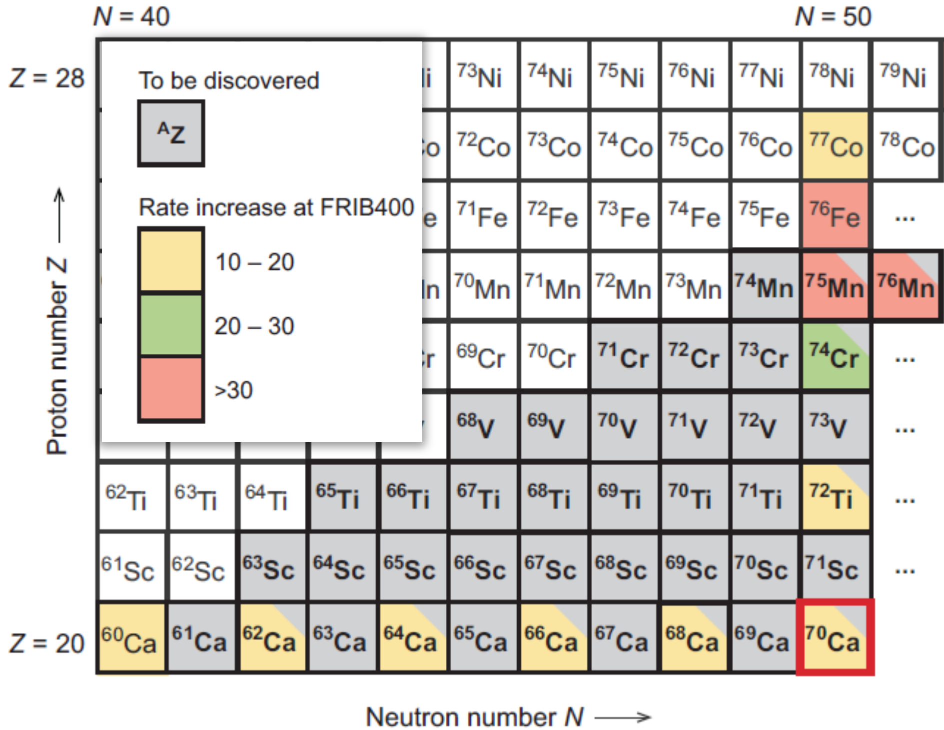
In-beam γ-ray spectroscopy with fast beams and direct reaction – the next decade

Alexandra Gade

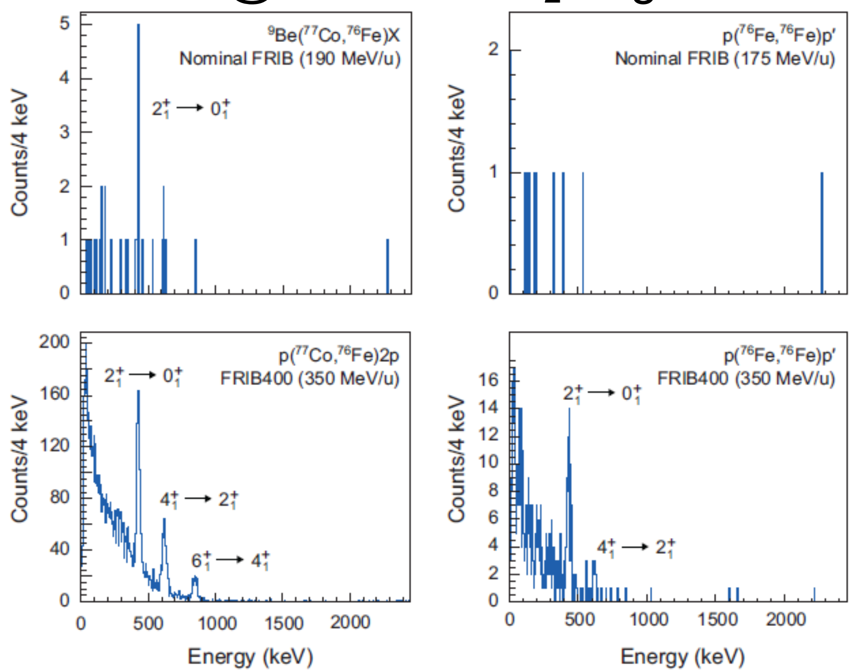
Professor of Physics

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Enormous opportunities with in-beam γ-ray spectroscopy in the FRIB400 era – using GRETA and extended LH_2 target

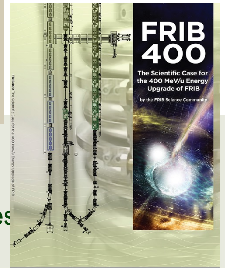


Example: Cool spectroscopy with GRETA@HRS and LH_2 target



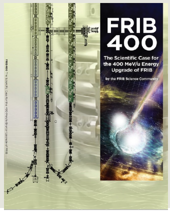
The gain is two-fold: Increased production of neutron-rich rare isotopes at FRIB400 and huge luminosity gain because a thick LH_2 target as being designed by LBNL (H. Crawford) can be used at the high beam energies

Science in this example region: Predicted to host a new Island of Inversion around ^{78}Ni



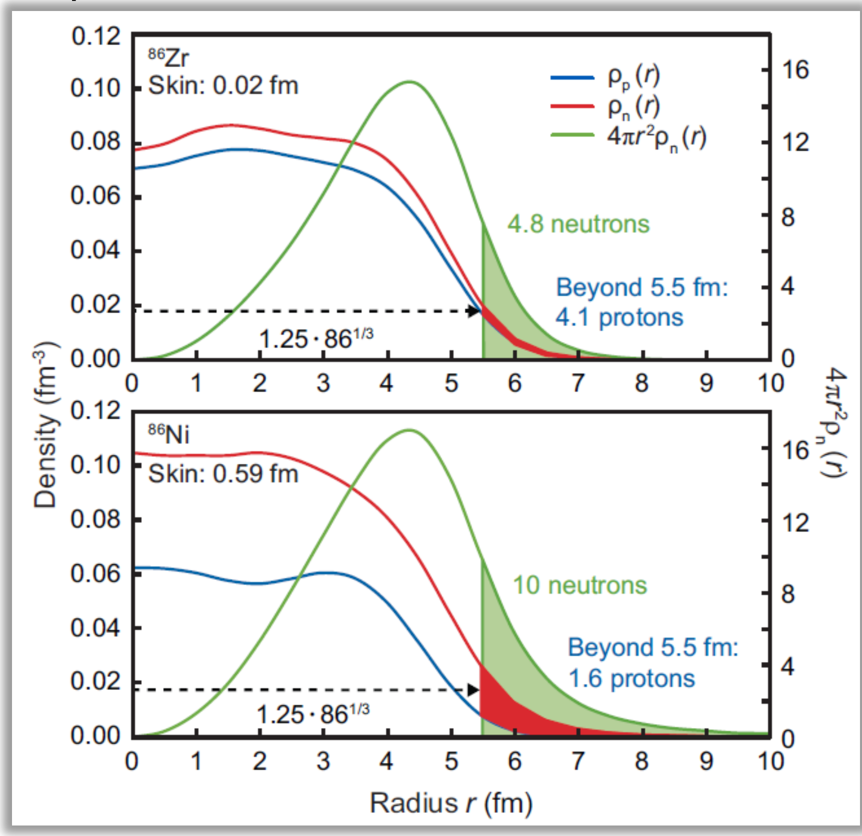
Needed: FRIB400, GRETA@HRS

Fast-beam direct reactions in the FRIB400 era – reaching the most exotic systems and majorly advancing their interpretation



- More nuclei with extreme skins come into reach for scattering or interaction cross section measurements
- Quasi-free scattering – such as (p,2p) and (p,pn) reactions – become practical due to minimized distortions and greatly increased nuclear transparency, both of which are an advantage for all fast-beam direct reaction interpretations
- Kinematic focusing improves transmission/efficiency for reaction experiments and fission
- Glauber multiple-scattering theory in the optical limit using the eikonal and sudden approximations becomes more reliable

Example: Extreme skins in reach with FRIB400



- Halo and skin studies via pion production become possible

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

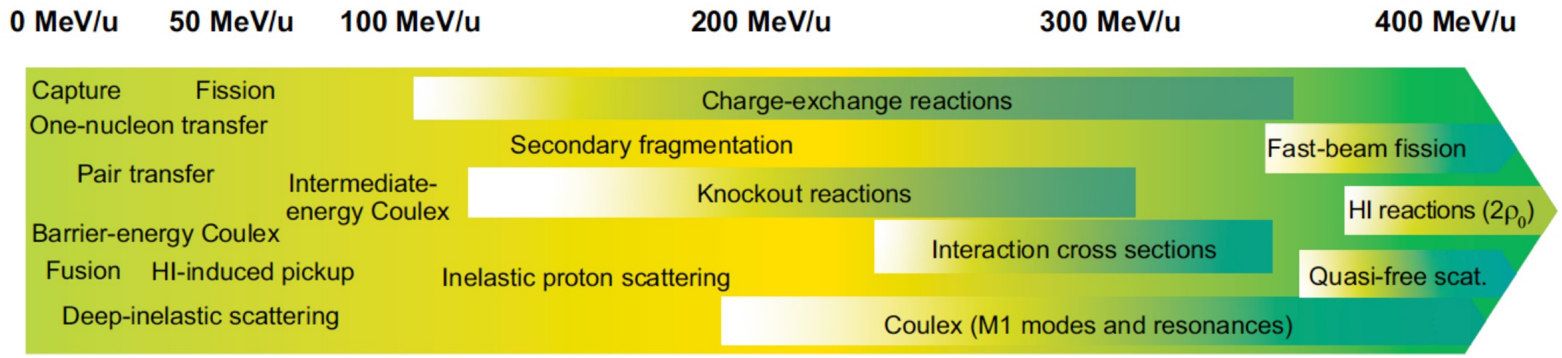
Needed: FRIB400, HRS(S800), GRETA, CAESAR

Systematic measurements along isotopic chains to improve reaction theory

Chloë Hebborn, November 15 2022

Theory Alliance FACILITY FOR RARE ISOTOPE BEAMS
Lawrence Livermore National Laboratory
MICHIGAN STATE UNIVERSITY

Exotic nuclei probed by reactions → Typically analyzed in few-body models



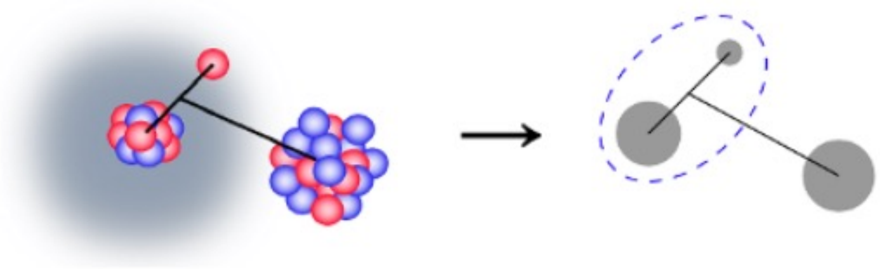


Fig. 1 Schematic representation of the possible reaction mechanisms that can be used to probe exotic nuclei at FRIB as a function of energy. Reactions beyond 200 MeV/u will require the FRIB400 upgrade. Figure adapted from FRIB400.

One can infer **nuclear properties, testing our predictions for exotic nuclei and refining theories of the nuclear force**

Theory analyses require:

1. **Reaction models** (e.g. DWBA, ADWA, Eikonal, CDCC, etc)
2. **Overlap function of the projectile** (not only bound states, scattering/resonant states too!)
3. **Projectile-target interaction** i.e. optical potentials

What are the uncertainties of these inputs and how can experimental campaigns reduce it?

Simultaneous measurements of multiple channels along isotopic chains to support theory

[Perspectives on few-body cluster structures **arXiv:2211.06281** & White paper on optical potentials **arXiv:2210.07293**]

Improvements in reaction theory

Why Multiple Reaction Channels?

Measurements of reactions at different energies

Complex reactions (e.g. transfer/knockout) & elastic scattering
→ Improve our constrain of optical potentials for specific exp.

Constrain different properties of the overlap function (e.g. low E for ANCs and high E for more internal part)

Develop more accurate global (dispersive) optical model with uncertainties

Why Full Isotopic Chains?

Support the development of use of EFT in reaction theory
→ Already successful for one-neutron halo
(cf Papenbrock's & Phillips' talks)
→ What about more complex & bound systems?

More robust connection to microscopic predictions
→ Test many-body methods
→ Test the nuclear force

Provide a testing grounds for our few-body reaction models

Quantifying model uncertainties of popular models
e.g. for transfer reactions → ADWA or DWBA?

Which Isotopic Chains? One including exotic structures, e.g., haloes, exotic decay... → Carbon, Magnesium (Crawford), ...

This is a theorist input… Experimental needs to make this possible: Active target? More workforce ? And … ?

E0 Searches Through Decay Spectroscopy

Ben Crider

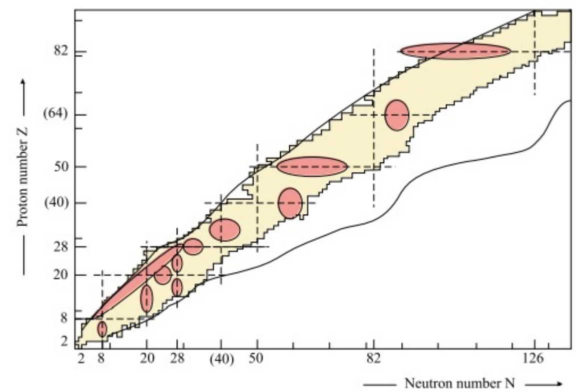
NSAC Long Range Plan Town Hall on Nuclear Structure, Reactions, and Astrophysics

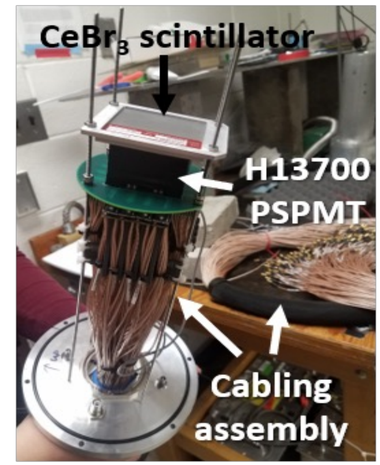
Nuclear Structure & Reactions Experiments Working Group

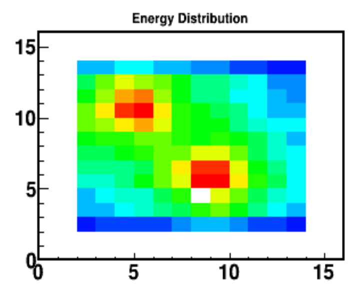
November 14 - 16, 2022

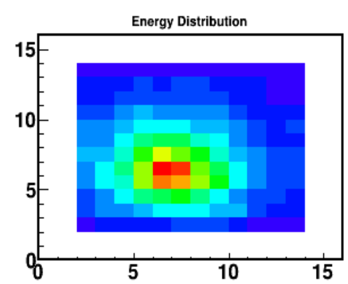
Sensitive E0 searches following beta decay require investment in ML methods

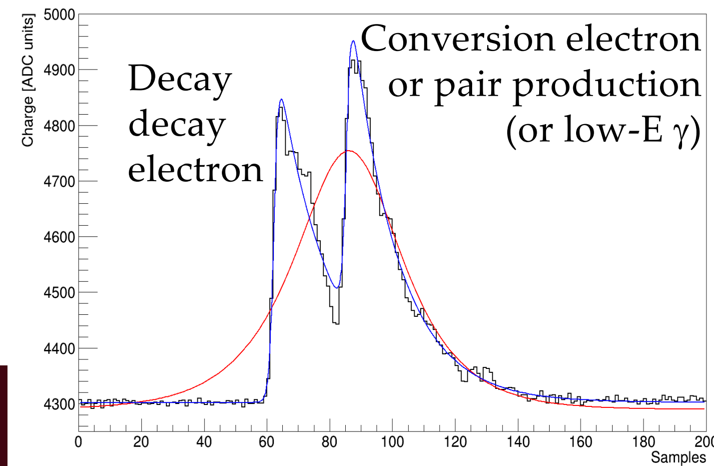
- E0 transitions provide model independent view of changes in nuclear structure
  - Dependence on state mixing and difference in mean-squared charged radii can help provide distinct fingerprint of configurations involved
- E0 searches enabled by implanting rare isotopes into solid state or scintillator detectors.
- Continued E0 searches in IoI during next LRP period
- Technique will also identify many low-energy isomeric states
- Optimized searches require investment in ML architectures.











Science: Exploring Nuclear Structure with the FDS

- Uniquely positioned for discovery experiments at the extremes due to low-rate sensitivity
- Critical experiment inputs for theoretical comparison
  - Half-lives
  - Delayed neutron and γ branches
  - Strength determination (above and below S_n)
  - Identification of isomeric states
- Required FDS detector configurations
  - Charged particle detection for ions and electrons
  - Neutrons (time-of-flight or thermal)
  - Photons
  - TAS