Opportunities For In-Beam Spectroscopy

- Introduction (context)

- A few physics examples
  - Discovery at the driplines
  - Ca isotopes as archetype
  - Octupole collectivity and the EDM
  - rp-process and astrophysics

- Conclusions and remarks

- Acknowledgements

Intellectual Challenges

The 2012 National Research Council (NRC) decadal survey on nuclear physics posed four over-arching questions that frame the intellectual challenges of the field.

- *How does subatomic matter organize itself and what phenomena emerge?*
- *How does visible matter come into being and how does it evolve?*
- *Are the fundamental interactions that are basic to the structure of matter fully understood?*
- *How can the knowledge and technological progress provided by nuclear physics best used to benefit society?*

In-beam spectroscopy is essential to answering all these questions!

Addressing the Challenges

1) Rare Isotope Beams

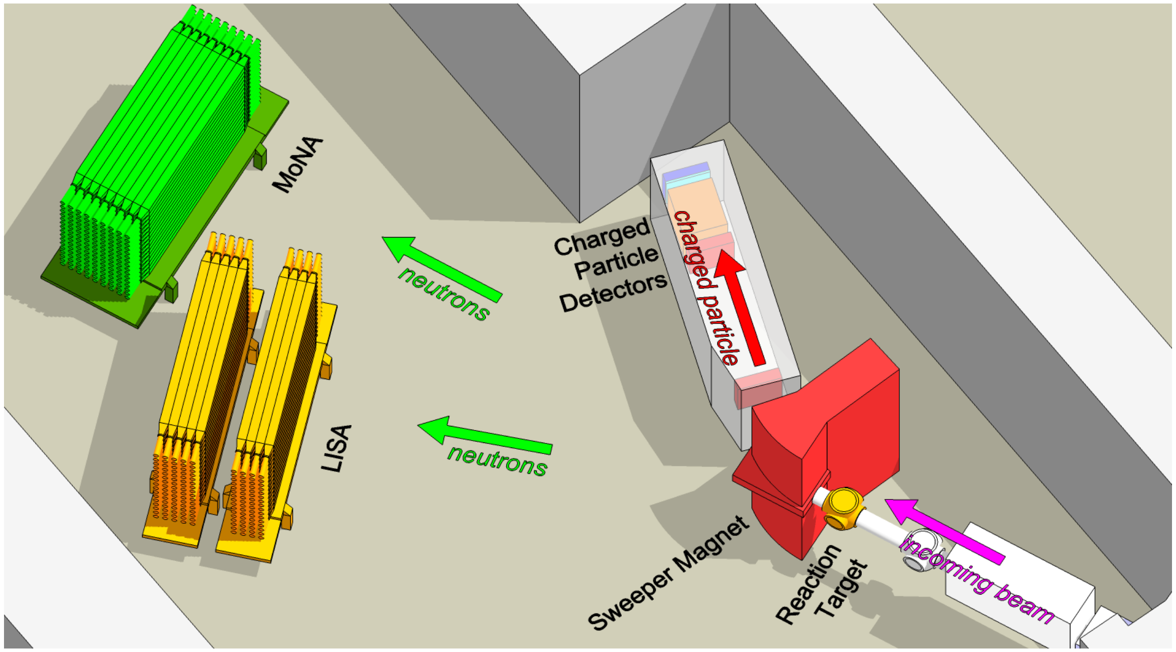
FRIB and the production of the most exotic nuclei

2) State-of-the-art instrumentation

Stable and RIB experiments (ATLAS, NSCL, CARIBU, FRIB…)

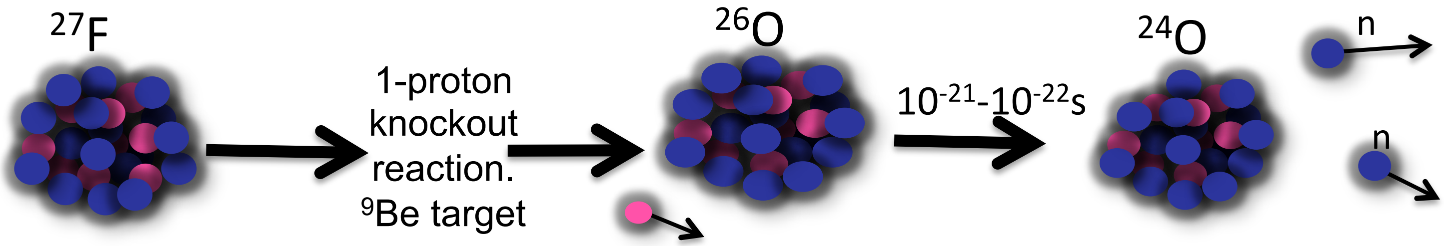
In-Beam Neutron Spectroscopy: Beyond the Driplines

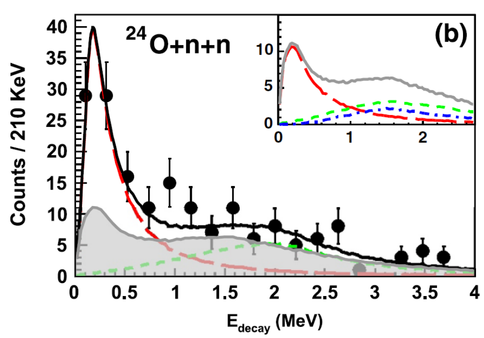
- Evolution of nuclear shell structure at extreme neutron to proton ratios.
- Study of nuclei beyond the neutron drip line
- Correlations in two neutron decays.
- New phenomena in exotic nuclei.

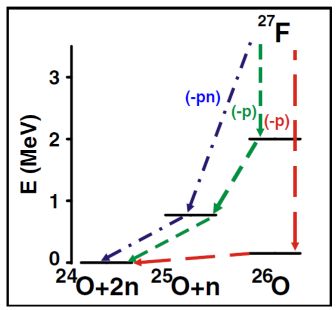


In the future MoNA will be combined with the High Rigidity Spectrometer (HRS)

Beyond the Driplines







Discovery of two-neutron unbound ^{26}O

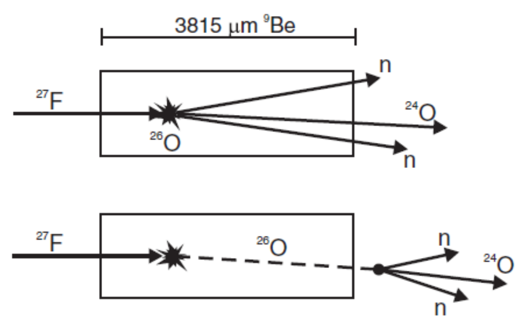
^{26}O g.s. resonance energy < 200 keV

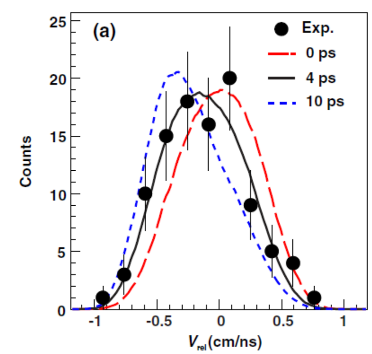
Lunderberg et al. PRL 108 (2012) 142503

Evidence for two-neutron radioactivity

$t_{1/2}$ ~ 4.5 ps for 2n decay of ^{26}O

Kohley et al. PRL 110 (2013) 152501

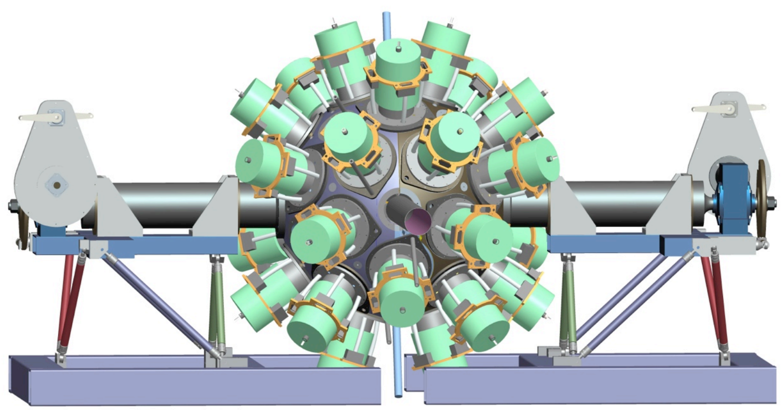




In-Beam Gamma-Ray Spectroscopy: GRETA

THE GAMMA-RAY ENERGY TRACKING ARRAY

GRETA



Input to the 2014 Nuclear Astrophysics and Low Energy Physics Town Meeting

(Texas A&M University, August 21-23, 2014)

- γ-ray tracking array with unmatched position resolution for precise Doppler reconstruction of γ rays emitted in flight
- High efficiency allows furthest scientific reach
- 4π coverage for angular distributions, correlations, polarization, g-factors (RIV), and liftetime measurements
- Concept proven with highly successful GRETINA science campaigns
- Community endorsed (NSAC 2002, 2007 LRPs, and FRIB SAC).

GRETA can be used for all γ-ray tagged reactions with fast and reaccelerated beams (Coulomb excitation at all energies, transfer, knockout, charge exchange, fragmentation, inelastic hadronic scattering, … coupled to separators, charged particle arrays, neutron detector arrays, …)

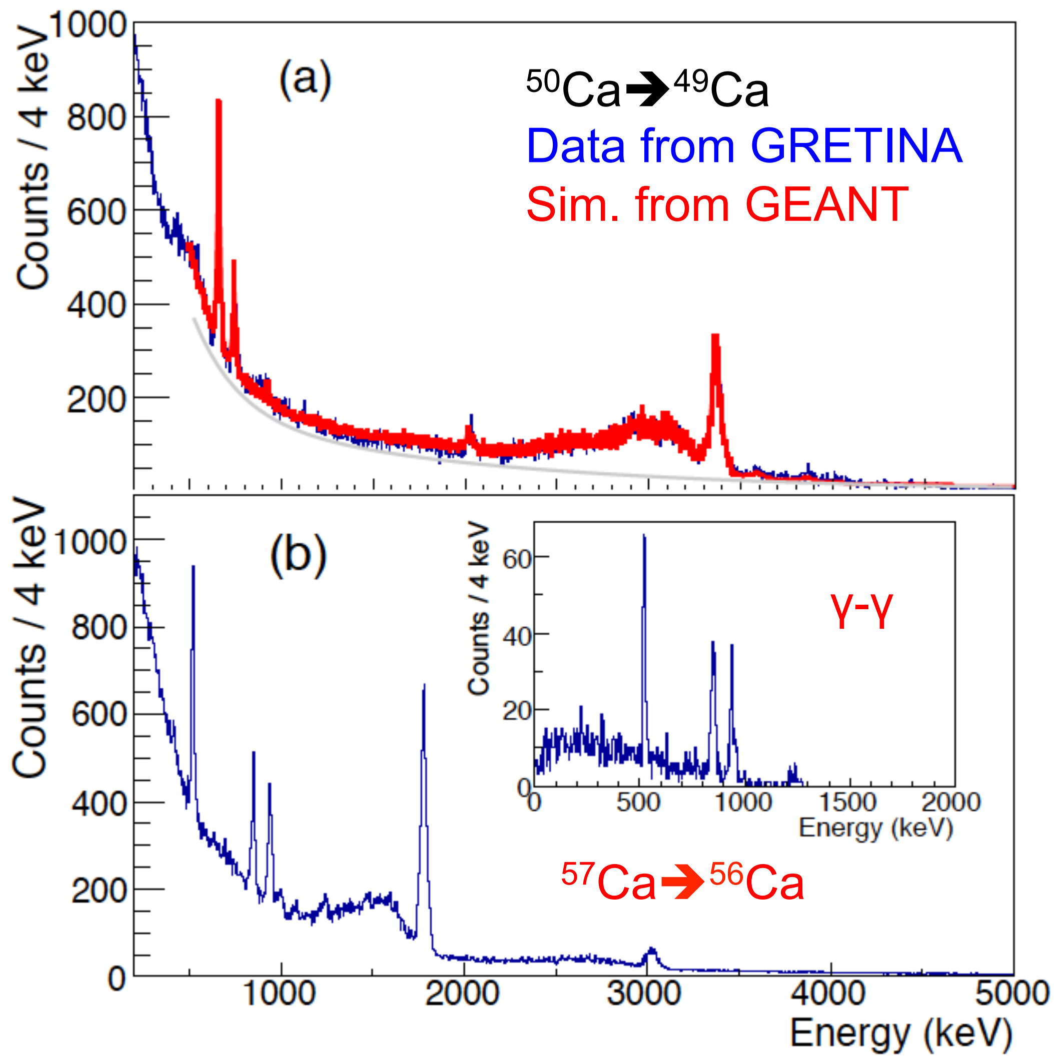
Maximizes the science reach at existing and future facilities. e.g. ANL, NSCL and FRIB.

Ca Isotopes: Archetype of Structural Evolution

Dramatic example of single-particle evolution (due to spin-isospin component of nn-interaction) resulting in new subshell structure at N=32,34

Microscopic calculations suggest particular sensitivity to inclusion of 3N forces

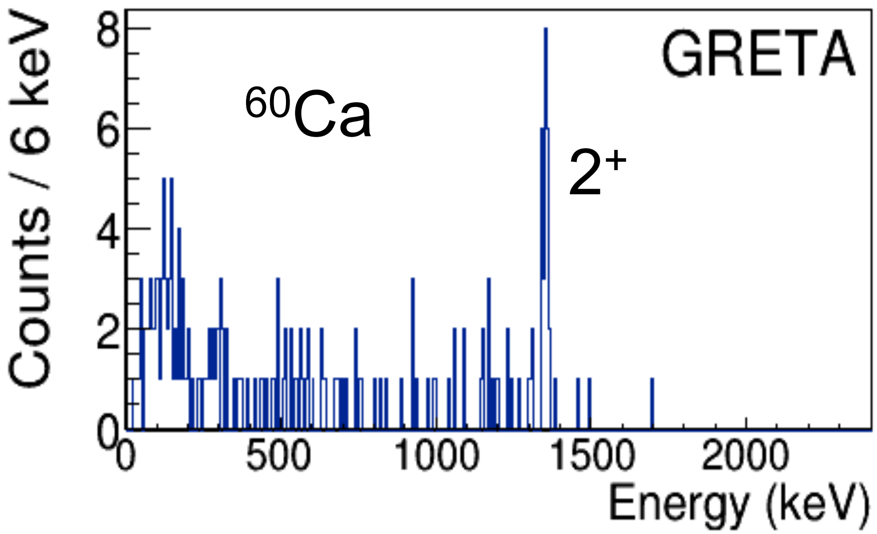
Detailed spectroscopy using one-nucleon knockout can be extended to a least ^{56}Ca with GRETA at FRIB



Spectroscopy of ^{60}Ca

- The structure around ^{60}Ca informs the location of the dripline in Z=20 chain
- Nuclear models, including ab-initio calculations, use the Ca chain as a test bed for the most modern interactions
- Spectroscopy of this key nucleus: ^{9}Be(^{61}Sc,^{60}Ca+γ)X at FRIB with fast-beam knockout possible
- The efficiency gain with GRETA over GRETINA is a game changer

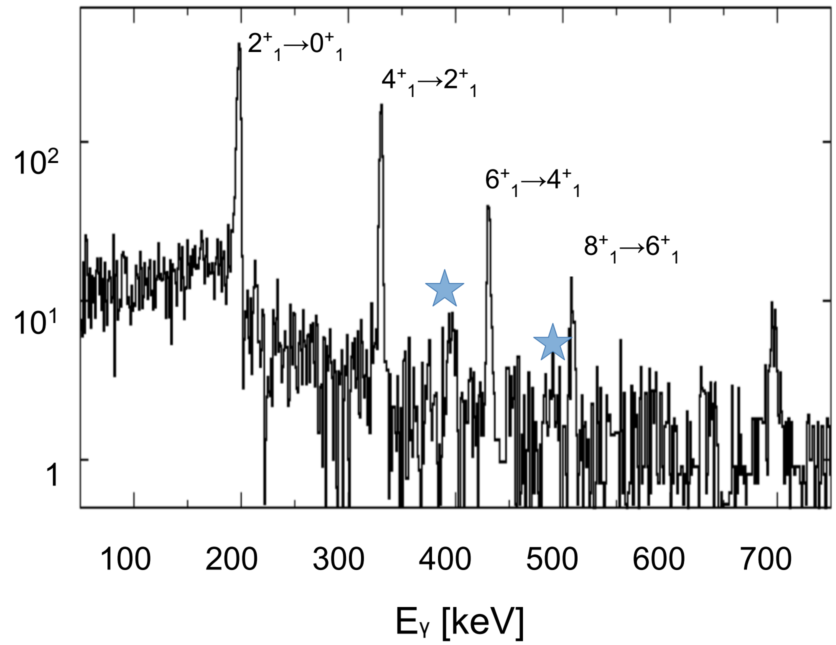
Simulated spectrum of ^{60}Ca populated in one-proton removal from ^{61}Sc



Simulation assumes rates at FRIB, performance parameters of proposed HRS, and GRETA for in-beam spectroscopy

New Regions of Octupoles

650 MeV ^{144}Ba , I_{beam} ~ 10 - 20 kpps



- Reaccelerated CARIBU beam
- Goal: measure B(E1) and B(E3) matrix elements for transitions decaying from octupole to yrast band labeled with ★

One of the first measurements with GRETINA at ATLAS.

M. Albers *et al.,* (2014) (ANL, LLNL, Rochester, LBNL, NSCL, FSU)

Octupoles and the EDM

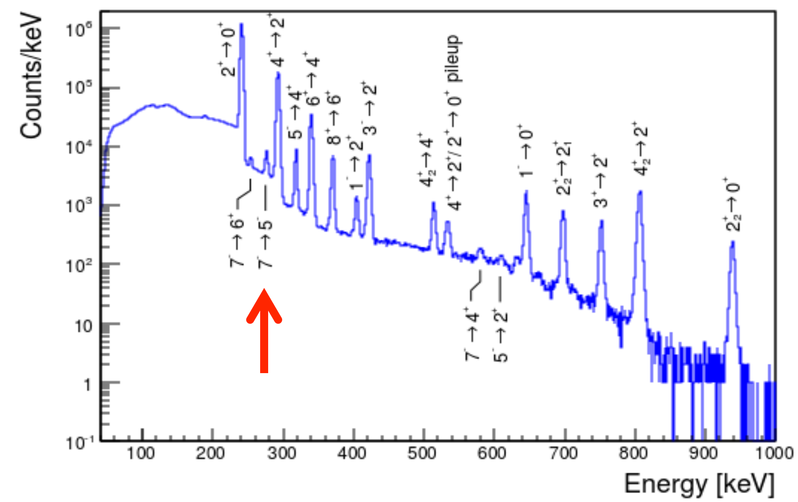
Search for permanent Electric Dipole Moment (EDM) indicating time-reversal (T) or charge-parity (CP) violation due to physics beyond the Standard Model

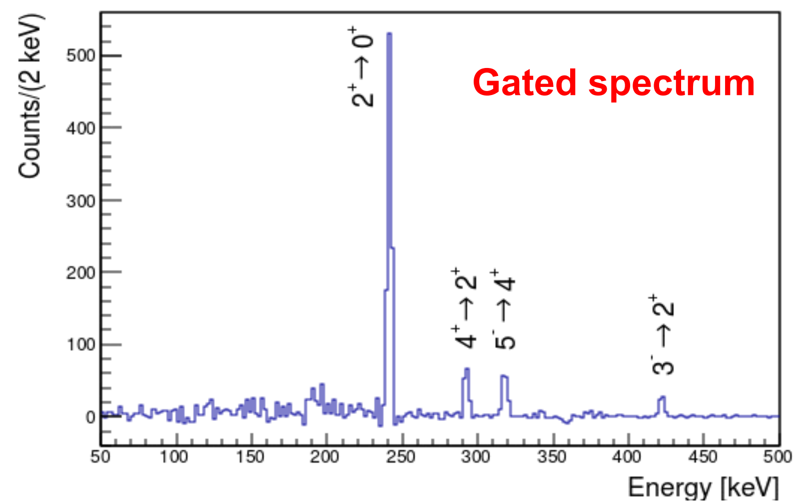
Nuclear octupole deformation can “amplify” the atomic EDM by several orders-of-magnitude (through Schiff moment induced contribution)

Likely candidates for EDM experiments at FRIB lie in the Ra, Rn, Pa region.

Must characterize the octupole collectivity through high statistics, multi-step, Coulomb excitation

GRETA+CHICO2 Simulation for ^{220}Ra





Astrophysics Example

PRL **113,** 032502 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

Determining the *rp*-Process Flow through ^{56}Ni: Resonances in ^{57}Cu$(p,\gamma)^{58}$Zn Identified with GRETINA

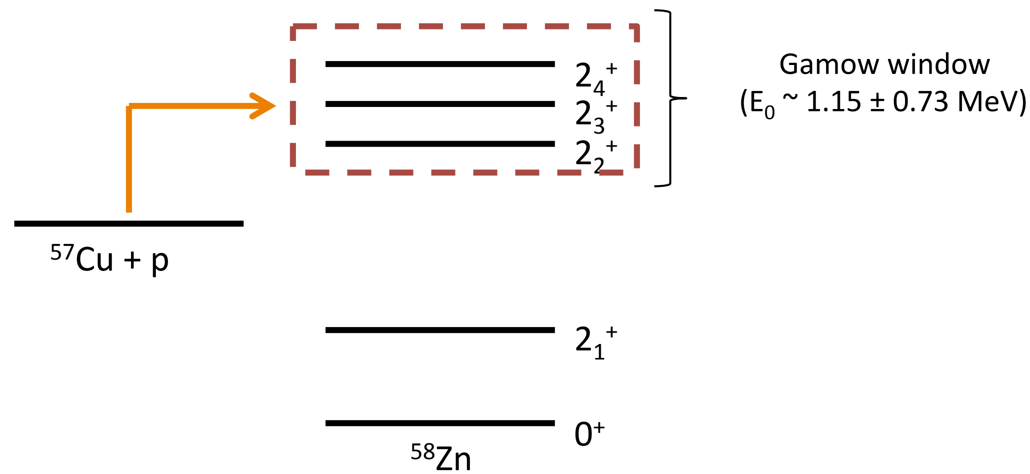
C. Langer,[1,2,*] F. Montes,[1,2] A. Aprahamian,[3] D. W. Bardayan,[4,†] D. Bazin,[1] B. A. Brown,[1,5] J. Browne,[1,2,5] H. Crawford,[6] R. H. Cyburt,[1,2] C. Domingo-Pardo,[7] A. Gade,[1,5] S. George,[8,‡] P. Hosmer,[9] L. Keek,[1,2,5] A. Kontos,[1,2] I-Y. Lee,[6] A. Lemasson,[1] E. Lunderberg,[1,5] Y. Maeda,[10] M. Matos,[11] Z. Meisel,[1,2,5] S. Noji,[1] F. M. Nunes,[1,5] A. Nystrom,[3] G. Perdikakis,[12,1,2] J. Pereira,[1,2] S. J. Quinn,[1,2,5] F. Recchia,[1] H. Schatz,[1,2,5] M. Scott,[1,2,5] K. Siegl,[3] A. Simon,[1,2,§] M. Smith,[3] A. Spyrou,[1,2,5] J. Stevens,[1,2,5] S. R. Stroberg,[1,5] D. Weisshaar,[1] J. Wheeler,[1,2,5] K. Wimmer,[12,1] and R. G. T. Zegers[1,2,5]

The ^{57}Cu(p,γ)^{58}Zn stellar reaction rate has a significant effect in the light-curve emitted in X-ray bursts. ^{58}Zn excitation energies are not known experimentally.

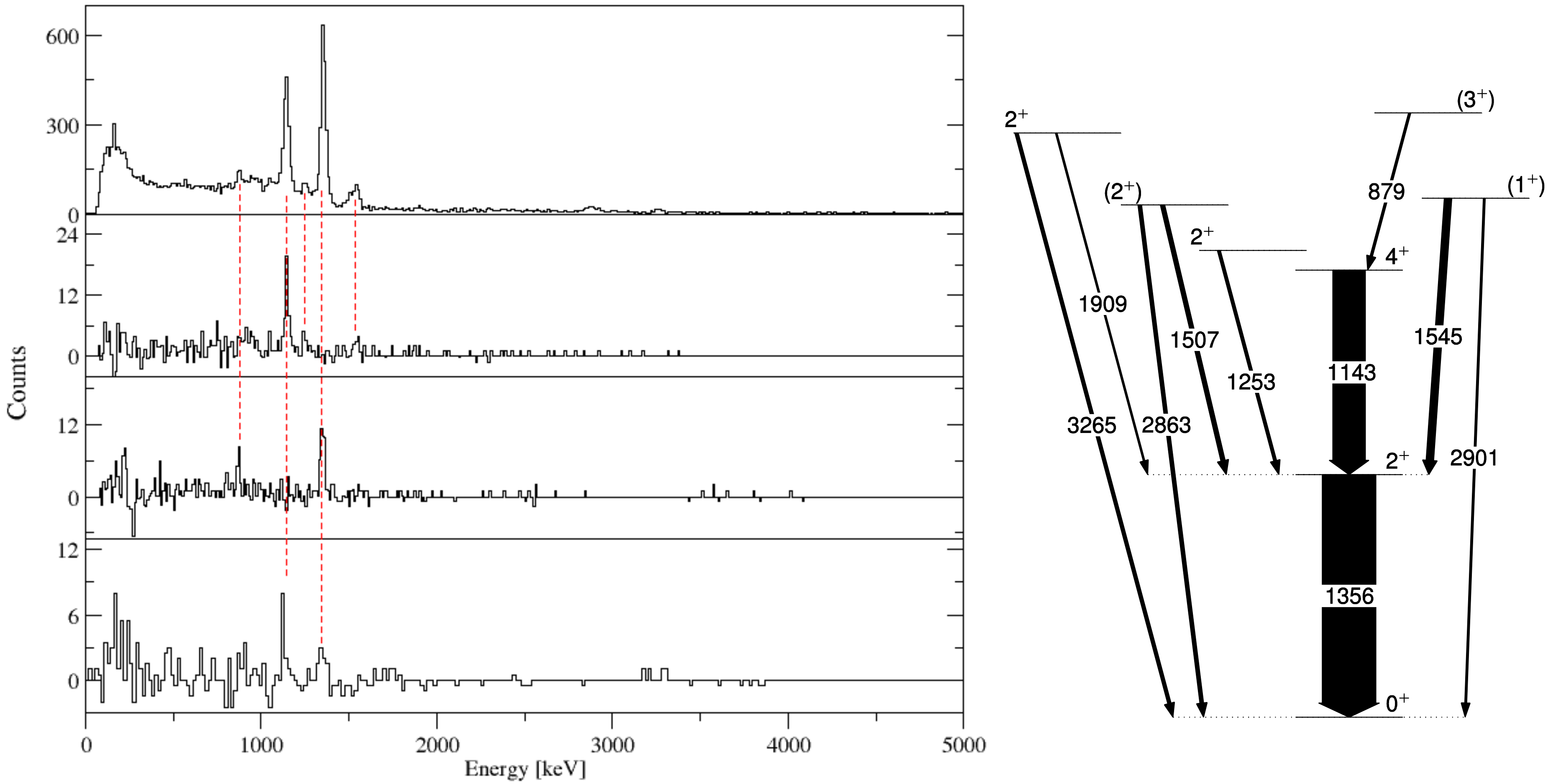
The effective lifetime of ^{56}Ni determines the amount of A =56 material in the neutron star crust.

^{57}Cu beam ~ 3 10^4 pps produced from stable ^{58}Ni @160 MeV/u on 225mg/cm^2 CD_2 target

Reaction rate dominated by 2^+ resonances



^{58}Zn Spectroscopy (Completes Isospin Triplet)



With FRIB and GRETA+S800 (or HRS) we will be able to investigate key rp-process nuclei and consequences of their structure on reaction rates.

Conclusion

Intellectual challenges from NRC Decadal Study

How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Overarching questions from NSAC Long Range Plan

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the universe?	What are new applications of isotopes to meet the needs of society?

Science drivers (thrusts) from NRC RISAC

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes

Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research

1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship

In-beam spectroscopy in essential to this entire field!

Suggested Text Needed in LRP

For FRIB, we need the **highest** recommendation:

"We recommend completion of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics…"

For GRETA, we must build on the endorsements in the 2002 and 2007 plans.

> *"The detection of γ-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions."* - 2002 NSAC Long Range Plan

> *"Construction of GRETA should begin immediately upon the successful completion of the GRETINA array"* - 2007 NSAC Long Range Plan

It must feature **clearly and prominently as an initiative**:

"Construction of GRETA should begin immediately. This is essential if the full scientific potential of existing and future facilities, especially FRIB, is to be fulfilled…"

Many thanks to:

Mike Carpenter, Heather Crawford, Paul Fallon, Alexandra Gade, Augusto Macchiavelli, Artemis Spyrou, Shaofei Zhu

and to you…

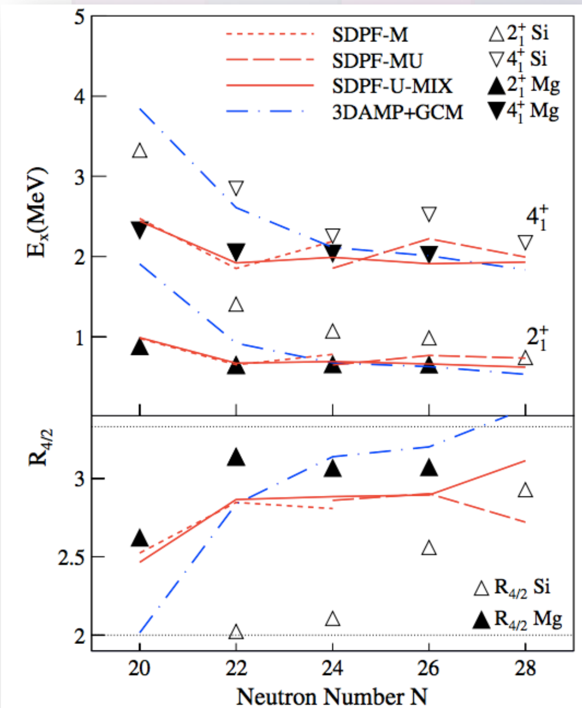
SPECTROSCOPY WITH FAST BEAMS

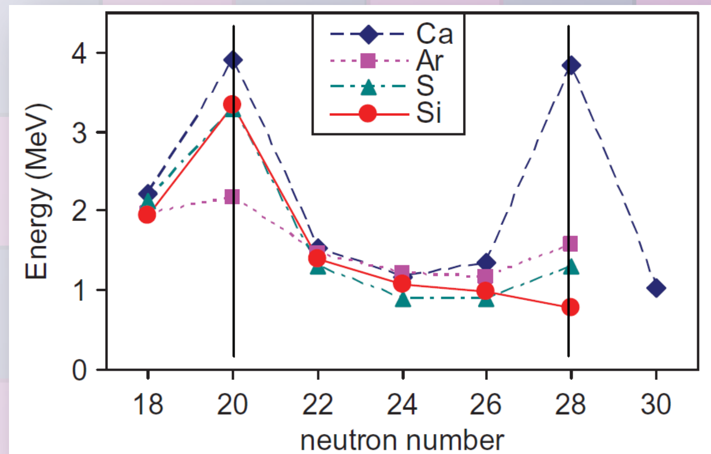
Heather Crawford
Ohio University

OHIO UNIVERSITY

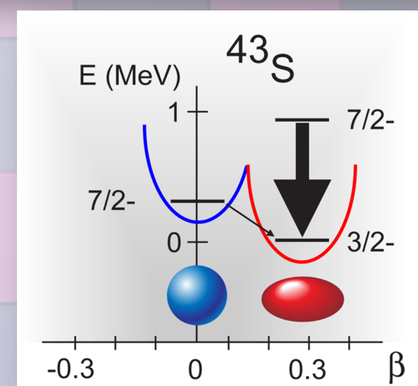
Shapes in Neutron-Rich Mg

The neutron-rich Mg isotopes from *N*=20 to *N*=28 are deformed, bridging two eroded shell gaps.

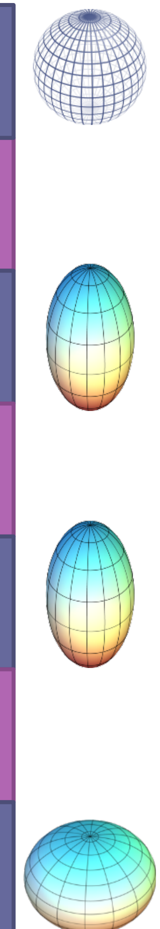




^{40}Mg is a (near)drip-line nucleus, at the intersection of *N*=28, along which shapes are believed to be rapidly changing.



^{48}Ca
^{47}K
^{46}Ar
^{45}Cl
^{44}S
^{43}P
^{42}Si
^{41}Al



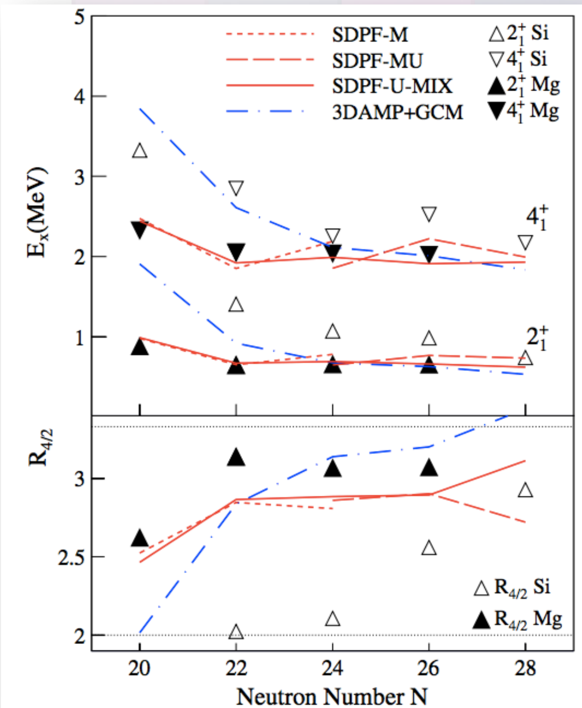
^{29}Mg | ^{30}Mg | ^{31}Mg | ^{32}Mg | ^{33}Mg | ^{34}Mg | ^{35}Mg | ^{36}Mg | ^{37}Mg | ^{38}Mg | ^{39}Mg | ^{40}Mg | ?

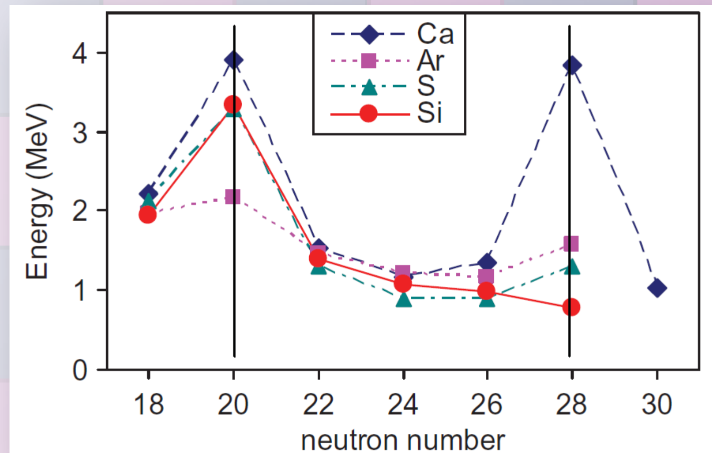
↑ N=28

Gaudefroy and Grevy, Nucl. Phys. News **20**, 13 (2010); Li *et al.*, PRC **84**, 054304 (2011).
Nowacki and Poves, PRC **79**, 014310 (2009); Doornenbal *et al.*, PRL **111**, 212502 (2013); Crawford *et al.*, PRC 89, 041303(R) (2014).

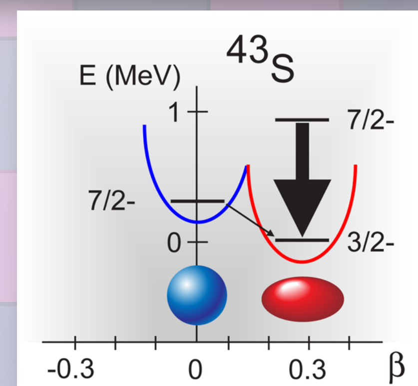
Shapes in Neutron-Rich Mg

The neutron-rich Mg isotopes from N=20 to N=28 are deformed, bridging two eroded shell gaps.





^{40}Mg is a (near)drip-line nucleus, at the intersection of N=28, along which shapes are believed to be rapidly changing.



^{48}Ca

^{47}K

^{46}Ar

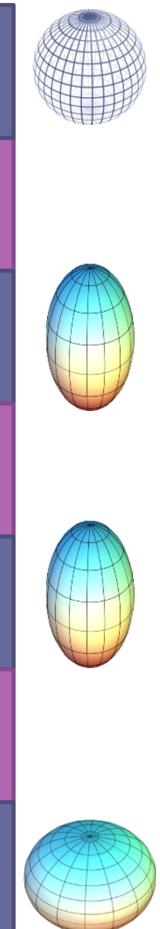
^{45}Cl

^{44}S

^{43}P

^{42}Si

^{41}Al

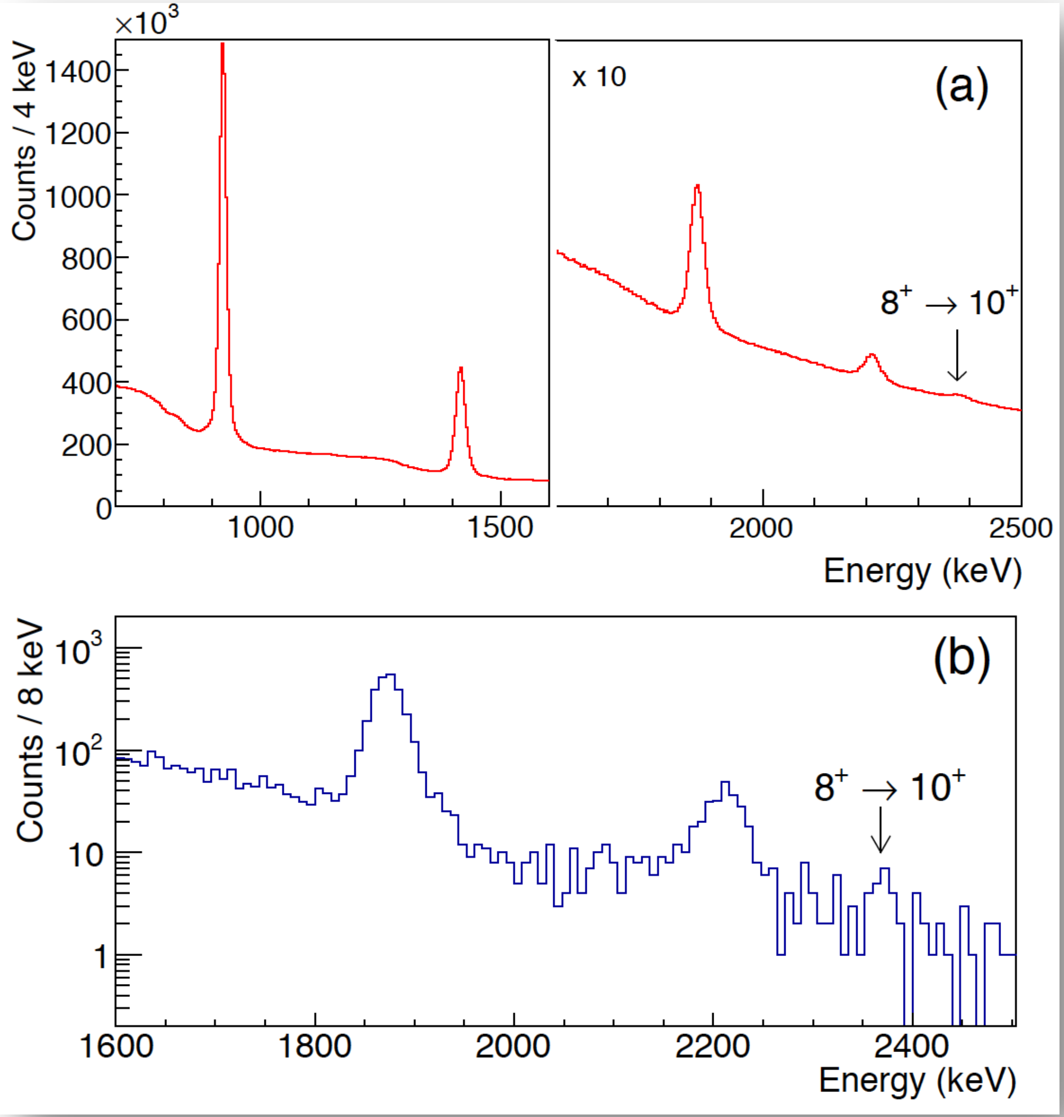


^{29}Mg ^{30}Mg ^{31}Mg ^{32}Mg ^{33}Mg ^{34}Mg ^{35}Mg ^{36}Mg ^{37}Mg ^{38}Mg ^{39}Mg ^{40}Mg ?

↑ N=28

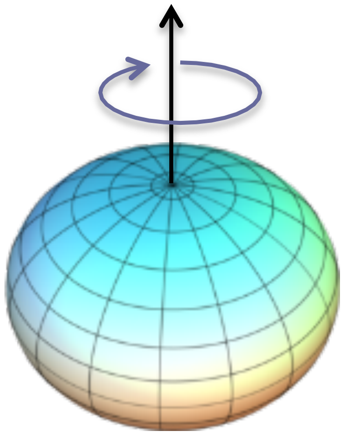
Gaudefroy and Grevy, Nucl. Phys. News 20, 13 (2010); Li *et al.*, PRC 84, 054304 (2011).
Nowacki and Poves, PRC 79, 014310 (2009); Doornenbal *et al.*, PRL 111, 212502 (2013); Crawford *et al.*, PRC 89, 041303(R) (2014).

In-Beam Spectroscopy at the Limits – $^{32,34}Mg$



Characterizing rotational structures in the Island of Inversion $^{32,34}Mg$ nuclei will provide insight into:

- extent and stability of deformation
- evolution of shape with spin and binding
- nucleon-core coupling

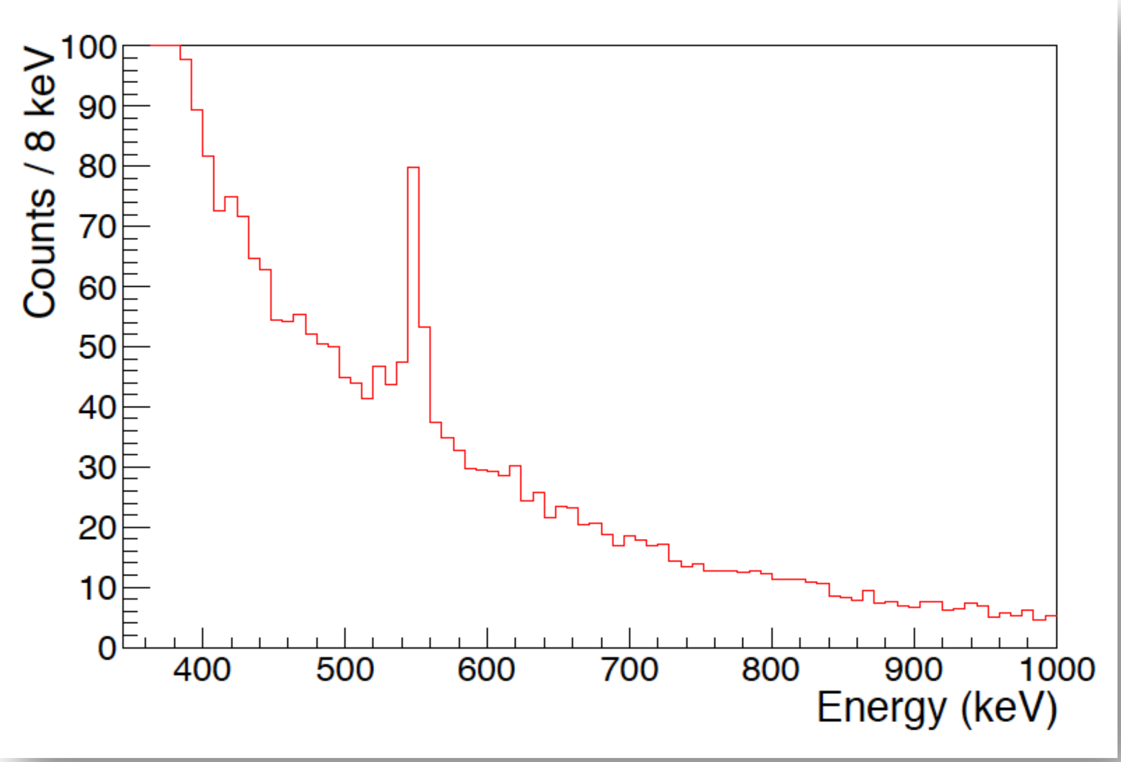


In-Beam Spectroscopy at the Limits – ^{40}Mg

A complete picture of changing shape in the Mg isotopes will require quantifying the degree of deformation, and mapping the evolution of nucleon single-particle states.

Nucleon knockout reactions can probe single-particle occupancies along the isotopic chain – but at the limits, the rates will be low, detailed spectroscopy will be demanding.

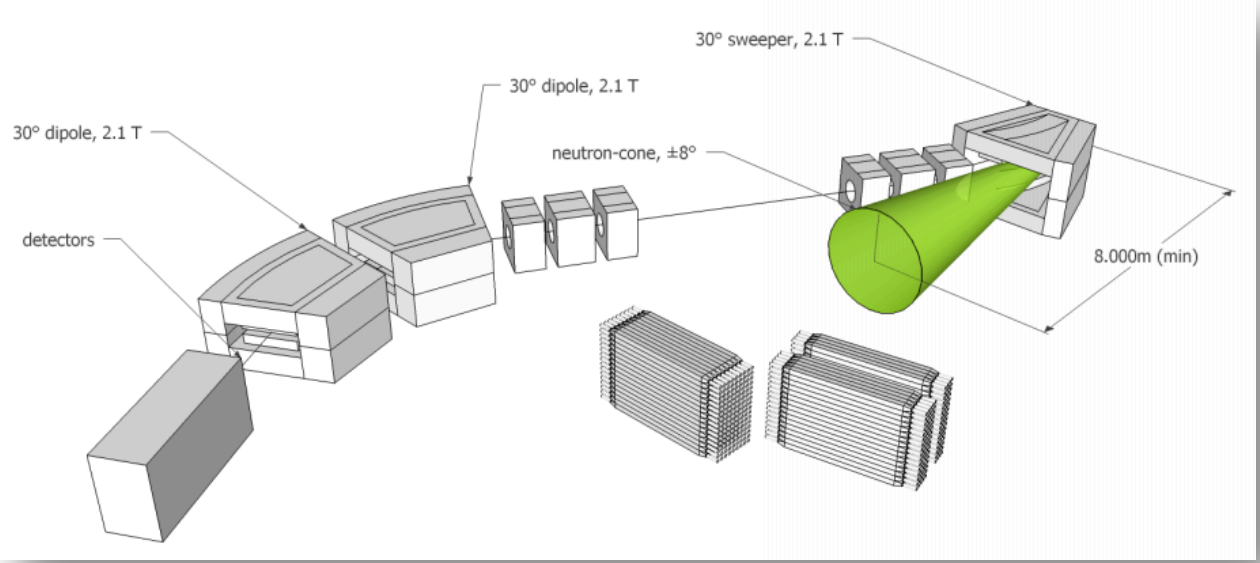
Coulomb excitation can provide quantification on the extent of collectivity. ^{40}Mg Coulex, with a predicted 9 pps at FRIB will require high-efficiency gamma-spectroscopy, with the resolution to observe a peak above background.

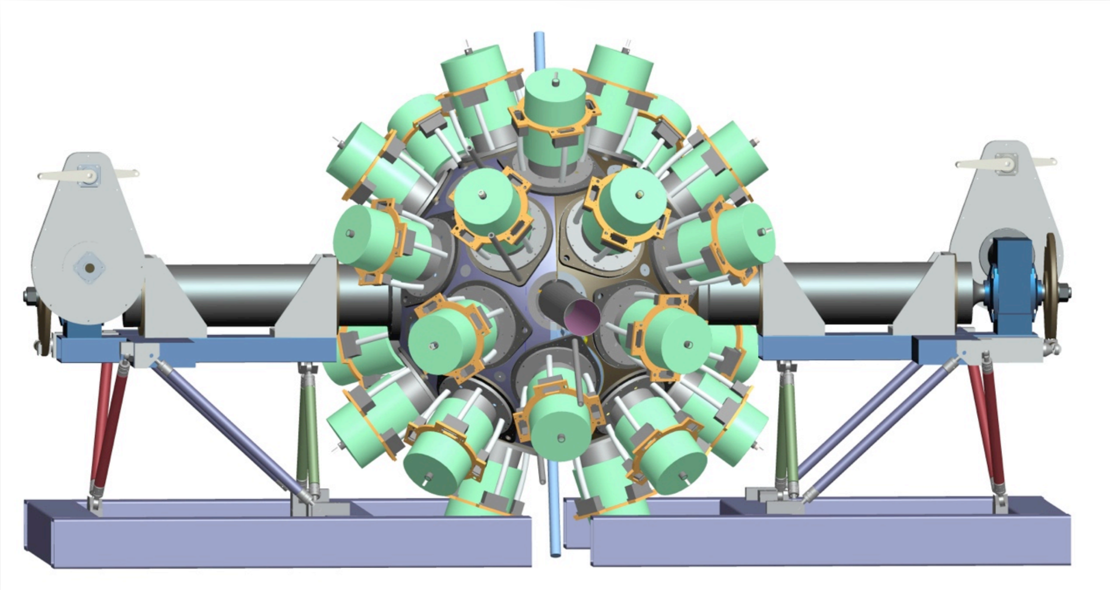


What Do We Need?

Neutron-rich Mg at FRIB ($\sim$ 200MeV/u) will be among the most demanding beams in terms of $B\rho \rightarrow {}^{40}$Mg $\sim$ 7 Tm

$\rightarrow$ HRS is critical requirement for spectroscopy with fast beams at FRIB





Spectroscopy with rates on the order of 1 pps, or < 0.1% branches require high-efficiency detectors; complex level schemes demand resolution

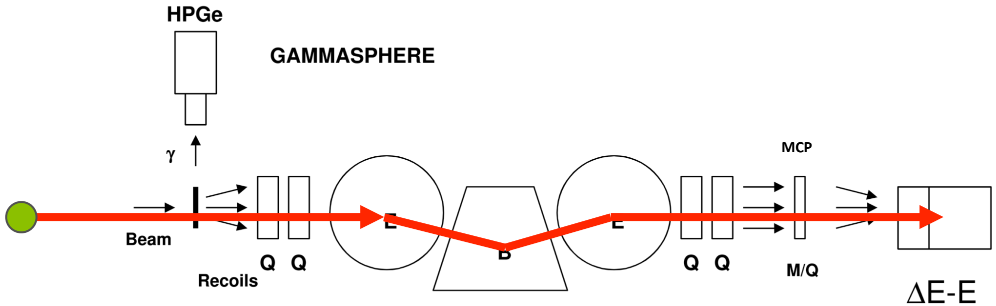
$\rightarrow$ GRETA will be a cornerstone for fast-beam physics

Unsafe Coulex to probe medium to high spin states in neutron rich nuclei

Premise: Identification of high-spins states which are inaccessible from beta-dacay or reaction studies provide a more complete knowledge base for understanding the nuclear structure not only at high-angular momentum but near the ground state as well.

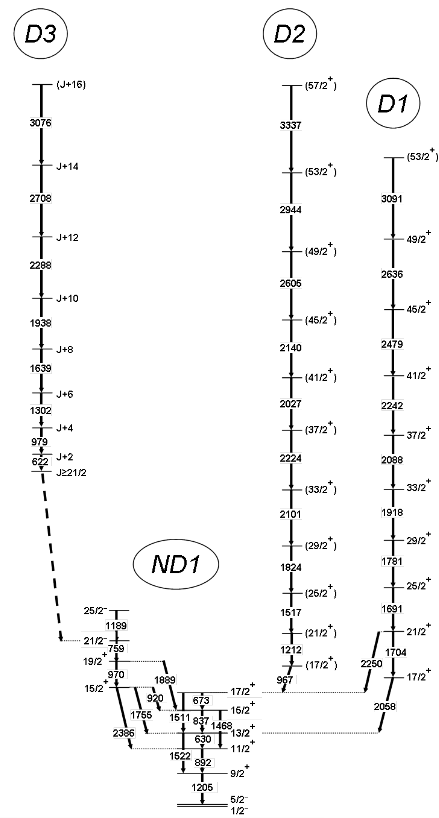
Low Energy Town Meeting
Nuclear Structure and Reactions
August 22, 2014
Michael P. Carpenter

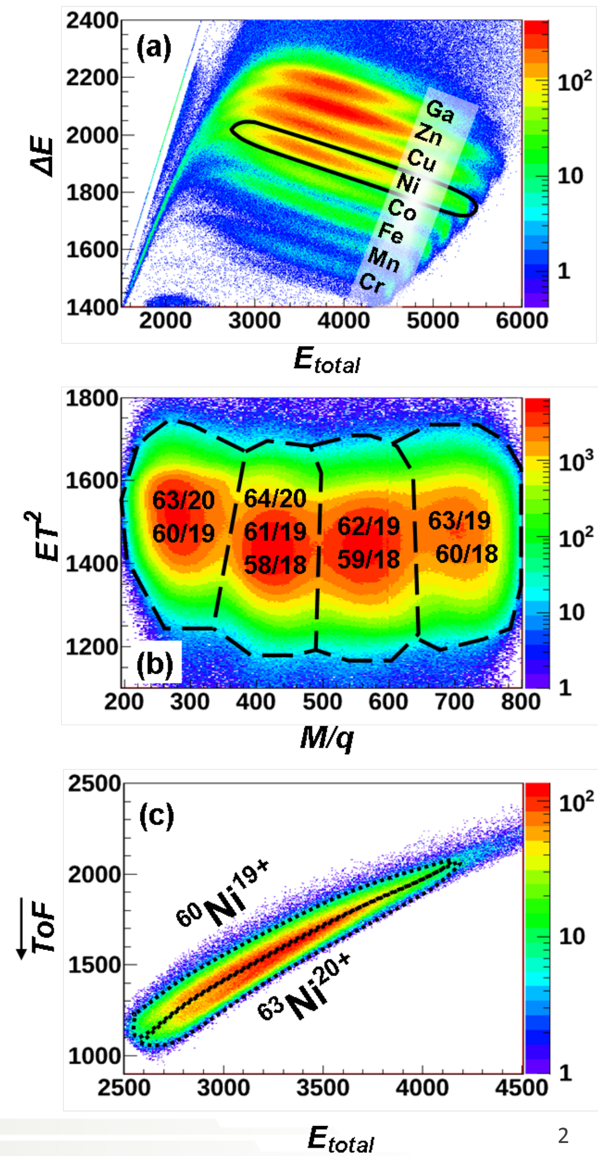
Accessing High-Spins of Neutron Rich Nuclides with Deep Inelastic and Other More Exotic Reactions



- Self supporting ^{26}Mg target, 0.973 mg/cm^2 thick
- ^{48}Ca beam @ 320 MeV (>200% above Coulomb barrier)
- Intensity ~ 200 pnA
- ^{26}Mg(^{48}Ca,*7n4p*)^{63}Ni – 2% of σ_{tot}
- Selectivity made using focal plane detectors
- 3 high-spin deformed bands observed – shape coexistence
- Previously ^{63}Ni only identified up to 13/2$^+$ state
- Also new studies of ^{61}Co and $^{62\text{-}65}$Ni.

M. Albers, S.Zhu *et al.*, PRC 88, 054314 (2013)





Will these techniques work with RIB's.

- Short Answer : Yes … But ….

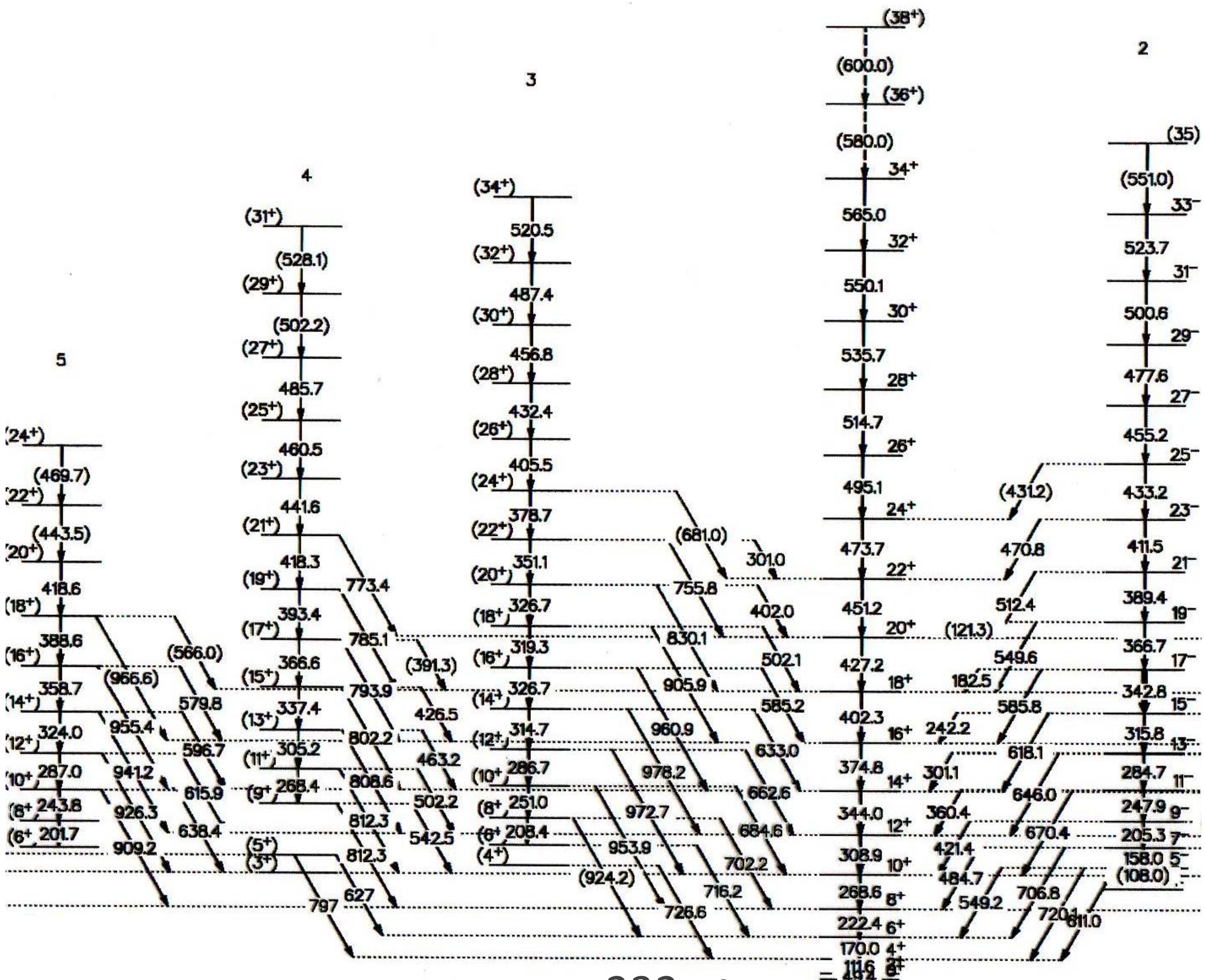
- Fusion-like reactions will have higher probabilities of neutron evaporaton as compound systems becomes more neutron-rich – limits the accesibility to neutron rich isotopes

- Deep-Inelastic Reactions are in principle but are not very selective – i.e. reaction channels can encompass hundreds of nuclei and this can be a show-stopper using RIB's with reduced intensities (compare 10^6 with 10^{10})

- But – With FRIB and CARIBU, we have access to reaccelerated neutron rich RIBs which offers the opportunity for direct excitation of the beam *i.e* Unsafe Coulex – excitation of beam using where E_{beam} ~ 5-6 MeV/u.

LARGEST and DOMINANT CROSS-SECTION is DIRECT EXCITATION OF BEAM

Here is an example (also see Partha's Talk)



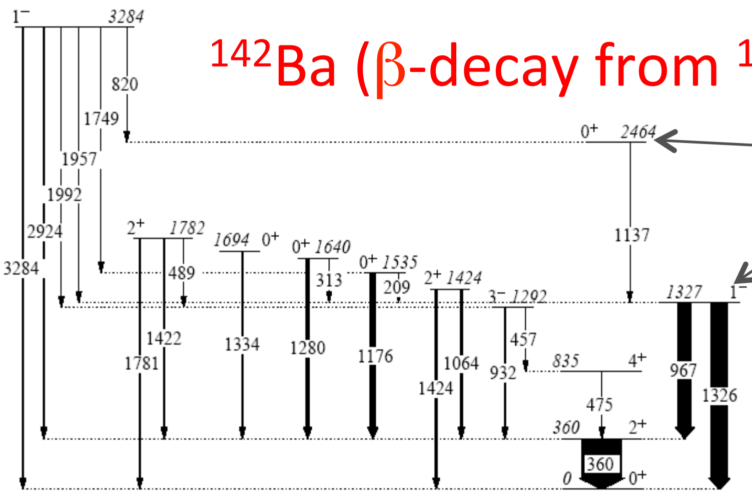
232Th

What is Needed?

- High Efficiency Gamma-ray Spectometer – GRETA
- High Efficiency and Highly pixelated particle counter at target – SUPER CHICO
- Reaccelerated RIB's at ~ 5-6 MeV/u
- Intensities for GRETA
  - 10^2 – 10^3 – γ-rays singles
  - 10^4 > γ-ray coincidences

These studies can begin now - CARIBU, REA3, ISAC2

^{142}Ba (β-decay from ^{142}Cs)



S. Zhu et al., to be published - Gammasphere

1-phonon octupole state firmly established
2-phonon octupole candidate

Unsafe Coulex of ^{142}Ba at ~110% over Coulomb could confirm 2-phonon character of state though identification of states on top of candidate state.

Requires Gammasphere or Gretina and I > 10^5

MICHIGAN STATE UNIVERSITY

Opportunities with excited-state lifetime measurements

Hiro IWASAKI
(NSCL/MSU)

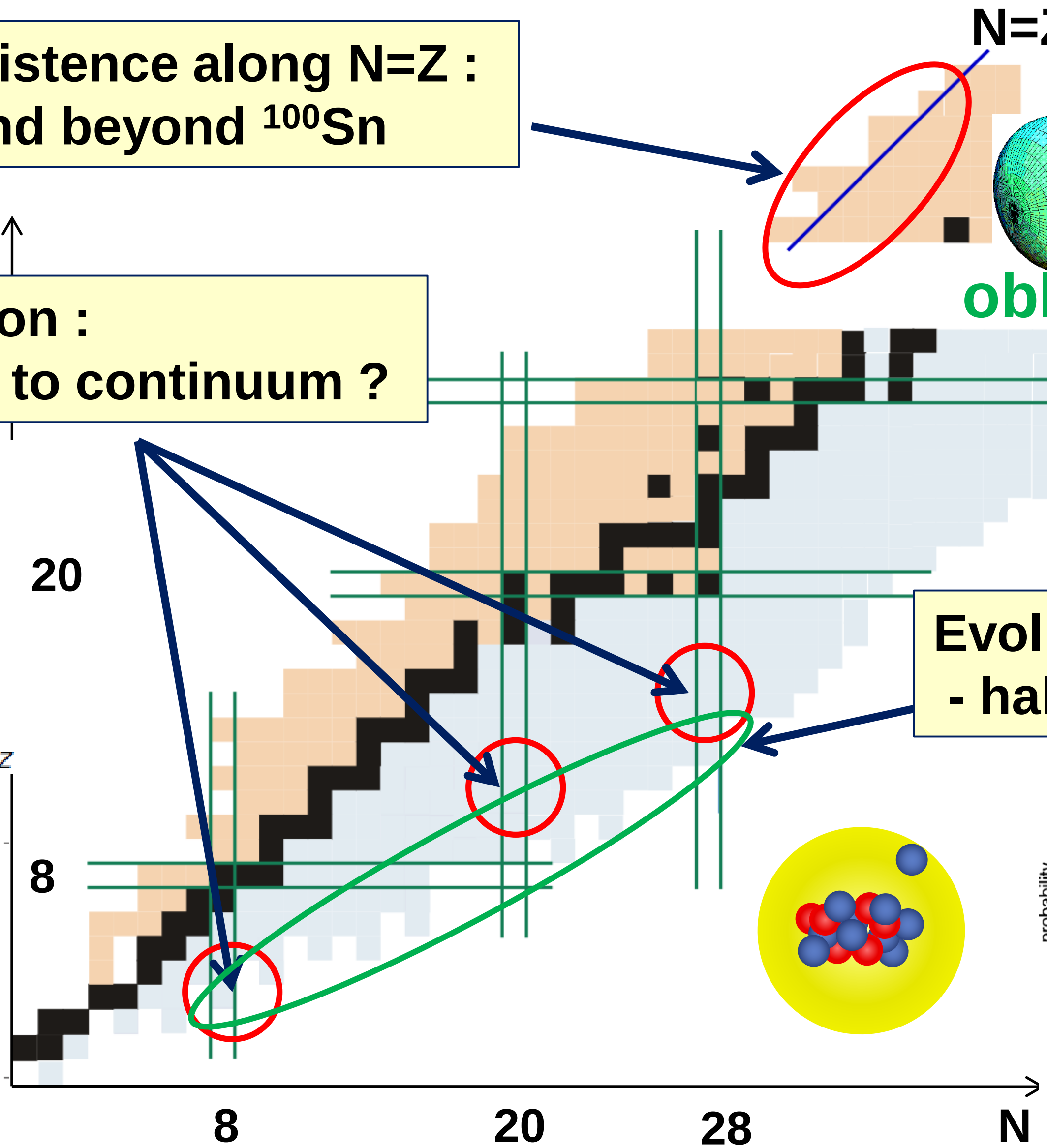
NSCL

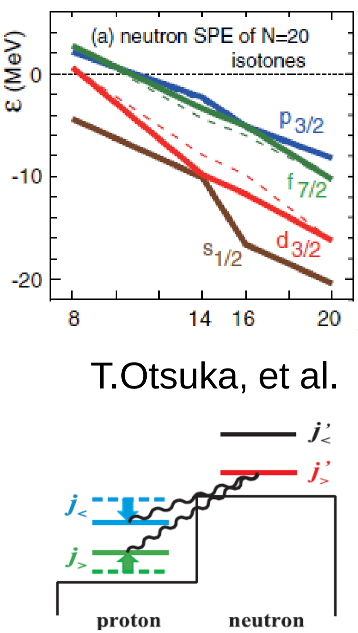
Spectroscopy of nuclei at the limit of stability

Shape coexistence along N=Z :
- toward and beyond ^{100}Sn

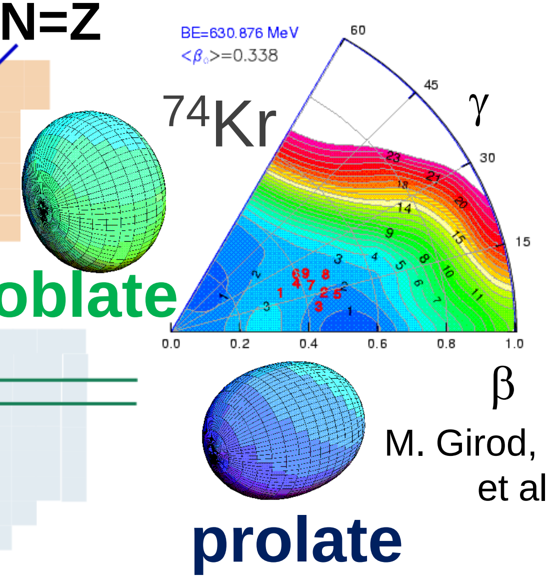
Shell evolution :
- from shell to continuum ?

Evolution of halo :
- halo vs collectivity

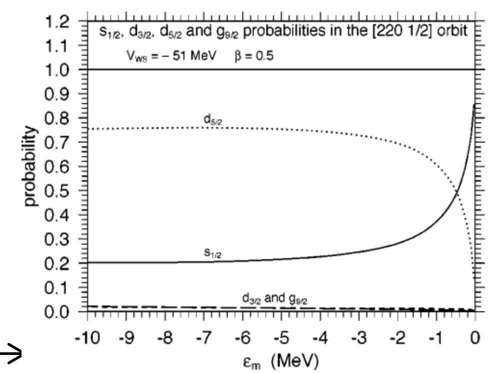




T.Otsuka, et al.

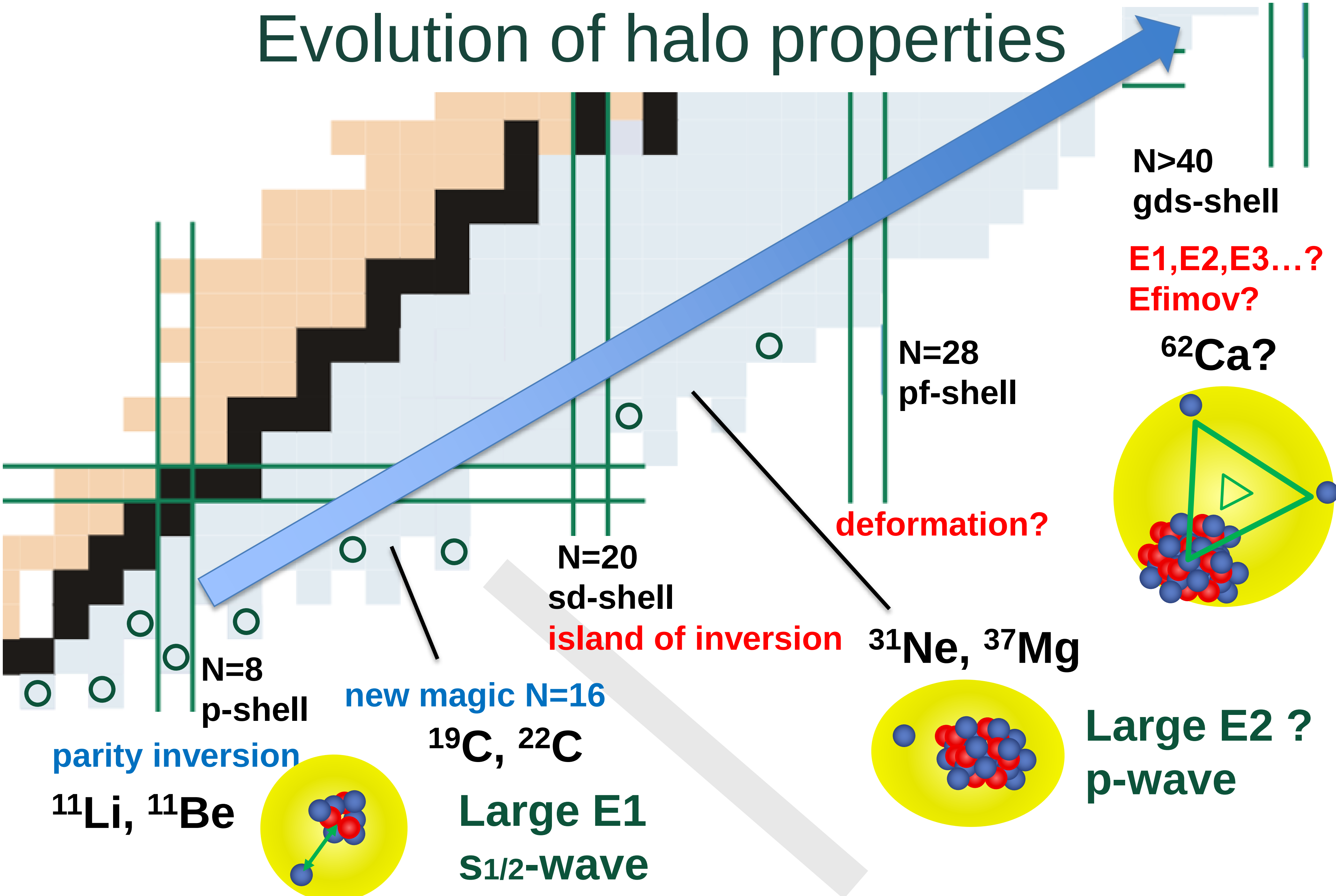


M. Girod, et al.

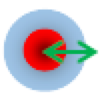
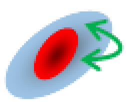


I.Hamamoto, et al.

Evolution of halo properties

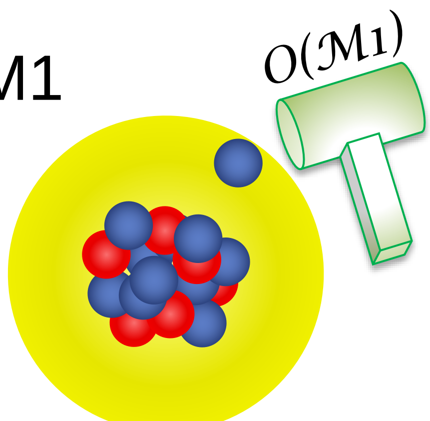


Characterization of halo with transition rate / level lifetime measurements

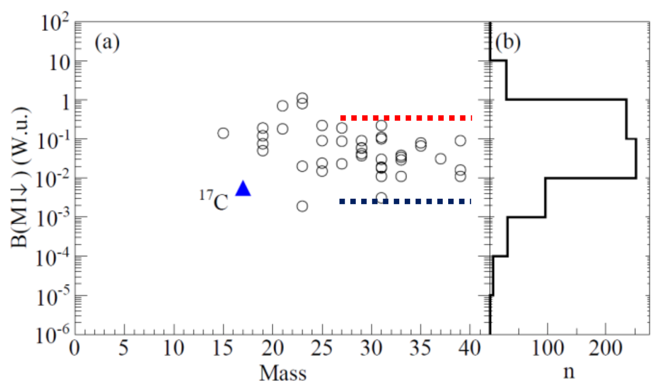
Type of halo	Configuration of valence neutron	B(E1) established	B(M1) - to be	B(E2) established-
Spherical 	Pure $s_{1/2}$ + core (0^+)	◎	×	△
Deformed 	Mixed (sd) or (pf) + core	◎	○	○

◎ Enhanced
○ Favored (unhindered)
× Hindered
△ Depend on core deformation

M1



^{17,19}C results from GRETINA



diminished
M1 strengths
due to s-wave halo

K.Whitmore, D.Smalley, HI, et al., to be submitted

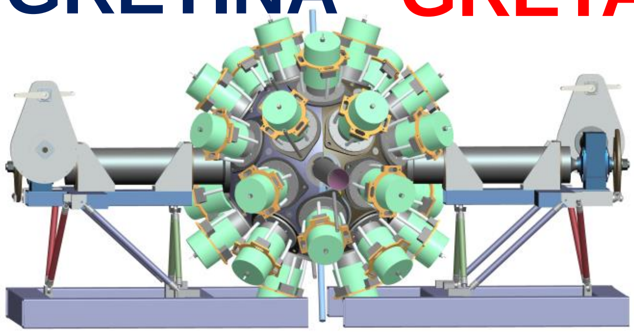
In-beam Gamma Setup at FRIB

MICHIGAN STATE UNIVERSITY

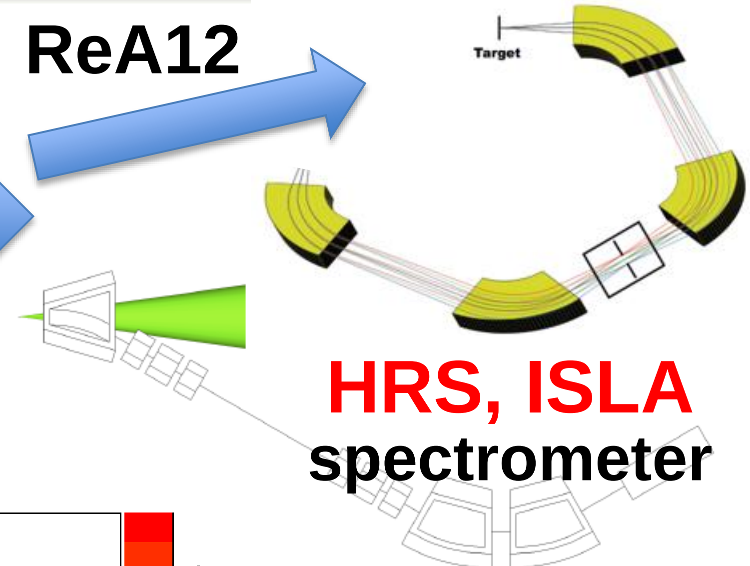
NSCL
FRIB

GRETINA **GRETA**

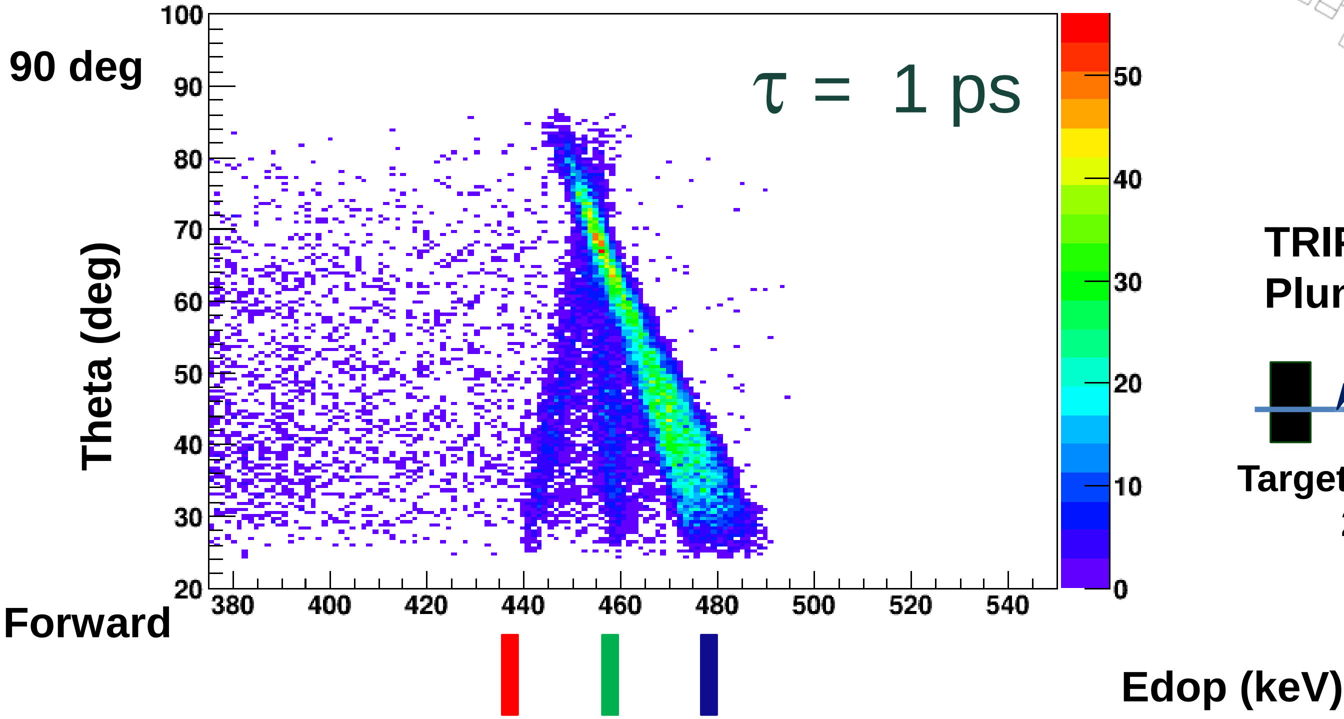
Fast RI beams



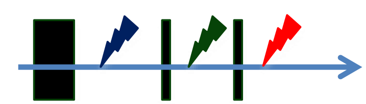
ReA12



HRS, ISLA spectrometer



TRIPLEX Plunger device



In-beam Gamma Setup at FRIB

MICHIGAN STATE UNIVERSITY

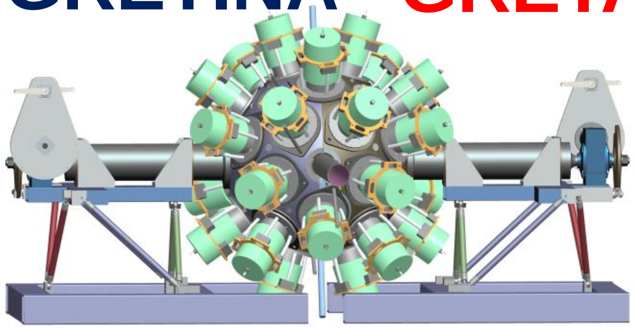
NSCL

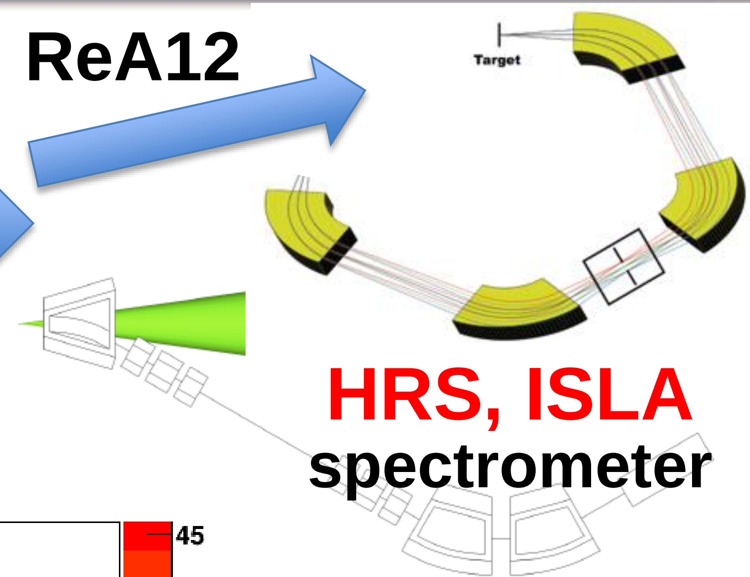
FRIB

GRETINA **GRETA**

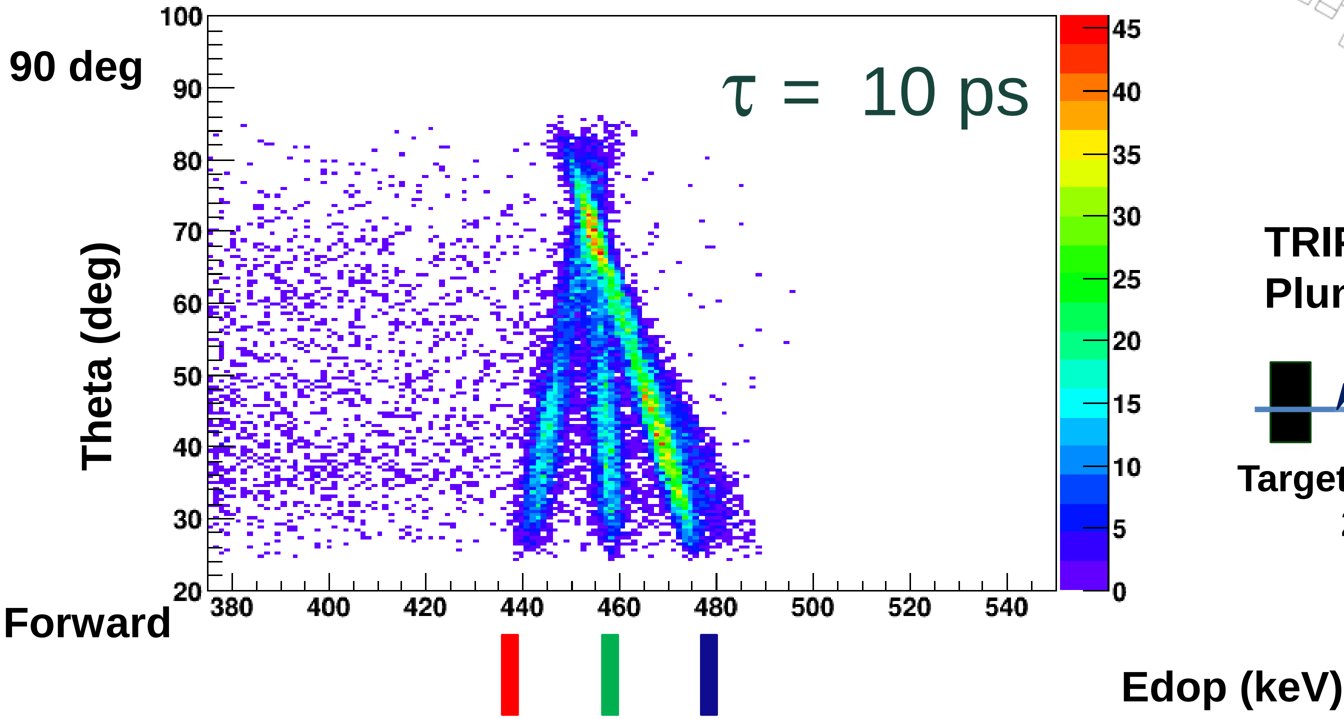
ReA12

Fast RI beams

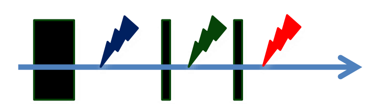




HRS, ISLA spectrometer



TRIPLEX
Plunger device



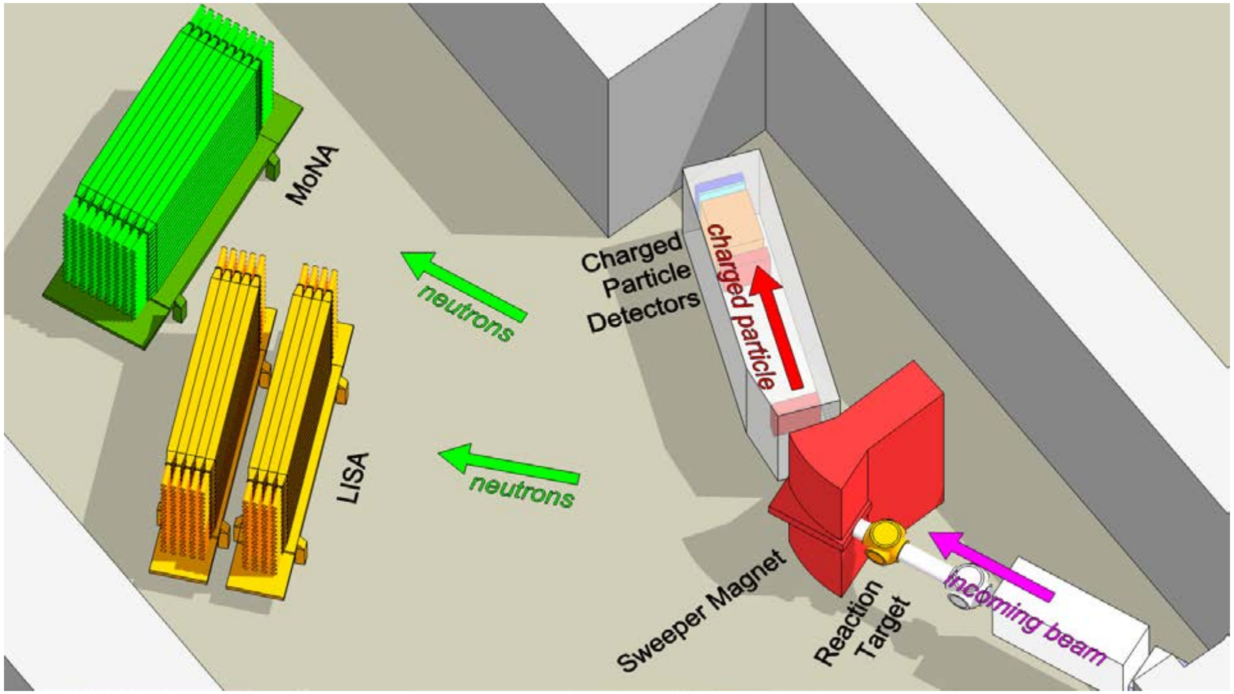
Target Degrader
2ndDegrader

Thank you

Nuclear Structure and Reactions with MoNA-LISA

Sharon Stephenson

Gettysburg College



2003: MoNA modules assembled by undergraduate students at NSCL

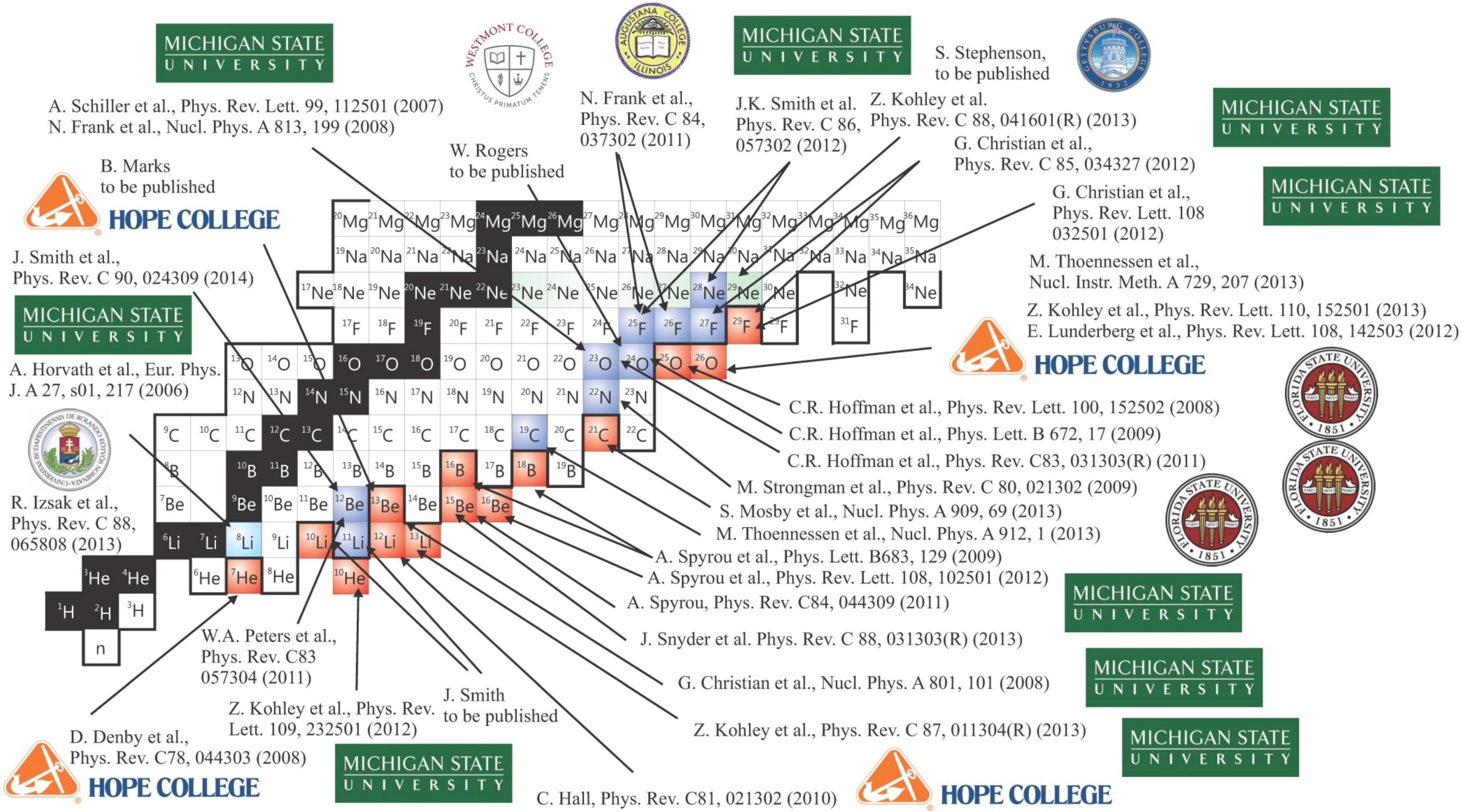
2004: Sweeper magnet built by FSU/NHMFL installed at NSCL

2011: LISA completed

2013: Hodoscope built by Augustana/NSCL installed at NSCL

2014: Liquid D target, development of segmented target

Physics with 10 years of MoNA



National Science Foundation
Gettysburg College

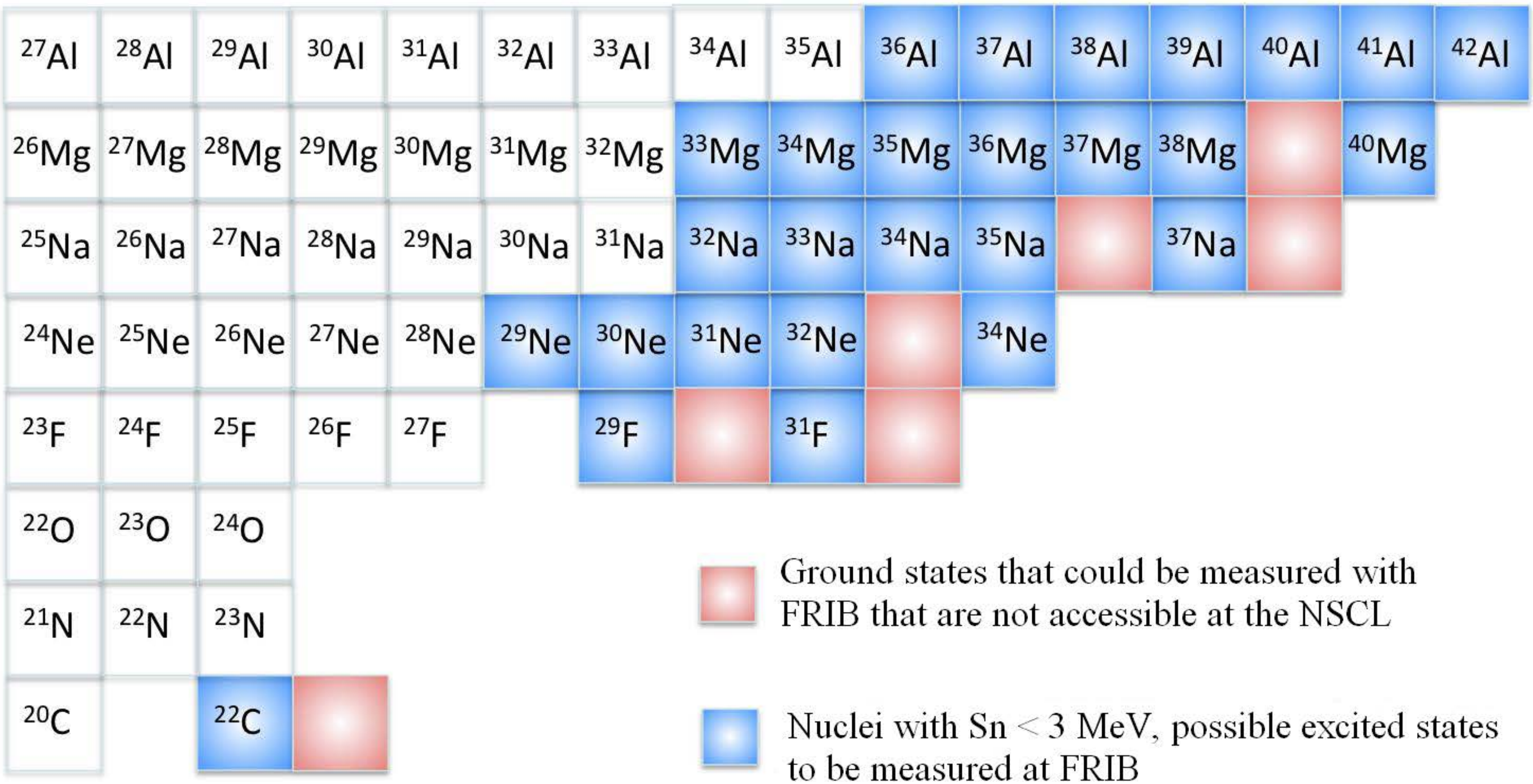
Highlights

- Discovery of 6 new isotopes: ^{15}Be, ^{16}Be, ^{18}B, ^{25}O, ^{26}O, ^{28}F
- First experimental determination of the N=16 shell closure in ^{24}O
- Observation of direct two-neutron emission in ^{16}Be
- First indication of two-neutron radioactivity in ^{26}O

- In addition to nuclear structure experiments MoNA has been used to:
  - measure the Coulomb dissociation of ^{8}Li to study the astrophysical relevant reaction ^{7}Li(n,γ)
  - exploit neutron-rich radioactive beams to constrain the symmetry energy
  - determine the mass and excitation energy of precursor intermediate products in projectile fragmentation reactions

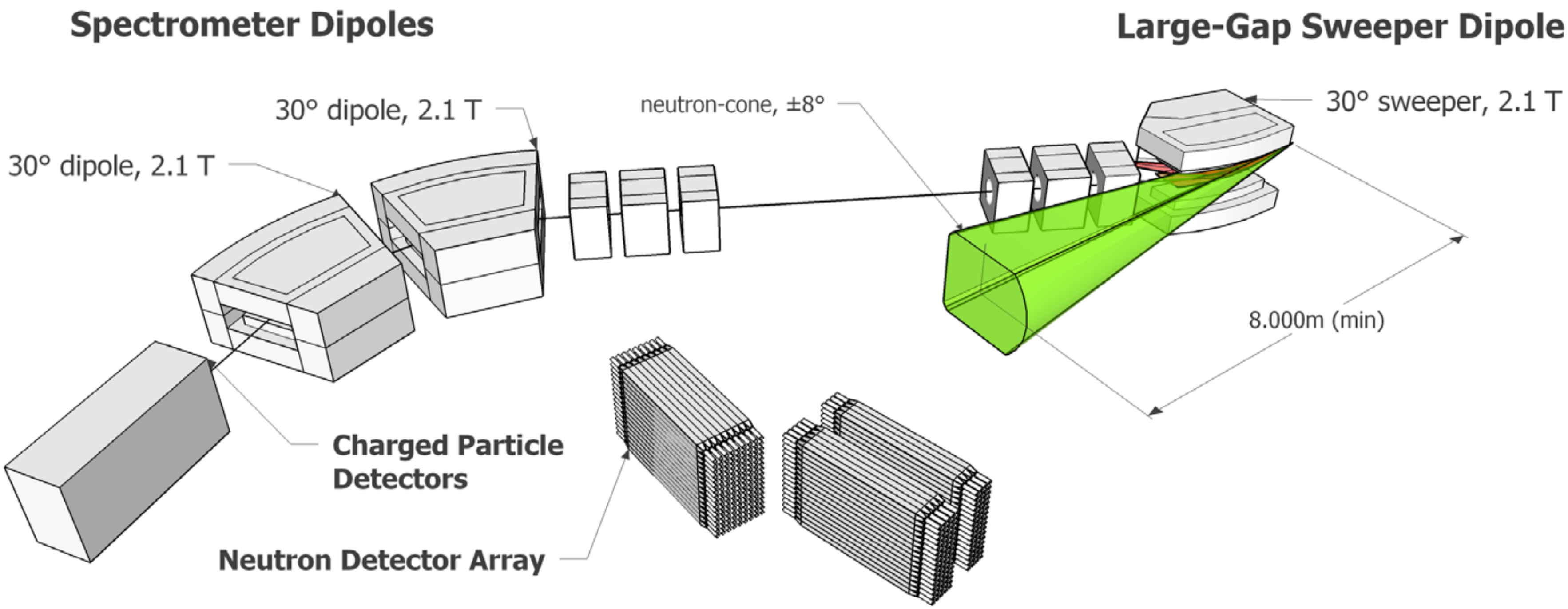
MoNA-LISA with FRIB

- Until now the nuclear structure experiments explored the transition between the *p* and *sd* shell and the evolution within in the *sd*-shell
- FRIB offers the opportunity to expand these studies into the *pf*-shell



High Rigidity Spectrometer HRS

- The 288 detectors of the two arrays are sufficient to cover the needed energy and angular range
- The main limitation is the small vertical gap of the Sweeper magnet (14cm)
- A large gap dipole as proposed with the HRS is required to explore the full capabilities of FRIB and MoNA-LISA



Conclusion

- MoNA-LISA is the ideal detector to explore the evolution of the *pf*-shell at and beyond the dripline
- In addition the MoNA-LISA/HRS setup can study reaction mechanisms of neutron rich beams (for example to understand the projectile fragmentation process and constrain the symmetry energy)
- MoNA-LISA is ready to go -- the construction of the HRS is essential

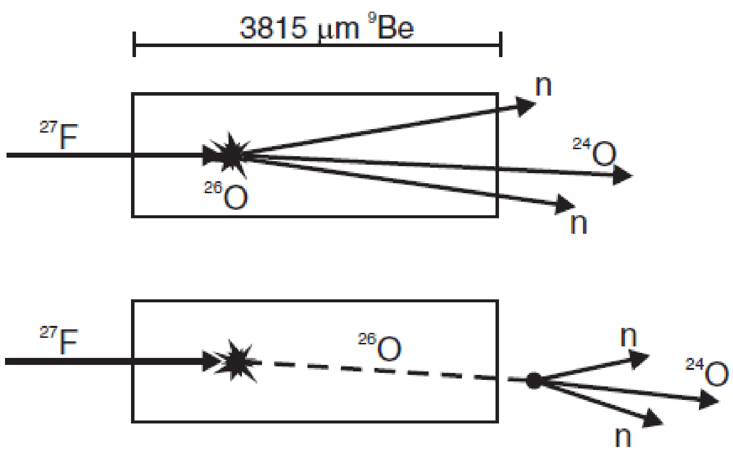
National Science Foundation
Gettysburg College

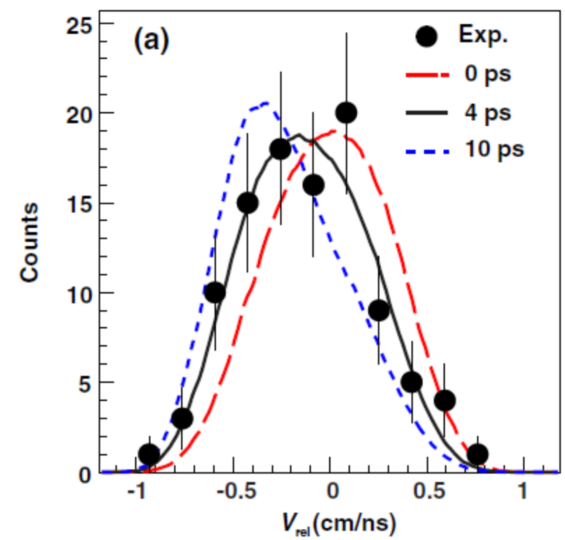
Search for Neutron Radioactivity

PRL 110, 152501 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

Study of Two-Neutron Radioactivity in the Decay of ^{26}O

Z. Kohley,[1,2,*] T. Baumann,[1] D. Bazin,[1] G. Christian,[1,3] P. A. DeYoung,[4] J. E. Finck,[5] N. Frank,[6] M. Jones,[1,3] E. Lunderberg,[4] B. Luther,[7] S. Mosby,[1,3] T. Nagi,[4] J. K. Smith,[1,3] J. Snyder,[1,3] A. Spyrou,[1,3] and M. Thoennessen[1,3]

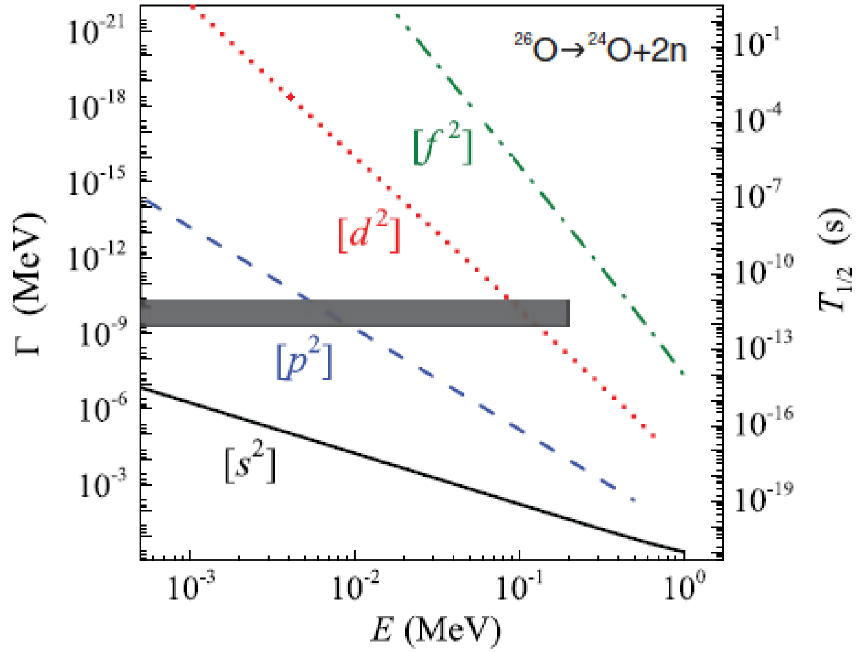


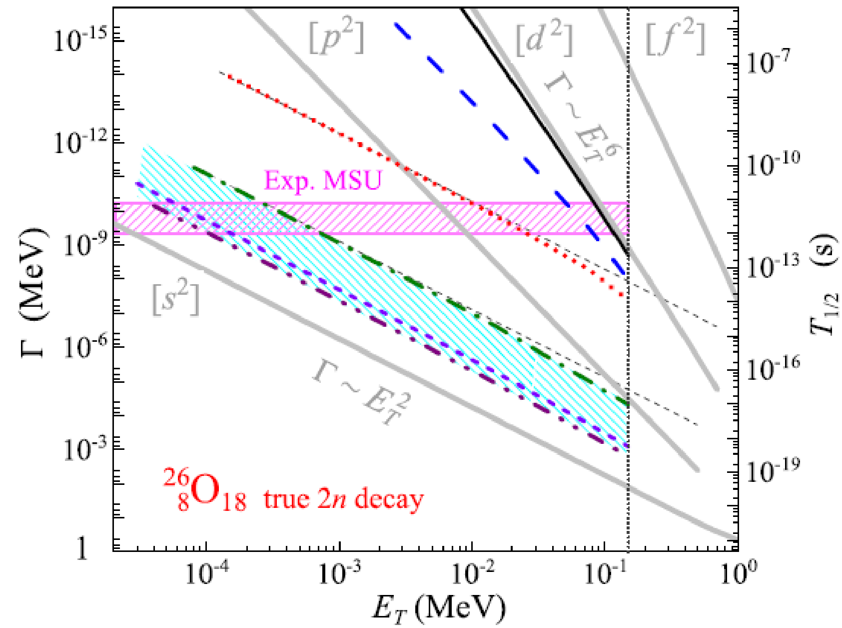


"The half-life of ^{26}O was extracted as $4.5^{+1.1}_{-1.5}$ (stat)±3(syst) ps"

National Science Foundation
Michigan State University

Decay-energy versus life-time





Experiment: $E_d < 200$ keV

Theory: $E_d = 100$ keV ↔ $T_{1/2} \approx 10^{-11}$ ps

$E_d = 600$ keV ↔ $T_{1/2} \approx 10^{-16}$ ps

"An upper limit of ~1 keV for the decay energy of the unbound ^{26}O is inferred based on the recent experimental lifetime value."

Z. Kohley et al., Phys. Rev. Lett. 110 (2013) 152501

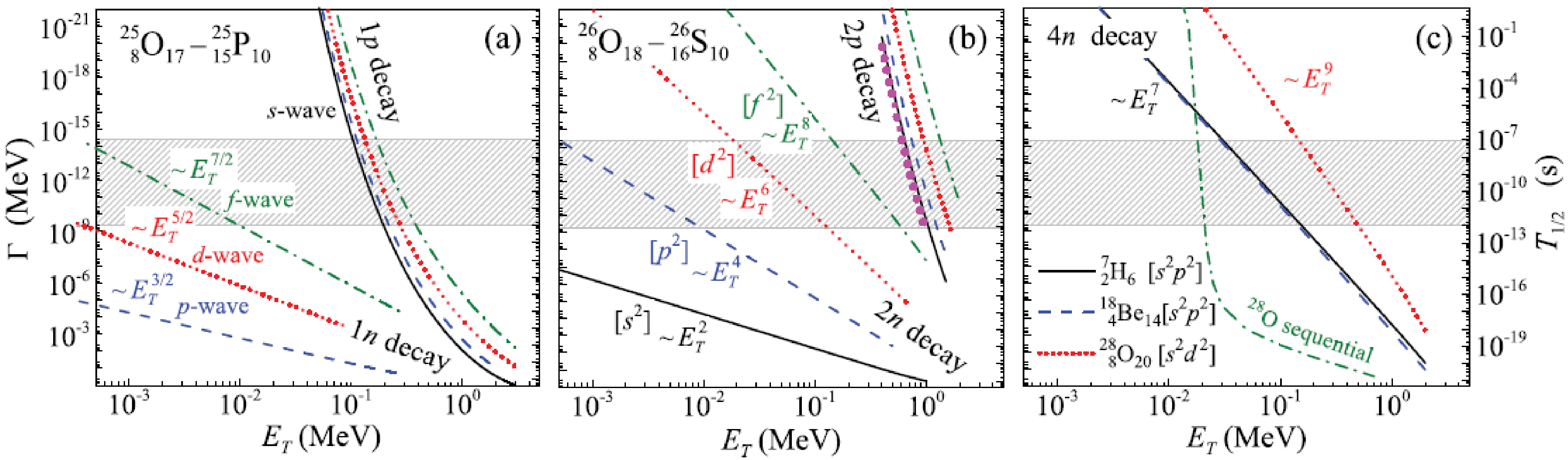
E. Lunderberg et al., Phys. Rev. Lett. 108 (2012) 142503

L.V. Grigorenko et al., Phys. Rev. C 84 (2011) 021303

L.V. Grigorenko et al., Phys. Rev. Lett. 111 (2013) 042501

Future possible cases…

With FRIB, MoNA-LISA and the HRS studies of isotopes beyond the dripline will be extended into the *pf*-shell



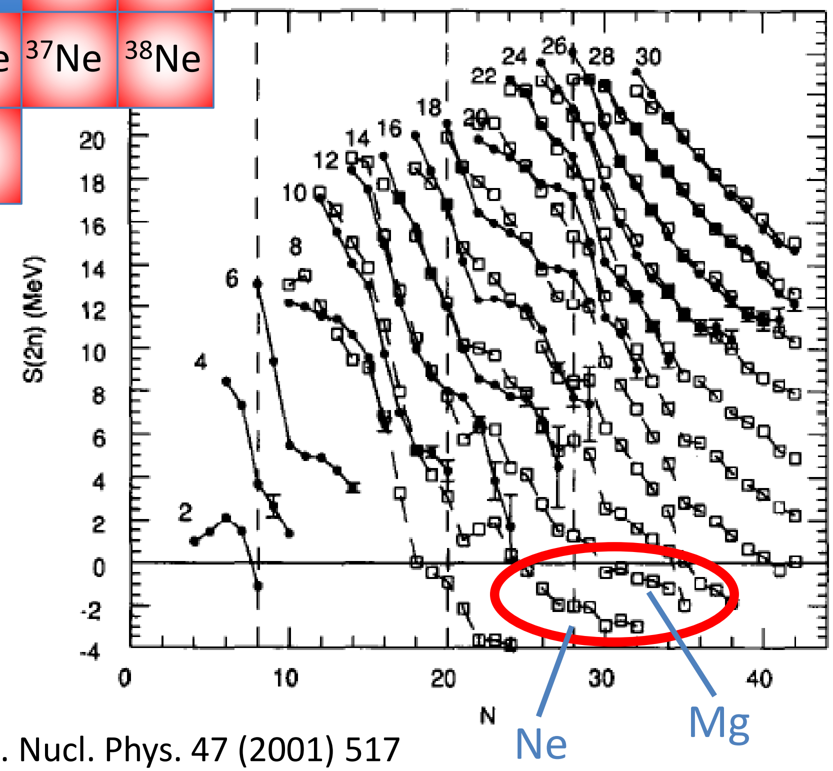
- Finite lifetimes for single neutron emitters are still unlikely
- Other two-neutron emitters could be possible in the 100 keV range
- How about four-neutron emitters?

L.V. Grigorenko et al., Phys. Rev. C 84 (2011) 021303

Beyond the dripline in the *pf*-shell

^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al	^{37}Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al	^{42}Al
^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg	^{36}Mg	^{37}Mg	^{38}Mg	^{39}Mg	^{40}Mg	^{41}Mg
^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na	^{35}Na	^{36}Na	^{37}Na	^{38}Na	^{39}Na	
^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne	^{33}Ne	^{34}Ne	^{35}Ne	^{36}Ne	^{37}Ne	^{38}Ne	
^{26}F	^{27}F	^{28}F	^{29}F	^{30}F	^{31}F	^{32}F	^{33}F	^{34}F	^{35}F			

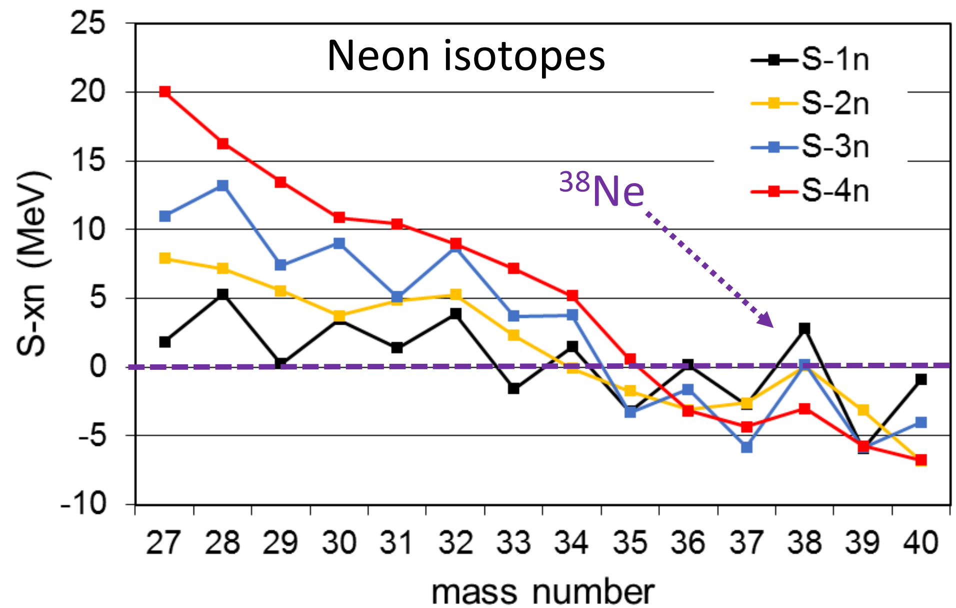
- The single particle energies within the $f_{7/2+}$ orbit change very little with increasing neutron number
- The separation energies stay almost constant
- Potential for several neutron unbound isotopes with low decay energy



B.A. Brown, Prog. Part. Nucl. Phys. 47 (2001) 517

Four-neutron emitter

- The FRDM predicts ^{38}Ne and ^{44}Mg to be direct four neutron emitters
- They are bound with respect to 1-, 2-, and 3-neutron emission but unbound with respect 4-neutron emission



Conclusion: Isotopes beyond the neutron dripline within the *pf*-shell offer a large discovery potential which can be explored with FRIB, MoNA-LISA and the HRS.

High Precision Hypernuclear Spectroscopy at JLab

Liguang Tang, Hampton University for

The JLab Hypernuclear Physics Collaboration

A. Acha,[7] P. Achenbach,[8] A. Ahmidouch,[9] I. Albayrak,[5] P. Ambrozewicz,[7] D. Androic,[4] K.A. Aniol,[31] A. Asaturyan,[10] R. Asaturyan,[10], y O. Ates,[1] R. Badui,[7] O. K. Baker,[1] **P. Baturin**,[7] H. Benaoum,[33] F. Benmokhtar,[11] P.Y. Bertin,[32] K. I. Blomqvist,[34] W. Boeglin,[7] J. Bono,[7] P. Bosted,[2] E. Brash,[12] H. Breuer,[35] P. Brindza,[2] P. Bydžovsky,[36] A. Camsonne,[32] P. Carter,[12] R. Carlini,[2] C. C. Chang,[35] **C. Chen**,[1] J.-P. Chen,[2] A. Chiba,[3] Seonho Choi,[37] M. Christy,[1] E.A. Chudakov,[2] E. Cisbani,[15] L. Cole,[1] S. Colilli,[15] **L. Coman**,[7] B. J. Craver,[38] **F. Cusanno**,[30] M. Dalton,[2] S. Danagoulian,[9] A. Daniel,[5] G. De Cataldo,[28] C.W. de Jager,[2] R. De Leo,[28] A.P. Deur,[38] V. Dharmawardane,[2] D. Doi,[3] K. Egiyan,[10] M. Elaasar,[13] R. Ent,[2] H. Fenker,[2] C. Ferdi,[32] R. J. Feuerbach,[2] E. Folts,[2] R. Fratoni,[15] S. Frullani,[15] Y. Fujii,[3] M. Furic,[4] M. Gabrielyan,[7] L. Gan,[14] **F. Garibaldi**,[15] D. Gaskell,[2] A. Gasparian,[9] O. Gayou,[39] E. F. Gibson,[16] F. Giulani,[15] **T. Gogami**,[3] J. Gomez,[2] M. Gricia,[15] P. Gueye,[1] Y. Han,[1] J. O. Hansen,[2] O. Hashimoto,[3] D. Hayes,[40] D.W. Higinbotham [2] E. Hiyama,[57] T. K. Holmstrom,[41] D. Honda,[3] T. Horn,[2, 11] B. Hu,[17] Ed V. Hungerford,[5] C. E. Hyde,[40,32] H. F. Ibrahim,[40] M. Iodice,[29] C. Jayalath,[1] X. Jiang,[42] M. Jones,[2] K. Johnston,[18] N. Kalantarians,[5] H. Kanda,[3] M. Kaneta,[3] F. Kato,[3] S. Kato,[19] L. J. Kaufman,[43] M. Kawai,[3] **D. Kawama**,[3] C. Keppel,[1] H. Khanal,[7] K. Kino,[44] M. Kohl,[1] L. Kramer,[7] B. Kross,[2] K. J. Lan,[5] L. Lagamba,[28] J. J. LeRose,[2] Y. Li,[1] R. A. Lindgren,[38] A. Liyanage,[1] M. Lucentini,[15] W. Luo,[17] D. Mack,[2] K. Maeda,[3] S. Malace,[1] A. Margaryan,[10] D. J. Margaziotis,[31] G. Marikyan,[10] **P. Markowitz**,[7] S. Marrone,[28] T. Maruta,[3] N. Maruyama,[3] **A. Matsumura**,[3] V. Maxwell,[2] K. McCormick,[28] Z. E. Meziani,[37] R.W. Michaels,[2] D.J. Millener,[20] **T. Miyoshi**,[5] A. Mkrtchyan,[10] H. Mkrtchyan,[10] B. Moffit,[41] P. A. Monaghan,[39] M. Moteabbed,[7] T. Motoba,[21, 22] C. Munoz Camacho,[45] S. Nagao,[3] **S. N. Nakamura**,[3] S. Nanda,[2] E. Nappi,[28] A. Narayan,[23] V.V. Nelyubin,[38] C. Neville,[7] G. Niculescu,[24] M. I. Niculescu,[24] B. E. Norum,[38] A. Nunez,[7] Nuruzzaman,[23] H. Nomura,[3] K. Nonaka,[3] A. Ohtani,[3] **Y. Okayasu**,[3] M. Oyamada,[3] K. D. Paschke,[39] C. F. Perdrisat,[41] N. Perez,[7] T. Petkovic,[4] E. Piasetzky,[46] J. Pochodzalla,[8] V. A. Punjabi,[47] Y. Qiang,[39] **X. Qiu**,[17] S. Randeniya,[5] B. Raue,[7] P. E. Reimer,[48] **J. Reinhold**,[7] B. Reitz,[2] R. Rivera,[7] J. Roche,[49] **V. M. Rodriguez**,[5, 6] A. Saha,[2] C. Samanta,[25] F. Santavenere,[15] **M. Sarsour**,[5] A. J. Sarty,[50] Y. Sato,[26] B. Sawatzky,[2] J. Segal,[2] E. K. Segbefia,[1] **T. Seva**,[4] D. Schott,[7] A. Shahinyan,[10] A. Shichijo,[3] N. Simicevic,[18] J. Singh,[38] S. Širca,[51] G. Smith,[2] R. Snyder,[38] P. H. Solvignon,[37] Y. Song,[17] M. Sotona,[36] R. Subedi,[52] V. A. Sulkosky,[41] M. Sumihama,[3] T. Suzuki,[3] V. Tadevosyan,[10] T. Takahashi,[3] H. Tamura,[3] **L. Tang**,[1, 2] N. Taniya,[3] K. Tsukada,[3] V. Tvaskis,[1] H. Ueno,[53] P. E. Ulmer,[40] G. M. Urciuoli,[30] M. Veilleux,[12] P. Veneroni,[15] E. Voutier,[54] W. Vulcan,[2] S. Wells,[18] F. R. Wesselmann,[27] B. B. Wojtsekhowski,[2] S. A. Wood,[2] T. Yamamoto,[3] C. Yan,[2] Y. Ye,[55] Z. Ye,[1] K. Yokota,[3] **L. Yuan**,[1] S. Zhamkochyan,[10] X. Zheng,[48] S. Zhou,[56] L. Zhu,[1] C. Zorn,[2]

60 graduate students (**15 awarded Ph.D.**) and 15 postdoctoral fellows

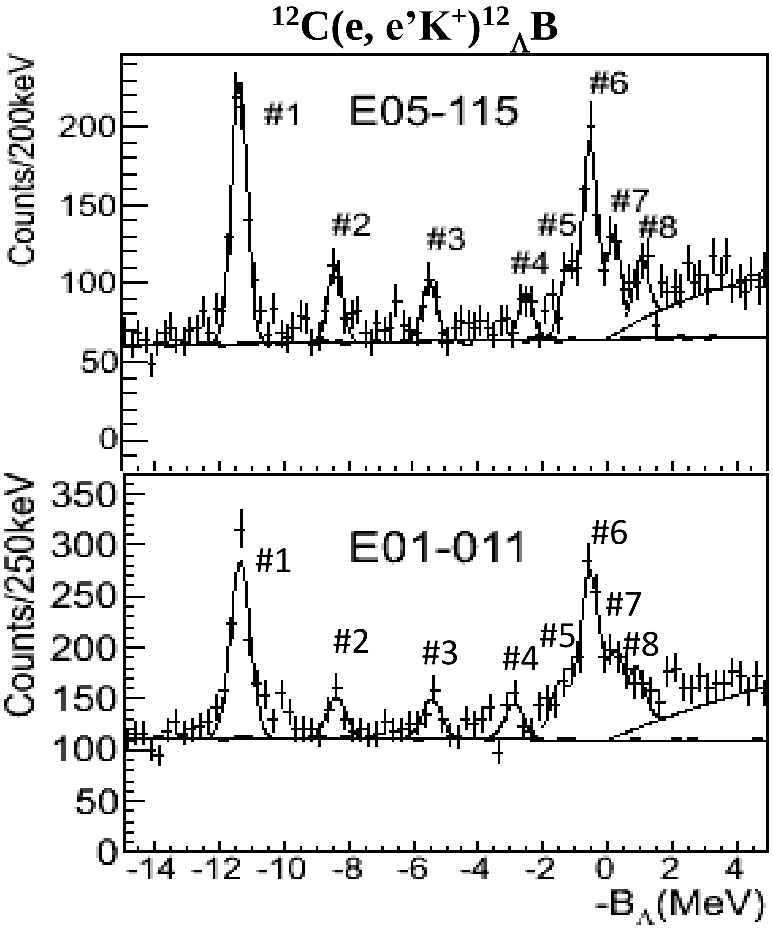
[1]Hampton University, USA, [2]JLab,USA, [3]Tohoku University, Japan, [4]University of Zagreb, Croatia, [5]University of Houston, USA, [6]Universidad Metropolitana, Puerto Rico, [7]Florida International University, USA, [8]Johannes Gutenberg-University, Germany, [9]North Carolina A&T State University, USA, [10]Yerevan Physics Institute, Armenia, [11]University of Maryland, USA, [12]Christopher Newport University, USA,[13]Southern University at New Orleans, USA, [14]University of North Carolina Wilmington, USA, [15]INFN, gruppo collegato Sanità, and Istituto Superiore di Sanità, Italy, [16] California State University, USA, [17]Lanzhou University, China, [18]Louisiana Tech University, USA, [19]Yamagata University, Japan, [20]Brookhaven National Laboratory, USA,[21]Osaka Electro-Communication University, Japan, [22]Kyoto University, Japan, [23]Mississippi State University, USA,[24]James Madison University, USA, [25]Virginia Military Institute, USA, [26]Institute of Particle and Nuclear Studies (KEK), Japan, [27]Xavier University of Louisiana, USA, [28]INFN and University of Bari, Italy, [29]INFN, Sezione di Roma Tre, Italy, [30]I NFN, Sezione di Roma1, Italy, [31]California State University, USA, [32]Universite´ Blaise Pascal/IN2P3, France, [33]Syracuse University, USA, [34]Universita¨t Mainz, Germany, [35]University of Maryland, USA,[36]Nuclear Physics Institute, Řež, near Prague, Czech Republic, [37]Temple University, USA, [38]University of Virginia, USA, [39]Massachussets Institute of Technology, USA, [40]Old Dominion University, USA, [41]College of William and Mary, USA, [42]Rutgers, the State University of New Jersey, USA, [43]University of Massachusetts Amherst, USA,[44]Osaka University, Japan, [45]CEA Saclay, France, [46]Tel Aviv University, Israel, [47]Norfolk State University, USA,[48]Argonne National Laboratory, USA, [49]Florida State University, USA, [50]St. Mary's University, Canada,[51]University of Ljubljana, Slovenia, [52]Kent State University, USA, [53]Yamagata University, Japan, [54]LPSC, Universite´ Joseph Fourier, France, [55]University of Science and Technology of China, China, [56]China Institute of Atomic Energy, China, [57]Institute of Physical and Chemical Research (RIKEN), Japan

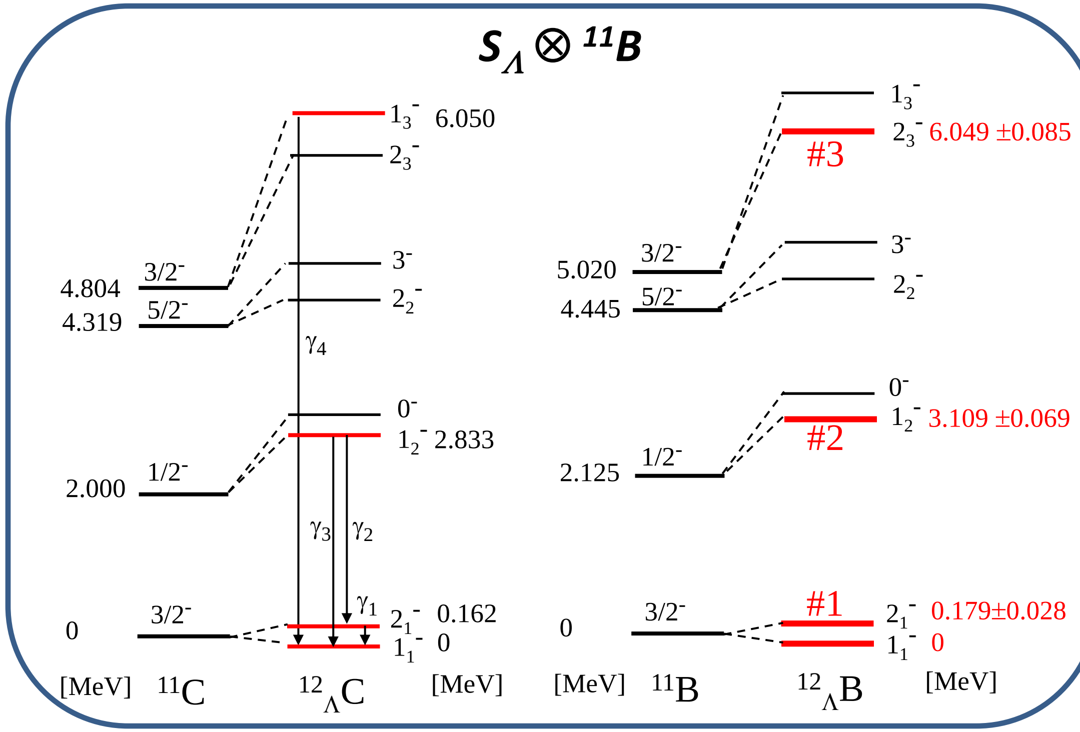
57 Institutes from 10 countries

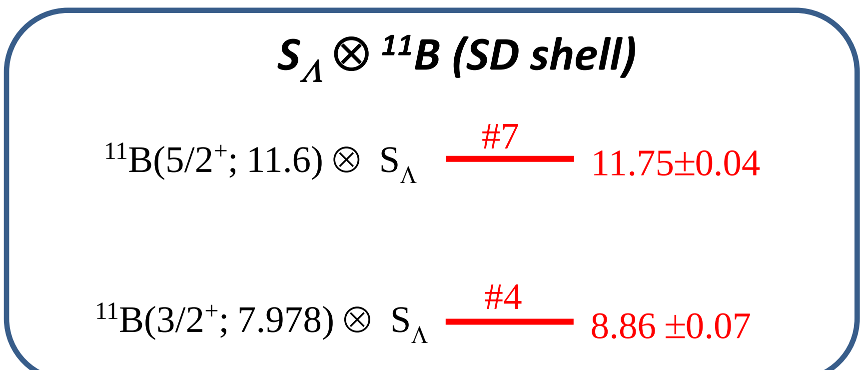
Hypernuclear Physics

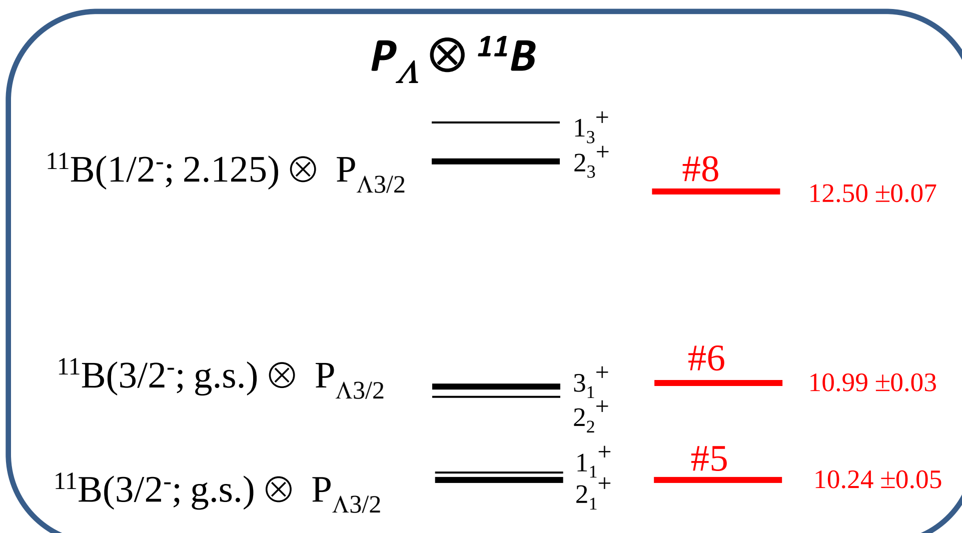
- Baryonic interactions and many body baryonic system
  – Primary effort of nuclear physics
- New flavor in SU(3): *YN* and *YY*
- Important linkage to Astrophysics: neutron stars, hyperon matter, …
- Short range baryonic interactions: ΛN - ΛN
- Baryonic structure of the nuclear medium probed by Λ
- Λ-Σ coupling: Charge Symmetry Breaking (CSB) and 3BF(ΛNN)
- Past: Hypernuclear Program at JLab (a hadron physics facility):
  - Proven the feasibility and technique of electro-production
  - Achieved the highest possible precision in mass spectroscopy
    ($\delta E \sim 500$ keV FWHM and $\delta B_{\Lambda} < \pm 100$ keV) – Unique
  - Studied the spectroscopy of a sequence of Λ-hypernuclei:
    $^{7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{10}_{\Lambda}$Be, $^{12}_{\Lambda}$B, $^{16}_{\Lambda}$N, $^{28}_{\Lambda}$Al, and $^{52}_{\Lambda}$V – the only new results exist in the past decade and near future

Example: Precision $^{12}{}_{\Lambda}B$ Spectroscopy and Shell Model

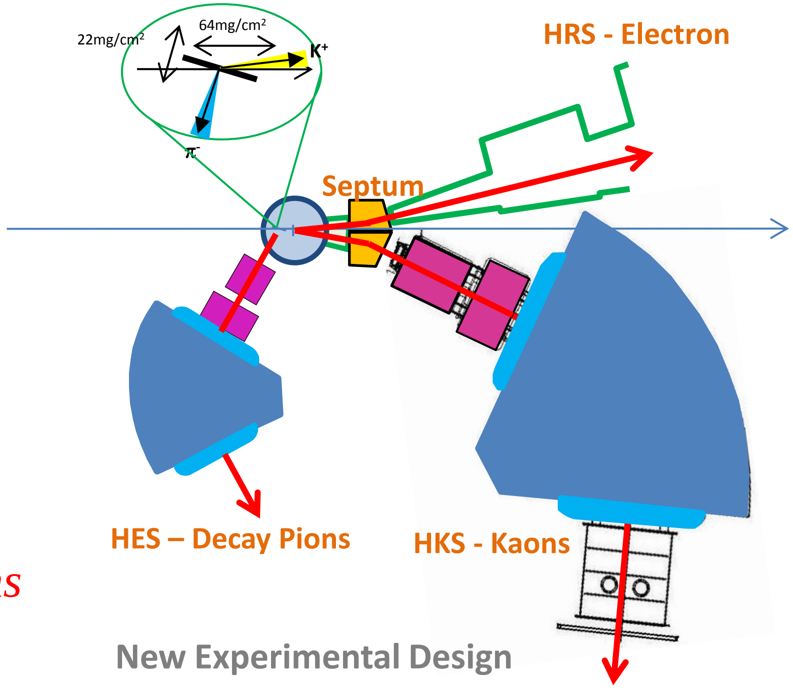








Future: Program on Hypernuclear Spectroscopy



Technical Features:

- High precision and high yield
  (δE ~ 600 keV FWHM and δB_Λ ~ ±50 keV)
- "Free" of accidental background
- All major equipment already exist

Physics:

- Few body
  Charge Symmetry Breaking (CSB) in ΛN interactions
- Medium heavy hypernuclei
  LS force; shell model on baryonic many-body system;
  structure or deformation of the core nuclei probed by Λ
- Heavy hypernuclei (A~200) – precise B_Λ and level spacing
  Importance of 3B/4B forces; many body vs QCD descriptions
- Decay pion spectroscopy (Ground state of light hypernuclei; δE ~ 130 keV & δB_Λ ~ ±20 keV)
  ΛN interactions; CSB; Λ-Σ coupling; drip line hypernuclei ($^{6}_{\Lambda}H$)

Hypernuclear Physics Programs and Facilities

JLAB program plays a unique role in the global effort on the strangeness nuclear physics

JLAB
Electroproduction

- Λ hypernuclei (few-body to heavy)
- High precision mass spectroscopy and precise B_{Λ} determination
- *The only facility at the moment and near future*

J-PARC
Hadronic production

- γ spectroscopy of Λ hypernuclei
- S = -2 Ξ and ΛΛ hypernuclei
- Kaonic nuclei ($K^{-}NNN$, …)

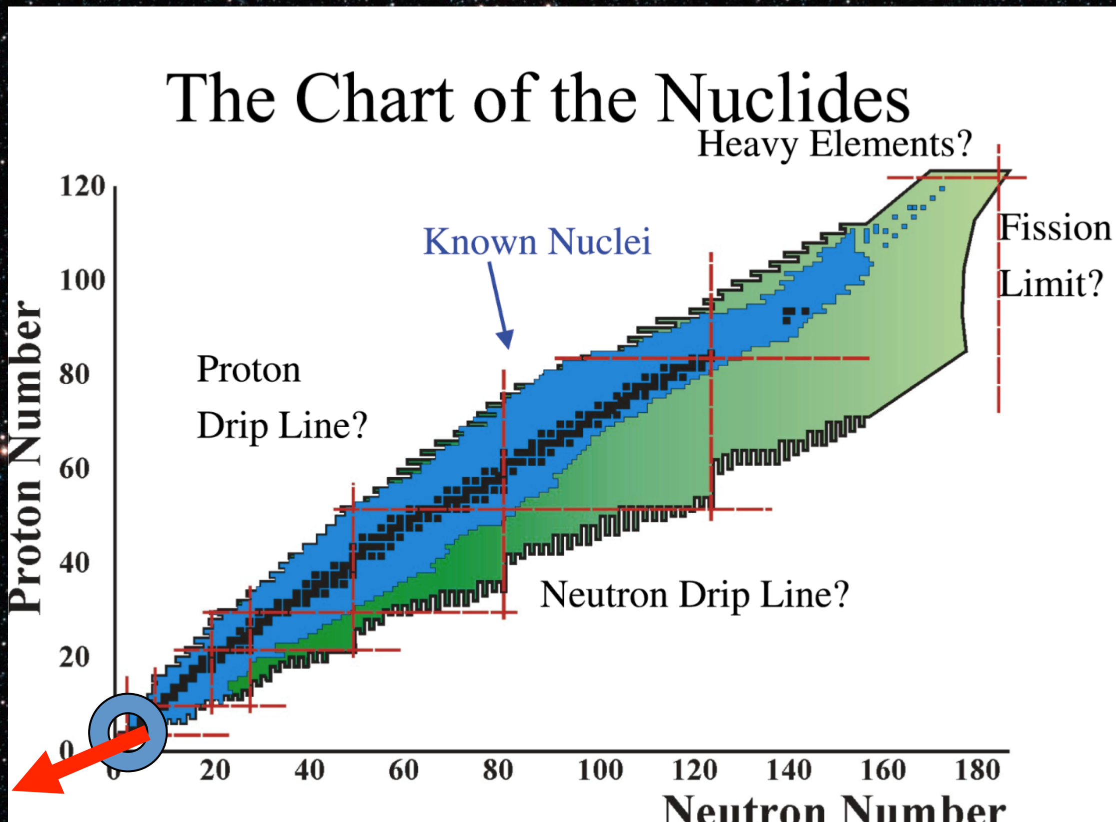
MAMI
Decay pion spectroscopy

- Ground state of light Λ hypernuclei
- Precise B_{Λ} on the ground state

PANDA @ Fair
Heavy Ion Collision

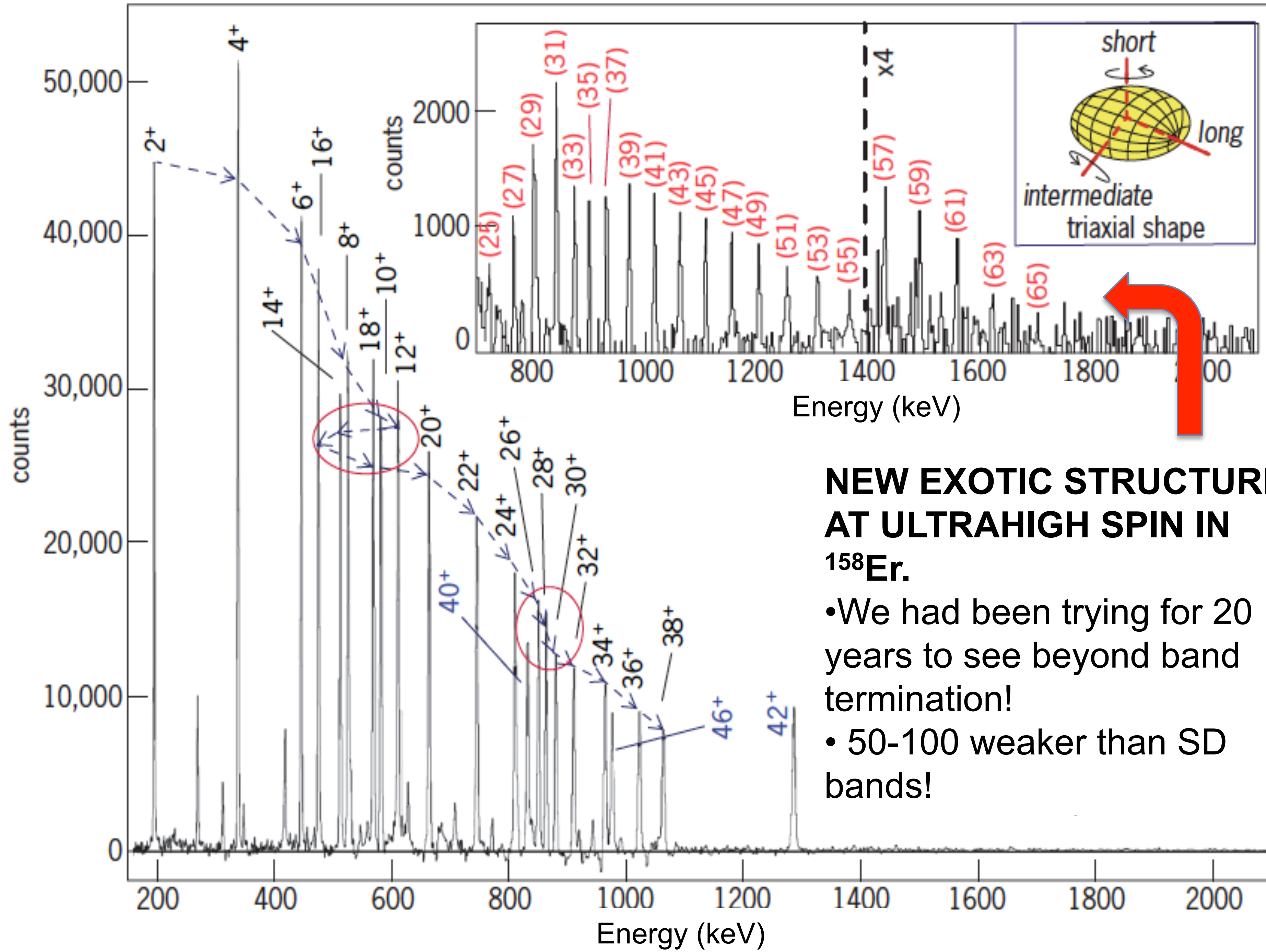
- Multi-strangeness
- Extreme p and n numbers
- Anti-hypernuclei
- Charm-hypernuclei

NUCLEI AT THE EXTREMES:
AT THE LIMITS OF ANGULAR MOMENTUM



Increasing Angular Momentum and Excitation Energy:

This is an excellent way to investigate nuclear structure. Remember these studies are ultra-sensitive to what the intruder shells are doing!

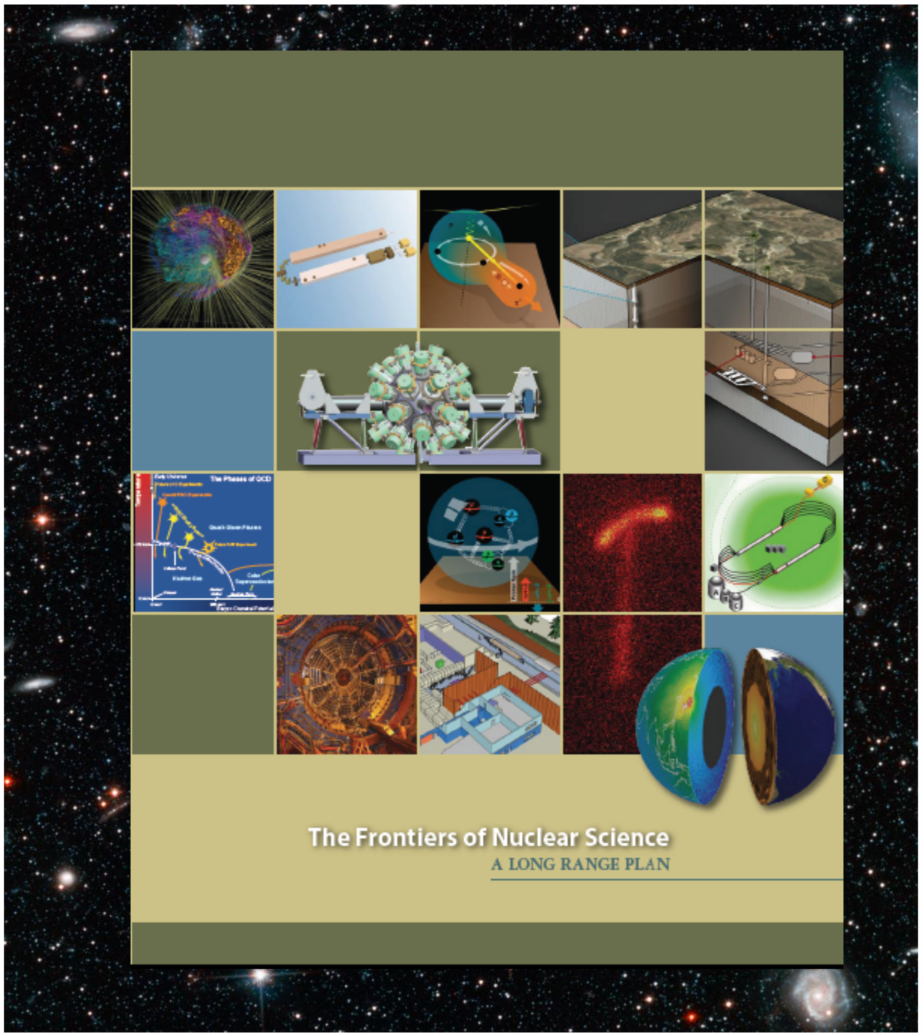


NEW EXOTIC STRUCTURE AT ULTRAHIGH SPIN IN ^{158}Er.

- We had been trying for 20 years to see beyond band termination!
- 50-100 weaker than SD bands!

RECENT ACHIEVEMENTS

Here we list several key achievements made since the last Long Range Plan. They have produced new insights into nuclear structure and nuclear astrophysics, and they highlight the increasingly strong research overlap between the physics of nuclei and nuclear astrophysics.



2007 LRP
8 topics chosen

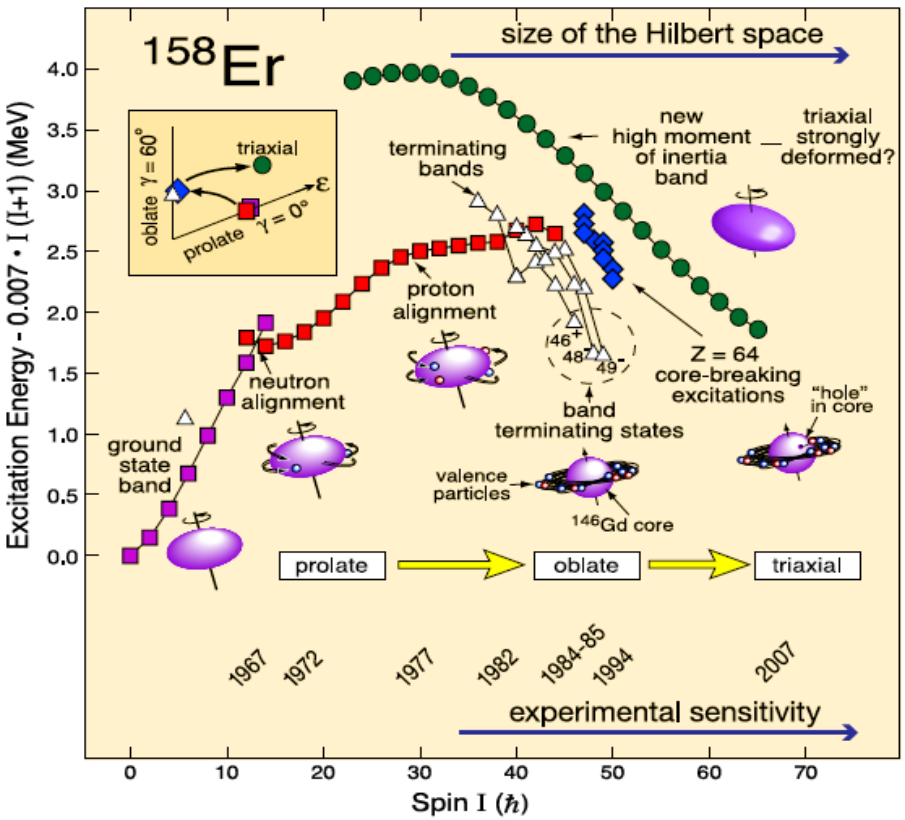
The physics and chemistry of superheavy elements. We continue to move closer to the predicted superheavy island of stability. Synthesis of superheavy elements up to Z = 118 in fusion reactions was reported, and the chemical properties of elements up to Z = 112 have been studied. In elements with Z = 100–102, energies of isomeric states provided new probes of higher-lying shells, the very shells governing the stability of superheavy nuclei.

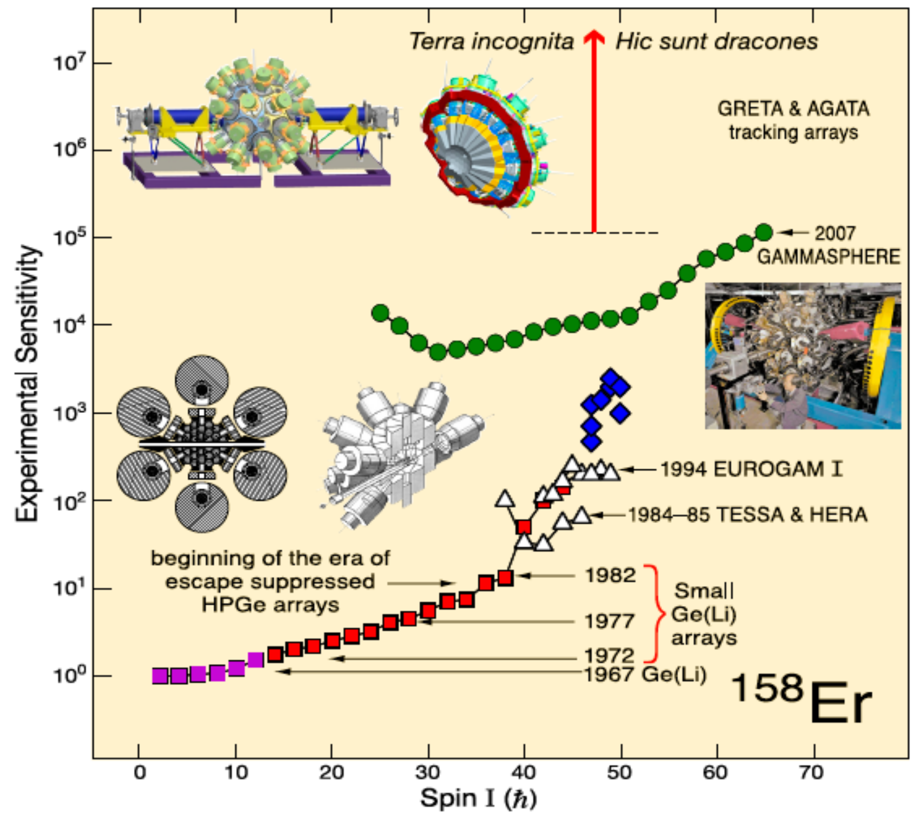
- **Collective behavior and symmetries.** Measurements of nuclei in shape transitional regions, near N = 90 and elsewhere, led to an interpretation in terms of quantum phase transitional behavior between different symmetries. A new class of many-body symmetries describing nuclei at the phase transitional point was developed. Pushing the limit of extreme nuclear spin, rotational behavior was discovered at high spins in $^{157,158}Er$, beyond the angular momenta at which many rotational bands terminate, challenging microscopic descriptions of collectivity.

Evolution of Gamma-Ray Spectroscopy and ^{158}Er

(NRC/Nat. Acad. Sci. Decadal Report June 2012, p 49
Nuclear Physics: The Heart of Matter)

NEW INSTRUMENTATION = NEW PHYSICS!





After decades of trying to go beyond Band Termination (I~50)

The return of collectivity at ultra-high spin in ^{158}Er

(Paul *et al.*, Phys.Rev.Lett. 98, 012501, 2007)

The Excitement has Continued and Increased since then!

Quadrupole moment measurements a ***complete surprise***!!

(Wang *et al*., Phys. Lett. B 702, 127, 2011)

[FSU, Daresbury,Liverpool, ANL, LBNL, USNA, UTK, ND, iTHEMBA, Lund]

Lots of theoretical interest: Robust triaxial shapes, tilted-axis cranking, large deformations, spins close to fission limit

Shi *et al*., PRL 108,09250, 2012

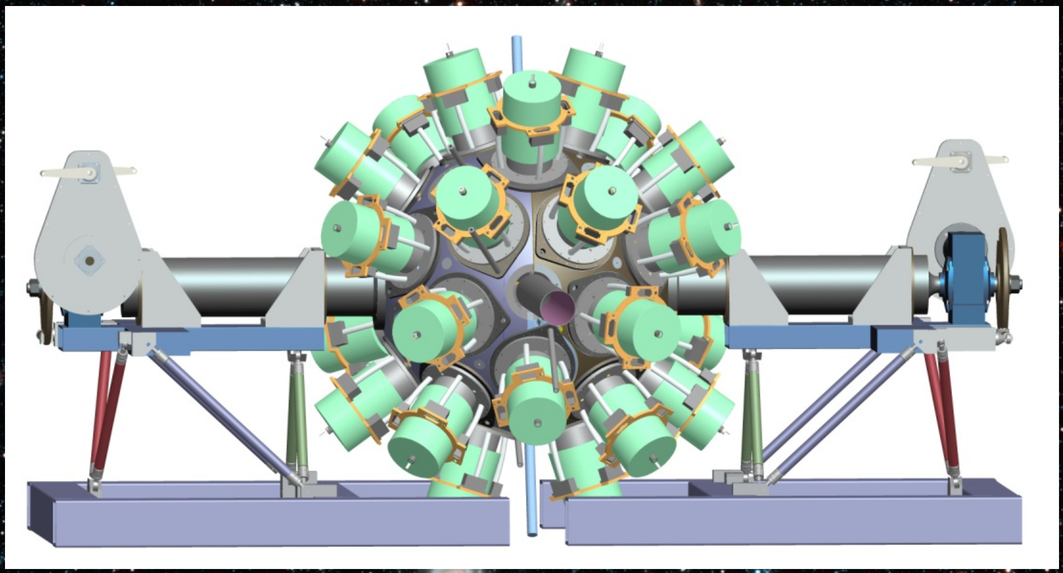
Kardan *et al*., PRC 86, 014309, 2012

Afanasjev, Shi, Nazarewicz, PRC 86, 031304 (R) (2012)

If the theoretical spin assignments of Fig. 4 turned out to be correct, the experimental band 1 in ^{158}Er would be the the highest spin structure ever observed. The current study stresses the need for more precise measurements of Q_t and reliable estimates of spins in these bands.

THE FUTURE AND RESOURCES NEEDED

- New exotic shape minimum at ultra-high spins (I~70).
- Fascinating spectroscopy at the limits awaits us.
- To fix the spins and excitation energies, and do complete spectroscopy WE NEED GRETA!
- Also stable beams from ATLAS at ANL.
- And targets from CATS (Nat. Cen. Accel. Targets. Sci.)



Study of ^{218}U: proton shell closure above ^{208}Pb

Near-term goal: Observe the low-spin states in this N = 126 nucleus at the upper end of the $\pi h_{9/2}$ shell

Scenarios:

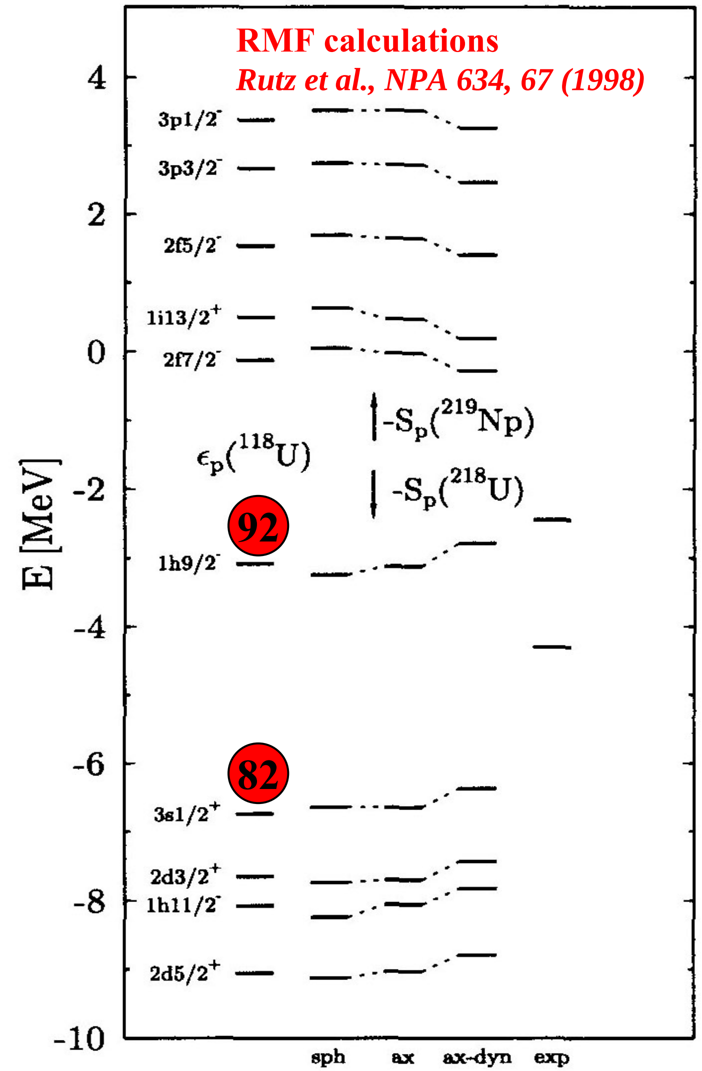
- ^{208}Pb-like behavior (2^+, 3^- change position)
- Seniority-type sequence like ^{216}Th (8^+ isomer)

Options for experiments:

1. Fusion-evaporation ($\sigma_{ER} \gtrsim 1$ nb) RDT run
   Gretina/Gammasphere + AGFA
2. Pre-FRIB ^{218}U Coulex run
   Gretina + particle detector + S800

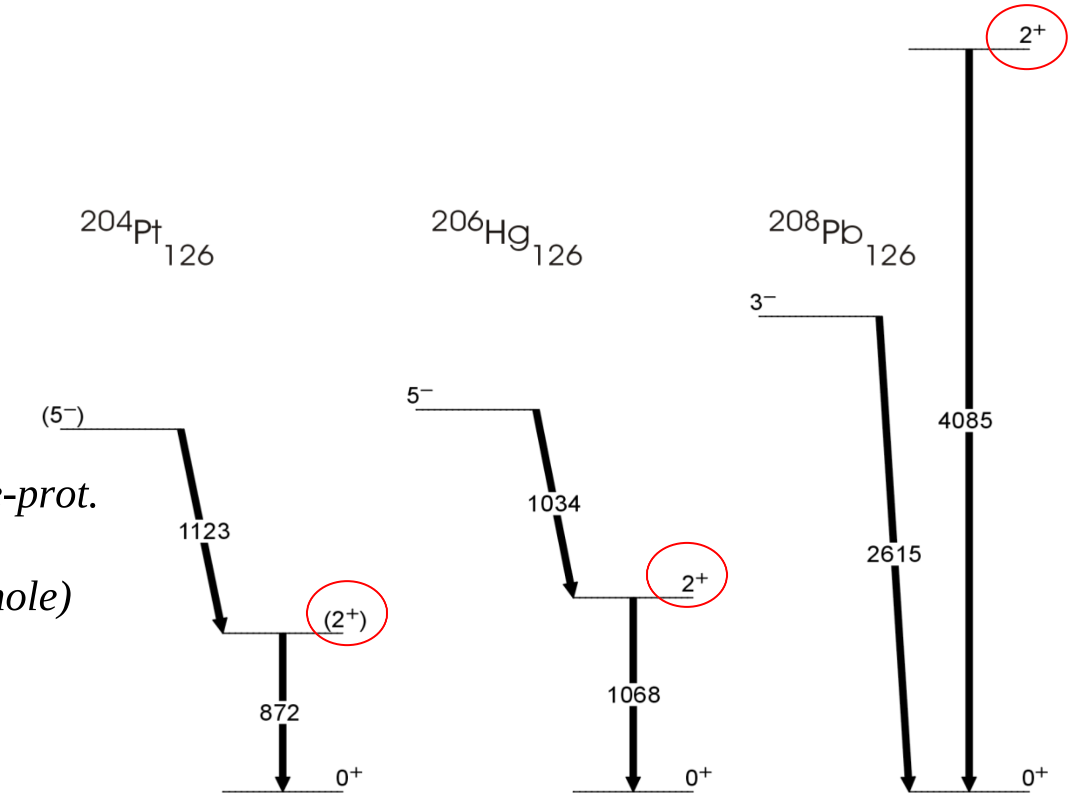
Far-term goal: Measure B(E2) and B(E3) (or B[E1]) FRIB Coulex experiment

Factors that likely affect the Z= 92 gap:
- **octupole correlations: alter $\pi 2f_{7/2}$ level**
- **proton pair scattering**



Also: Afanasjev & Frauendorf PRC 71, 024308 (2005)

What if 2^+ and 3^- change position at the sub-shell closure?



single-prot. state ($h_{1/2}$ hole)

<u>Exaggerated example:</u> *possible change between ^{216}Th and ^{218}U in the in the low-spin region (perhaps ^{208}Pb like)*

No E1/E3 competition (not like in ^{216}Th)!

Possible change of decay pattern for even-spin states!

Prompt spectroscopy gains in importance over delayed spectroscopy!

Impact of 3^- state: description of nearby odd-mass nuclei (particle-core coupling).

Outline of ^{218}U RDT experiment

Use Leppanen's reaction*: **^{40}Ar + ^{182}W → ^{218}U + 4n** ; E_{lab}=184 MeV (mid-tgt.).

σ_{ER}=1.2 nb; do excitation function.

Tag on g.s. α decay: $t_{1/2}$ = 6 ms.

Need to run fast: ≥ 50 pnA; need GRETINA or Digital Gammasphere.

Educated guess for AGFA transmission: ≥ 50%; experiment is doable.

ToF=890 ns (4.8 m); this helps if isomeric transitions are present (if ^{216}Th-like).

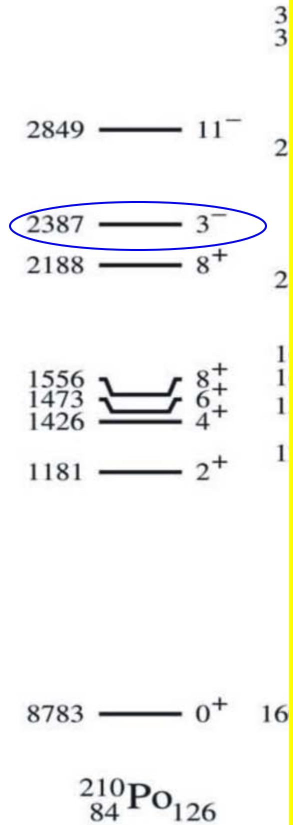
But, an additional Ge setup at the focal-plane is desirable.

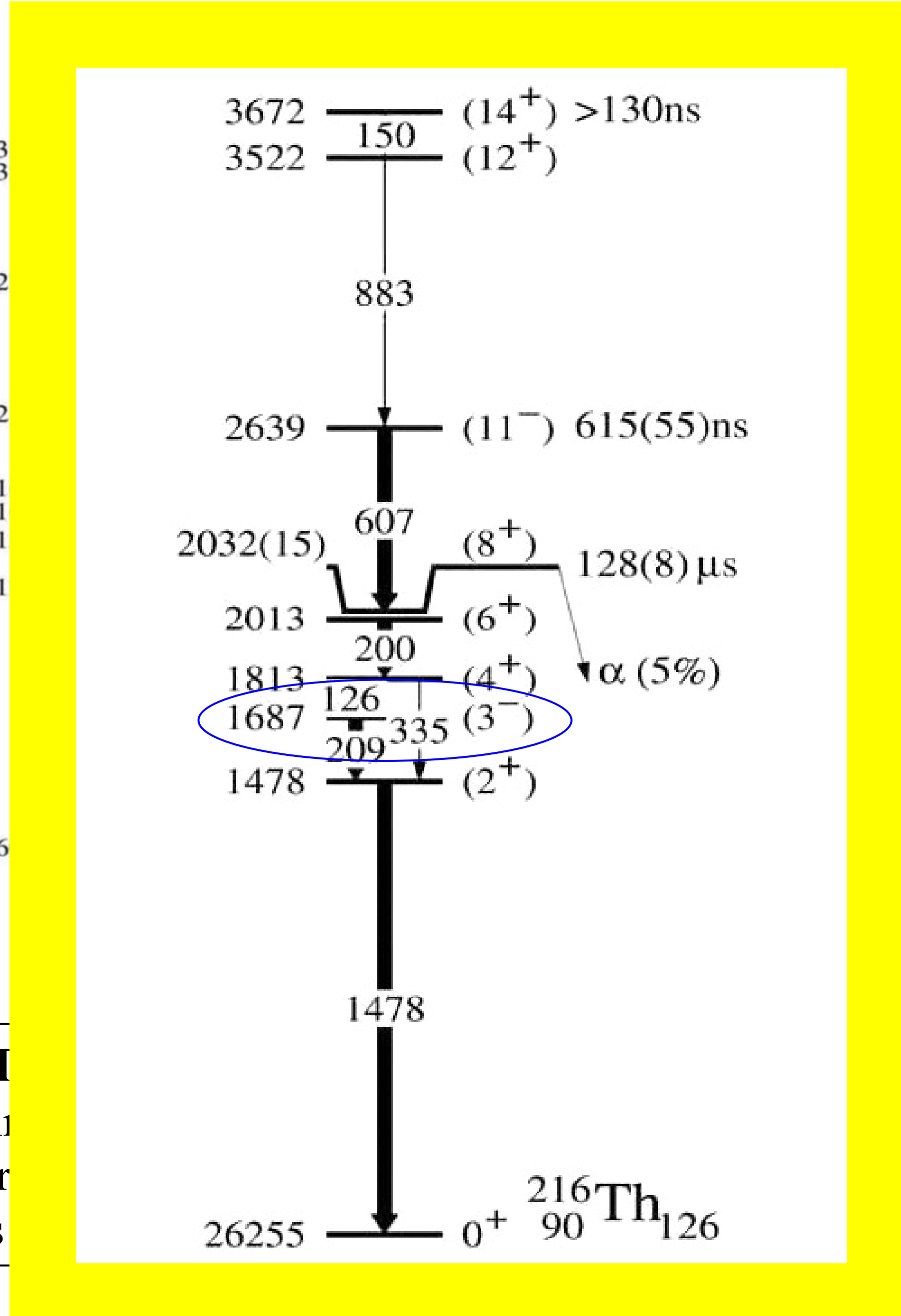
However, the main objective is to determine the 2^+ and 3^- states!

Leppanen et al. PRC 75, 054307 (2007)

Thanks for your attention!

N=126 mid-shell nuclei





Leppanen et al.
PRC 75, 054307
(2007)

^{216}Th RDT … **7, 2001)**

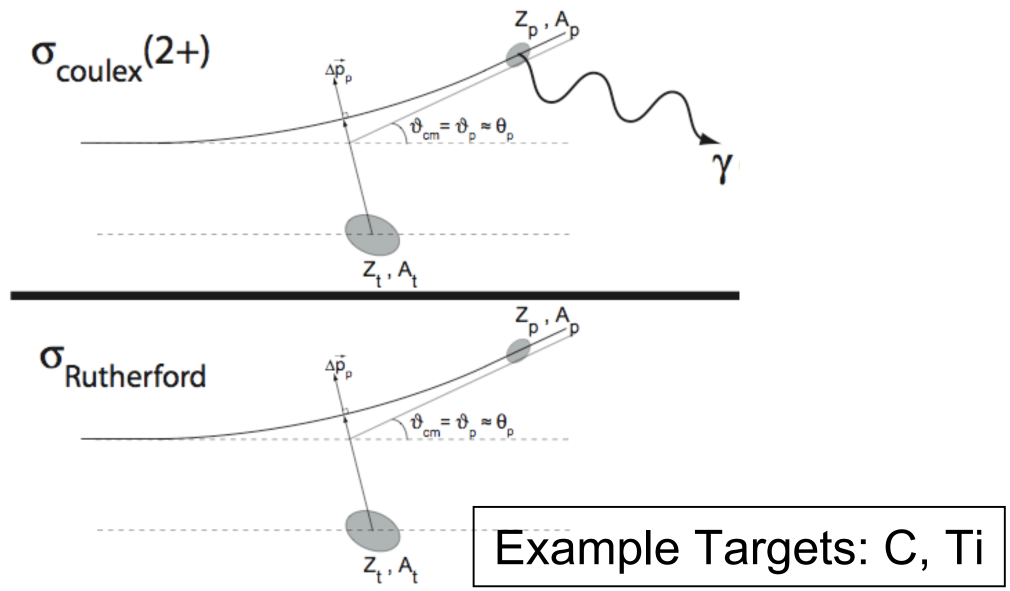
Physics is i… …ut with puzzles:

– us isomer… …gly seen “prompt”

– 3⁻ state is … …g by itself

Structure of Exotic Nuclei by Safe Coulex: Complete Set of 2_1^+ E&M Moments

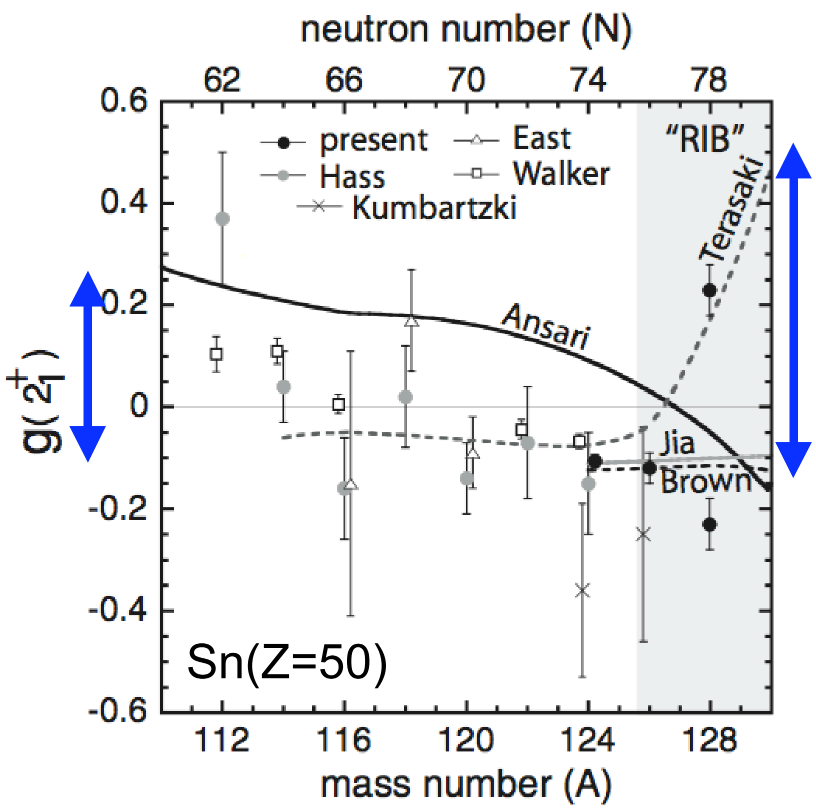
J.M. Allmond
Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831

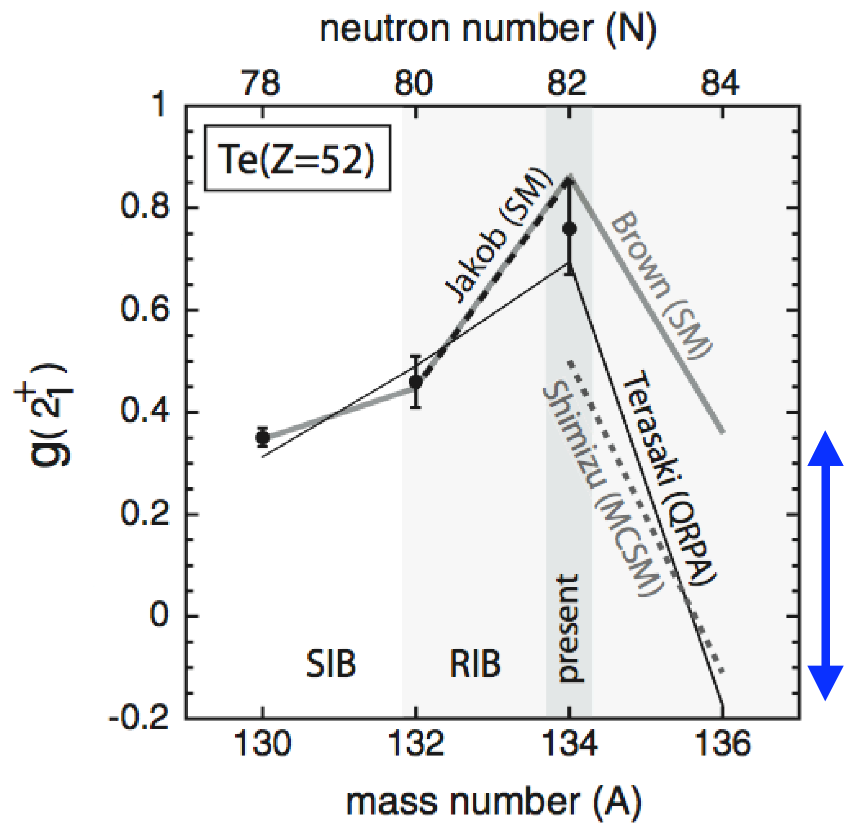


[1] D.C. Radford et al., PRL **88**, 222501 (2002).
[2] N.J. Stone et al., PRL **94**, 192501 (2005).
[3] E. Padilla-Rodal et al., PRL **94**, 122501 (2005).
[4] J.M. Allmond et al., PRC **84**, 061303(R) (2011); PRC **87**, 054325 (2013).
[5] A.E. Stuchbery et al., PRC **88**, 051304(R) (2013).
[6] J.M. Allmond et al., PRC **86**, 031307(R) (2012); PRL **112**, 172701 (2014).

g Factors

sensitive test of wavefunction components



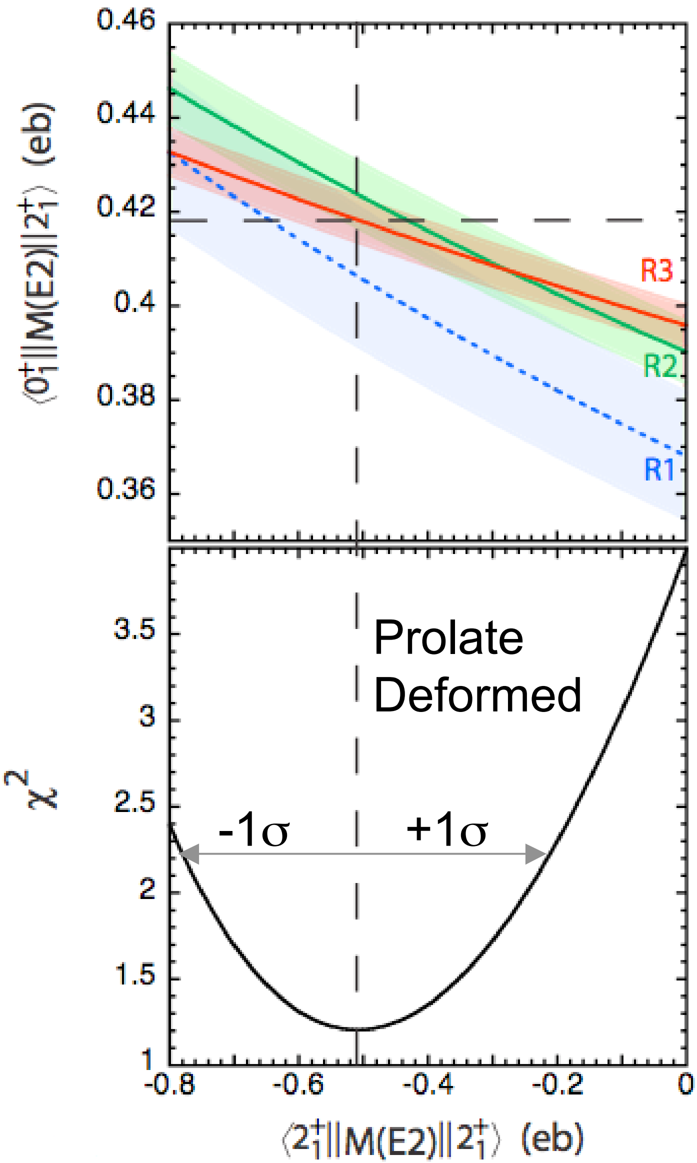


Predictions for B(E2) and Q are often similar but not for g

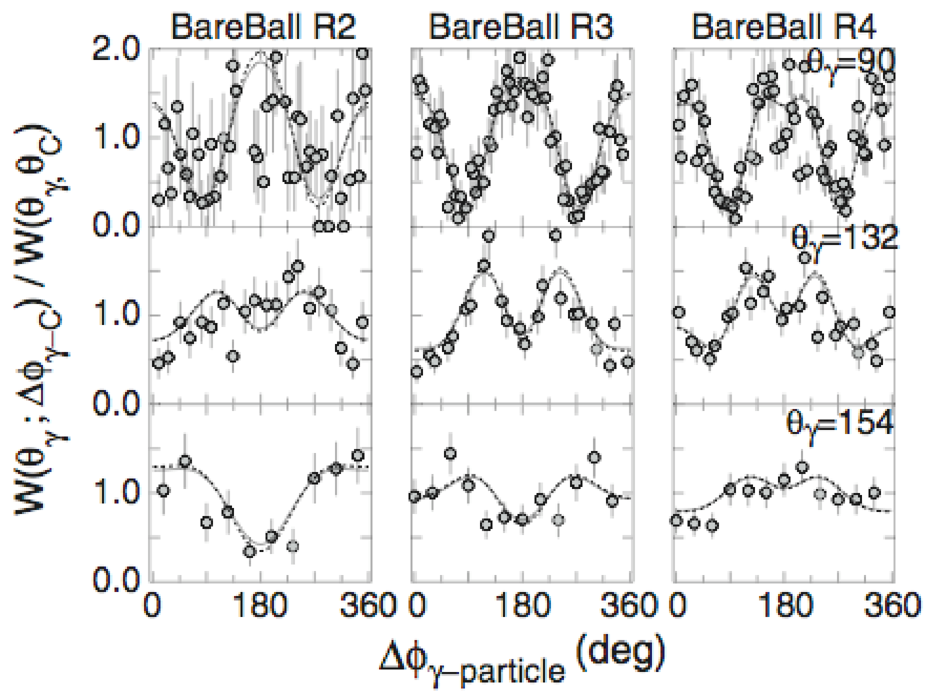
g-factor by RIV can be done using Coulex with B(E2) and Q measurements

Safe Coulex at Back C.M. Angles

Can extract all three E&M moments at backward c.m. angles



B & Q from particle-γ yields per $\theta_{particle}$
g from $\Delta\phi$ particle-γ ang. dist. (RIV)



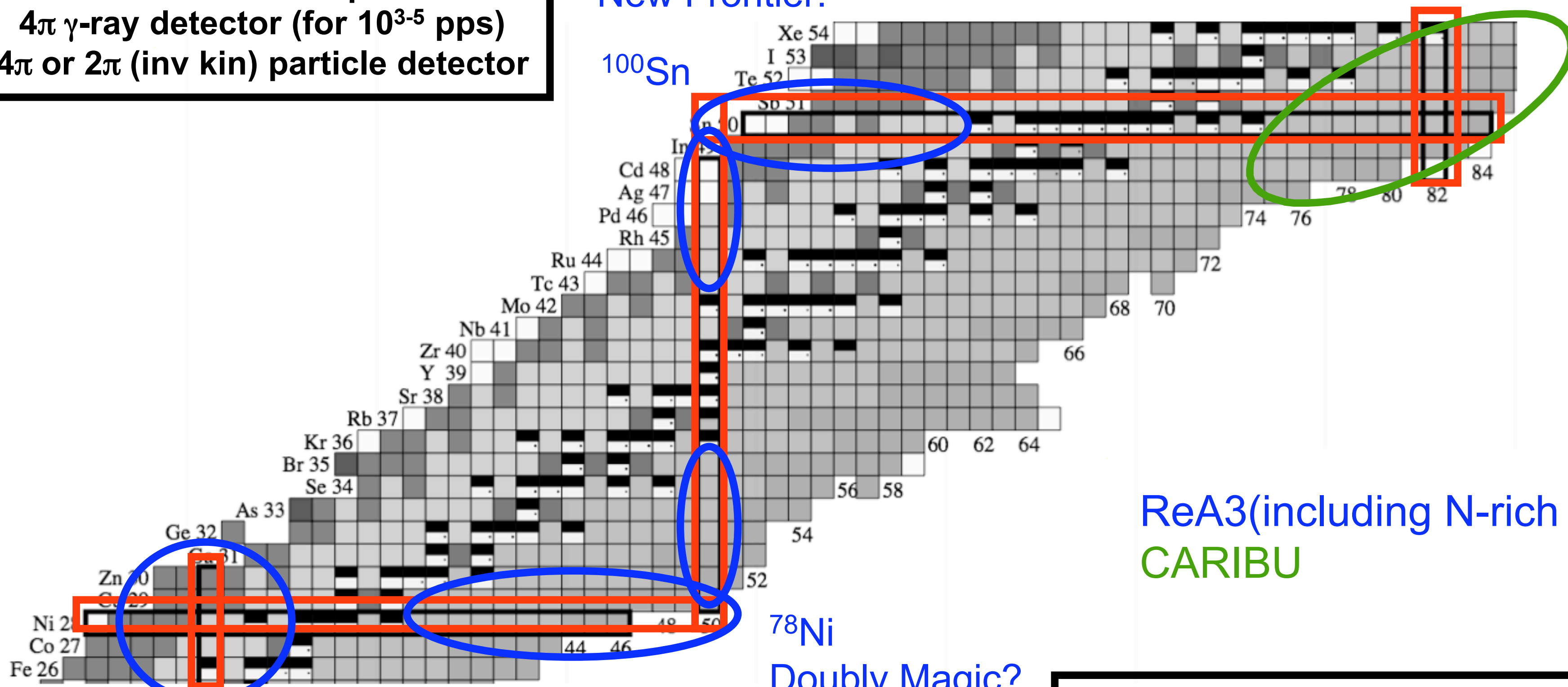
*Safe Coulex At and Near Shell Closures

Primary Facility Requirements:
1-3 MeV/u (~Pure) Beams
Small Beam Spot
4π γ-ray detector (for 10^{3-5} pps)
4π or 2π (inv kin) particle detector

Doubly Magic?
New Frontier!

^{100}Sn

Explore p-n interactions!



ReA3(including N-rich Ca)
CARIBU

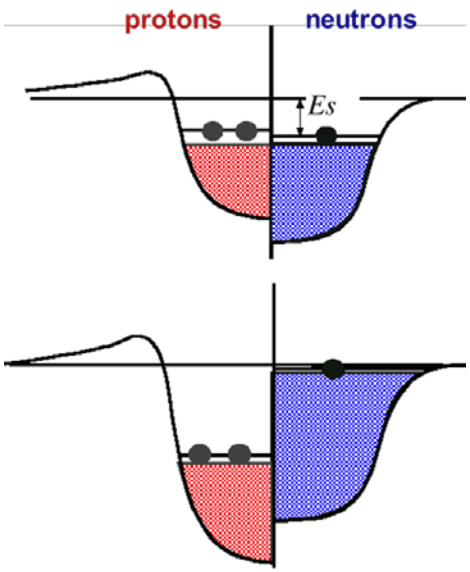
^{78}Ni
Doubly Magic?
New Frontier!

Explore p-n interactions and
N~Z shape coexistence!

Measure Complete E&M Set:
$B(E2; 2_1)$ - Coherent Motion
$Q(2_1)$ - Shape
$|g(2_1)|$ - Currents / Orbits

*** ^{13}C target would allow Coulex and simultaneous sub-barrier 1N transfer for single-neutron ANCs and τ (DSAM)**

Near and sub-barrier fusion as a probe of nuclear structure



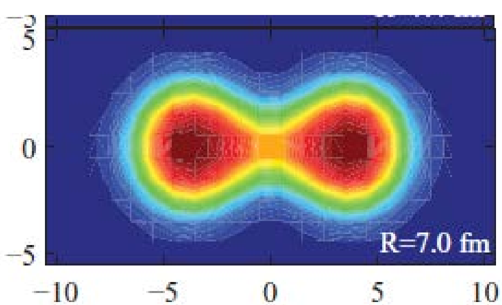
Neutron-rich and proton-rich nuclei probe intrinsically different environments due to the Coulomb barrier

Very neutron-rich nuclei:
N/Z ≈ 2 - 2.5, S_n < 1 MeV

- Diffuseness of neutron distribution (neutron skins & halos)
- More states near the Fermi surface (level density)
- Breakdown of the single-particle description (Clustering at low ρ)
- Redefinition or disappearance of magic numbers

Sub-barrier fusion is particularly sensitive to the tail of the nuclear matter distribution, hence provides a good probe of the neutron and proton distributions.

Measuring fusion for an isotopic chain of projectile nuclei one can sensitively examine the dependence of fusion on the isospin degree-of-freedom.



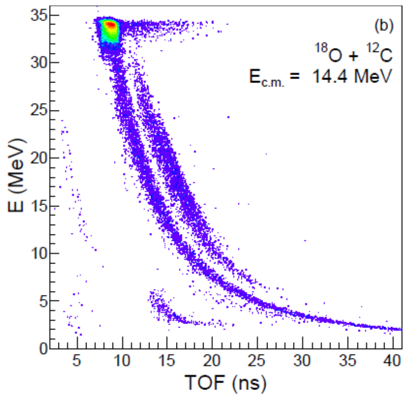
A.S. Umar et al., PRC 85 055801 (2012)

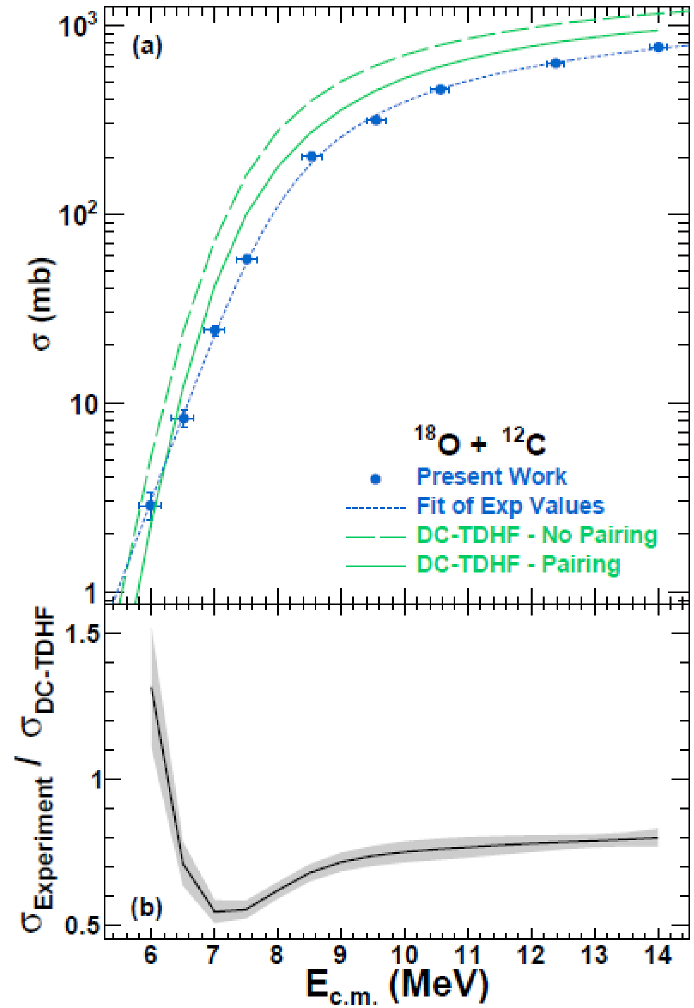
Comparison of high quality, experimental data with microscopic models provides information about the density distributions of neutrons and protons.

Present status of sub-barrier fusion with n-rich light nuclei

Measuring the fusion cross-section near and below the barrier with low intensity beams

Beam intensity: $10^4 - 10^5$ pps





- Direct measurement of evaporation residues by Energy-TOF allows determination of the fusion cross-section to the 2-3 mb level (one order of magnitude lower than prior measurements!)
- It is now possible to perform microscopic calculations that include pairing (density constrained TDHF), providing a relevant comparison for the experimental data.
- The experimental data manifest a significant enhancement in the sub-barrier region. Can be interpreted as:
  - Larger tunneling probability, weaker barrier/deviation from inverted parabolic shape (sensitivity to n/p density distributions)
  - Pairing configuration changes as reaction dynamics proceeds

Theoretical support:
S. Umar/V. Oberacker, Vanderbilt University

Future Plans and Challenges

1) Establish a high quality, systematic set of sub-barrier fusion excitation functions for neutron-rich nuclei in this mass range. [e.g. $^{19,20,22}O$ beams; ^{12}C, ^{18}O targets]

- **Stringent test of microscopic models (both statics and dynamics)**
- **Astrophysical implications : Constrain neutron star crust models**

Challenge: Availability of low energy, neutron-rich beams with sufficient intensity
Challenge: Improved detector systems to reduce sensitivity to background

2) Utilize (measure) the multiplicities, kinetic energies, and angular distributions of the emitted particles (proton, alpha, and neutron) to examine the decay characteristics of the compound nuclei.

- **Access information on the level density of dilute nuclear matter**
- **Clustering effects in low density nuclear matter at low excitation**

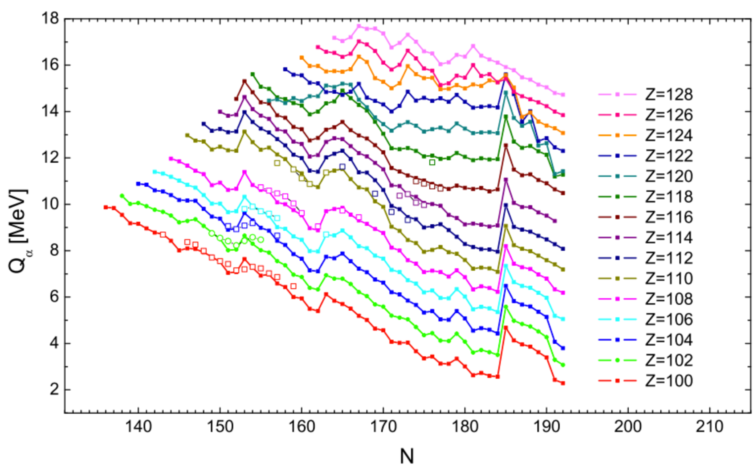
Challenge: Efficient measurement of low energy emitted particles, **including neutrons** in coincidence with the evaporation residue

3) Improve microscopic models (e.g. to allow pairing to evolve as the reaction dynamics proceeds)

Grand Challenge Theoretically: develop TDHFB code on 3D lattice for nuclear reactions

Investigation of Deep Inelastic, Multi-nucleon Transfer Reactions for the Creation of Super- and Hyper-heavy Elements

S. Wuenschel, J.B. Natowitz, K. Hagel, M. Barbui, G. Giuliani, E.J. Kim, N. Blando, H. Zheng, S. Kowalski, K. Schmidt, Z. Majka, Z. Sosin, A. Wieloch.



- This experiment
  - TAMU K500
  - 7.5 MeV/A 197Au + 232Th
  - Thick target (11 mg/cm2)
  - Observe alpha decays

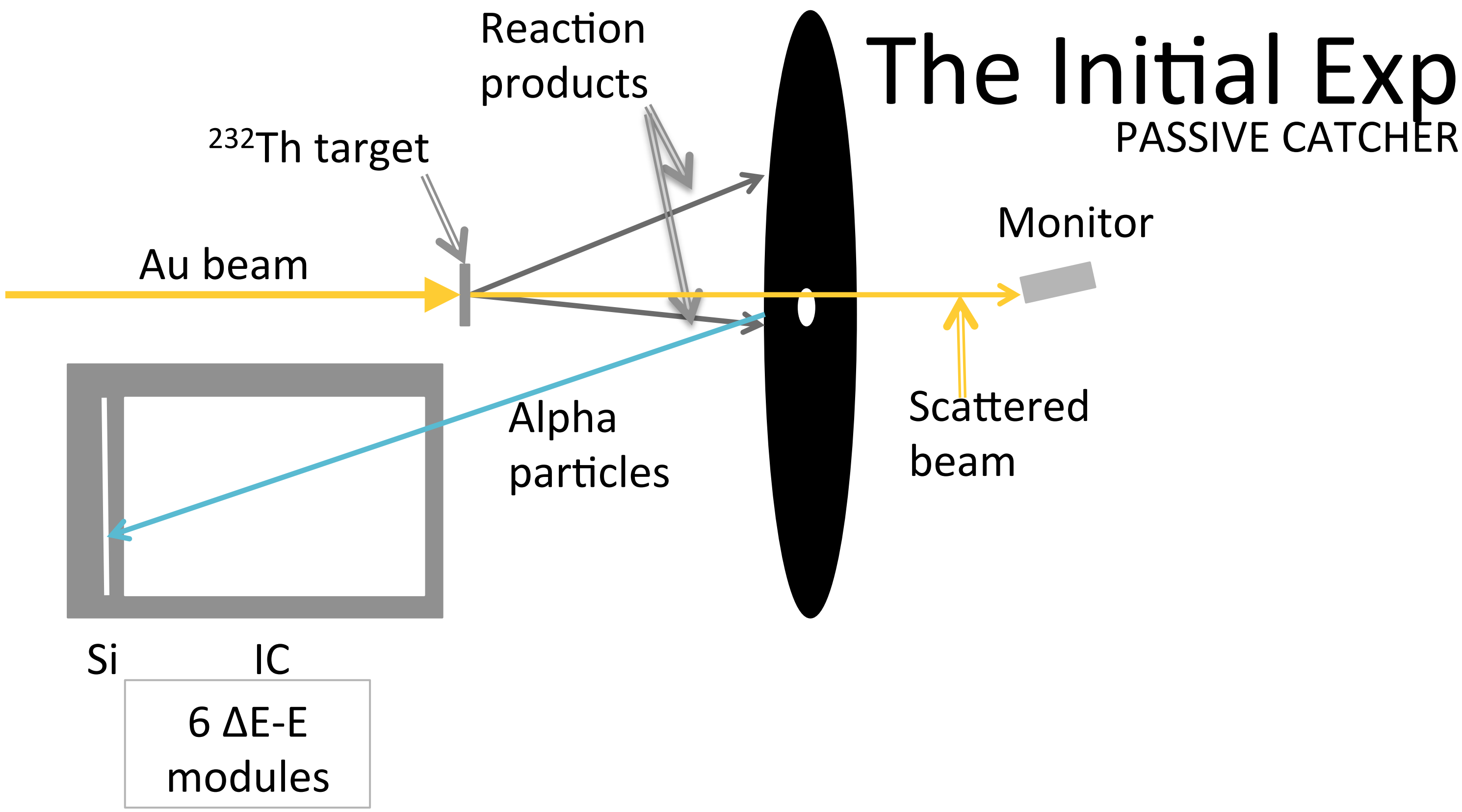
Alternative methods may provide favorable cross sections for heavy element production.

- Multi-nucleon transfer
- Asymmetric fission of heavier, transient systems

Observing alpha particles emitted from reaction residues

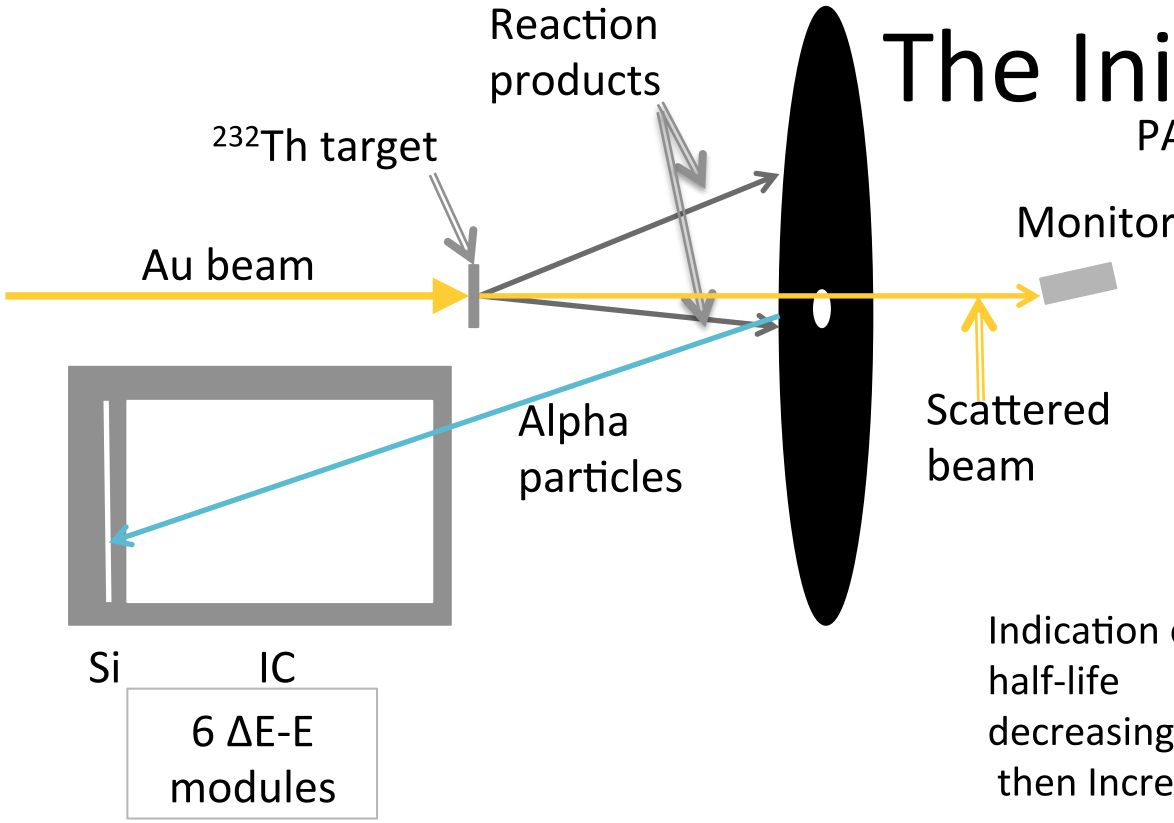
CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

The Initial Experiment

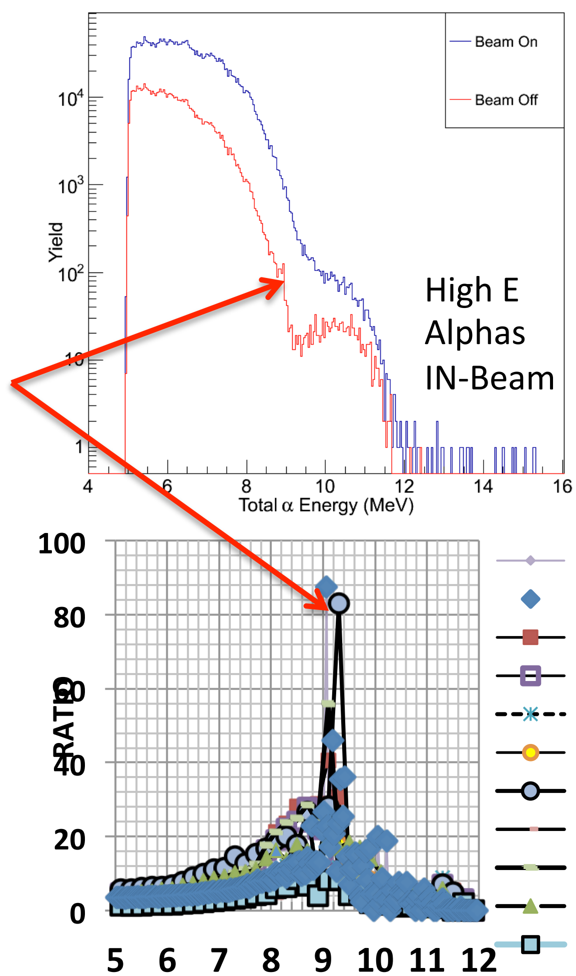


The Initial Experiment

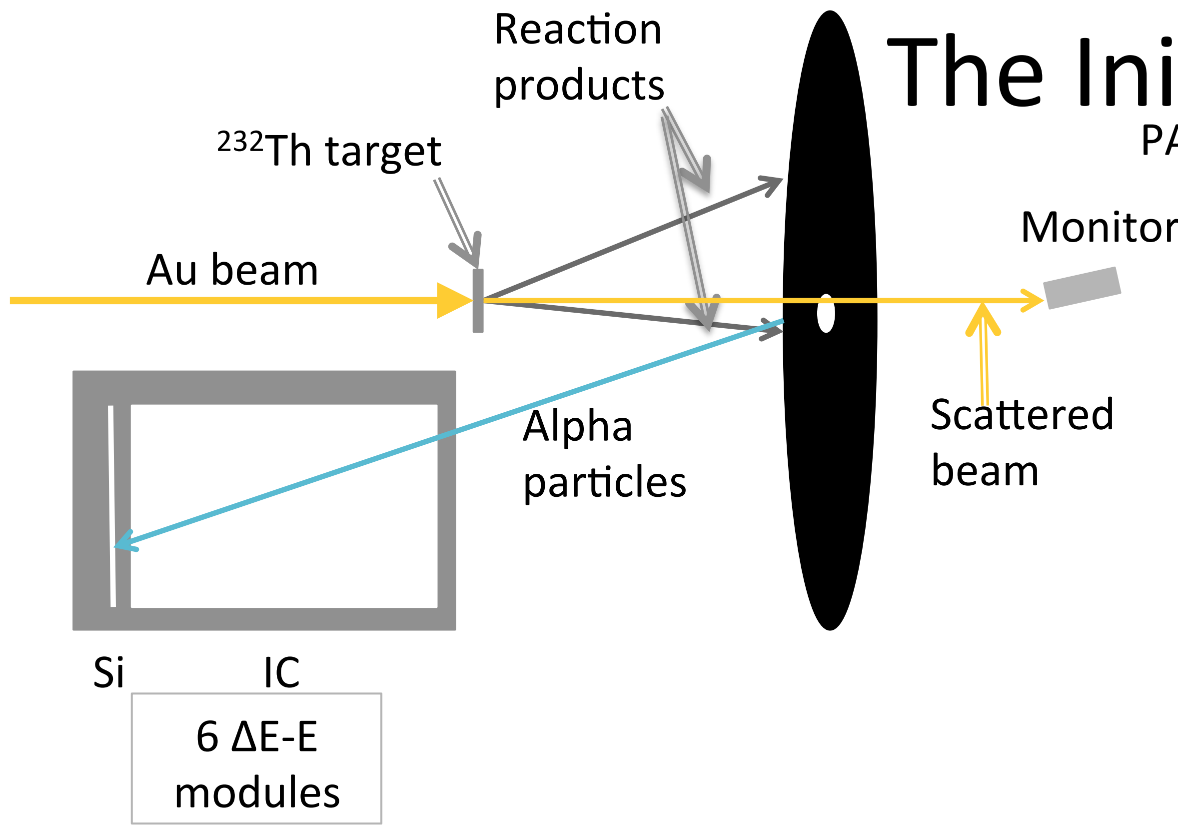
PASSIVE CATCHER

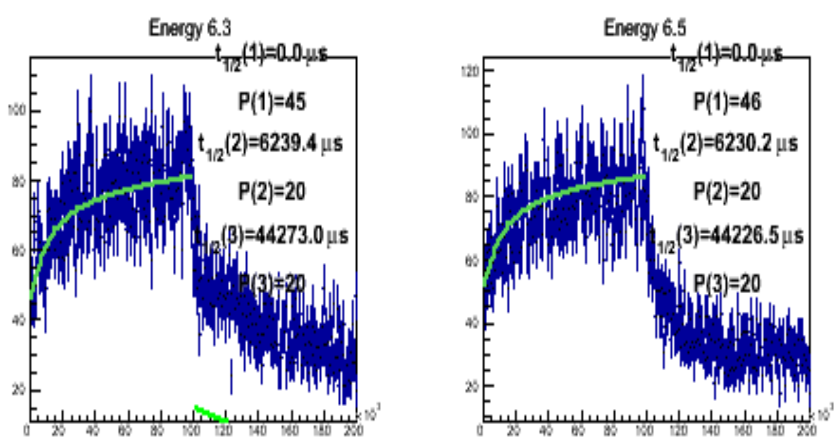


Indication of half-life decreasing then Increasing



The Initial Experiment

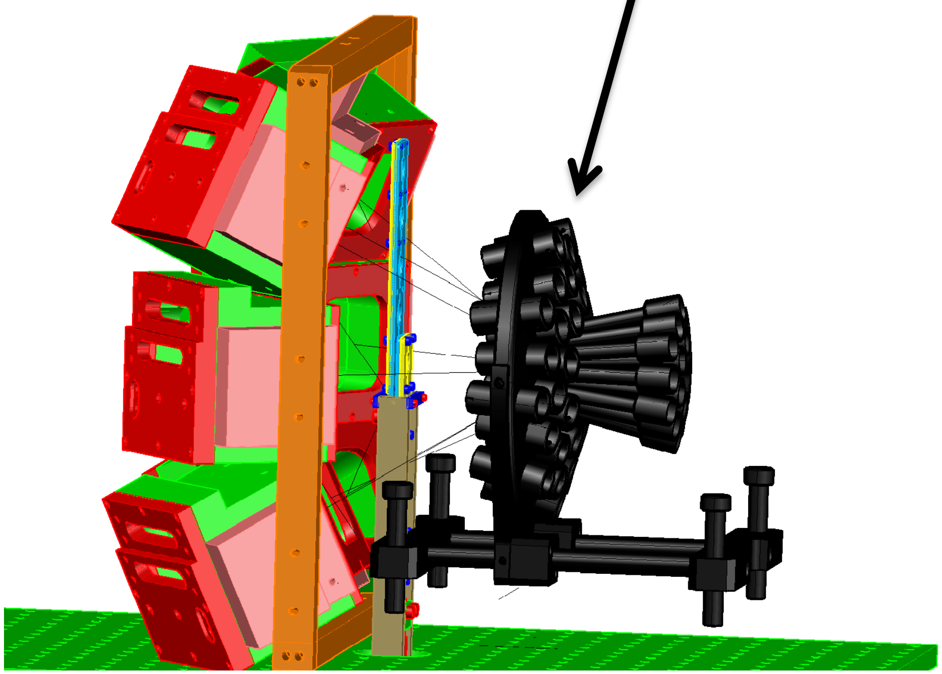




Time distributions gated on alpha energy 100ms on, 100 ms off. Half-lives determined from fitting beam on and beam off data with three components

Outlook

Active Catcher



- Separate alpha decays from ternary fission alpha particles
- Build decay chains
- Fission
- Improve efficiency, segmentation
- Implantation Depth

Will explore:

- U+Th
- Diamond detectors
- Longer Term – Dubna SHE Factory ?

Study of inputs for statistical model

S. M. Grimes
Physics and Astronomy Department, Ohio University, Athens OH

- Dominant reaction model for E/A <=10 MeV relevant to astrophysical nuclear synthesis calculations
- Important to Energy production
- Useful in radioisotope production estimations for medical physics
- Level densities are a fundamental input in statistical model calculations
- Often based on neutron resonance counting
- Need spin cutoff parameter sigma(=$<J^2>^{1/2}$) to convert ½+ density to total
- Can also use evaporation spectra to deduce level density

Models for spin cutoff parameter

1. Rigid body: $\sigma^2=0.0145*A^{5/3}*((U\text{-delta})/a)^{1/2}$
2. Statistical mechanical : $\sigma^2=6/\pi^2 ((U\text{-delta})*a)^{1/2}\langle m^2\rangle$

a	is level density parameter
U	is excitation energy
$\langle m^2\rangle$	is average z projection squared of orbits at Fermi-level
delta	is level density paring and shell shift

First form shows rise at closed shells. Second shows more structure with A and dip at closed shells

Most data points are from 28 <=A<=65 and support tentatively statistical mechanical calculations. Need more data for A>=65.

Data for σ come from angular distribution measurements of compound reactions. If angular momentum brought and removed is substantial, at zero degree and at 180 degree, cross sections exceed 90 degree cross section.

Reactions with p,n as projectiles are nearly isotropic.
Alpha or ^{12}C projectiles can give information about σ.
Evaporation spectra can give both sigma and level density information

Radioactive beams can produce compound systems farther from stability, but even 12C and 24Mg beams can reach nuclei 2-4 units from stability.

Resources

- Beams of ions with E/A 5-10 MeV both stable and radioactive
- Spectrometers for 1-25 MeV neutrons and protons and 4-34 MeV alphas.

γ- strength function in statistical nuclear physics

A. Voinov
Physics and Astronomy Department, Ohio University, Athens OH

Statistical model of nuclear reactions

Optical transmission coefficients

Level densities

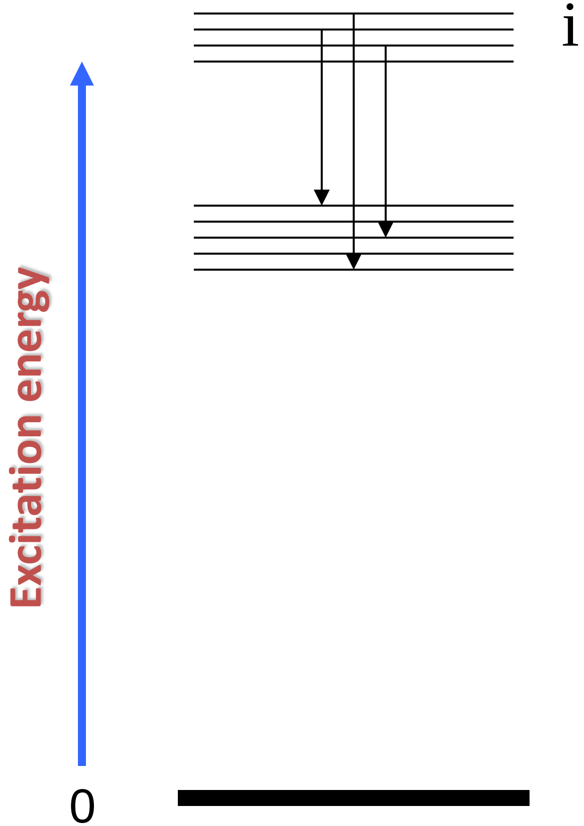
Gamma strength functions

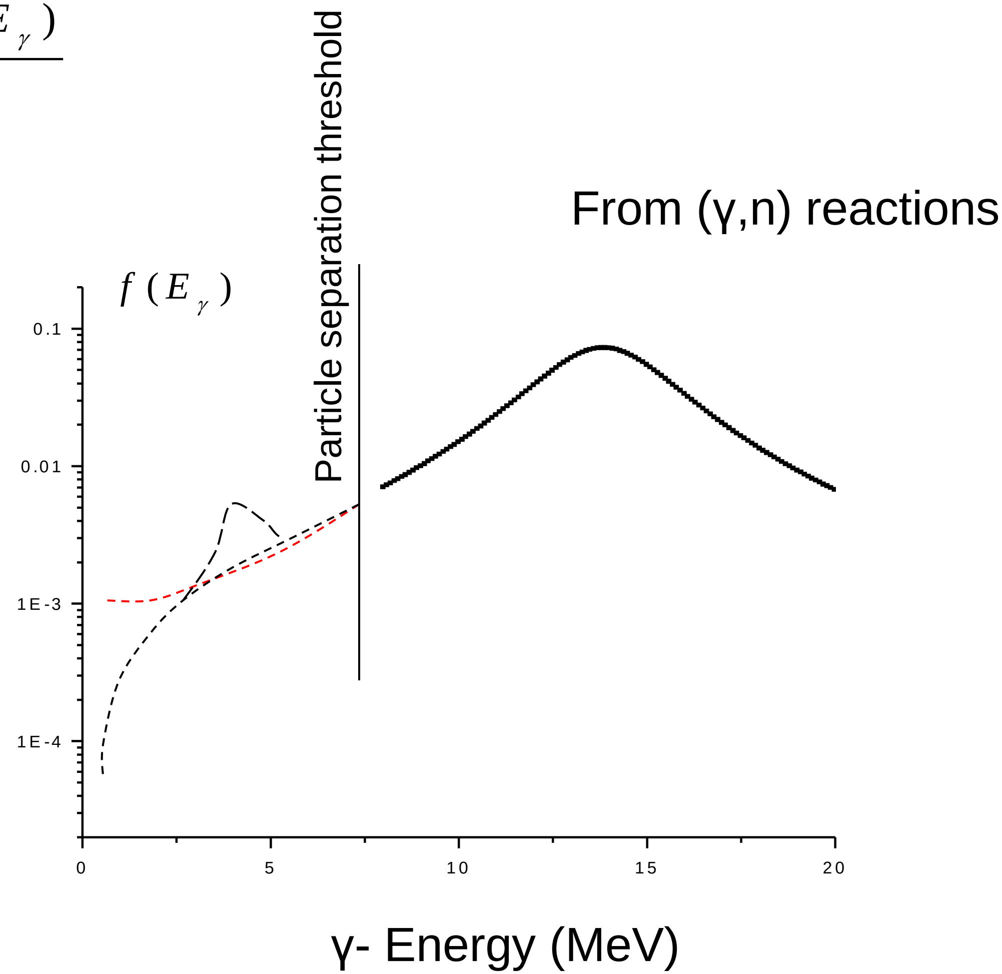
Most uncertain input parameters, leading to factor of 2 of uncertainty in reaction rate calculations.

Efforts should be directed to experimental study of nuclear structure in statistical regime where the nuclear behavior is determined by many individual levels

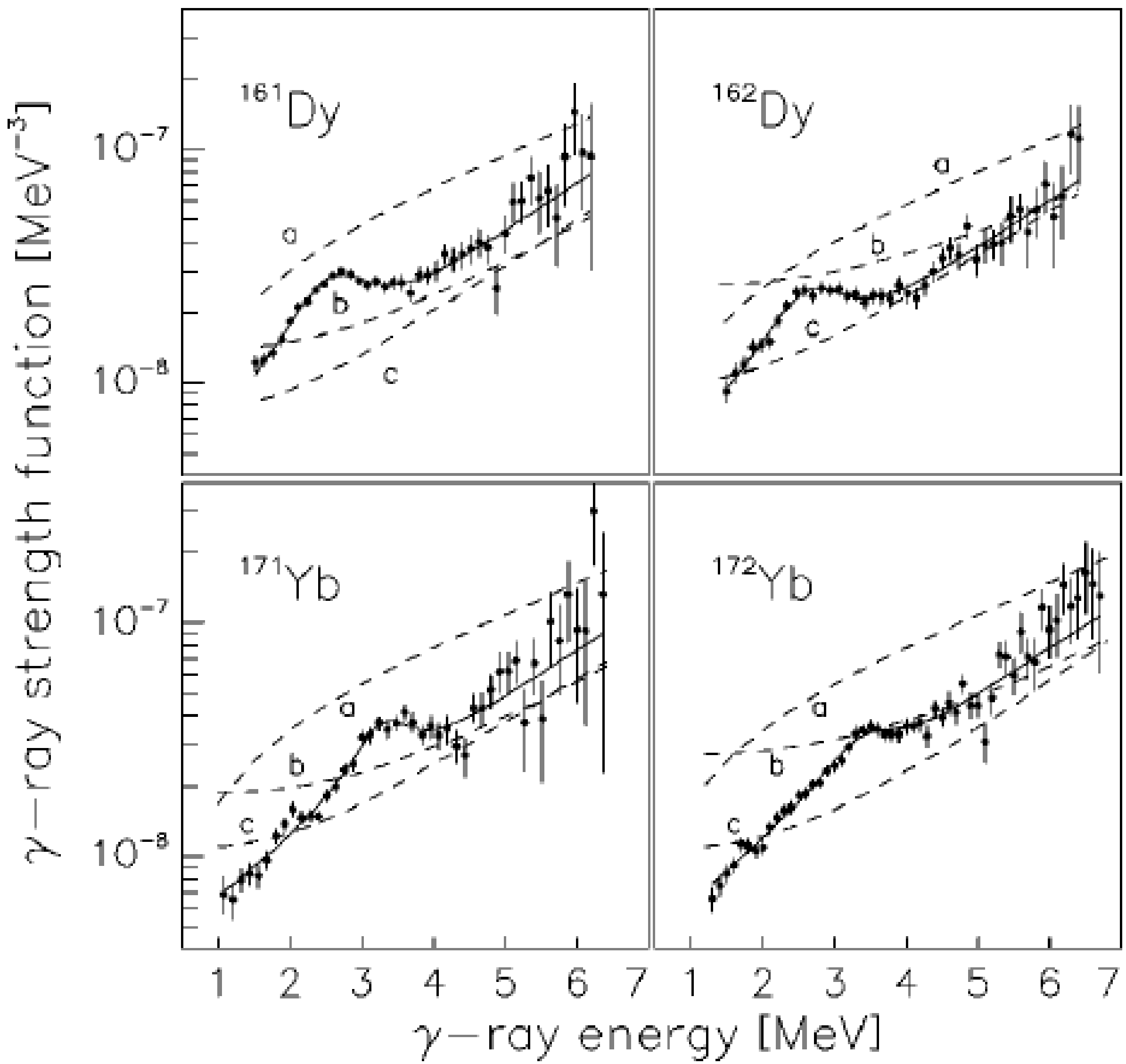
γ – strength function in continuum

$$f(E_\gamma) = \frac{\Gamma(E_\gamma)}{E_\gamma^3 D_i} \sim \frac{\sigma_{abs}(E_\gamma)}{E_\gamma}$$

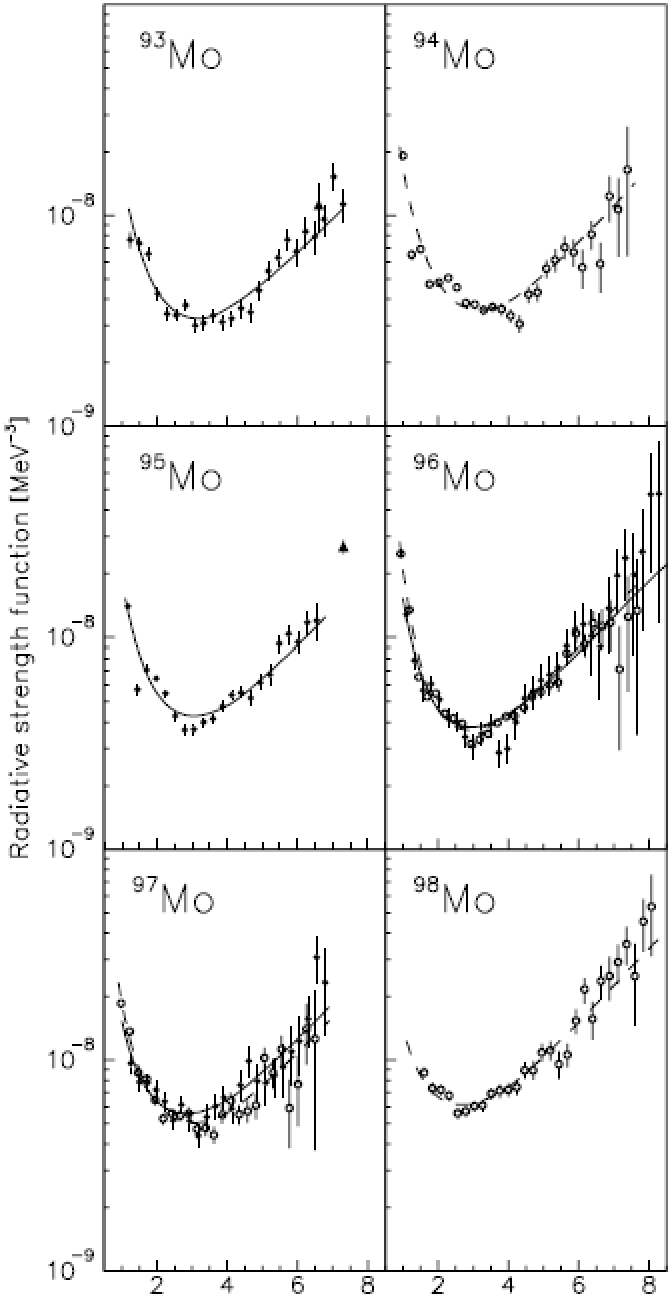




Low-energy resonances in rare earth nuclei



A. Voinov et al. Phys.Rev. C 64, 044313(2001).



Low-energy enhancement for Mo isotopes

M. Guttormsen et al,
Physical Review C71, 044307(2005).

Statements

- Origin of driving forces of electromagnetic transitions between complex excited states is still poorly studied .
- Work which has already done revealed new phenomena in the energy region below the particle separation threshold (resonances, low-energy enhancements).
- Experimental efforts are suggested to be directed to systematic study of average strength of γ-transitions from nuclear reactions with light and heavy ion beams
- The study of electromagnetic transitions in continuum for nuclei off of the stability line would be very important for future experiments with radioactive beams

Resources

Low-energy beams (3-10 MeV/A) . High efficient charged particle spectrometers in combination with high efficient γ- detectors

- ANL, ATLAS, Gamma-sphere, Microball, GRETINA
- NSCL reaccelerated beams
- Texas Cyclotron, STARS Liberace spectrometer

- University low-energy accelerators