Experimental Studies of Nuclei – Structure and Reactions

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NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics
November 14, 2022

The (Really) Big Picture

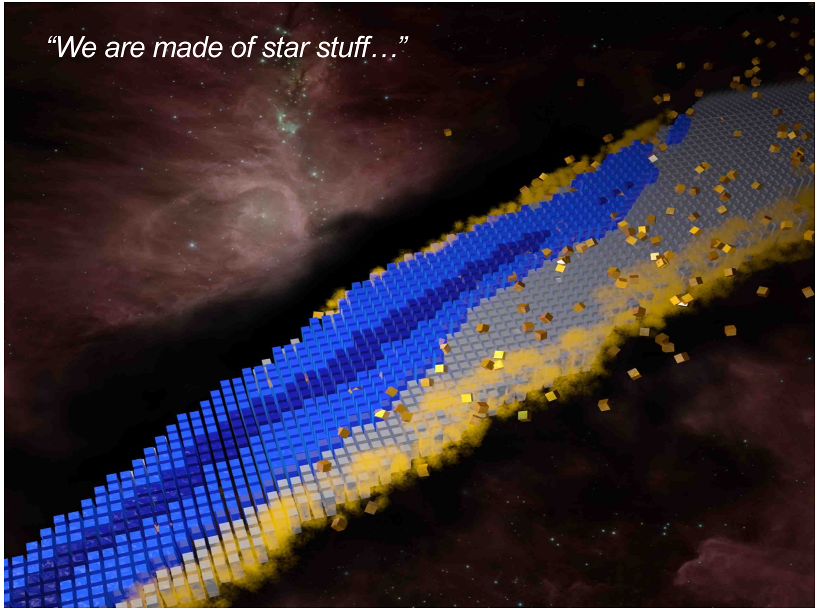
or The 30,000 ft view

National Research Council Report - 2013

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- 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 be used to benefit society?

NSAC 2015 Long Range Plan: Nuclear Structure, Reactions, and Astrophysics

- **The origin and evolution of nuclei**
  - Where do nuclei and elements come from?
  - What combinations of neutrons and protons can form a bound nucleus?
- **The origin of nuclear patterns**
  - How are nuclei organized?
    - Emergent phenomena in complex systems



Goals Realized since the 2015 Long Range Plan

Missions Accomplished

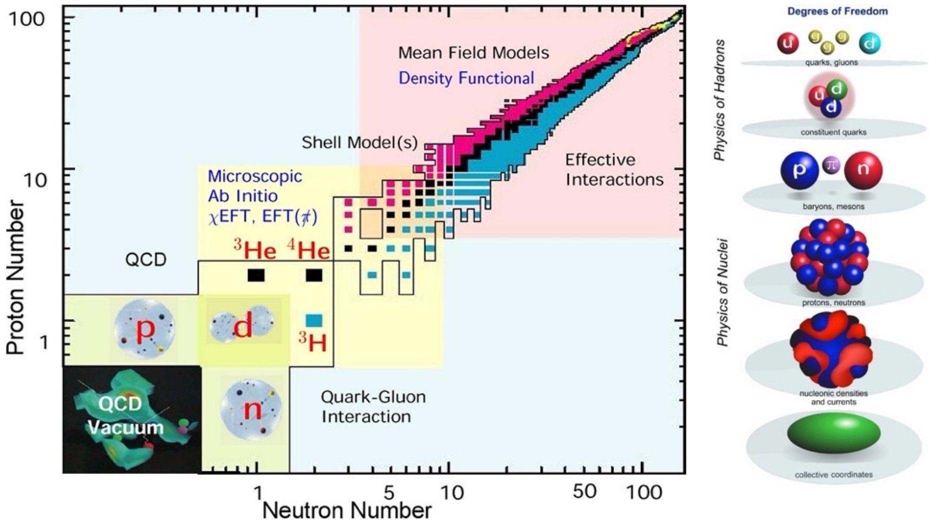
- FRIB is complete and has started operations
- GRETA is funded and on-track to deliver to FRIB in early 2025
- HRS has started with CD-1 and CD-2/3a planned for FY2023
- ATLAS has remained the premier US stable beam facility and continues to expand capabilities
- The network of ARUNA laboratories and university-based groups remains healthy and a vital part of our community
- The FRIB Theory Alliance has been created and is thriving

The Key Role of Theory

There has been and continues to be active development in theory toward the goal to “develop a predictive understanding of nuclei and their interactions grounded in fundamental QCD and electroweak theory”.

“New measurements drive new theoretical and computational efforts which, in turn, uncover new puzzles that trigger new experiments.”

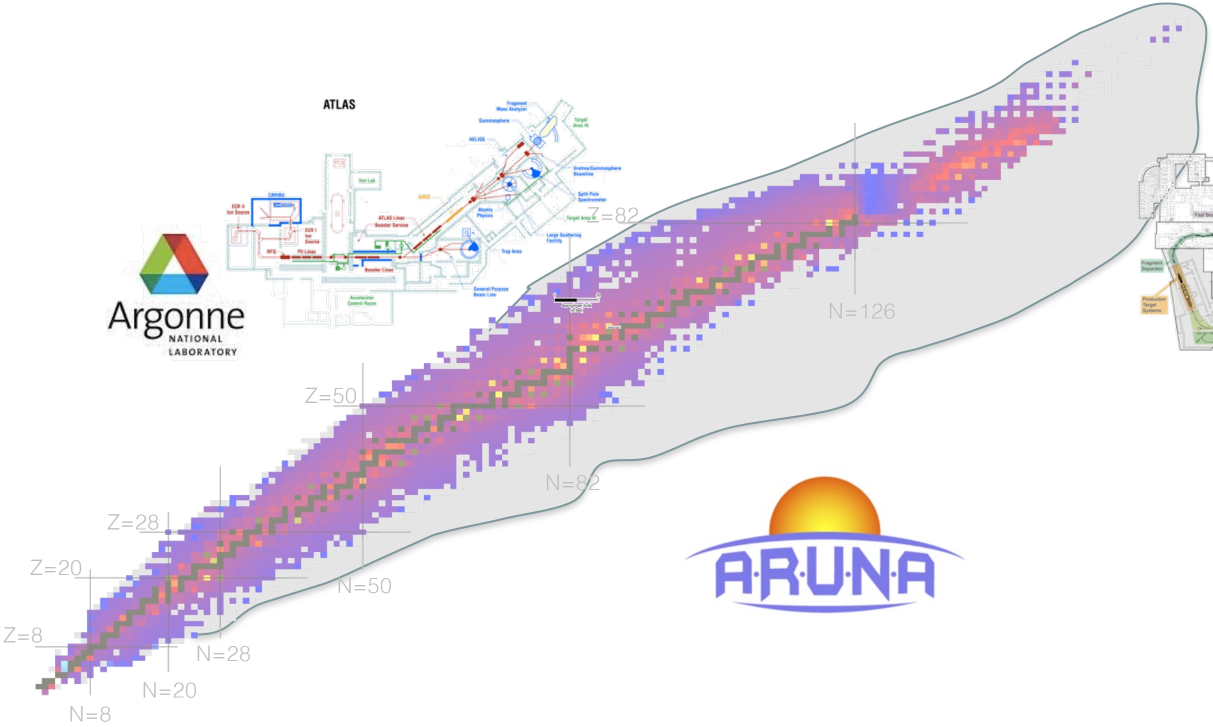
“A strong interplay between theoretical research, experiment, and advanced computing is essential for realizing the full potential of … discoveries.”

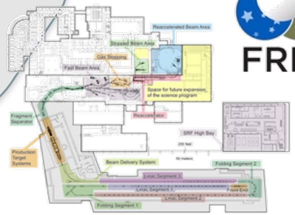


Progress relies on understanding which measurements can best inform a given theory or approach – close collaboration through analysis and publication will maximize science output and impacts in nuclear structure.

The Facilities Are Central – FRIB, ATLAS, ARUNA++

Delivering your favorite beams, always fresh!





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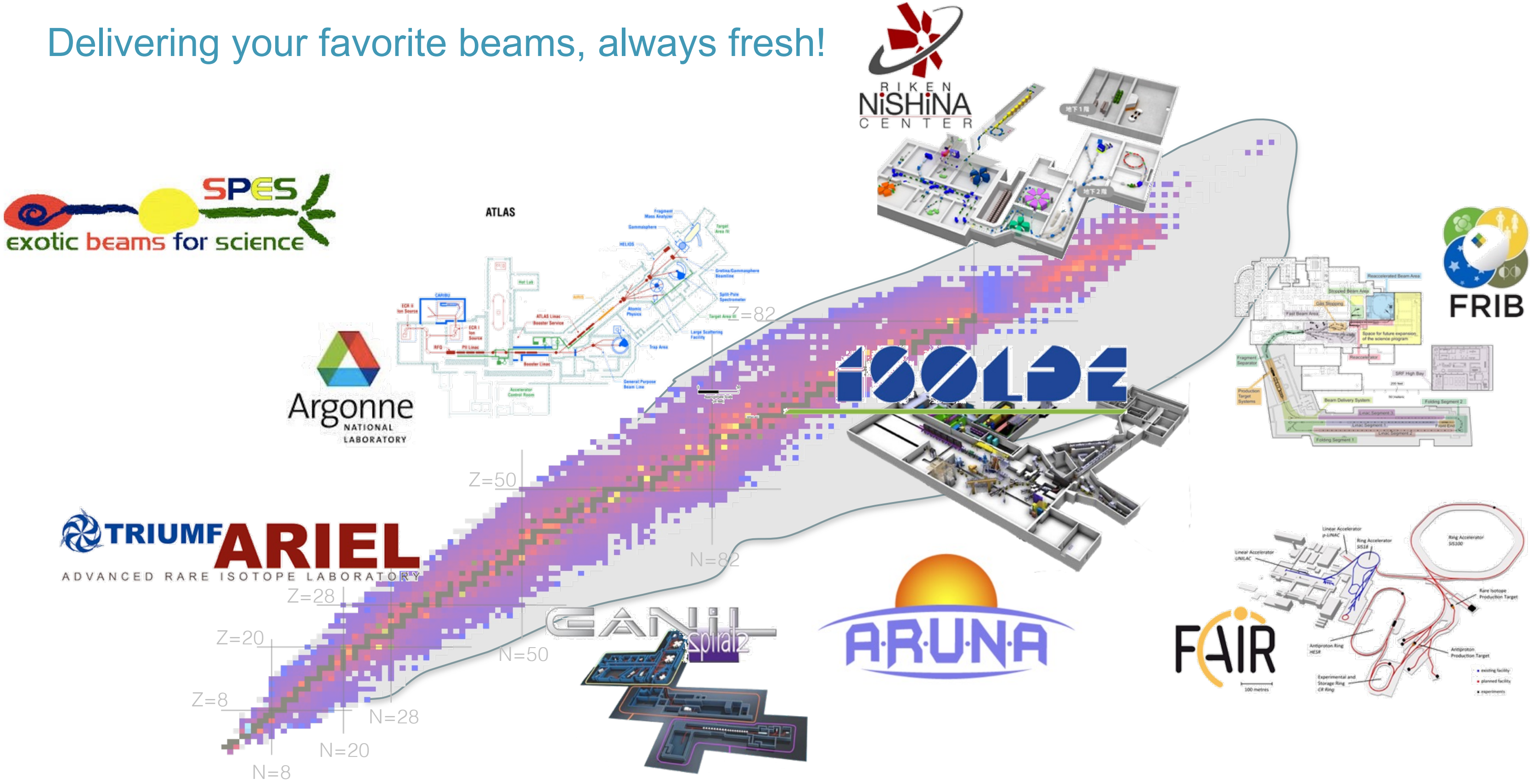
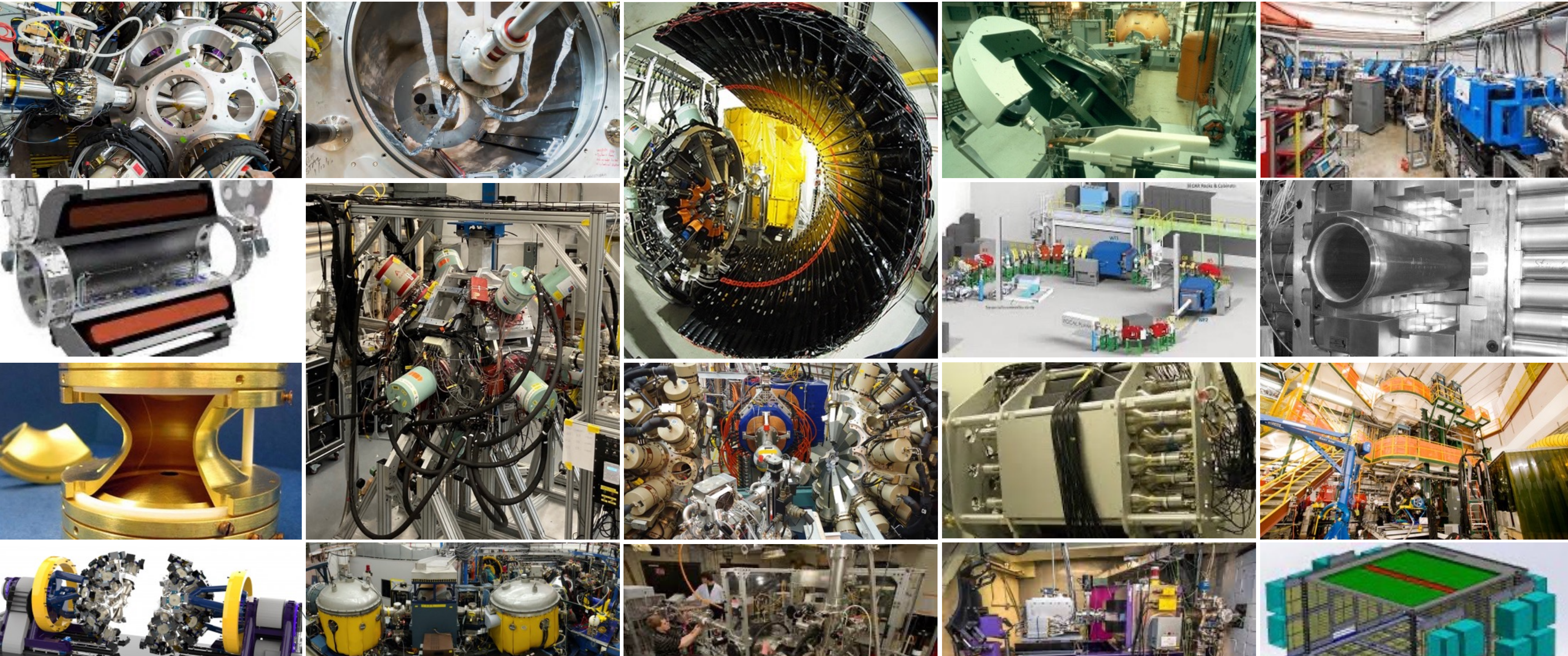


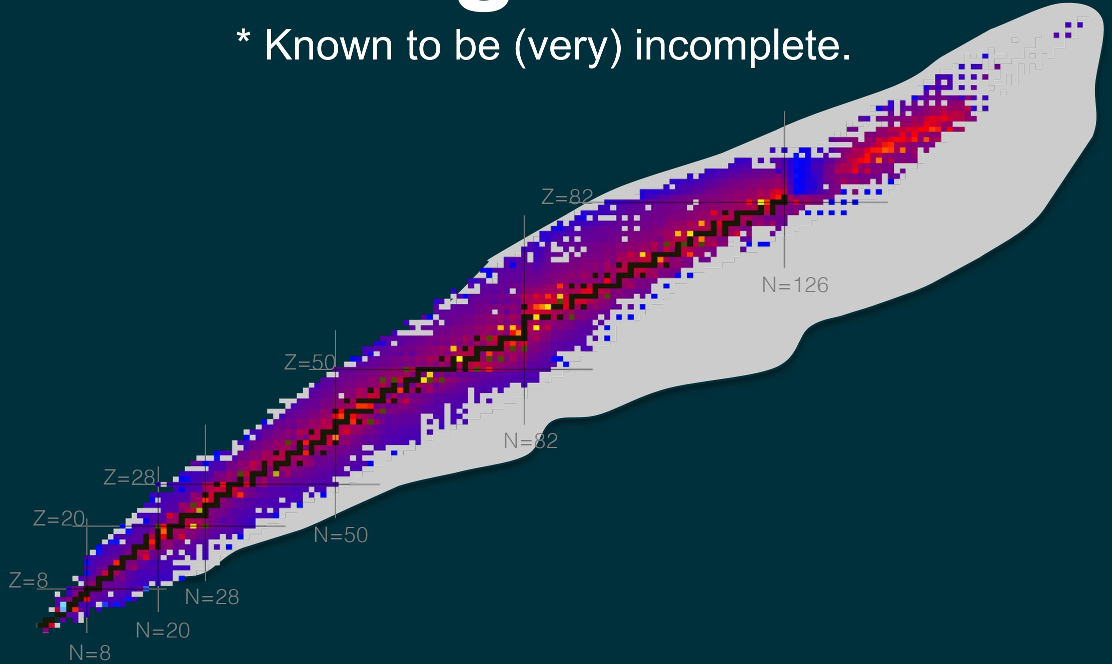
The Equipment Continuously Adds Capabilities

For all your charged particle, neutron and photon detection needs



Highlights* since the 2015 Long Range Plan

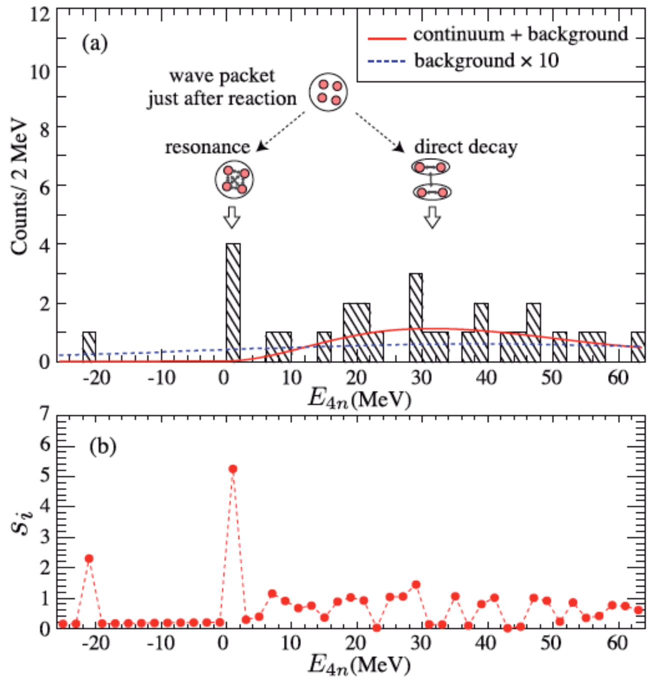
* Known to be (very) incomplete.



The Tetraneutron

Limits of Existence | Understanding Nuclear Forces

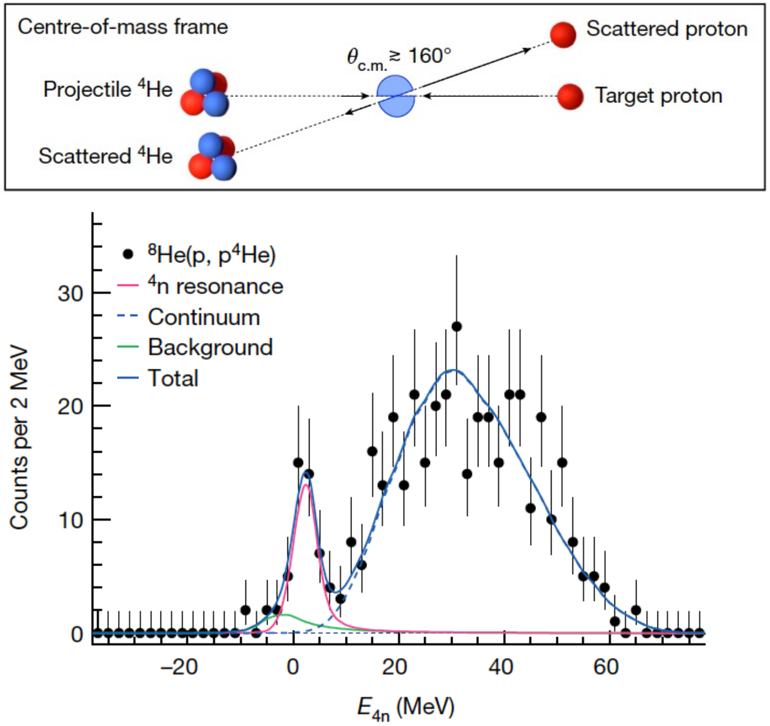
- Few-body systems of neutrons offer unique opportunity to understand structure at the limit of nuclear stability, and to provide insight into pure neutron-neutron interactions
- Experimentally forming a tetraneutron (4*n*) system is extremely challenging, requiring creation of a four-neutron system in an almost recoilless condition
- First indication of a bound tetraneutron came in 2002 from the break-up reaction of ^{14}Be into ^{10}Be+4n – but theory cannot reproduce a bound 4n system
- Double charge exchange in the ^{4}He(^{8}He,^{8}Be) was used at the SHARAQ spectrometer at RIBF
  - A possible resonance was reported at $0.83(0.65)_{stat}(1.25)_{sy}$ MeV for the 4*n* system with an upper limit of $\Gamma \leq 2.6$ MeV



Marqués *et al*., PRC **65**, 044006 (2002).
Kisamori *et al*., PRL **116**, 052501 (2016).

The Tetraneutron

Limits of Existence | Understanding Nuclear Forces



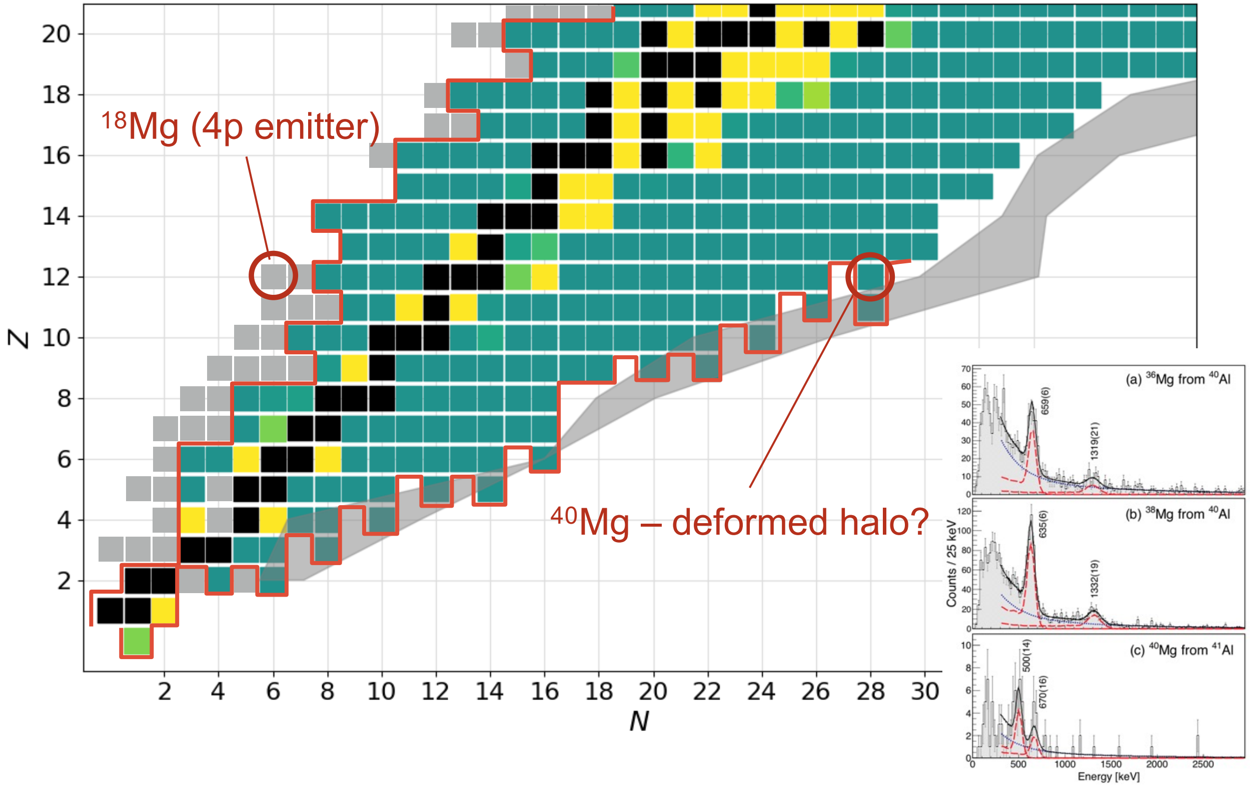
- Most recently quasi-elastic knockout of an α particle induced by a proton target from ^{8}He -- ^{8}He(p,pα) - was performed at SAMURAI at RIBF to populate the 4*n* system
- The measurement approach was validated using the ^{6}He(p,pα) reaction populating the di-neutron in agreement with theory
- The 4*n* resonance was identified at $2.37(0.38)_{stat}(0.44)_{sys}$ MeV with a width Γ of $1.76(0.22)_{stat}(0.30)_{sys}$ MeV

Duer *et al*., Nature **606**, 678 (2022).

To The Driplines And Beyond

Limits of Existence | Nuclear Forces

- Neutron halo systems offer unique opportunities to study the nuclear force
- Systems beyond the proton dripline are very sensitive to continuum couplings and recent studies continue to extend the nuclei identified and characterized
- Significant progress has been made – ^{40}Mg and ^{18}Mg

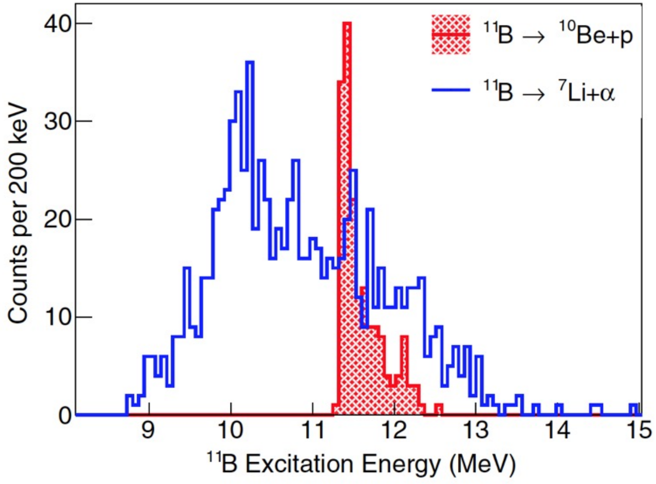


Jin *et al.*, PRL **127**, 262502 (2021).
HLC *et al.*, PRL **122**, 052501 (2019).

The Near-Threshold Resonance in ^{11}B

Limits of Existence | Exotic Decay Modes

- A narrow near-threshold resonance in ^{11}B has been identified which undergoes direct proton decay - offers a unique case to study quantum near-threshold many-body dynamics
- One of the first clear hints of this resonance was seen via observation of the β^-p$^+$ decay of ^{11}Be in the p-ATTPC at TRIUMF
- Follow up experiments were performed at ReA3 using proton resonance scattering and at FSU using the ^{10}Be(d,n) reaction, both firmly identifying the resonance state

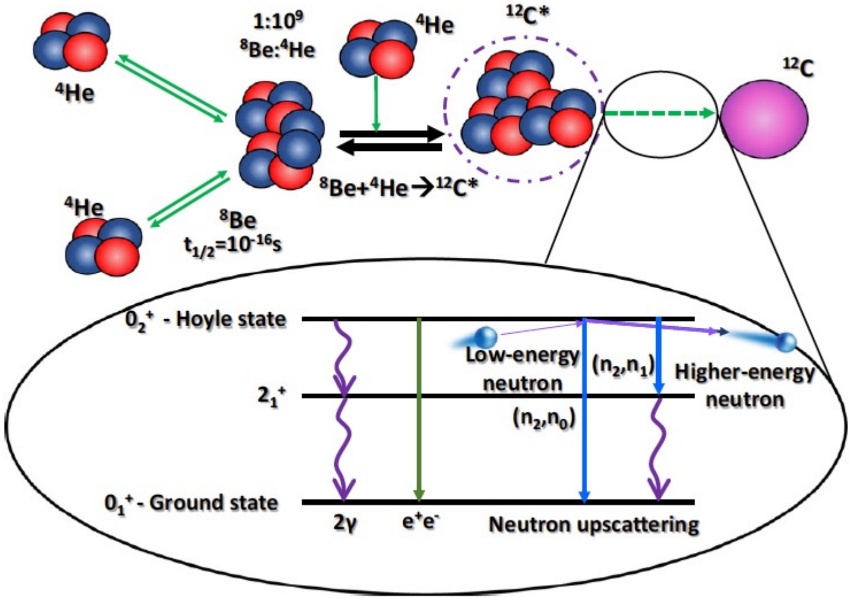


Ayyad *et al.*, PRL **123**, 082501 (2019).
Ayyad *et al.*, PRL **129**, 012501 (2022).
Lopez-Saavedra *et al.*, PRL **129**, 012502 (2022).

The Hoyle State and ARUNA

Reactions | Astrophysics

- A pair of measurements, one at TAMU and one at Edwards Accelerator Lab (OU) used the TexAT TPC to study properties of the Hoyle state in ^{12}C
- The branch for direct decay of the Hoyle state into 3α particles was measured at TAMU, agreeing with model predictions
- Neutron upscattering can enhance the overall triple-α reaction rate – this has now been measured at OU and shown to be a much smaller enhancement than previously expected



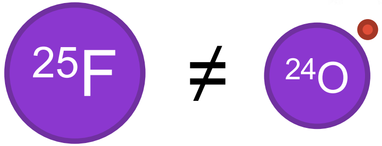
Bishop *et al*., PRC **102**, 041303(R) (2020).
Bishop *et al*., Nature Communications **13**, 2151 (2022).

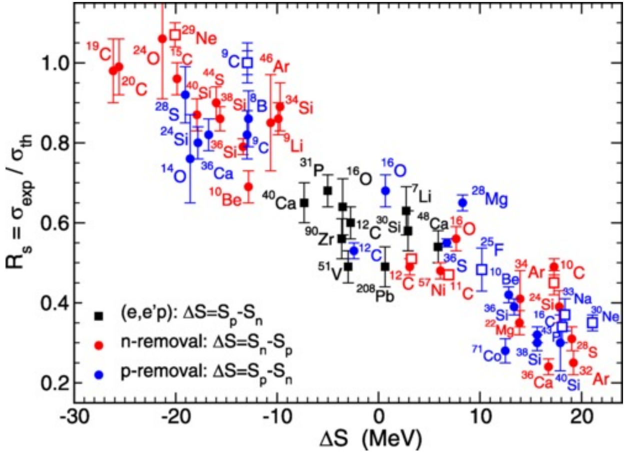
Direct Reactions and the Core of ^{25}F

Reactions | Limits of Existence

- Direct reactions continued to be a key tool, enabling an understanding of the overlap of initial and final state wavefunctions
- Consider the case of ^{25}F and the ^{24}O core ⇒

$$C^2 S_{\text{g.s. to g.s}} = 0.36(13)$$





- Spectroscopic factors are not without open questions. A fully consistent description of structure + reactions remains a challenge to theory

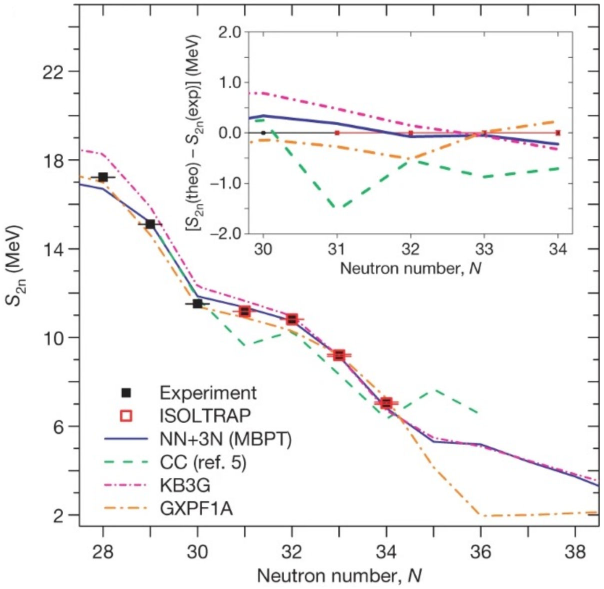
Tang *et al.*, PRL **124**, 212502 (2020).
HLC *et al.*, to be published.
Tostevin and Gade, PRC**, 103**, 054610 (2021).

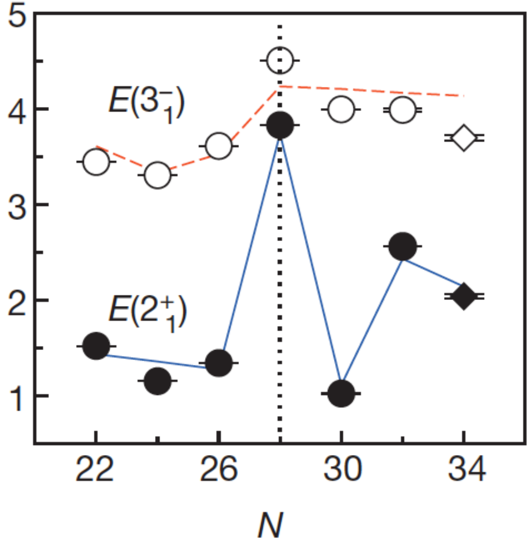
The Calcium Isotopes

Evolution of Shells | Collectivity | Tests of Theory

^{46}Ca	^{47}Ca	^{48}Ca	^{49}Ca	^{50}Ca	^{51}Ca	^{52}Ca	^{53}Ca	^{54}Ca	^{55}Ca	^{56}Ca	^{57}Ca	^{58}Ca	^{59}Ca	^{60}Ca

- At the time of the last LRP, first spectroscopy and mass measurements had pushed as far as ^{54}Ca
- All data pointed to new shell closures at N=32,34





Gallant *et al.*, PRL **109**, 032506 (2012).
Wienholtz *et al.*, Nature **498**, 346 (2013).
Steppenbeck *et al.*, Nature **502**, 207 (2013)

The Calcium Isotopes

Evolution of Shells | Collectivity | Tests of Theory

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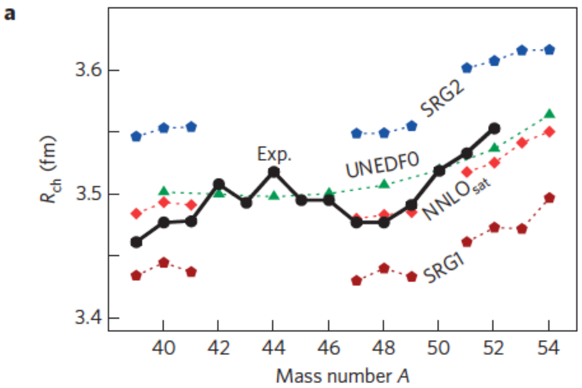
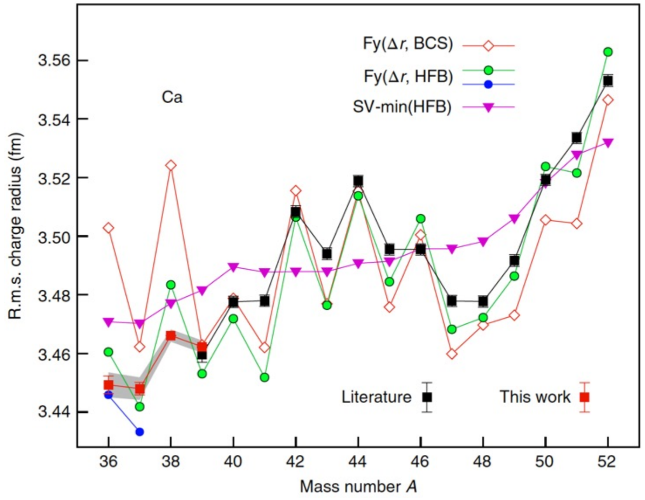
- Laser spectroscopy measured radii out to ^{52}Ca and raised questions about the magicity at *N*=32
- Measurements extending toward the proton dripline also highlighted a nuclear density functional (Fayans functional) that better describes the radii trend to ^{52}Ca
- Radii measurements in the *Z*=19 chain also lead to questions regarding the presence of a shell-gap at *N*=32





Garcia Ruiz *et al*., Nature Physics **12**, 594 (2016).
Miller *et al*., Nature Physics **15**, 432 (2019).
Koszorús *et al*., Nature Physics **17**, 439 (2021).
Reinhard and Nazarewicz, PRC **95**, 064328 (2017).

The Calcium Isotopes

Evolution of Shells | Collectivity | Tests of Theory

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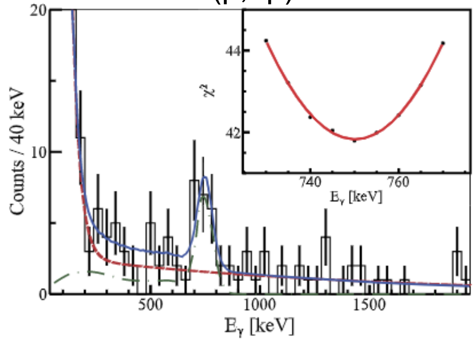
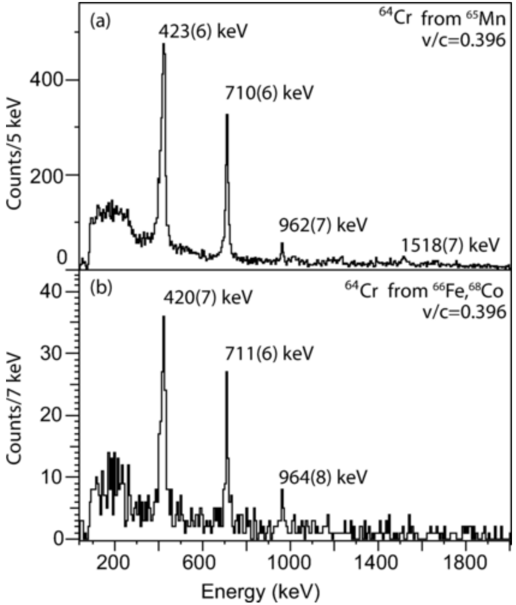
- First spectroscopy in ^{55,57}Ca offered a first peak toward ^{60}Ca, and the *very limited* data suggests a structural change beyond *N*=36 toward more collective structure
- Spectroscopy in the isotopic chains above Ca has also been pushed out – ^{58,60,61}Ti, ^{62,64,66}Cr etc.

^{58}Sc(p,2p)^{57}Ca



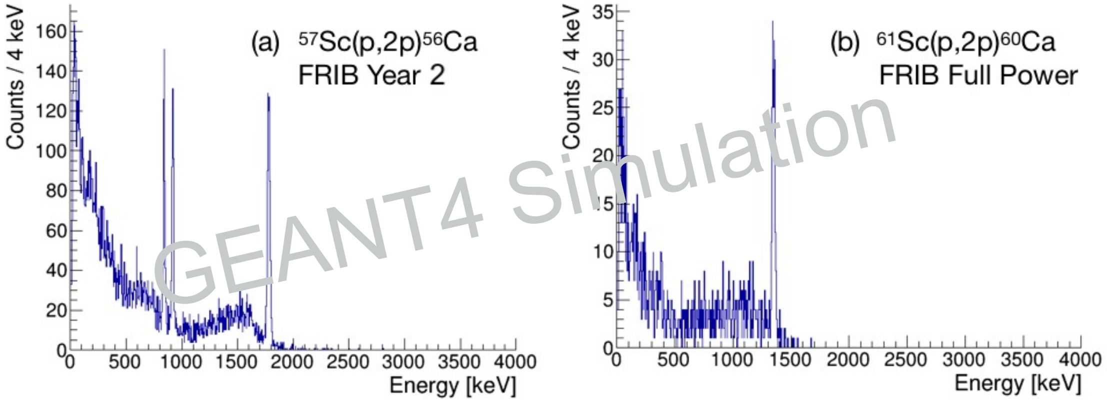


Gade *et al*., PRL **112**, 112503 (2014).
Wimmer *et al*., PLB **792**, 16 (2019).
Gade *et al*., PRC **103**, 014314 (2021).
Koiwai *et al*., PLB **827**, 136953 (2022).

The Calcium Isotopes

Evolution of Shells | Collectivity | Tests of Theory

^{46}Ca ^{47}Ca ^{48}Ca ^{49}Ca ^{50}Ca ^{51}Ca ^{52}Ca ^{53}Ca ^{54}Ca ^{55}Ca ^{56}Ca ^{57}Ca ^{58}Ca ^{59}Ca ^{60}Ca

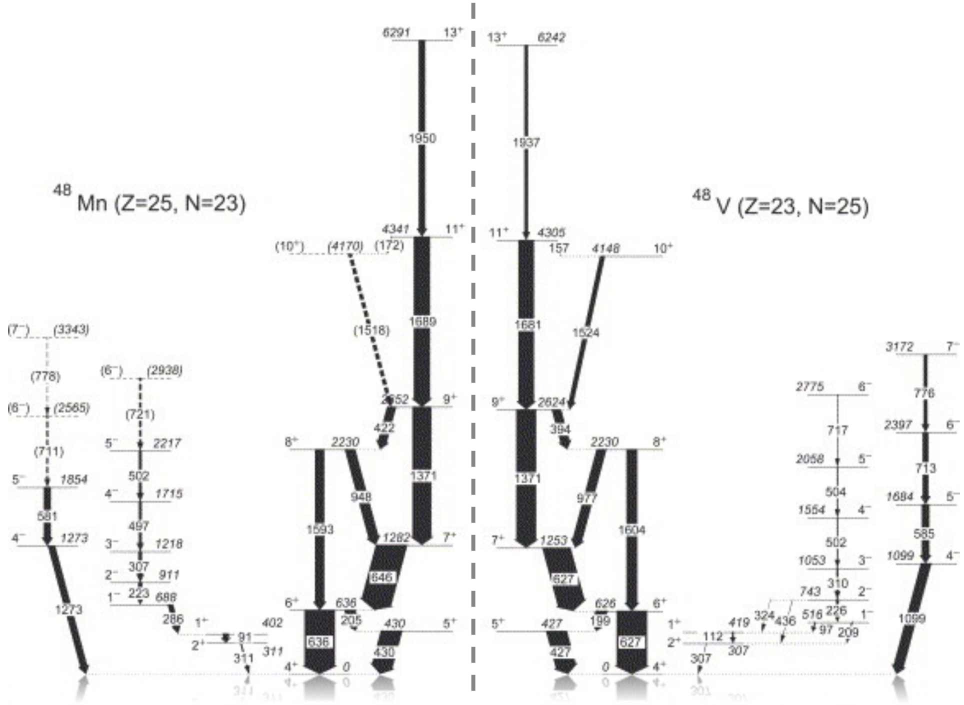


- This story is not over – FRIB opens the door to push spectroscopy and knockout cross-sections, as well as precision measurements (e.g. masses, radii), toward and to ^{60}Ca

- These future data will also be timely to confront theoretical models – *the $_{20}Ca$ chain is the $_{8}O$ chain for the next decade*

The Reflections Across *N*=*Z*

Symmetries | Nuclear Forces | Collectivity



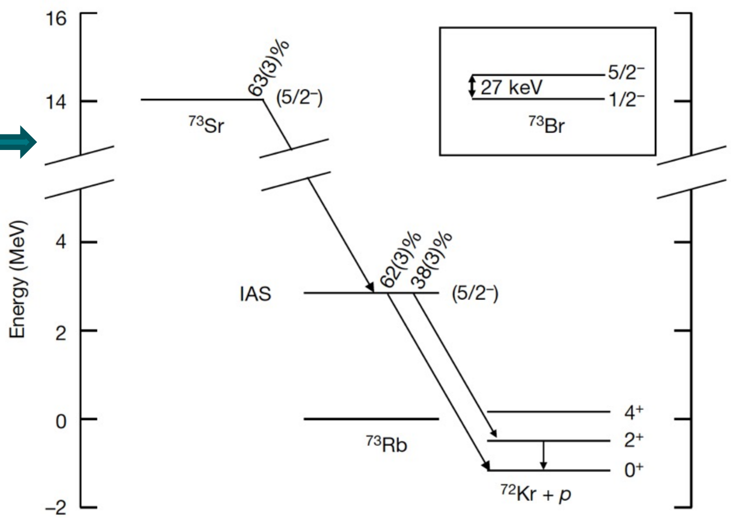
Bentley and Lenzi, Prog. Part. Nucl. Phys. **59**, 497 (2007).

- Mirror pairs of nuclei across *N*=*Z*, and more generally chains of isobaric analogue states offer a unique opportunity to understand nuclear forces
- Detailed spectroscopic studies have extended well into the *fp* shell
- Anomalies persist that are not fully understood – e.g. J=2 anomaly – much more to learn heading up toward ^{100}Sn

The Reflections Across *N*=*Z*

Symmetries | Nuclear Forces | Collectivity

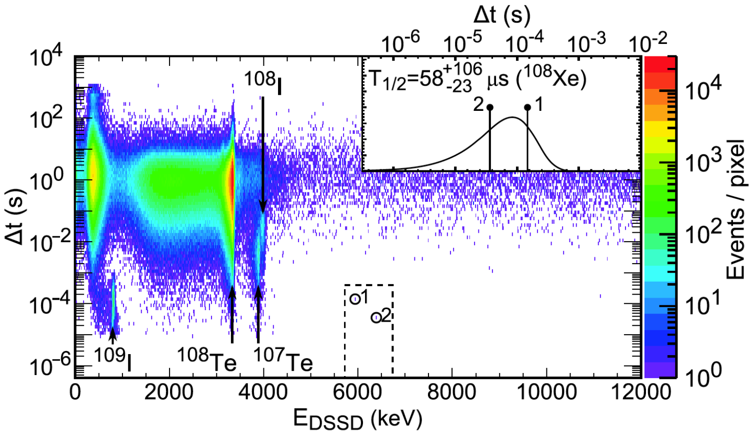
- An example of isobaric-spin-symmetry breaking has been identified in the ^{73}Br/^{73}Sr mirror pair, where these nuclei have different ground-state spins
  - Only other example is in the ^{16}F/^{16}N pair, but this is explained as a consequence of the Coulomb force
- In the *A*=70 isospin triplet (^{70}Kr/^{70}Br/^{70}Sr) the reduced transition probability *B(E2)* deviates from the expected linear trend with T_Z – possibly an indication of a shape change between the mirror partners?



Hoff *et al*., Nature, **580**, 52 (2020).
Wimmer *et al*., PRL **126**, 072501 (2021).

The Doubly-Magic Holy Grail – ^{100}Sn

Shell Structure | Nuclear Forces

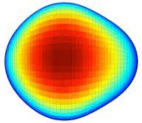


- Superallowed alpha decay has been reported in ^{108}Xe

Auranen *et al*., PRL **121**, 182501 (2018).

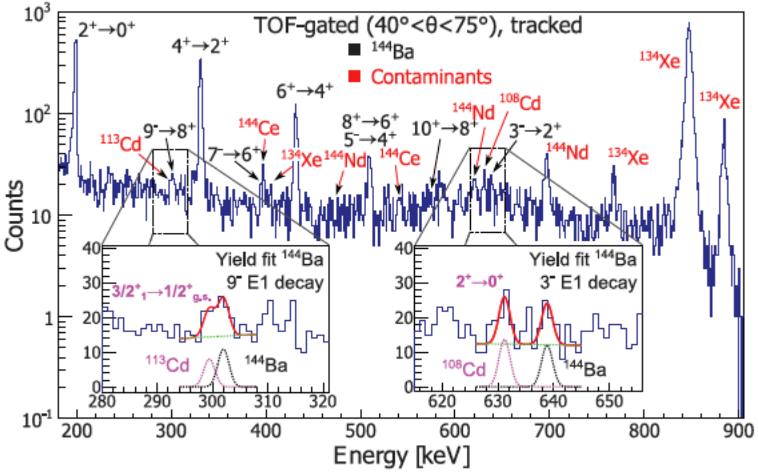
- Experiment has been pushing toward ^{100}Sn for the better part of a decade, and will continue to do so in the next
- Decay studies have managed to reach this key nucleus with additional measurements already planned at FRIB
- In-beam reaction studies are similarly covering the $_{50}$Sn chain and pushing to the proton dripline; precision mass measurements are doing the same

The Pear-Shaped Nuclei of the Chart



Collectivity | Symmetries

- CARIBU at ATLAS, combined with CHICO2 and GRETINA, enabled detailed Coulomb excitation studies of the neutron-rich Ba
- ^{144,146}Ba were confirmed to exhibit octupole collectivity with *B*(*E3*) transition probabilities of order 48 W.u.
- ^{143}Ba was described as a doubly-decoupled structure with a decoupled neutron and a decoupled octupole phonon on ^{142}Ba

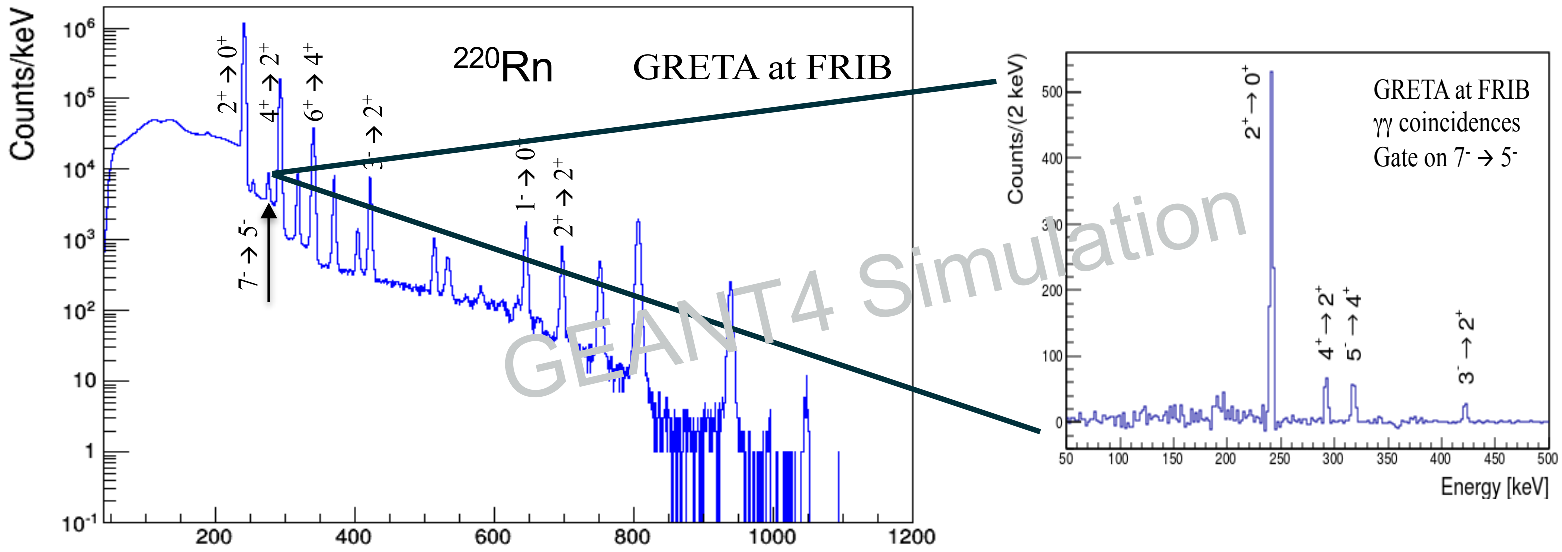


Bucher *et al*., PRL **116**, 112503 (2016).
Bucher *et al*., PRL **118**, 152504 (2017).
Morse *et al*., PRC **102**, 054328 (2020).

The Pear-Shaped Nuclei of the Chart

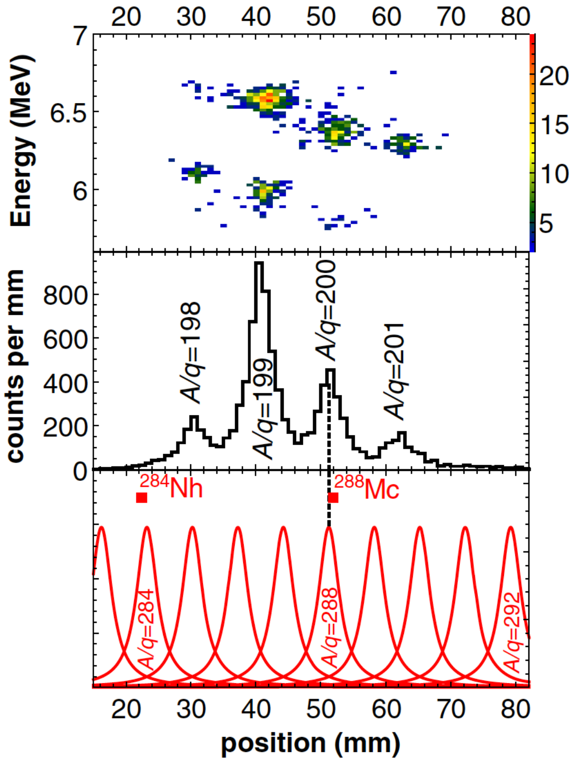
Collectivity | Symmetries

- Development at ATLAS (ν-CARIBU) and the ReA facility at FRIB ensure that low-energy Coulex will feature strongly in the next decade



The Heaviest Elements – Mammoths of the Chart

Limits of Stability | Evolution of Shells



- The first definitive assignment of the mass number *A* for a superheavy element was made for $^{288}_{115}$Mc using the FIONA device at the BGS at LBNL
- This provided the first anchor for the superheavy isotopes on the nuclear chart
- With this accomplishment, the next step is moving towards precision measurements of the SHE

Gates *et al.*, PRL **121**, 222501 (2018).

The Heaviest Elements – Mammoths of the Chart

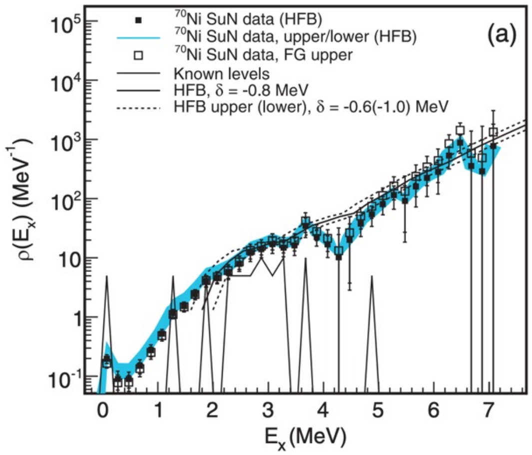
Limits of Stability | Evolution of Shells

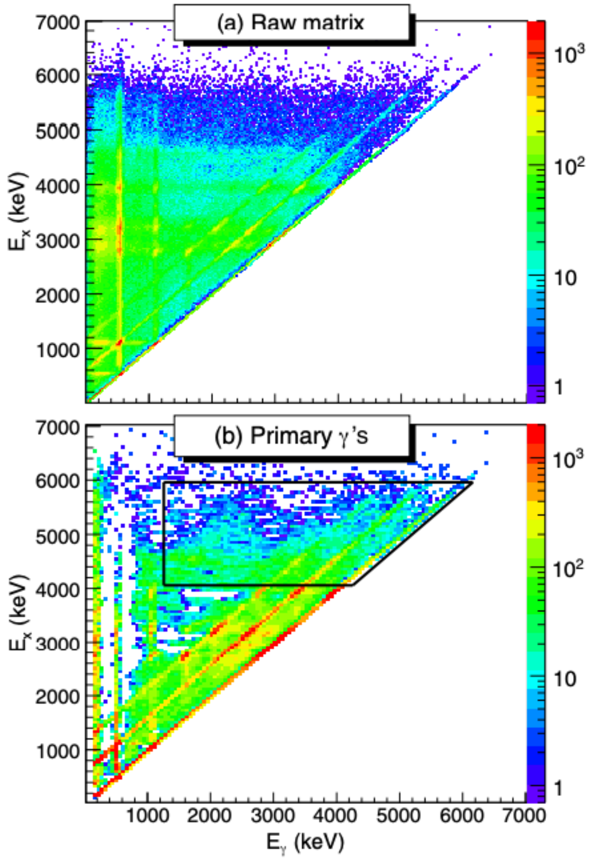
- Spectroscopy of the heavy elements (Z~100) – both prompt and decay spectroscopy – has been used to understand the single particle orbitals which are impactful to the stability of the SHE
- Gammasphere (or GRETA) + AGFA at ANL provides a key capability for such studies
  - Completed: Prompt spectroscopy including ^{254}Rf, ^{251}Md, ^{255}Lr and ^{254}No
  - Planned: Studies of prompt transitions in ^{249}Md, decay spectroscopy of Md - Db

The Statistical Structure of Nuclei

Reactions

- Where direct measurements of reaction rates are not possible, or experimentally challenging (such as neutron-capture rates) indirect approaches become critical – this can include calculations which require knowledge of statistical nuclear properties (level density, γ-ray strength functions)
- Approaches to measure such properties have been developed and continue to become increasingly important
- The β-Oslo method is one such development widely used since the last LRP

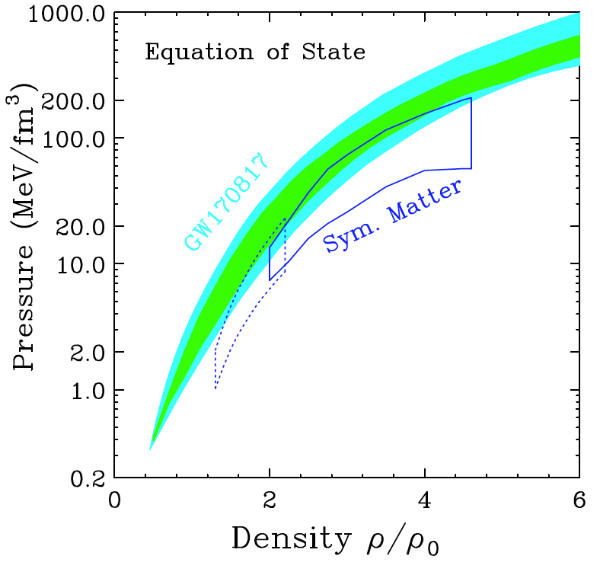




Spyrou *et al.*, PRL **113**, 232502 (2014).
Liddick *et al.*, PRL **116**, 242502 (2016).

The Equation of State and Low-Energy Nuclear Experiment

Reactions



Tsang *et al*., PLB **795**, 533 (2019).
Estee *et al*., PRL **126**, 162701 (2021).

- Experiments on nucleus-nucleus collisions in the laboratory were carried out to constraint the symmetry energy contribution to the Equation of State (EoS) of nuclear matter
- Measurements using the SπRIT TPC at RIBF on a range of Sn isotopes using neutron-rich RIB were used to characterize the symmetry energy at high density over a range of $\delta = (\rho_n - \rho_p)/\rho$
- Gravitational wave observations now add new constraints to the EoS – the next years will inevitably see much progress in this area

Looking Forward

The Road Ahead

A belabored metaphor… but a bright future

- The user facilities and university laboratories form a solid **bedrock** for our community
- Detectors and instrumentation, which continue to be developed and evolve are the **tarmac** which finishes the road

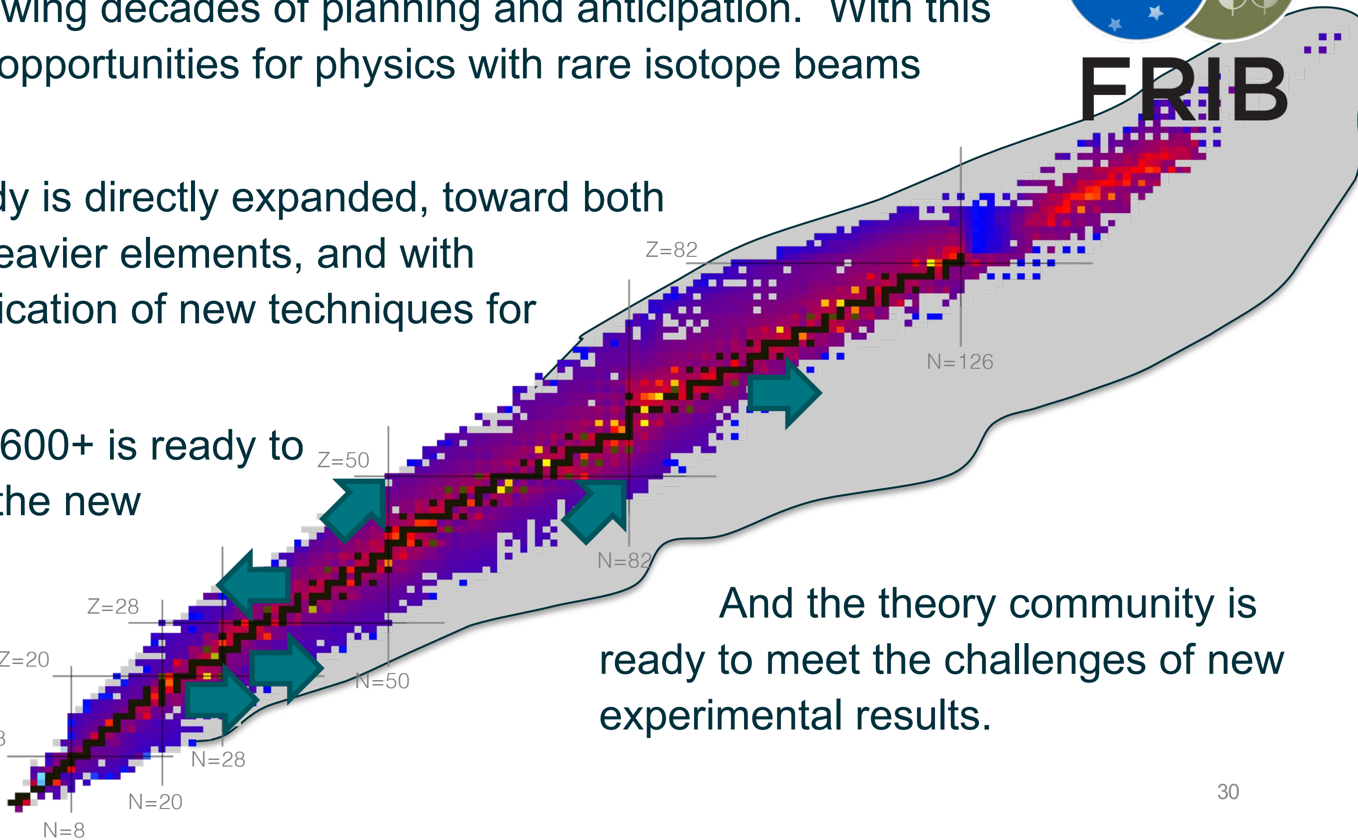
- Theory provides the **signposts**, though there will always be times to turn off the GPS
- Our community of **drivers** is engaged and excited
- The physics is our **destination**, with clear paths ahead in some areas, though always opportunities to explore new routes

Future Opportunities

FRIB is complete, following decades of planning and anticipation. With this milestone comes new opportunities for physics with rare isotope beams from fragmentation.

The landscape for study is directly expanded, toward both driplines, toward the heavier elements, and with intensity enabling application of new techniques for these exotic systems.

A user community of 1600+ is ready to take full advantage of the new facility



And the theory community is ready to meet the challenges of new experimental results.

Future Opportunities

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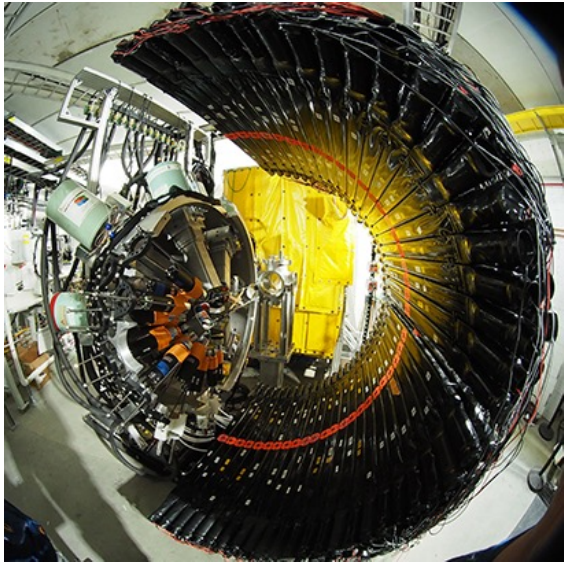


The first experiments have been completed with a first PRL accepted.

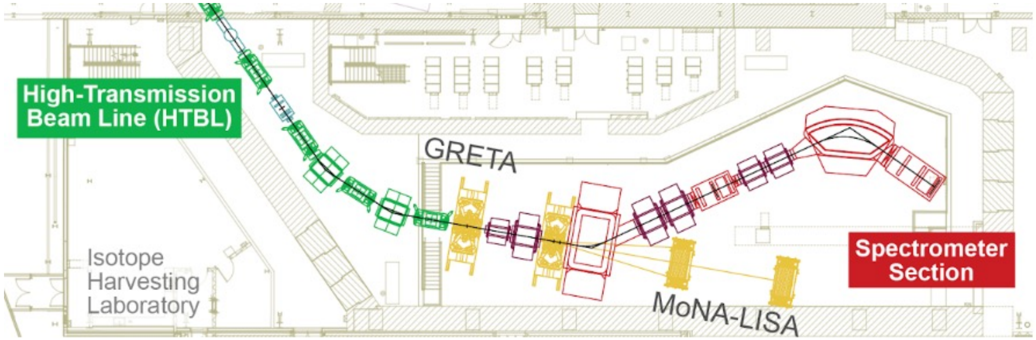
The FDSi, GRETINA and the S800 have already featured strongly at FRIB – in the future capabilities will only expand with GRETA, the HRS, FDS, SECAR, JENSA, BECOLA, LEBIT,…

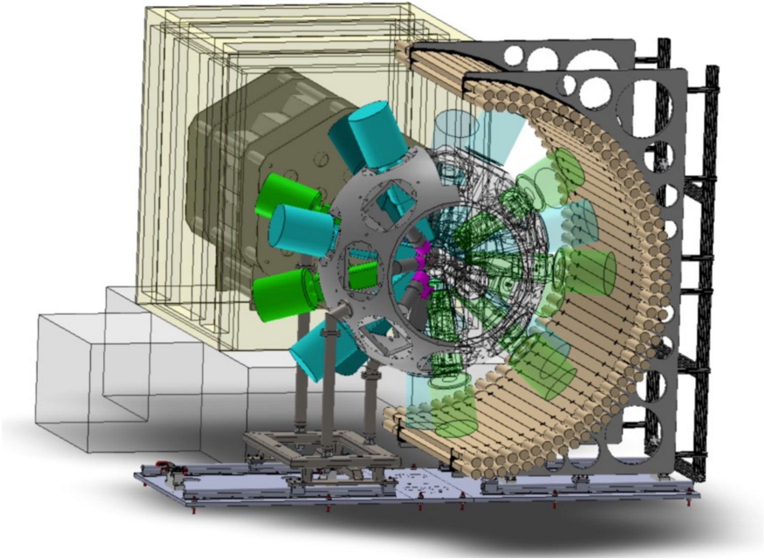
The FRIB 400 MeV upgrade can further extend the reach of this cutting-edge facility.

Future Opportunities

The nature of FRIB beam time requires us to be strategic with our approach to experiments

- Measurements should be as ‘complete’ as possible
- Each experiment is an opportunity for broader participation, student and postdoc training and community building



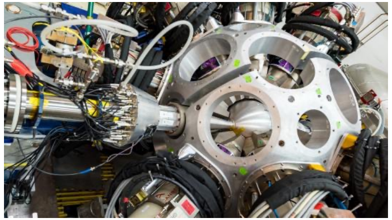


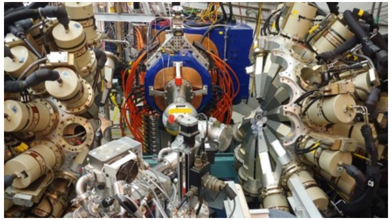
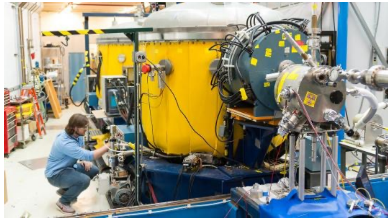
Future Opportunities

ATLAS continues to be the premier stable beam facility for the U.S., but is also constantly evolving and adding capabilities

- A large national and international user community fields a diverse physics program using the full suite of ATLAS systems
- nuCARIBU and the *N*=126 factory will continue to add to the accessible physics
- Equipment is keeping pace – FMA, HELIOS, Gammasphere, AGFA, CPT, MUSIC, GRETINA/GRETA, …





Future Opportunities

The ARUNA labs play an important role in our field, leading the way in many areas

- Excellent science output, complementing the capabilities of the major user facilities
- Education and training
- Diverse and flexible technical capabilities

Building our community in a diverse and equitable way

- The RENEW-type programs have provided an infusion of funds to open new pipelines for students across the country
- This is just a start, and something we must continue to make a priority

What will be the science highlights in 2030?

- Delineation of the neutron dripline toward Z=20
- Discovery of a direct 6-proton emitter (?)
- Identification of correlated 2n emission after β decay
- Invariant mass spectroscopy of unbound states in $^{39,40,(41,42)}$Mg
- A full understanding of the “quenching problem” in direct reactions
- Measurement of the structure of ^{60}Ca and toward ^{70}Ca
- The single-particle structure of ^{101}Sn and perhaps ^{99}Sn pinned down
- Lifetime of ^{104}Te measured, and a new understanding of α preformation
- Spectroscopy along decay chains of SHE (Z > 104)
- The discovery of new element(s) – 119, 120

Thank You