First FRIB experiment: new microsecond isomer in ^{32}Na discovered with the FDSi

T.J. Gray – ORNL

On behalf of the FDSi Group

- The accelerator we use to generate the isotopes:

  The **F**acility for **R**are **I**sotope **B**eams (**FRIB**)

Oak Ridge National Laboratory

- The accelerator we use to generate the isotopes:

  The **F**acility for **R**are **I**sotope **B**eams (**FRIB**)

- The detectors we use to study the isotopes

  The **F**RIB **D**ecay **S**tation **i**nitiator (**FDSi**)

- The accelerator we use to generate the isotopes:

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- The detectors we use to study the isotopes

  The **F**RIB **D**ecay **S**tation **i**nitiator (**FDSi**)

- (some of) the science we get out

  New microsecond isomer in ^{32}Na

Atomic Versus Nuclear Shells

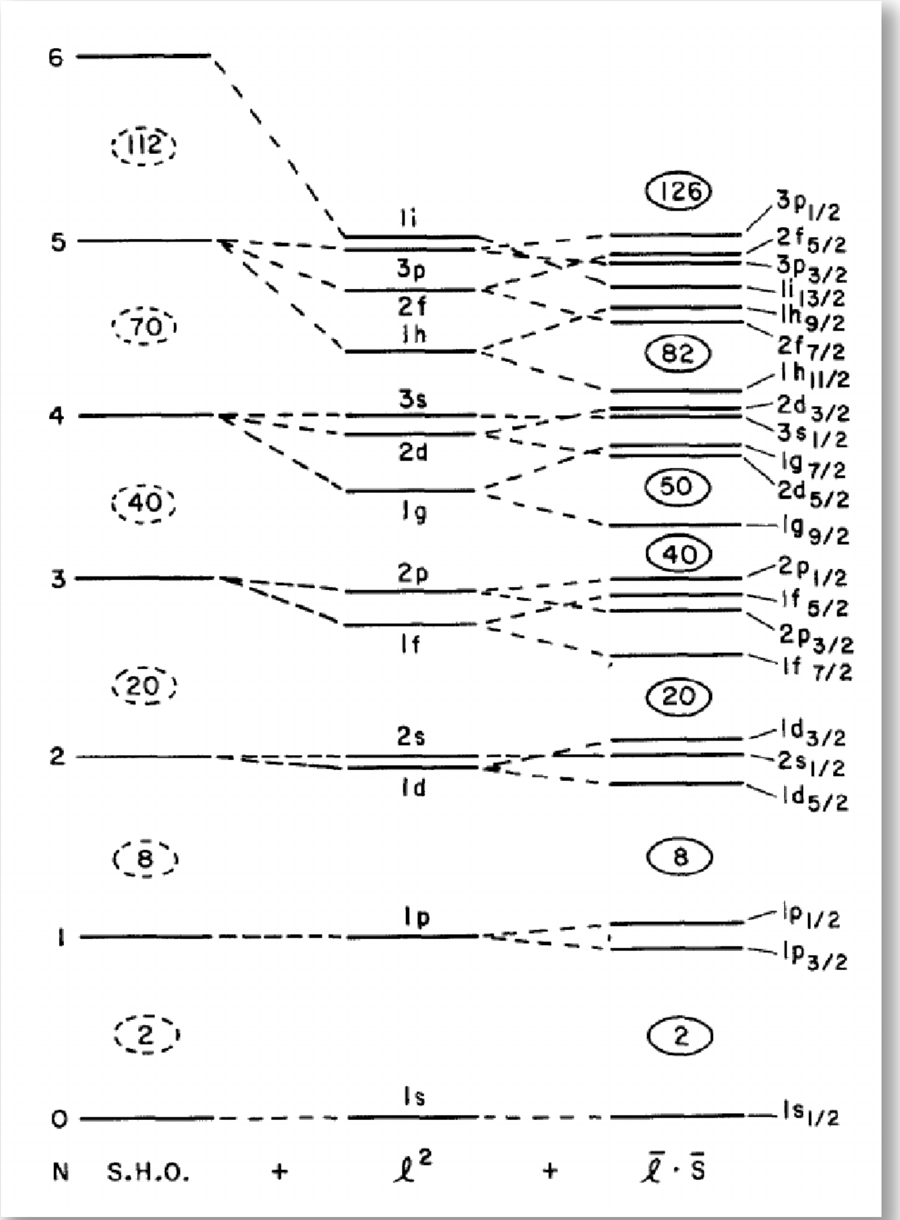
Many body finite quantum systems often exhibit shell structure

Atomic magic numbers: 2, 10, 18, 36, 54, 86

Nuclear magic numbers: 2, 8, 20, 28, 50, 82, 126

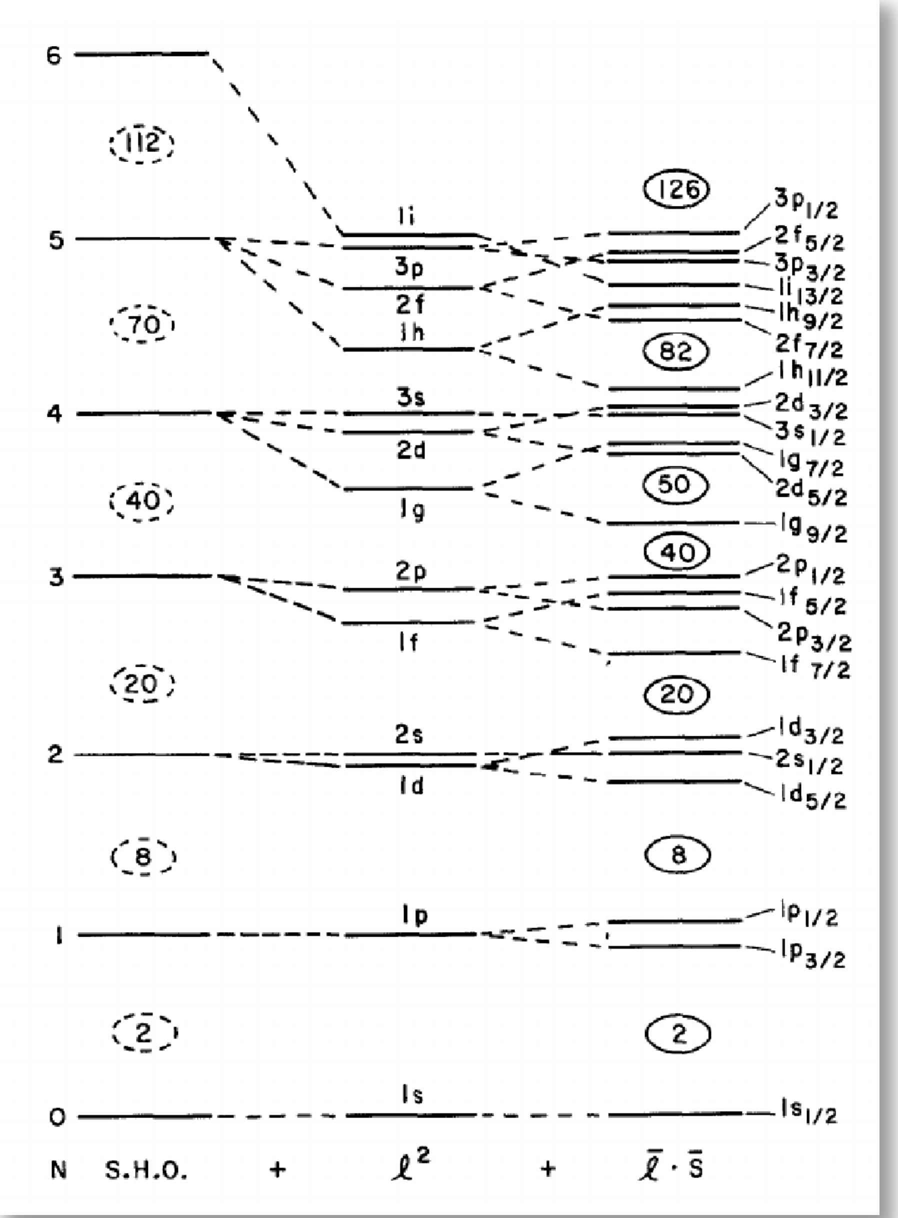
Magic numbers = closed shell locations
i.e., location of binding/seperation discontinuities

Nuclear shell model

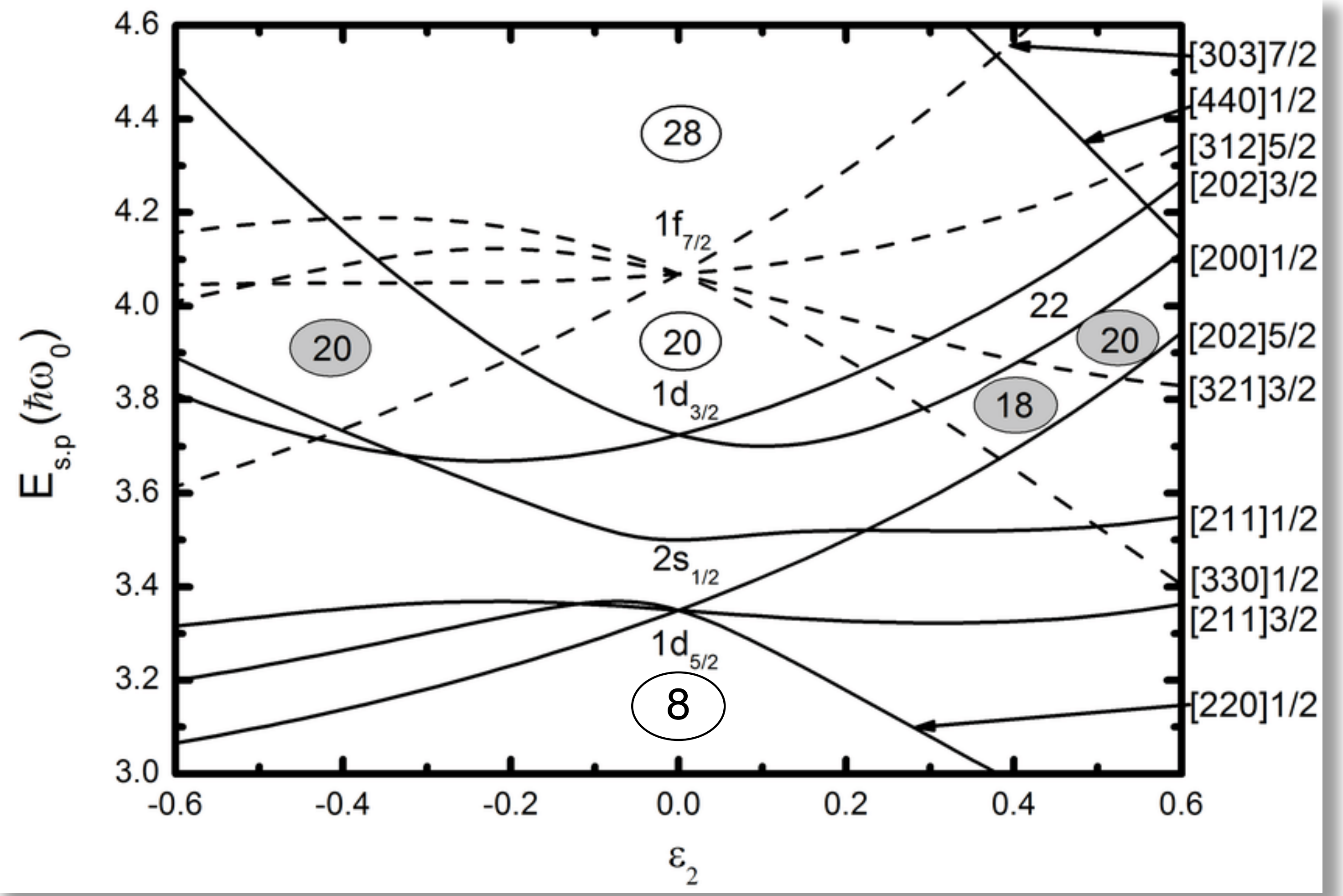


Spherical shell model

Nuclear shell model



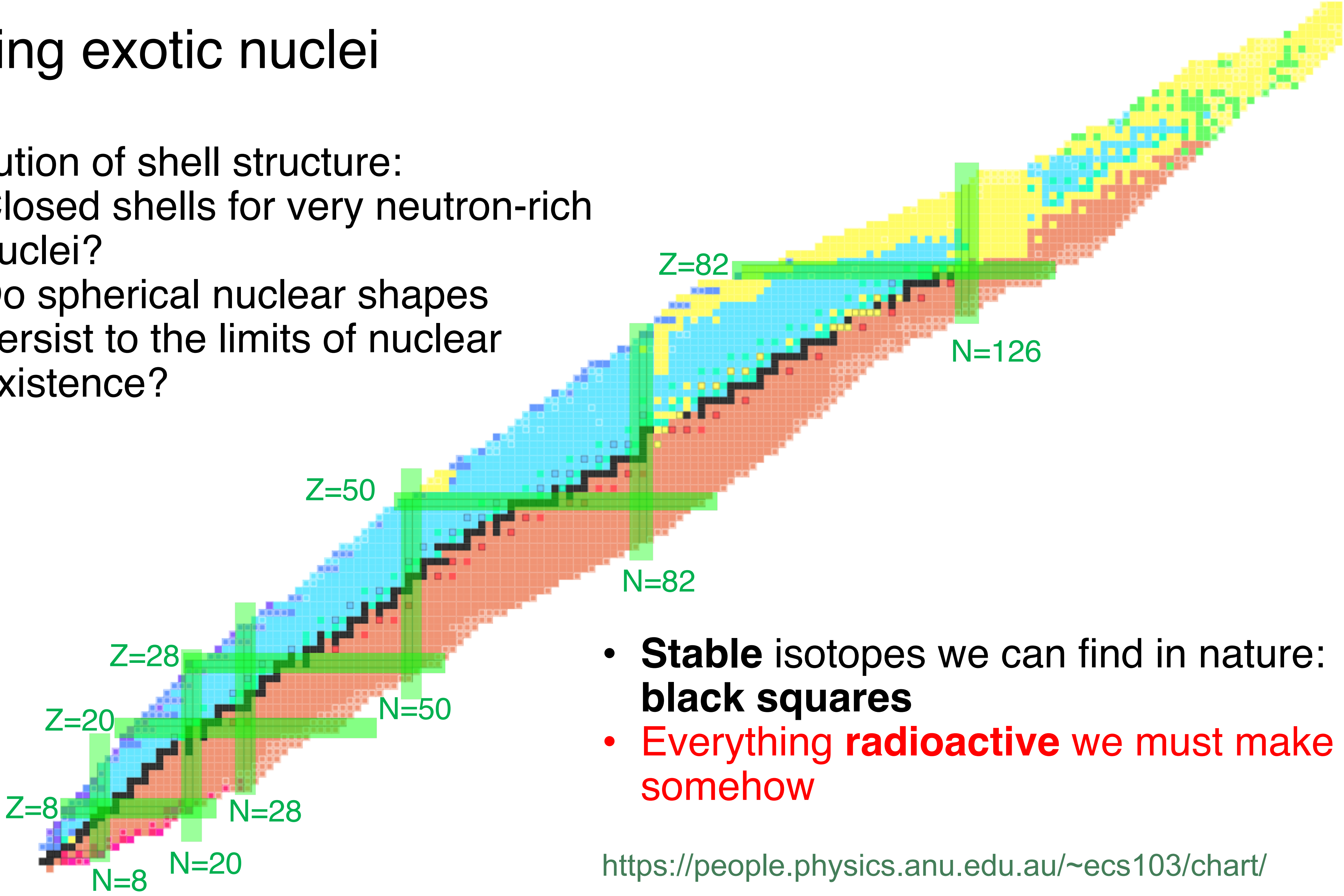
Spherical shell model



"Deformed" shell model

Studying exotic nuclei

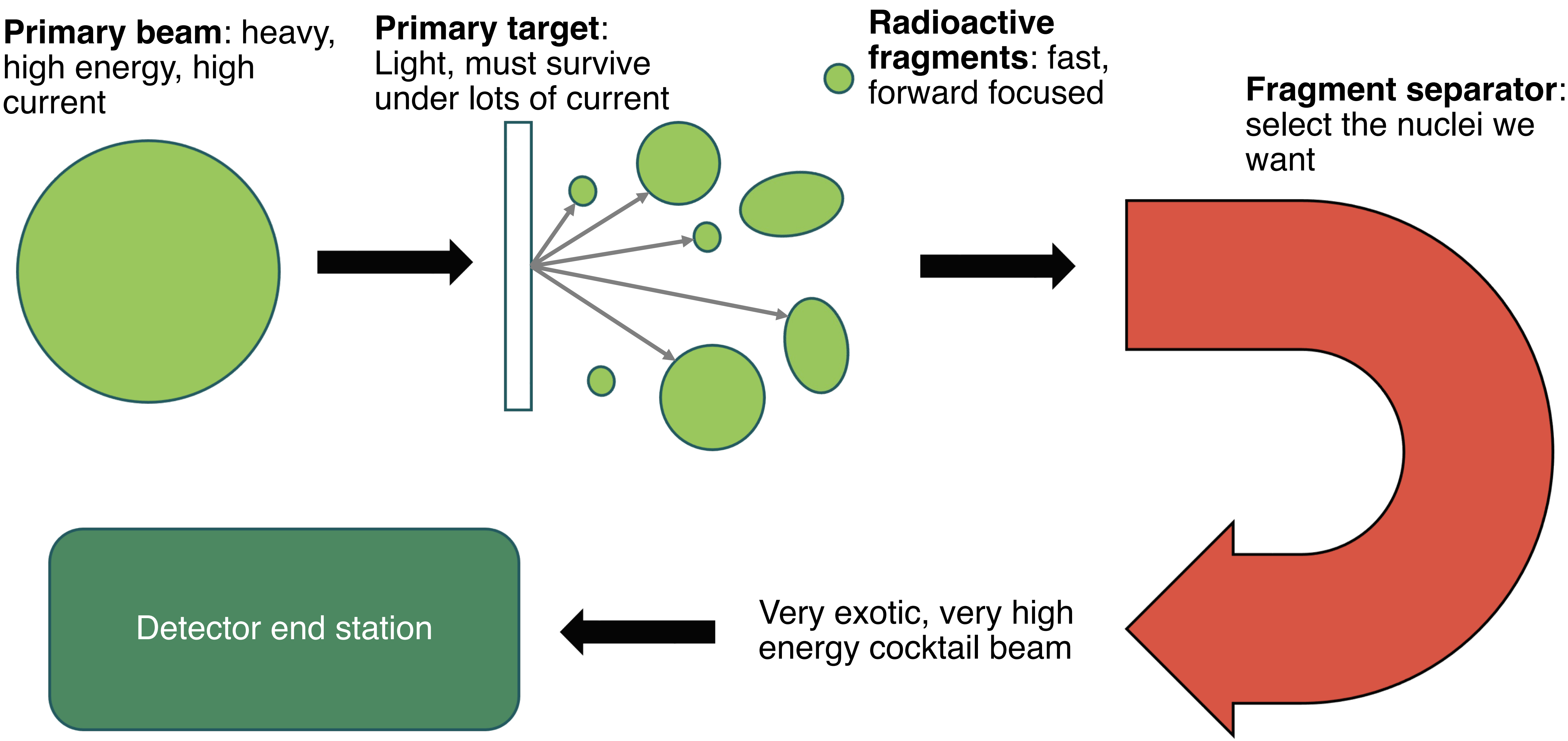
- Evolution of shell structure:
  - Closed shells for very neutron-rich nuclei?
  - Do spherical nuclear shapes persist to the limits of nuclear existence?



- **Stable** isotopes we can find in nature: **black squares**
- Everything **radioactive** we must make somehow

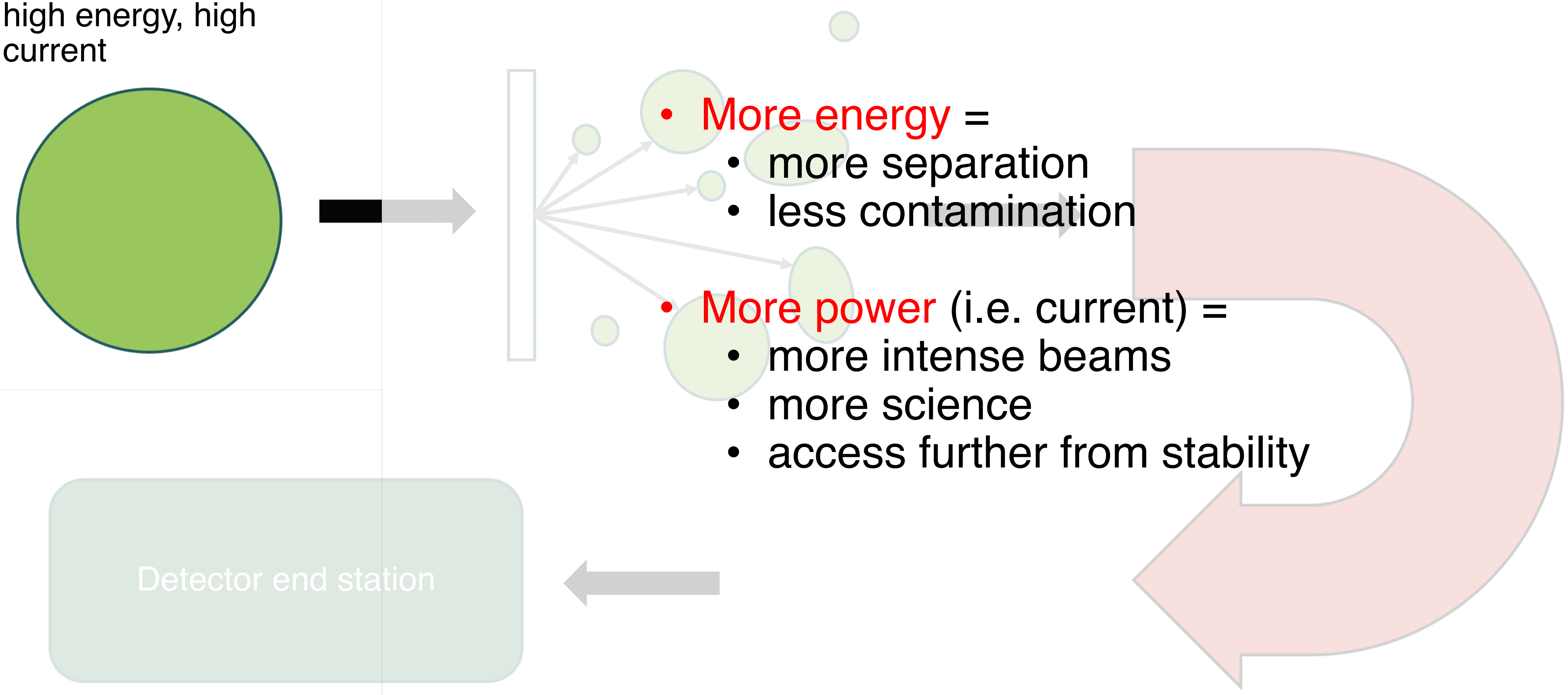
https://people.physics.anu.edu.au/~ecs103/chart/

Fragmentation to produce radioactive beams



Fragmentation to produce radioactive beams

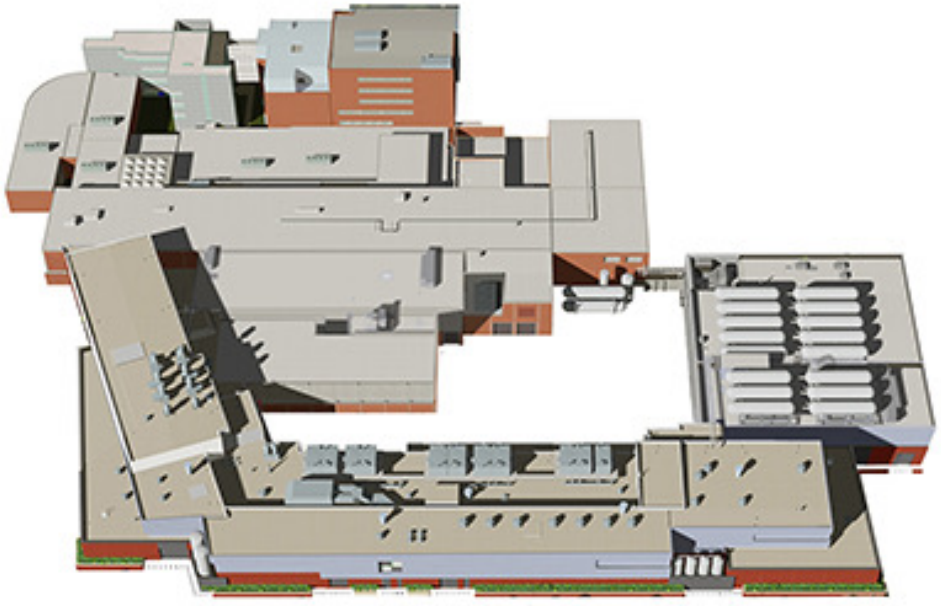
Primary beam: heavy, high energy, high current



- More energy =
  - more separation
  - less contamination
- More power (i.e. current) =
  - more intense beams
  - more science
  - access further from stability

Facility for Rare Isotope Beams (FRIB) – A DOE User Facility

https://frib.msu.edu

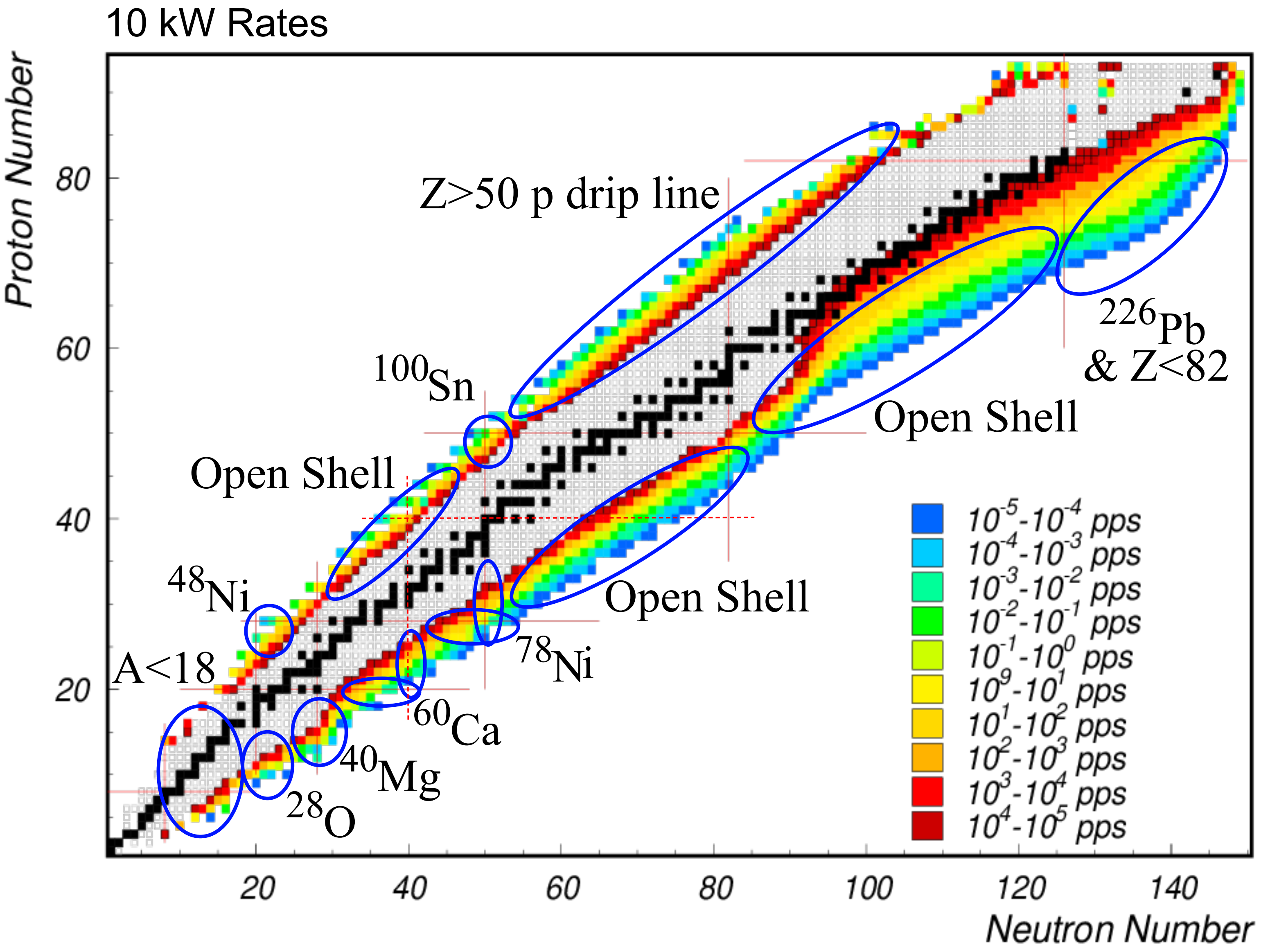


More energy: 200 MeV/u (upgrade planned), up to Uranium primary beam

More power: 400 kW full power, unprecedented access to exotic nuclei; will produce 80% of isotopes predicted to exist for $Z < 93$

- Properties of rare isotopes
- Nuclear astrophysics
- Fundamental interactions
- Applications for society, including in medicine, homeland security, and industry.

Facility for Rare Isotope Beams (FRIB) – A DOE User Facility



Challenges of Decay Measurements at FRIB

- Long decay chains of short-lived isotopes (~40 isotopes populated)
- Short and similar (10-100 ms) lifetimes
- Simultaneous or sequential electrons, X-rays, gamma rays, and neutrons
- Multi-neutron branching ratios
- Large dynamic ranges

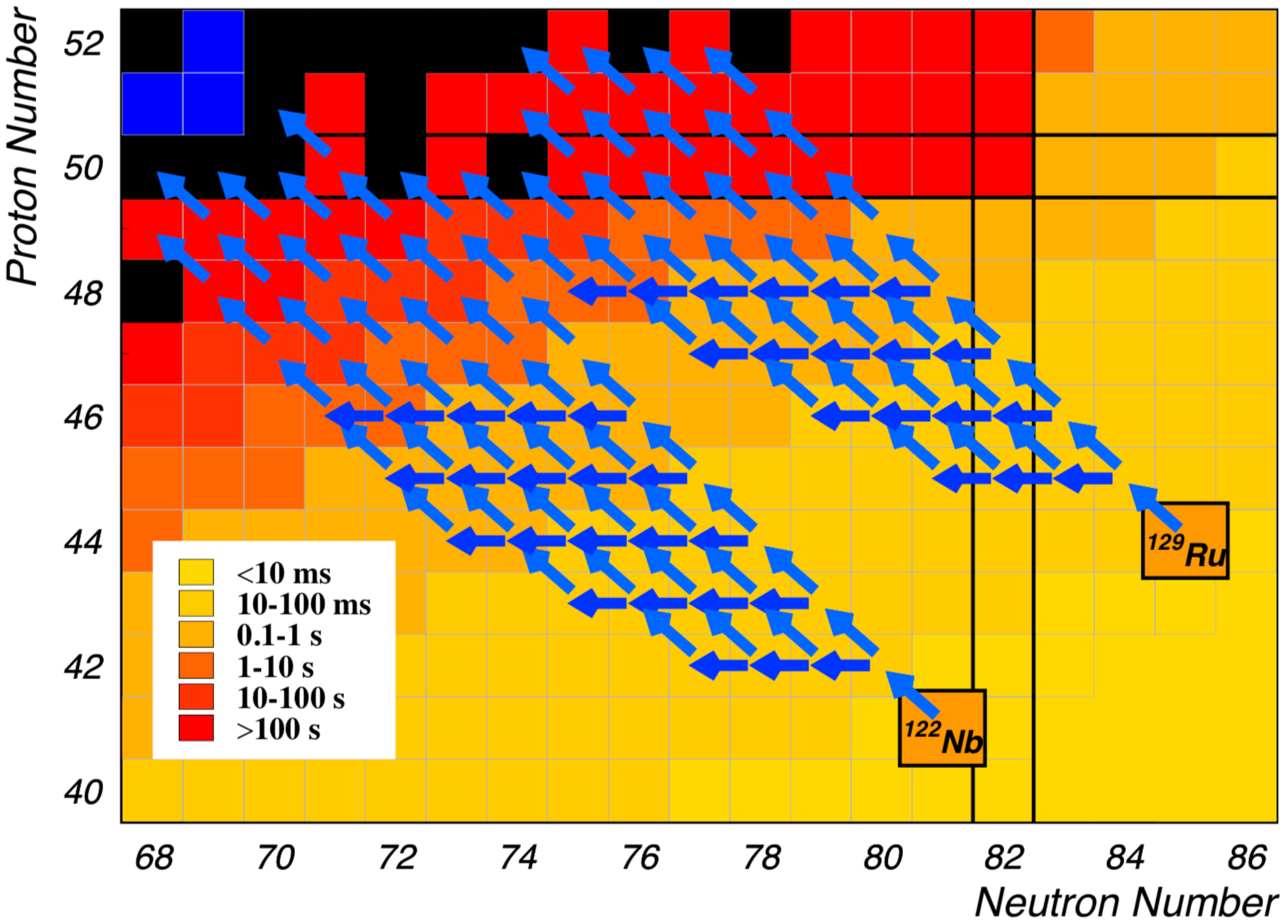


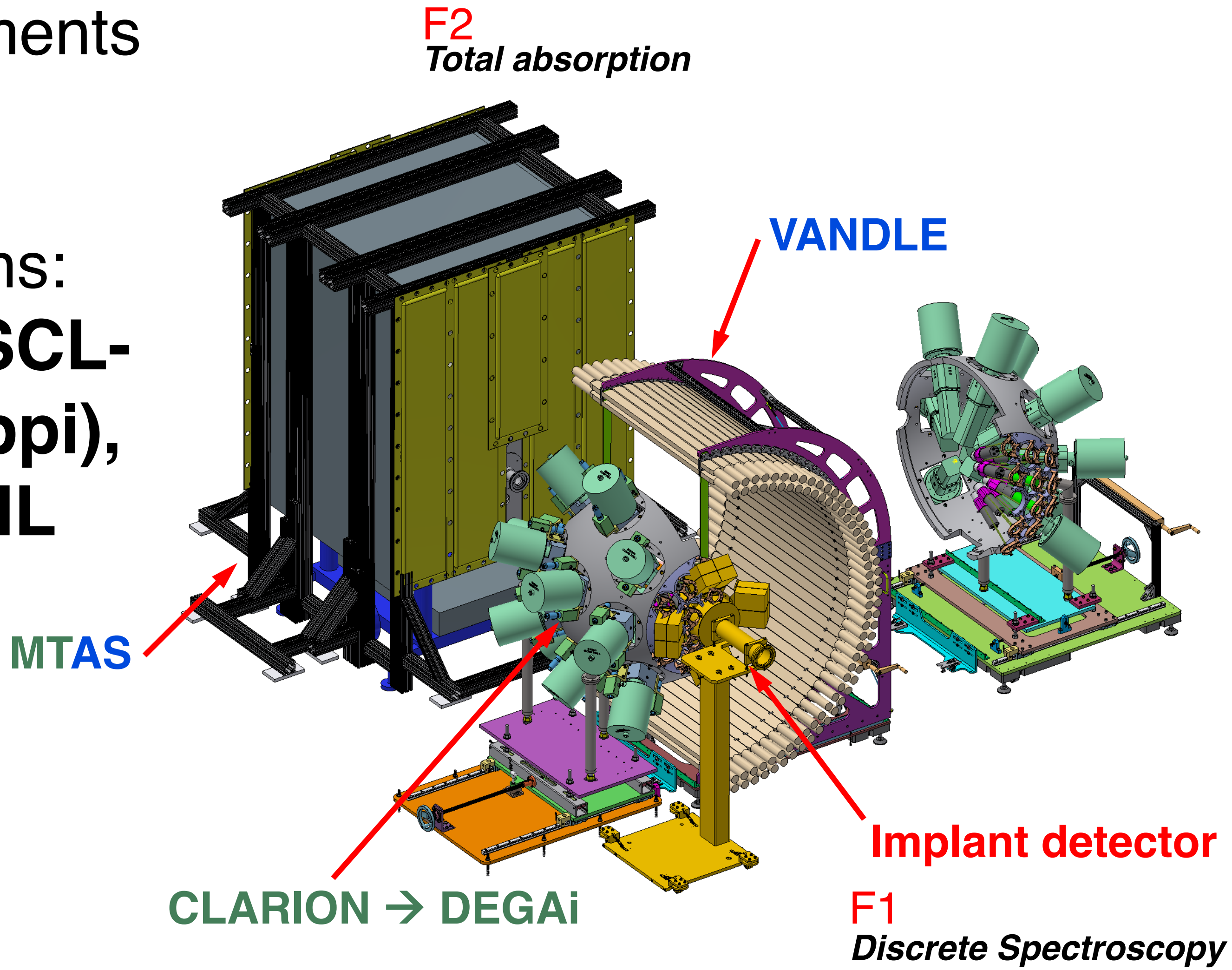
Figure Courtesy of R. Grzywacz

The **F**RIB **D**ecay **S**tation **i**nitiator (FDSi)

- Integration of community detectors
- Reconfigurable infrastructure
- Complete / Tandem measurements

- Many contributing organizations: **ORNL, UTK, ANL, FRIB-NSCL-MSU, FSU, MSU (Mississippi), URSinus, UNC, LLNL, LBNL**

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



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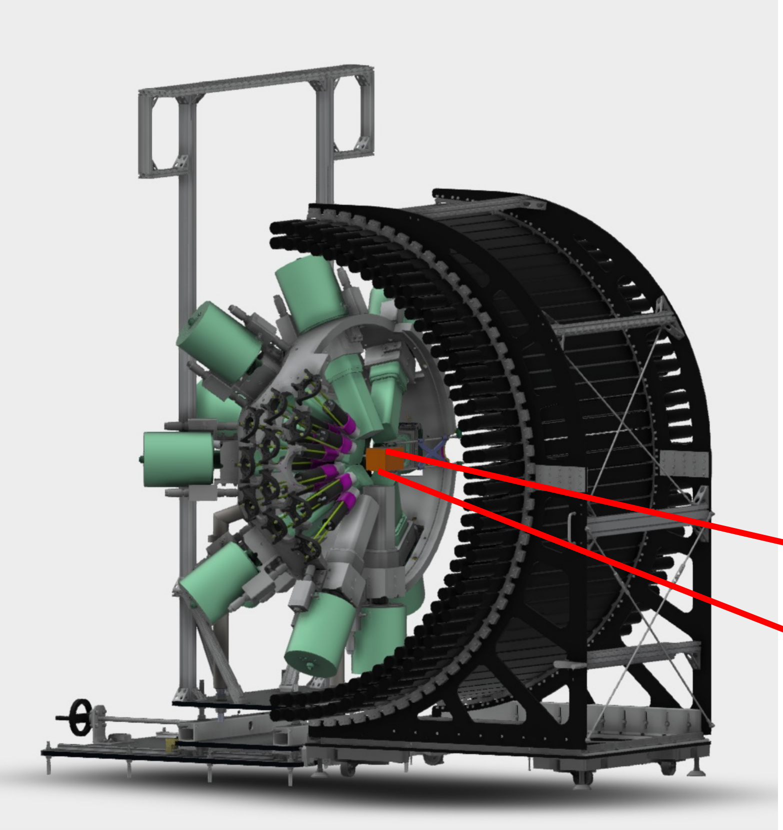
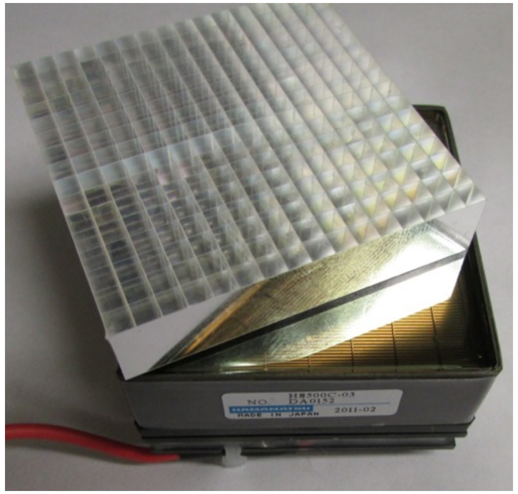
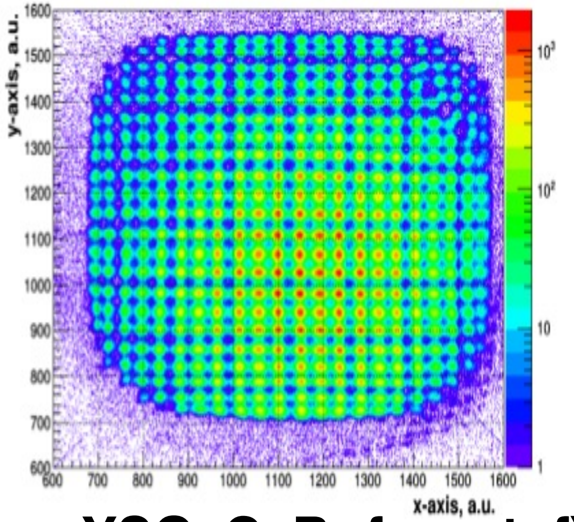
Implant detector for the first experiment

Developed by Robert Grzywacz and the UTK group

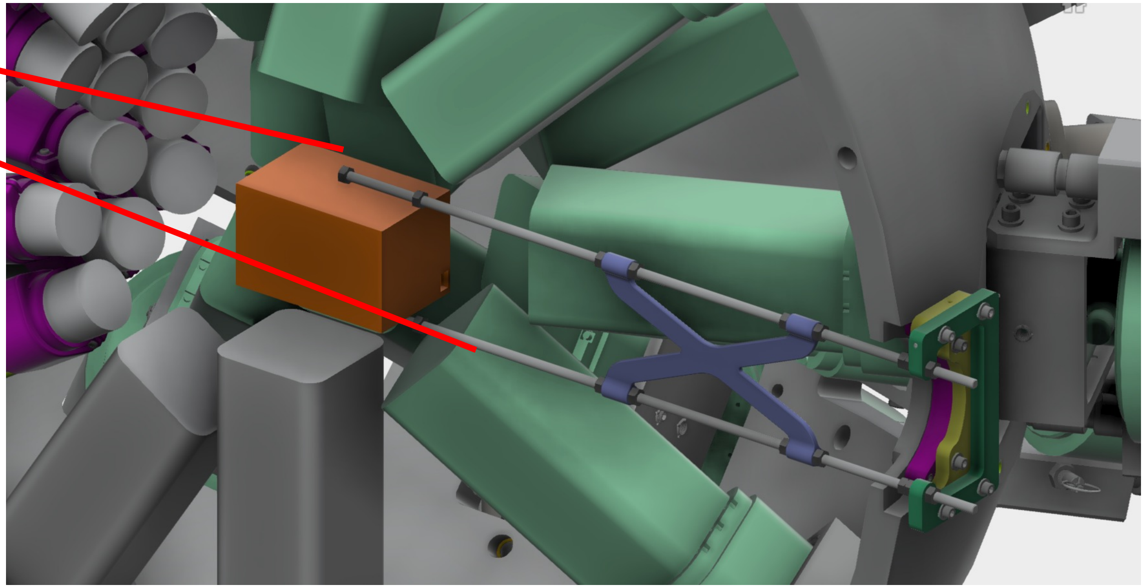


High stopping power and fast

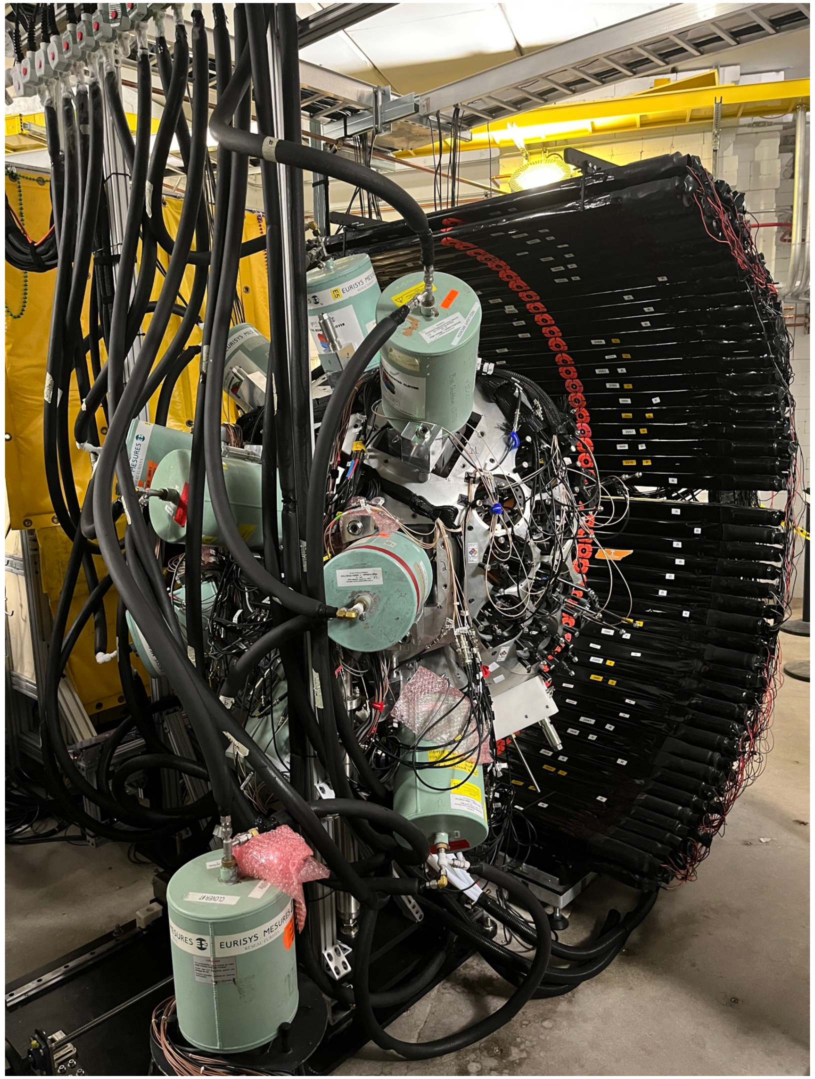


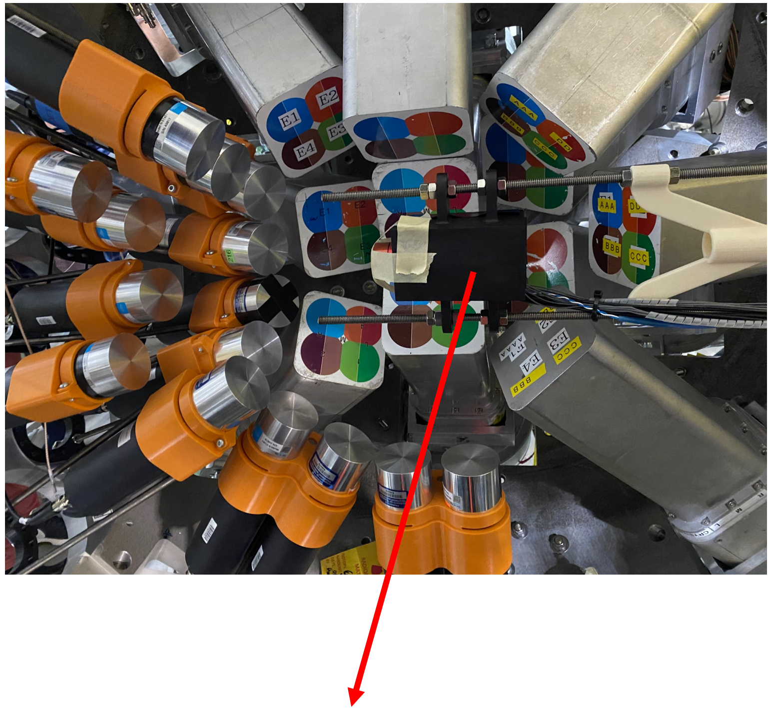


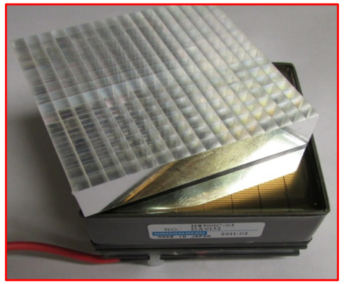
Implant detector (e.g., YSO, CeBr for n-tof)

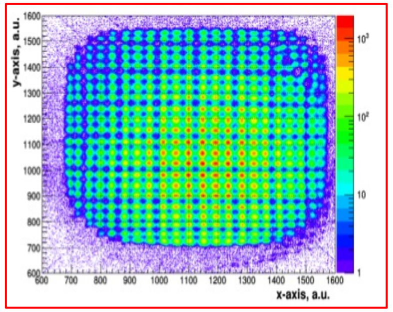


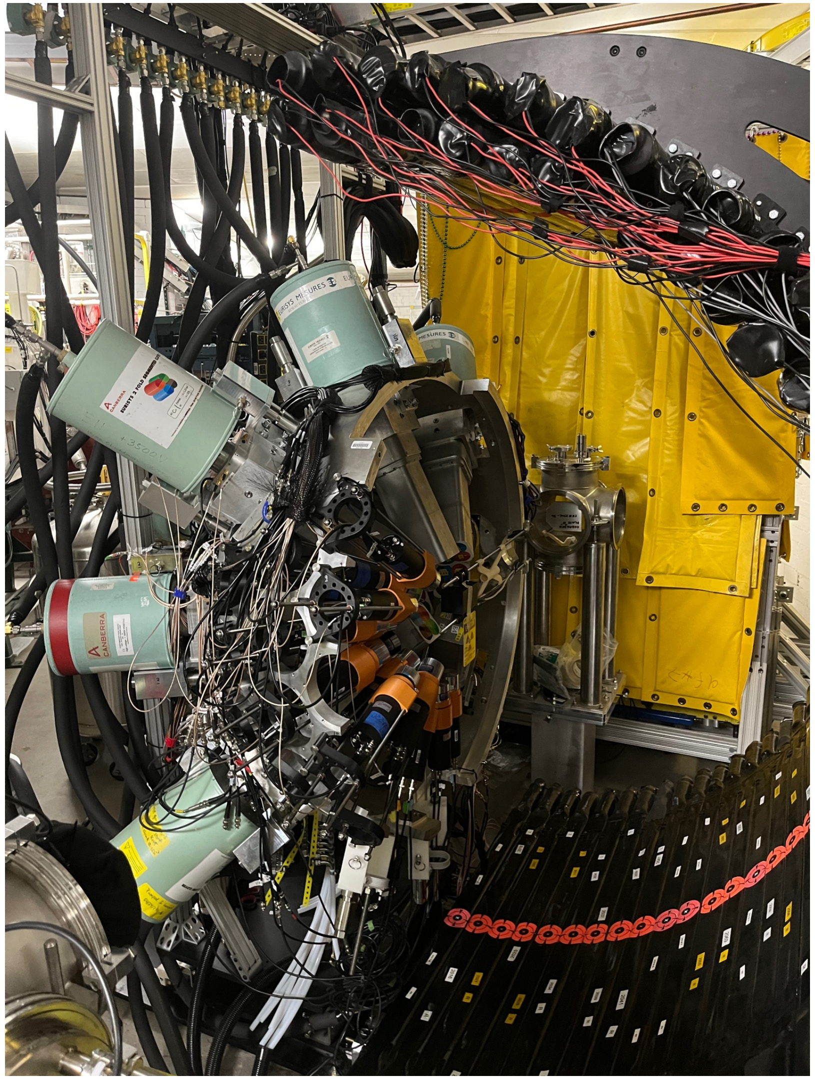
The FDSi Setup for 1st FRIB Experiment





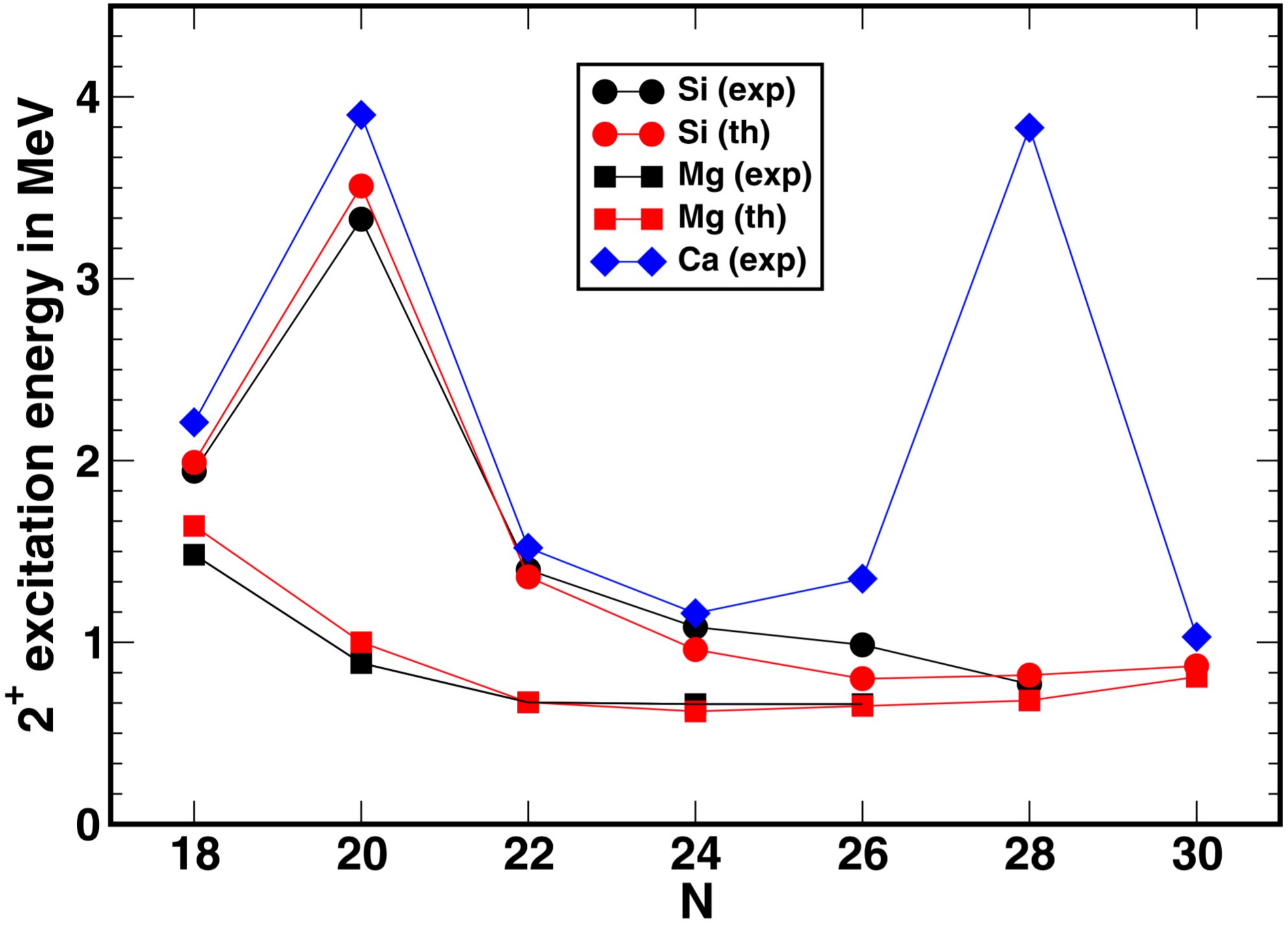


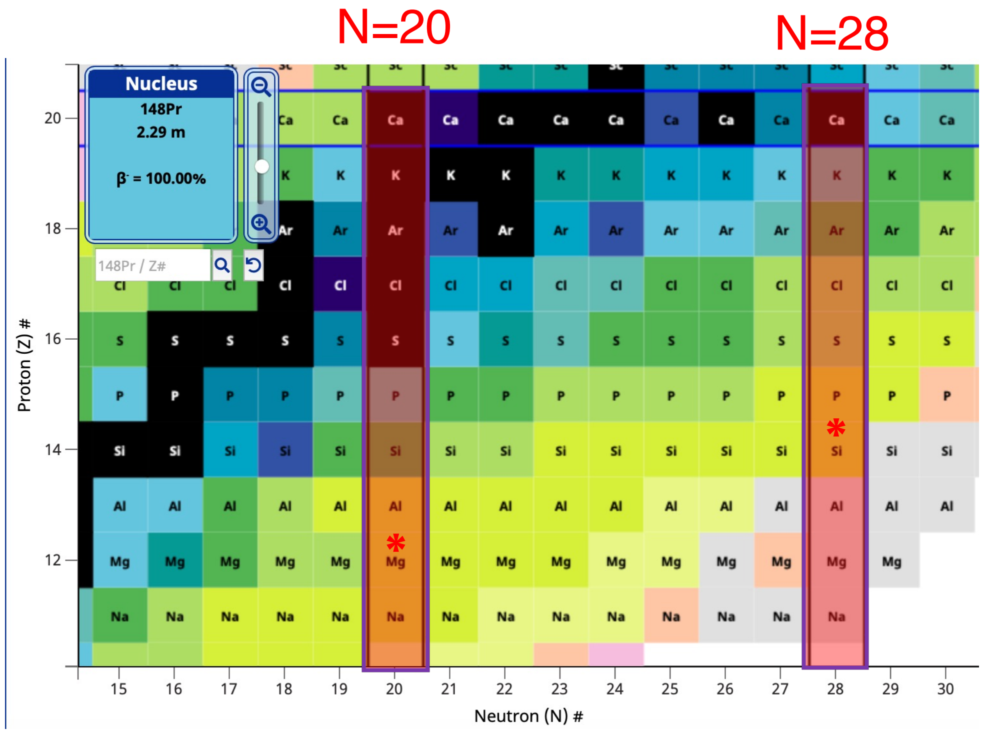




First FRIB experiment

"Decay Spectroscopy Near N=28: Shell Structure, Shapes and Weak Binding" - Heather Crawford (**LBNL**) – May 5, 2022





*calculated values with the SDPF-U-MIX interaction.

A. Poves, J. Phys. G: Nucl. Part. Phys. **44**, 084002 (2017).

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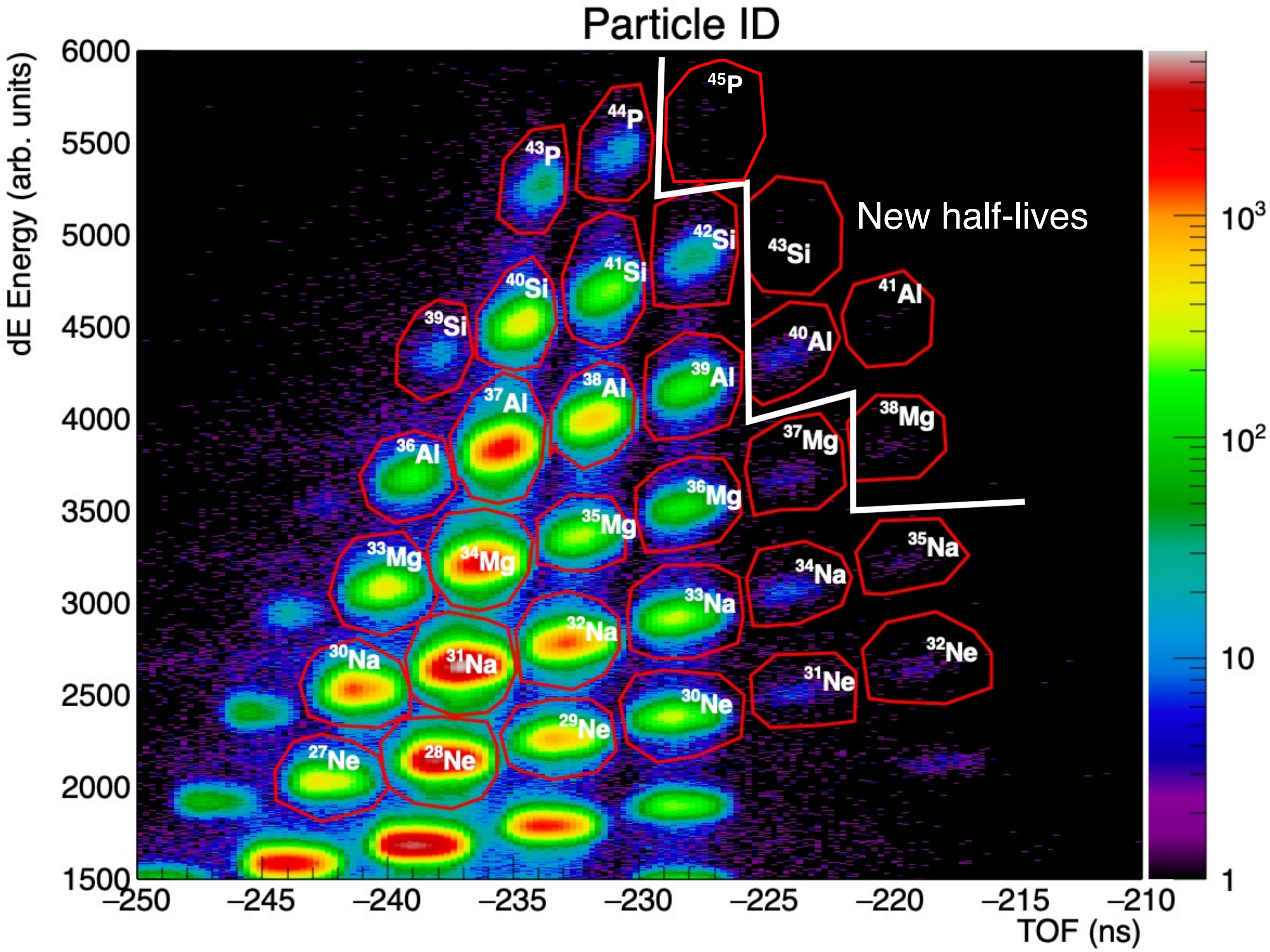
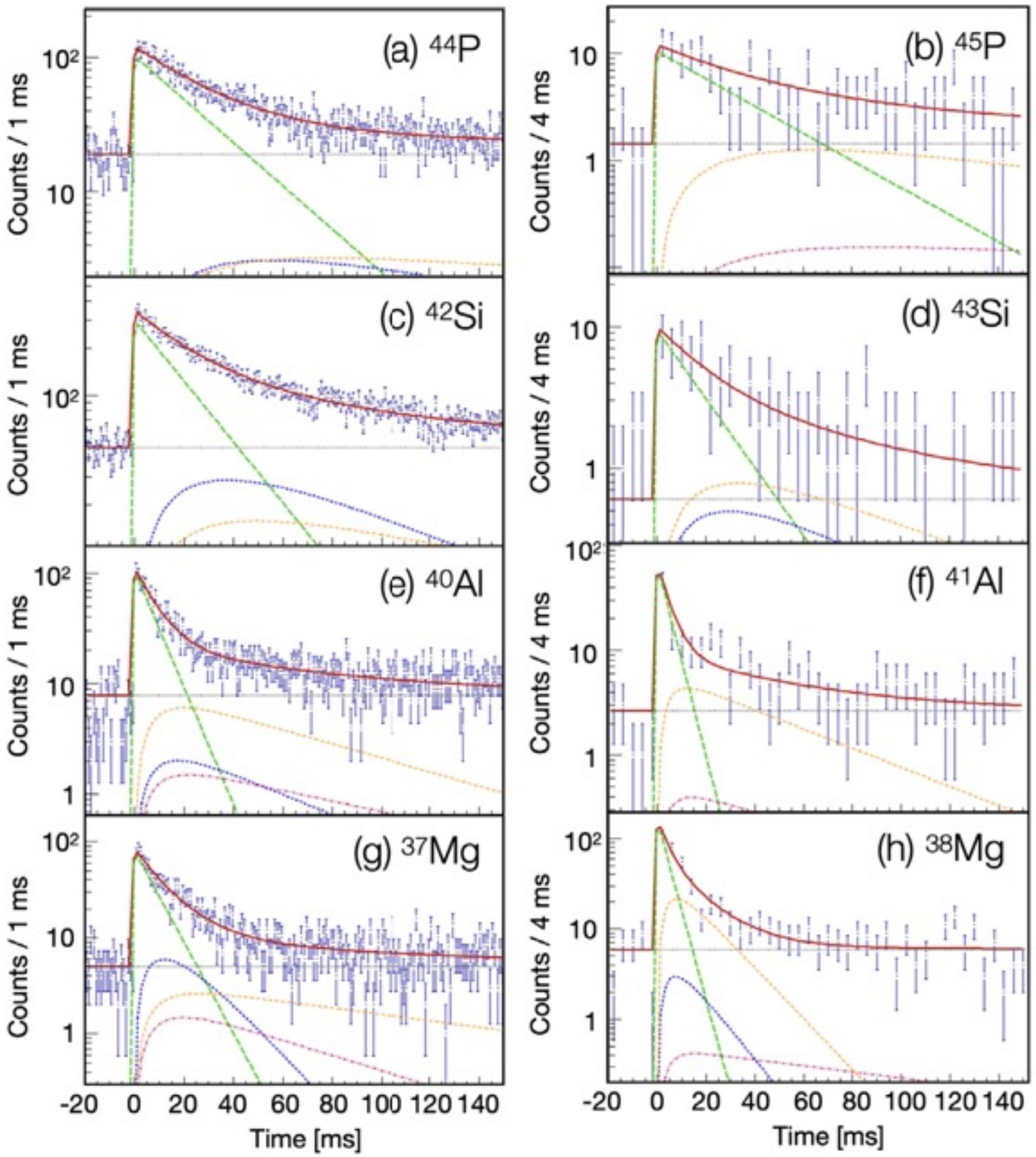
Particle ID from the first experiment

- Many radioactive isotopes produced
- Up to and past N=28 (^{42}Si)
- 5 isotopes with half-lives previously unmeasured



New half-lives from beta-implant time differences

- Position-sensitive implant detector detects both **implants and betas**
- Correlate over 100s of ms
- Build up **beta-implant time difference** for each isotope independently
- Fit with background + **Bateman equations**
    - daughters, granddaughters, beta-n branches etc.



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New half-lives from beta-implant time differences

PHYSICAL REVIEW LETTERS **129,** 212501 (2022)

Editors' Suggestion | Featured in Physics

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

H. L. Crawford,[1,*] V. Tripathi,[2] J. M. Allmond,[3] B. P. Crider,[4] R. Grzywacz,[5] S. N. Liddick,[6,7] A. Andalib,[6,8] E. Argo,[6,8] C. Benetti,[2] S. Bhattacharya,[2] C. M. Campbell,[1] M. P. Carpenter,[9] J. Chan,[5] A. Chester,[6] J. Christie,[5] B. R. Clark,[4] I. Cox,[5] A. A. Doetsch,[6,8] J. Dopfer,[6,8] J. G. Duarte,[10] P. Fallon,[1] A. Frotscher,[1] T. Gaballah,[4] T. J. Gray,[3] J. T. Harke,[10] J. Heideman,[5] H. Heugen,[5] R. Jain,[6,8] T. T. King,[3] N. Kitamura,[5] K. Kolos,[10] F. G. Kondev,[9] A. Laminack,[3] B. Longfellow,[10] R. S. Lubna,[6] S. Luitel,[4] M. Madurga,[5] R. Mahajan,[6] M. J. Mogannam,[6,7] C. Morse,[11] S. Neupane,[5] A. Nowicki,[5] T. H. Ogunbeku,[4,6] W.-J. Ong,[10] C. Porzio,[1] C. J. Prokop,[12] B. C. Rasco,[3] E. K. Ronning,[6,7] E. Rubino,[6] T. J. Ruland,[13] K. P. Rykaczewski,[3] L. Schaedig,[6,8] D. Seweryniak,[9] K. Siegl,[5] M. Singh,[5] S. L. Tabor,[2] T. L. Tang,[2] T. Wheeler,[6,8] J. A. Winger,[4] and Z. Xu[5]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[4]*Department of Physics and Astronomy, Mississippi State University, Mississippi State, Mississippi 39762, USA*
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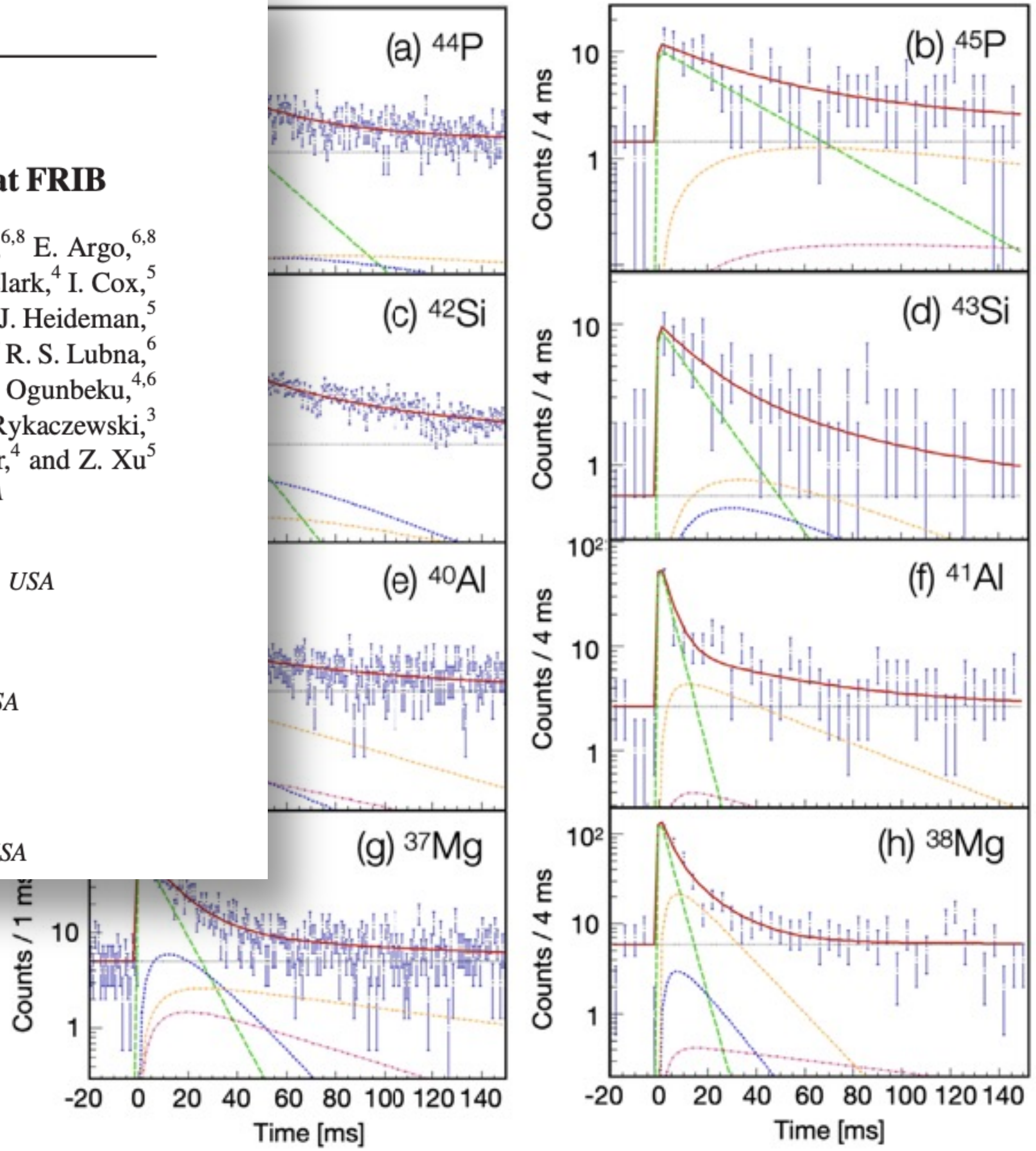
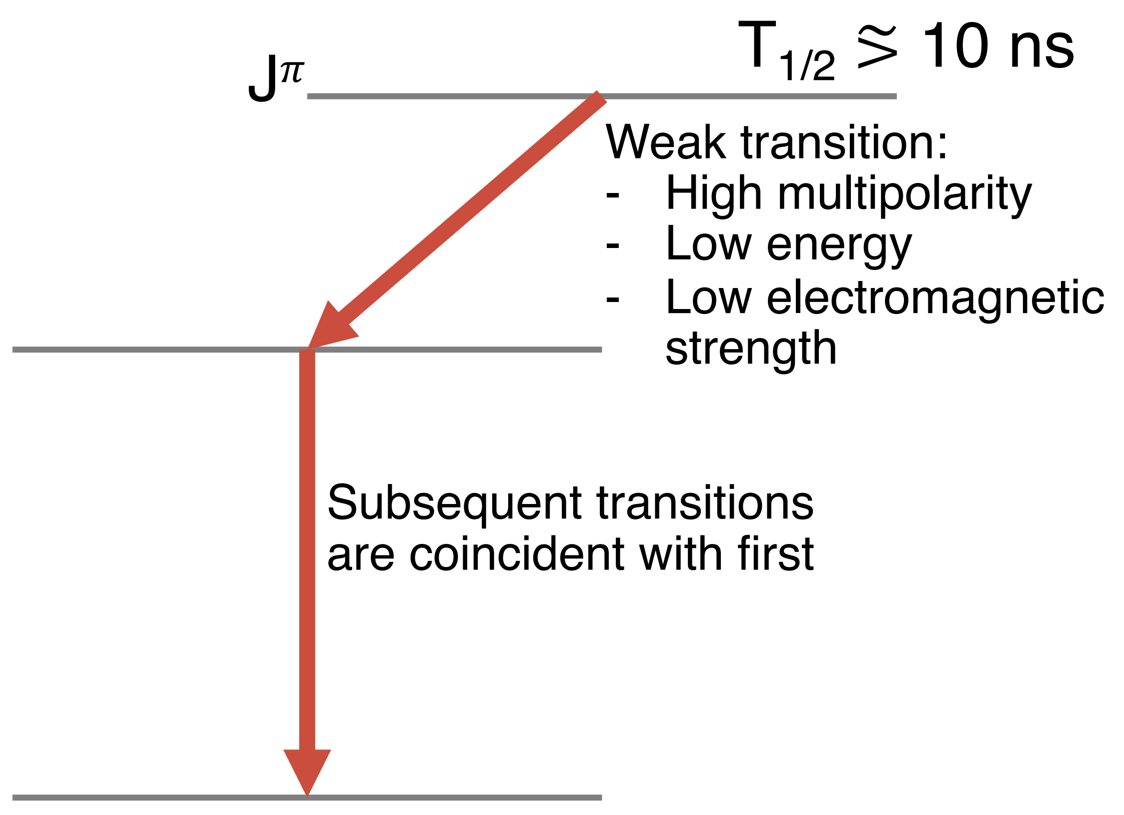


Beam isomers

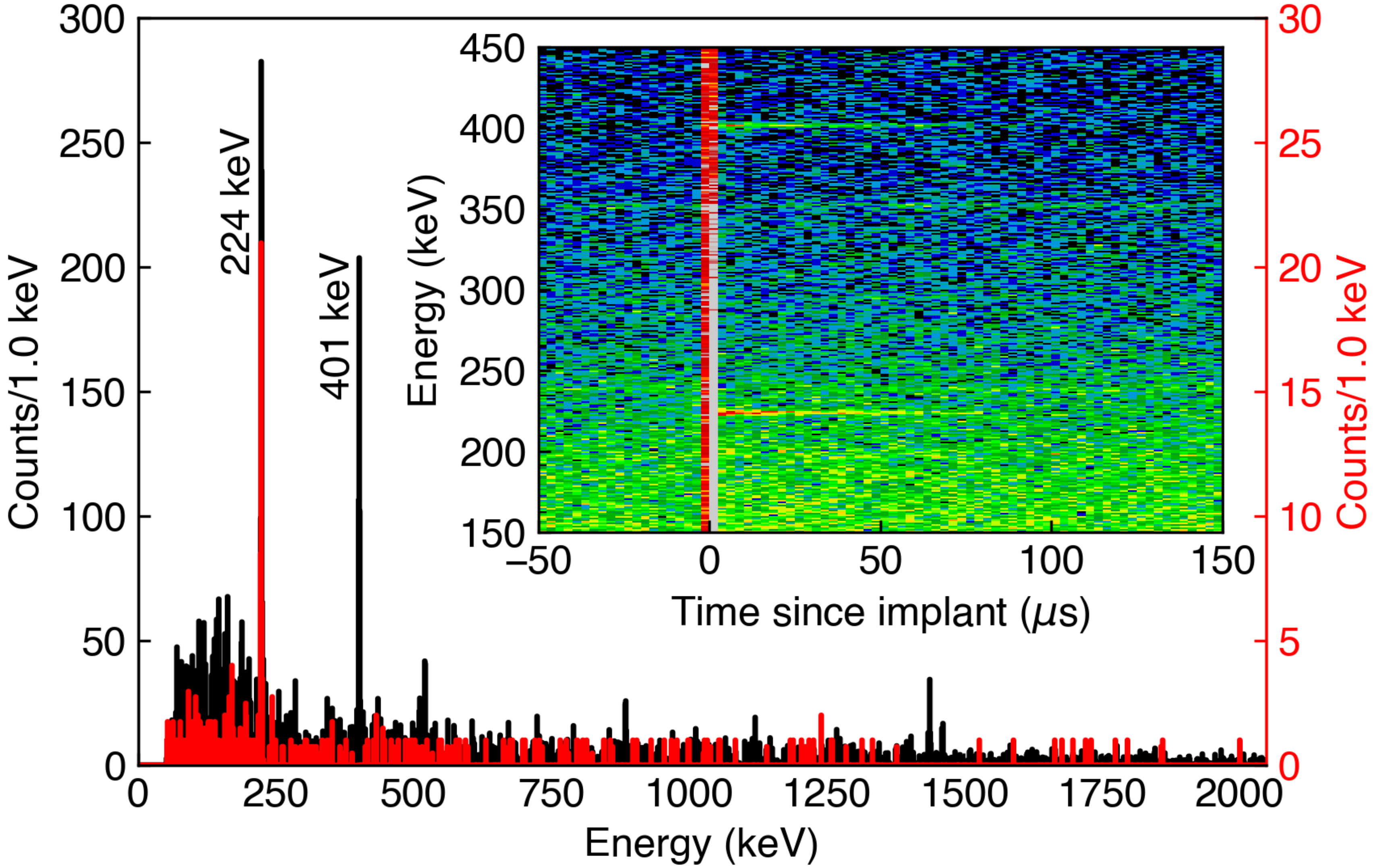
- Isomer = long-lived excited state
- Beam isomer = isomer present in the beam
  - Useful for identification – if we see gammas associated with particular ions we can positively identify the ion
- Lack of micro-second isomers in region
  - 9 μs, in ^{26}Na, 0.4 μs in ^{43}S, 2.6 μs in ^{44}S



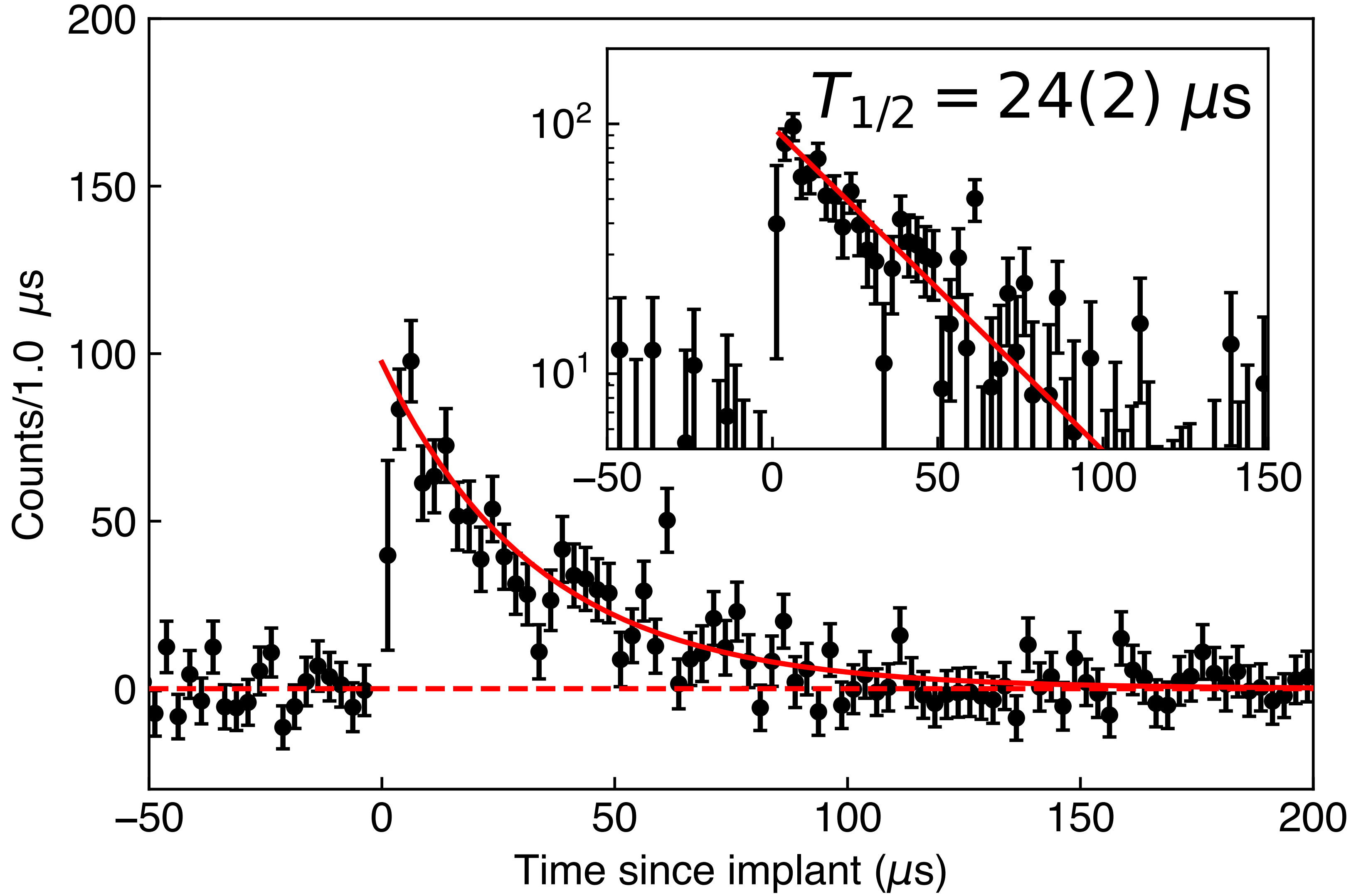
New beam isomer in ^{32}Na

Isomer found with a cascade two delayed transitions in coincidence

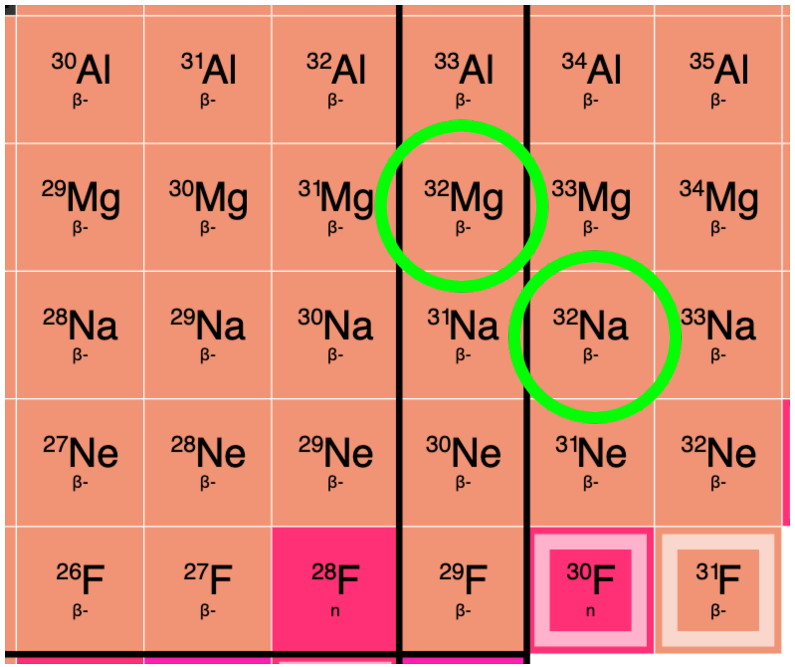
- Singles
- Gate on 401 keV



New beam isomer in ^{32}Na



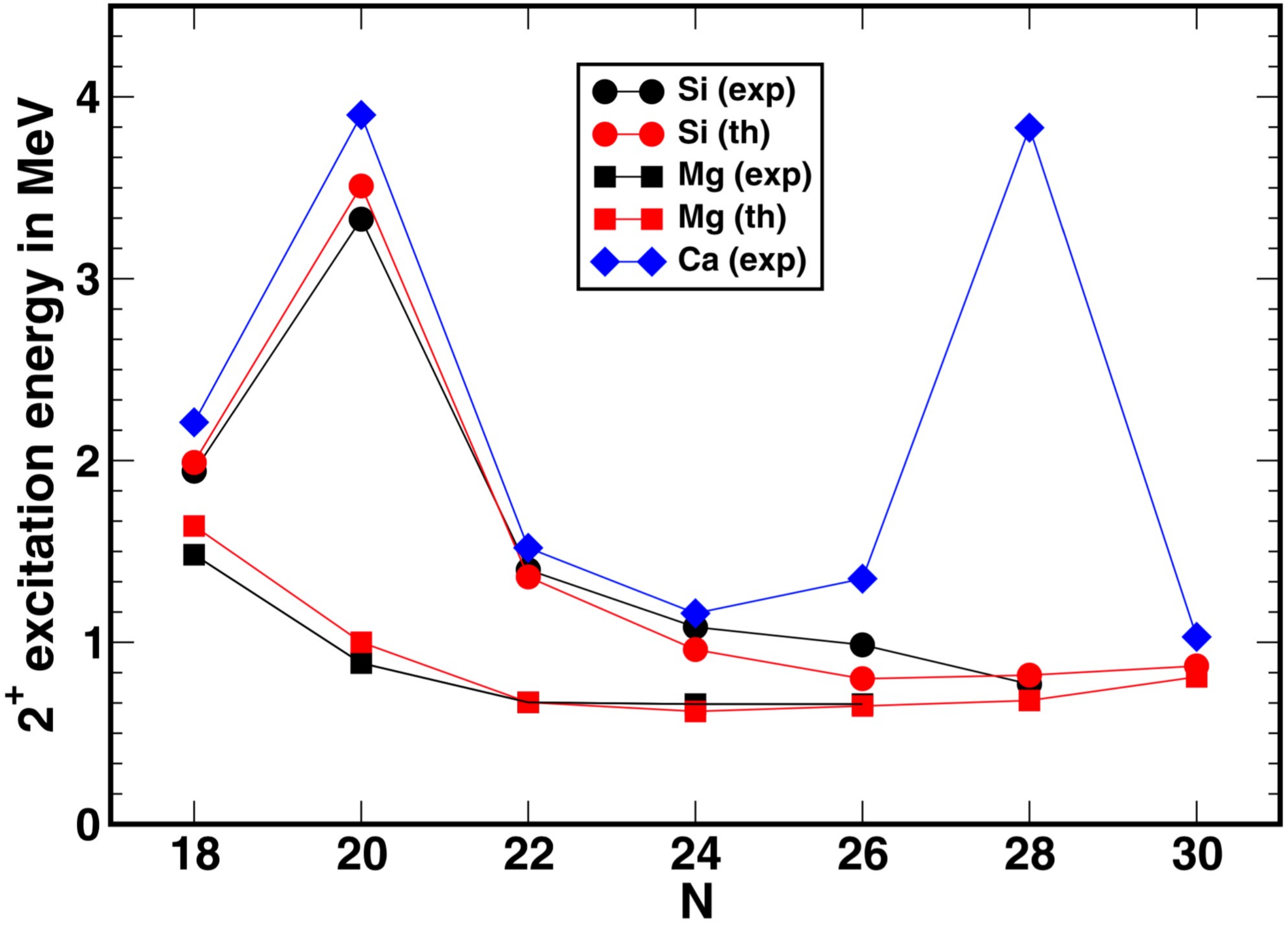
- Low population in the beam: ~2–3%
- Physics interest: ^{32}Na is neighbour to ^{32}Mg, the "poster child" of the island of inversion



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

Island of inversion

Crossing or elimination of the spherical states?



- ^{32}Mg, Z=12, N=20
- Deformed ground state in ^{32}Mg – "2p2h" excitation
- Low-lying 0^+ excited states
- Question: **is there an excited spherical 0^+ state in ^{32}Mg, and if so where?**
- **Perhaps ^{32}Na can shed some light**

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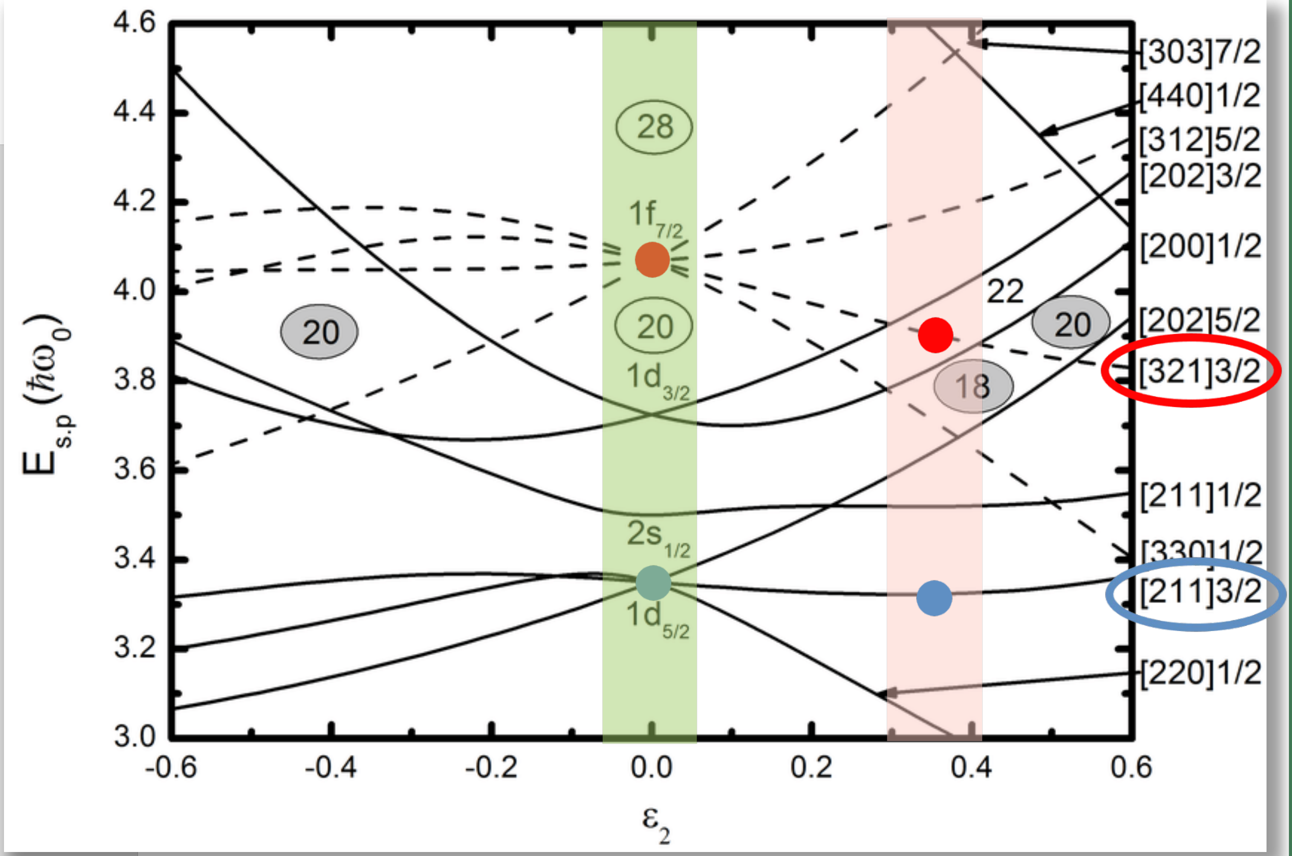
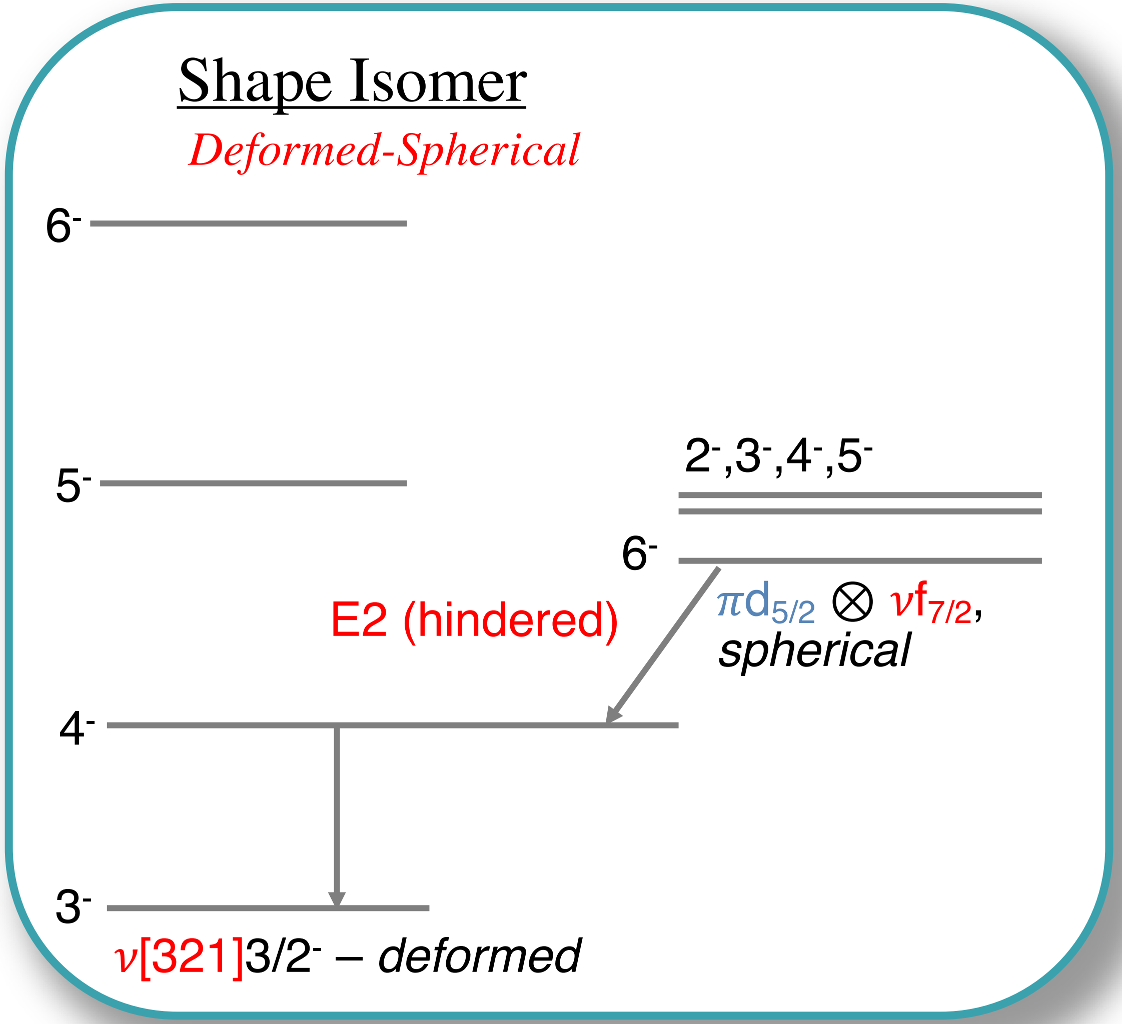
^{32}Na "ground state" configurations

Deformed configuration:
π[211]3/2$^+$ ⊗ ν[321]3/2$^-$
→ 3$^-$ (parallel)
→ 0$^-$ (anti-parallel)
with rotational bands built on these

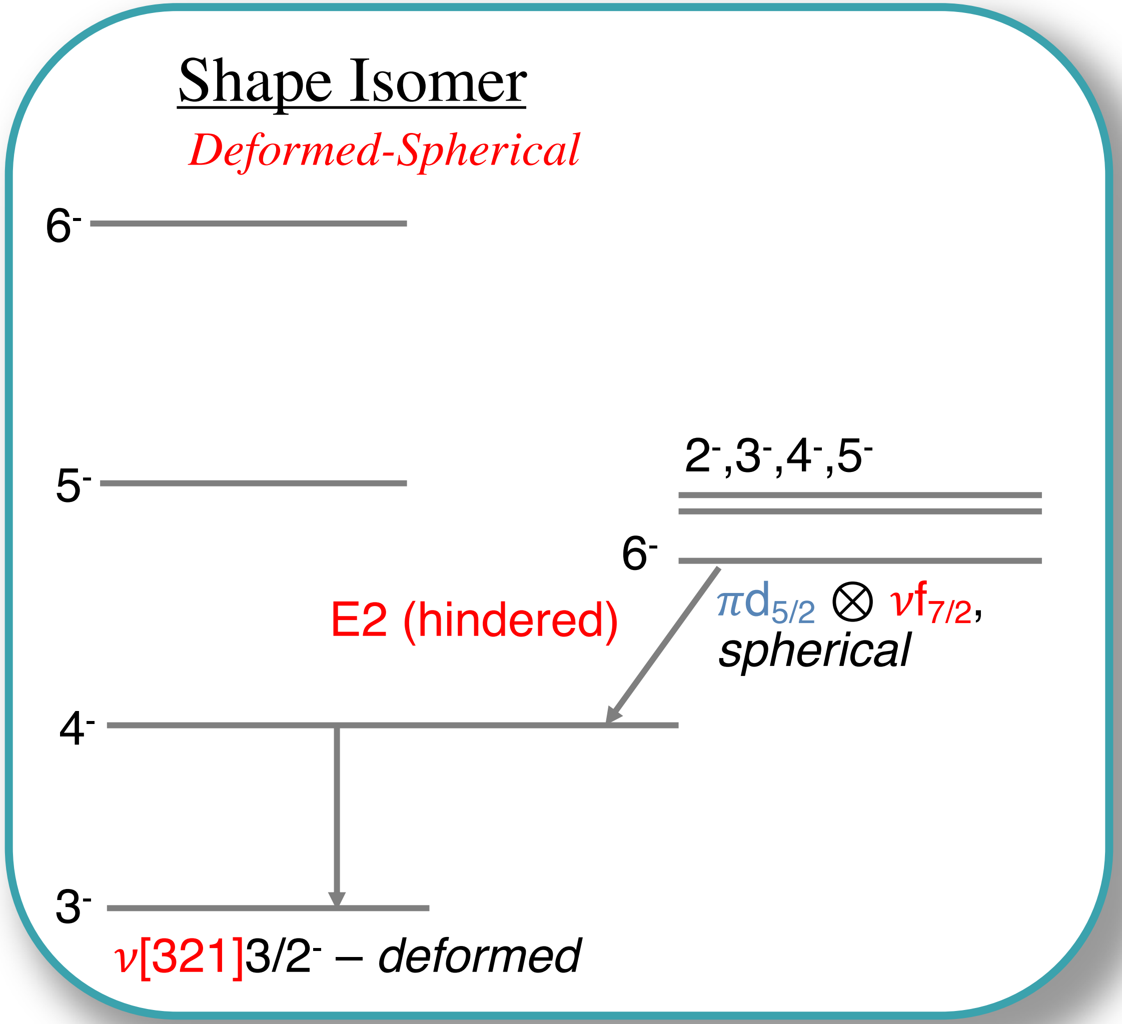
Spherical configuration:
$\pi d_{5/2}$ ⊗ $\nu f_{7/2}$, 5 states at almost the same energy, with the lowest being 6$^-$

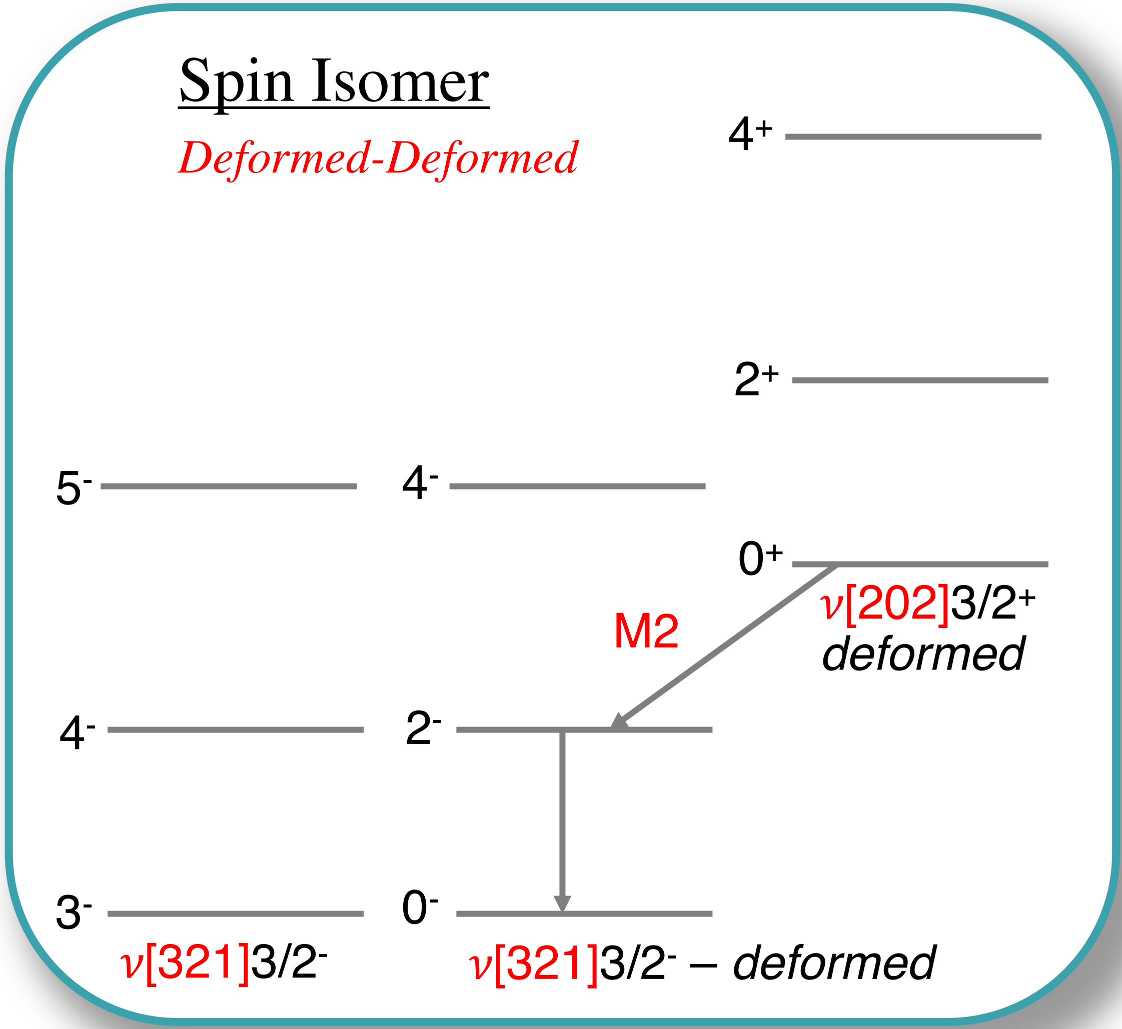


Two isomer possibilities

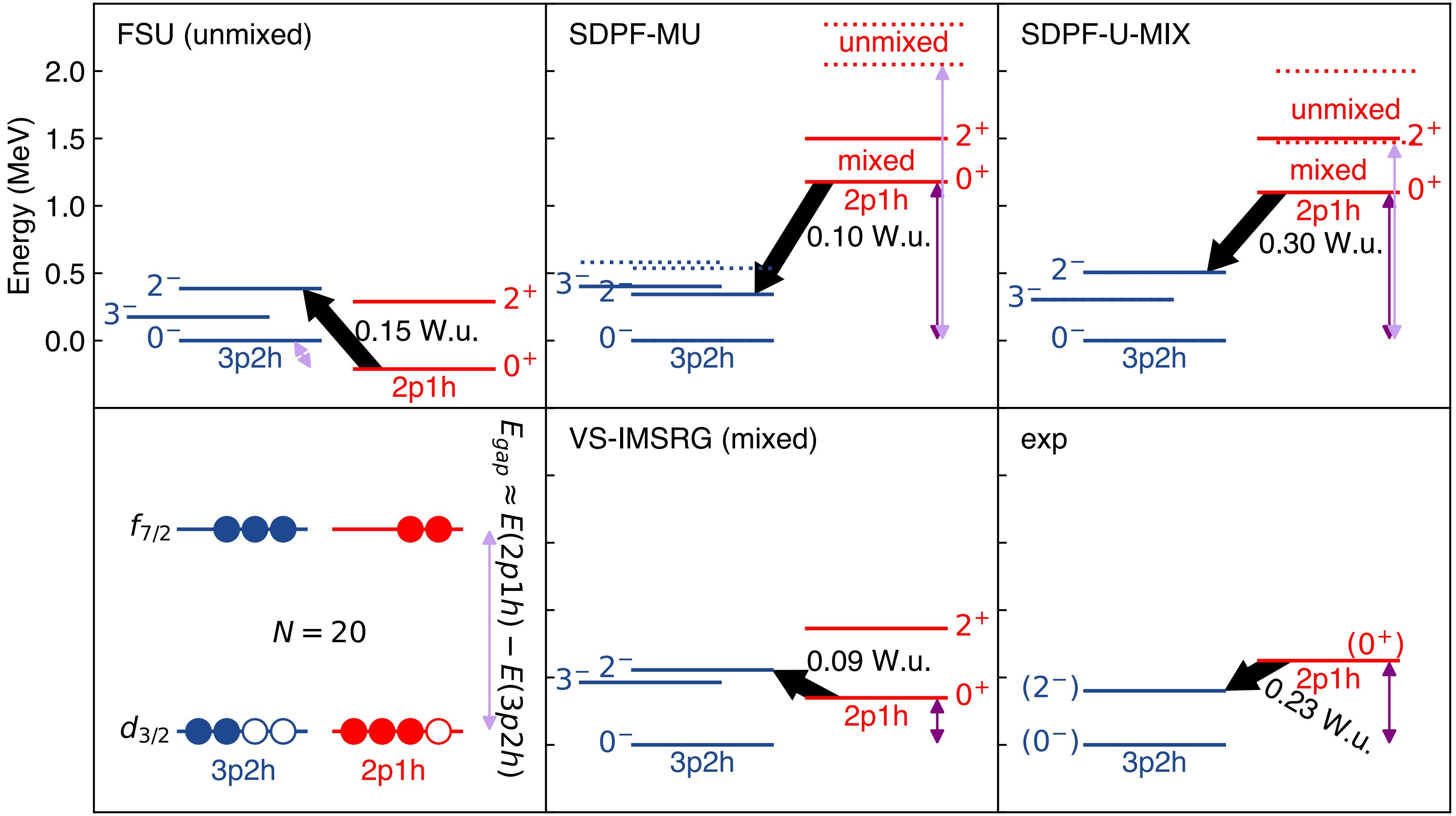


Two isomer possibilities





Shell-model predictions

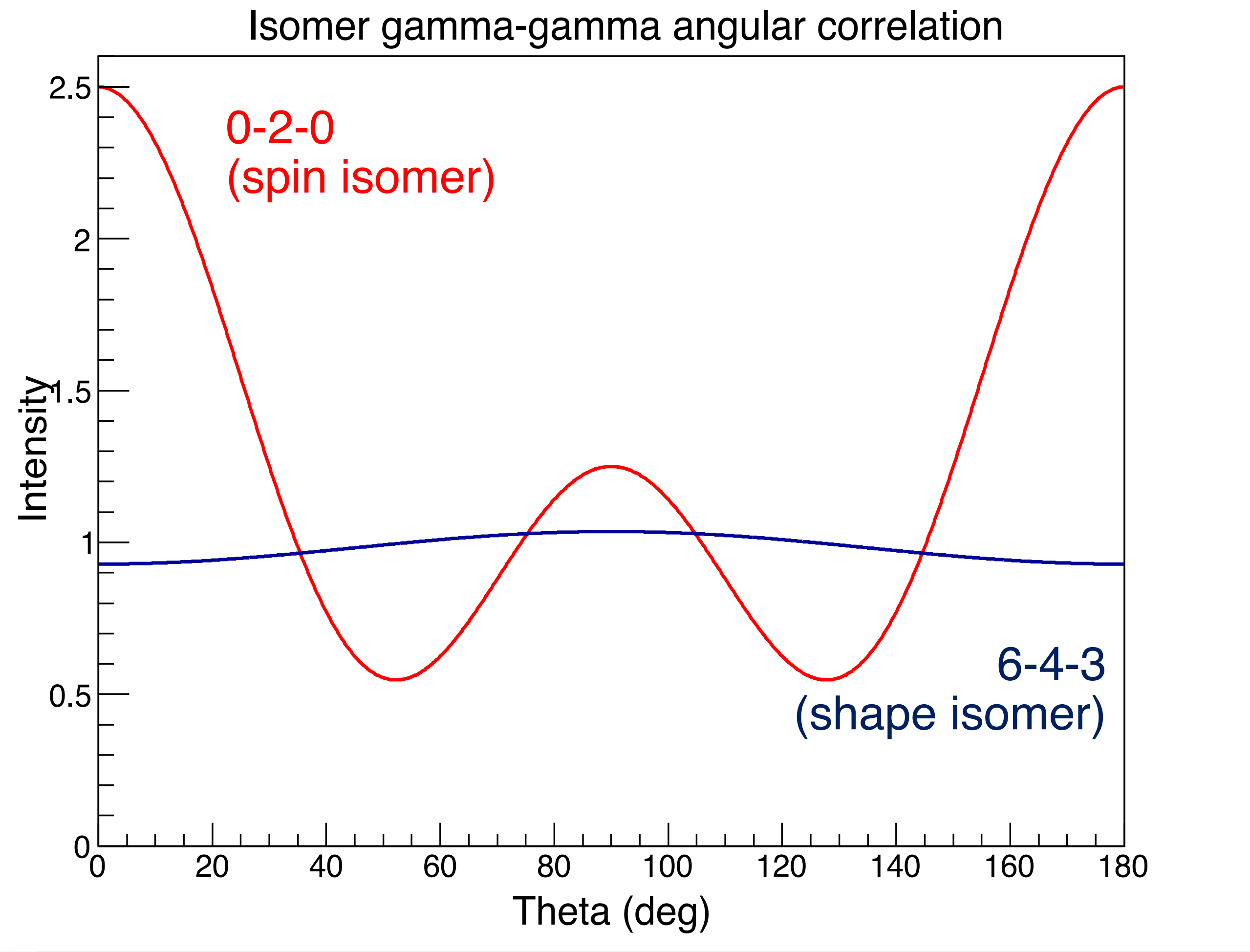


- SM predicts spherical states high in excitation (2 – 5 MeV): **does not agree with shape isomer scenario**
- All SM interactions give low-lying 0^+, 0^-, and 2^- states with M2 strength approximately correct
- However: large disagreement between SM calculations on the relative locations of these states, and this indicates the **gap energy is not well constrained** in the calculations

*SDPF-U-MIX courtesy of A. Poves, VS-IMSRG courtesy of J. Holt and T. Miyagi

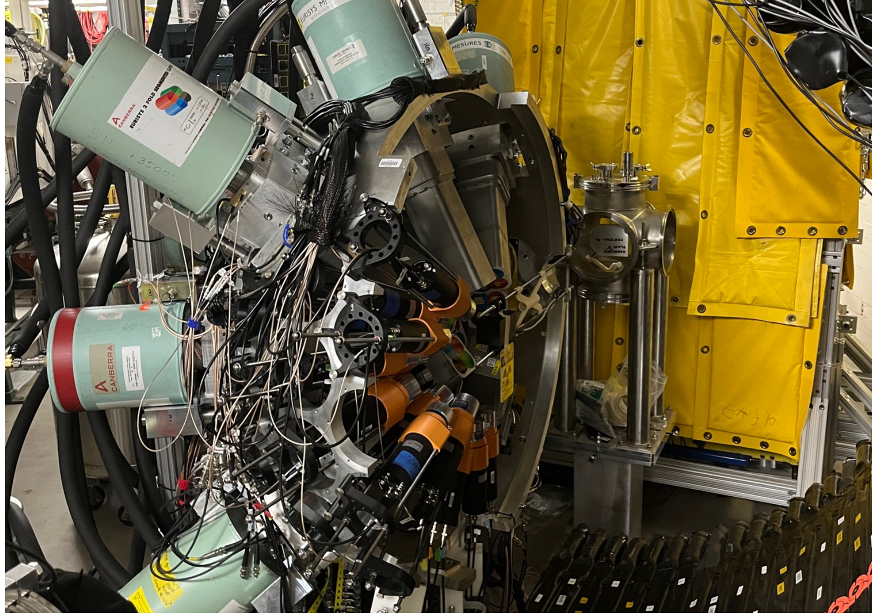
^{32}Na summary

- SM supports the spin isomer, and the isomeric energy is a valuable constraint for SM interactions in the region
- γ-γ angular correlation measurement is necessary to confirm spin assignments, this will distinguish between the two possibilities
- If the isomer is a spherical shape isomer, this indicates significant physics is missing from the SM calculations



First FRIB experiment summary

- 5 new ground state half-lives, PRL published
- New μs isomer in ^{32}Na discovered
- Multifaceted data on many isotopes, rich beta-decay data set from FDSi



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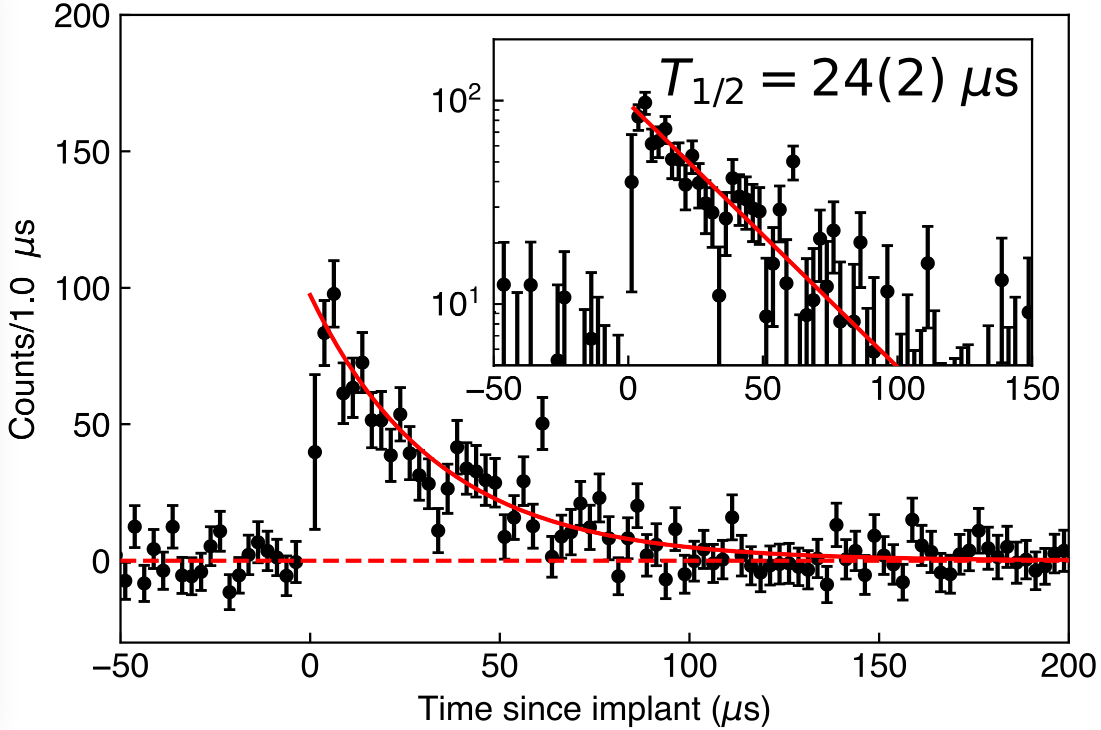

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FDS Users Executive Committee:

- Benjamin Crider (chair) – MissSU
- Kay Kolos (secretary) – LLNL
- Charlie Rasco – ORNL
- Artemis Spyrou – NSCL-MSU
- Vandana Tripathi – FSU

FDSi Project

Project Oversight:	Georg Bollen
Project Management:	Mitch Allmond
FRIB technical contact:	Sean Liddick
FDSi Coordination:	Robert Grzywacz (Spokesperson) Sean Liddick Darek Seweryniak Mitch Allmond
Facility Engineer:	Ben Arend
Alignment Engineer:	Dave Sanderson
FDSi Engineer:	Gary Hollenhead
XSiSi Engineer:	Russ Knaack
Engineer Support	Toby King

FDSi Group:
J. M. Allmond, R. Grzywacz, K. Rykaczewski, C. Rasc, A. Macchiavelli **(ORNL)**, D. Seweryniak, M.P. Carpenter **(ANL),** S.N. Liddick, A. Spyrou, C. Wrede, H. Schatz **(FRIB)**, R. Grzywacz, K.L. Jones, M. Madurga **(UTK)**, V. Tripathi **(FSU)**, B. Crider **(MSU (Mississippi)**, H.L. Crawford **(LBNL)**, L. Riley **(URSinus)**, R.V.F. Janssens **(UNC)**, A. Rogers (**UML)**, K. Kolos, J.T. Harke **(LLNL)**, M. Karny **(Warsaw)**

FDSi Working Groups:

•**DEGAi** — J.M. Allmond, M.P. Carpenter, A. Macchiavelli, V. Tripathi, M. Madurga, R.V.F. Janssens, B. Crider, S.N. Liddick, K. Kolos, J.T. Harke, H.L. Crawford

•**NEXTi** — R. Grzywacz, M. Madurga, M. Rajabali, A. Fijalkowska

•**TAS** — K. Rykaczewski, A. Spyrou, C. Rasco, M. Karny, S. Lyons, R. Grzywacz

•**XSiSi** — D. Seweryniak, R. Grzywacz, A.M. Rogers, J. Wu, A. Estrade Vaz, K. Rykaczewski, B. Crider

Acknowledgements

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PHYSICAL REVIEW LETTERS **129,** 212501 (2022)

Editors' Suggestion | Featured in Physics

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

H. L. Crawford,[1,*] V. Tripathi,[2] J. M. Allmond,[3] B. P. Crider,[4] R. Grzywacz,[5] S. N. Liddick,[6,7] A. Andalib,[6,8] E. Argo,[6,8] C. Benetti,[2] S. Bhattacharya,[2] C. M. Campbell,[1] M. P. Carpenter,[9] J. Chan,[5] A. Chester,[6] J. Christie,[5] B. R. Clark,[4] I. Cox,[5] A. A. Doetsch,[6,8] J. Dopfer,[6,8] J. G. Duarte,[10] P. Fallon,[1] A. Frotscher,[1] T. Gaballah,[4] T. J. Gray,[3] J. T. Harke,[10] J. Heideman,[5] H. Heugen,[5] R. Jain,[6,8] T. T. King,[3] N. Kitamura,[5] K. Kolos,[10] F. G. Kondev,[9] A. Laminack,[3] B. Longfellow,[10] R. S. Lubna,[6] S. Luitel,[4] M. Madurga,[5] R. Mahajan,[6] M. J. Mogannam,[6,7] C. Morse,[11] S. Neupane,[5] A. Nowicki,[5] T. H. Ogunbeku,[4,6] W.-J. Ong,[10] C. Porzio,[1] C. J. Prokop,[12] B. C. Rasco,[3] E. K. Ronning,[6,7] E. Rubino,[6] T. J. Ruland,[13] K. P. Rykaczewski,[3] L. Schaedig,[6,8] D. Seweryniak,[9] K. Siegl,[5] M. Singh,[5] S. L. Tabor,[2] T. L. Tang,[2] T. Wheeler,[6,8] J. A. Winger,[4] and Z. Xu[5]

[1] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2] *Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[3] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[4] *Department of Physics and Astronomy, Mississippi State University, Mississippi State, Mississippi 39762, USA*
[5] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37966, USA*
[6] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[7] *Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[8] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[9] *Argonne National Laboratory, Argonne, Illinois 60439, USA*
[10] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

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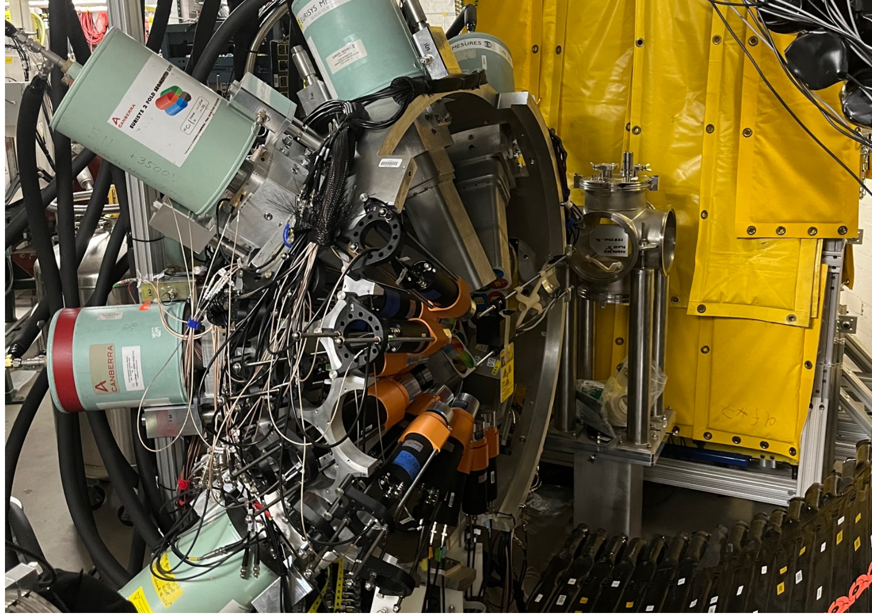
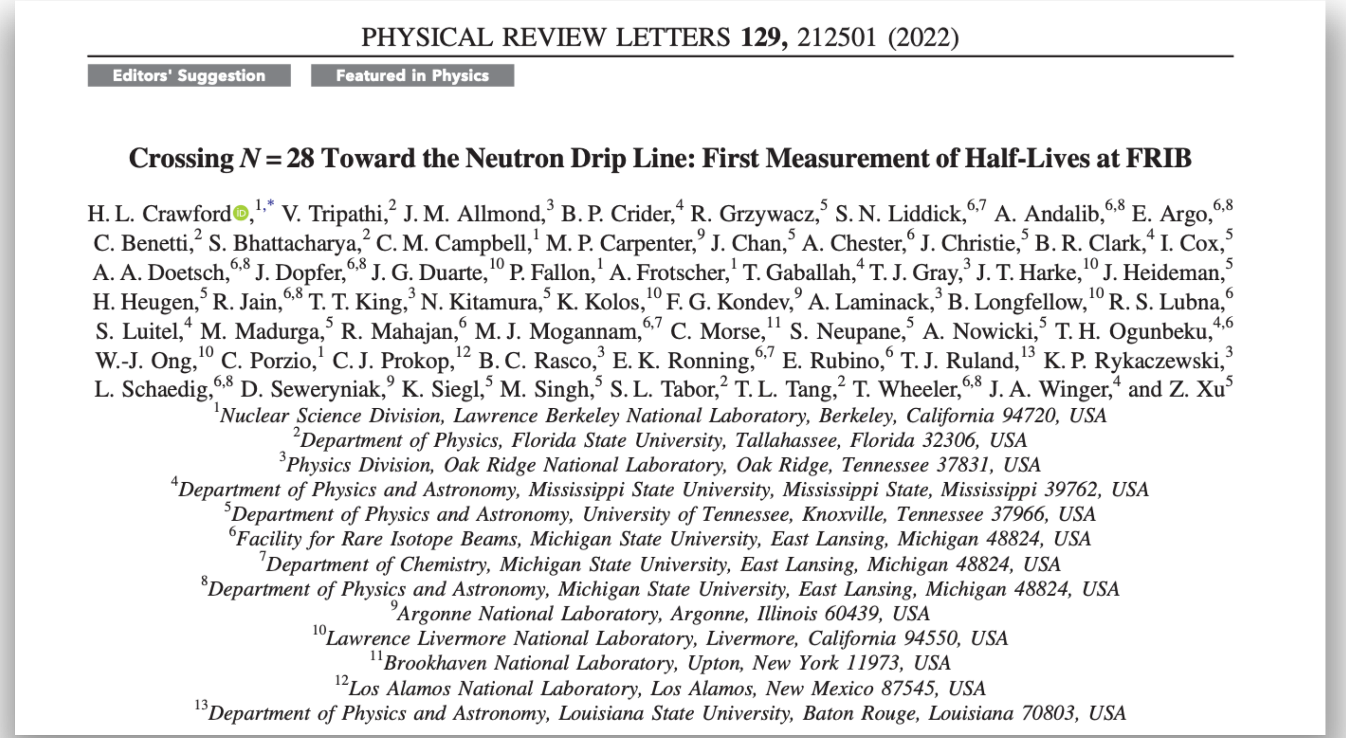
Contact: graytj@ornl.gov

First FRIB experiment summary

- 5 new ground state half-lives, PRL published
- New μs isomer in ^{32}Na discovered
- Multifaceted data on many isotopes, rich beta-decay data set from FDSi





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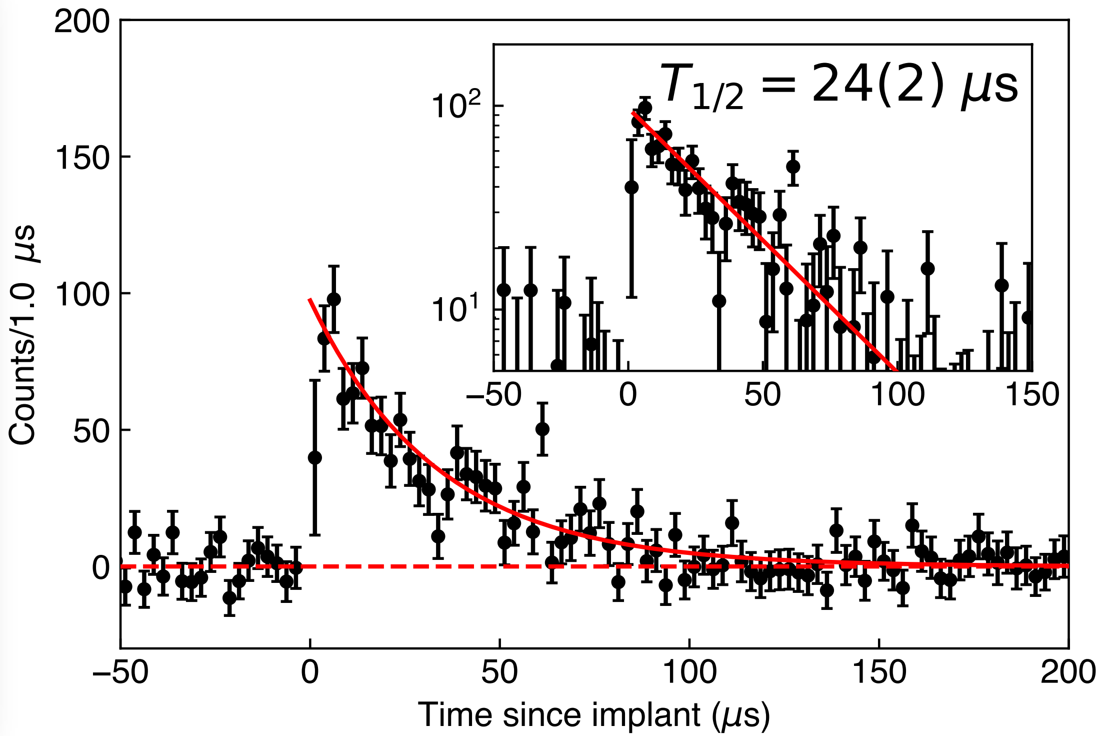
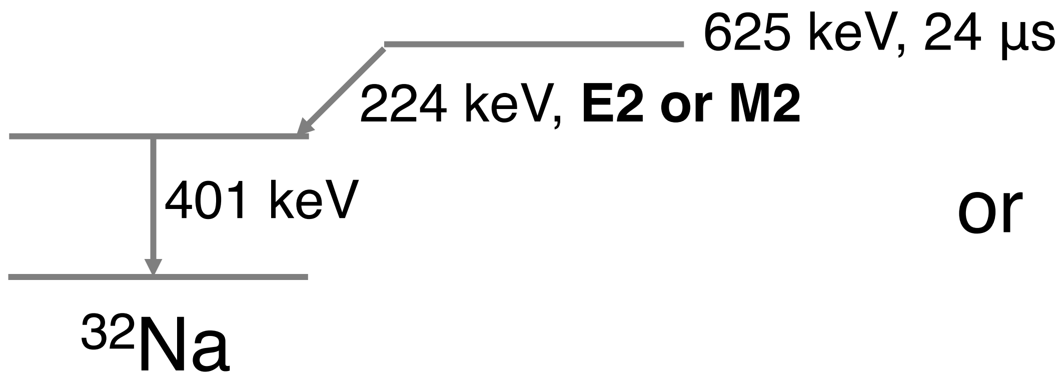
[9]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[10]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[11]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[12]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[13]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*



Multipolarities and Half Lives for 5 < A < 44

Isomer decay most likely by E2 or M2; higher multipolarity too long lived

***third option =** an unobserved very low-energy E1,M1,E2 γ ray, followed by the two observed γ rays



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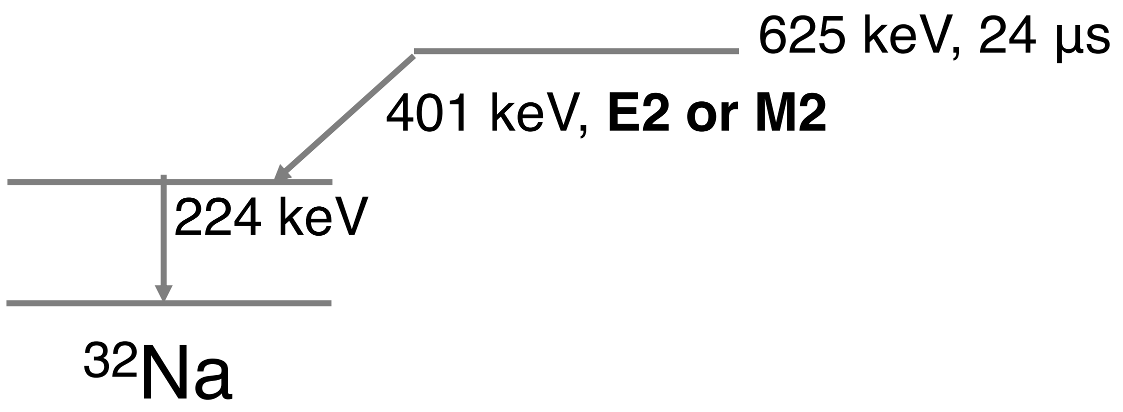
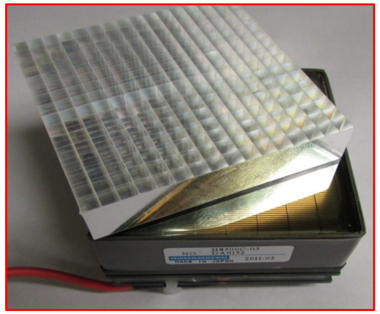


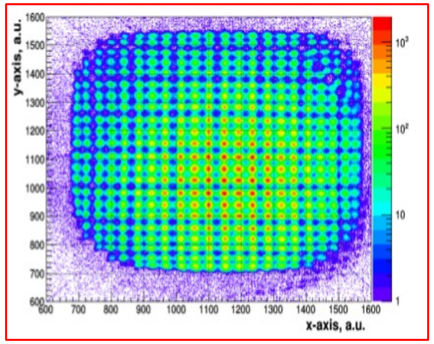
Table of Isotopes

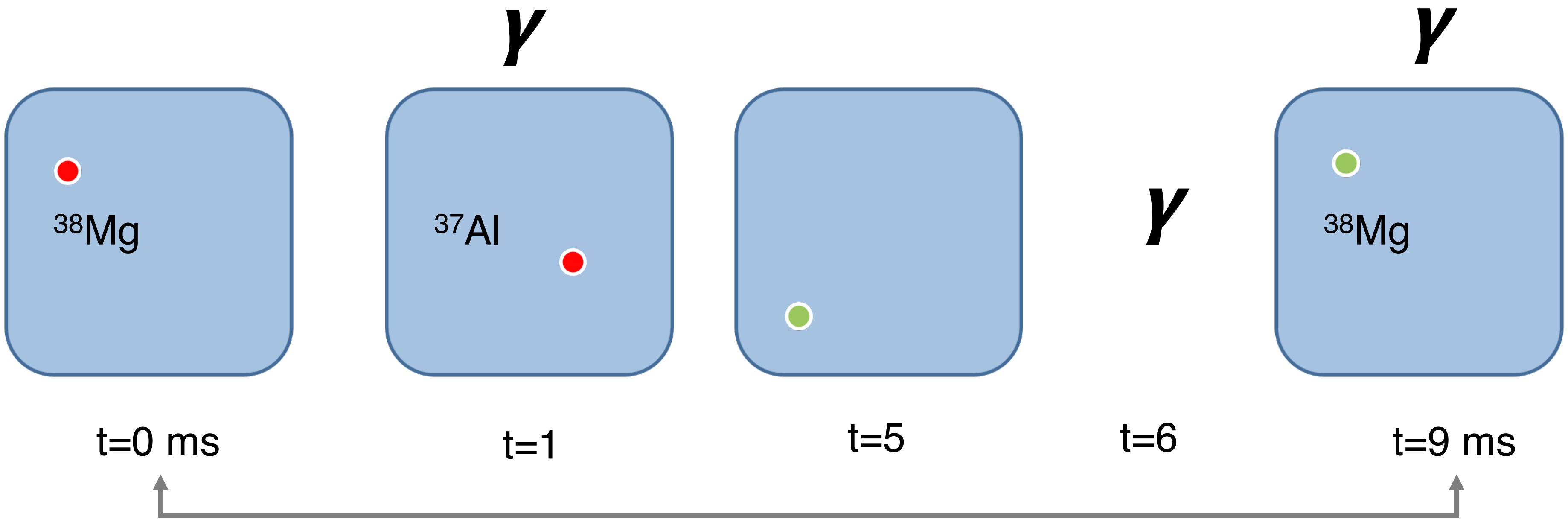
	Max Enhancement of s.p. Estimate	224 keV $T_{1/2}$ (μs)	401 keV $T_{1/2}$ (μs)
E2	100	> 0.0017	> 0.0001
M2	5	> 1	> 0.06
E3	50	> 14080	> 239
M3	10	> 2316709	> 39319

How do we measure beta half-lives? – ion-beta correlation

- Implant detector is sensitive to both implanted ions and subsequent beta decay
- Need to correlate ions with betas over long time-scales (10s or 100s of ms)







Correlate these: same position

Tag this beta event to be associated with the PID from the earlier implant

- Implanted ion
- Decay