Astromers: ASTROphysically metastable isoMERS

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NUSTAR Annual Meeting 2024

1 March, 2024

Los Alamos
NATIONAL LABORATORY

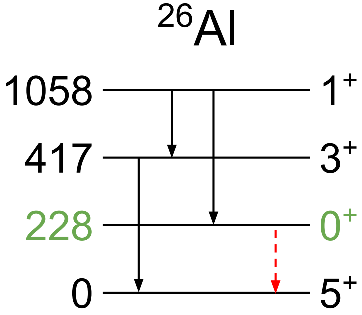
Release Caveat

Nuclear Isomers are Metastable Excited States

Isomers are excited states which live unusually long due to quantum mechanical (QM) mismatch with lower states.

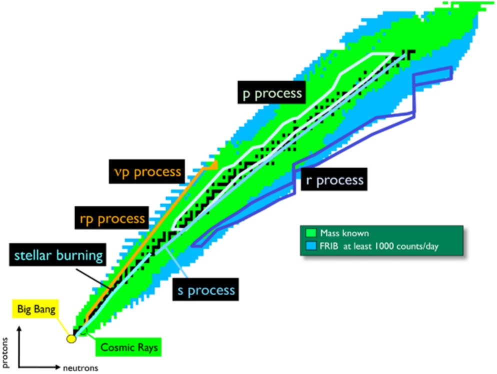
- ^{26}Al has isomer at 228 keV.
- QM mismatch due to large spin difference.

- Transition to ground inhibited
- Transition from ground also inhibited



Red: Slow Black: fast

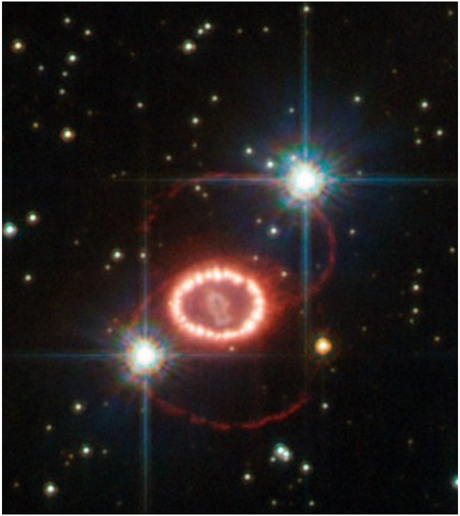
Astrophysical Nucleosynthesis: How Elements are Made



https://www.int.washington.edu/PROGRAMS/14-2b/

- Many sites: stellar interiors, novas, supernovas, neutron star mergers
- Multi-physics astrophysical models and nucleosynthesis networks
- Requires vast nuclear physics inputs

^{26}Al is Astrophysically Significant



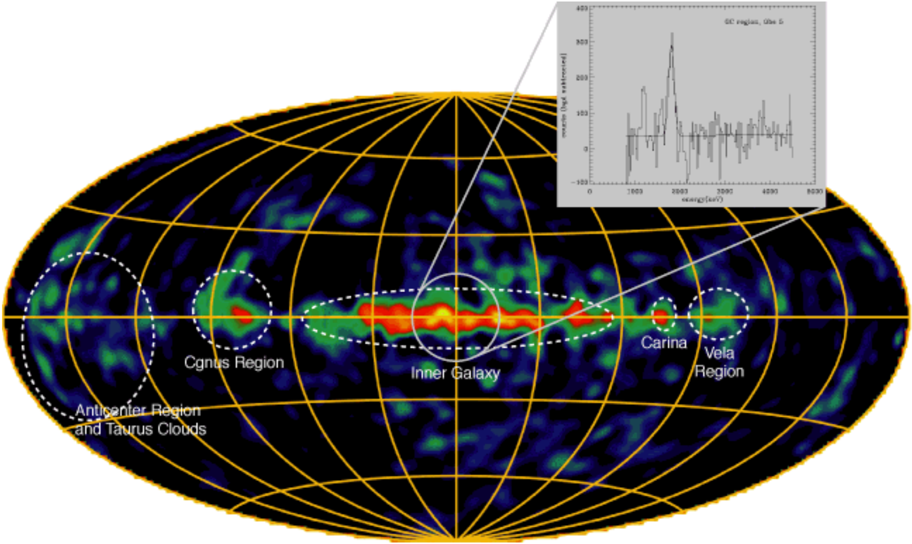
Supernova 1987A, HST

First radioisotope observed in space!

Tracer of star formation:

- Made in massive (short-lived) stars
- Where massive stars die, star formation is happening
- Lives long enough to build up
- Decays quickly enough to be detectable and stay correlated with where it was produced

COMPTEL Map of 1809 keV γ-ray Sources (^{26}Al β decay)

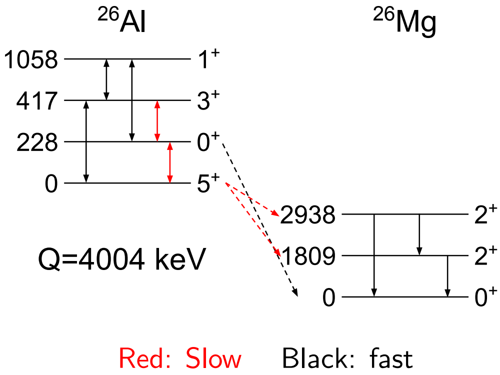


heasarc.gsfc.nasa.gov

^{26}Al has a Complicating Isomer

- GS half-life: $\sim$ 700 kyr
- Isomer half-life: $\sim$ 6 sec

- Can't use thermal equilibrium if isomer β decays faster than thermally replenished
- Can't use GS if isomer is populated in production

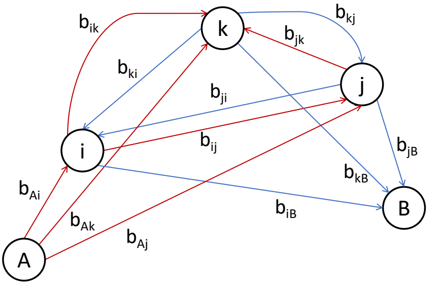


Must we treat isomer and ground state as separate species?

Does ^{26}Al have an astromer?

Picture Nucleus as a Graph

Graph: a set of objects (vertices) with pairwise connections (edges). Edges may be directed and/or weighted.



Misch et al., ApJS 252, 1 (2020)

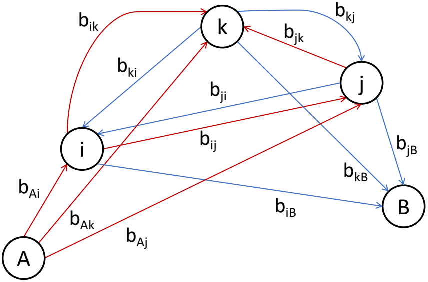
Nuclear states are vertices.

- A: ground state
- B: isomer
- i, j, k: “intermediate” states

Transitions are edges.

- Blue: down transitions
- Red: up transitions
- b: transition probabilities (computed from thermally mediated rates)

Effective Transitions are Random Walks



Misch et al., ApJS 252, 1 (2020)

Transitions from ground **(A)** to isomer **(B)**:

- Step from **A** to **i**, **j**, or **k**
- Make any number of transitions between **i**, **j**, and **k**
- Successful transitions end with step to **B**

Effective transition rates from successful transition probabilities:

$$P_{iB} = b_{iB} + \sum_j b_{ij} P_{jB}$$ ← Matrixize, pop into equation solver

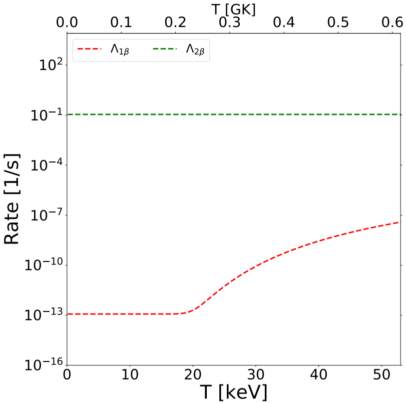
$$\Lambda_{AB} = \lambda_{AB} + \sum_i \lambda_{Ai} P_{iB}$$

^{26}Al β-decay Rates

Red: Ground state (1) decay rate

Green: Isomer (2) decay rate

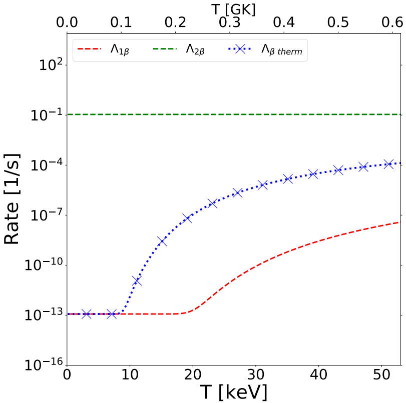
Rise in $\Lambda_{1\beta}$ not important for our purposes here.



^{26}Al β-decay Rates

Blue: Thermal decay rate

Around $T \sim 10$ keV, isomer should begin to be populated.

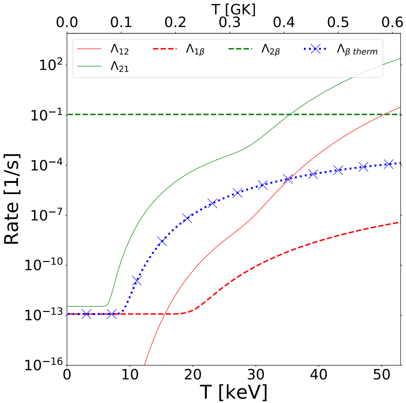


^{26}Al Transition and β-decay Rates

Red solid: GS → isomer transition rate

Green solid: Isomer → GS transition rate

Transition rate from GS to isomer initially much slower than $\Lambda_{\beta\ \mathrm{therm}}$. But then how could the isomer contribute so much?

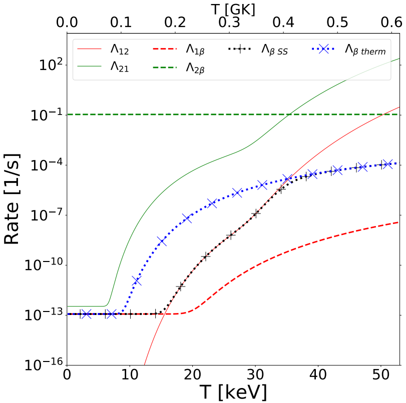


^{26}Al Transition and β-decay Rates

Black: Steady-state decay rate

$T < 15$ keV:
$\Lambda_{\beta\ SS}$ is GS decay rate

$T = 15 - 35$ keV:
$\Lambda_{\beta\ SS}$ follows GS $\rightarrow$ isomer transition rate

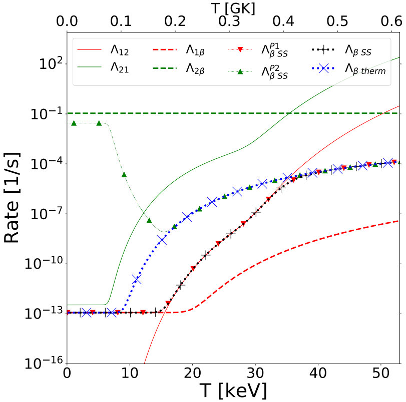


^{26}Al Transition and β-decay Rates

Red triangles: GS production

Green triangles: Isomer production

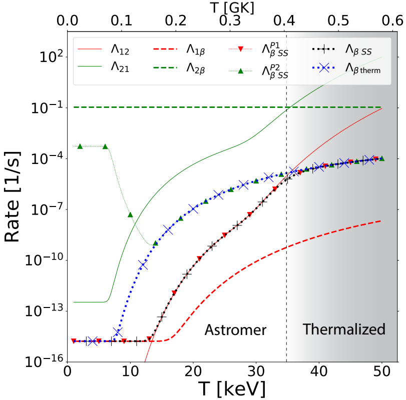
Lines with triangles show steady-state rates if isotope is produced purely in one state or the other.



Misch et al., ApJS 252, 1 (2020)

Thermalization:

Above $T \sim 35$ keV, Λ_{21} dominates $\Lambda_{2\beta}$. Transitions dominate decays, and nucleus can thermalize.



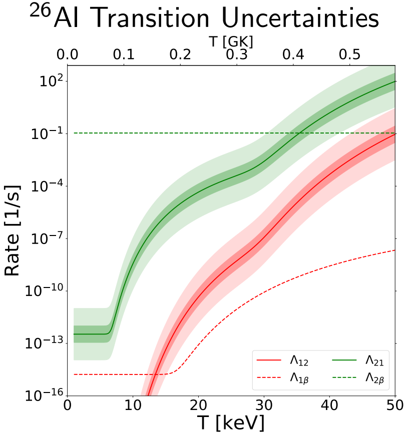
Misch et al., ApJS 252, 1 (2020)

Below the thermalization temperature (T_{therm}), the GS and astromer must be treated as separate species.

Incomplete Data Drives Uncertainties

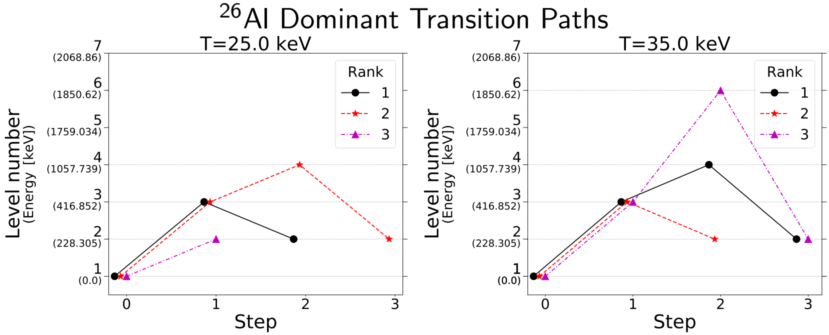
How do we figure out which transitions are important?

What's with the kinks?



Pathfinding Enables Detailed Scrutiny

Use pathfinding algorithm to determine dominant transition routes. New path opens at $T \sim 30$ keV.



Misch et al., ApJS 252, 1 (2020)

Forward/reverse paths identical (detailed balance, reversible Markov chain)

Pathfinding identifies key missing nuclear transition data.

The *s*-Process of Nucleosynthesis

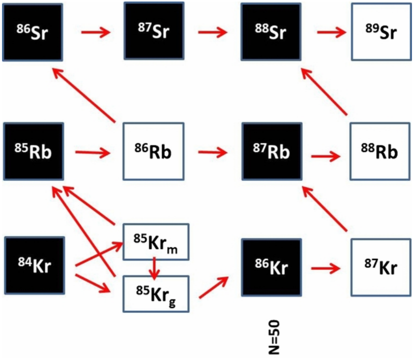
Let's look at the slow neutron capture process: the *s* process

Main *s* process: $1.5 - 3\ M_\odot$ asymptotic giant branch stars

^{85}Kr is an *s*-Process Branch Point

- GS $T^{\beta}_{1/2} = 10.739$ y
- Affects production of nearby nuclides, including ^{87}Rb cosmochronometer ($T_{1/2} = 5 \times 10^{10}$ y)

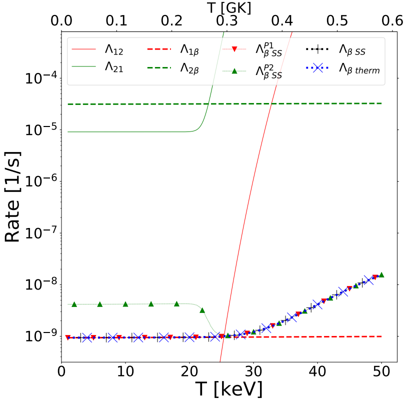
- Isomer at 304.871 keV
- Isomer $T_{1/2} = 4.480$ h
- 78.8 % β decay

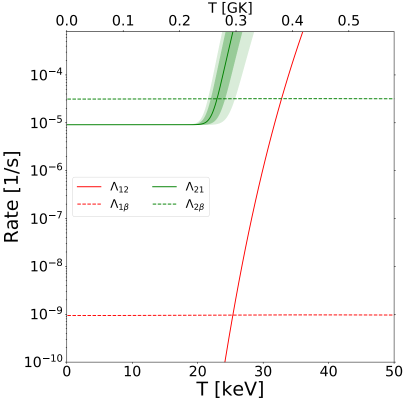


Straniero et al. (2014)

Is ^{85}Kr an astromer?

^{85}Kr is an *s*-Process Astromer





Misch et al., ApJS 252, 1 (2020)

- Main *s*-process at $T \sim 8$ keV (interpulse) to $T \sim 30$ keV (pulse)
- Preliminary results show astromer has substantial effect
- Fed by neutron capture, pumped by pulses

The r-Process of Nucleosynthesis

Let's look at the rapid neutron capture process: the r process

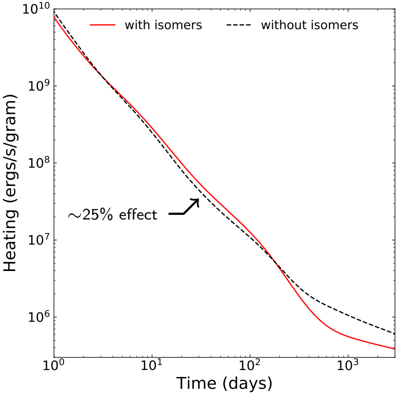
Primary suspects: Neutron star mergers, type II supernovas

Astromers Affect *r*-Process Heating

Astromers don't change total energy release, but can drastically change timing.

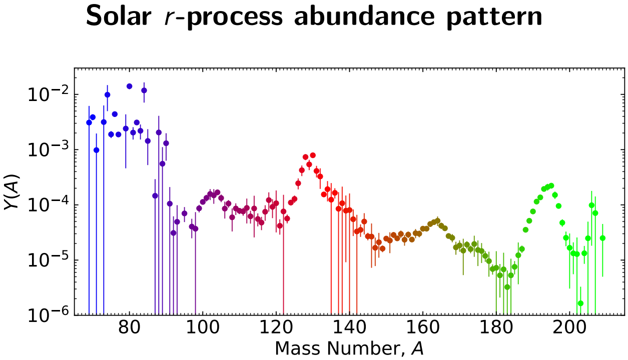
Classify astromers based on structure effects:

- **Accelerants** move energy release to earlier times
- **Batteries** store energy until later times
- **Neutral** astromers can still generate electromagnetic signals



Misch et al., ApJ Letters 913, 1 (2021)

r-Process Nucleosynthesis Makes Three Peaks

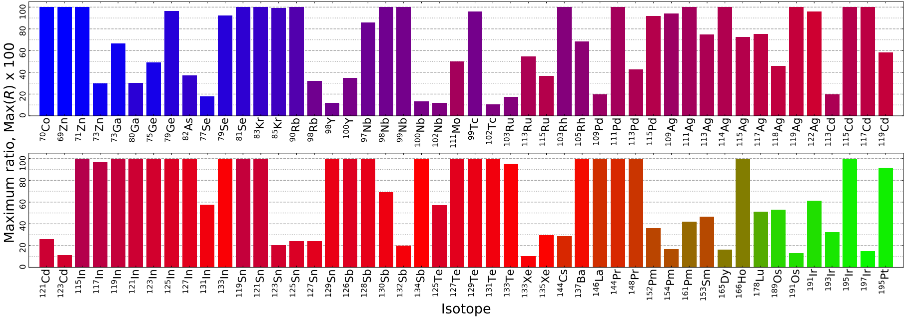


Misch et al. (in prep)

- Three main abundance peaks: $A \sim 80$, $A \sim 130$, $A \sim 195$
- Isomers in peaks most likely to be influential due to high population

We Find Many Dynamically Populated Isomers

We put all known neutron-rich isomers ($T_{1/2} > 100\mu$s) into a decay network and showed for the first time that isomers are **dynamically populated** in the *r*-process.



Misch et al., ApJ Letters 913, 1 (2021)

Isomer population ratio: $R = \frac{Y_m}{Y_g + Y_m}$

$A \sim 80$ (first peak), $A \sim 130$ (second peak), $A \sim 195$ (third peak)

But Which Isomers are Important Astromers?

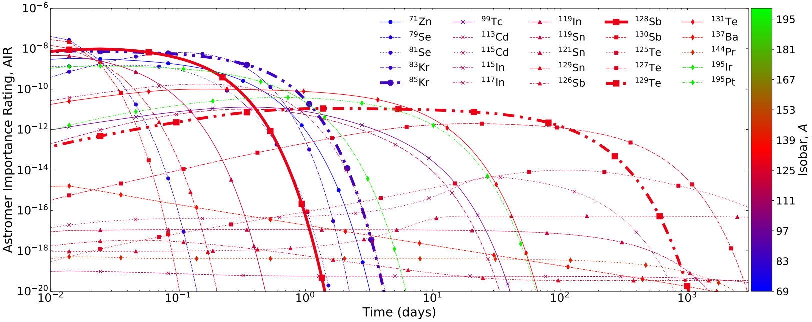
Does populated mean important?

We need a metric to find influential astromers!

AIR: Astromer Importance Rating Identifies Astromers

AIR = Activity × Imbalance × Ratio

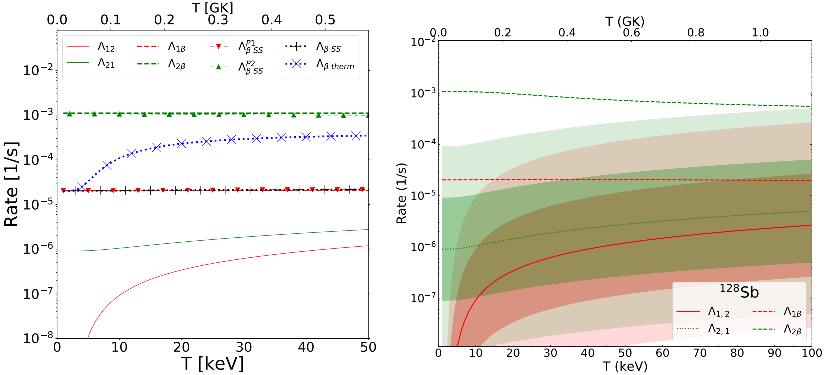
Activity: catches isomers present and doing something
Imbalance: rejects isomers in equilibrium with GS
Ratio: fraction of abundance in isomer state, rejects pass-throughs



Adapted from Misch et al., ApJ Letters 913, 1 (2021)

AIR enables us to identify potentially influential astromers.

^{128}Sb Astromer is a β Accelerant



Misch et al., ApJS 252, 1 (2020)

- ^{128}Sn β decay feeds isomer almost exclusively
- ^{128}Sb isomer decays faster than ^{128}Sn, so get two decays worth of energy on ^{128}Sn decay timescale instead of pileup
- **Can greatly increase early heating, but huge uncertainties.**

Future Work

We need to grow our theoretical tools.

- Incorporate other nuclear processes (captures, α decay, fission, etc.)
- Account for ionization, which can stabilize isomers
- Put into realistic simulations
- Make robust predictions of observable consequences

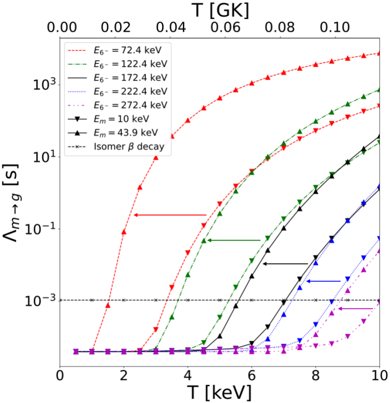
Future Work

We need more data!

- Unmeasured isomer energies
- Unmeasured intermediate states and transitions
- Unmeasured decay feeding. For example, ^{77}Ga β feeding unmeasured, almost certainly feeds ^{77}Ge isomer
- Capture cross sections on excited states

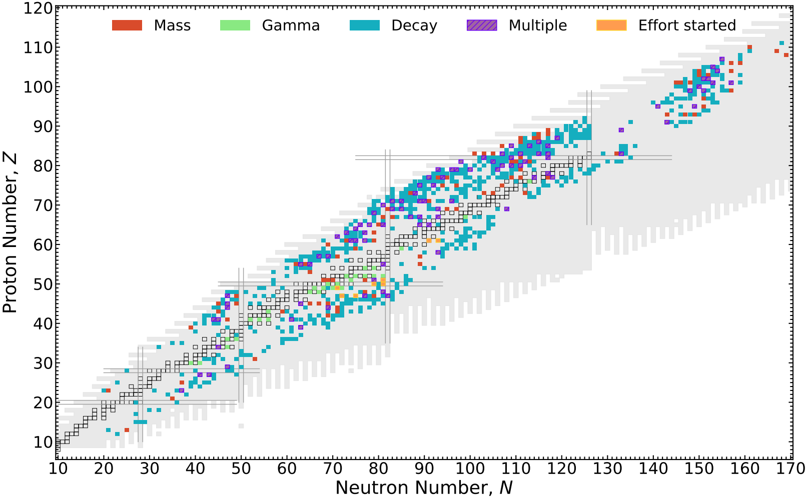
^{128}Sb is Missing a Connecting State

- Isomer newly measured at 43.9 keV
- Shell model calculations predict 6^- state at $\sim$ 175 keV that connects GS and astromer with $\Delta J = 1, 2$ transitions.
- **Uncertainties in excited level structure create large uncertainties in thermalization.**



Hoff et al., PRL (2023)

Known Missing Data



Misch & Mumpower, EPJ Special Topics (in press)

Isomer Measurement at CARIBU

Photo courtesy of Kay Kolos

Me discovering an isomer!

Well, measuring an isomer mass.

Well, helping tune the beam.

Well, pointing at a pressure indicator for... something.

Pressure was nominal!

Summary

Astromers are isomers which remain metastable in astrophysical conditions.

- Isomers can impact astrophysical nucleosynthesis
- Below T_{therm}, **treat as separate astromer species**
- Affects isotopic composition and electromagnetic observables

- Many require more data: energies, connecting states, reaction cross sections, and more.
- Experimental campaigns may reveal many more important astromers!