Total Absorption Spectroscopy of "Astromers" in ^{70}Cu

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19th Russbach School on Nuclear Astrophysics
March 8, 2024

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U.S. DEPARTMENT OF ENERGY | Office of Science

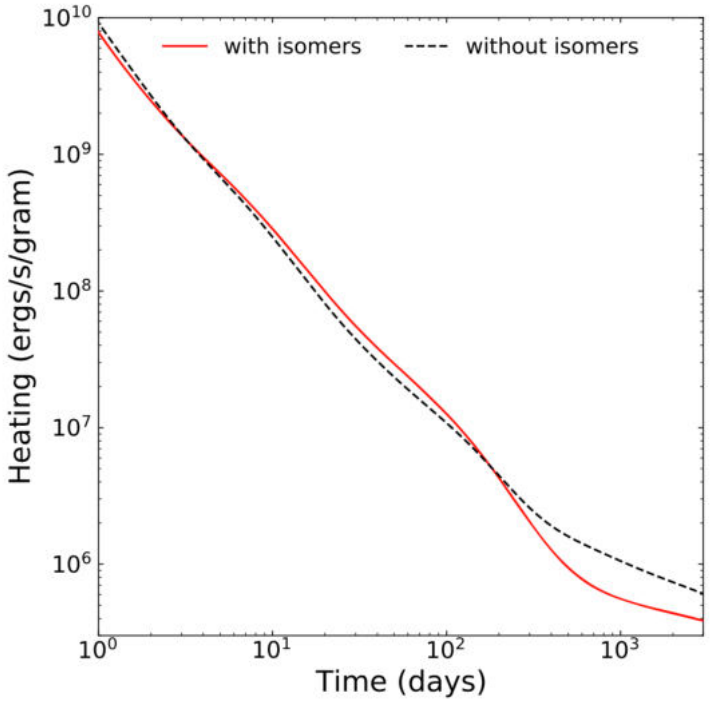
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, under Award Number DE-SC0000661.

What is an “astromer”?

- **Isomers**: long-lived (~1ns or longer) meta-stable nuclear states
- **Astromers:** isomers that have some astrophysical relevance

Astromers can impact:

- Nucleosynthesis pathways
- Energy emitted from radioactive decays



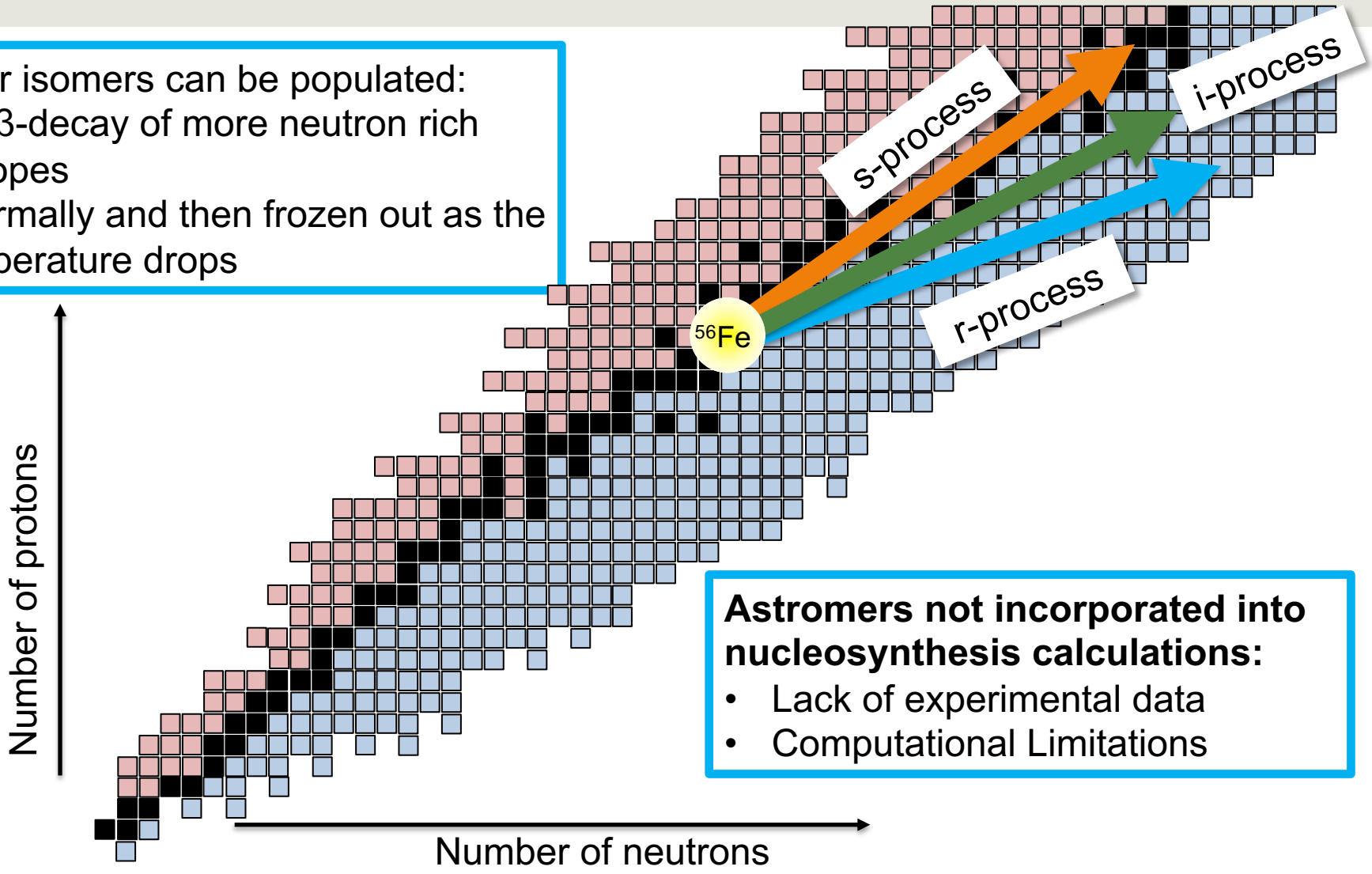
- Example: ^{26}Al and ^{26m}Al
  - ^{26}Al (spin: 5^{+}, $t_{1/2}$: 1.06x10^{6} yrs)
  - ^{26m}Al (spin: 0^{+}, $t_{1/2}$: 9.2 s)
  - Because of spin and half-life differences, the ground state and isomer must be treated as different species

Ward and Folwer, ApJ **238** (1980)
Fujimoto, et al, MNRAS **493** (2020)
Misch, et al. ApJL **913** (2021)

Astromers in nucleosynthesis calculations

Nuclear isomers can be populated:

- Via β-decay of more neutron rich isotopes
- Thermally and then frozen out as the temperature drops



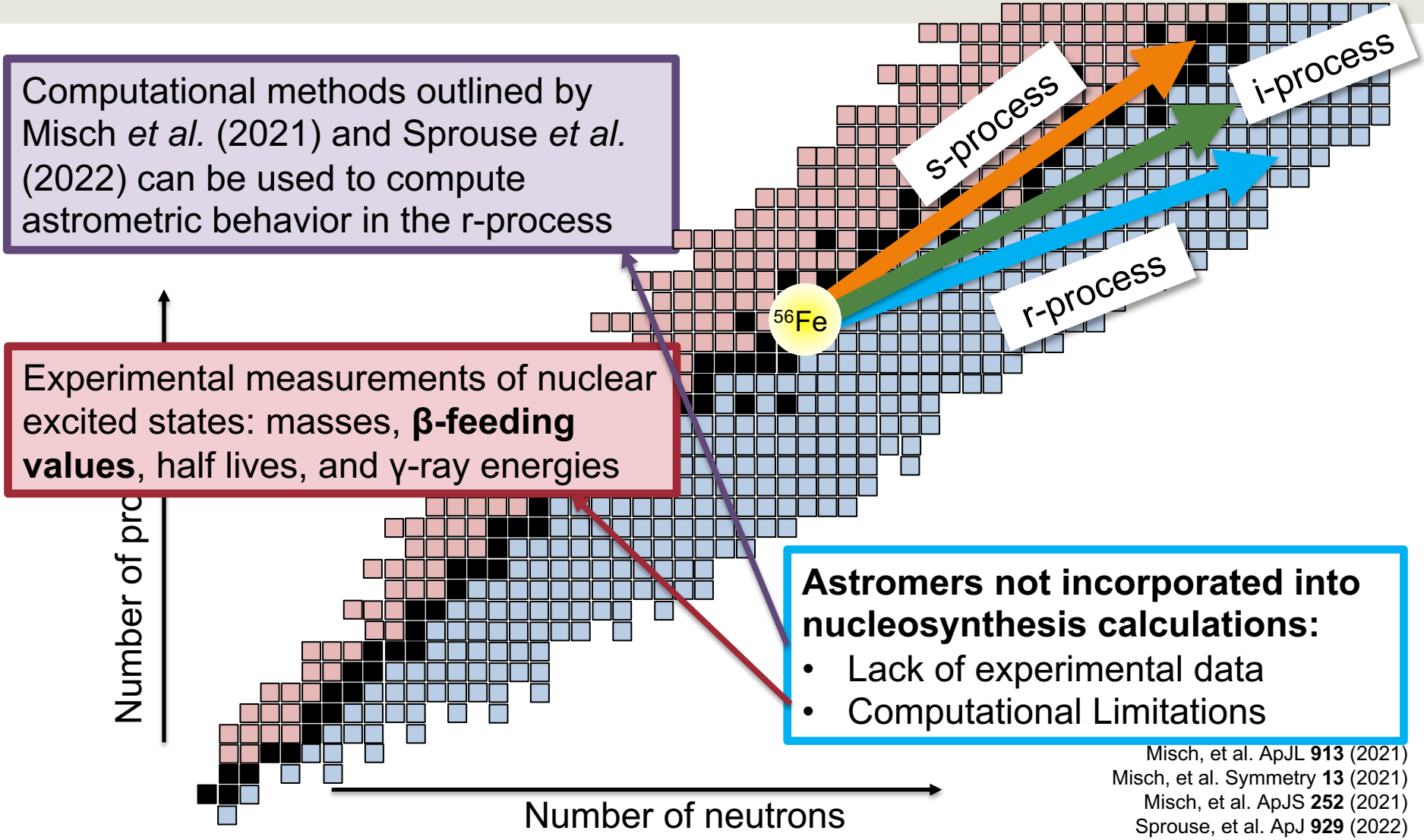
Astromers not incorporated into nucleosynthesis calculations:

- Lack of experimental data
- Computational Limitations

Astromers in nucleosynthesis calculations

Computational methods outlined by Misch *et al.* (2021) and Sprouse *et al.* (2022) can be used to compute astrometric behavior in the r-process

Experimental measurements of nuclear excited states: masses, **β-feeding values**, half lives, and γ-ray energies



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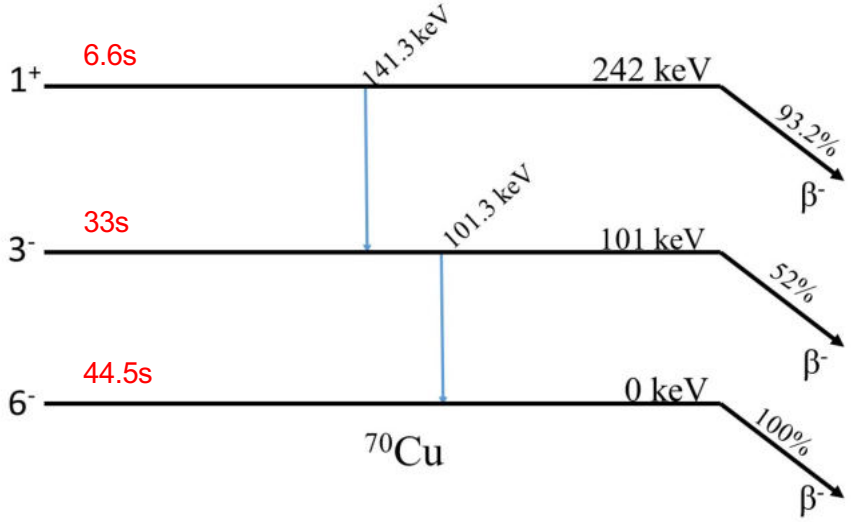
Misch, et al. ApJL **913** (2021)
Misch, et al. Symmetry **13** (2021)
Misch, et al. ApJS **252** (2021)
Sprouse, et al. ApJ **929** (2022)

^{70}Cu has two astromers

- ^{70}Cu has two isomers ($J^{\pi}=1^{+},3^{-}$) and a $J^{\pi}=6^{-}$ ground state



Isomer/Ground State	Half Life (s)
6^{-} (gs)	44.5(2)
3^{-} (m1)	33(2)
1^{+} (m2)	6.6(2)

P. Vingerhoets et al., *Phys. Rev. C* **82**, 064311 (2010)

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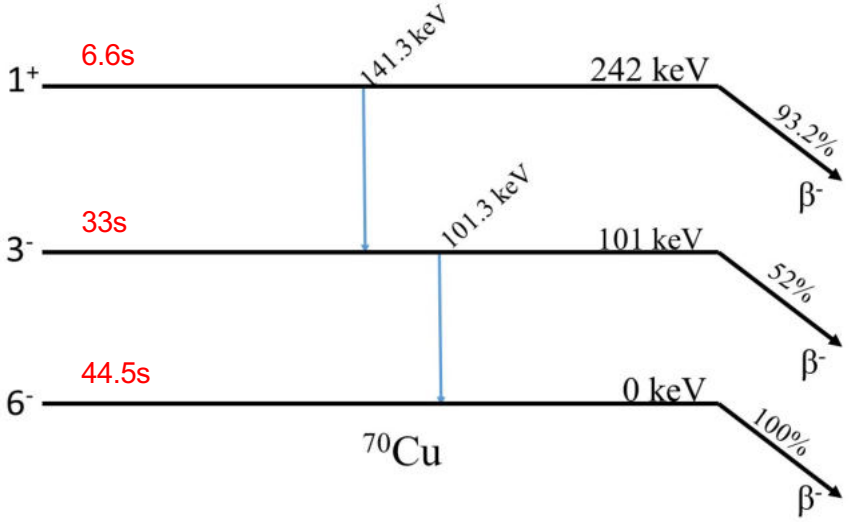

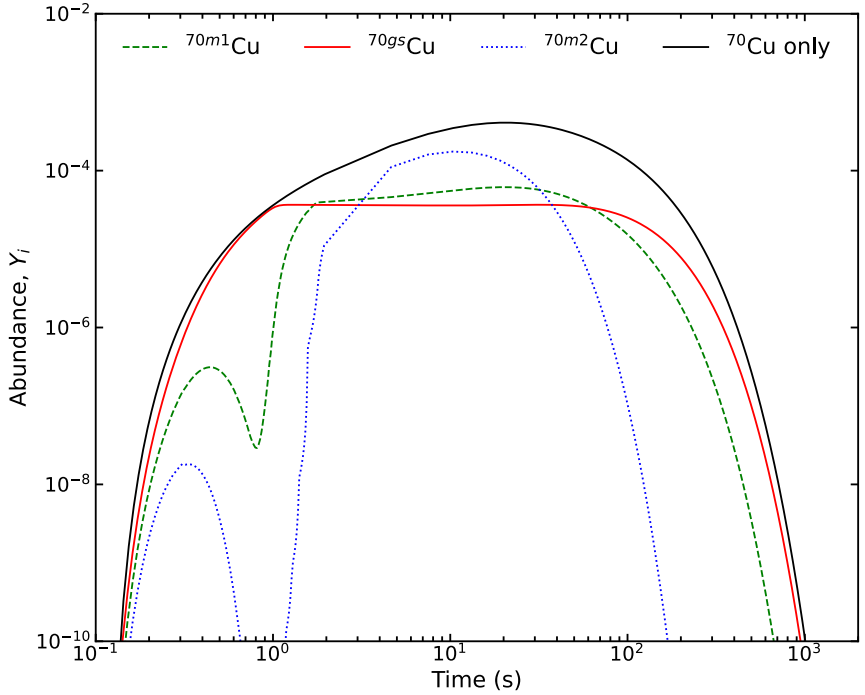

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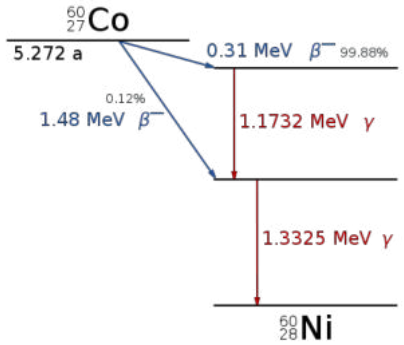
The 1^{+} and 3^{-} isomers in ^{70}Cu are “astromers”

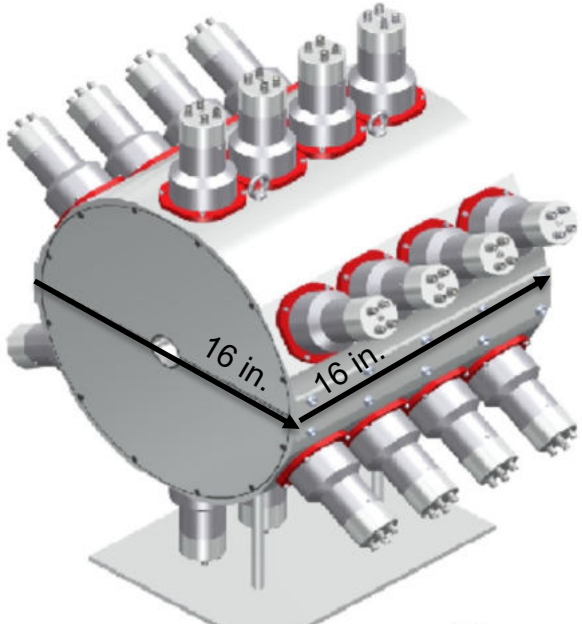
G.W. Misch and M.R. Mumpower (2024)
P. Vingerhoets et al., *Phys. Rev. C* **82**, 064311 (2010)

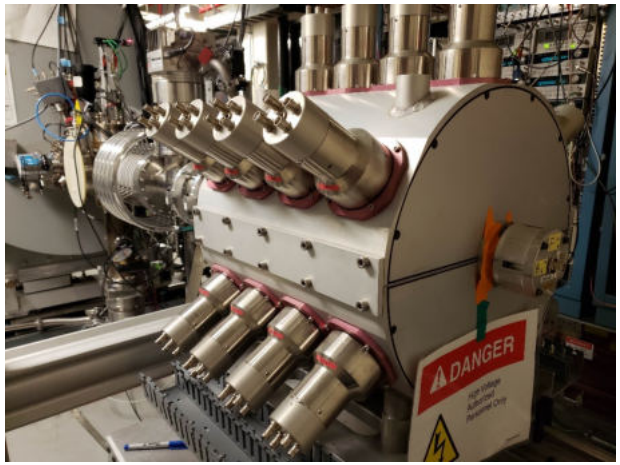
Summing NaI(Tl) Total Absorption Spectrometer

Summing NaI(Tl) (SuN) total absorption spectrometer

- 8 Segments give information about individual γ-rays
- Summing γ-rays from all segments gives information about excitation energies

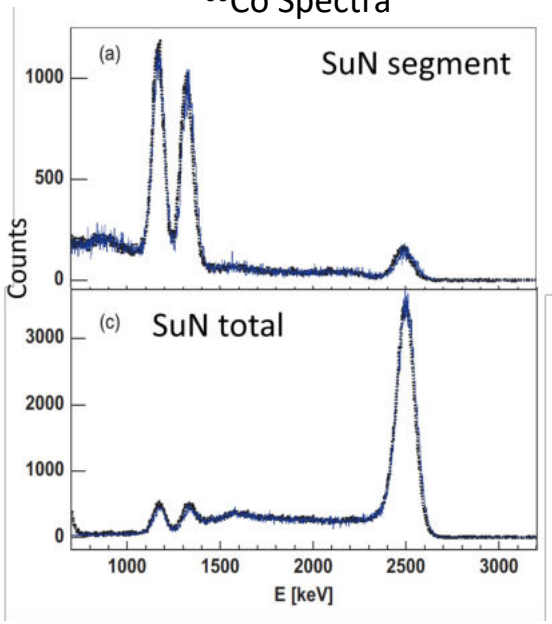






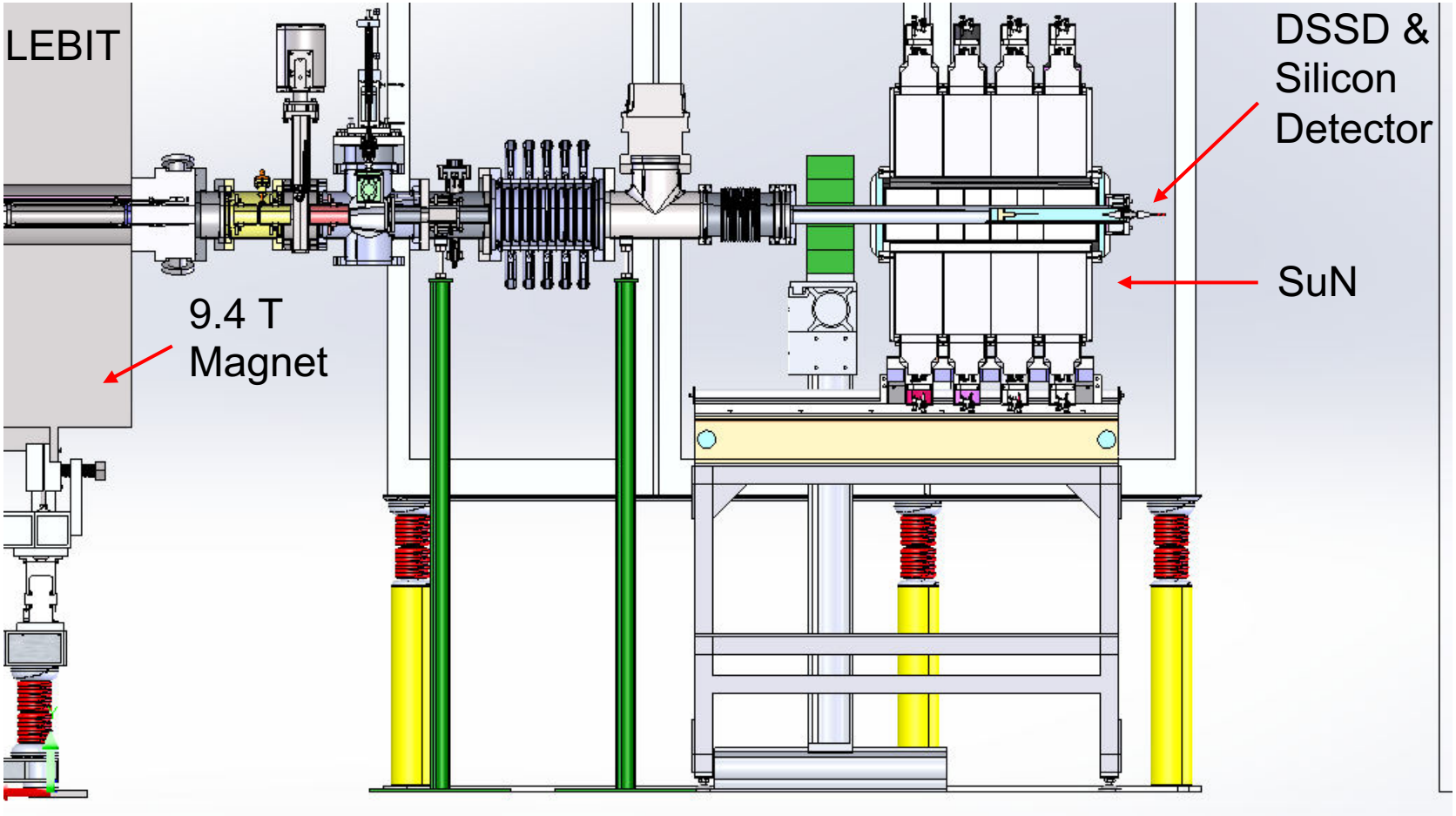
Efficiency at 1 MeV—85%
Resolution at 1MeV—6%

^{60}Co Spectra



Simon et al., NIM A 703 (2013): 16-21

SuN/LEBIT Ion Trap Experiments (SuNLITE)

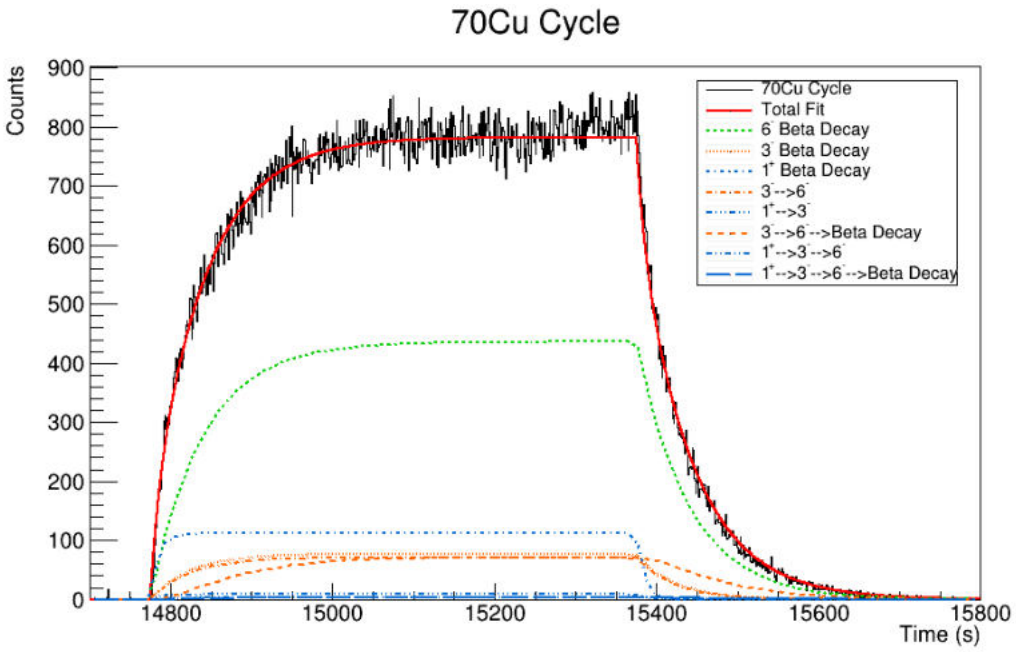


Experiment took place at the NSCL at MSU

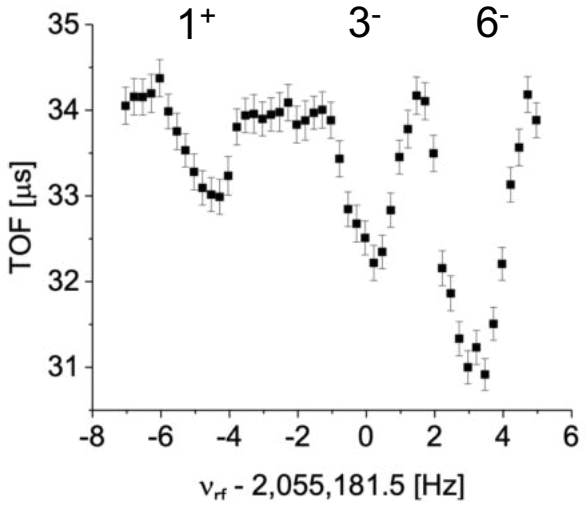
CAD drawing courtesy of C. Snow

Separation of two isomeric and ground states

- Need to separate out 6^- ground state γ-rays from 1^+ and 3^- isomeric state γ-rays in ^{70}Cu beam

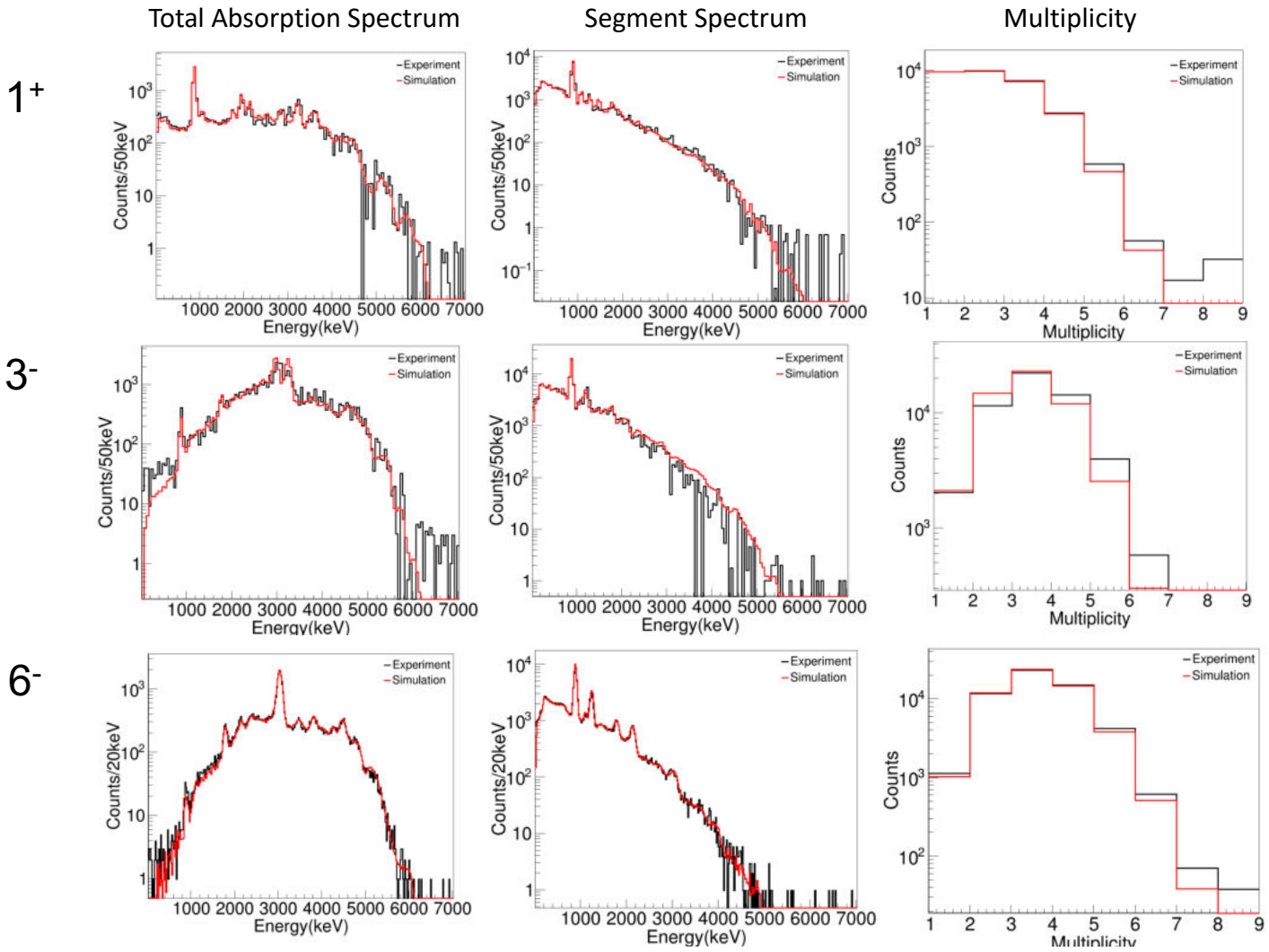


Spin Parity State	Beam Percentage
6-	69(4)%
3-	23(4)%
1+	8(7)%

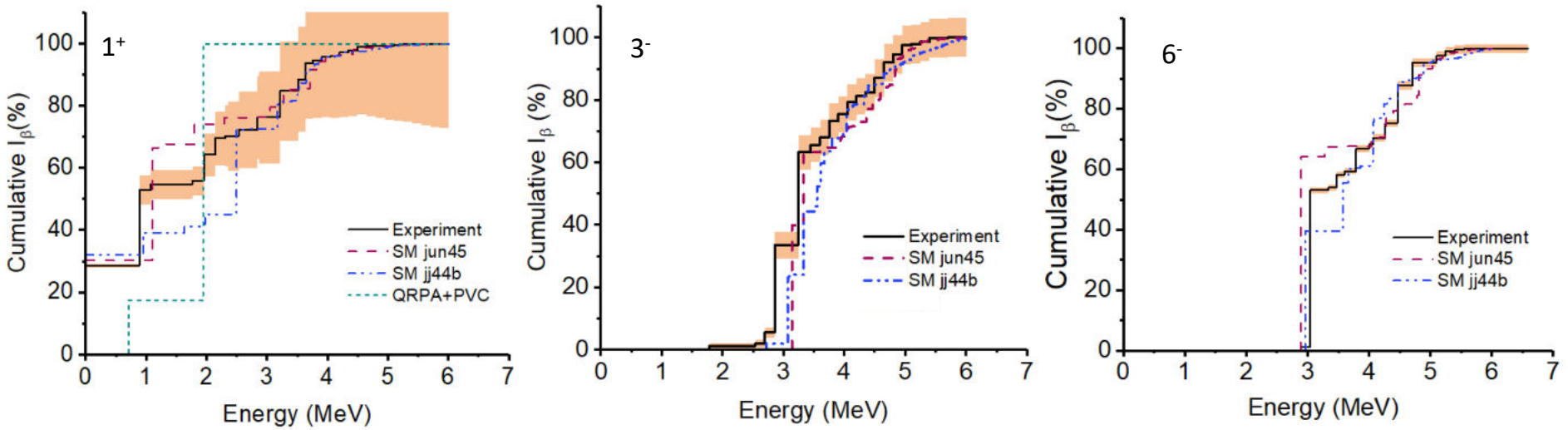


- ^{70}Cu beam cycled on/off every 10 minutes

Final χ^2 minimization results



Extraction of β-feeding values

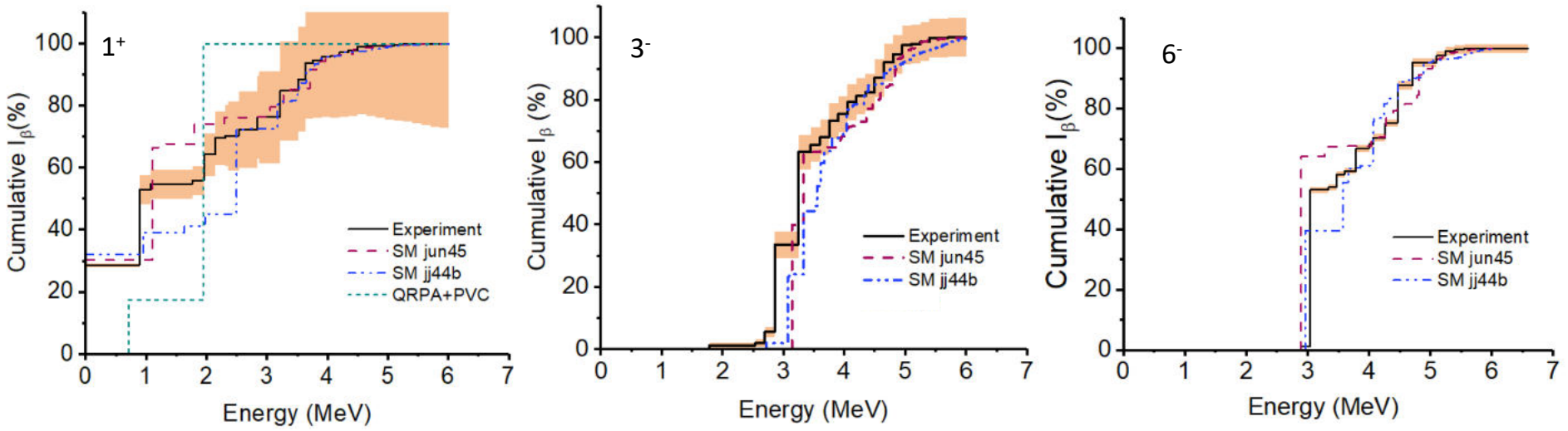


Experimental I_β values compare well to theory

- Shell Model with jun45[a] and jj44b[b] Hamiltonians
- QRPA+PVC[c,d]
  - Compared to 1^+ isomer

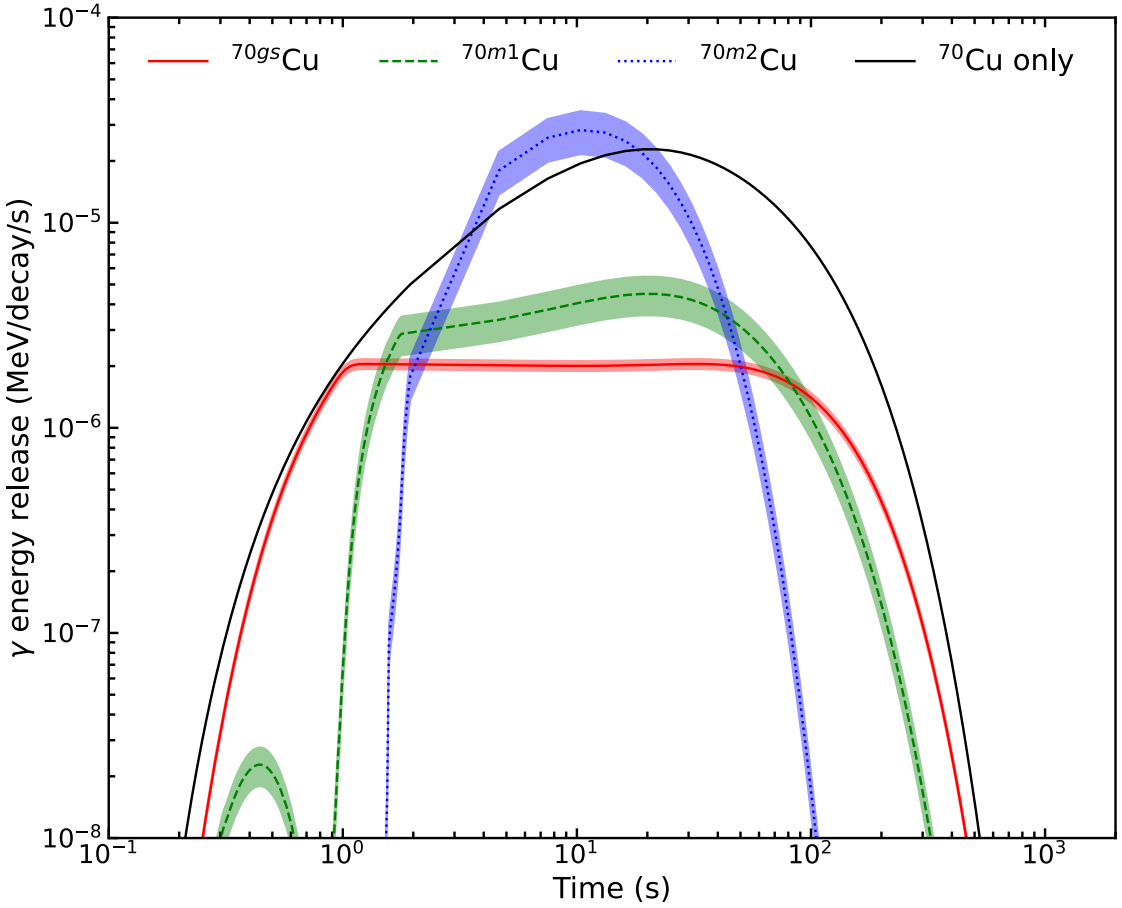
[a] Honma, et al. PRC **80** 064323 (2009)
[b] Mukhopadhyay, et al. PRC **95** (2017)
[c] Robin, et al. Eur Phys J A **52** 205 (2016)
[d] Robin, et al. PRC **98** 051301 (2018)

Extraction of average γ-ray energy



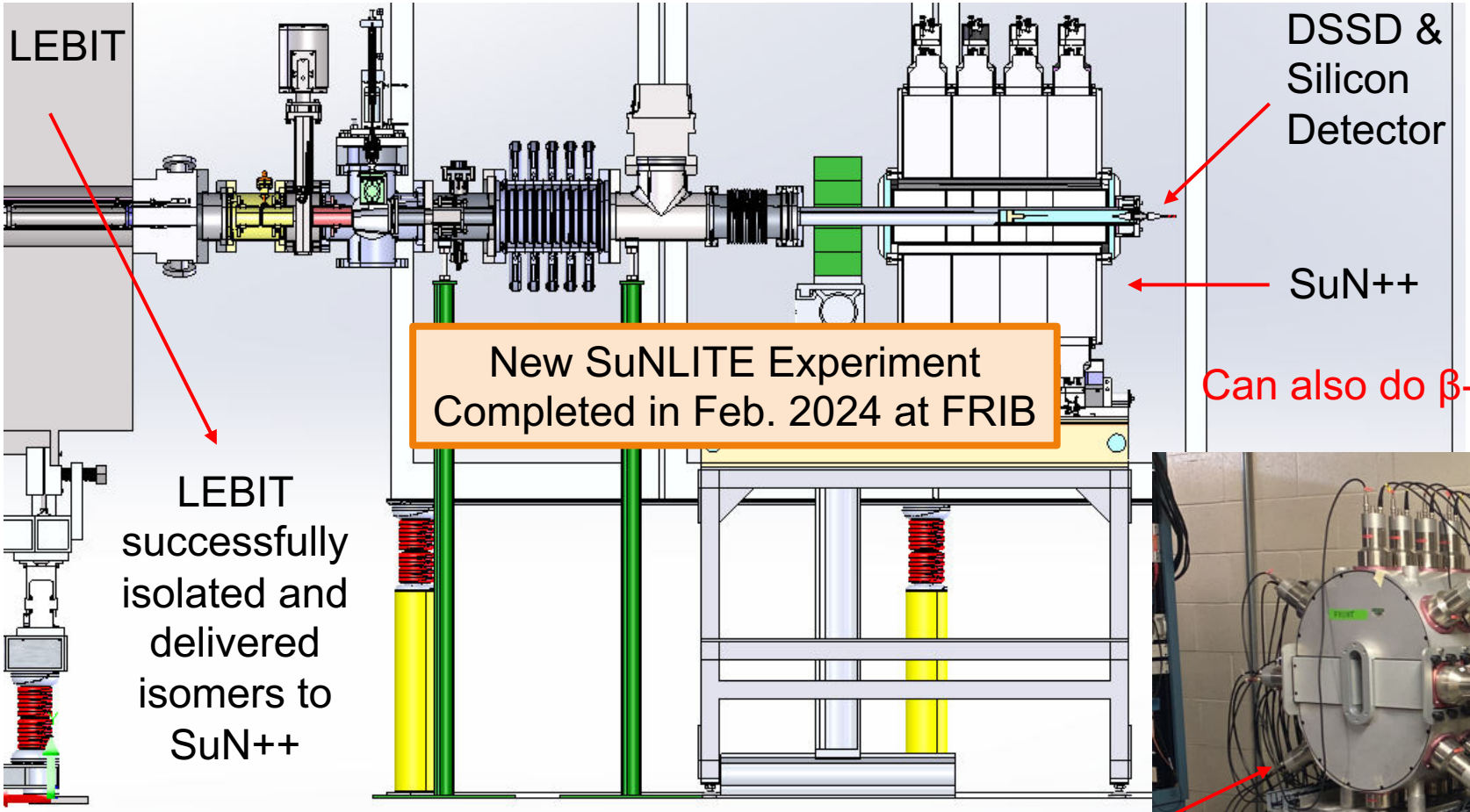
Ground/Isomeric State	Average γ-ray energy (MeV)
6-	3.6(2)
3-	3.5(7)
1+	1.5(4)

Isomers have different overall energy release



The population of these astromers greatly impacts energy release compared to treatment of ^{70}Cu as a single species

SuN++/LEBIT Ion Trap Experiments (SuNLITE++)



SuN was upgraded to SuN++
12 NaI and 8 $CeBr_3$ detectors added

CAD drawing courtesy of C. Snow

Summary and Future Prospects

Summary

- Nuclear isomers can play important roles in stellar nucleosynthesis but because of lacking experimental data they are often neglected
- For the first time we identify the 1^+ and 3^- isomers in ^{70}Cu as “astromers”
- We measured the β-decay of the 6^- ground state and 3^- and 1^+ isomeric states in ^{70}Cu to ^{70}Zn using SuN and LEBIT and extracted experimental β-feeding values and average γ-ray energy
- ^{70}Cu proves to be a good example of how the population of astromers will impact electromagnetic signals from heavy element nucleosynthesis
  - Cumulative affects from many astromers will impact time-dependent γ-spectra and alter observable signals

Future Prospects: We need more experimental data about astromers to begin to understand the role they play in stellar nucleosynthesis

Acknowledgements


S. N. Liddick, A. Spyrou, I. Yandow, R. Ringle, B. A. Brown, A. Chester, A. Hamaker, C. Harris, R. Lewis, K. Lund, J. Owens-Fryar, A. Palmisano, D. Puentes, M. K. Smith, C. Sumithrarachchi

G. W. Misch, M. Mumpower, T. Sprouse

P. A. DeYoung

S. Lyons

A. Richard

K. Childers


M. Wiedeking

Y. Xiao.

R. Sandler


TECHNISCHE UNIVERSITÄT DARMSTADT

C. Robin, G. Martinez, D. A. Terrero

This work is supported by the US Department of Energy National Nuclear Security Administration through Grant No. DOE-DE-NA0003906