Nuclear Shell Model to the Rescue: Efforts to Resolve a Mystery in Beta Delayed Neutron Emission

SDSU San Diego State University
UCI University of California, Irvine

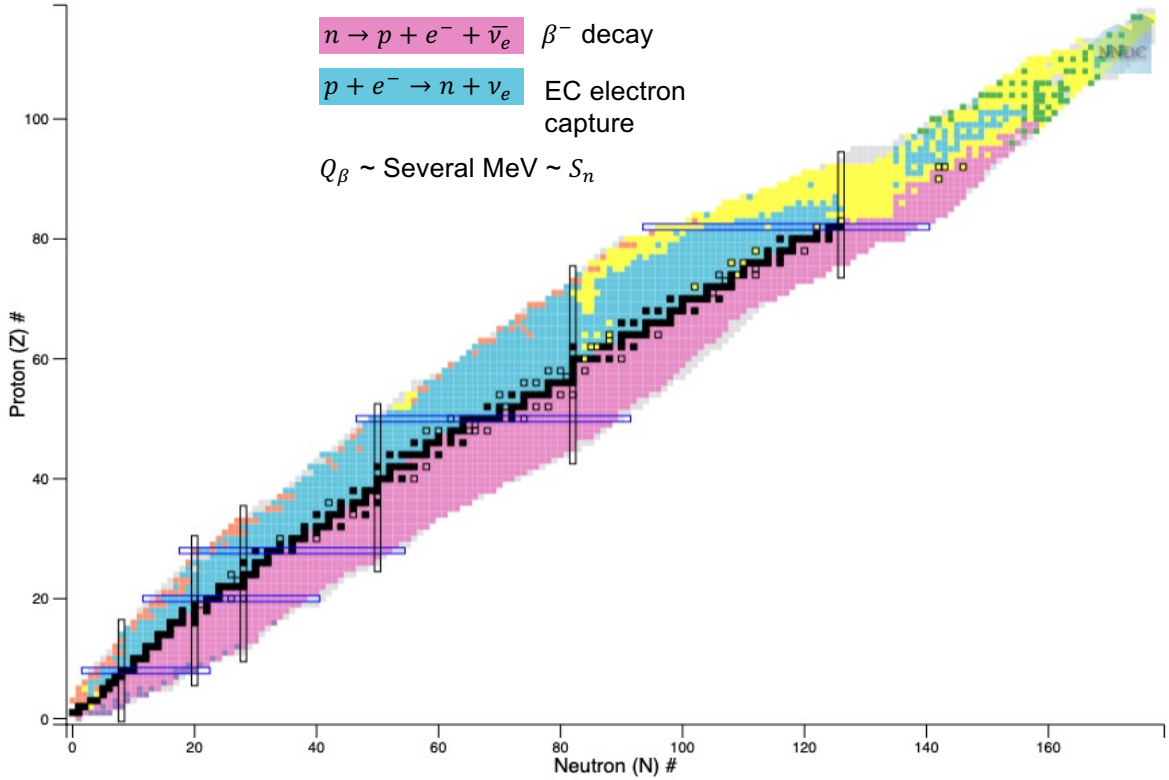
APS Division of Nuclear Physics 2022 Conference,
New Orleans, Louisiana
October 30, 2022

Oliver Gorton (SDSU, UCI, LLNL)
Calvin Johnson (SDSU)
Jutta Escher (LLNL)

LLNL-PRES-837979
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 with support from the ACT University Collaboration program. Lawrence Livermore National Security, LLC

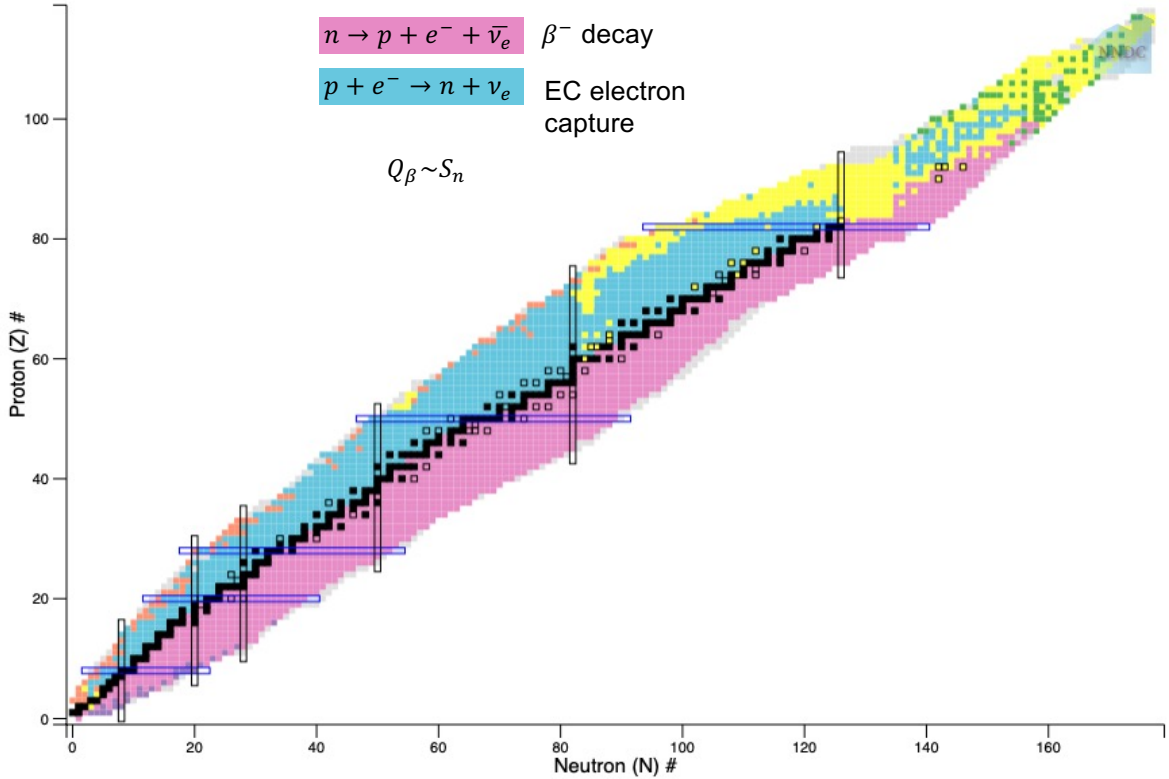
Lawrence Livermore National Laboratory

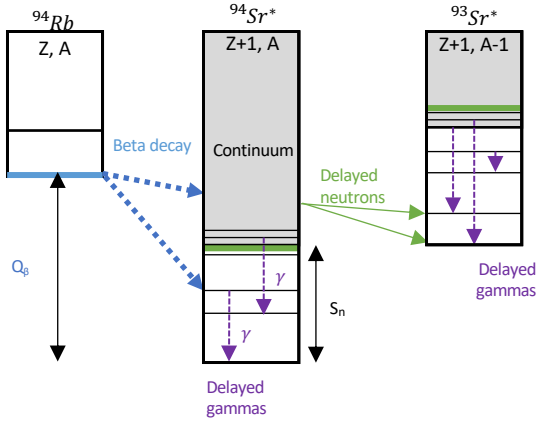
Beta decay is the most common radioactive decay mode!



NuDat 3.0 https://www.nndc.bnl.gov/nudat3/

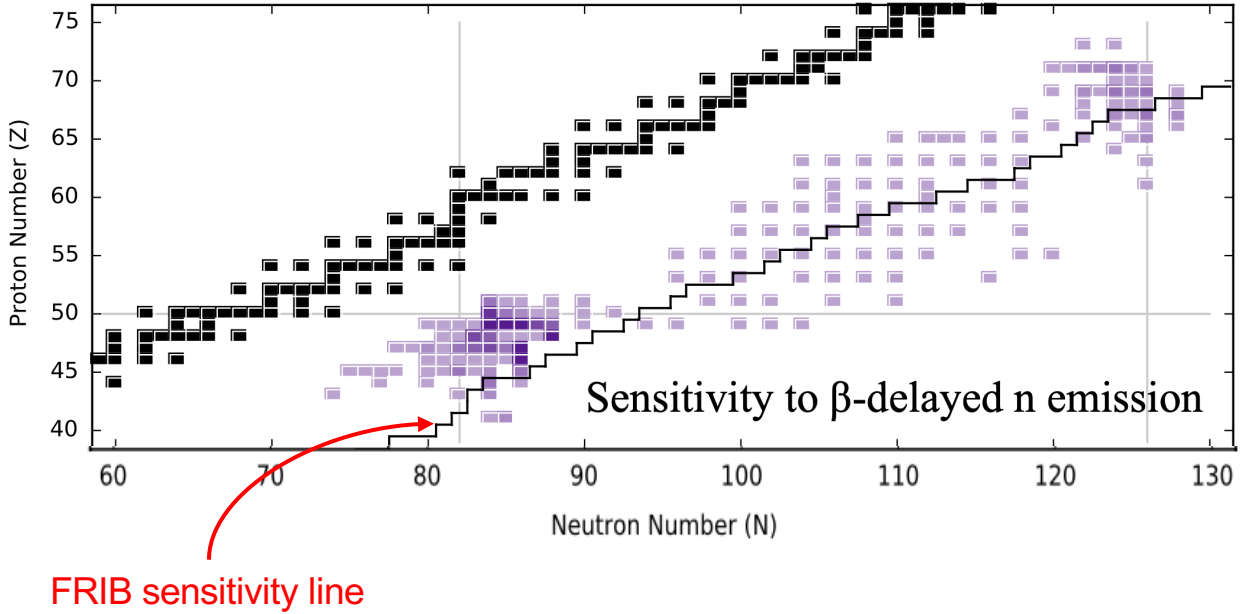
Beta decay is a precursor to delayed gammas and neutrons





- Beta-delayed neutrons
- Beta-delayed gammas/photons

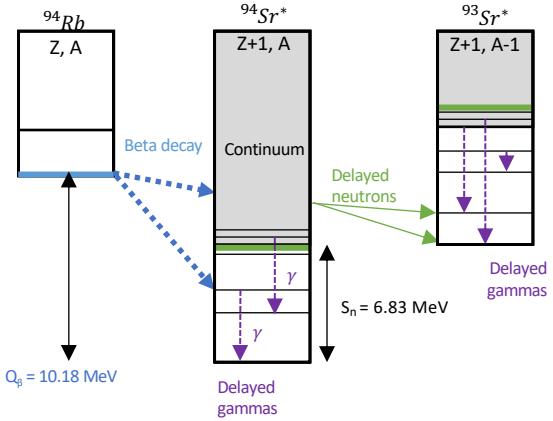
Beta-delayed neutron emission is important for astrophysical element synthesis

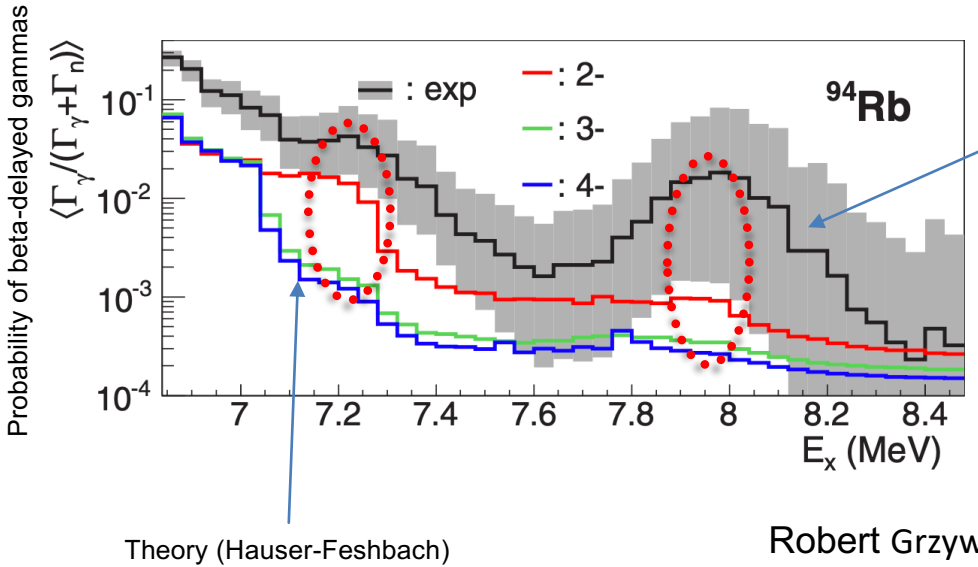


It's important to have a strong theoretical description of BDNE

Mumpower, et al., 2015 https://doi.org/10.1016/j.ppnp.2015.09.001

Crisis: Statistical models underpredict beta-delayed photon intensity





Robert Grzywacz et al. are also investigating the nonstatistical nature of neutron emission near Sn-134!

Valencia, et al., 2017 https://link.aps.org/doi/10.1103/PhysRevC.95.024320

Why are we getting this so wrong? New questions:

- Does beta decay create a well-equilibrated (statistical) nucleus? ✅ SM
- Does an unexpectantly large “forbidden” beta decay block neutron emission? ✅ SM
- Is the gamma-ray decay strength greatly enhanced? ✅ SM

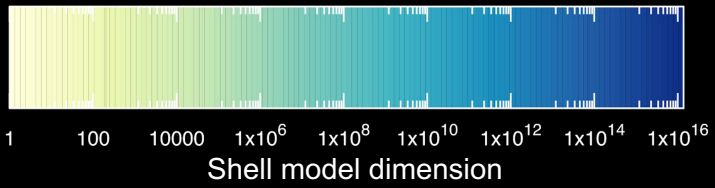
The issue: Nuclear structure for short-lived nuclei is lacking

My quest: Use shell model (SM) calculations to supply them!

One small problem…

Because they include so many correlated configurations,

Shell-models have enormous dimensions!

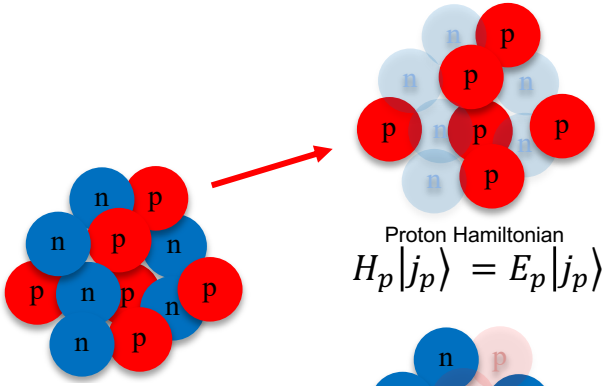


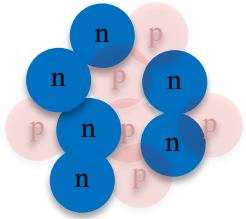
e.g. ^{94}Rb has dimension 10^{13}

Proton and Neutron Approximate Shell Model (PANASH)

$$H = H_p + H_n + H_{pn}$$

Bipartite Partitioning
(Orders of magnitude smaller!)



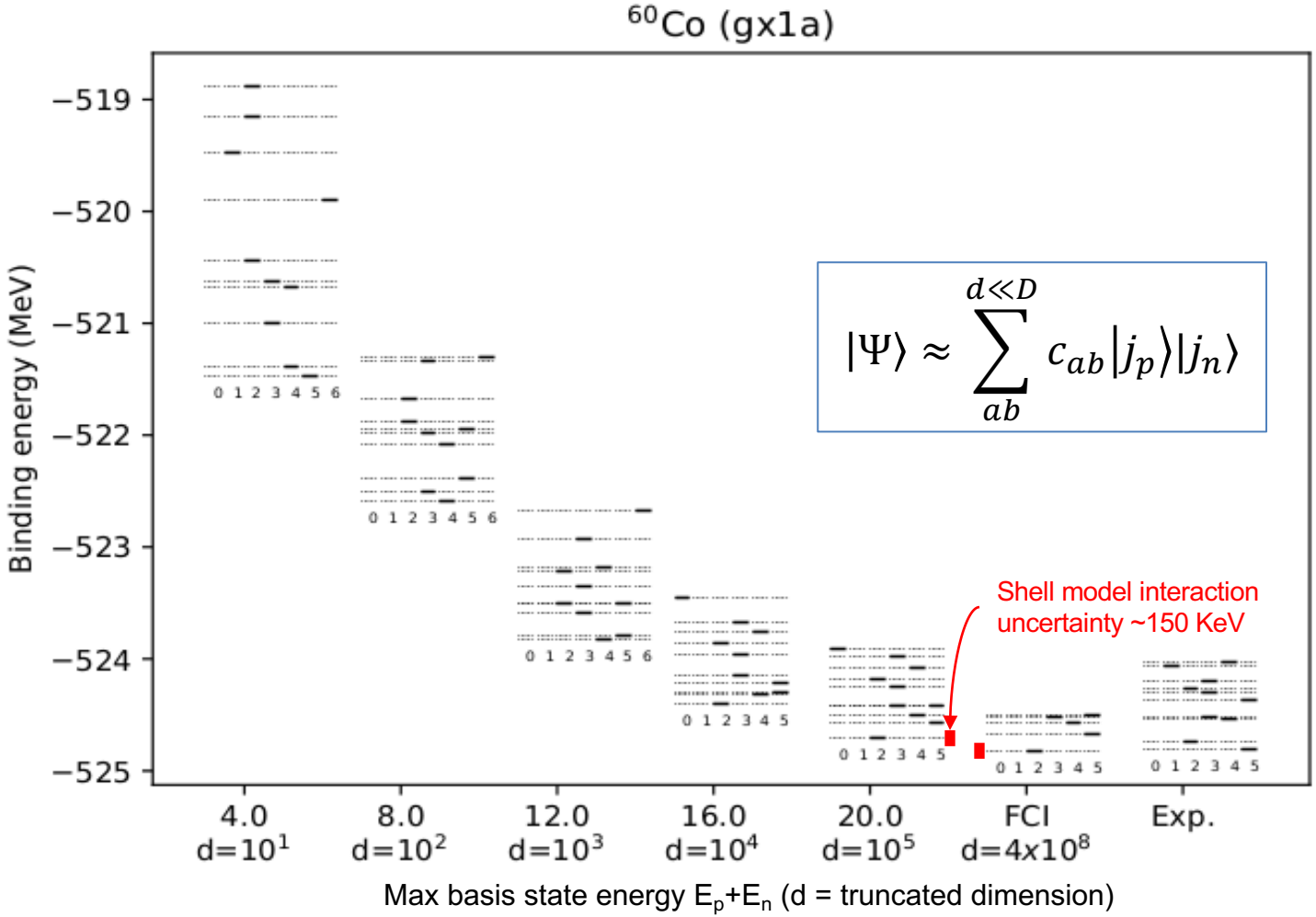


$$|j_p j_n|\, J\rangle = |j_p\rangle \otimes |j_n\rangle|_J$$
j-j coupled basis

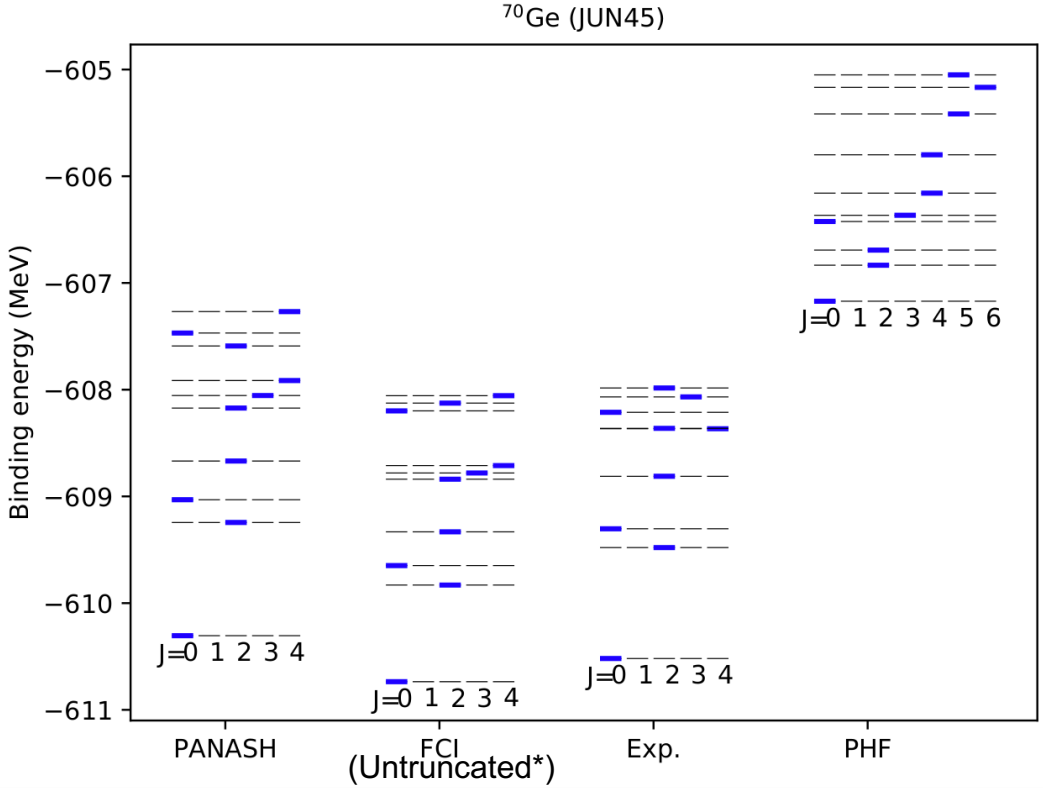
- Wave functions factorize into PN-partition eigenstates
- Coefficients decay exponentially
- Proton neutron entanglement decreases when N>Z (arxiv 2210.14338)

$$|\Psi\rangle \approx \sum_{ab}^{d \ll D} c_{ab} |j_p\rangle |j_n\rangle$$

(There is some freedom in the sum)


^{60}Co (gx1a)
Binding energy (MeV)
−519
−520
−521
−522
−523
−524
−525
0 1 2 3 4 5 6
0 1 2 3 4 5 6
0 1 2 3 4 5 6
0 1 2 3 4 5
0 1 2 3 4 5
0 1 2 3 4 5
$|\Psi\rangle \approx \sum_{ab}^{d \ll D} c_{ab} |j_p\rangle |j_n\rangle$
Shell model interaction uncertainty ~150 KeV
4.0 d=10^1
8.0 d=10^2
12.0 d=10^3
16.0 d=10^4
20.0 d=10^5
FCI d=4x10^8
Exp.
Max basis state energy E_p+E_n (d = truncated dimension)

Convergence of spectra (preliminary)

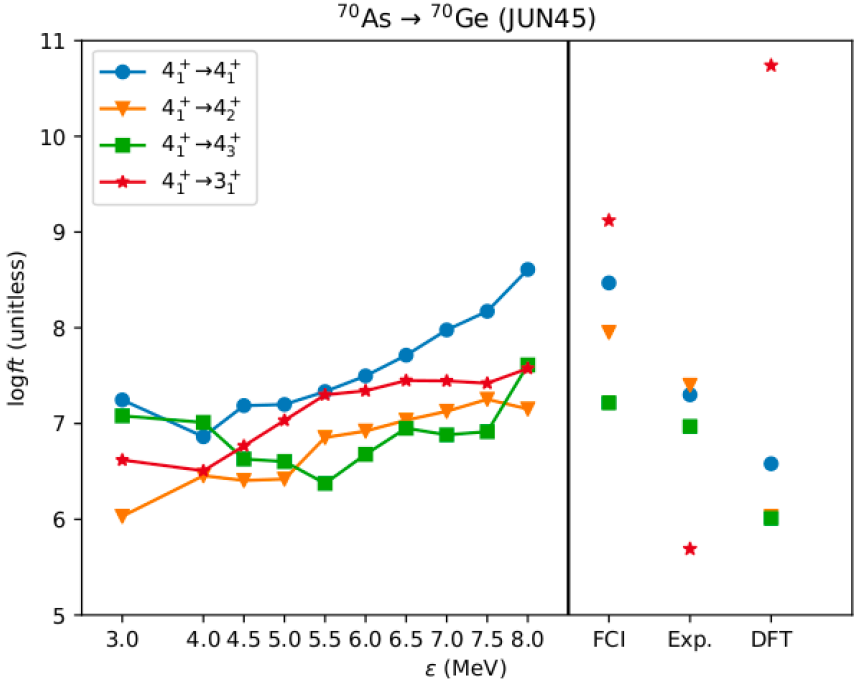


Ge70 is a complicated nucleus!

M-scheme untruncated dimension: 280M
PANASH (this work) dimension: 14k

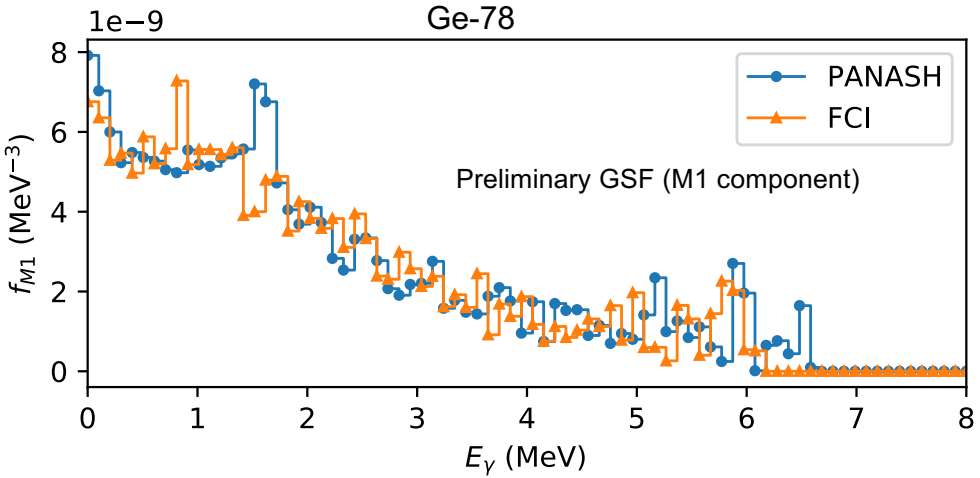
- 217 of 701 protons components
- 1190 of 47722 neutron components

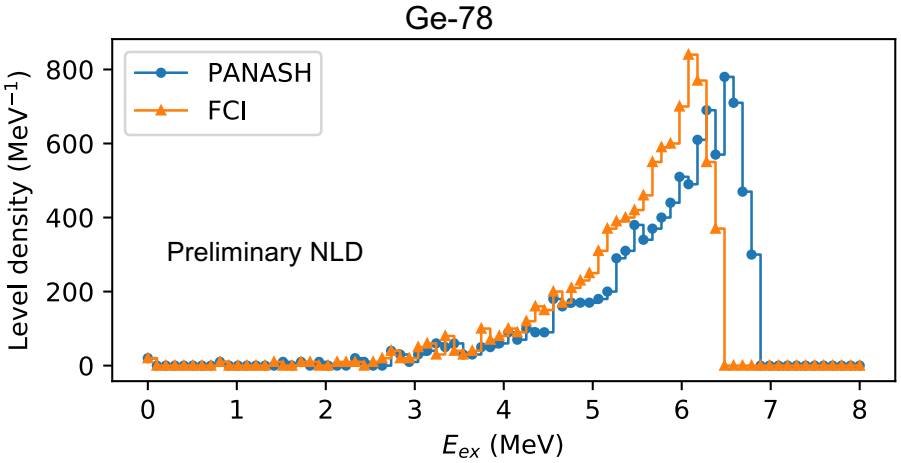
We can predict beta decay rates



- Large log*ft* values correspond to small transition probabilities
- Leads to small-number errors
- The distribution/ratio of these will matter for beta-delayed neutron emission

We can calculate photon strength functions (PSFs) and level densities (LDs)





PANASH (this work): used 30% of proton/neutron eigenstate components: 34x basis reduction

Agreement with results of Frauendorf & Schwengner (PRC 105, 034335, 2022) w/ similar interaction

With all these ingredients from the shell model, we expect new insights into beta delayed processes