

Nuclear structure effects unveiled by β -delayed neutrons

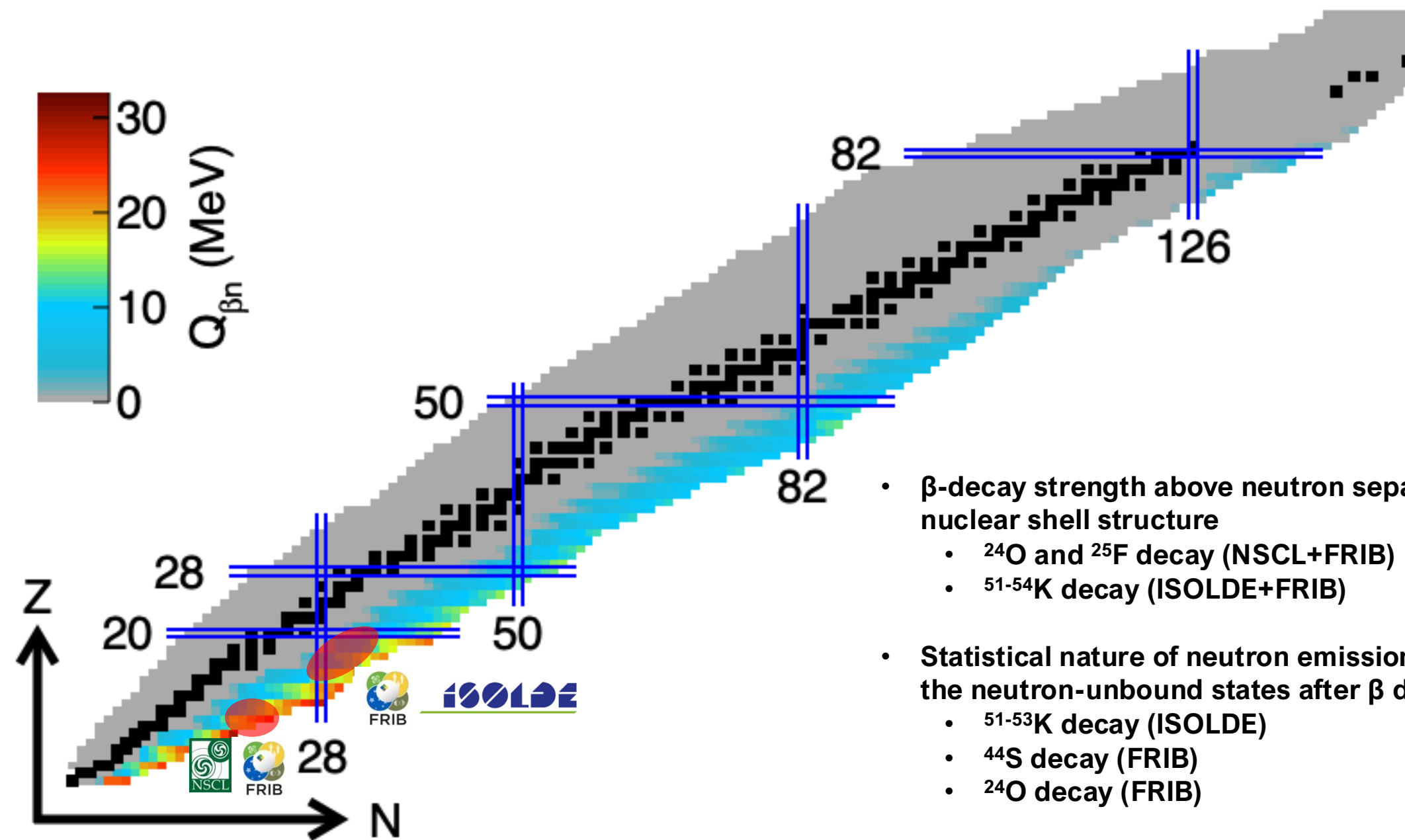
Zhengyu Xu

Future directions in nuclear beta decay at FRIB,
8-19, September 2025, FRIB



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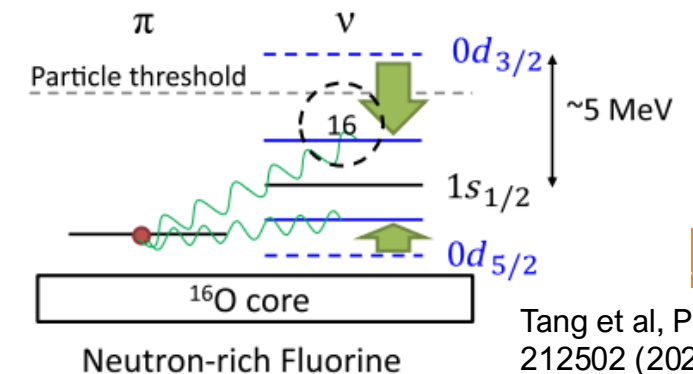
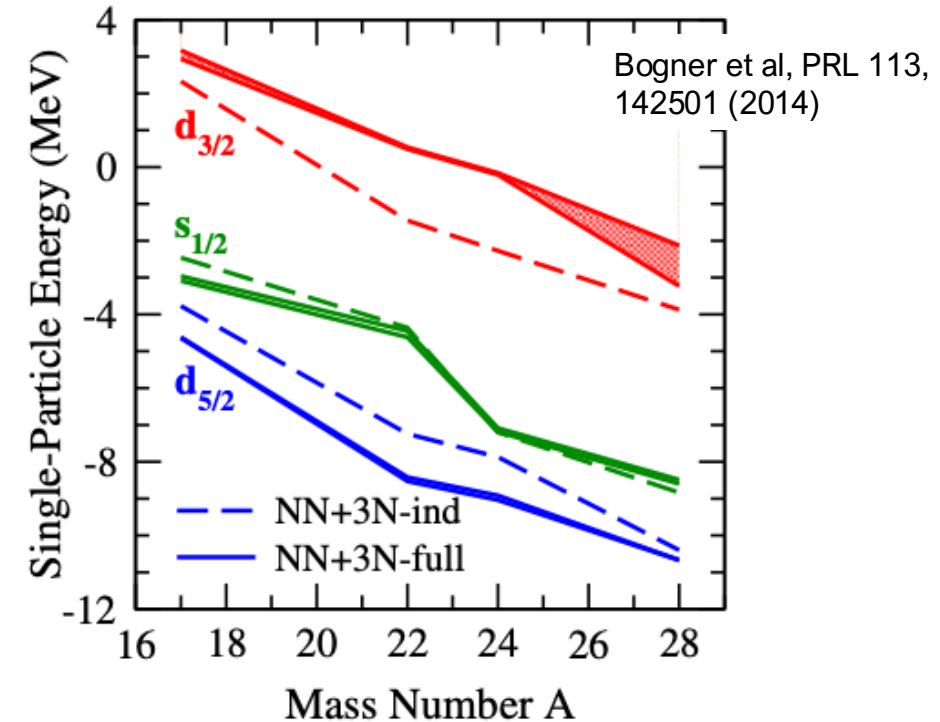




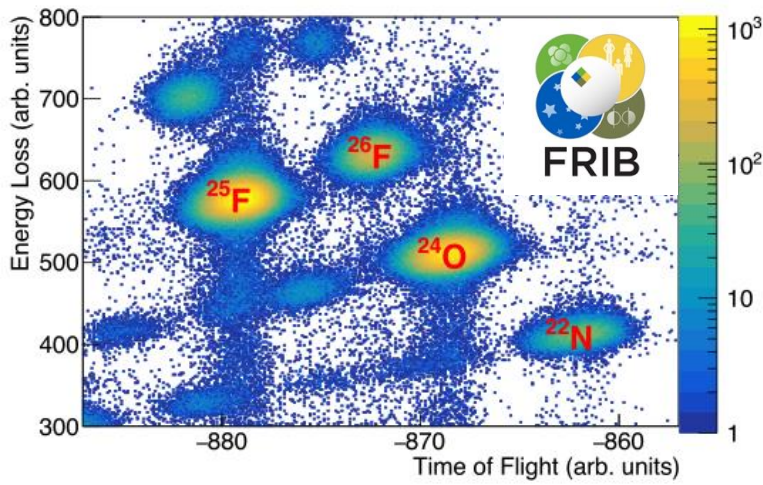
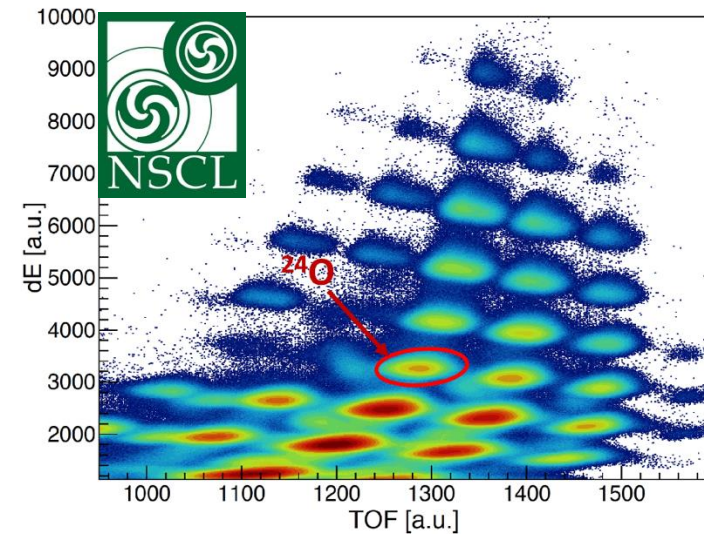
- β -decay strength above neutron separation energy and nuclear shell structure
 - ^{24}O and ^{25}F decay (NSCL+FRIB)
 - $^{51-54}\text{K}$ decay (ISOLDE+FRIB)
- Statistical nature of neutron emission, and the width of the neutron-unbound states after β decay
 - $^{51-53}\text{K}$ decay (ISOLDE)
 - ^{44}S decay (FRIB)
 - ^{24}O decay (FRIB)

The evidence of $N=16$ shell closure and β -delayed neutron emission from ^{24}O and ^{25}F

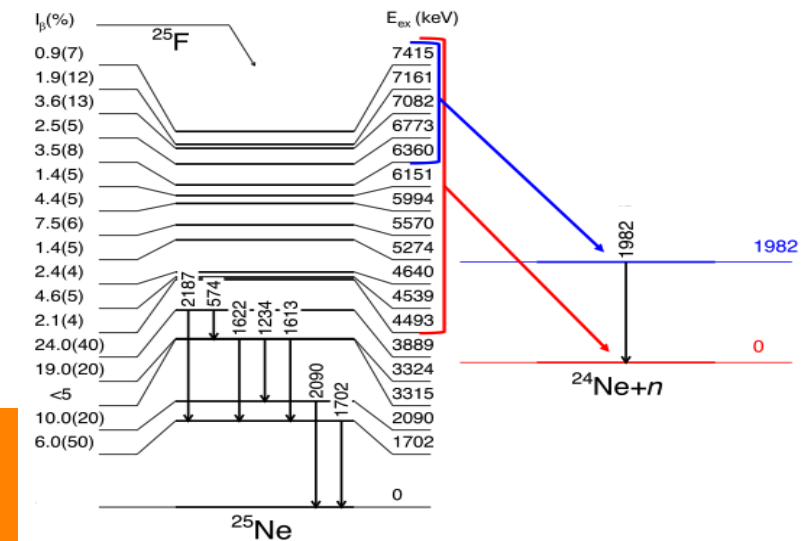
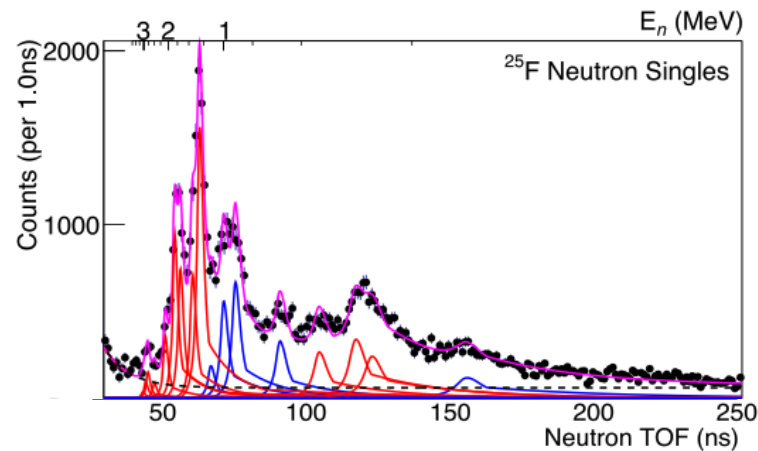
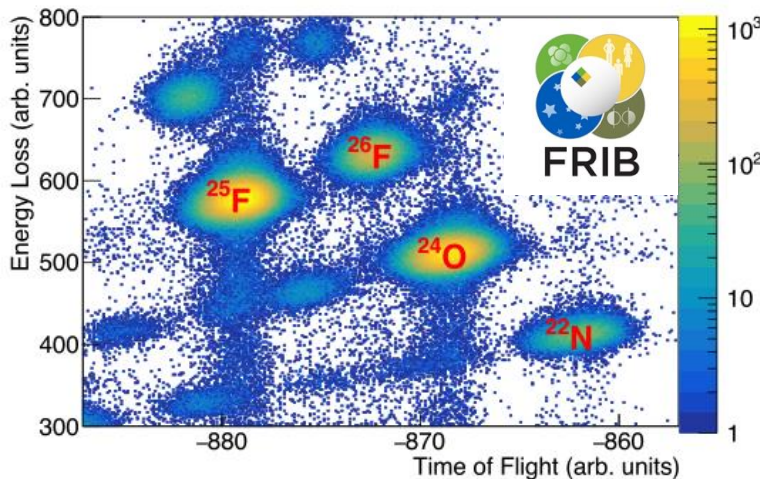
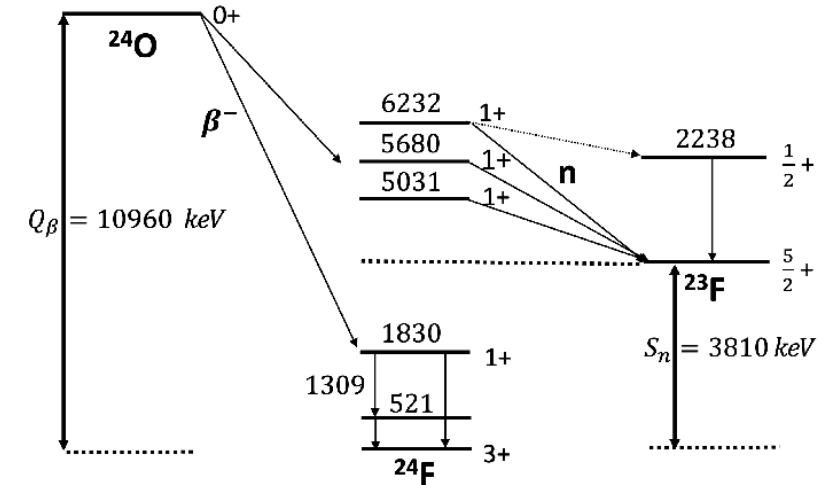
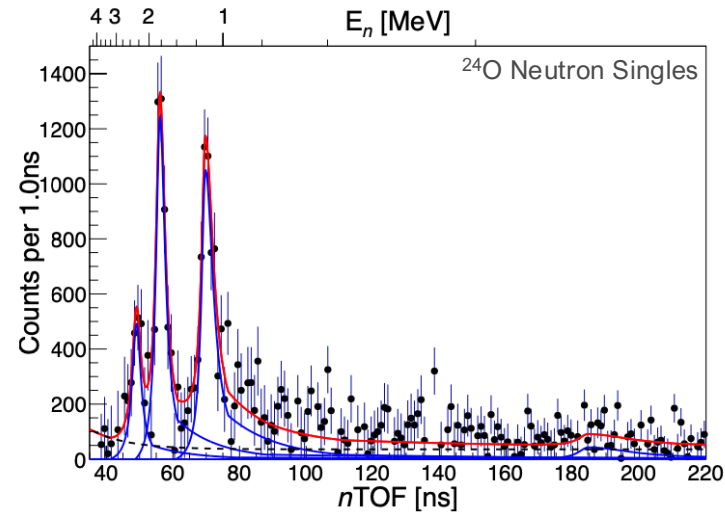
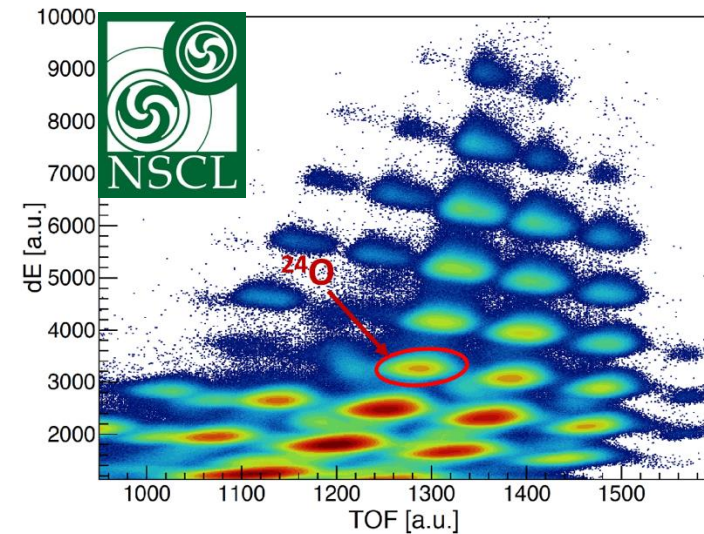
- ^{24}O is doubly magic due to the $N=16$ shell closure (Kanungo2009, Tshoo2012)
- Due to the attractive p - n interaction, adding a proton to the $d_{5/2}$ orbital will reduce the size of the $N=16$ shell gap
- The cross sections from $^{25}\text{F}(p,2p)^{24}\text{O}$ suggest a strong reduction of the $N=16$ shell gap in ^{25}F (Tang2020, Crawford2022)
- Interesting to investigate the evolution of the $N=16$ shell gap using the $^{24}\text{O} (\rightarrow ^{24}\text{F})$ and $^{25}\text{F} (\rightarrow ^{25}\text{Ne})$ decay
- Both decays had been studied with γ -ray spectroscopy (Reed1999, Padgett2005)



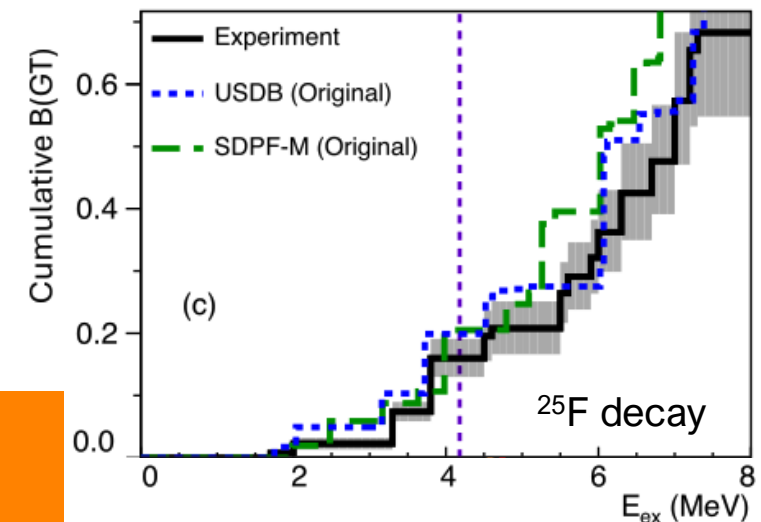
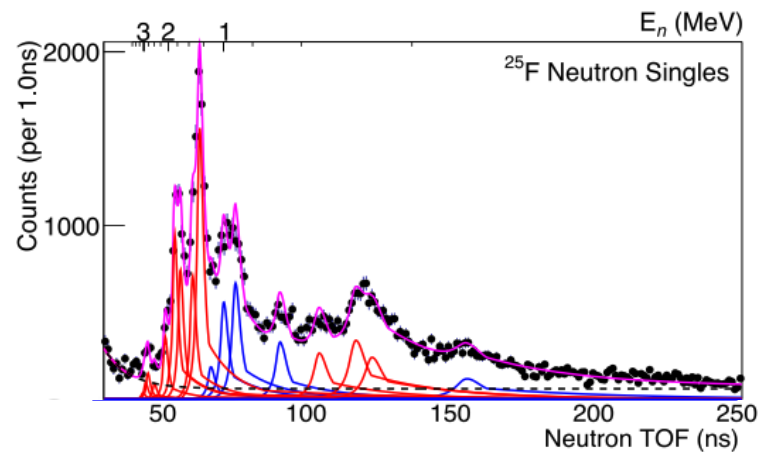
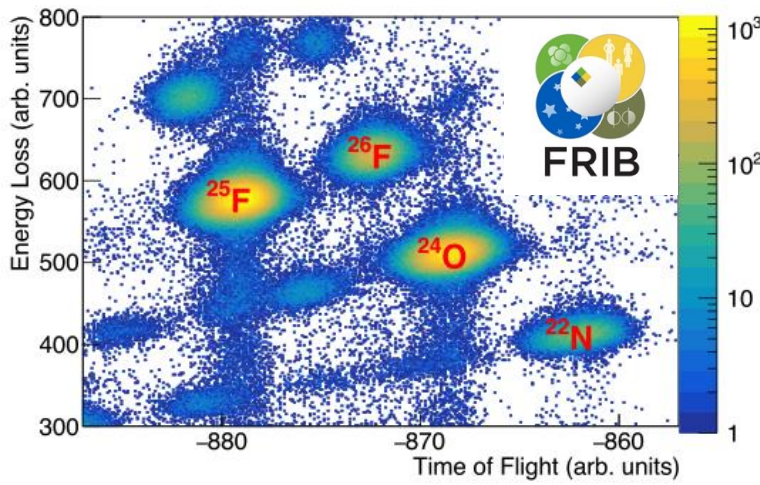
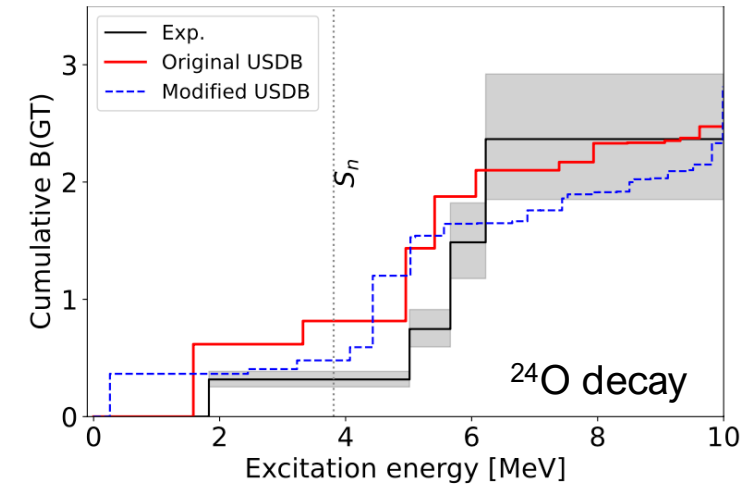
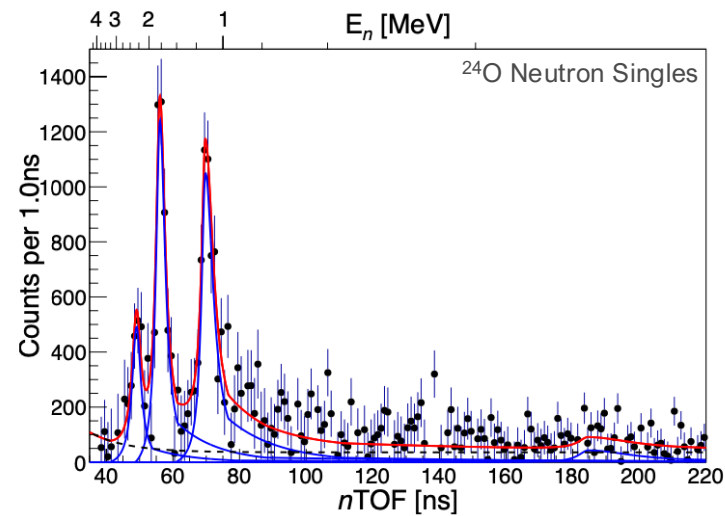
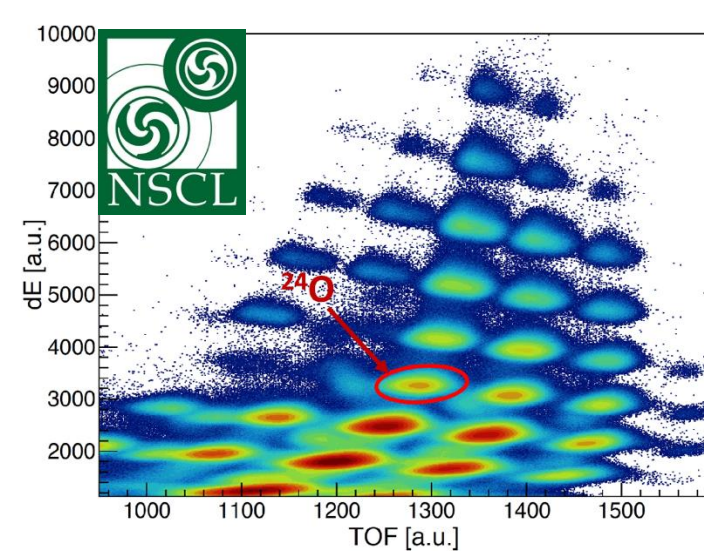
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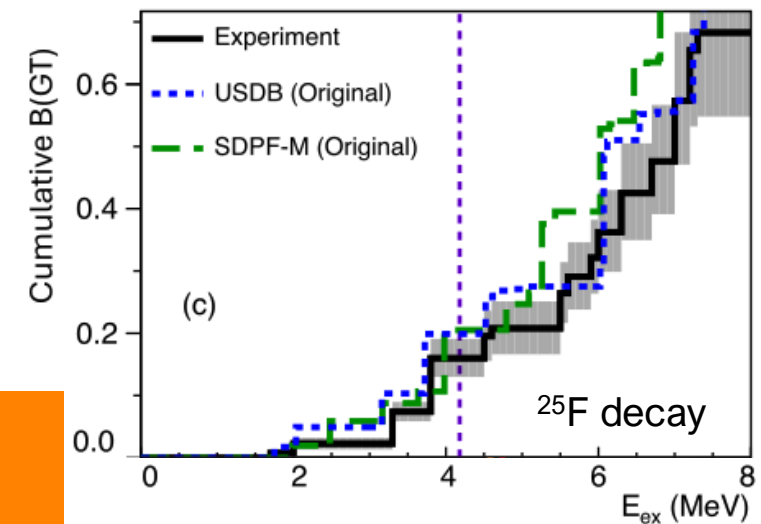
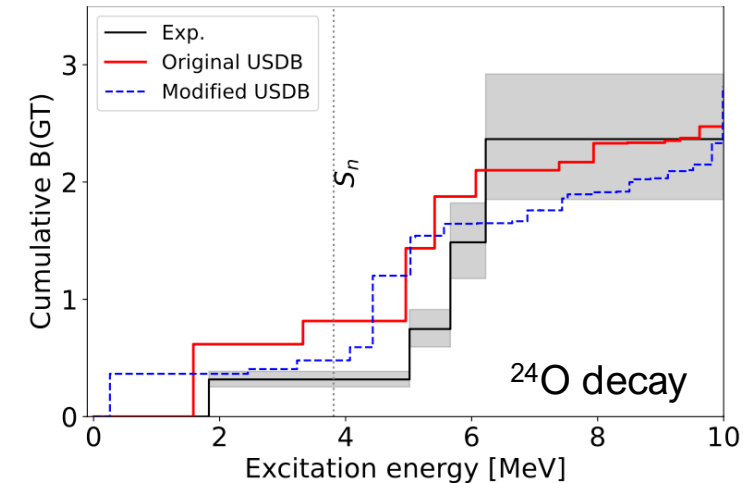


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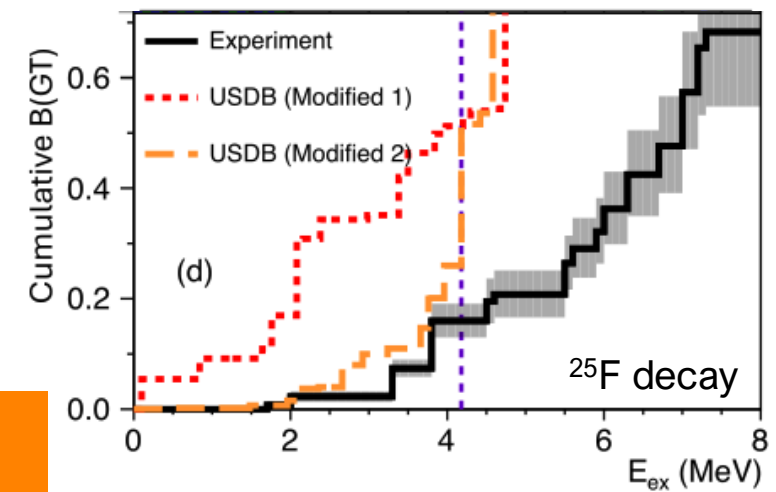
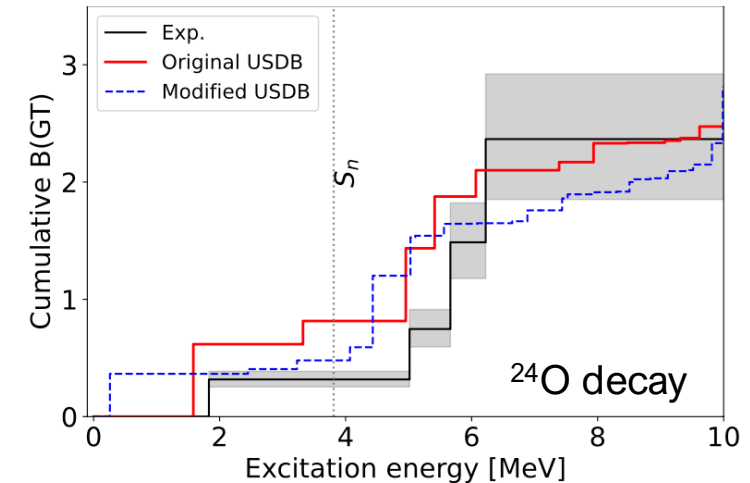
The evidence of $N=16$ shell closure and β -delayed neutron emission from ^{24}O and ^{25}F

- The original USDB interaction shows good agreement for both ^{24}O and ^{25}F
 - USDB suggests a good $N=16$ shell closure in the ground state of both ^{24}O and ^{25}F



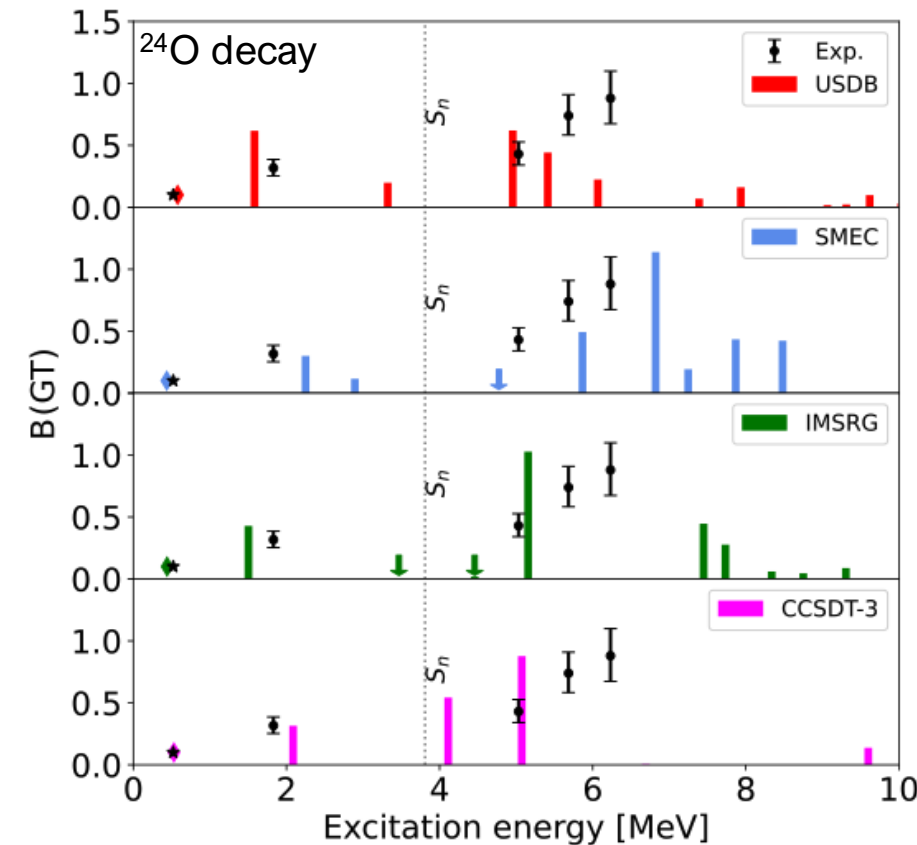
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 - Modifying the USDB interaction induced strong discrepancies
 - No theory can interpret beta decay and p2p cross section simultaneously (still an open question)



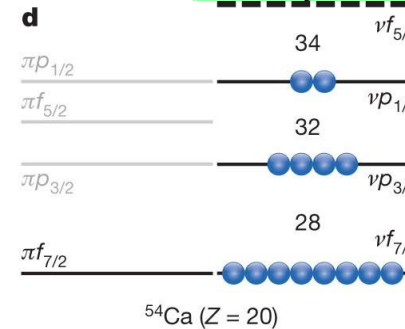
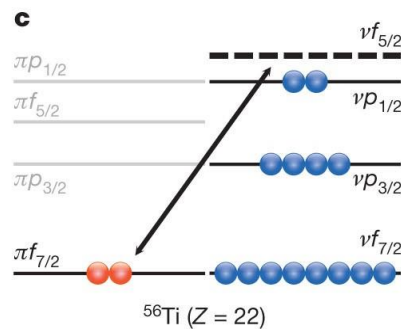
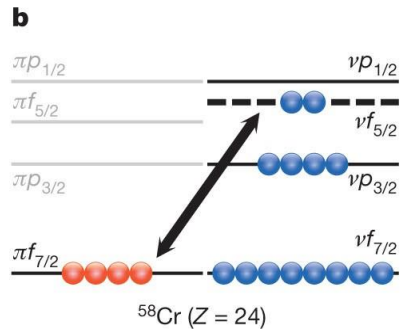
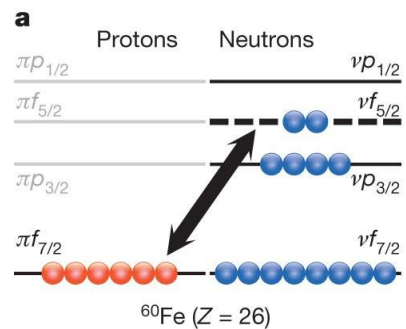
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 - Modifying the USDB interaction induced strong discrepancies
 - No theory can interpret beta decay and p2p cross section simultaneously (still an open question)
- Ab-initio calculations on ^{24}O are consistent with the bound state, but exhibit discrepancies above S_n (in collaboration with S. Novario and B. S. Hu)
- Neupane et al., Phys. Rev. C 110, 034323 (2024)
- J. Peltier et al., Phys. Lett. B 866, 139576 (2025)



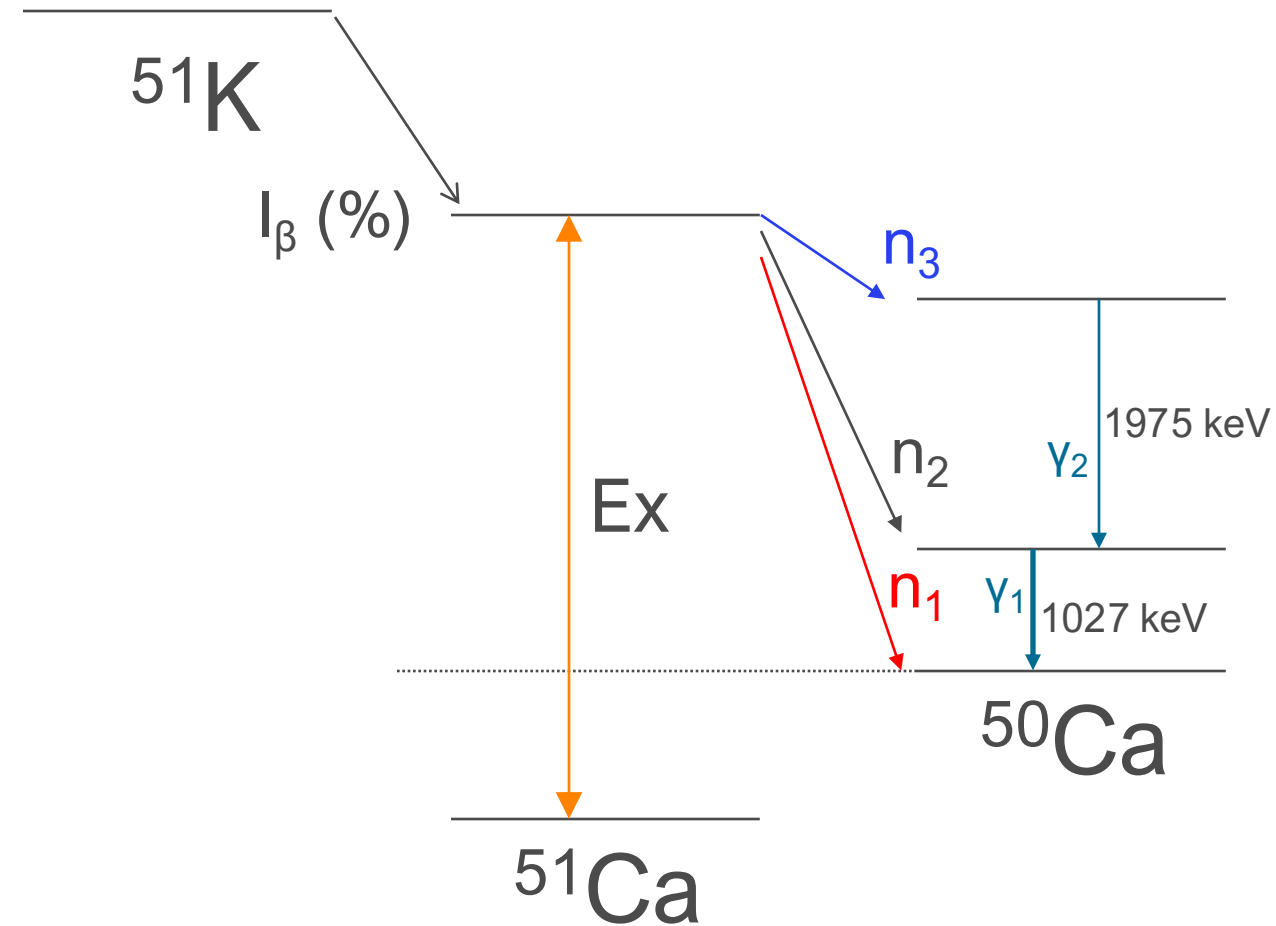
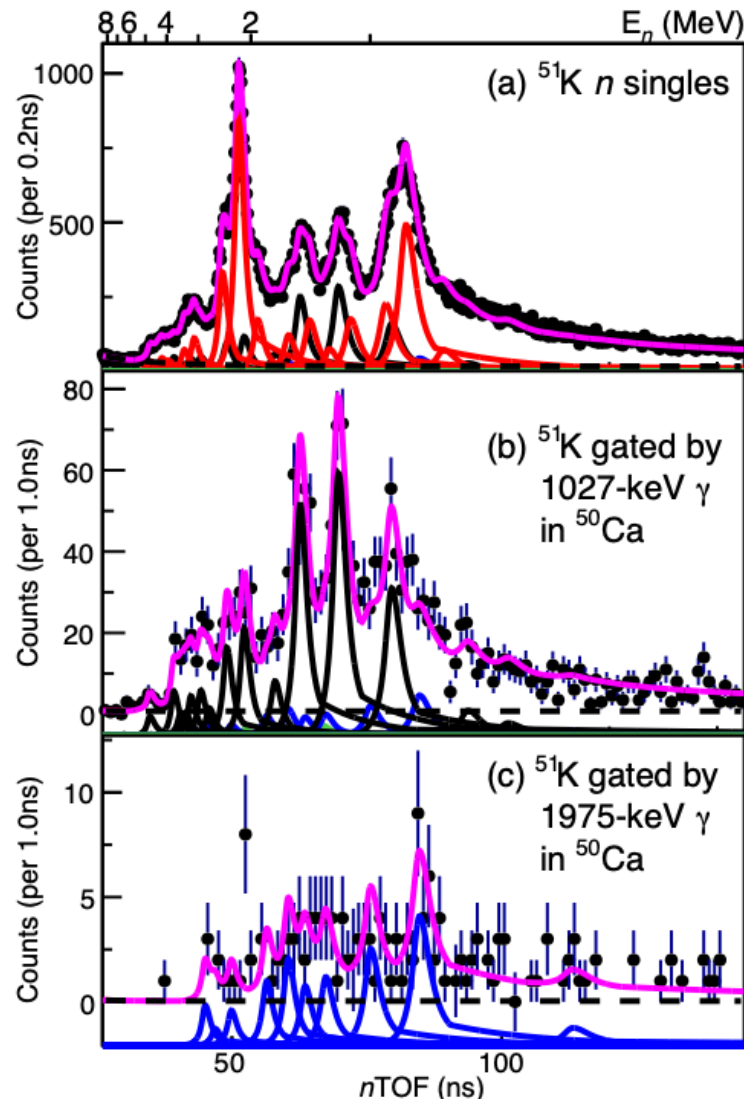
Decay spectroscopy of $^{51-54}\text{K}$ and the $N=34$ shell gap south of ^{54}Ca

- ^{54}Ca is a doubly magic nucleus with $Z=20$ and $N=34$ (Steppenbeck2013, Michimasa18, Chen2019)
- No $N=34$ shell gap in ^{56}Ti ($Z=22$) and ^{57}V ($Z=23$) (Iimura2023)
- What about potassium ($Z=19$)?
- β decay of $^{51-54}\text{K}$ reveal their ground-state properties

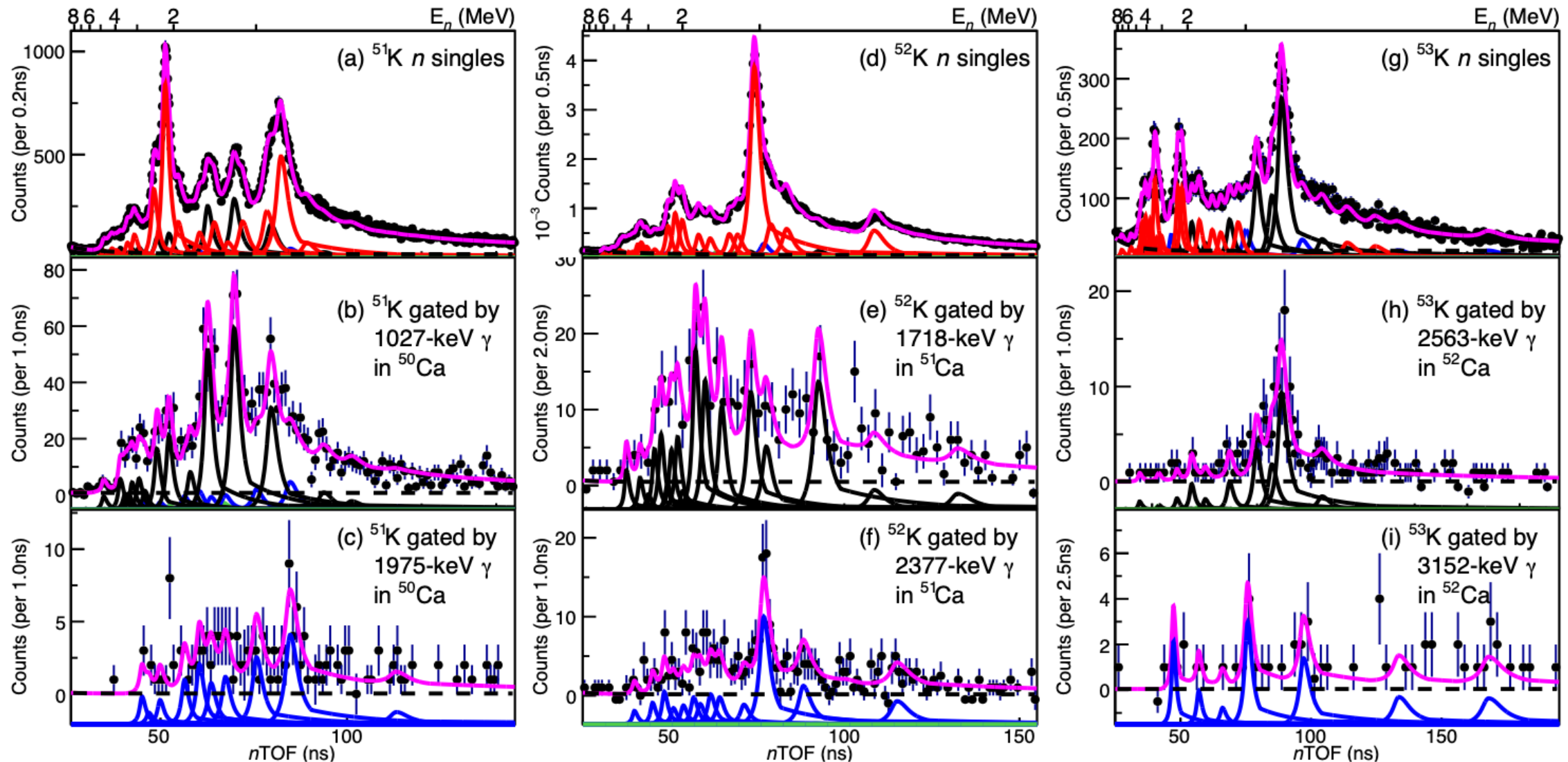


50V 20.89 MeV	51V 20.38 MeV	52V 18.36 MeV	53V 15.79 MeV	54V 14.6 MeV	55V 13.42 MeV	56V 12.43 MeV	57V 11.45 MeV	58V 10.39 MeV
49Ti 19.77 MeV	50Ti 19.08 MeV	51Ti 17.31 MeV	52Ti 14.19 MeV	53Ti 13.29 MeV	54Ti 12.41 MeV	55Ti 11.09 MeV	56Ti 9.82 MeV	57Ti 8.71 MeV
48Sc 18.89 MeV	49Sc 18.37 MeV	50Sc 16.18 MeV	51Sc 12.83 MeV	52Sc 12.13 MeV	53Sc 11.66 MeV	54Sc 10.06 MeV	55Sc 8.22 MeV	56Sc 7.22 MeV
47Ca 17.68 MeV	48Ca 17.23 MeV	49Ca 15.1 MeV	50Ca 11.51 MeV	51Ca 11.17 MeV	52Ca 10.82 MeV	53Ca 9.2 MeV	54Ca 7.04 MeV	55Ca 5.41 MeV
46K 15.78 MeV	47K 15.24 MeV	48K 13.01 MeV	49K 10.04 MeV	50K 9.59 MeV	51K 9.05 MeV	52K 7.55 MeV	53K 5.92 MeV	54K 4.16 MeV
47Ar 11.74 MeV	48Ar 8.73 MeV	49Ar 7.84 MeV	50Ar 7.02 MeV	51Ar 5.57 MeV	52Ar 4.29 MeV	53Ar 2.86 MeV		
46Cl 9.4 MeV	47Cl 7.46 MeV	48Cl 6.69 MeV	49Cl 5.82 MeV	50Cl 4.16 MeV	51Cl 2.59 MeV	52Cl 1.48 MeV		
45S 7.29 MeV	46S 6.3 MeV	47S 5.6 MeV	48S 4.39 MeV	49S 2.95 MeV				

Decay spectroscopy of $^{51-54}\text{K}$ and the $N=34$ shell gap south of ^{54}Ca

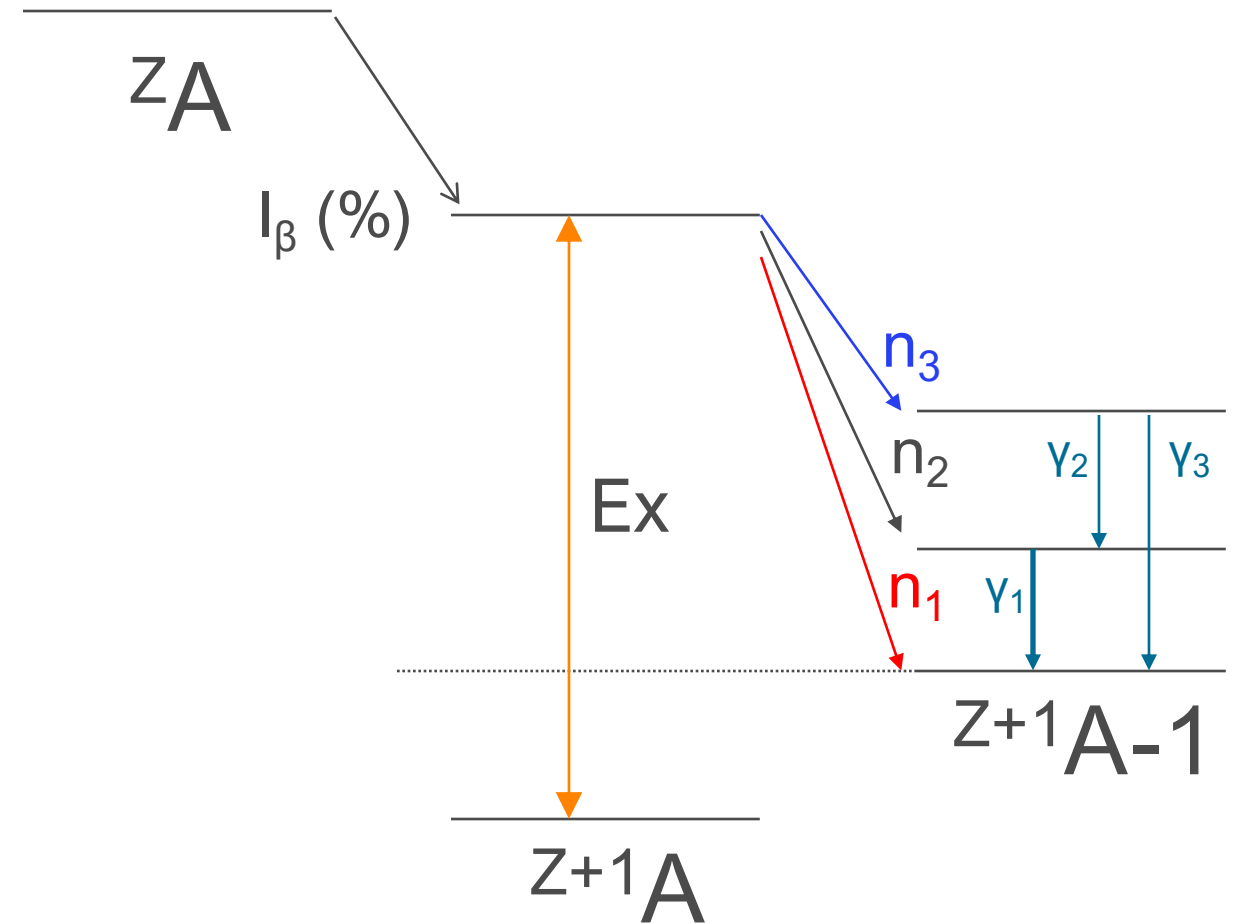


Decay spectroscopy of $^{51-54}\text{K}$ and the $N=34$ shell gap south of ^{54}Ca



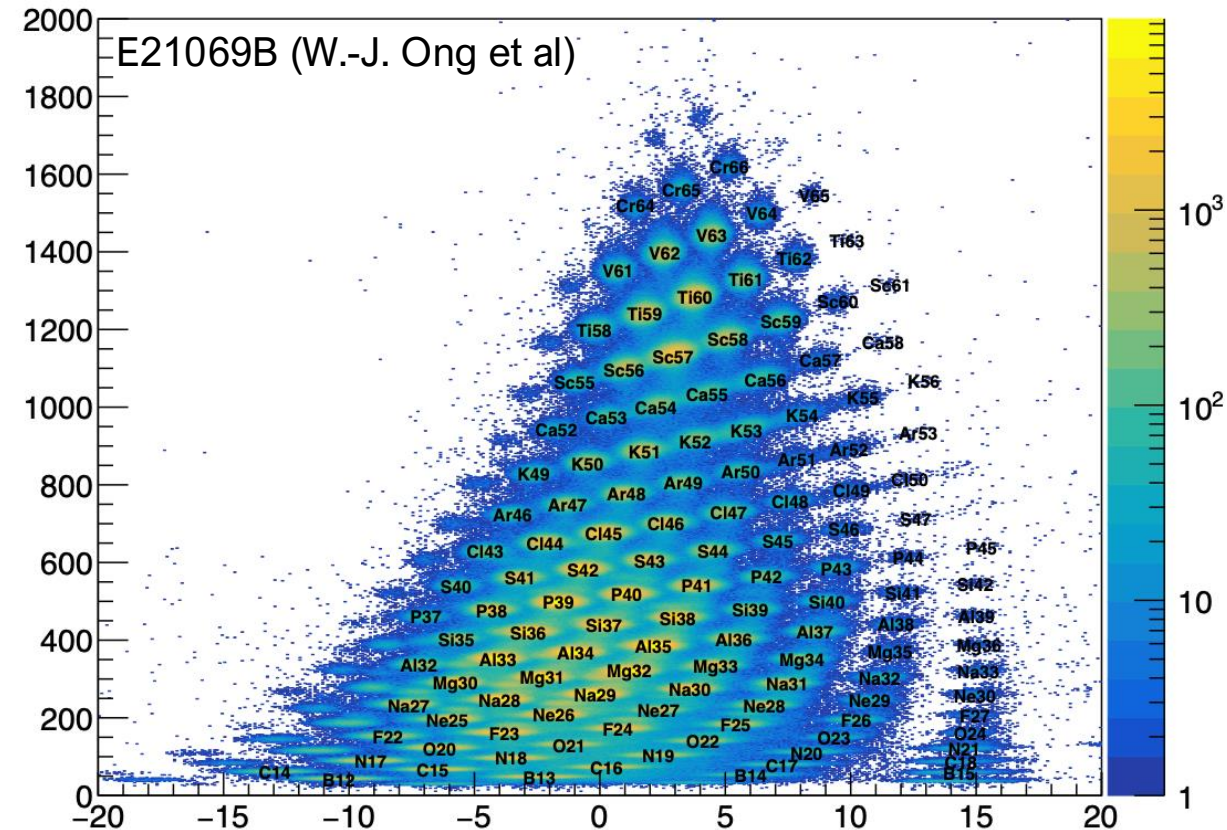
Decay spectroscopy of $^{51-54}\text{K}$ and the $N=34$ shell gap south of ^{54}Ca

- n_1, n_2, n_3 , and Ex can be extracted simultaneously from the analysis
- $I_\beta = n_1 + n_2 + n_3 \dots$
- I_β is reconstructed as a function of Ex

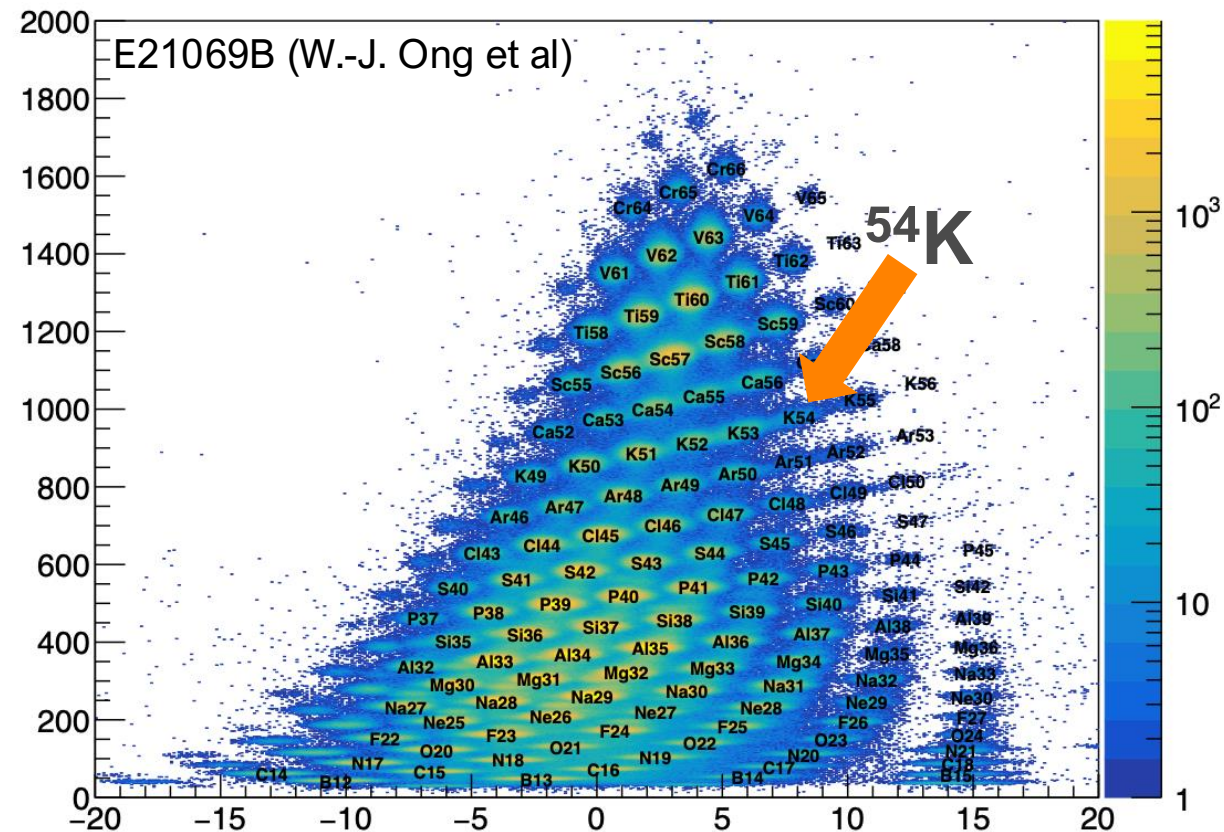


Decay spectroscopy of $^{51-54}\text{K}$ and the $N=34$ shell gap south of ^{54}Ca

- ^{54}K was measured at FRIB in Jan 2024
- Decay spectroscopy around ^{54}Ca with both focal planes of FDSi
- Over a hundred exotic isotopes were produced and implanted at FDSi
- A new isomer was discovered in ^{54}Sc (Ogunbeku2025)
- 15 new half lives were extracted (W.-J. Ong et al., under peer review)

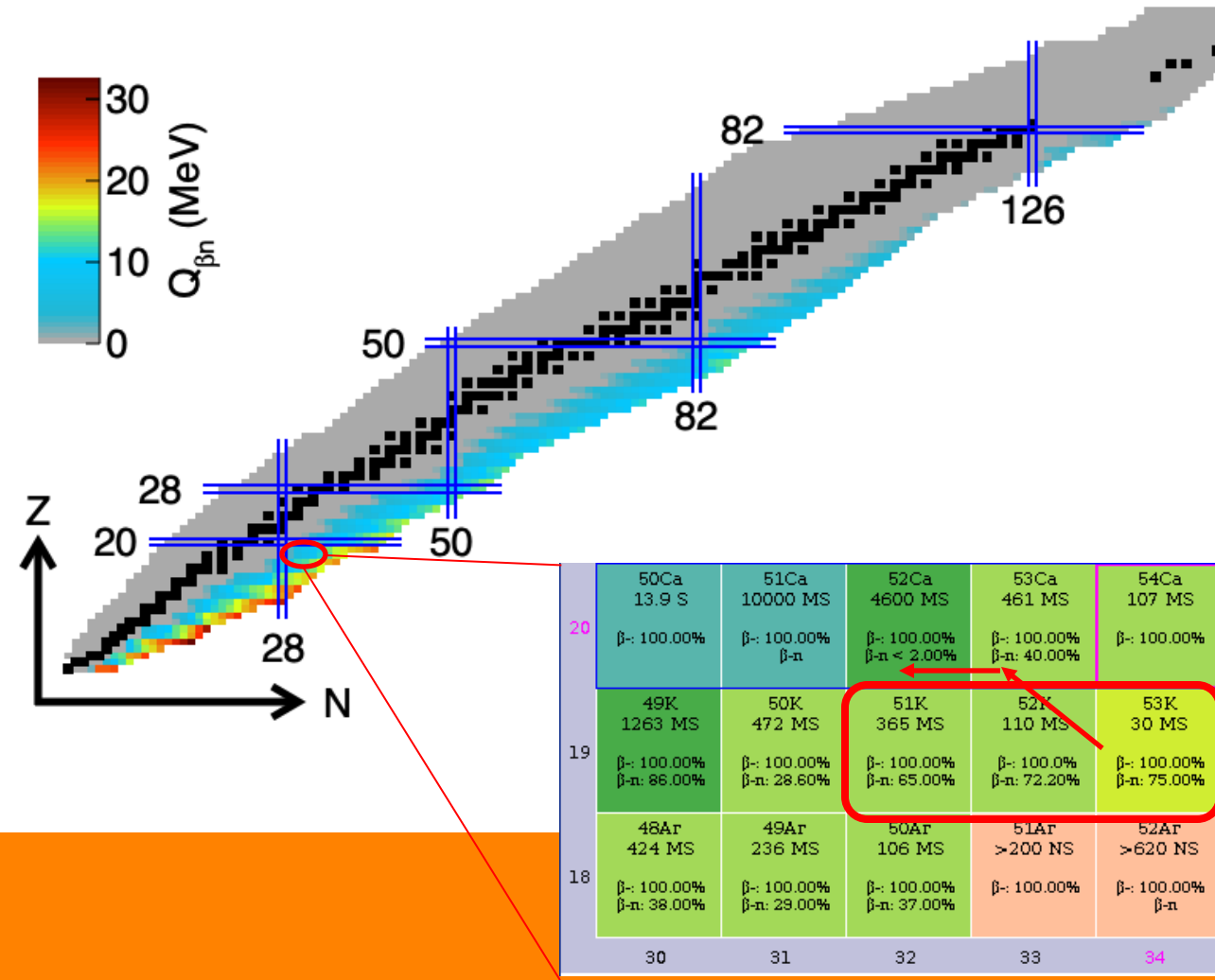


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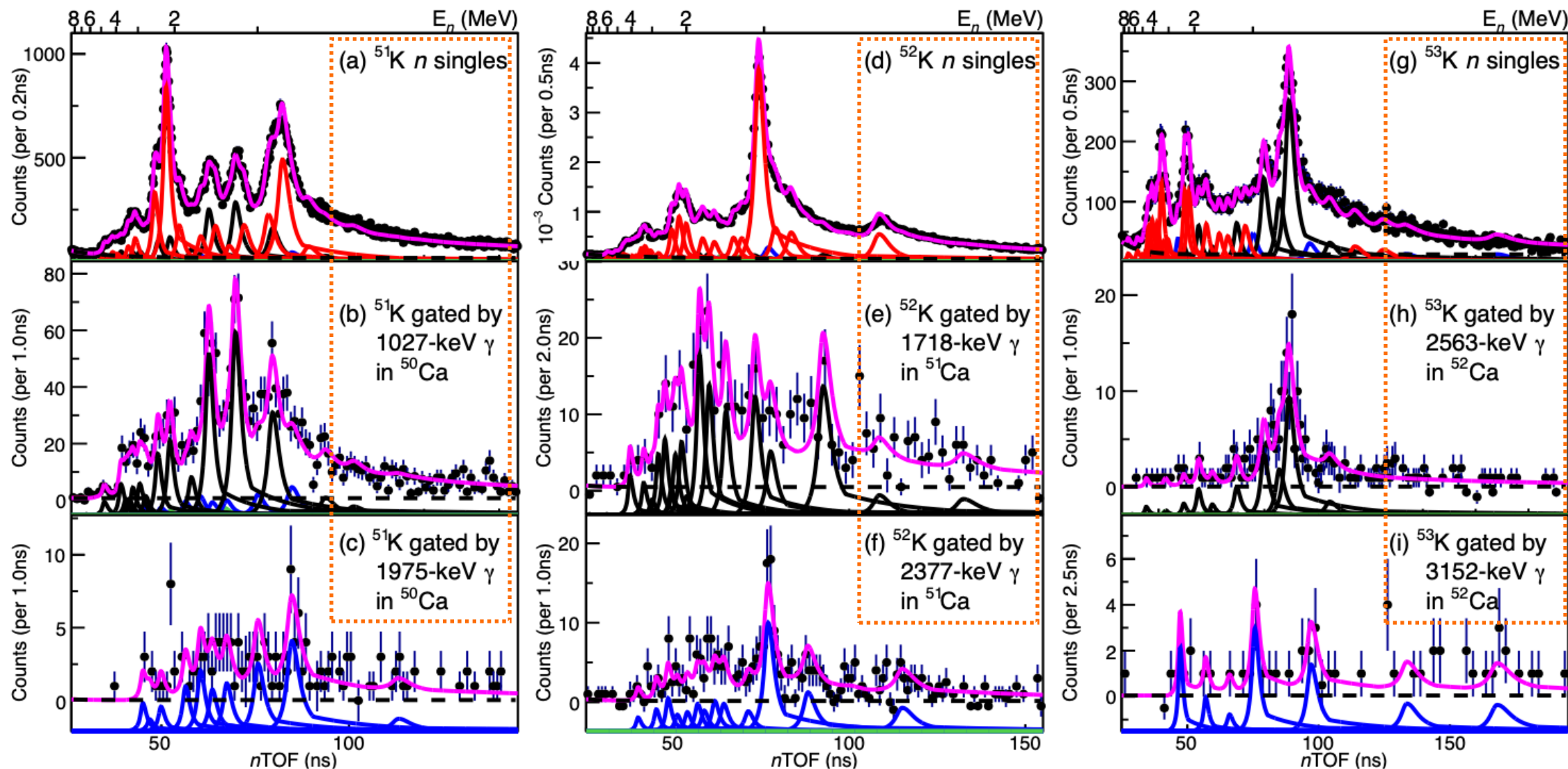


Compound-nucleus and doorway-state decays of β -delayed neutron emitters $^{51,52,53}\text{K}$

- Become neutron-unbound at low E_x (neutron excess)
- $^{51,52,53}\text{Ca}$ reside near doubly magic nuclei ($Z=20$, $N=28, 32, 34$)
- Valuable insights into βn emission with low nuclear level density (NDL)



Compound-nucleus and doorway-state decays of β -delayed neutron emitters $^{51,52,53}\text{K}$



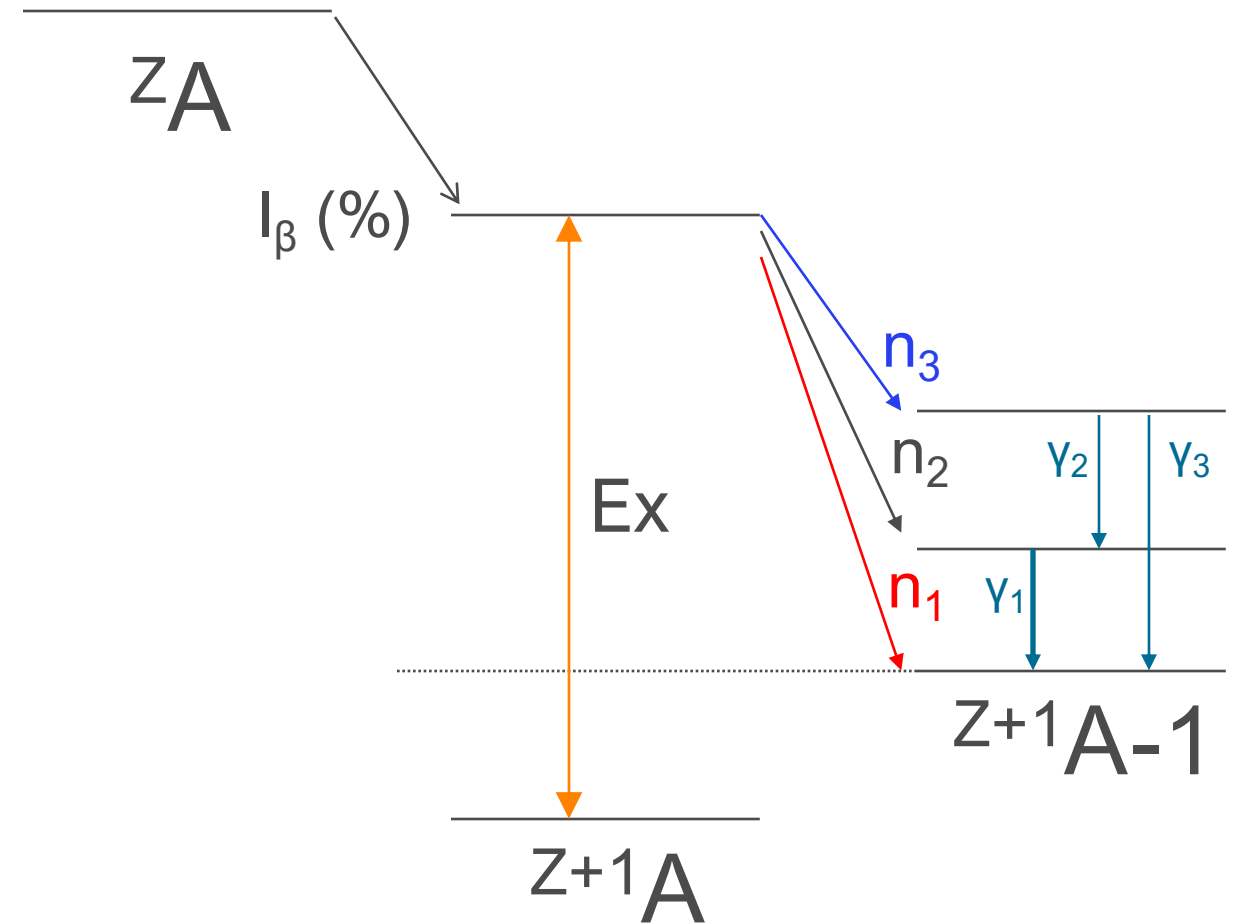
Compound-nucleus and doorway-state decays of β -delayed neutron emitters $^{51,52,53}\text{K}$

- n_1 , n_2 , and n_3 are determined by both β decay feeding and neutron emission
- Variation in the β feeding can be canceled by the normalization
- The new variables exclusively depend on the neutron-emission mechanism

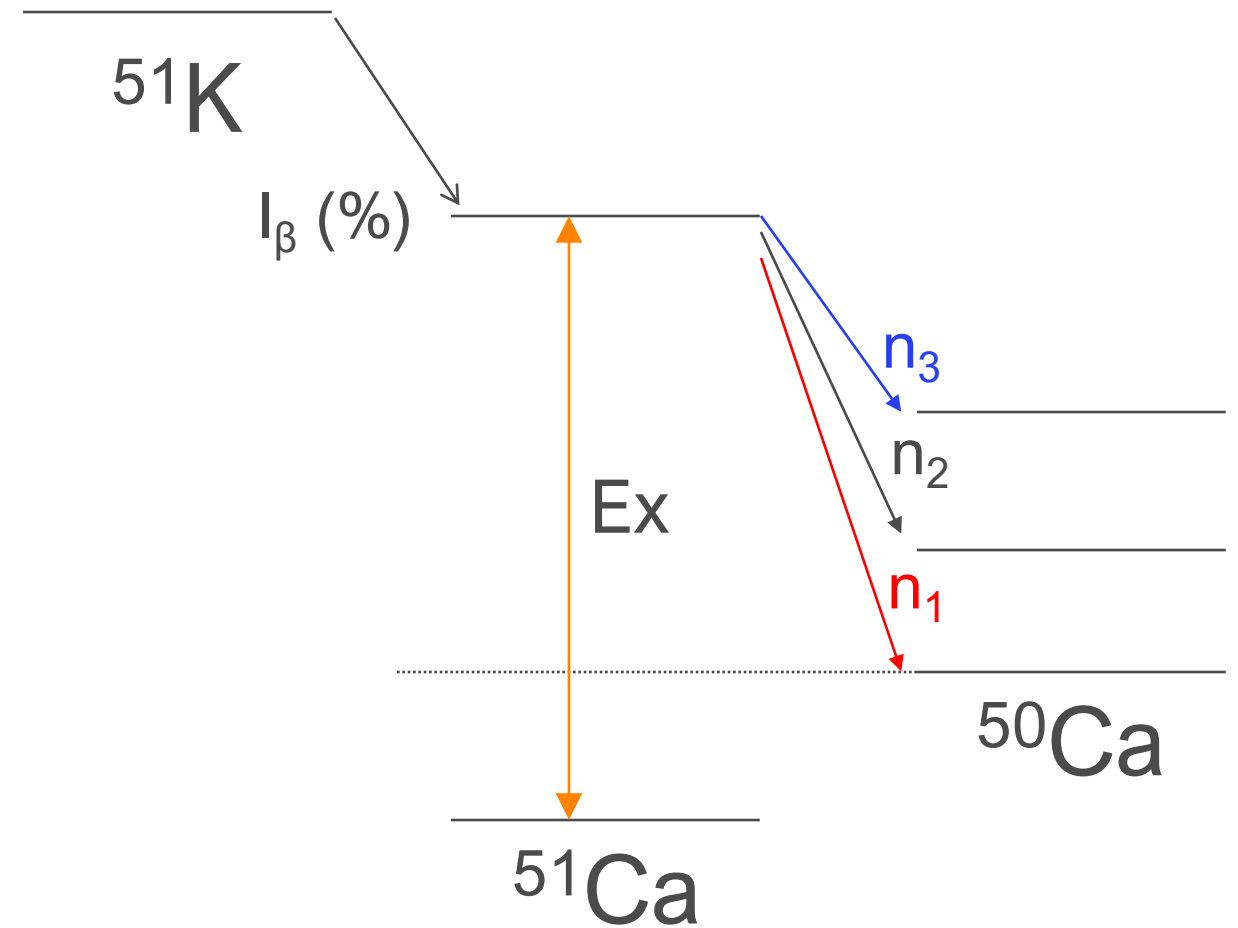
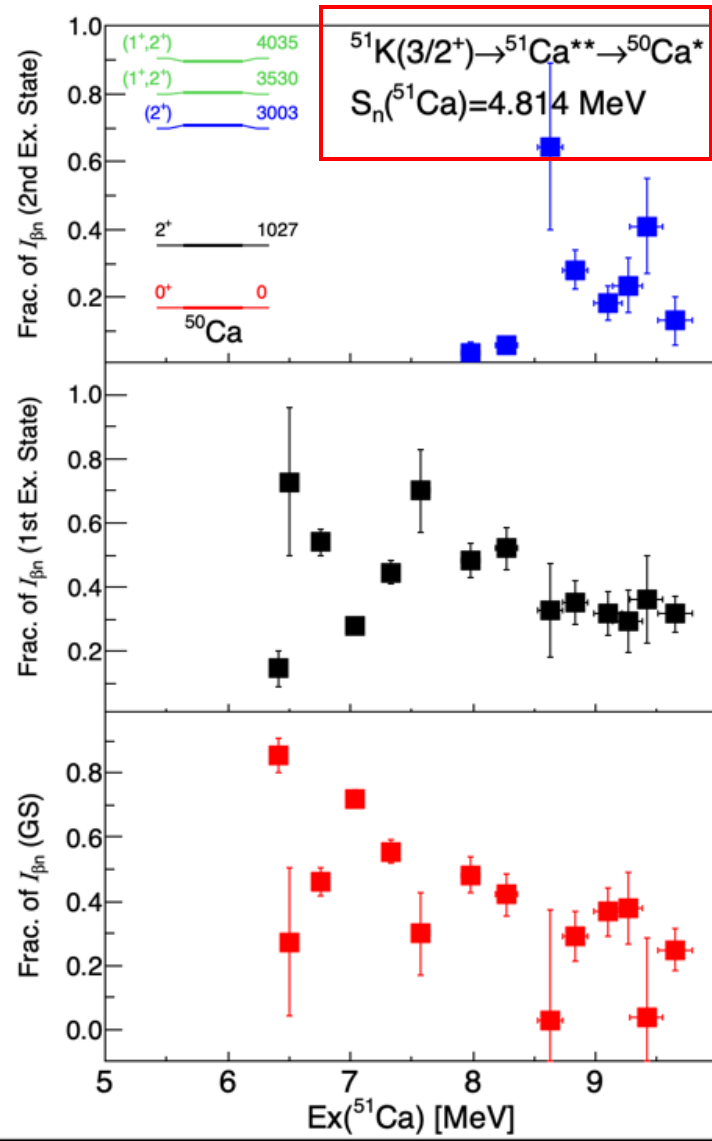
$$n_1/(n_1+n_2+n_3)$$

$$n_2/(n_1+n_2+n_3) \quad \text{as a function of } E_x$$

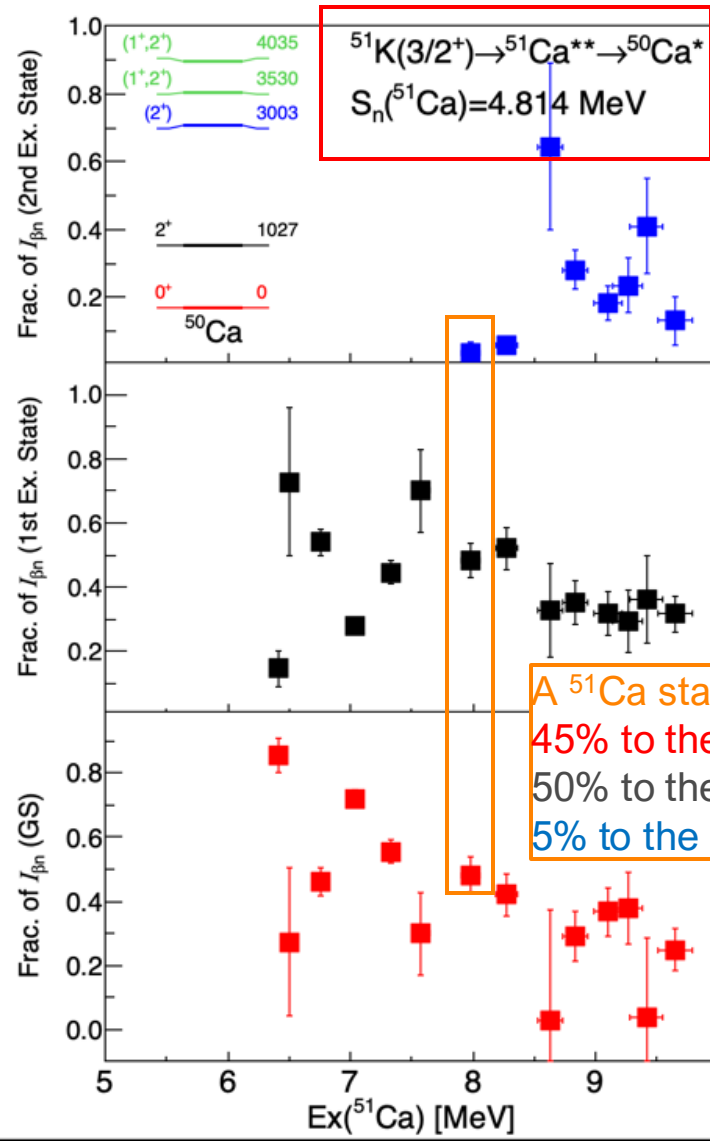
$$n_3/(n_1+n_2+n_3)$$



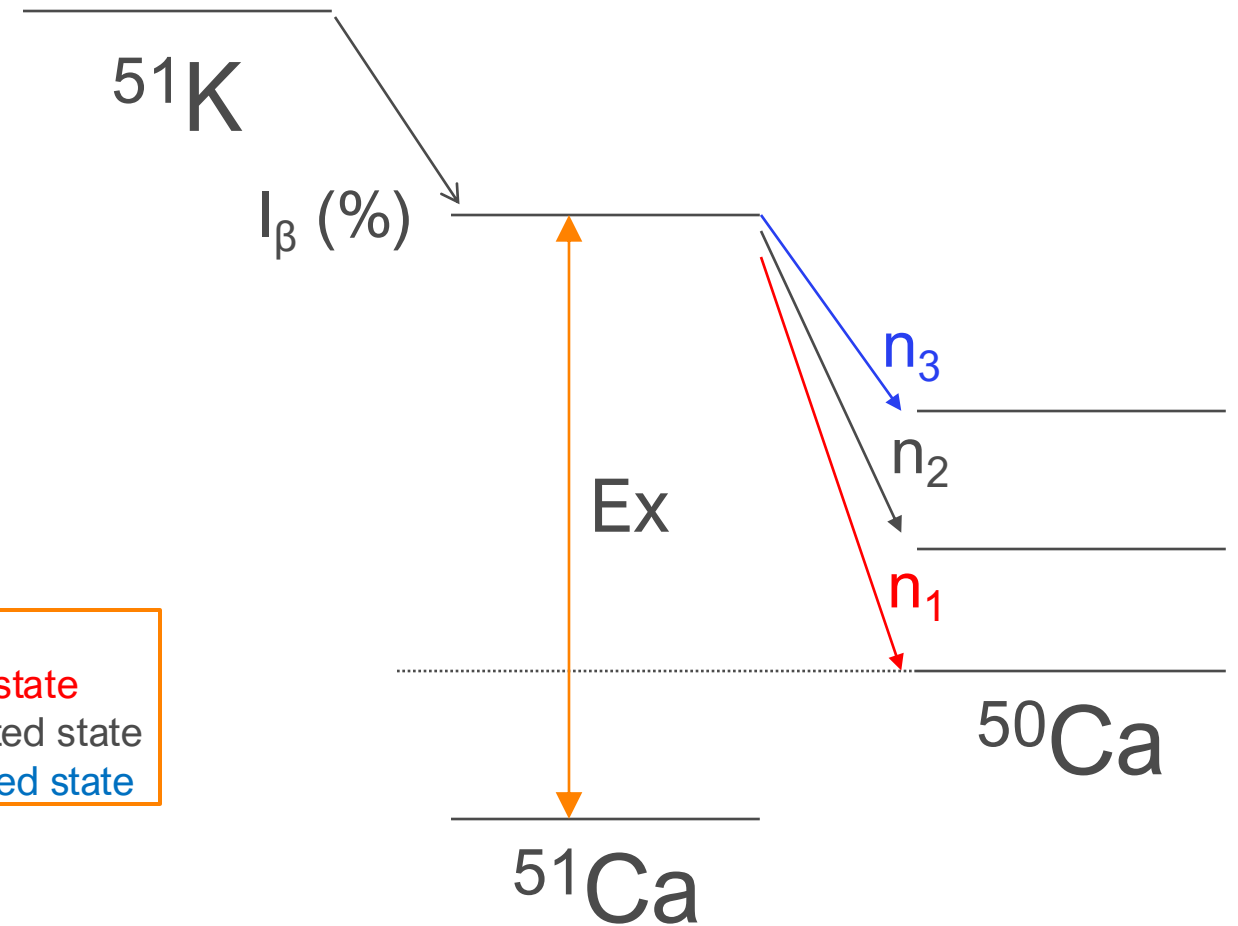
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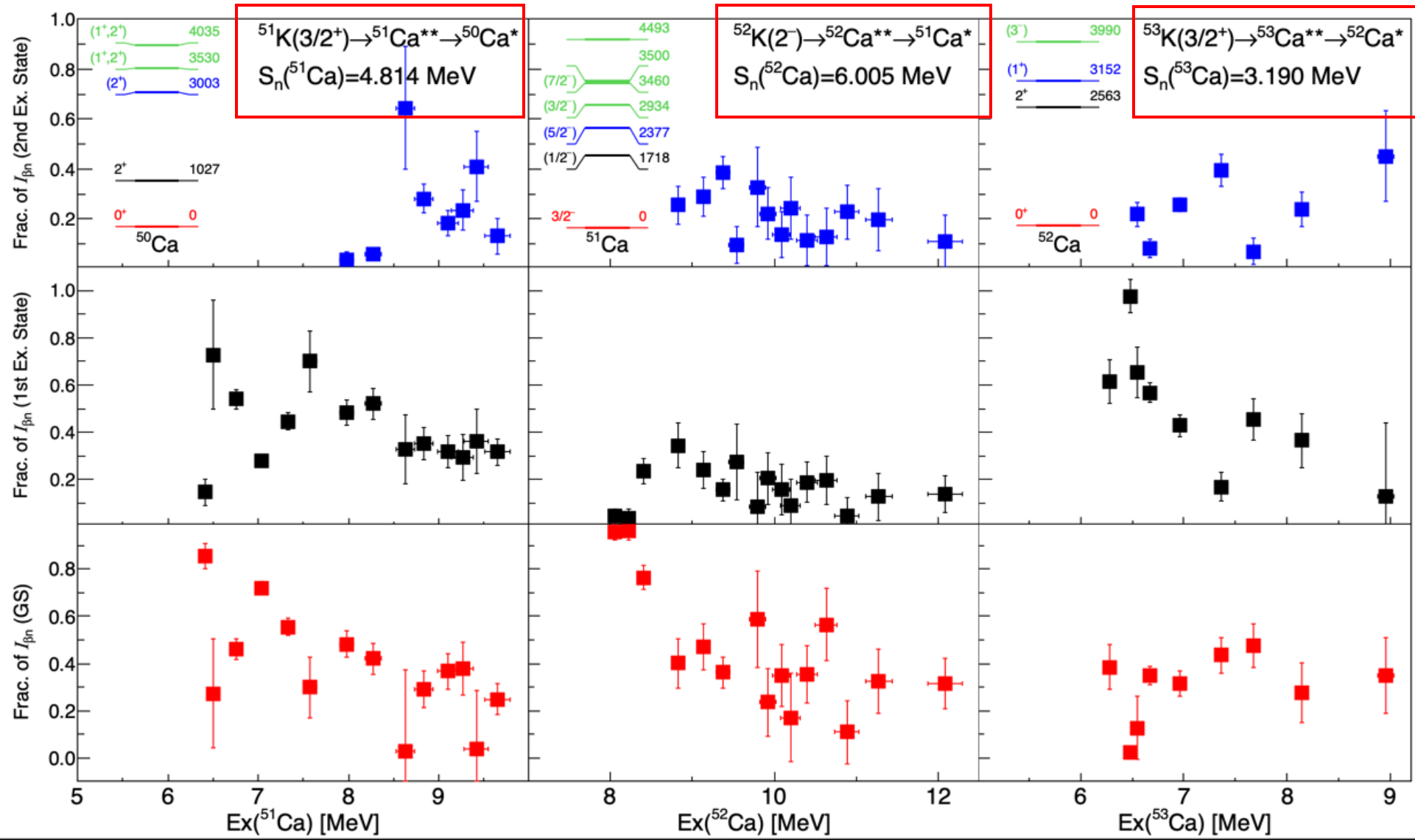
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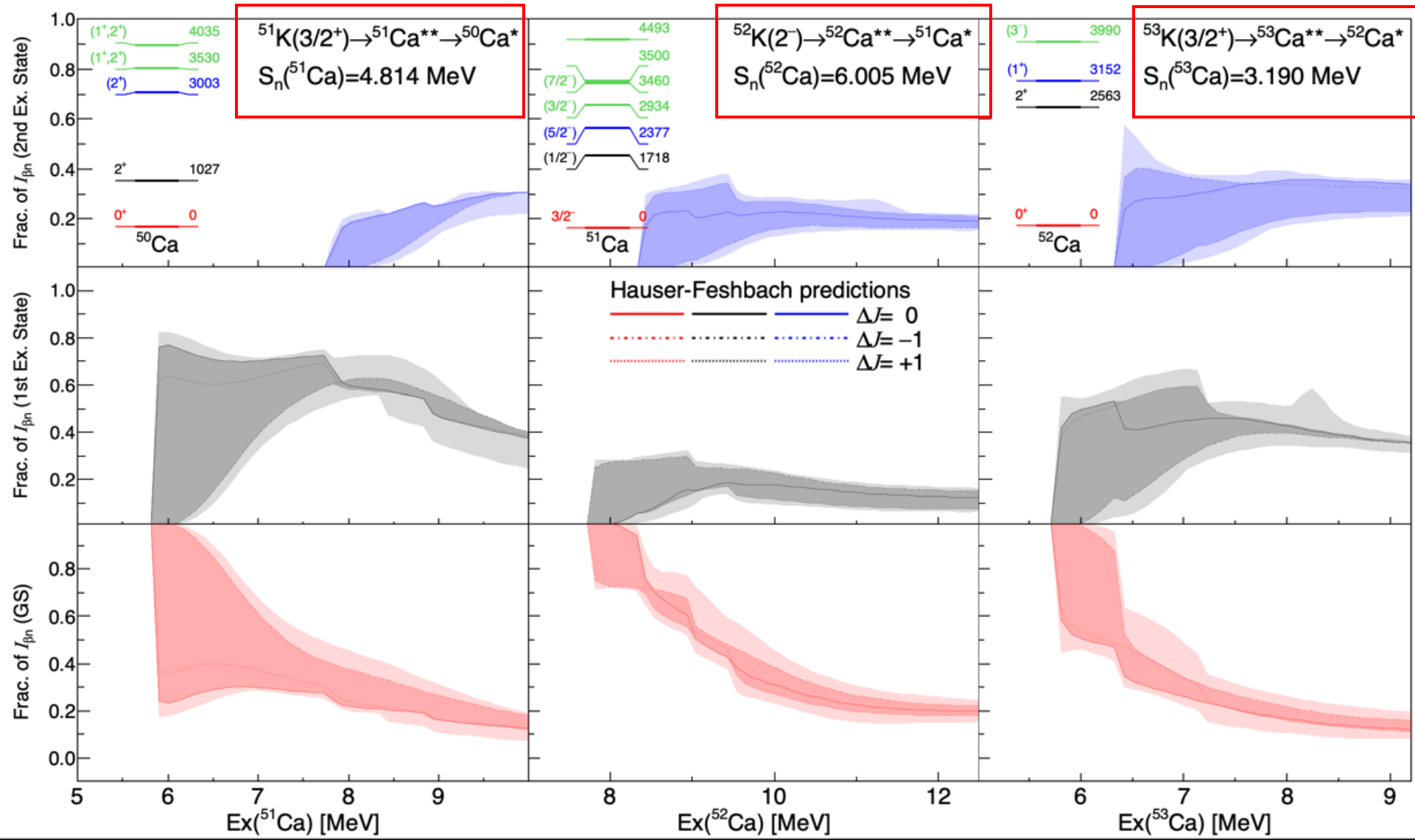
A ^{51}Ca state at 7 MeV
 45% to the ^{50}Ca ground state
 50% to the ^{50}Ca 1st excited state
 5% to the ^{50}Ca 2nd excited state



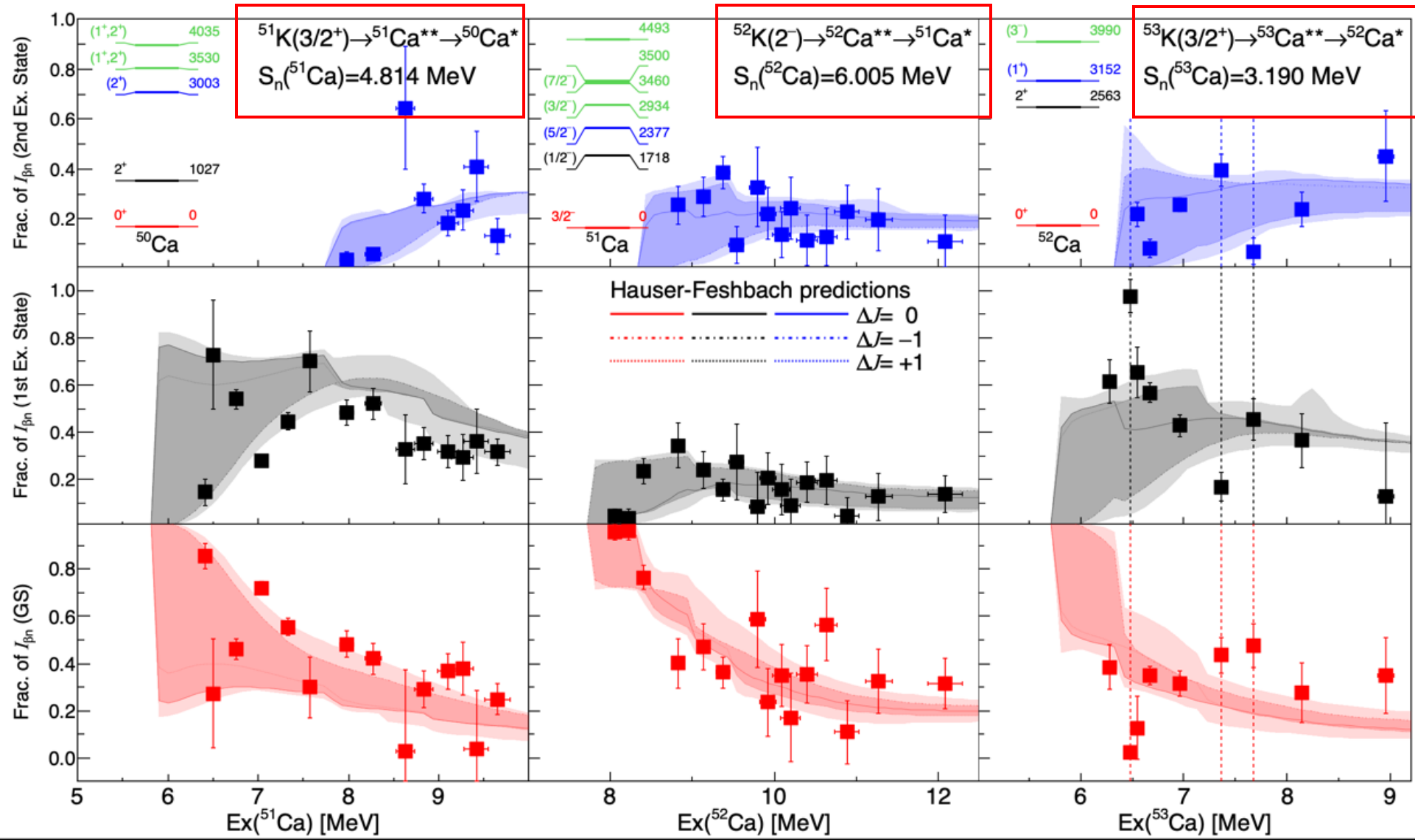
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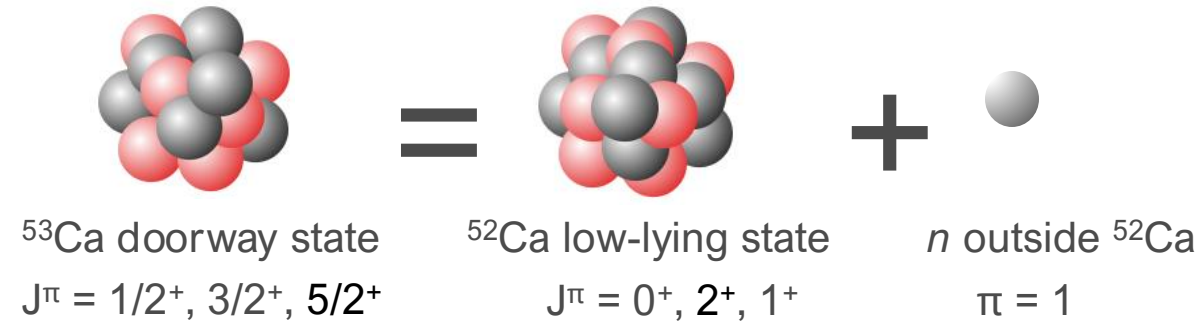


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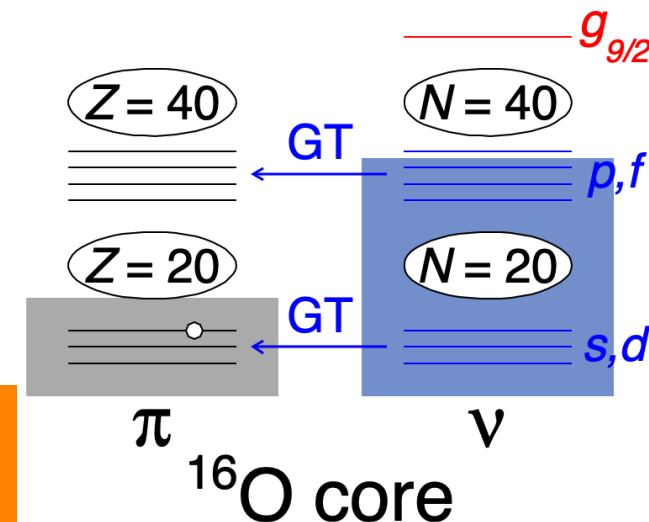
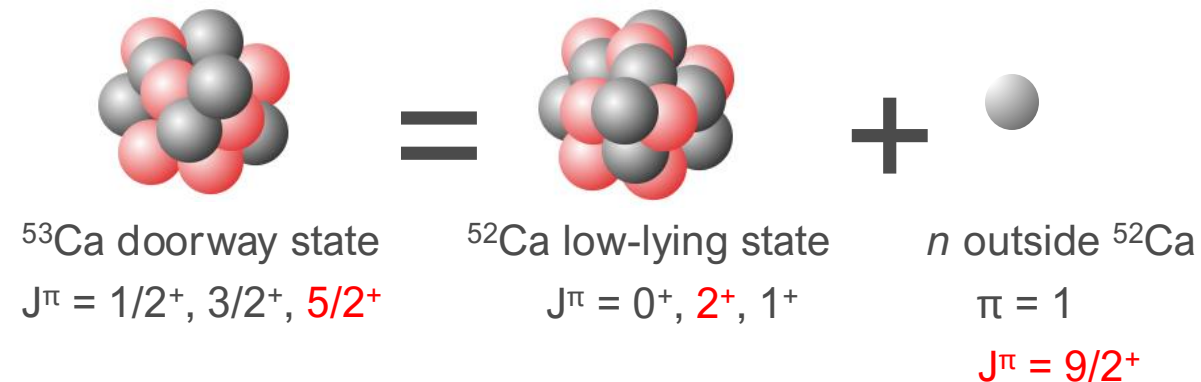
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- States populated in β decay — neutron/proton particle-hole configuration, no open neutron-emission channel
- Doorway states in daughter — neutron particle configuration, with open neutron-emission channel
- When the two states mix (**with the same spin and parity!**), the neutron-emission properties of the former are driven by the latter.



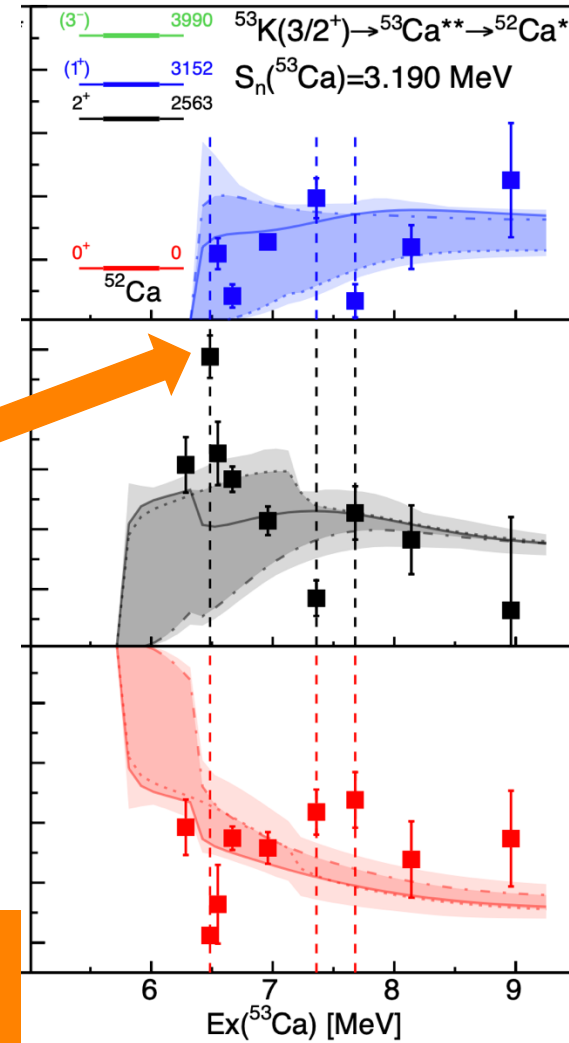
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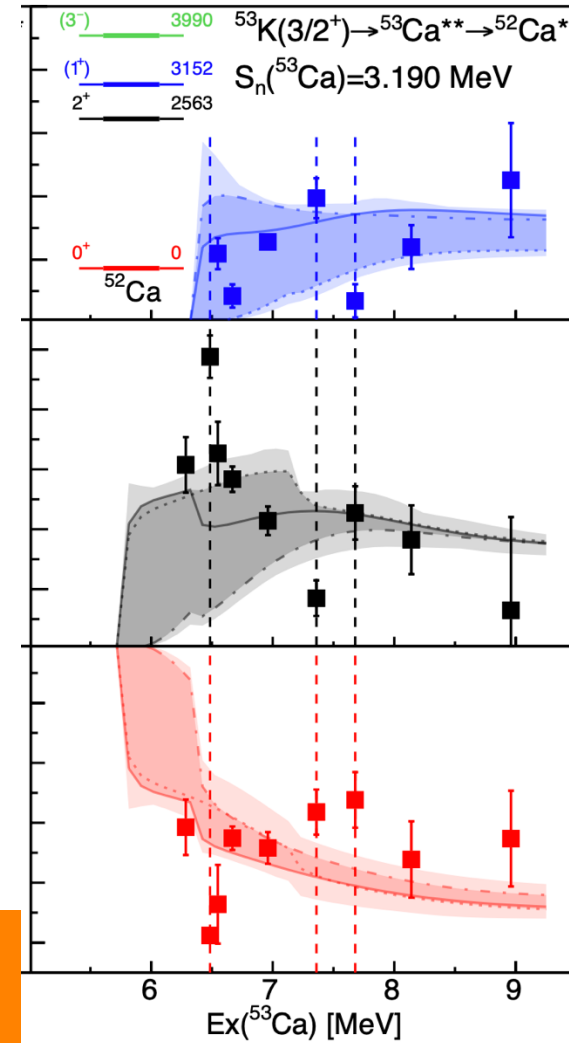
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- States populated in β decay — neutron/proton particle-hole configuration, no open neutron-emission channel
- Doorway states in daughter — neutron particle configuration, with open neutron-emission channel
- When the two states mix (**with the same spin and parity!**), the neutron-emission properties of the **former** are driven by the **latter**.
- Such a doorway state will predominantly decay to the 2^+ state in ^{52}Ca



Compound-nucleus and doorway-state decays of β -delayed neutron emitters $^{51,52,53}\text{K}$

- The comparison with the statistical model (HF) shows extremely good agreement (unexpected!)
- The few deviations are attributed to the doorway-state decays with open neutron-emission channels
- Calculating the mixing ratio with doorway states needs more advanced microscopic models
- Z.X et al., Phys. Rev. Lett. 133, 042501 (2024)



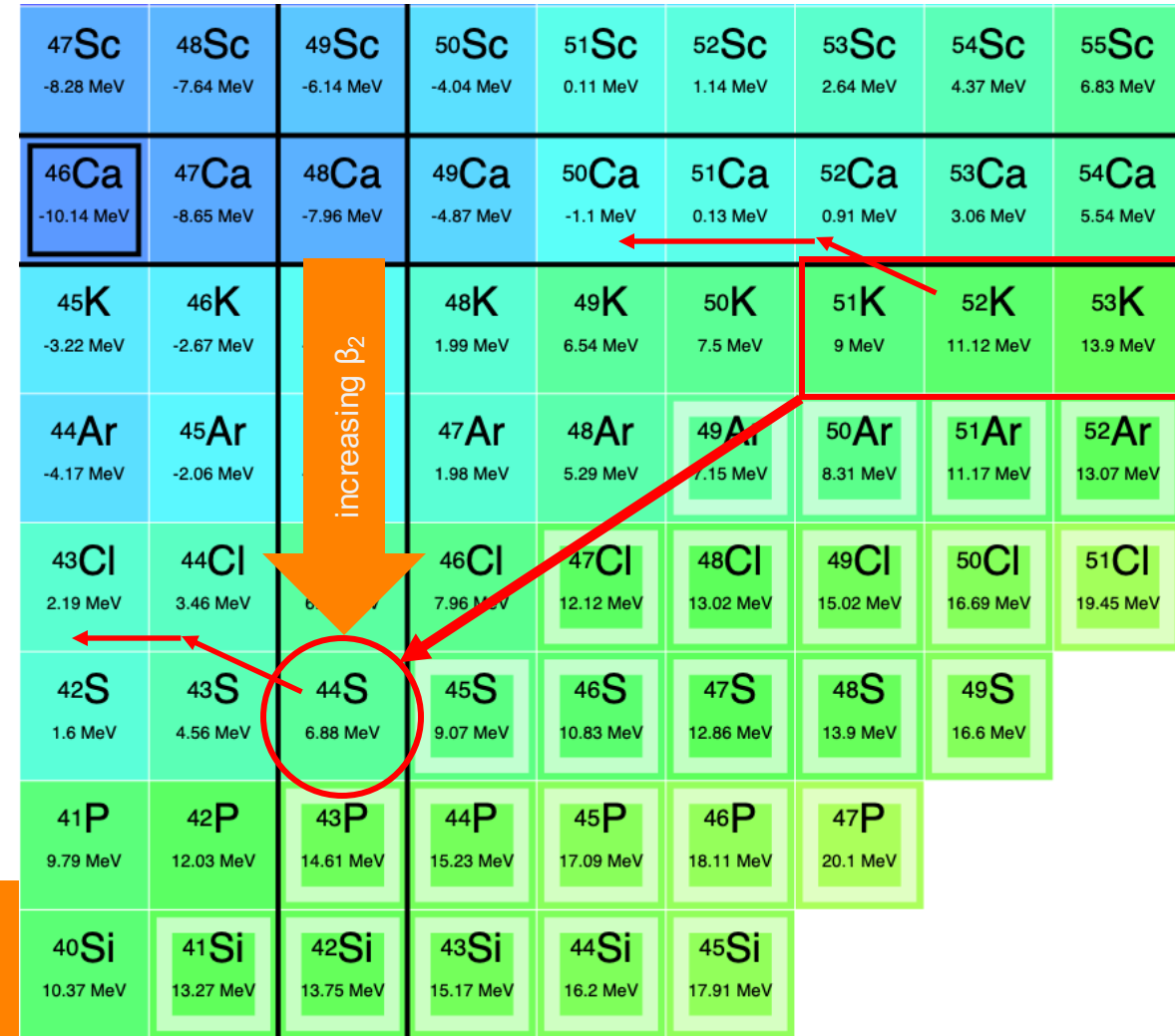
β -delayed neutron emission in deformed ^{44}S

- We observed apparent statistical βn decays from $^{51-53}\text{K}$, even though the NLD is very low
- Nuclear deformation develops from ^{48}Ca to ^{42}Si
- How does nuclear deformation affect βn decay?

47Sc -8.28 MeV	48Sc -7.64 MeV	49Sc -6.14 MeV	50Sc -4.04 MeV	51Sc 0.11 MeV	52Sc 1.14 MeV	53Sc 2.64 MeV	54Sc 4.37 MeV	55Sc 6.83 MeV
46Ca -10.14 MeV	47Ca -8.65 MeV	48Ca -7.96 MeV	49Ca -4.87 MeV	50Ca -1.1 MeV	51Ca 0.13 MeV	52Ca 0.91 MeV	53Ca 3.06 MeV	54Ca 5.54 MeV
45K -3.22 MeV	46K -2.67 MeV	47K -0.64 MeV	48K 1.99 MeV	49K 6.54 MeV	50K 7.5 MeV	51K 9 MeV	52K 11.12 MeV	53K 13.9 MeV
44Ar -4.17 MeV	45Ar -2.06 MeV	46Ar -1.23 MeV	47Ar 1.98 MeV	48Ar 5.29 MeV	49Ar 7.15 MeV	50Ar 8.31 MeV	51Ar 11.17 MeV	52Ar 13.07 MeV
43Cl 2.19 MeV	44Cl 3.46 MeV	45Cl 6.34 MeV	46Cl 7.96 MeV	47Cl 12.12 MeV	48Cl 13.02 MeV	49Cl 15.02 MeV	50Cl 16.69 MeV	51Cl 19.45 MeV
42S 1.6 MeV	43S 4.56 MeV	44S 6.88 MeV	45S 9.07 MeV	46S 10.83 MeV	47S 12.86 MeV	48S 13.9 MeV	49S 16.6 MeV	
41P 9.79 MeV	42P 12.03 MeV	43P 14.61 MeV	44P 15.23 MeV	45P 17.09 MeV	46P 18.11 MeV	47P 20.1 MeV		
40Si 10.37 MeV	41Si 13.27 MeV	42Si 13.75 MeV	43Si 15.17 MeV	44Si 16.2 MeV	45Si 17.91 MeV			

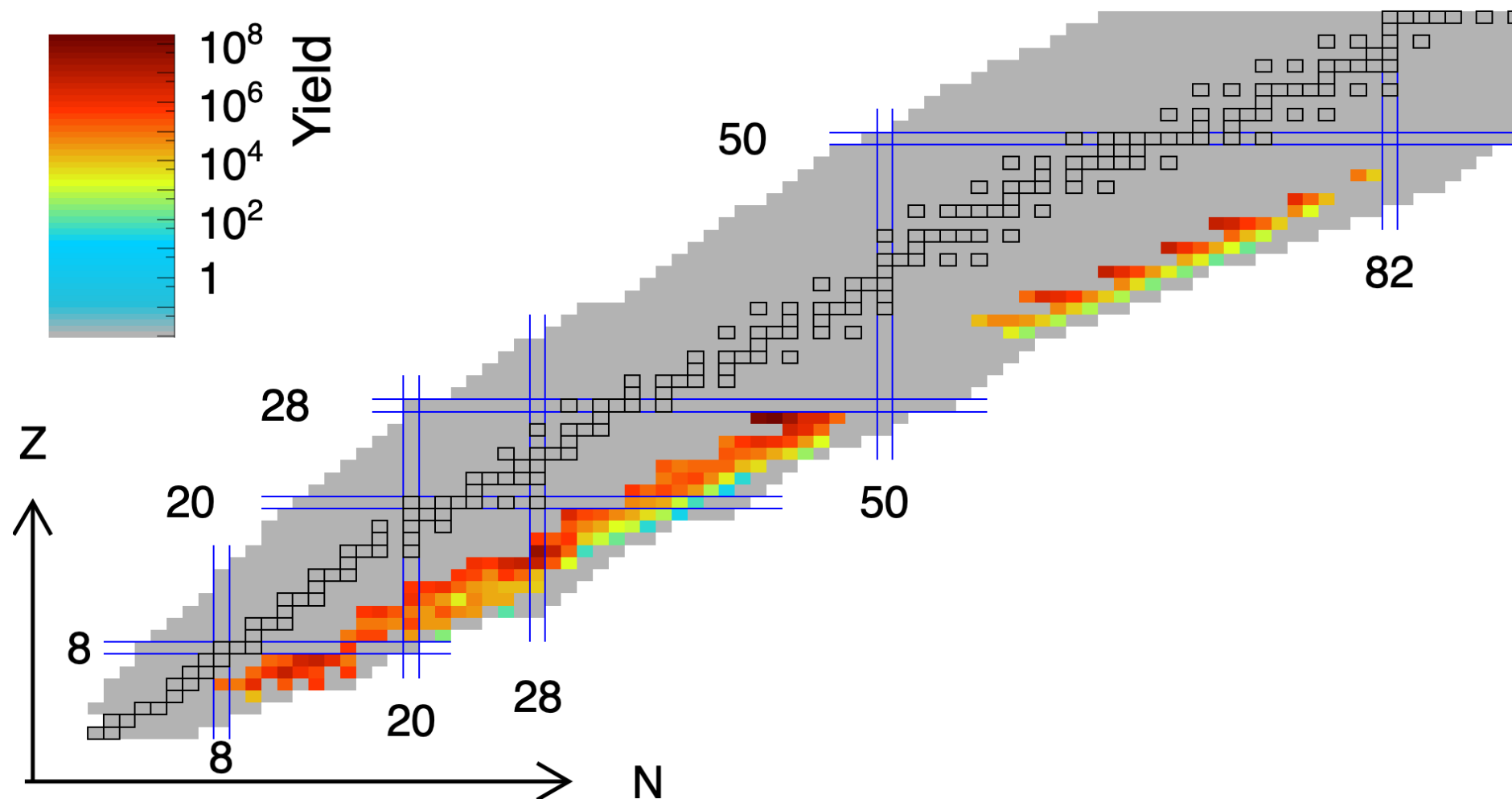
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- Nuclear deformation develops from ^{48}Ca to ^{42}Si
- How does nuclear deformation affect βn decay?
- ^{44}S is a unique nucleus to provide insight
 - Moderately deformed ($E_{2+} \sim 1.3$ MeV)
 - 0^+ ground state (only populates 1^+ states in ^{44}Cl)
 - Reasonable P_n value ($\sim 20\%$)
 - Massive rate with the ^{48}Ca beam at FRIB

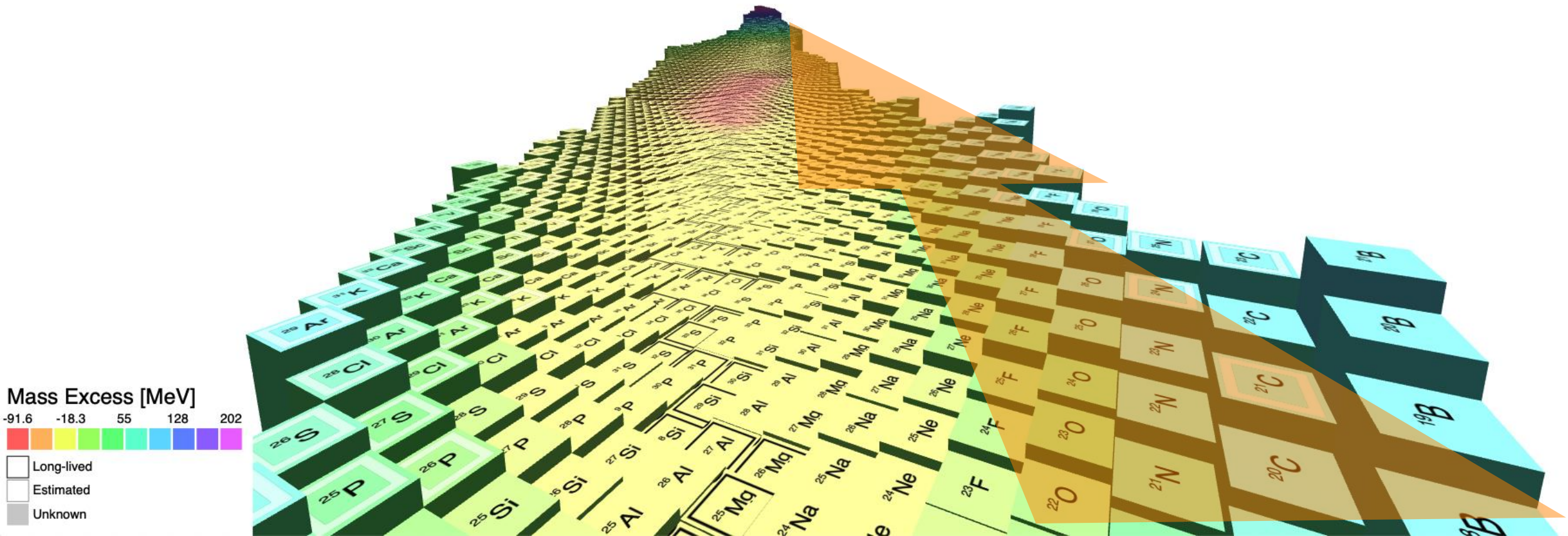




Isotopes with $Q_{\beta n} > 5$ MeV measured at FDSi



Thanks very much for your attention



<https://people.physics.anu.edu.au/~ecs103/chart3d/>