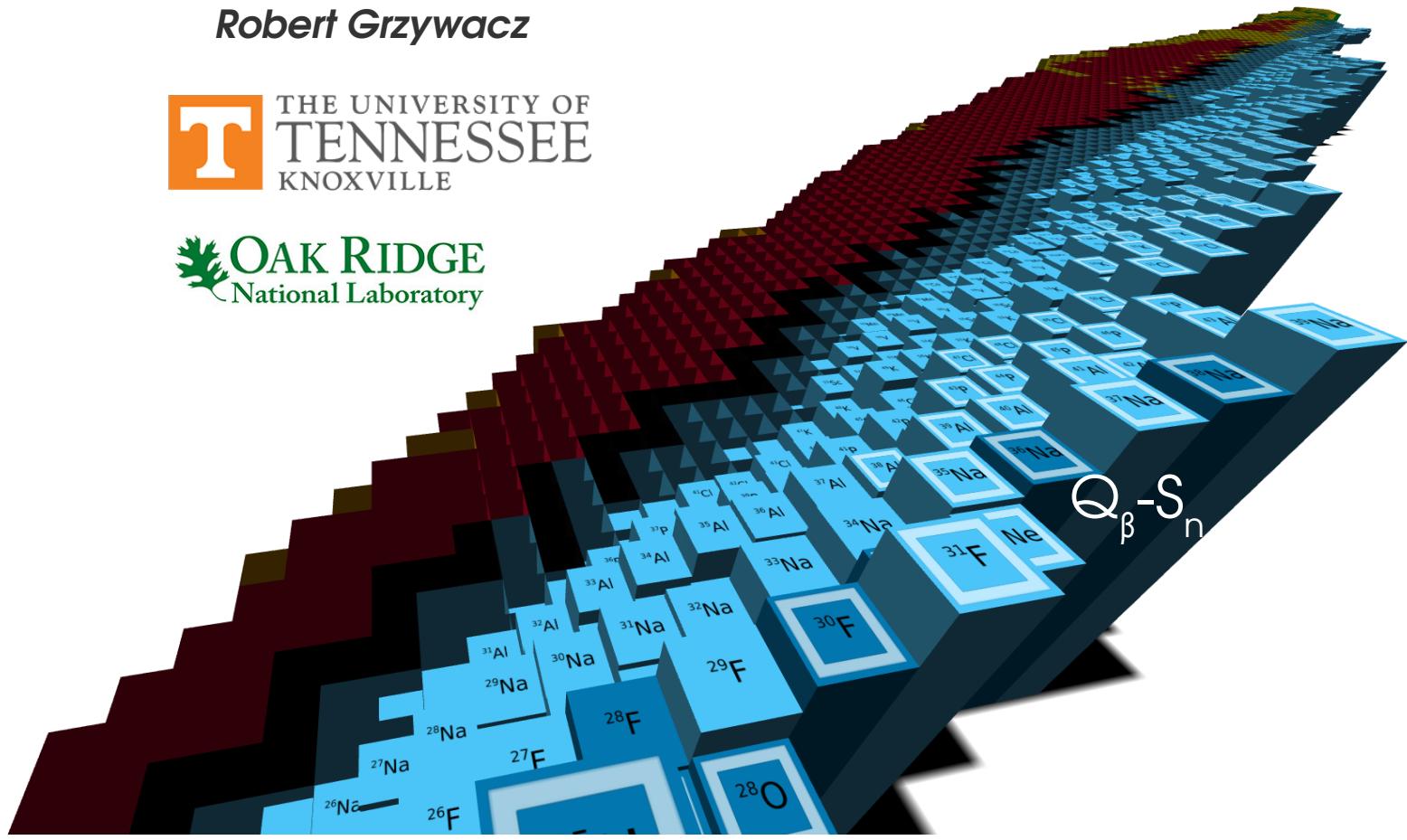


Statistical and shell effects in beta-delayed neutron emission

Robert Grzywacz



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



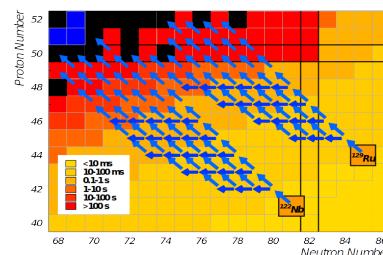
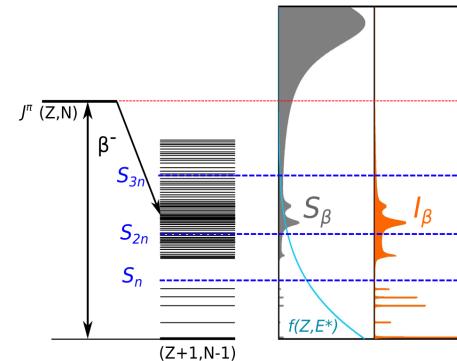
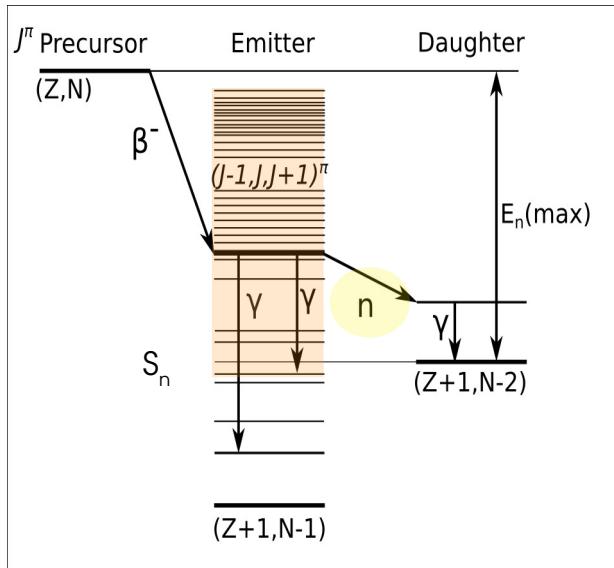
National Nuclear Security Administration



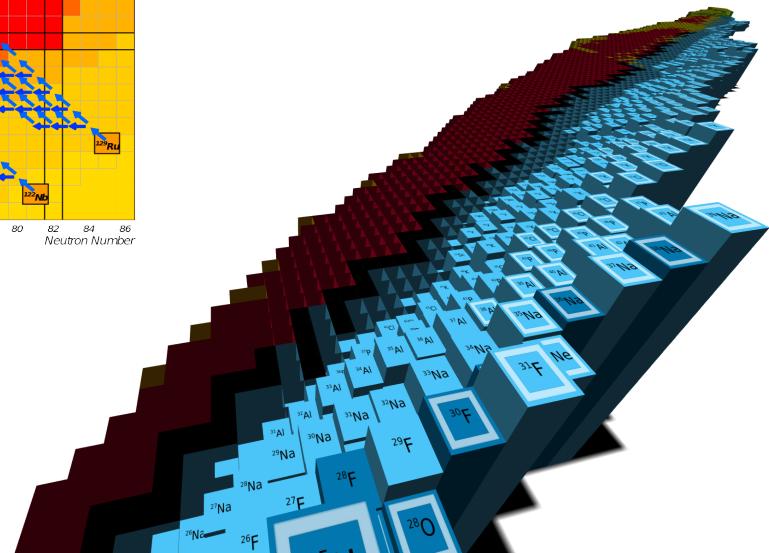
Office of Science

Beta-delayed neutron emission

- Prevalent decay mode for very neutron rich nuclei.
- Opportunity: access to nuclei with large Q_β - S_n
- Relevance: r-process path nuclei are βn precursors.



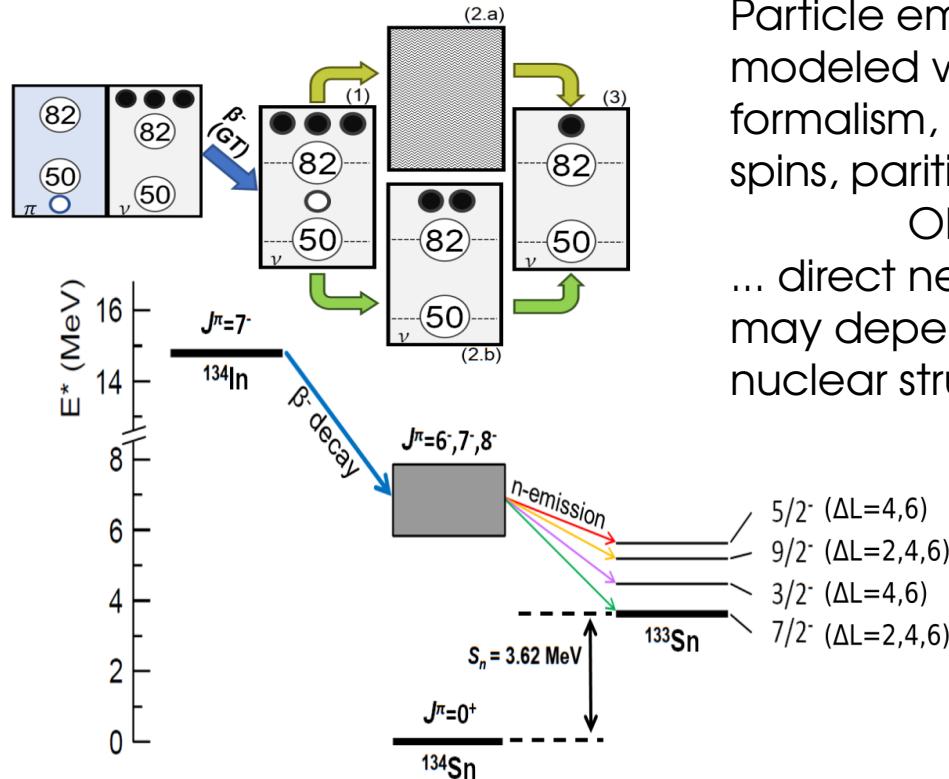
Two-step process:
Beta decay - selective Gamow-Teller - shell structure
Neutron emission – compound nucleus stage.



Does neutron emission proceed via compound nucleus ?

Selective Gamow-Teller transformations
populate highly excited
states in daughter nucleus.

Test case:
 ^{134}In decay



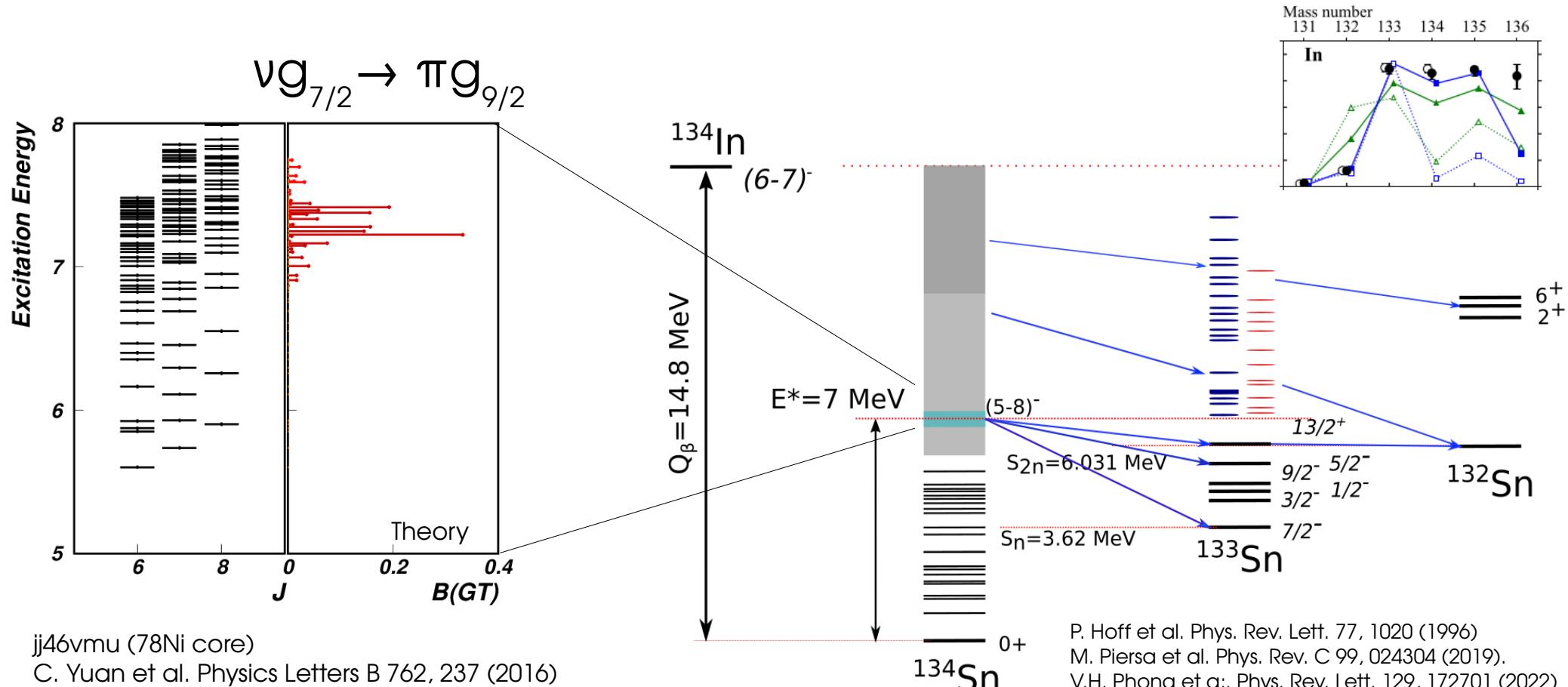
Decays near doubly magic-nuclei
candidates for the testing universality of the C.N. hypothesis.

Particle emission from C.N.
modeled with Hauser-Feshbach
formalism, depends only on
spins, parities and E^* ...

OR

... direct neutron emission,
may depend also on details of
nuclear structure

Gamow-Teller decay of ^{134}In and population of excited states in $^{134,133,132}\text{Sn}$



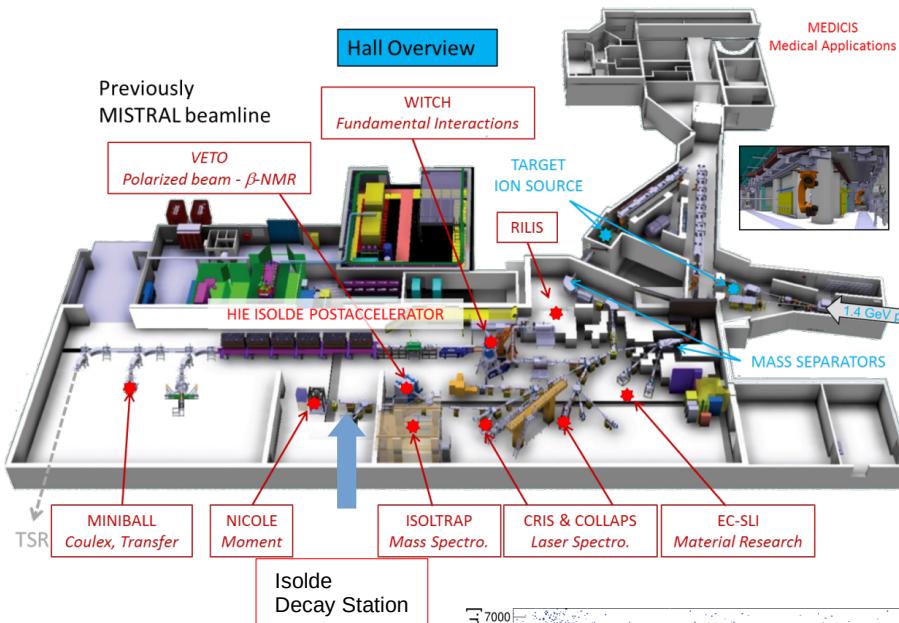
jj46vmu (78Ni core)

C. Yuan et al. Physics Letters B 762, 237 (2016)

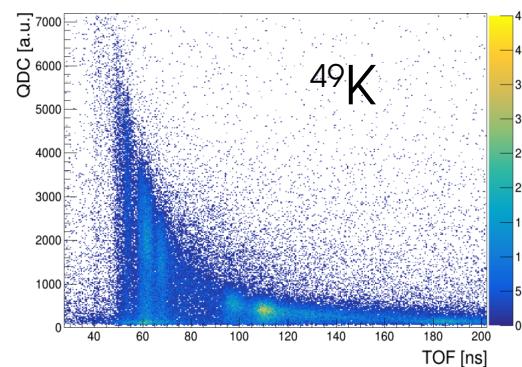
P. Hoff et al. Phys. Rev. Lett. 77, 1020 (1996)
 M. Piersa et al. Phys. Rev. C 99, 024304 (2019).
 V.H. Phong et al.; Phys. Rev. Lett. 129, 172701 (2022)
 K. L. Jones et al. Nature 465, 454 (2010).

See also: A. Korgul ARIS 2023 Friday 4

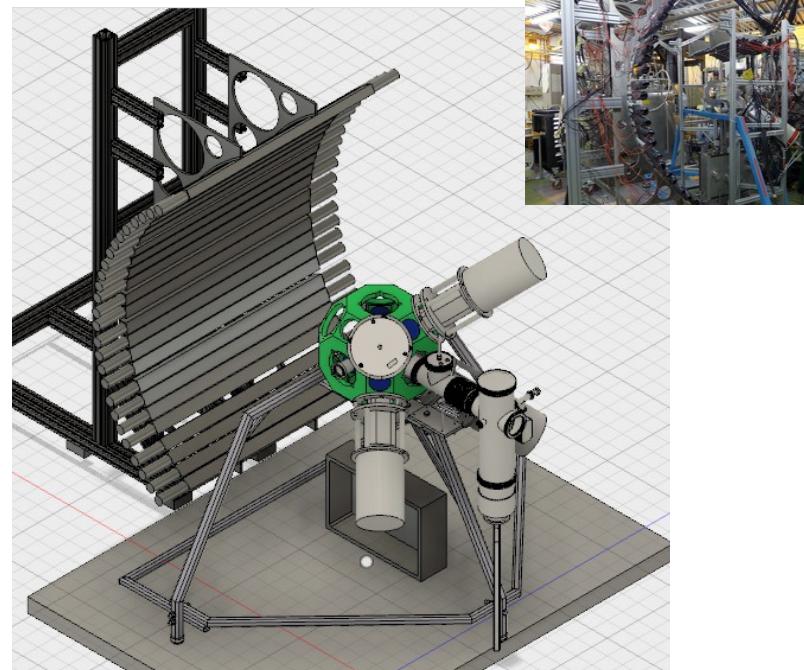
Isolde Decay Station Experiment (~8h, PI: M. Madurga, R.G.)



$$TOF \sim \frac{L}{\sqrt{(E)}}$$



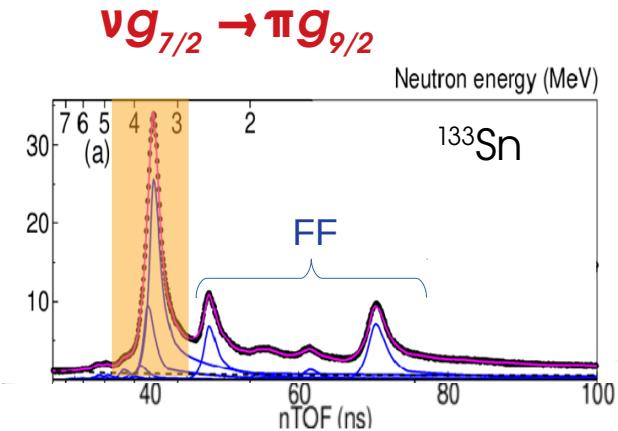
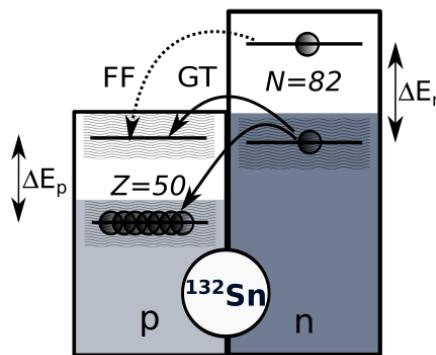
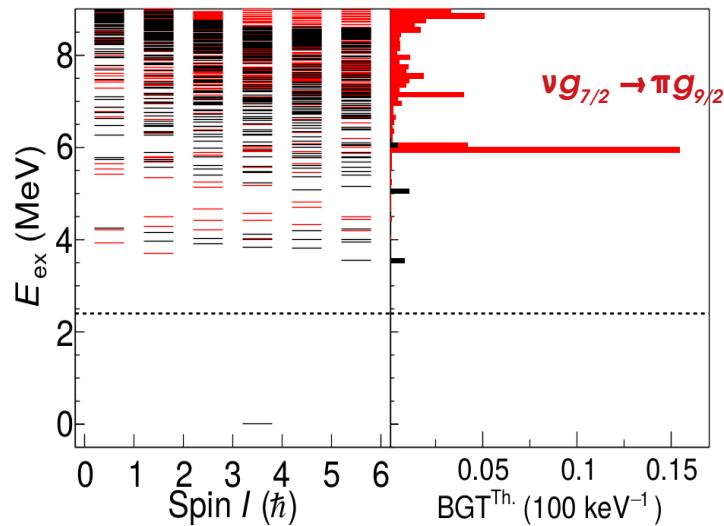
26 IDS Neutron modules (INDiE)
4 HPGe clover detectors



- Efficiency of the setup:
- Beta-particles (~80 %)
 - Gamma rays (~4% at 1 MeV)
 - Neutrons (~5% at 1 MeV)
 - Fully digital

The decay of ^{133}In at IDS

- Laser-ionization ion source enabled separation of $^{133}\text{In}^m$ and $^{133}\text{In}^{\text{gs}}$ decays.
- Decay dominated by the Gamow-Teller transitions



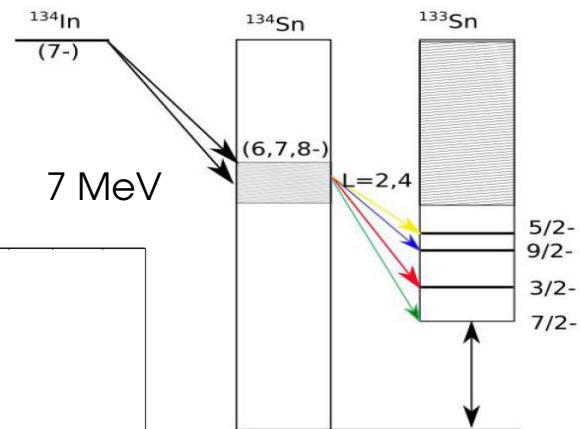
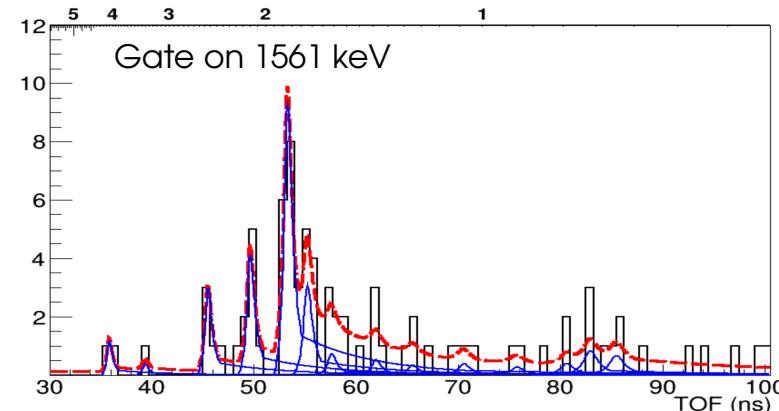
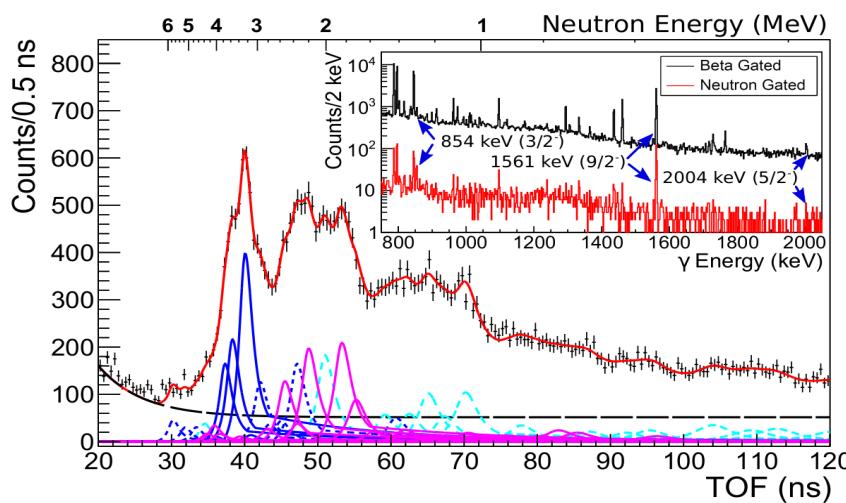
β^- : 100.00%					
98955	4470	13750	13750	13750	13750
132Sn	132Sn	132Sn	132Sn	132Sn	132Sn
53.7 S	1.46 S	1.050 S	53.0 MS	0.290 S	1.975 MS
-40404	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
0.26 S	0.207 S	0.170 S	2140	2.0843	3.86E+3
131In	131In	131In	134In	135In	136In
0.26 S	0.207 S	0.170 S	1.58E+3	3.86E+3	9.78E+3
-100.00%	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
-53777	-53777	-53777	-53777	-53777	-53777
130Cd	131Cd	132Cd	133Cd	134Cd	135Cd
162 MS	68 MS	97 MS	57 MS	66 MS	91 MS

The decay of ^{133}In : a rosetta stone for the r -process nuclei 2023

Z. Y. Xu,¹ M. Madurga,¹ R. Grzywacz,^{1,2} T. T. King,¹ A. Algara,^{3,4} A. N. Andreyev,^{5,6} J. Benito,⁷ T. Berry,⁸

Decay of ^{134}In - selective population of unbound states in ^{134}Sn

- GT decay of ^{134}In is also dominated by the $\nu g_{7/2} \rightarrow \pi g_{9/2}$ transformation
- The neutrons emitted from $^{134}\text{Sn}^*$ populate single particle states in ^{133}Sn
- Neutron TOF spectrum deconvolution
- Response function (GEANT4) verified by ^{49}K , ^{133}In and ^{17}N decays
- Individual ^{133}Sn feedings from neutron-gamma coincidences

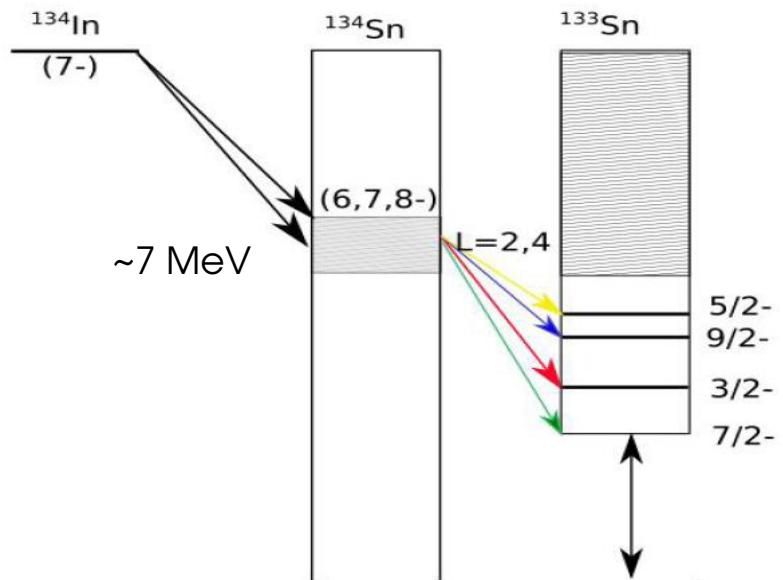
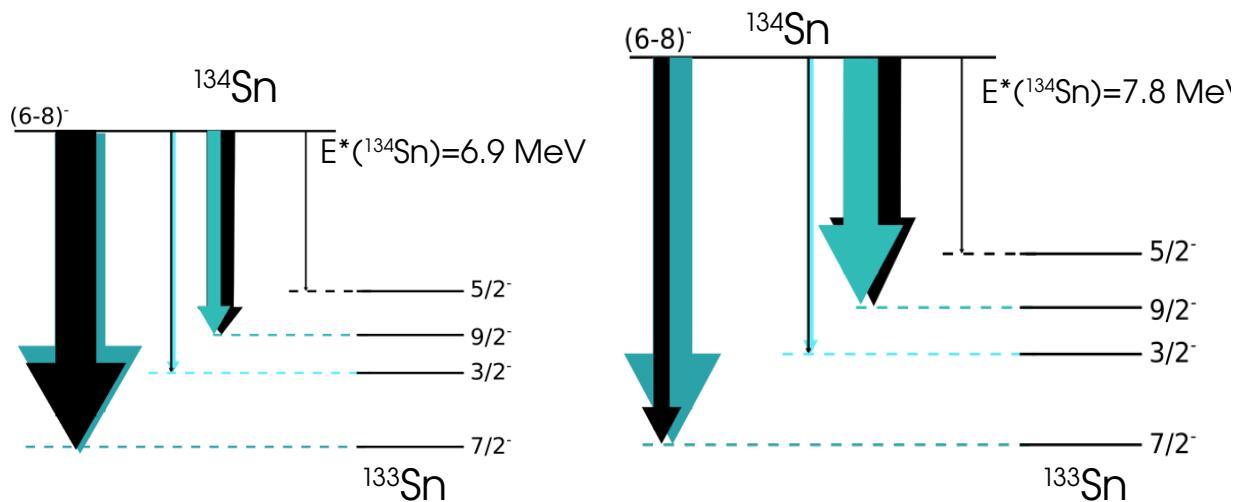


J. Heideman, RG, Z. Xu, M. Madurga T.
Kawano, J. E. Escher et al. PRC in press

Is the decay of ^{134}In “statistical”?

The statistical model predicts neutron intensities to excited states in ^{133}Sn as a function of E^* and J^π of states in ^{134}Sn .

Measured intensity pattern disagree with the C.N. predictions for five strongest neutron emitting states.



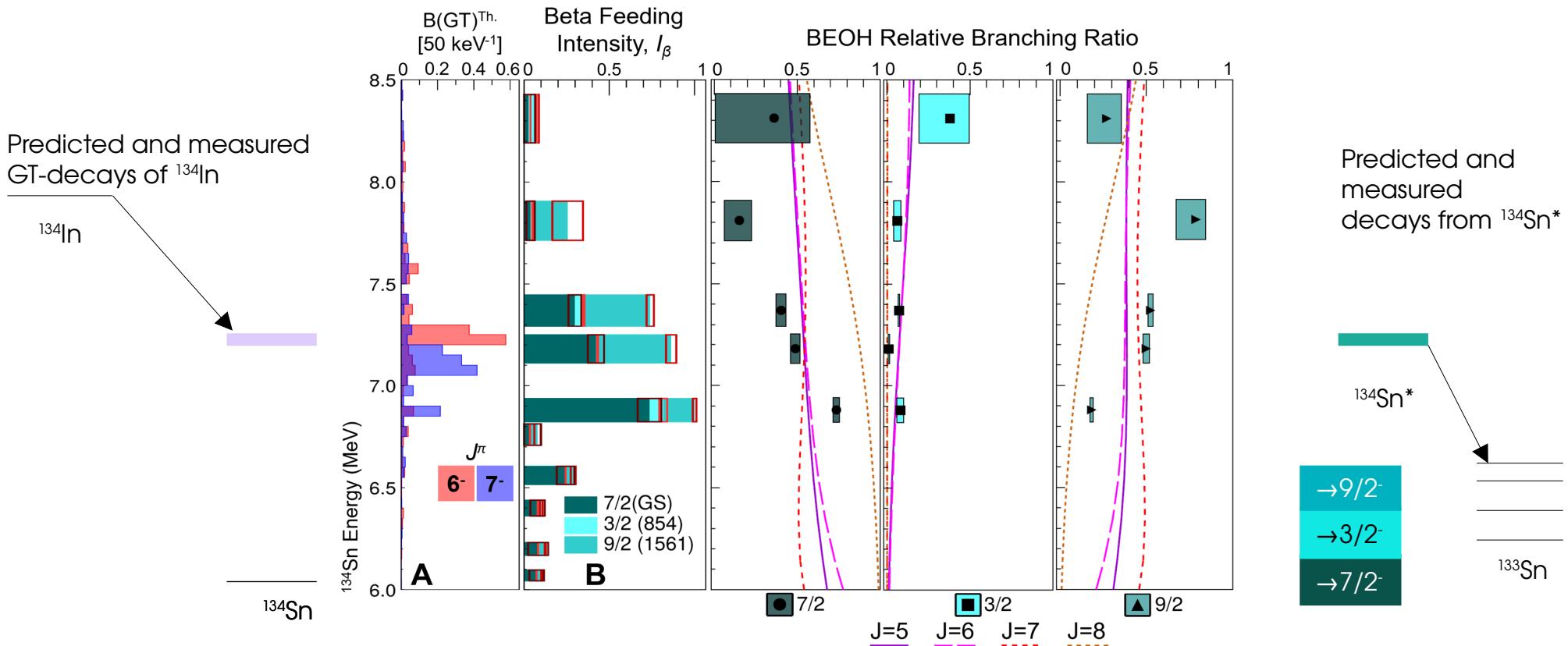
J. Heideman, RG, Z. Xu, M. Madurga T. Kawano, J. E. Escher et al. PRC in press

“Compound Nucleus”
Experiment

(Hauser Feshbach BeoH code)

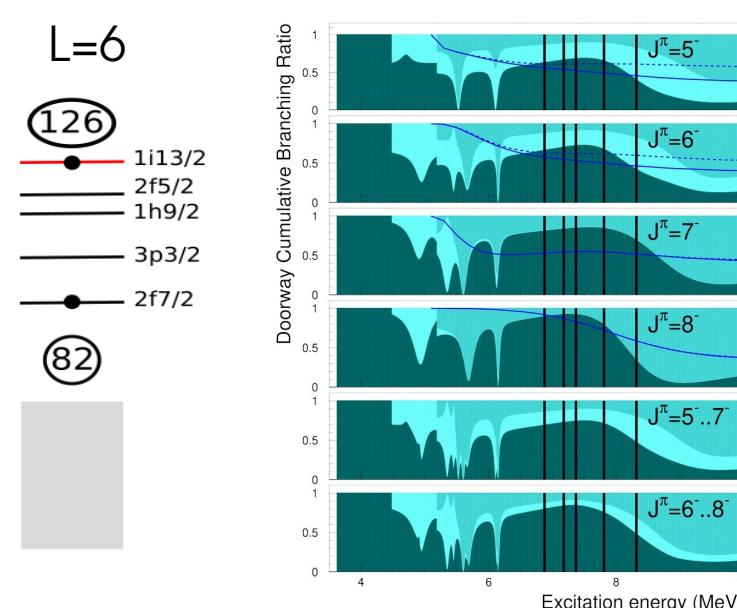
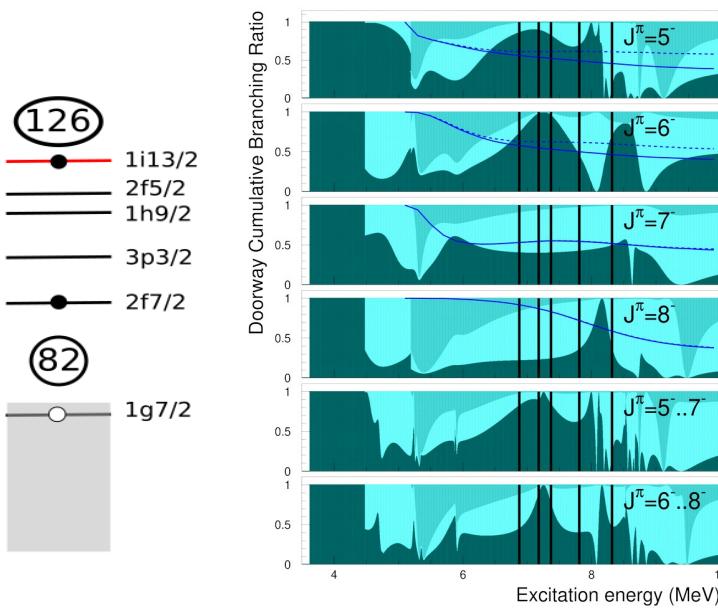
S. Okumura, T. Kawano, Journal of Nuclear Science and Technology 55, 1009 (2018).
T. Kawano, P. Talou, I. Stetcu, and M. B. Chadwick, Nuclear Physics A 913, 51 (2013).
M. R. Mumpower, T. Kawano, and P. Möller, Physical Review C 94, 064317 (2016).

The neutron emission branching ratios from ^{134}Sn do not agree with Hauser-Feshbach model predictions.



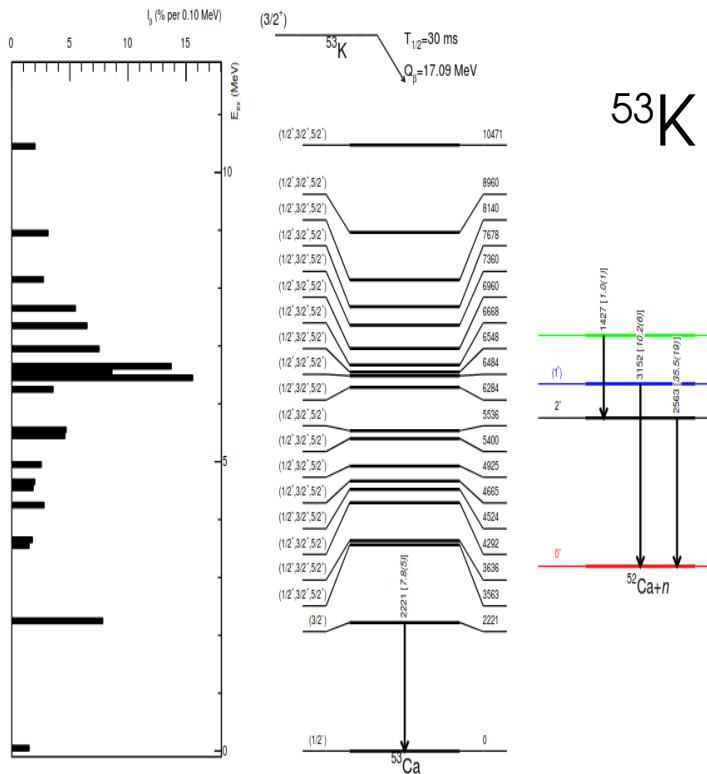
Doorway state decay model

- How can nuclear shell structure in ^{134}Sn affect the neutron emission probabilities ?
- Before reaching C.N. stage neutron emission proceeds via configurations with strong neutron emission probability **states with significant spectroscopic overlap with excited states in ^{133}Sn**
- Model: Relative neutron emission probabilities from calculated spectroscopic factors from the shell model, transmission coefficients using optical model (Koning-Delaroche)



$^{51-53}\text{K}$ decays – neutron TOF spectra

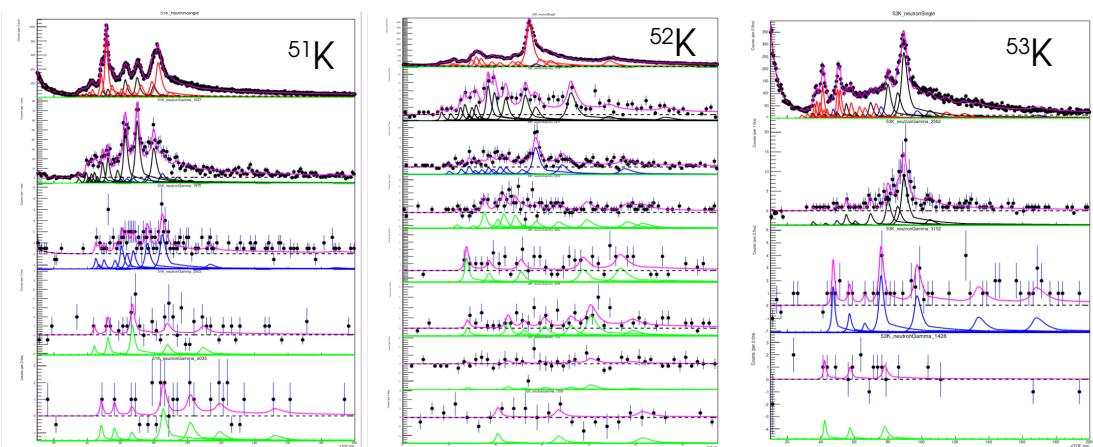
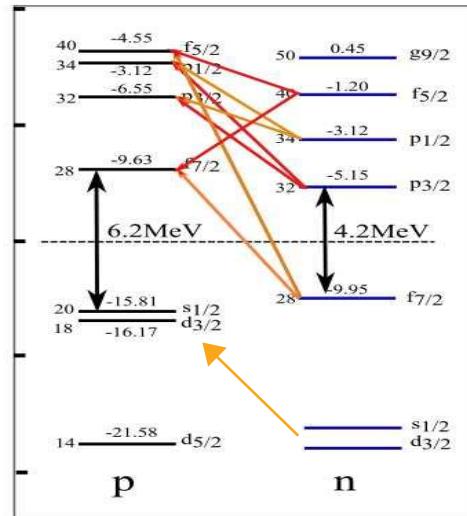
(IDS PI: A. Gottardo, R.G.)



^{53}K

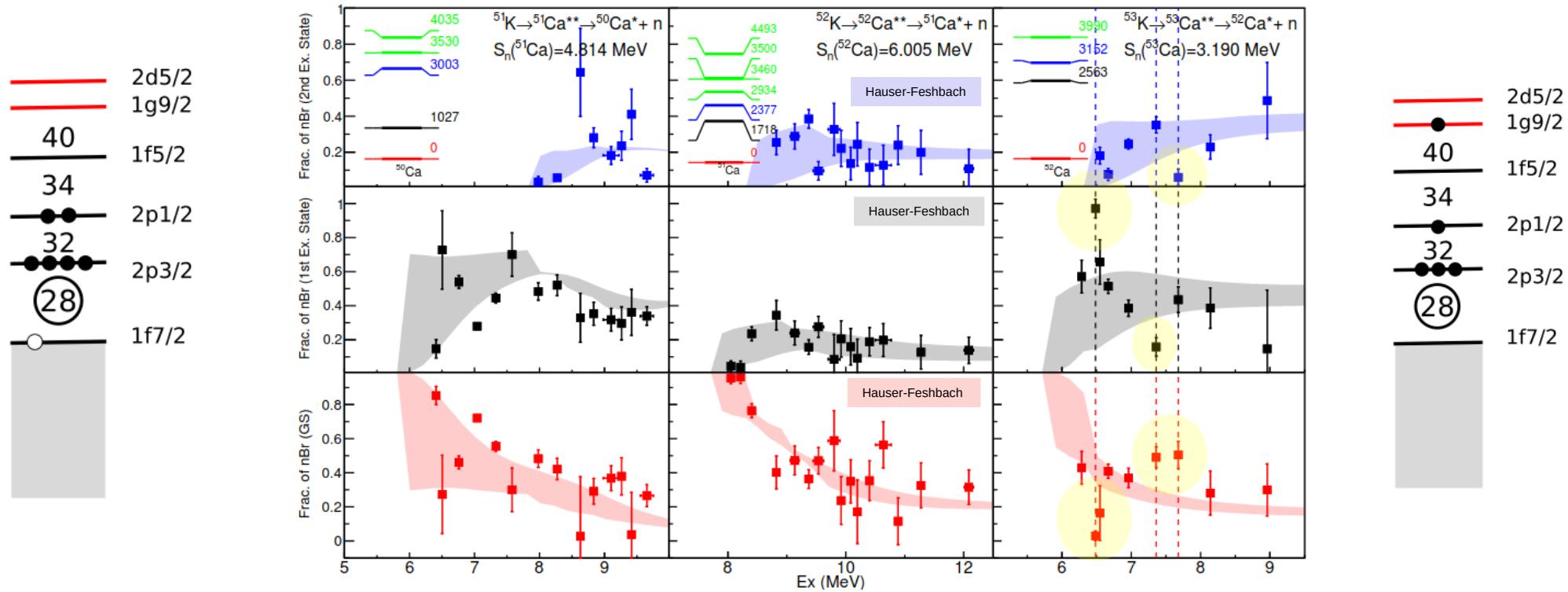
$$\text{vf}_{7/2} \rightarrow \pi f_{7/2}$$

$$\text{vd}_{3/2} \rightarrow \pi d_{3/2}$$



$^{51-53}\text{K}$ decays – statistical and doorway state emission

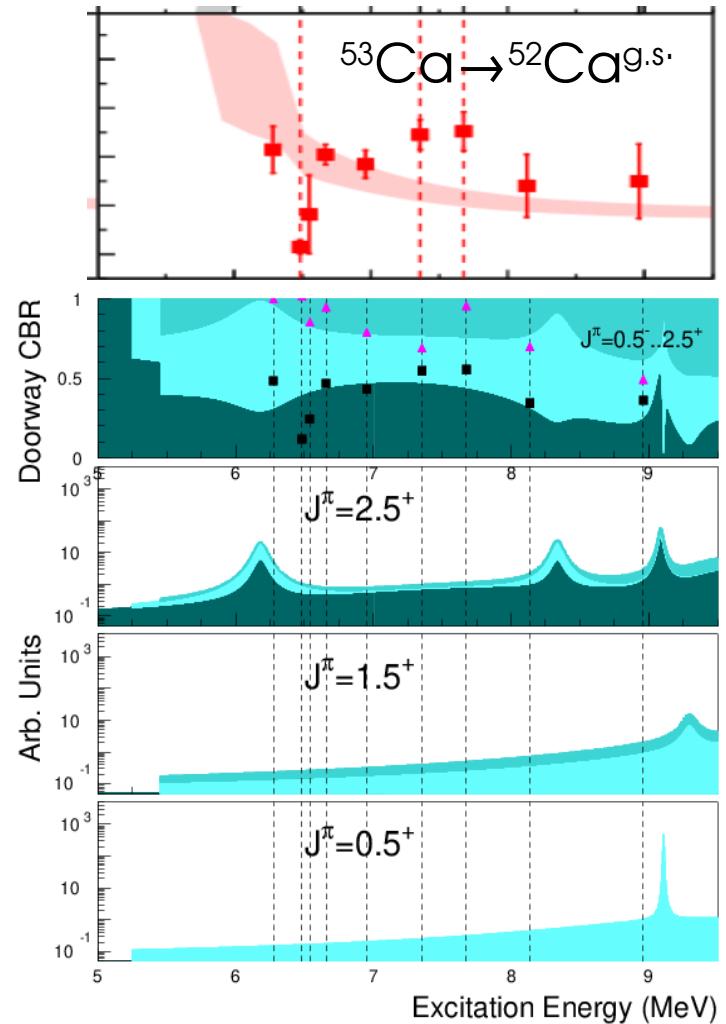
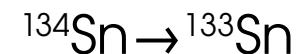
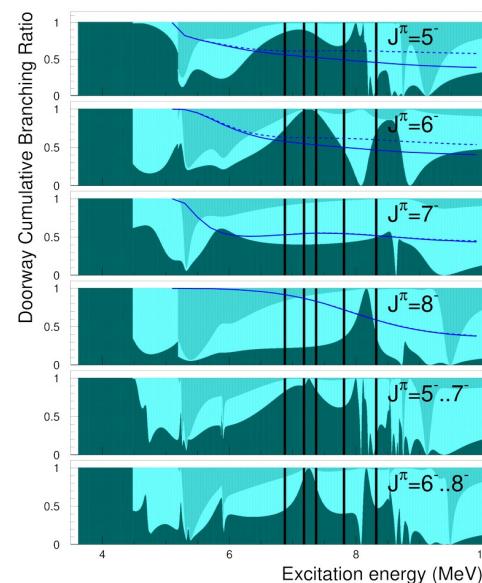
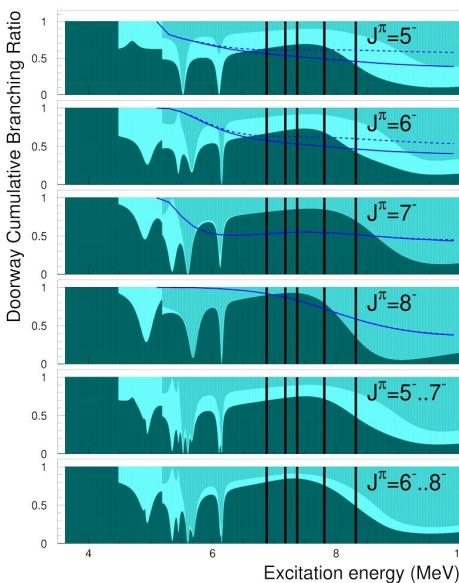
- Majority of $^{51-53}\text{K}$ decays paths consistent with Hauser-Feshbach predictions.
- Doorway state emission observed at ~ 6.5 MeV and 7.6 MeV in ^{53}K decay.



^{53}K and ^{134}In decays

^{53}K – sparse spectrum of doorway states ($1g_{9/2}$ and $2d_{5/2}$)
 Evidence for the doorway state decay at $E^*=6.5$ MeV
 Doorway states for $^{51,52}\text{K}$ decays predicted for $E>10$ MeV.

^{134}In – richer and more fragmented spectrum of doorway states ($1i_{13/2}$, $2g_{9/2}$)



... this is only a beginning

- Gamow-Teller transitions $\text{vg}_{7/2} \rightarrow \pi\text{g}_{9/2}$ identified in the decay of ^{134}In
- Neutron emission from excited states in ^{134}Sn populated in ^{134}In β -decay cannot be explained using “compound nucleus” postulate
- Evidence for non-statistical behavior seen in ^{53}K decay, $^{52,51}\text{K}$ agree with HF
- Direct neutron emission model via doorway states ?
- Future studies, expand the pool of precursors
- Impact on two-neutron emission, neutron-gamma competition
- What is the impact on the r-process ?
- High-statistics experiments planned at IDS with ^{134}In and ^{135}In decays
- Measure L-values for neutron emission in nuclear orientation experiments

Stirred or shaken



<https://www.istockphoto.com>

J. Heideman, RG, Z. Xu, M. Madurga T. Kawano, J. E. Escher et al. PRC in press

J. Heideman,¹ R. Grzywacz,^{1,2} Z. Y. Xu,¹ M. Madurga,¹ J. E. Escher,³ T. Kawano,⁴ A. Algara,^{5,6} A. N. Andreiev,^{7,8} J. Benito,⁹ T. Berry,¹⁰ M. J. G. Borge,¹¹ C. Costache,¹² H. De Witte,¹³ A. Fijalkowska,^{14,15} L. M. Fraile,⁹ H. O. U. Fynbo,¹⁶ A. Gottardo,¹⁷ C. Halverson,¹ L. J. Harkness-Brennan,¹⁸ A. Illana,^{13,19} L. Janiak,^{14,20} D. S. Judson,¹⁸ T. T. King,¹ A. Korgul,¹⁴ T. Kurtukian-Nieto,²¹ I. Lazarus,²² R. Lică,^{23,12} R. Lozeva,²⁴ N. Marginean,¹² R. Marginean,¹² C. Mazzocchi,¹⁴ C. Milai,¹² R. E. Mihai,¹² A. I. Morales,⁵ R.D. Page,¹⁸ J. Pakarinen,^{19,25} M. Pieras-Silkowska,¹⁴ Zs. Podolyák,¹⁰ M. Singh,¹ C. Sotty,¹² M. Stepaniuk,¹⁴ O. Tengblad,¹¹ A. Turturica,¹² P. Van Duppen,¹³ V. Vedia,⁹ S. Viňals,¹¹ N. Warr,²⁶ R. Yokoyama,¹ and C. X. Yuan²⁷

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Joe Heideman

Zhengyu Xu

$$\Psi_n(E) = \frac{\left(\frac{\Gamma_n}{2}\right)^2}{(E_0 - E)^2 + \left(\frac{\Gamma_n}{2}\right)^2},$$

$$\Gamma_n = \sum_i \Gamma'_{n,i} = \sum_i \Gamma_{n,i} \frac{S_{n,i}}{S_n}$$

