β-delayed two-neutron spectroscopy of ^{134}In
A novel window into nuclear structure

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Motivation for the study of ^{134}In

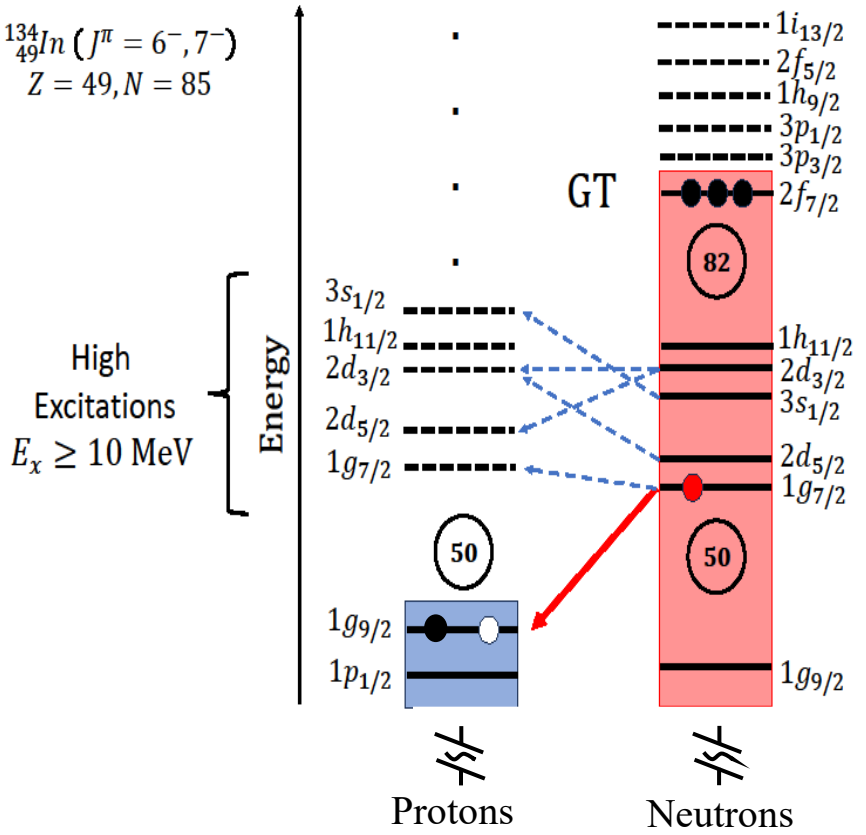
- Proximity to ^{132}Sn
  - High Q_β and low S_{2n} (14.46, 6.031 MeV)
  - $P_{2n} \approx 10\%$
  - Two-neutron energy correlations a viable probe for nuclear structure

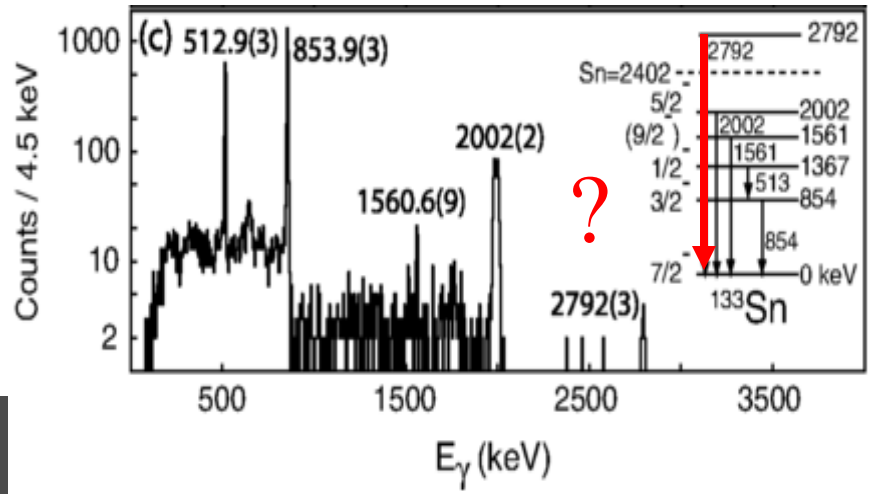
- Search for $\nu i_{13/2}$ s.p. state
  - $^{132}Sn(^{9}Be, ^{8}Be)^{133}Sn^{*}$, $E_n \approx 400$ keV

    J. Allmond *et al.*; *Phys. Rev. Lett.*, **112** 172701 (2014)

- Nonstatistical neutron emission

    J. Heideman *et al.; Phys. Rev. C.*, **108** 24311 (2023)





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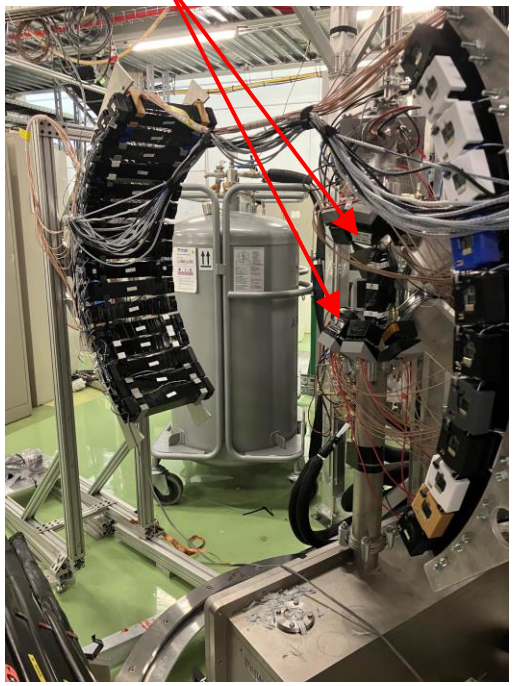
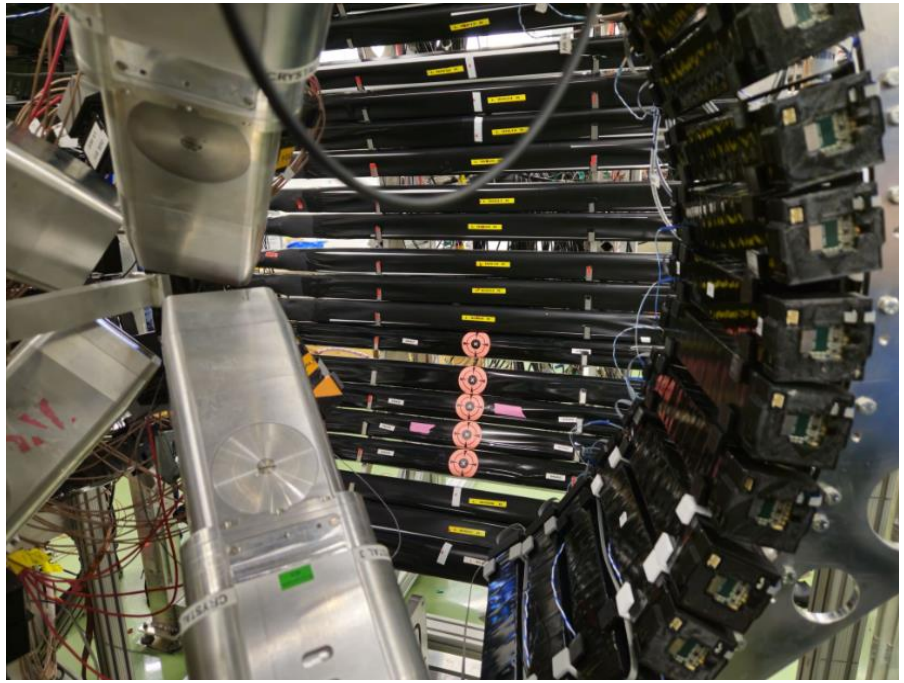
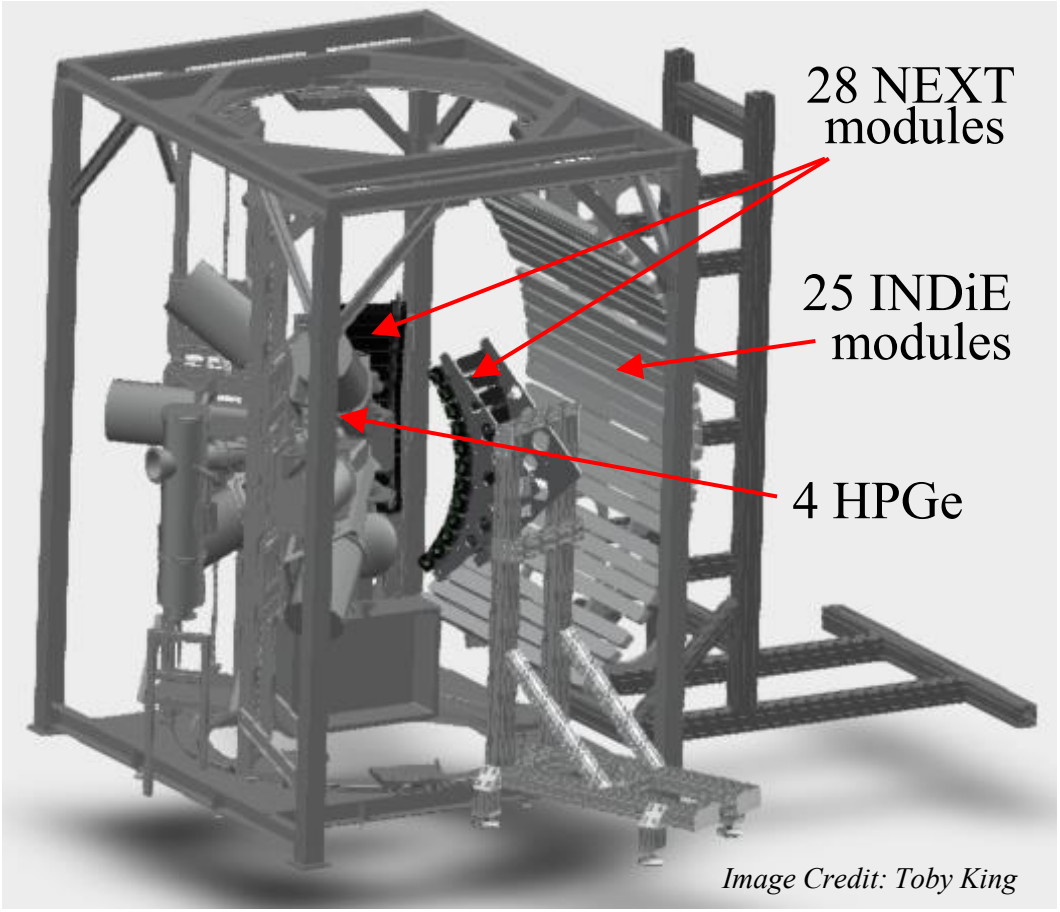
Detection Setup

8 OGS





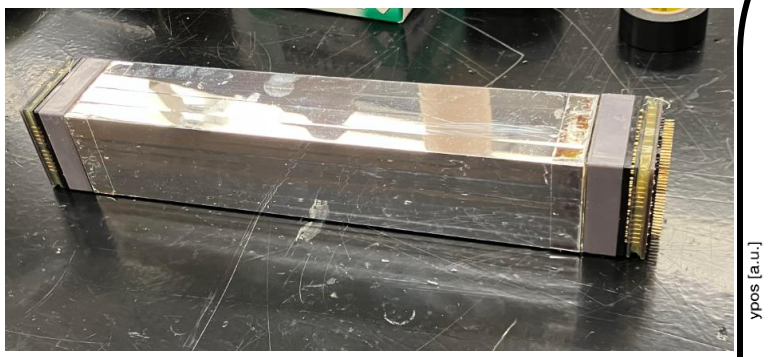
3-sided β^- trigger
~80% efficiency

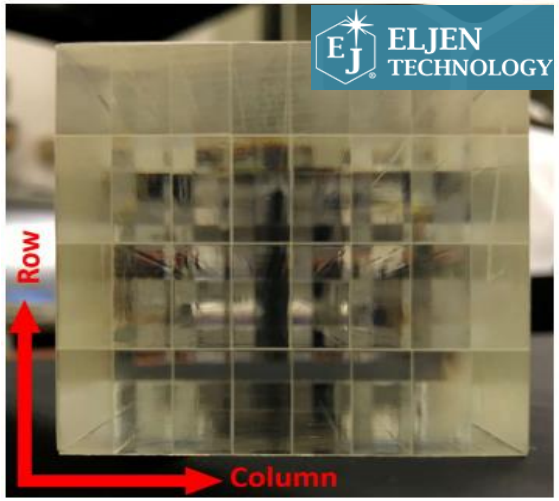


[1] W. A. Peters et al; *Nuclear Instruments and Methods in Physics Research Section A* ***836***, 122-133 (2016)
[2] S. Neupane, J. Heideman, R. Grzywacz et al.; *Nuclear Instruments and Methods in Physics Research Section A,* **1020** 165881 (2021)
[3] J. Heideman, D. Perez-Loureiro, R. Gryzwacz et al.; *Nuclear Instruments and Methods in Physics Research Section A,* ***946***, 162528 (2019)

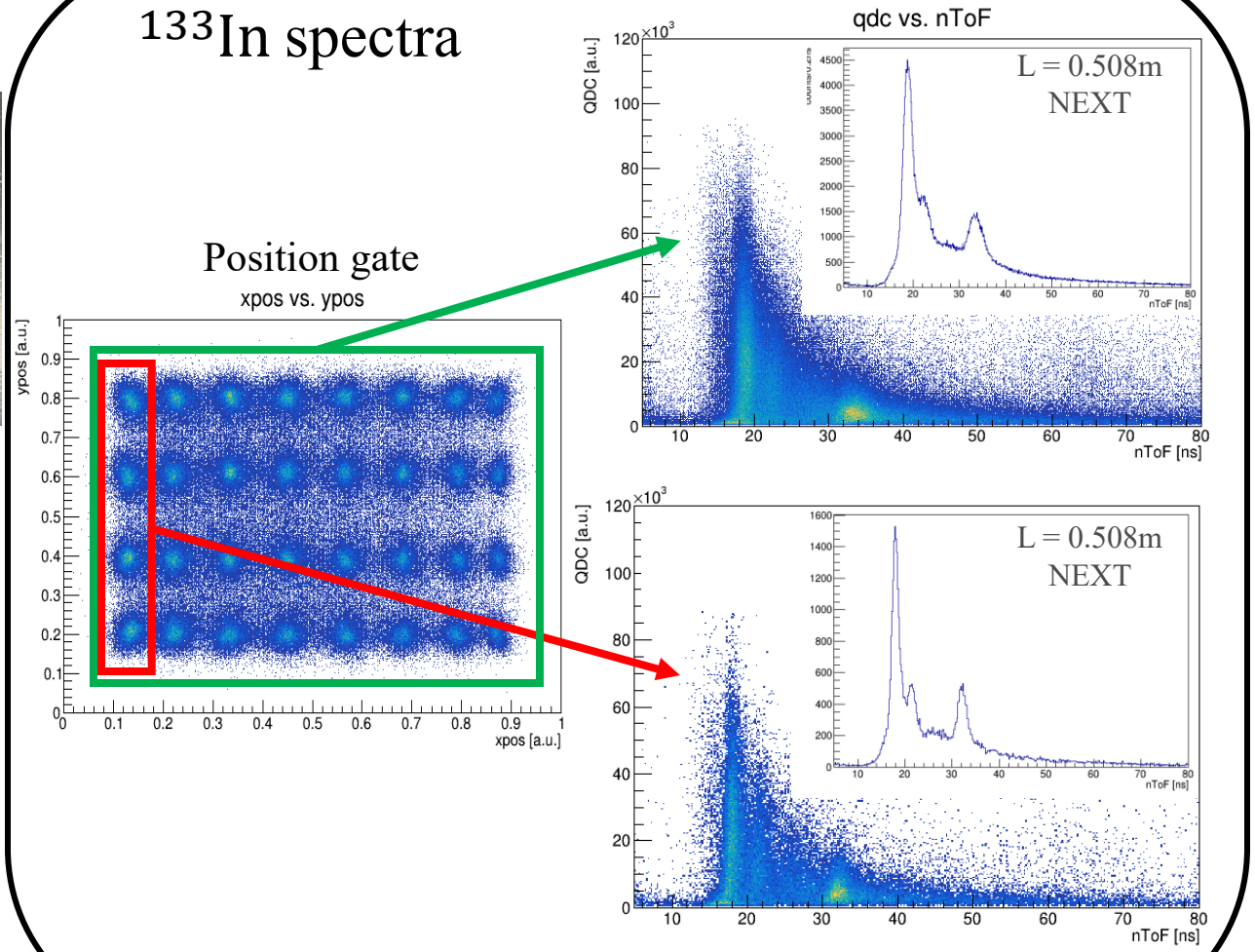
The NEXT detector

Neutron dEtector with multi-neutron (Xn) Tracking





^{133}In spectra

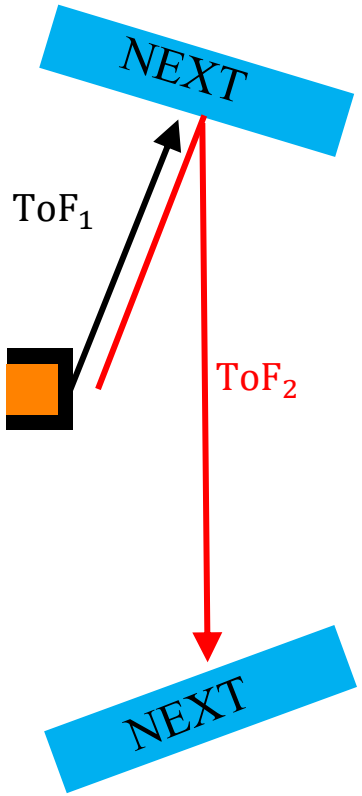


[1] S. Neupane, J. Heideman, R. Grzywacz et al.; *Nuclear Instruments and Methods in Physics Research Section A,* **1020** 165881 (2021)
[2] J. Heideman, D. Perez-Loureiro, R. Gryzwacz et al.; *Nuclear Instruments and Methods in Physics Research Section A,* ***946***, 162528 (2019)
[3] Vertilon Corporation. SIB064B-1018 User Guide
[4] Hamamatsu Corporation. H12700A User Guide

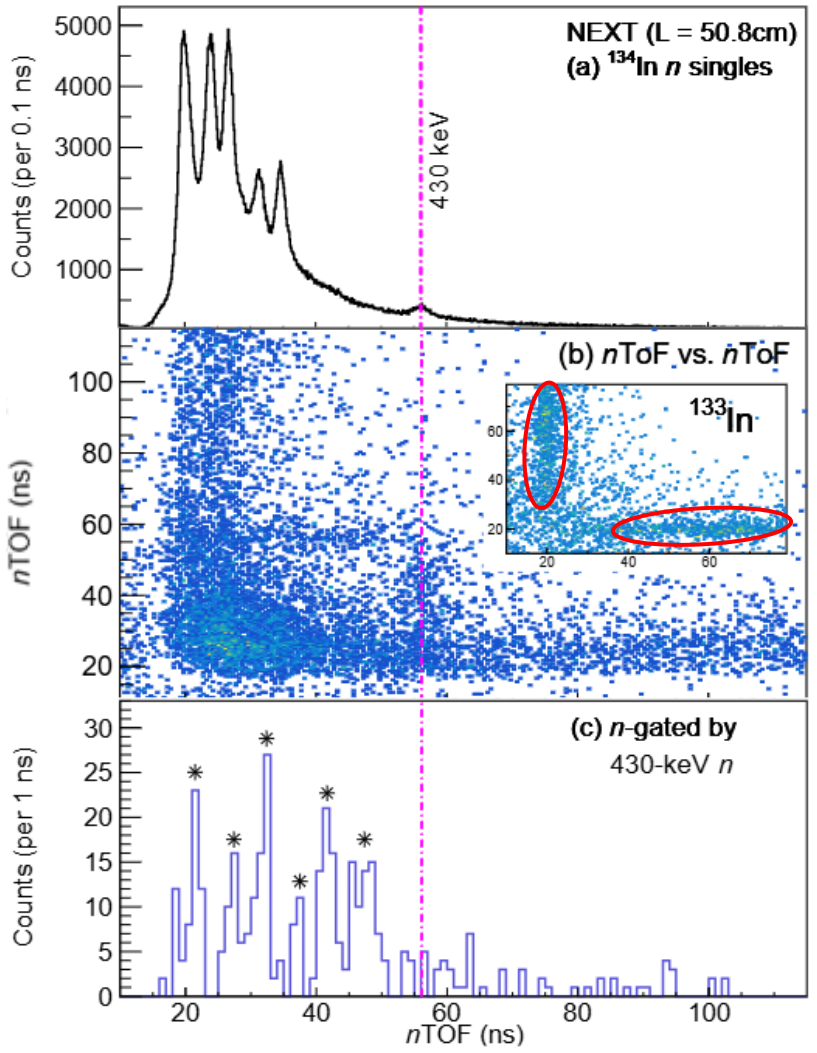
THE UNIVERSITY OF TENNESSEE SYSTEM

Two-Neutron Events in NEXT

- Minimizing scattering events in NEXT
  - PSD + max light loss
  - Rejection criterion using ^{133}In
- Bands represent two-neutron events
- βn residue with $\approx$ 56 ns (430-keV)
  - 6 candidates for 2n emission
- Important breakthrough in neutron spectroscopy!

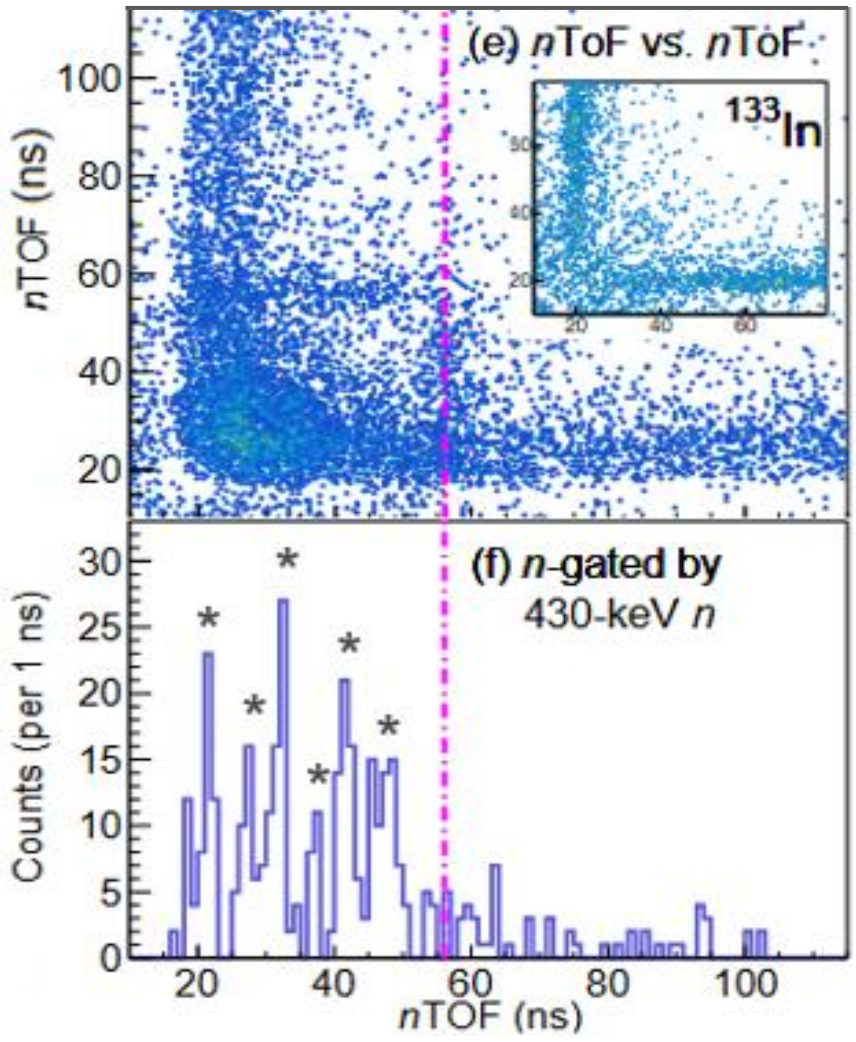


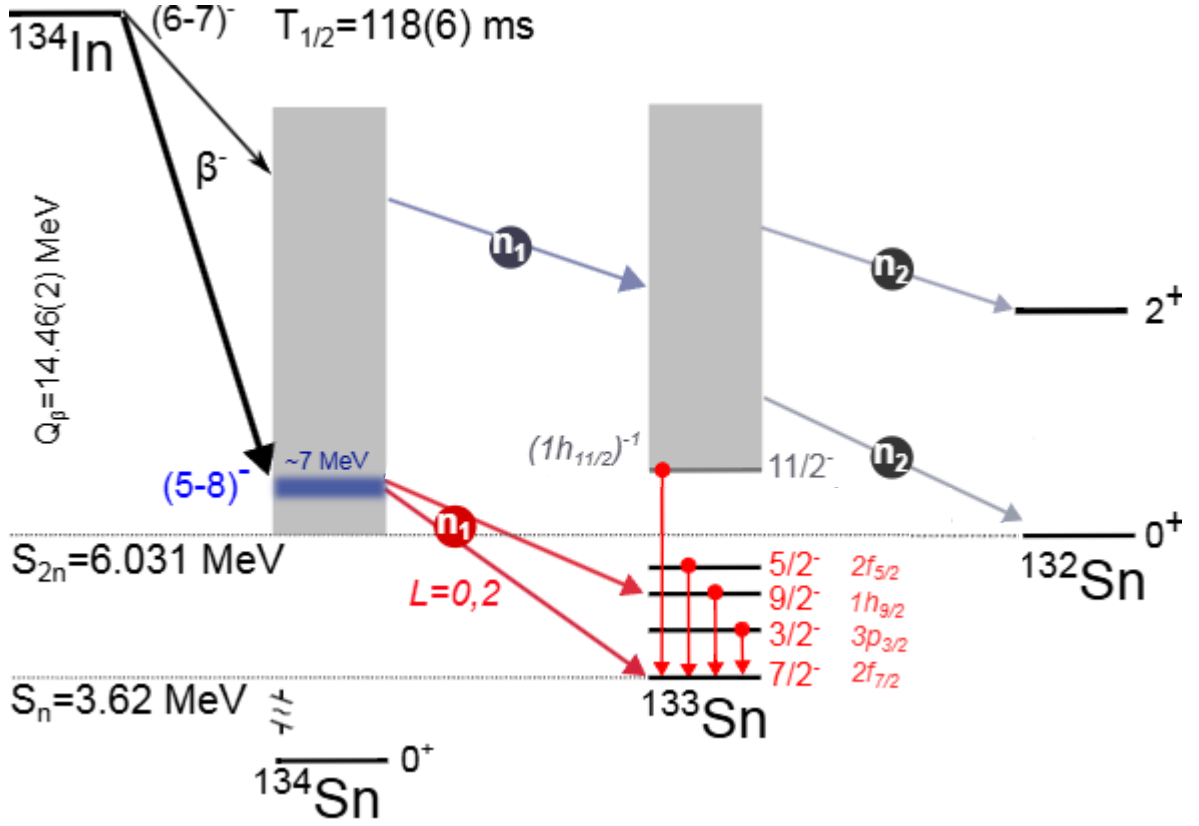
Maximally, $\mathrm{ToF}_2 \gtrsim 3 \cdot \mathrm{ToF}_1$ for scattered neutrons



[1] P. Dyszel, R. Grzywacz, Z. Y. Xu, N. Kitamura, A. Korgul, M. Madurga, S. Neupane *et al; Phys. Rev. Lett.* **135**, 152501 (2025)

Assignment of $i13/2$ s.p. state





- $S_{1n}(^{133}Sn) = 2399(3)$ keV
  - $E_x = 2399(3) + 430(7) = 2829(8)$ keV
  - $1i_{13/2}$ only possible candidate

[1] M. Piersa-Silkowska *et al.; Phys. Rev. C.,* **104** 44328 (2021)
[2] J. M. Allmond *et al.; Phys. Rev. Lett.,* **112** 172701 (2014)
[3] P. Dyszel, R. Grzywacz, Z. Y. Xu, N. Kitamura, A. Korgul, M. Madurga, S. Neupane *et al; Phys. Rev. Lett.* **135**, 152501 (2025)

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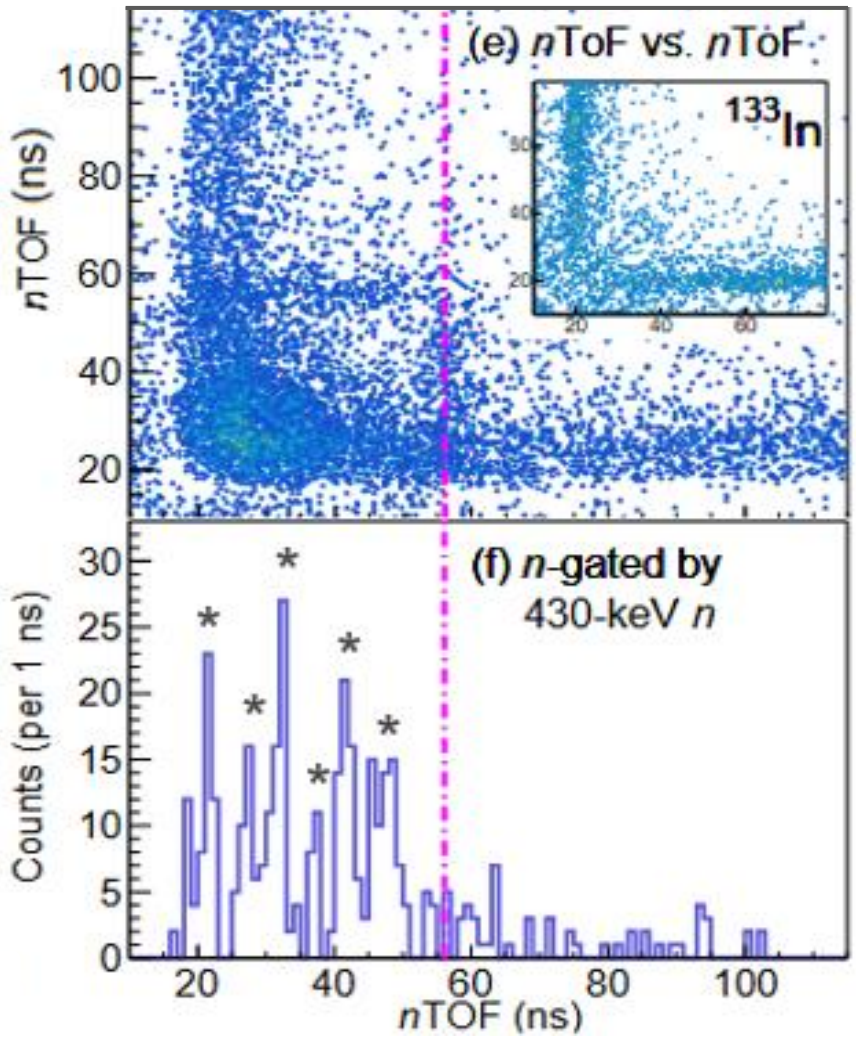

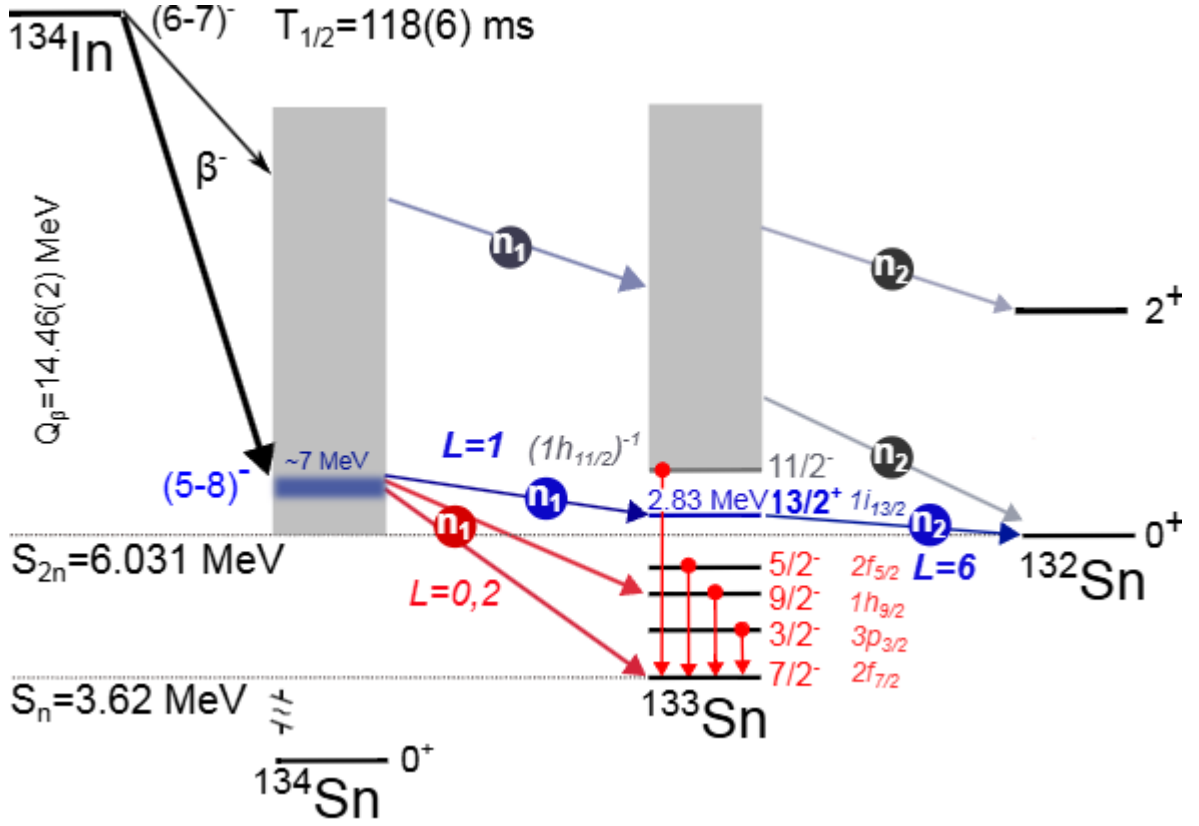

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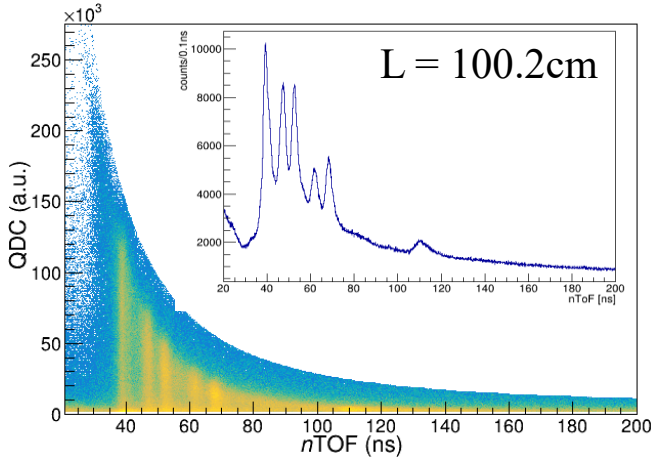
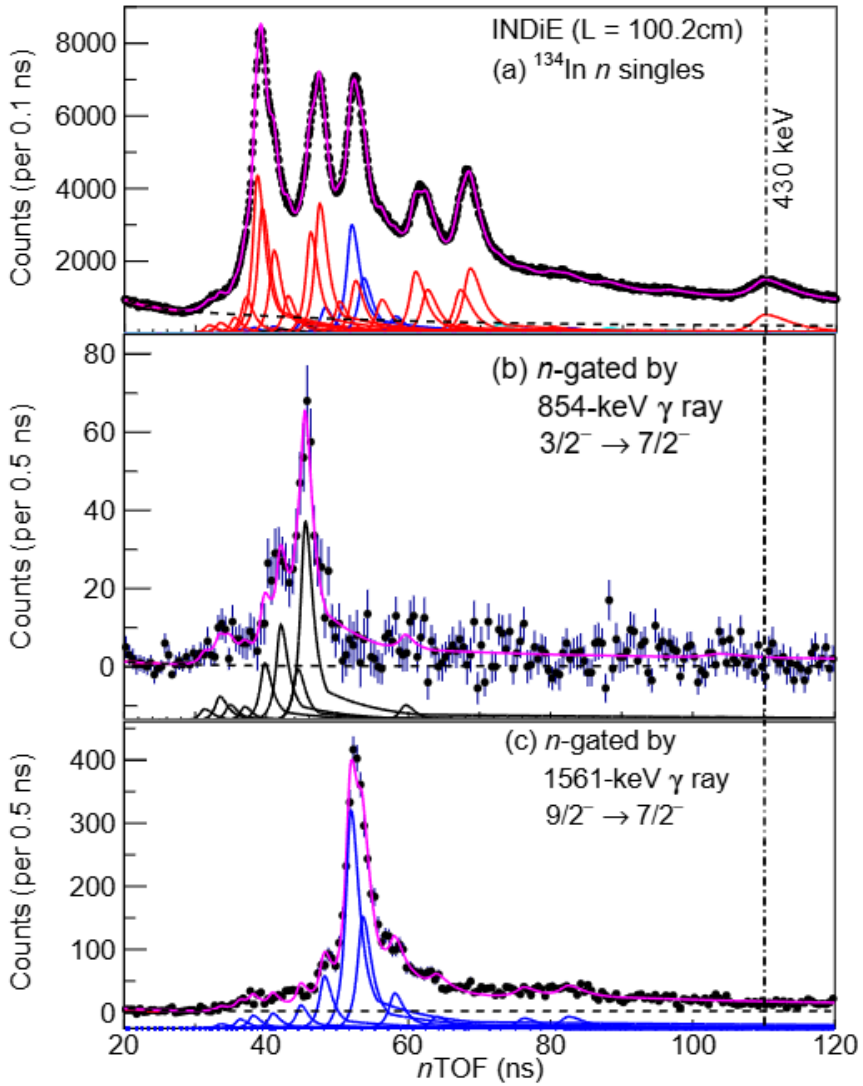
Deconvolution of INDiE

- Fragmentation of neutron spectrum
  - Neutron-singles
  - βn residues
- Obtain experimental branching ratios
  - Relative $I_{\beta n}(i \rightarrow f)/I_{\beta}(i)$
  - Compare to models
- Two-neutron events “hiding” in n-singles



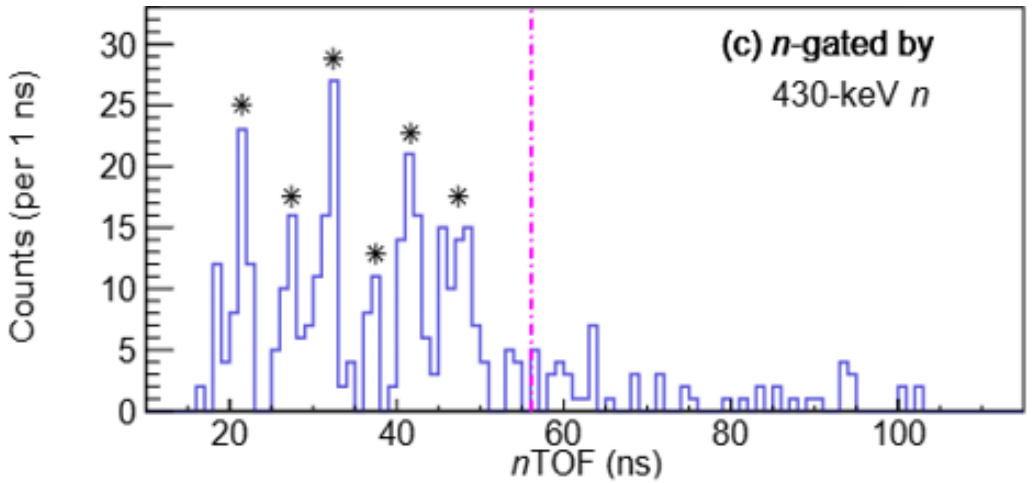


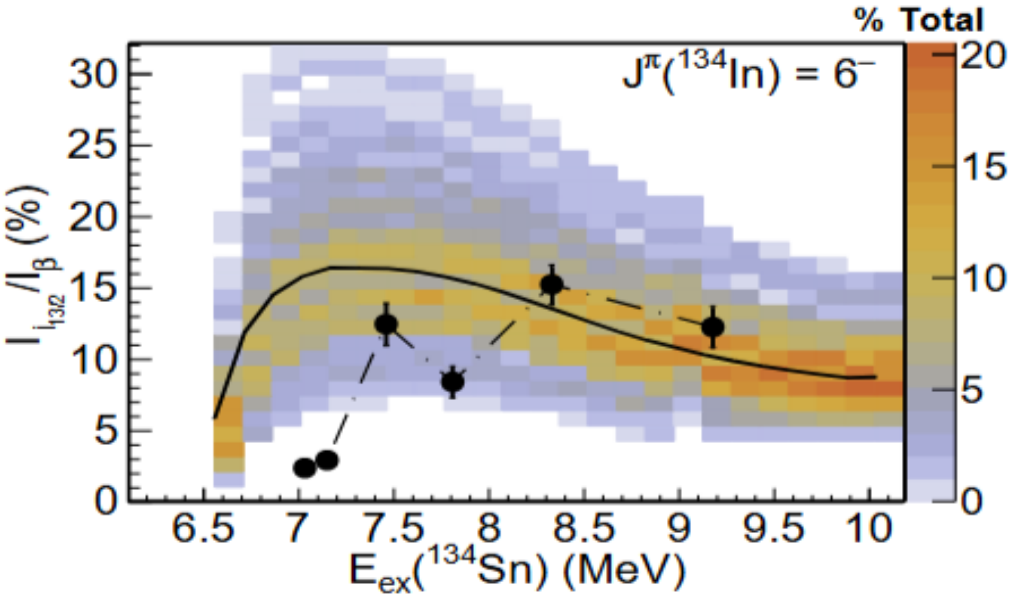
[1] P. Dyszel, R. Grzywacz, Z. Y. Xu, N. Kitamura, A. Korgul, M. Madurga, S. Neupane *et al; Phys. Rev. Lett.* **135**, 152501 (2025)

Comparison with Hauser-Feshbach

- Implemented 2n events in INDiE deconvolution
  - $E_x = S_{2n}(^{134}Sn) + E_{1n}(*) + E(i_{13/2})$

- HF statistical model (BeoH code) + KDUQ-OMP
  - GT transitions for $J_P^\pi = 6^-$
  - 2n emission viable ~6.5 MeV
  - Suppressed branching from resonance
    - γ-competition?
    - $L =$ even n-emission competition?





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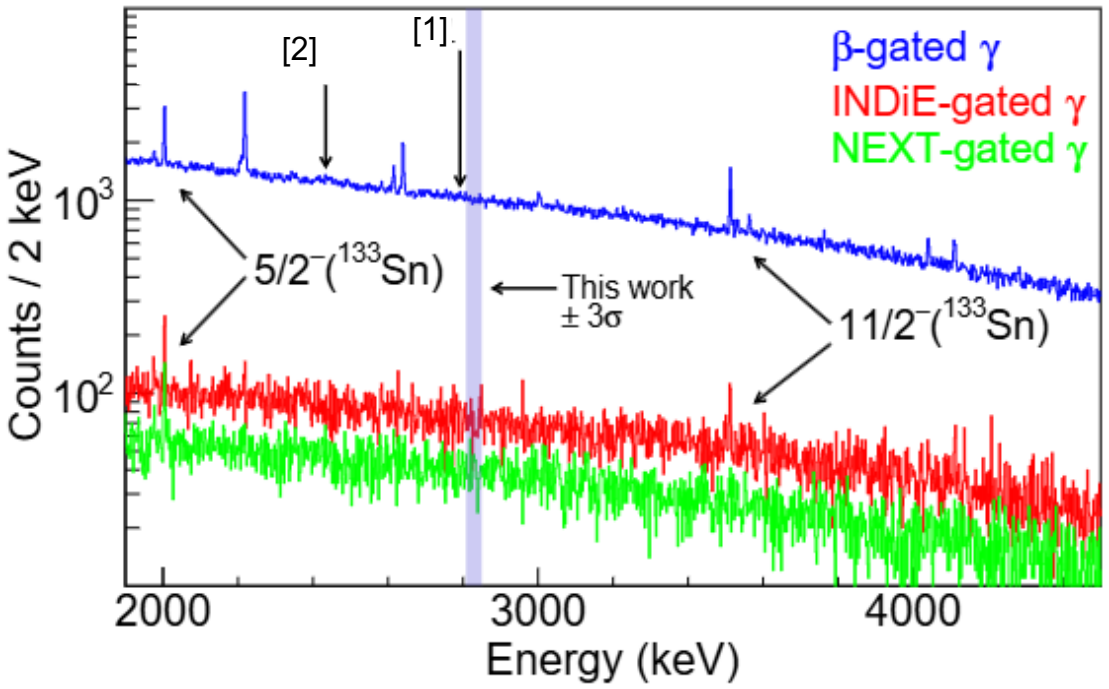

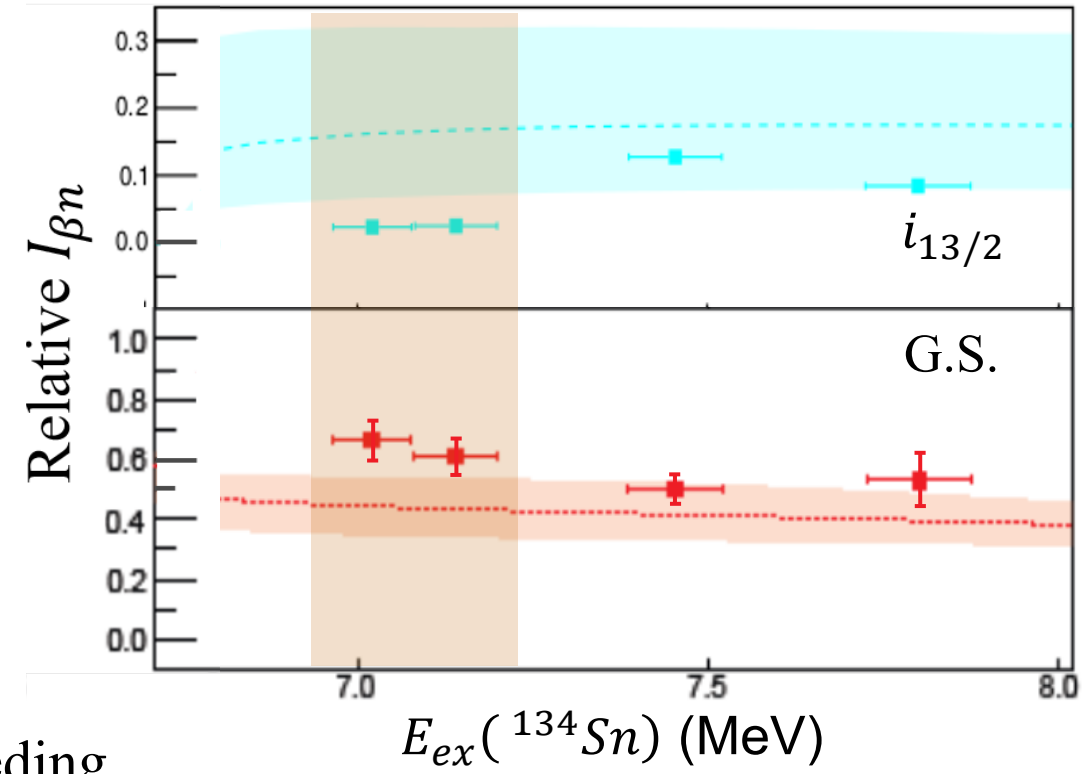

- No EM deexcitations observed which suppress feeding
- Branching to G.S. underpredicted, branching to $i_{13/2}$ overpredicted
- Suggests intermediate nucleus has knowledge of structure

[1] J. Allmond *et al.*; *Phys. Rev. Lett.*, **112** 172701 (2014)
[2] M. Piersa-Silkowska *et al.; Phys. Rev. C.* **4**, (2021)
[3] P. Dyszel, R. Grzywacz, Z. Y. Xu, N. Kitamura, A. Korgul, M. Madurga, S. Neupane *et al; Phys. Rev. Lett.* **135,** 152501 (2025)

Conclusion

- Performed first beta-delayed two-neutron spectroscopy of the r-process nucleus ^{134}In
- Assignment of the $i_{13/2}$ single-particle state in ^{133}Sn using two-neutron energy correlations in NEXT
  - $E_n = 430(7)$ keV
  - $E^*_{i13/2}(^{133}Sn) = 2829(8)$ keV
  - Feeding via multiple excited states in ^{134}Sn
- Observed suppressed branching to $i_{13/2}$ from excited states in ^{134}Sn populated at GT resonance, as compared to HF statistical model with optical model extension (KDUQ)

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First β-Delayed Two-Neutron Spectroscopy of the r-Process Nucleus ^{134}In and Observation of the $i_{13/2}$ Single-Particle Neutron State in ^{133}Sn

P. Dyszel,[1] R. Grzywacz,[1] Z. Y. Xu,[1] N. Kitamura,[2] M. Karny,[3] A. Korgul,[3] M. Madurga,[1] S. Neupane,[4] A. Algora,[5] A. N. Andreyev,[6] M. Araszkiewicz,[3,7] R. A. Bark,[8] J. Benito,[9] N. Bernier,[9] M. J. G. Borge,[10] M. Caballero,[9] P. Chuchala,[3] T. E. Cocolios,[11] C. Costache,[12] J. G. Cubiss,[6,13] H. DeWitte,[11] J. E. Escher,[4] D. Fernandez-Ruiz,[10] A. Fijalkowska,[3] L. M. Fraile,[9] H. O. U. Fynbo,[14] J. Gouge,[1] J. L. Herraiz,[9] A. Illana,[9] P. M. Jones,[8] D. S. Judson,[15] P. Kamińska,[3] T. Kawano,[16] K. Kolos,[4] M. Labiche,[17] R. Lică,[12] M. Llanos-Expósito,[9] G. G. DeLorenzo,[9] N. Marginean,[12] I. Michelon,[18] C. Mihai,[12] E. Nácher,[5] C. Neacsu,[12] J. S. Nielsen,[14] B. Olaizola,[10] J. N. Orce,[19] C. A. A. Page,[6] R. D. Page,[15] J. Pakarinen,[20,21] A. Perea,[10] M. Piersa-Siłkowska,[1,9,22] Zs. Podolyák,[23] J. S. Prieto,[10] M. Rajabali,[24] J. Shaw,[11] K. Solak,[3] M. Stryjczyk,[25,20] O. Tengblad,[10] P. G. T. Vicente,[9] N. Warr,[26] J. Wilson,[6] Z. Yue,[6] and S. Zajda[3]

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