Beta-decay and neutron emission - a ~~strained~~ great relationship

U.S. DEPARTMENT OF ENERGY
Office of Science

National Science Foundation

NNSA National Nuclear Security Administration

Robert Grzywacz

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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Beta-decay and neutron emission – forming the current paradigm

1939: Discovered...

R. B. Roberts, R. C. Meyer, and P. Wang, Phys. Rev. 55, 510 (1939) in n-induced fission

...and explained (?).

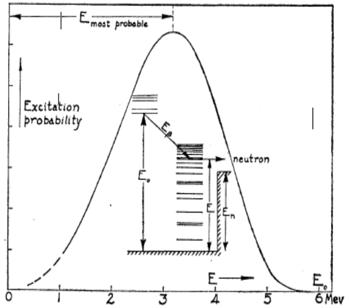
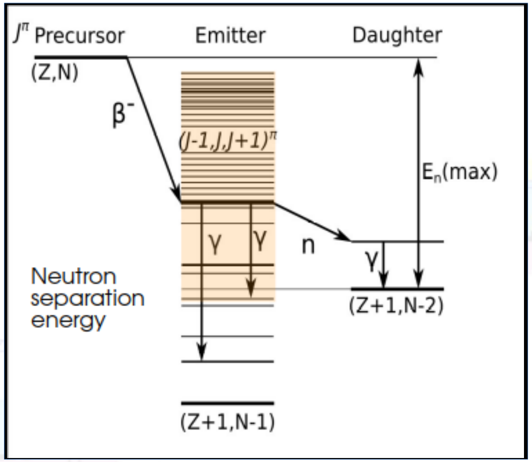


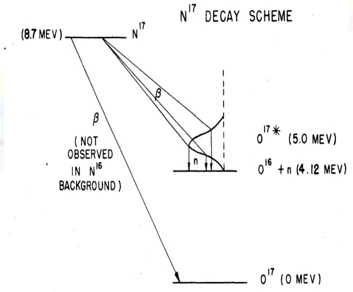
FIG. 9. The distribution in excitation of the product nuclei following beta-decay of fission fragments is estimated on the assumption of comparable matrix elements for the transformations to all excited levels. With sufficient available energy E_0 and a small enough neutron binding E_n it is seen that there will be an appreciable number of delayed neutrons. The quantity plotted is probability per unit range of excitation energy.

N. Bohr and J. A. Wheeler, Phys. Rev. 56, 426 (1939).



T. Kawano, P. Möller, and W. B. Wilson, Phys. Rev. C 78, 054601 (2008)

Observation of broad resonances



N17, A DELAYED NEUTRON EMITTER

L. W. Alvarez

November 5, 1948

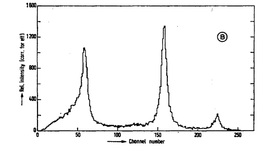
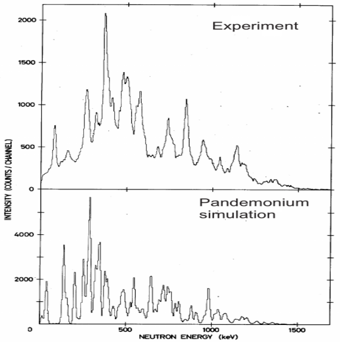


Fig. 2. Neutron spectrum from ¹⁷N decay: (A) experimental pulse height distribution, (B) neutron spectrum after correction for detector efficiency and thermal neutrons.

BETA-DELAYED PARTICLE EMISSION FROM NEUTRON-RICH NUCLEI

P.G. Hansen
EP Division, CERN, Geneva, Switzerland
and
B. Jonson
Department of Physics, Chalmers University of Technology, Göteborg, Sweden

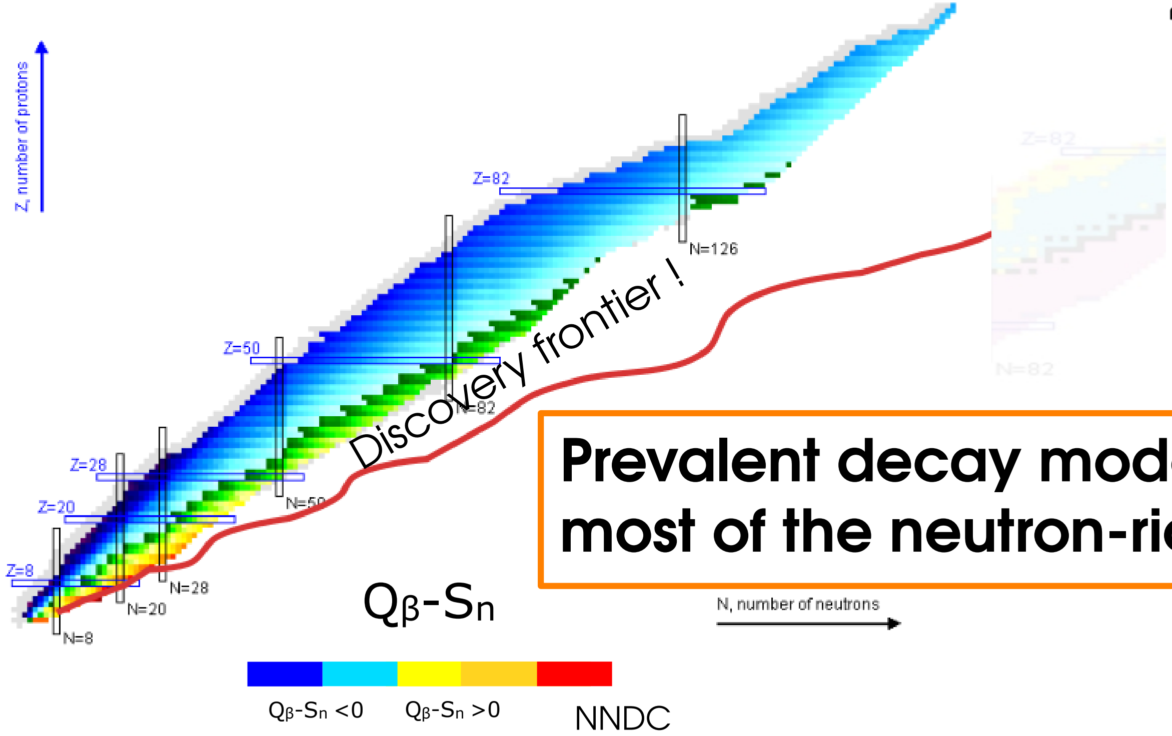
βn-precursors from fission, neutron Pandemonium

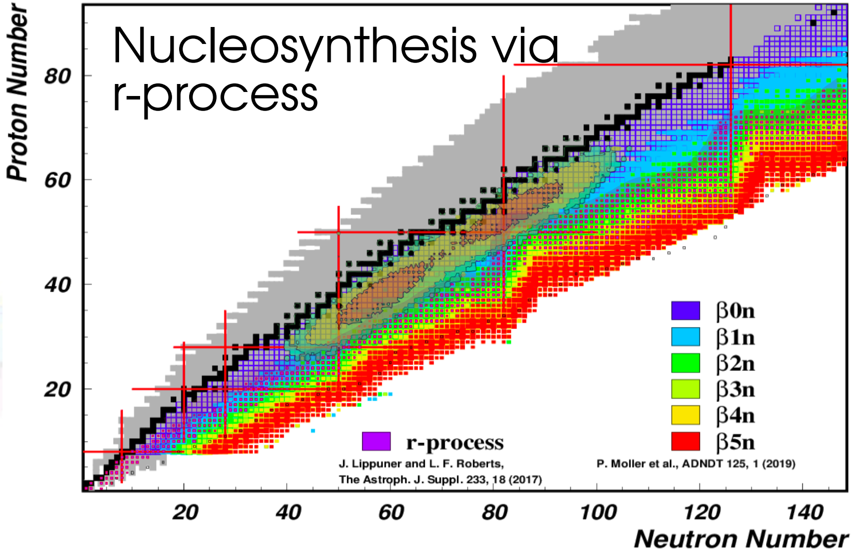


J. Hardy
Nucl. Phys. A305, 15(1978)

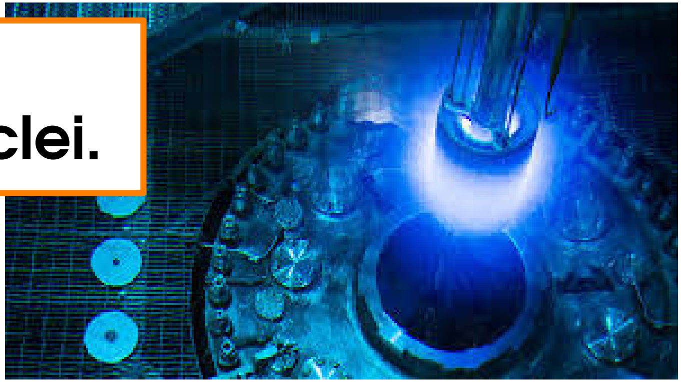
Beta-delayed neutron emission becomes the dominant decay channel far from stability !

- **Access** to isotopes with large P_{xn}
- Increasing Q_β and decreasing S_n.

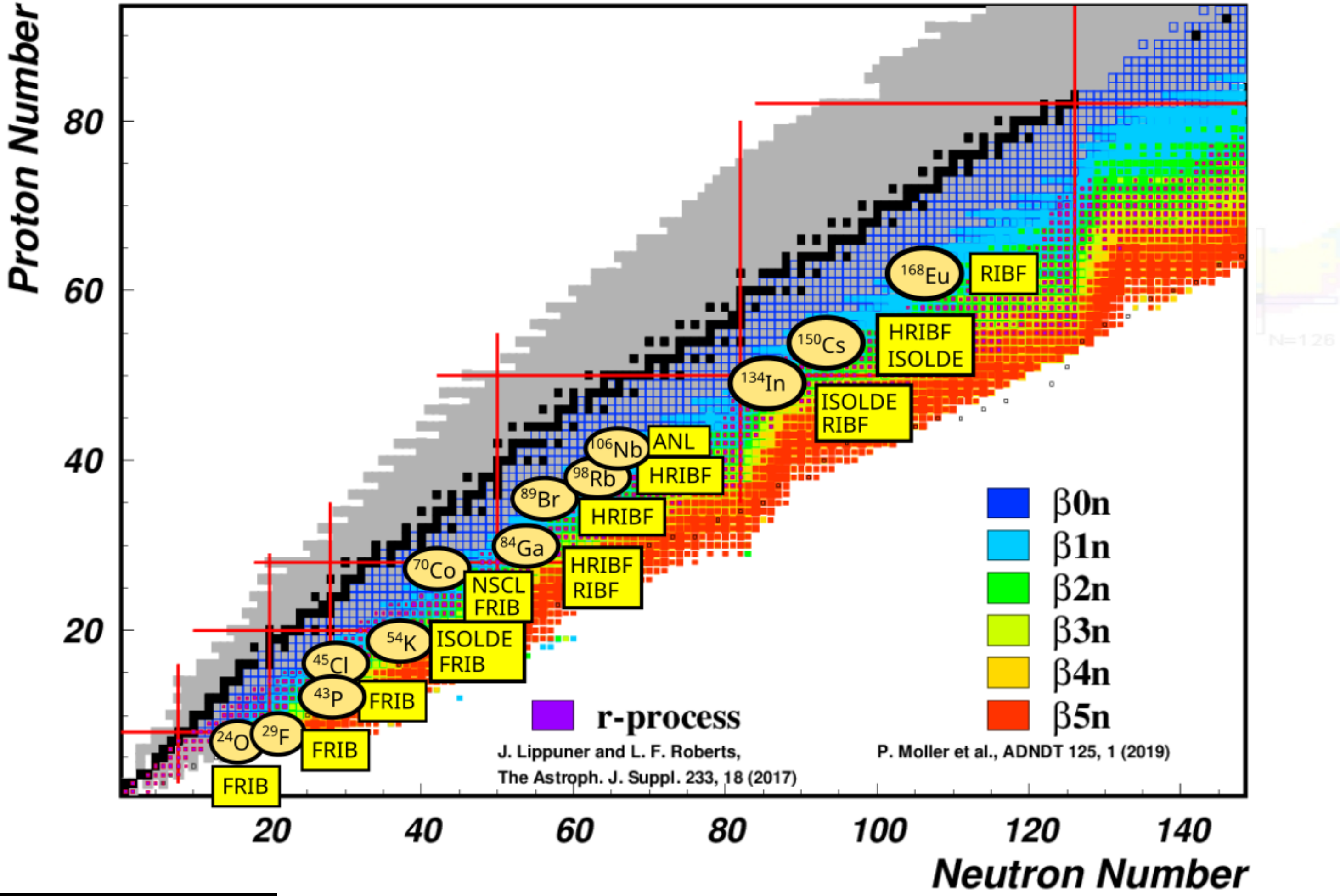




Prevalent decay mode for most of the neutron-rich nuclei.



Neutron spectroscopy with VANDLE/INDIE/3Hen/BRIKEN/NEXT



Publications:

Phys.Rev.Lett. 111, 132502 (2013)
Phys.Rev.Lett. 117, 092502 (2016)
Acta Phys.Pol. B49, 417 (2018)
NIM A946, 1 162528 (2019)
NIM A1020, (2021), 165881
Phys.Rev. C 100, 031302(R) (2019)
Phys.Rev. C 102, 044331 (2020)
Nucl.Data Sheets 173, 144 (2021)
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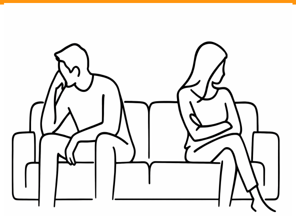
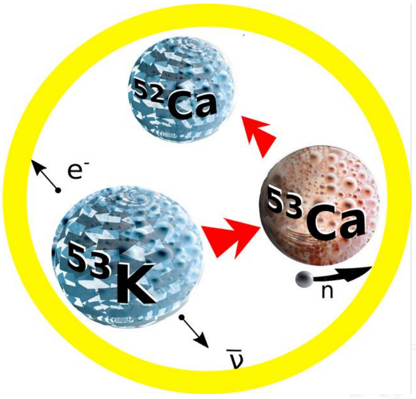
Phys. Lett. B 866 (2025) 139576
Nucl. Inst. Meth. (2025) 170239
Phys. Rev. Lett. 134 (2025)172701
Phys.Rev.Lett. 135, 152501 (2025)
arXiv:2412.04333 (nucl-ex)
(accepted to Phys. Rev. Lett)
Phys. Rev. Lett. 136, 092502(2026)

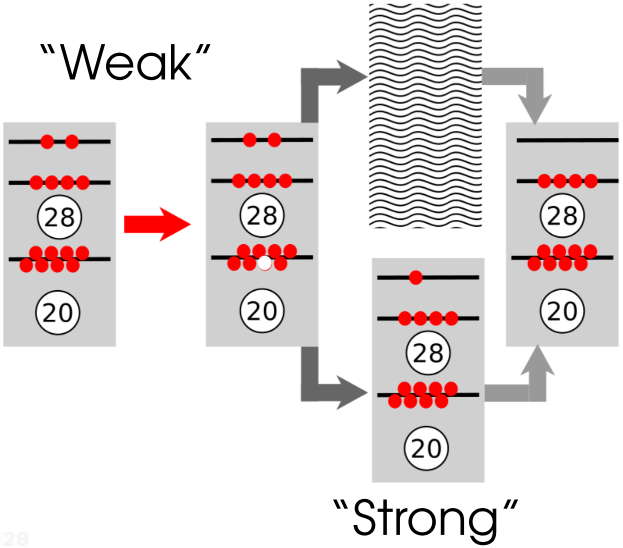
Beta-decay and neutron emission - a strained relationship

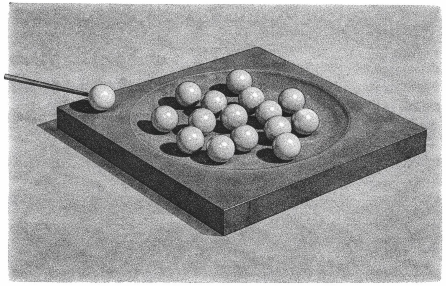
Phase space factor
B(GT) -shell structure
GT- selection rules.



Angular momentum conservation
Transmission coefficients
Reaction mechanism (direct or compound)



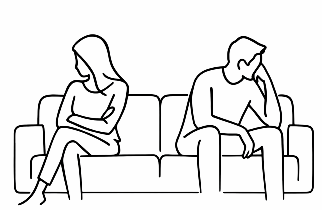




Bohr's model of a neutron-nucleus collision , Nature 137, 351 (1936).

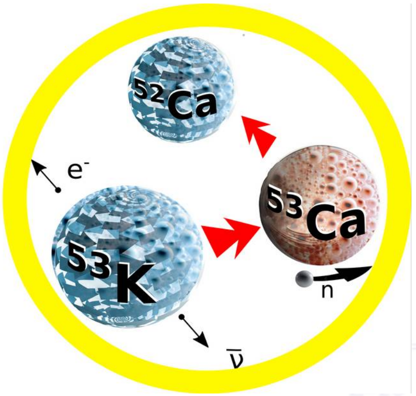
Does neutron emission proceed via intermediate “compound nucleus” stage ?

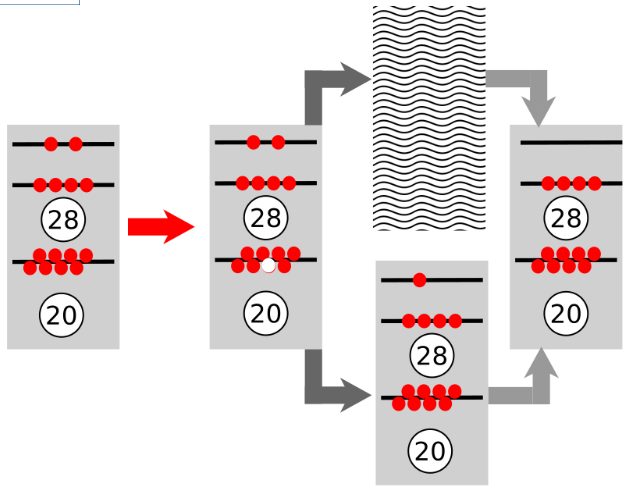
Selective Gamow-Teller transformations populate highly exited states in daughter nucleus.

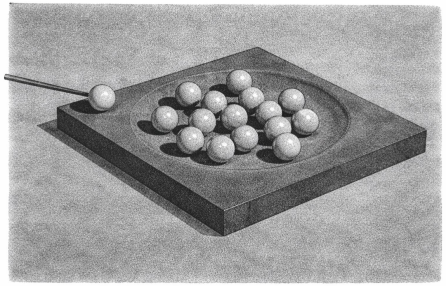


Particle emission from C.N. modeled with Hauser-Feshbach formalism, depends only on spins, parities and E*...

T. Kawano, P. Möller, and W. B. Wilson, Phys. Rev. C 78, 054601 (2008)







Bohr’s model of a neutron-nucleus collision , Nature 137, 351 (1936).

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

“Evidence of nonstatistical neutron emission following β-decay near doubly magic 132Sn”
J. Heideman et al. (IDS Collaboration) Phys. Rev. C 108, 024311(2023)
Z. Y. Xu et al. Phys. Rev. Lett. 133, 042501 (2024)
P. Dyszel et al. Phys. Rev. Lett. (2025)

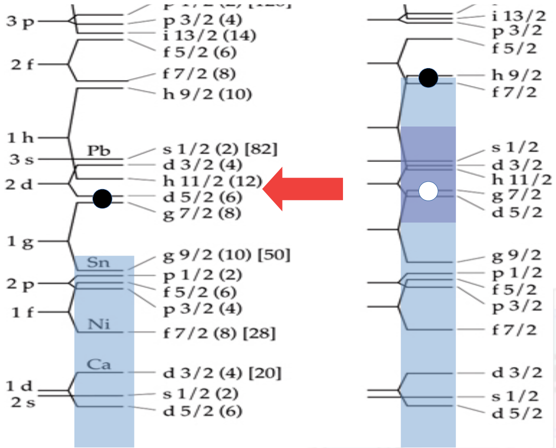
Can beta-delayed neutron emission be used as surrogate reaction ?

Gamow-Teller decays and shell structure far from stability

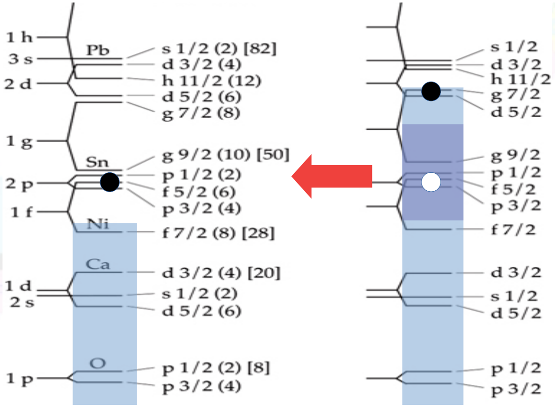
ν occupied →π empty

Heavy and medium mass nuclei:
Beta decay populates highly-excited,neutron unbound, **particle-hole** states,

GT: spin-orbit partners only



^{132}Sn

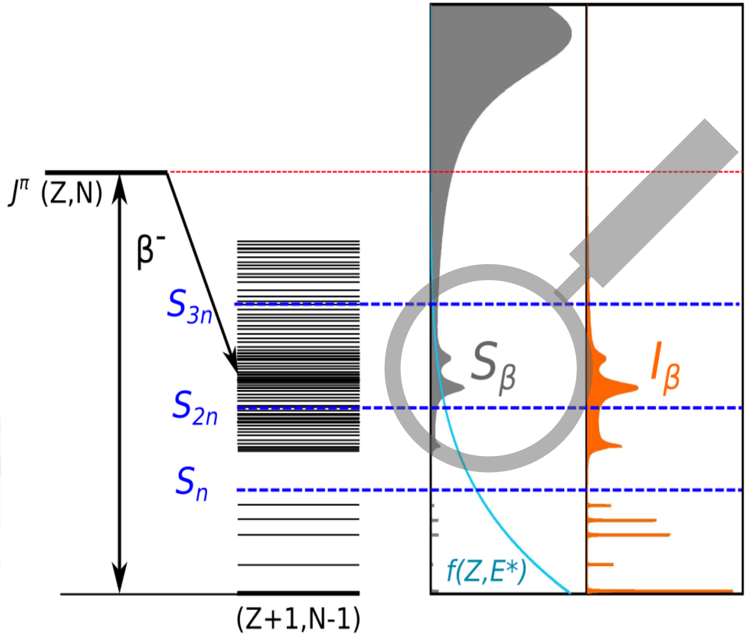


^{78}Ni

GT - transitions generate **highly excited states** in neutron-rich nuclei !

Beta-delayed neutron emission

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i) \qquad S_\beta(E_i) = \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle$$



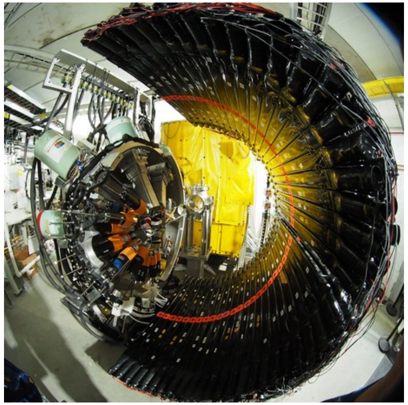
Traditionally used to study β-strength distribution.

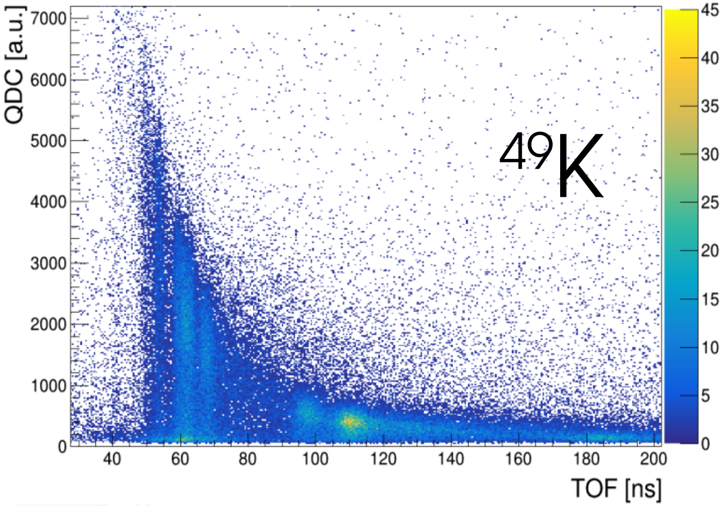
(electrons and neutrinos are lousy observables)

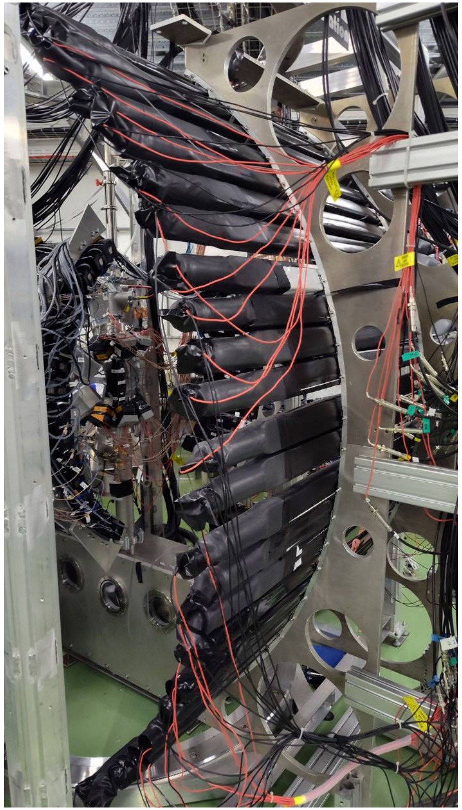
Large P_{xn} requires significant amount of strength S_β above S_{xn} !

TOF-based (digital) neutron detectors: energy measurements (<5 MeV)

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

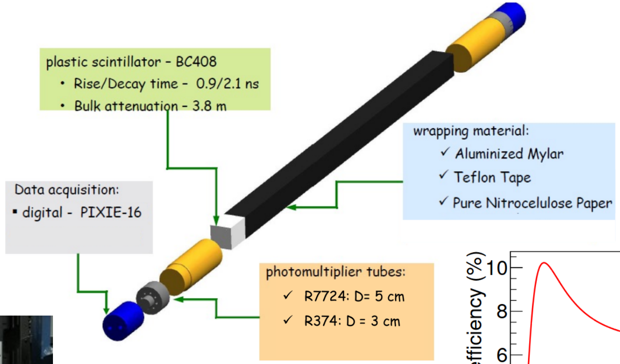


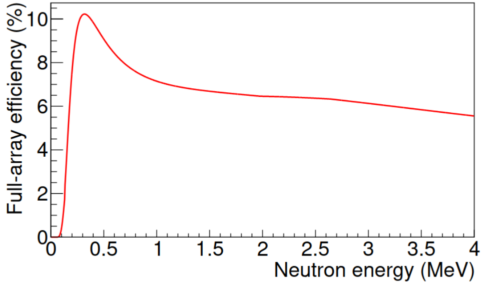


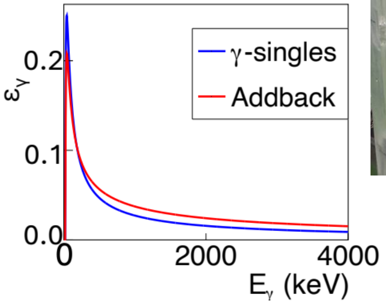


INDiE ~100cm TOF

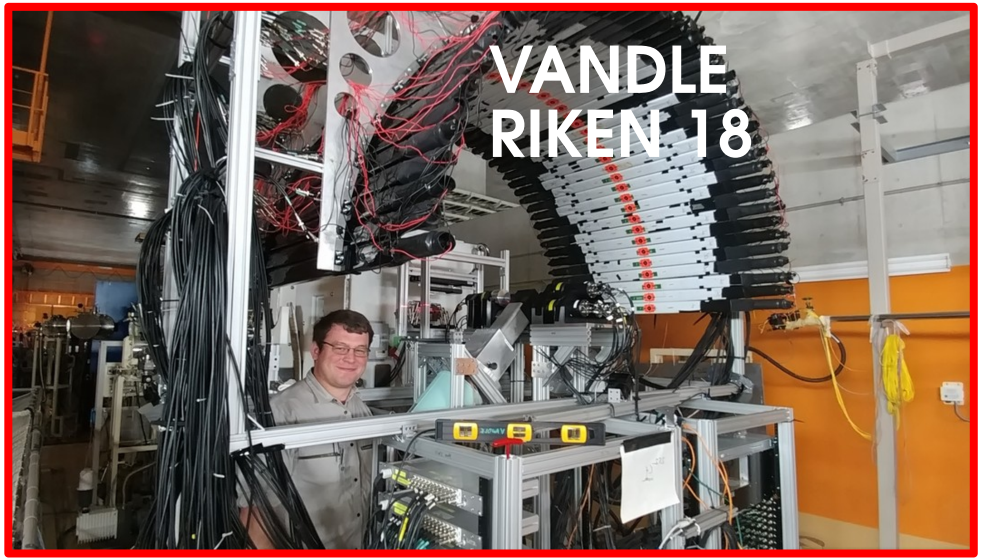
Segmented scintillator for ior implantation

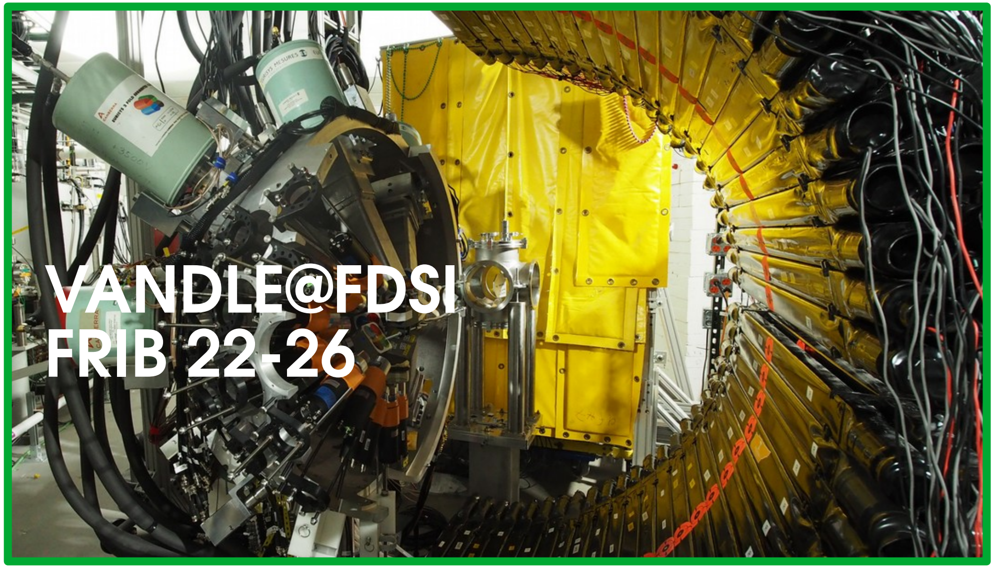


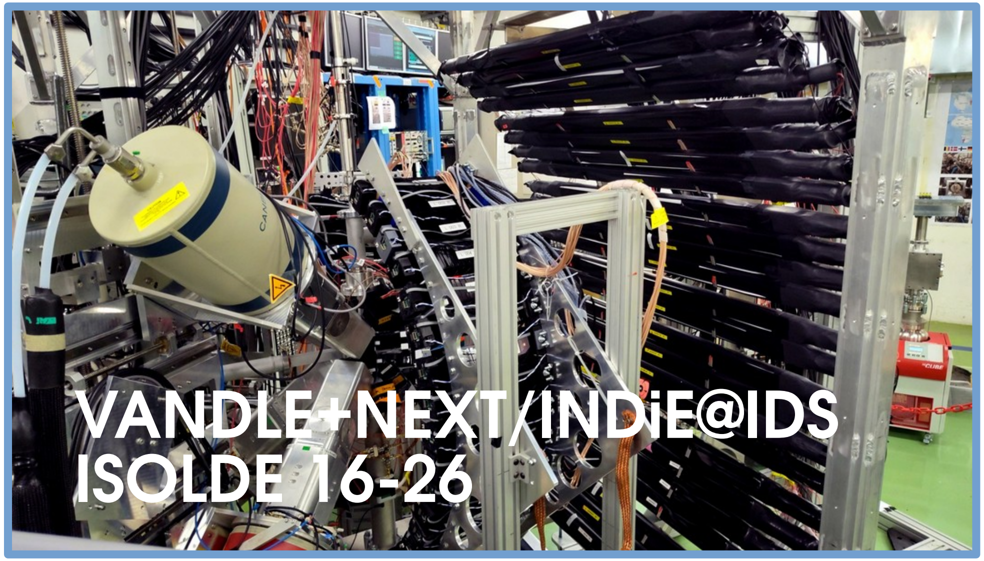


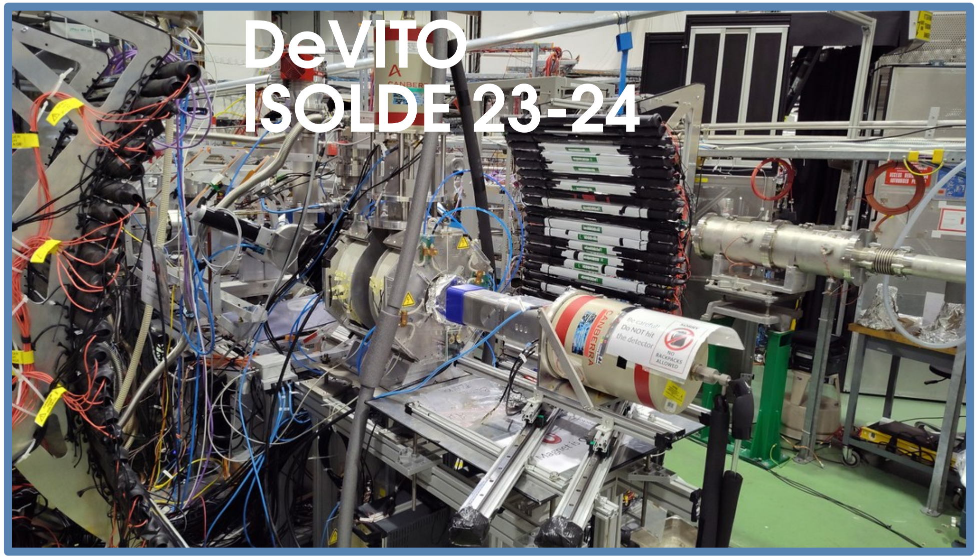


W.A.Peters et al.
NIM A836 (2016) 122–133

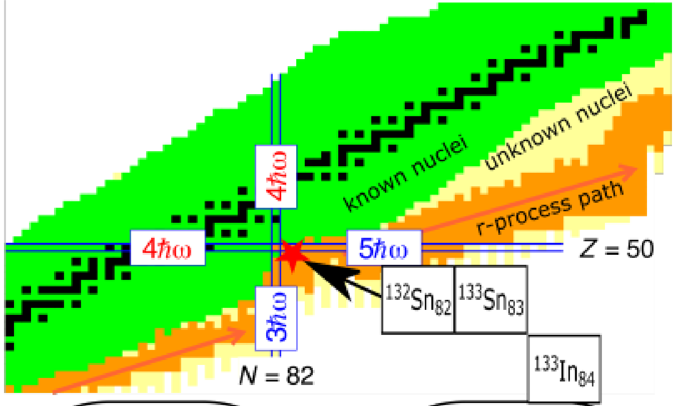

VANDLE
RIKEN 18

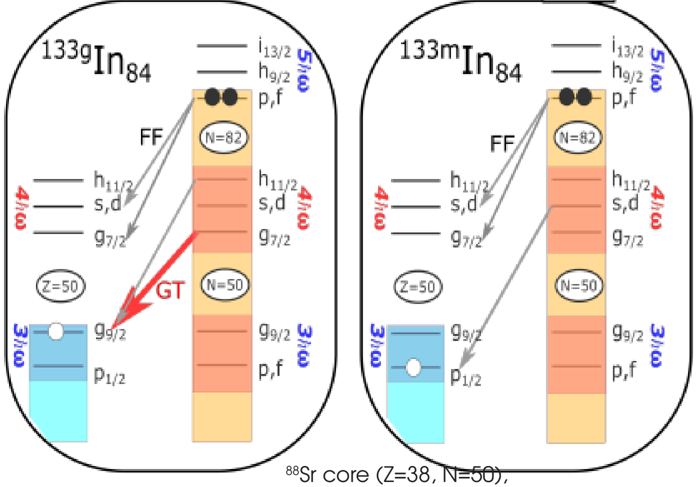

VANDLE@FDSI
FRIB 22-26


VANDLE+NEXT/INDiE@IDS
ISOLDE 16-26

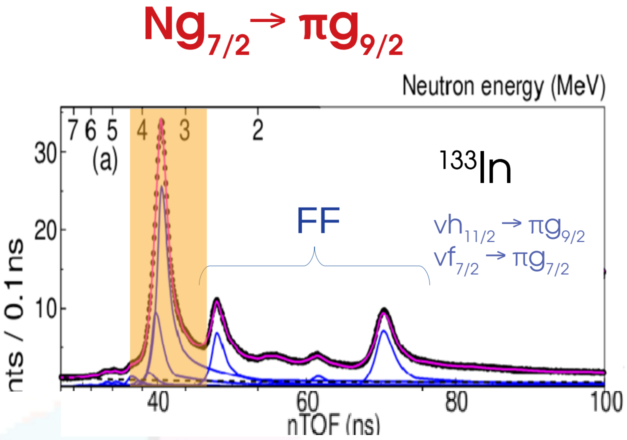

DeVITO
ISOLDE 23-24

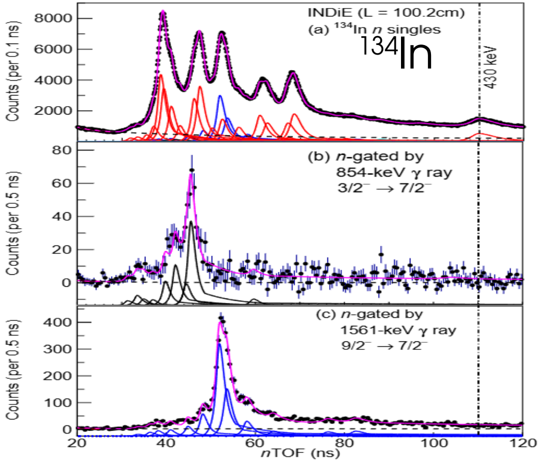
The decay of ^{133}In at Isolde Decay Station
N=82 shell-gap, forbidden and allowed transitions

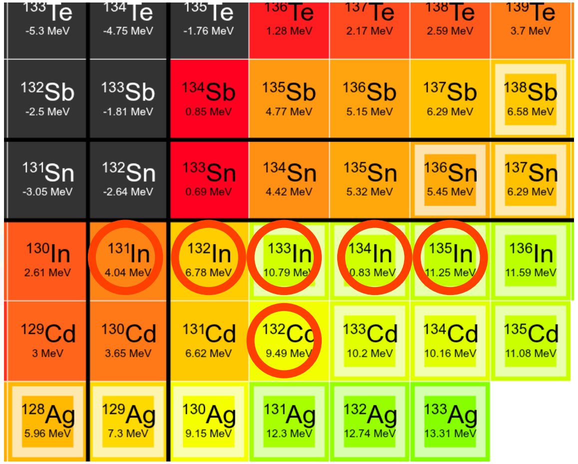


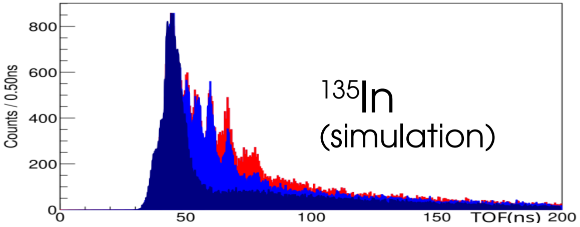


^{88}Sr core (Z=38, N=50),
neutrons $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$, $1f_{7/2}$
protons: $1p_{1/2}$, $0g_{9/2}$, $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$





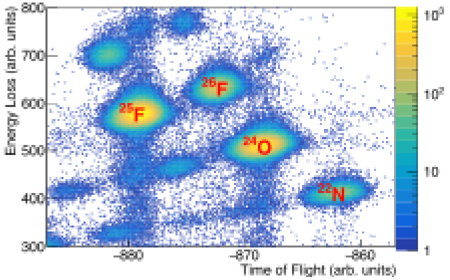


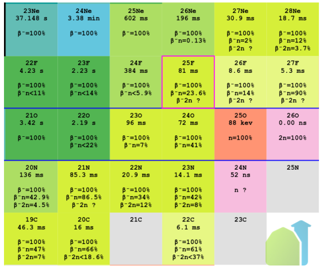


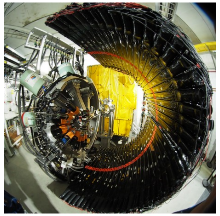
Z. Y. Xu et al. Phys. Rev. Lett. 131, 022501 (2023)
Z. Y. Xu et al. Phys. Rev. C 108, 014314 (2023)
P. Dyszel et al. Phys. Rev. Lett. 135, 152501 (2025)

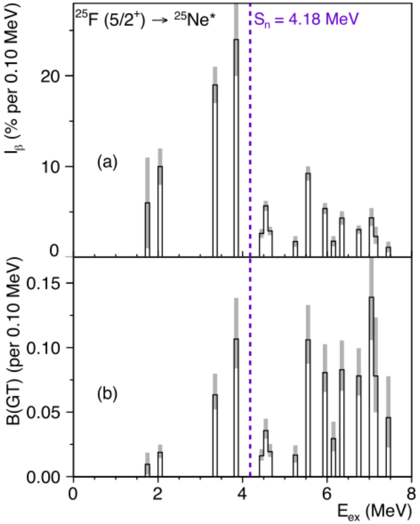
The evidence of N = 16 shell closure and β-delayed neutron decay of ^{25}F

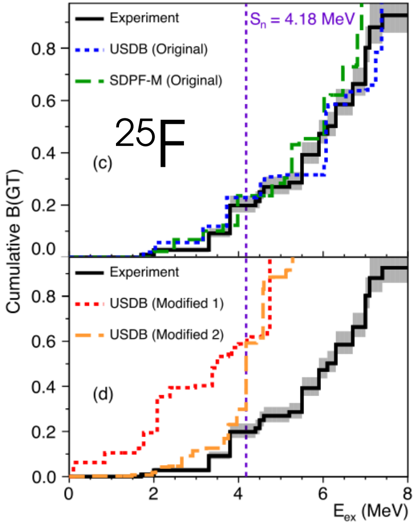
FACILITY FOR RARE ISOTOPE BEAMS

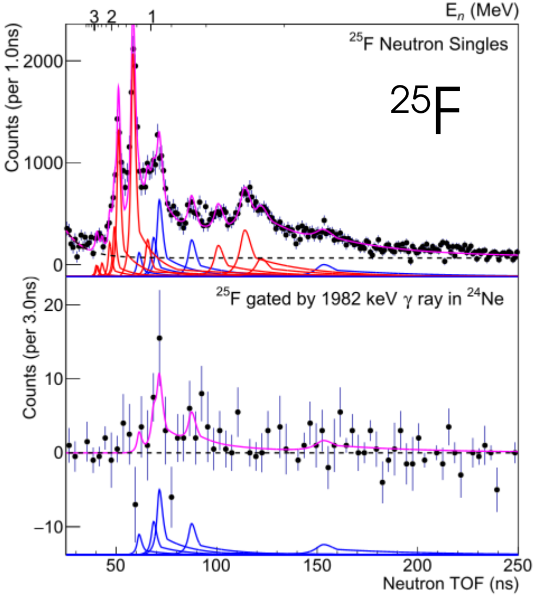






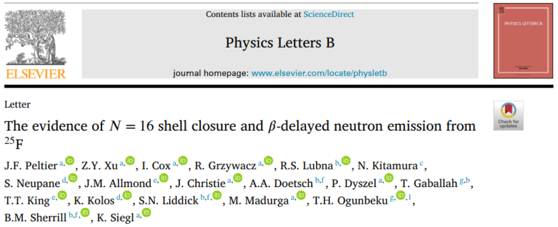






No evidence for disappearance of the N=16 shell closure for ^{24}O, ^{25}F and ^{25}Ne

N=16 shell quenching suggested by:
T. L. Tang, et al.
How Different is the Core of 25F from 24O g.s. ?,
Phys. Rev. Lett. 124 (2020) 212502.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Letter

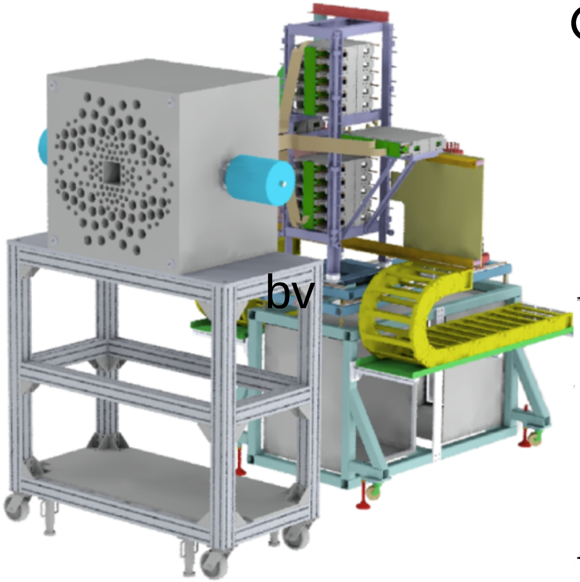
The evidence of $N = 16$ shell closure and β-delayed neutron emission from ^{25}F

J.F. Peltier [a], Z.Y. Xu [a], I. Cox [a], R. Grzywacz [a], R.S. Lubna [b], N. Kitamura [c], S. Neupane [d], J.M. Allmond [c], J. Christie [a], A.A. Doetsch [b,f], P. Dyszel [a], T. Gaballah [g,b], T.T. King [c], K. Kolos [d], S.N. Liddick [b,f], M. Madurga [a], T.H. Ogunbeku [g,1], B.M. Sherrill [b,f], K. Siegl [a]

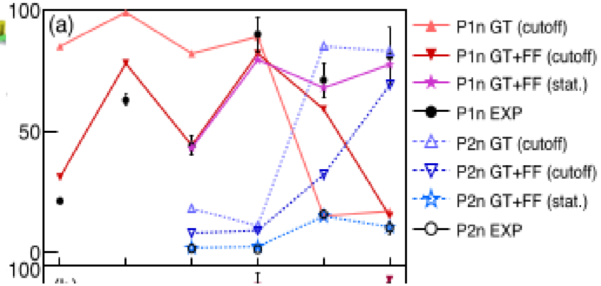
P_{2n}/P_{1n} measurements with neutron counters

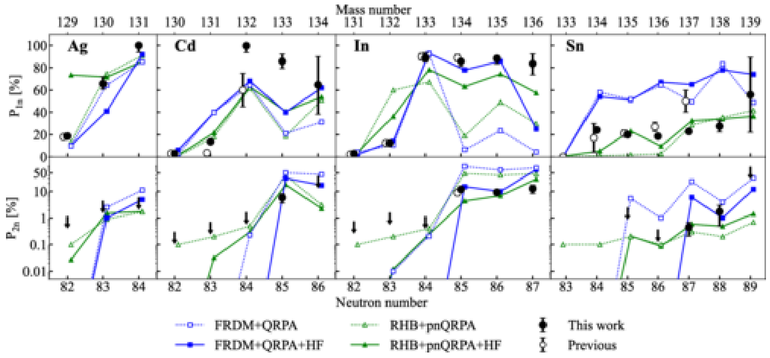
Very efficient multi-neutron detection
Insensitive to gamma-rays
and n-scattering effects.

BRIKEN



$P_{1n}>P_{2n}$





A. Tarifeno-Saldivia et al. J. Instrum. 12 P04006 (2017) ,
A. Tolosa-Delgado et al. NIM A 925, 133(2018),
B. C. Rasco et al. NIM A 911 79 (2018)

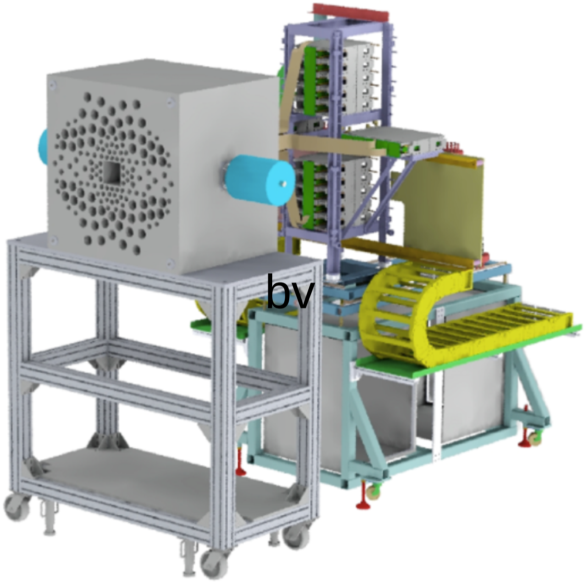
R. Yokoyama et al. Phys. Rev. C 100, 031302(R) (2019).

R. Yokoyama et al. PRC 108, 064307 (2023)

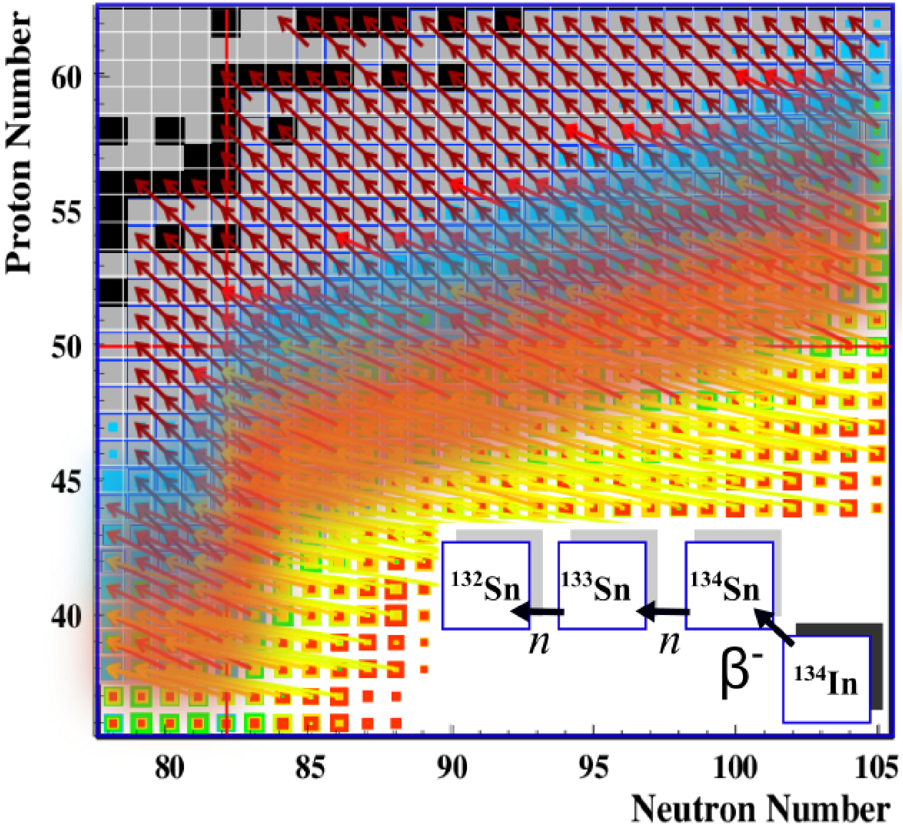
V. H. Phong et al. Phys. Rev. Lett. 129, 172701

P_{2n}/P_{1n} measurements with neutron counters

BRIKEN



$P_{1n} > P_{2n}$



A. Tarifeno-Saldivia et al. J. Instrum. 12 P04006 (2017) ,
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B. C. Rasco et al. NIM A 911 79 (2018)

R. Yokoyama et al. Phys. R

R. Yokoyama et al. PRC 108, 064307 (2023)

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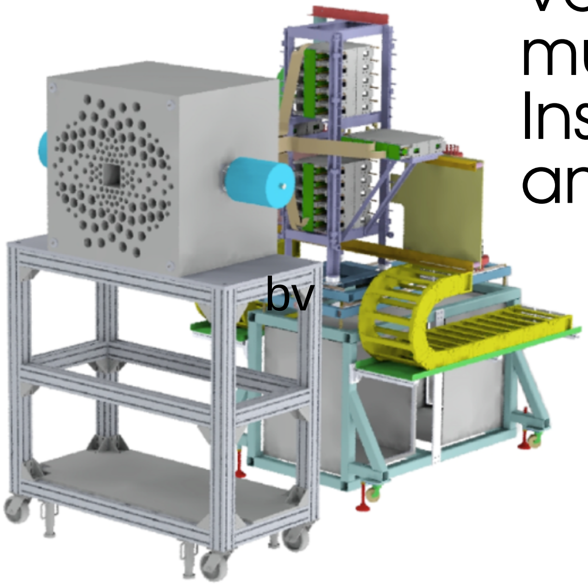
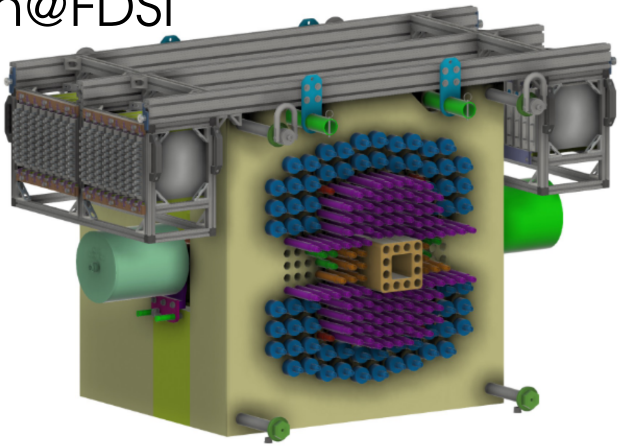
P_{2n}/P_{1n} measurements with neutron counters

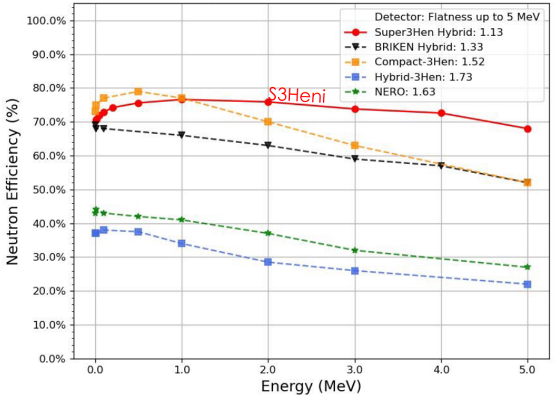
BRIKEN



Very efficient
multi-neutron detection
Insensitive to gamma-rays
and n-scattering effects.

Super-3Hen@FDSi





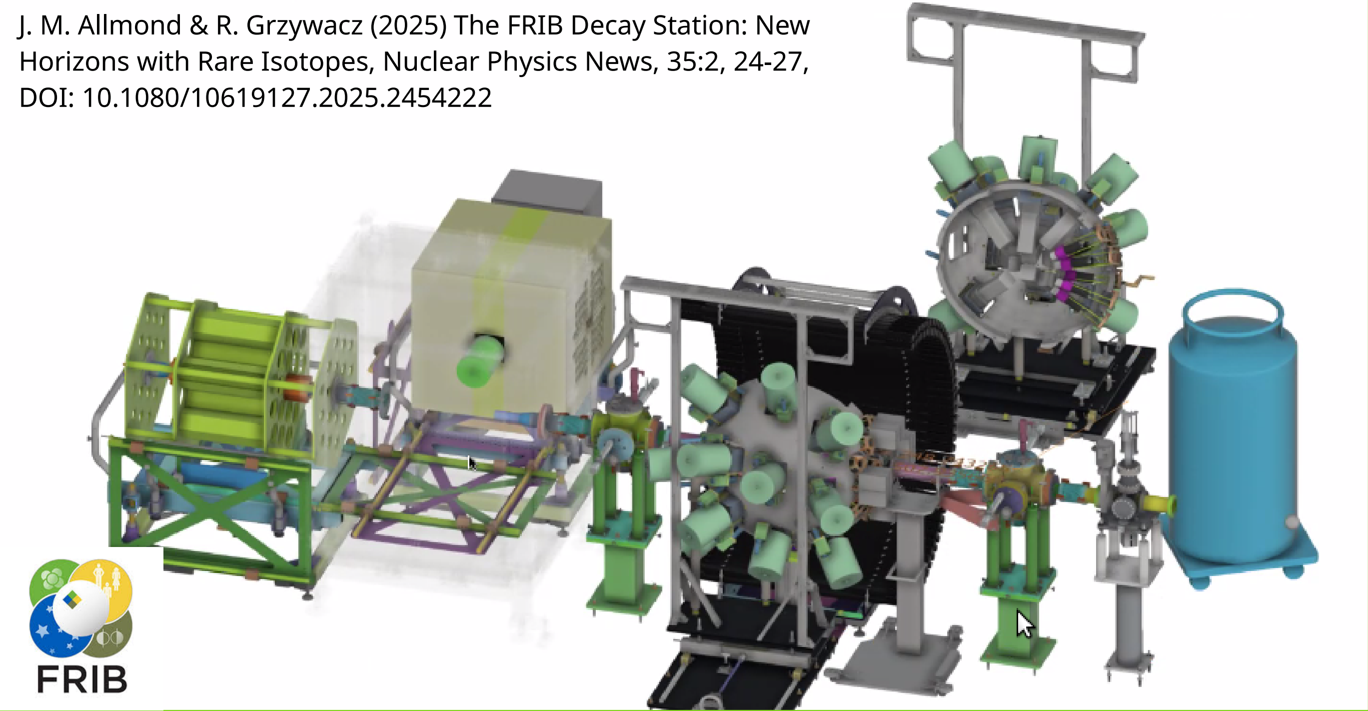
MCNP - James Huffman (MSU)
GEANT4 - Charlie Rasco (ORNL)

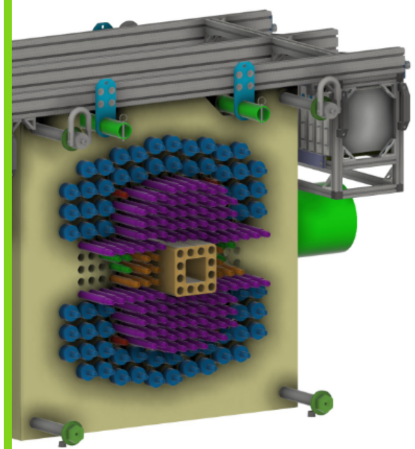
A. Tarifeno-Saldivia et al. J. Instrum. 12 P04006 (2017) ,
A. Tolosa-Delgado et al. NIM A 925, 133(2018),
B. C. Rasco et al. NIM A 911 79 (2018)

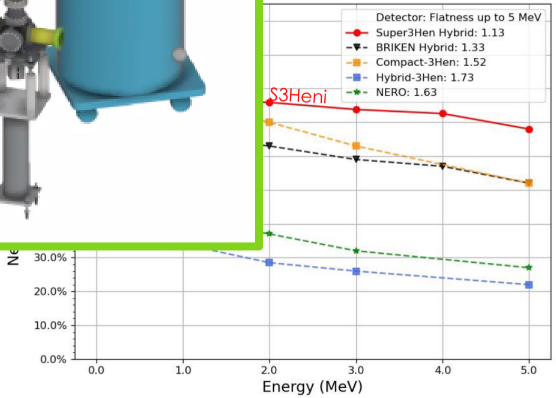
P_{2n}/P_{1n} measurements with neutron counters

BRIKEN

J. M. Allmond & R. Grzywacz (2025) The FRIB Decay Station: New Horizons with Rare Isotopes, Nuclear Physics News, 35:2, 24-27, DOI: 10.1080/10619127.2025.2454222







A. Tarifeno-Saldivia et al. J. Instrum. 12 P04006 (2017) ,
A. Tolosa-Delgado et al. NIM A 925, 133(2018),
B. C. Rasco et al. NIM A 911 79 (2018)

V. H. Phong et al.
Phys. Rev. Lett. 129, 172701

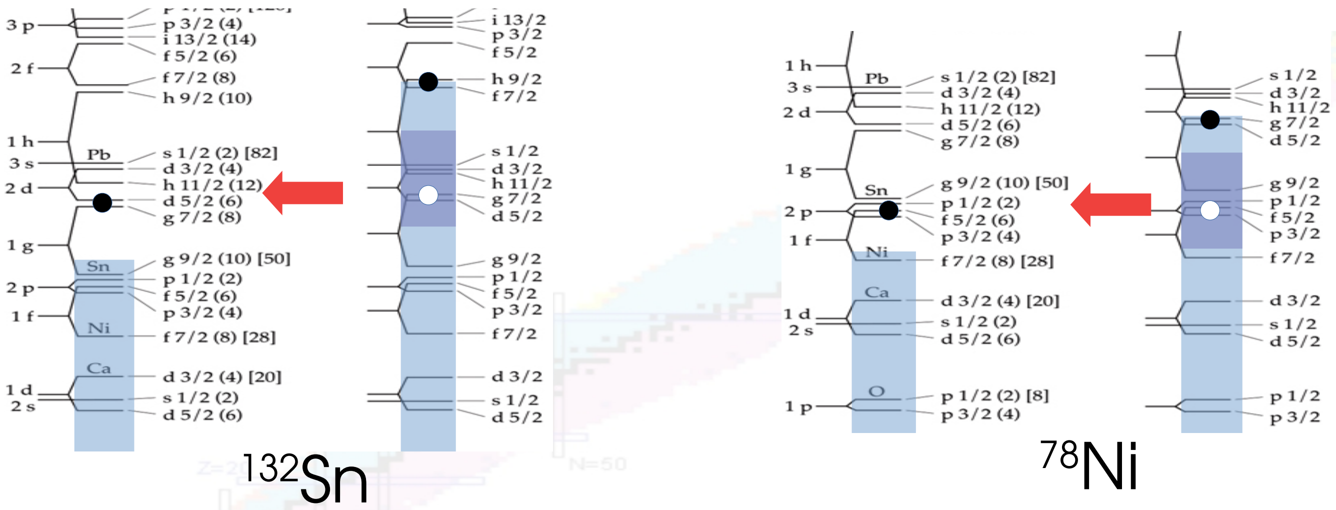
MCNP - James Huffman (MSU)
GEANT4 - Charlie Rasco (ORNL)

Gamow-Teller decays and shell structure far from stability

ν occupied →π empty

Heavy and medium mass nuclei:
Beta decay populates highly-excited,neutron unbound, **particle-hole** states,

GT: spin-orbit partners only

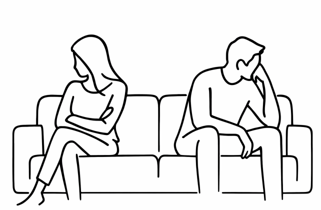


Neutron emitting states are very narrow (“long” lived) due to **small wavefunction overlap** between emitter and daughter

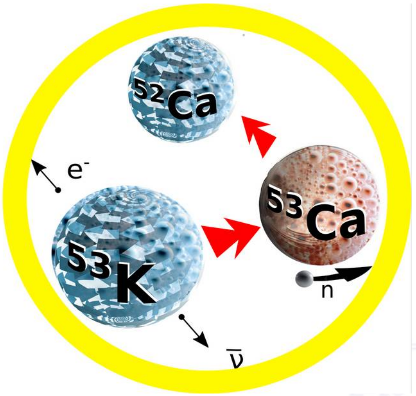
e.g. F.M. Nuh et al. Nuclear Physics A293(1977) 410, M. Piersa et al. Phys. Rev. C 99,(2019) 024304

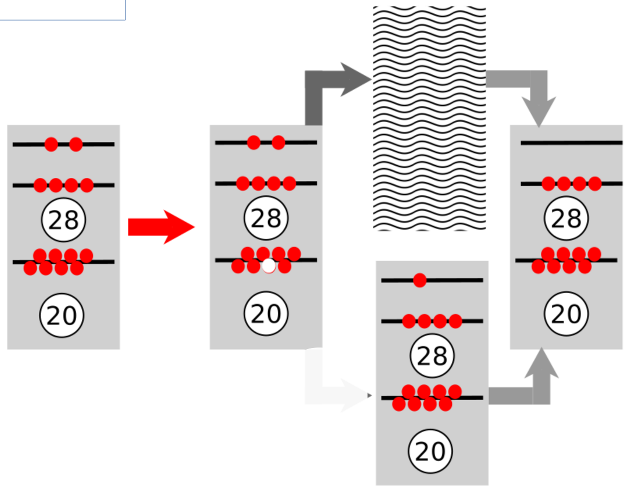
Does neutron emission proceed via intermediate “compound nucleus” stage ?

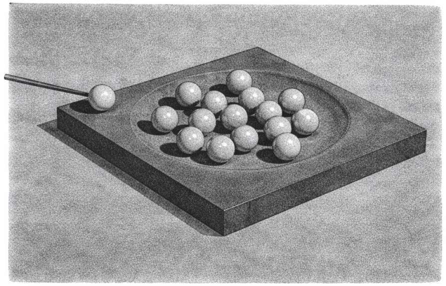
Selective Gamow-Teller transformations populate highly exited states in daughter nucleus.



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





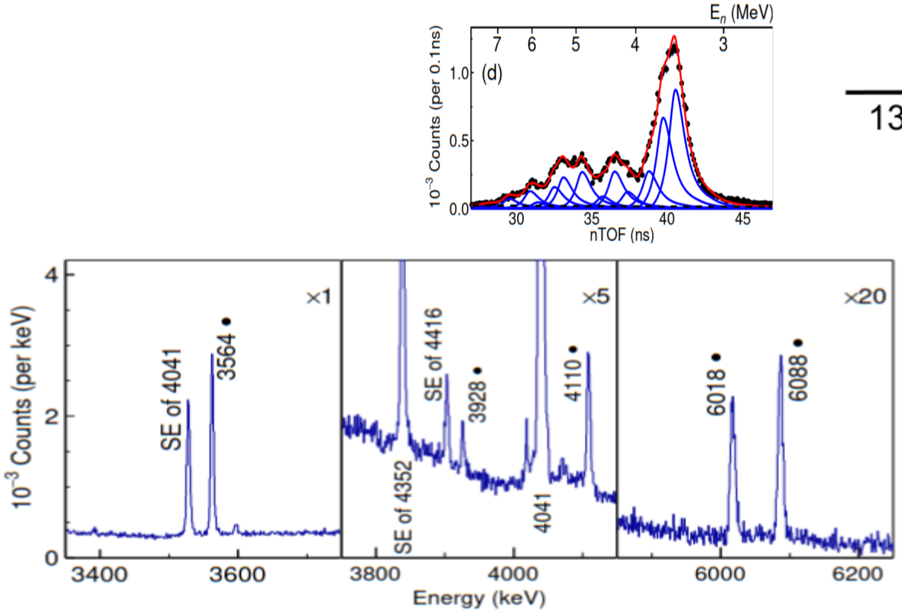


Bohr’s model of a neutron-nucleus collision , Nature 137, 351 (1936).

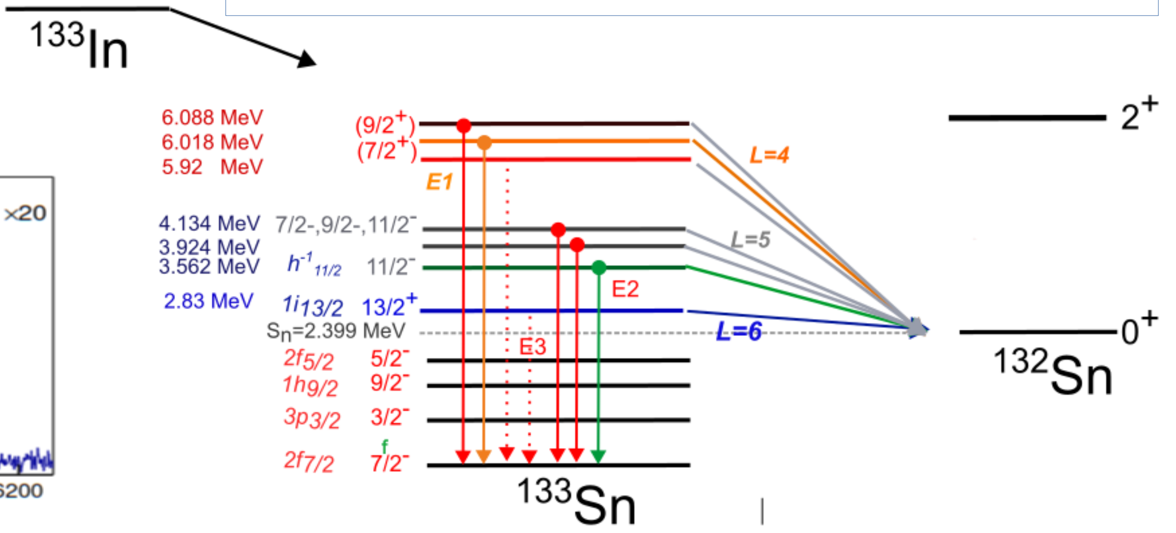
... direct neutron emission, may depend also on details of nuclear structure.

“Evidence of nonstatistical neutron emission following β-decay near doubly magic 132Sn”
J. Heideman et al. (IDS Collaboration) Phys. Rev. C 108, 024311(2023)
Z. Y. Xu et al. Phys. Rev. Lett. 133, 042501 (2024)

γ-ray emission from neutron unbound states



$\Gamma_\gamma \sim \Gamma_n < 1$ keV << 0.1-0.5 MeV

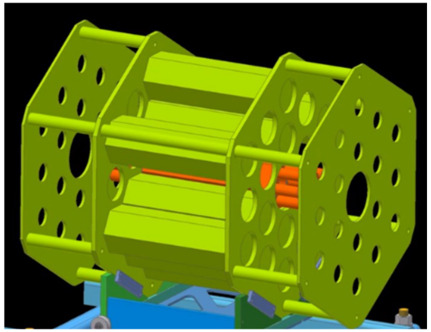


Z. Y. Xu et al. Phys. Rev. Lett. 133, 042501 (2024)

Neutron emitting states are **indeed** very narrow ("long" lived) due to **small wavefunction overlap** between emitter and dughter.

e.g. F.M. Nuh et al. Nuclear Physics A293(1977) 410, M. Piersa et al. Phys. Rev. C 99,(2019) 024304

Neutron and gamma-ray emission near S_n with MTAS



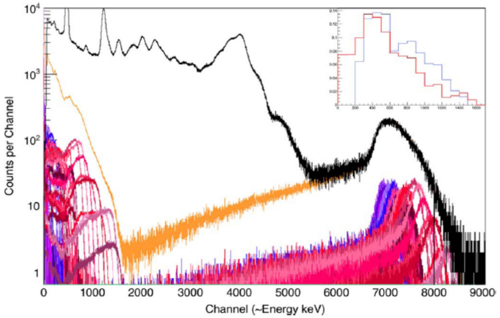
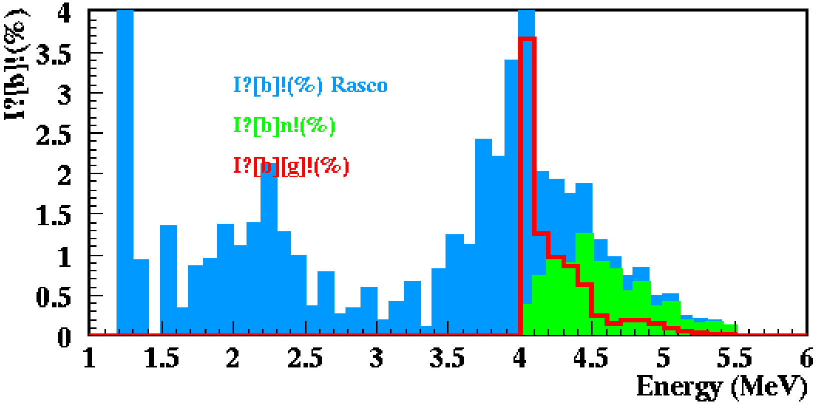
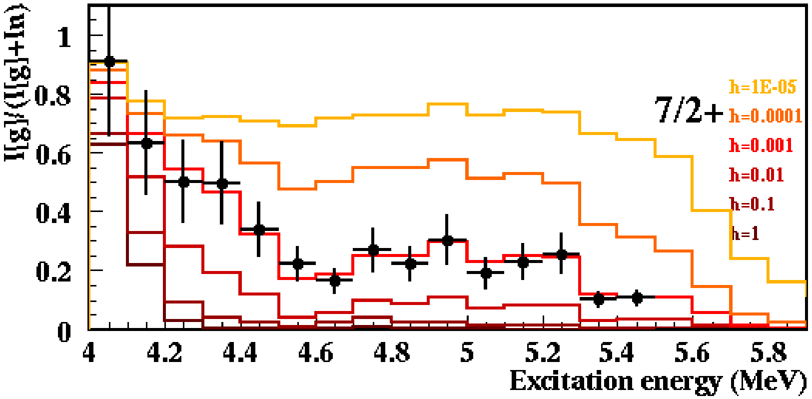


Fig. 12. The MTAS spectrum of ^{137}I decay (black) with the simulated response function of MTAS to the β-delayed neutrons (yellow—all βn neutrons, other colours —mono energetic neutrons). Inset shows the resulting neutron intensity per 100 keV vs. neutron energy (red) in comparison to the literature data based on [20] (blue). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)





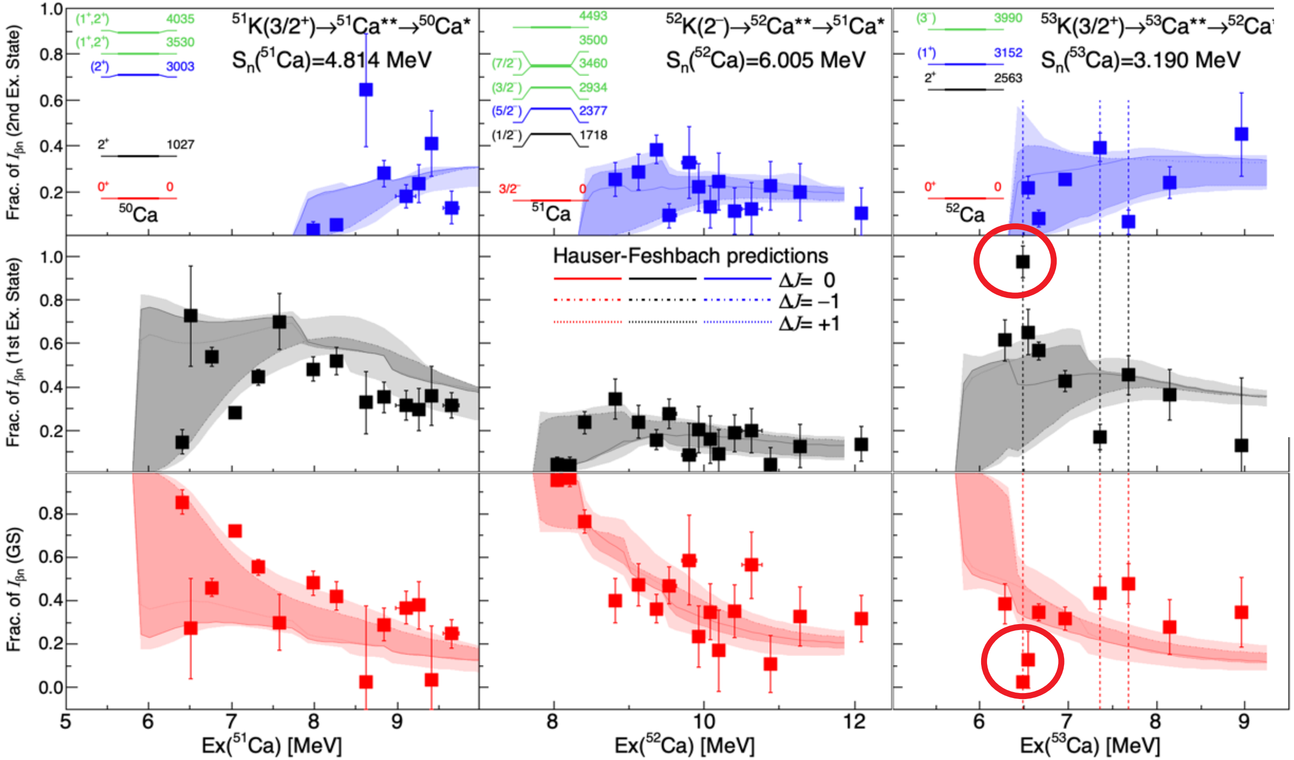
M. Karny et al. NIM A 836, , 83, (2016)
B. Rasco et al. Phys. Rev. C 95, 054328 (2017)

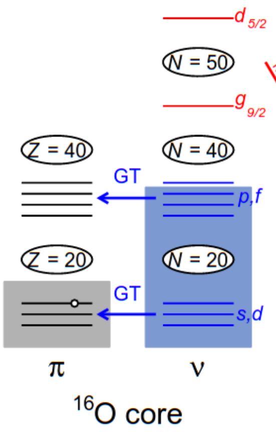
Neutron emission
~1000 hindered
vs.
"natural width"

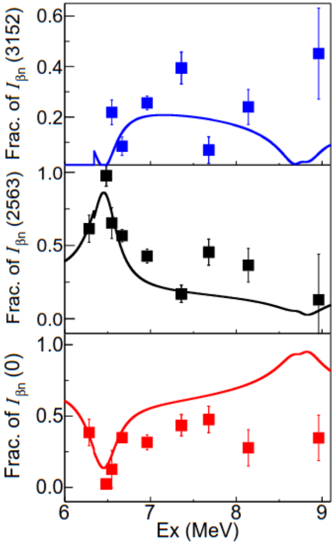
"Slow" emission
due to orbital angular
momentum cannot explain
the data !

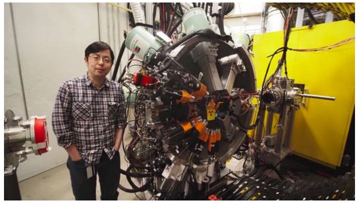
Statistical and doorway state neutron emission $^{51-53}$K

Decay of ^{53}K:
Enhanced population of 2^+ in ^{52}Ca
Reduced population of 0^+(g.s.) in ^{52}Ca





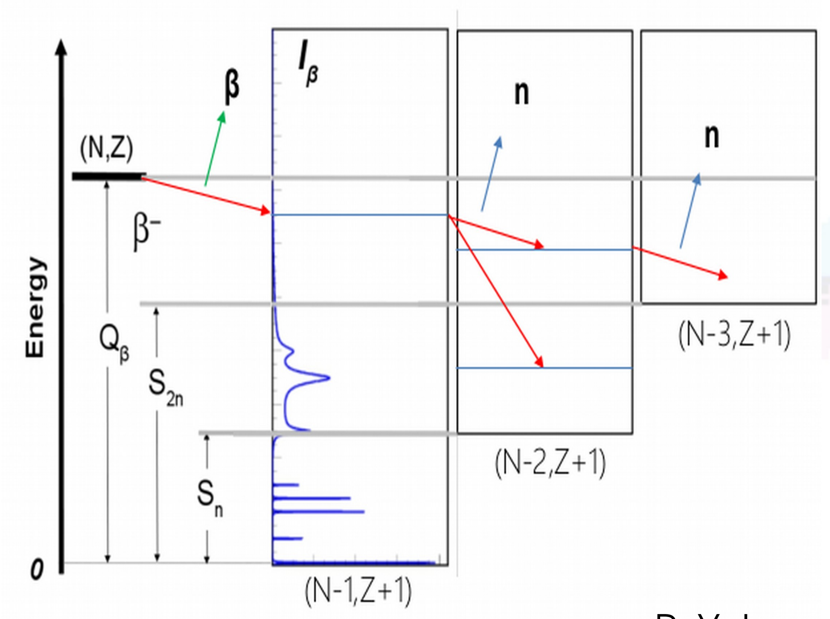


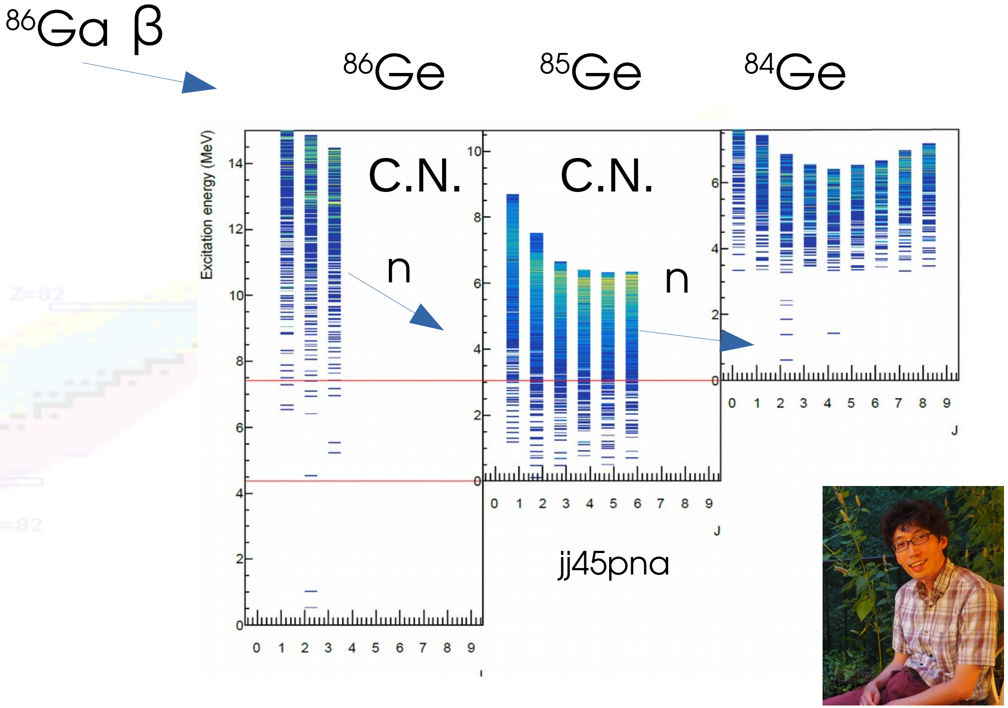


Z. Y. Xu et al. Phys. Rev. Lett. 133, 042501 (2024)

βn-process and multi-neutron emission – need for 2n spectroscopy

What determines relative 1n/2n emission probability?
Intermediate C.N. nuclei ?



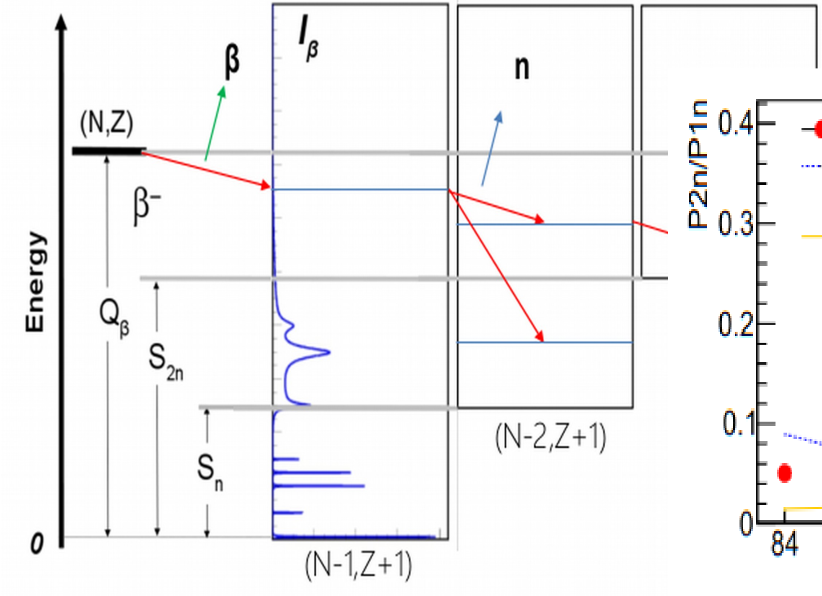


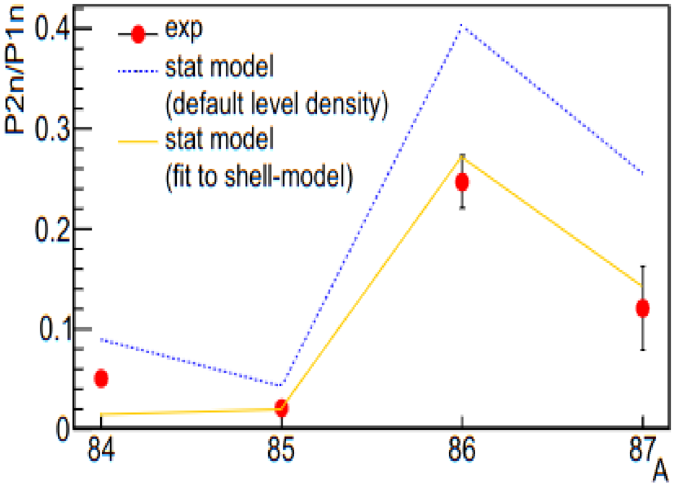
R. Yokoyama et al. Phys. Rev. C 100, 031302(R) (2019).

R. Yokoyama et al. PRC 108, 064307 (2023)

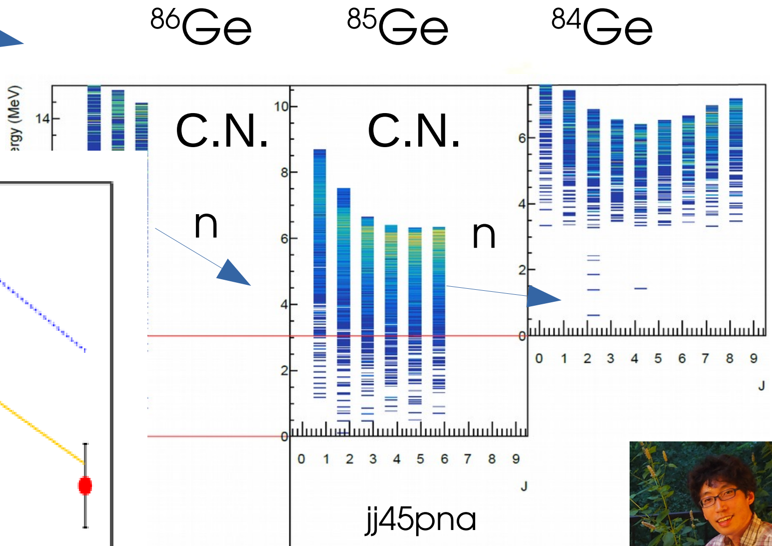
βn-process and multi-neutron emission

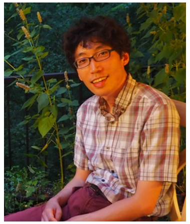
What determines relative 1n/2n emission probability?





^{86}Ga β



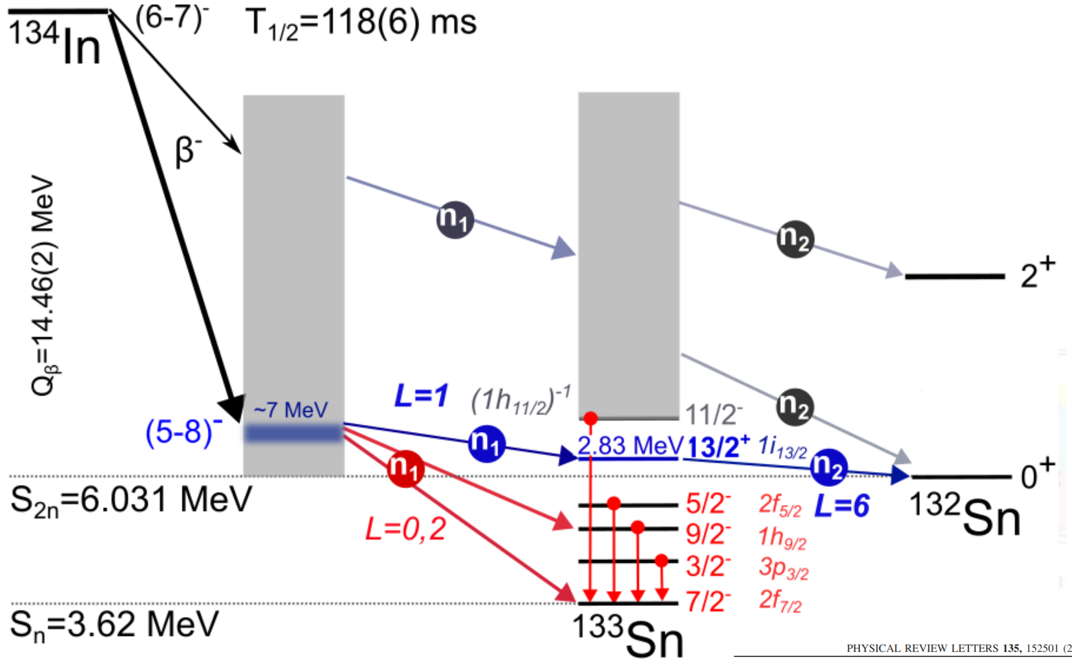


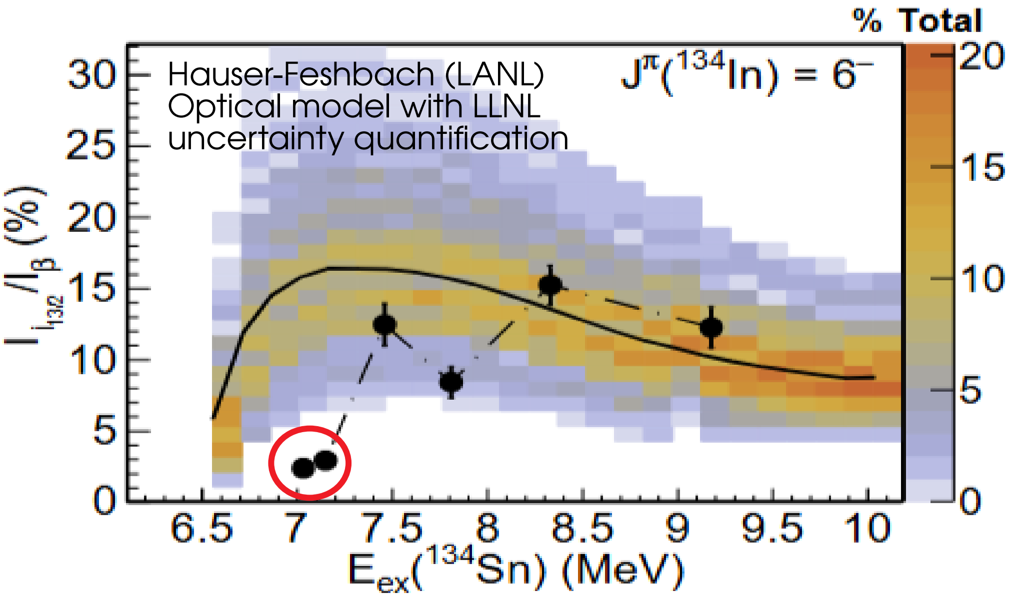
Shell-model level densities

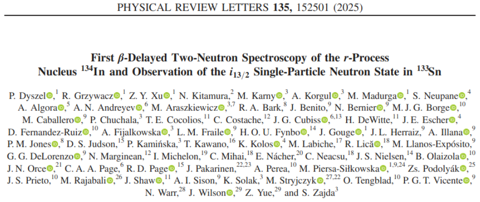
R. Yokoyama et al. Phys. Rev. C 100, 031302(R) (2019).

R. Yokoyama et al. PRC 108, 064307 (2023)

Non-statistical population of 13/2⁺ state



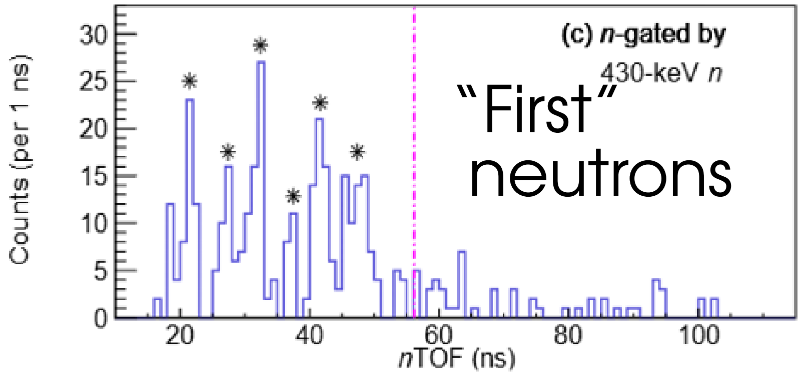




PHYSICAL REVIEW LETTERS **135,** 152501 (2025)

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

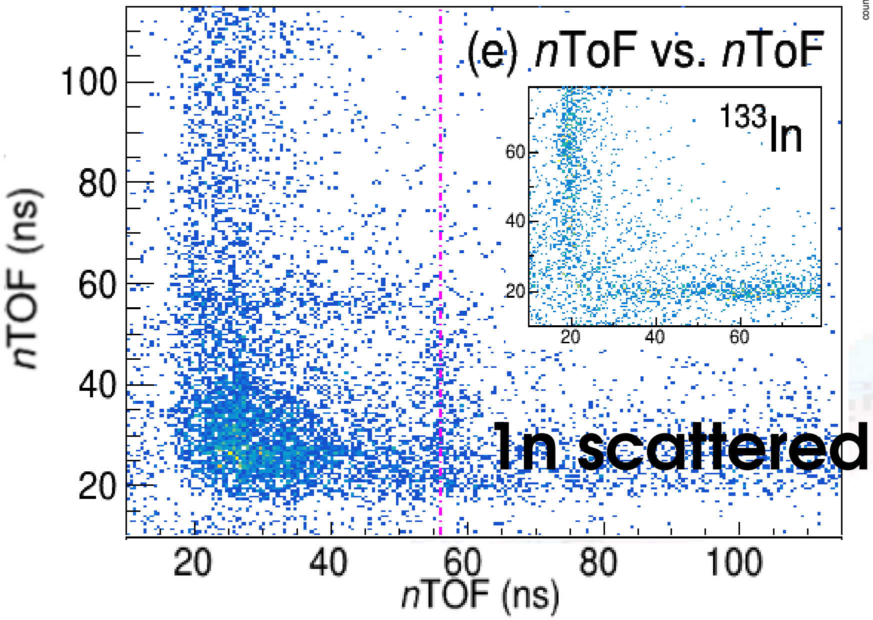
P. Dyszel,[1] R. Grzywacz,[1] Z. Y. Xu,[1] N. Kitamura,[2] M. Karny,[3] A. Korgul,[3] M. Madurga,[1] S. Neupane,[4] A. Algora,[5] A. N. Andreyev,[6] M. Araszkiewicz,[3,7] R. A. Bark,[8] J. Benito,[9] N. Bernier,[9] M. J. G. Borge,[10] M. Caballero,[9] P. Chuchala,[3] T. E. Cocolios,[11] C. Costache,[12] 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,[18] M. Llanos-Expósito,[9] G. G. DeLorenzo,[9] N. Marginean,[12] I. Michelon,[19] C. Mihai,[18] E. Nácher,[20] C. Neacsu,[18] J. S. Nielsen,[14] B. Olaizola,[10] J. N. Orce,[21] C. A. A. Page,[6] R. D. Page,[15] J. Pakarinen,[22,23] A. Perea,[10] M. Piersa-Siłkowska,[1,9,24] Zs. Podolyák,[25] J. S. Prieto,[10] M. Rajabali,[26] J. Shaw,[11] A. I. Sison,[9] K. Solak,[3] M. Stryjczyk,[27,22] O. Tengblad,[10] P. G. T. Vicente,[9] N. Warr,[28] J. Wilson,[29] Z. Yue,[29] and S. Zajda[3]

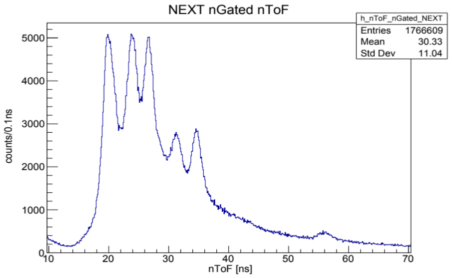


S. Okumura, T. Kawano, P. Jaffke, P. Talou, S. Chiba; *Journal of Nucl. Sci. and Tech.*, **55** 1009-1023 (2018)
A. E. Lovell, T. Kawano, S. Okumura, I. Stetcu, M. R. Mumpower, P. Talou; *Phys. Rev. C.*, **103** 14515 (2021)
C.D. Pruitt, J. E. Escher, R. Rahman; *Phys. Rev. C.*, **107** 14602 (2023)

First 2n energy measurement in β2n

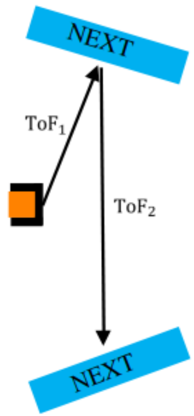
2n
(NEXT/NEXT)

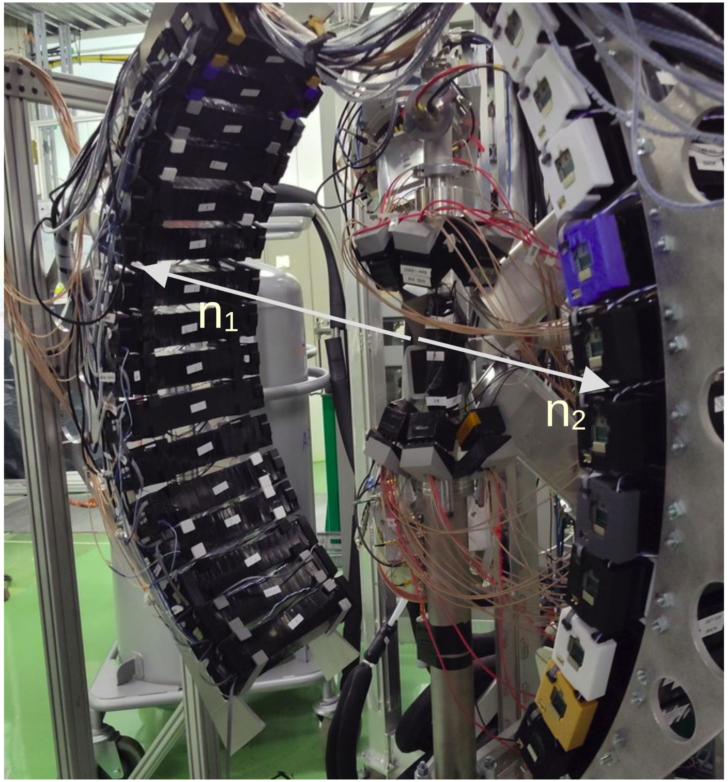




^{133}In (P_{2n}<1.2%)

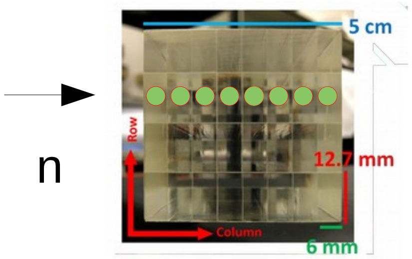
^{134}In (P_{2n}=11.9%)

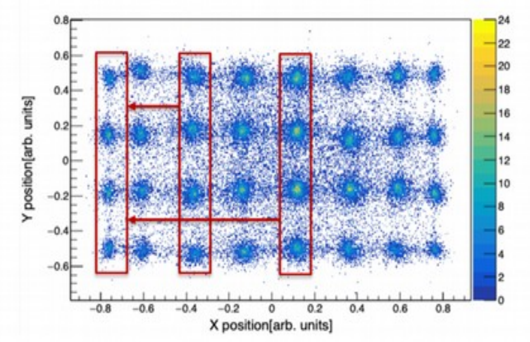


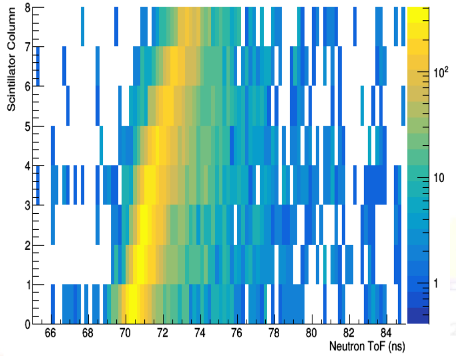


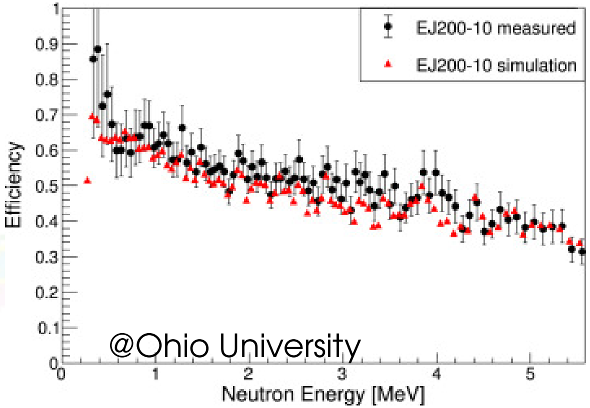
Neutron dEtector with Xn Tracking (NEXT)

Mono-energetic neutrons at the University of Kentucky



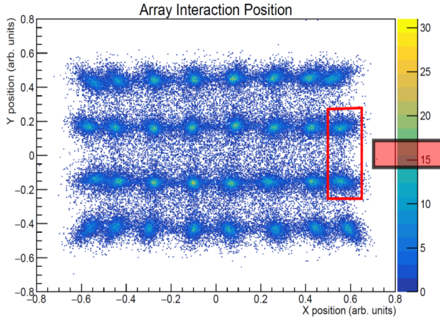


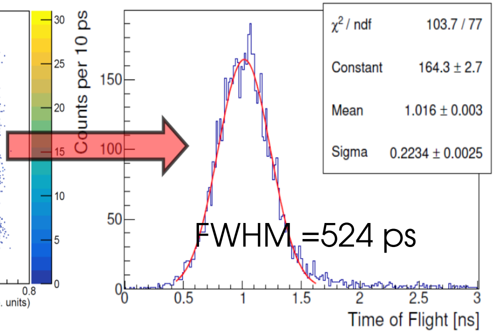


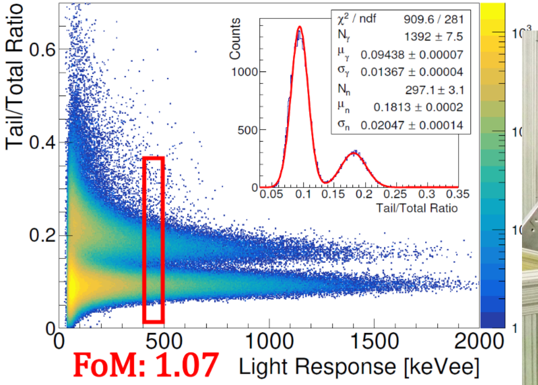


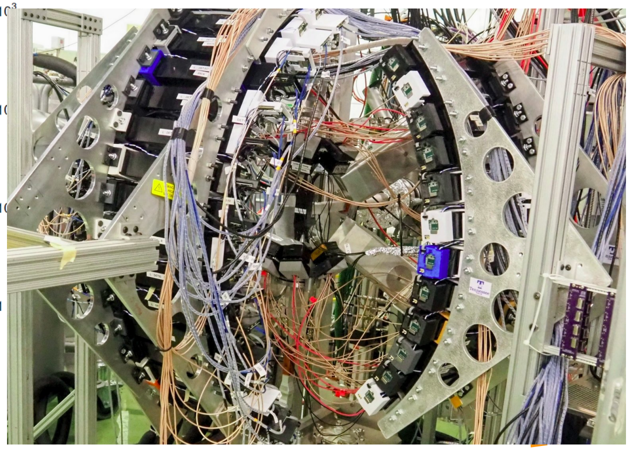
With ^{252}Cf source at UTK

$$FoM = \frac{\bar{\mu}_\gamma - \bar{\mu}_n}{2.35(\sigma_\gamma + \sigma_n)}$$





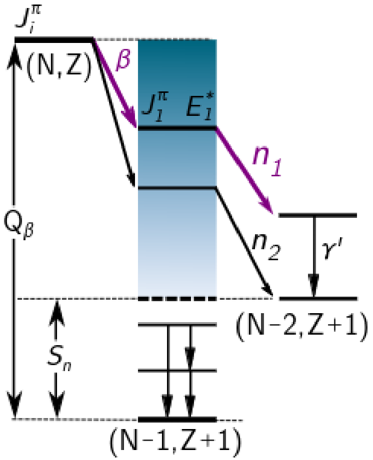


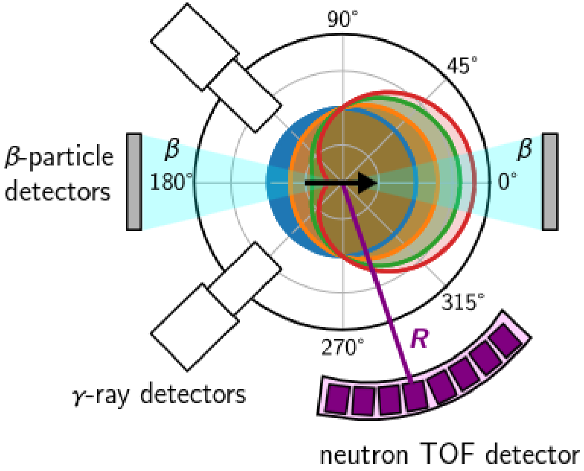


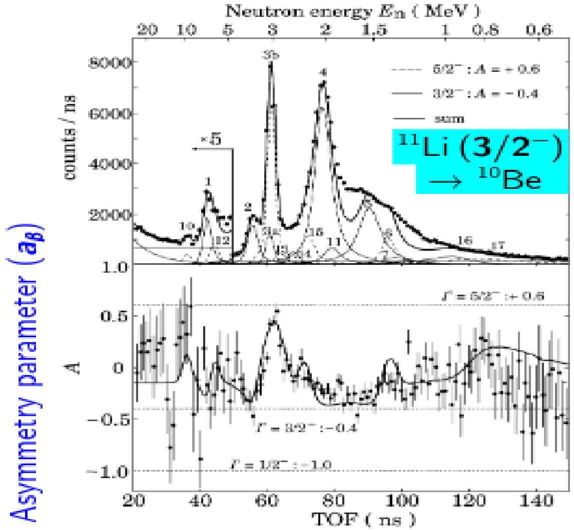
J. Heideman et al. NIM A 946 (2019), 162528
S. Neupane NIM A 1020, 21 (2021), 165881

Anisotropic β-decay of spin-polarized nuclei (Osaka method)

Spin-parity assignments
from β-decay asymmetry



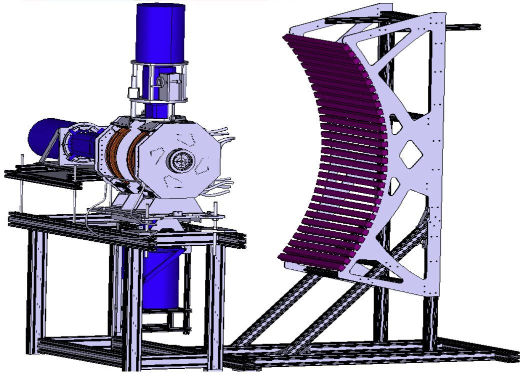




Hirayama et al., PLB 611, 239 (2005).

DeVITO
(ISOLDE)

Monika Piersa-Silkowska (CERN)



Angular distribution of β particles:

$W(\theta) \sim 1 + \mathbf{a}_\beta \mathbf{P} \cos\theta$ (allowed β transitions)

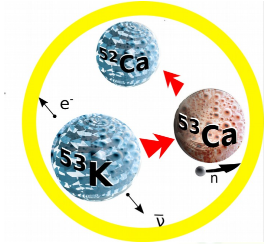
Asymmetry parameter $\mathbf{a}_\beta$ depends on the spins

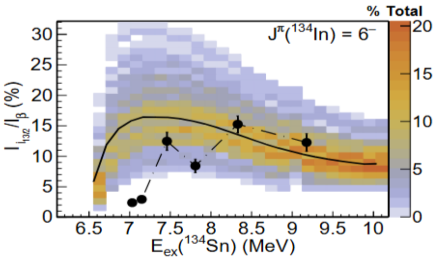
$$\mathbf{a}_\beta = \begin{cases} -1 & (I_f = I_i - 1) \\ \dfrac{-1/(I_i+1) - 2\tau\sqrt{I_i/(I_i+1)}}{1+\tau^2} & (I_f = I_i) \\ \dfrac{I_i}{I_i+1} & (I_f = I_i + 1) \end{cases}$$

τ – mixing ratio of the Fermi and GT transitions

Expanding the scope: β-decay → neutron emission

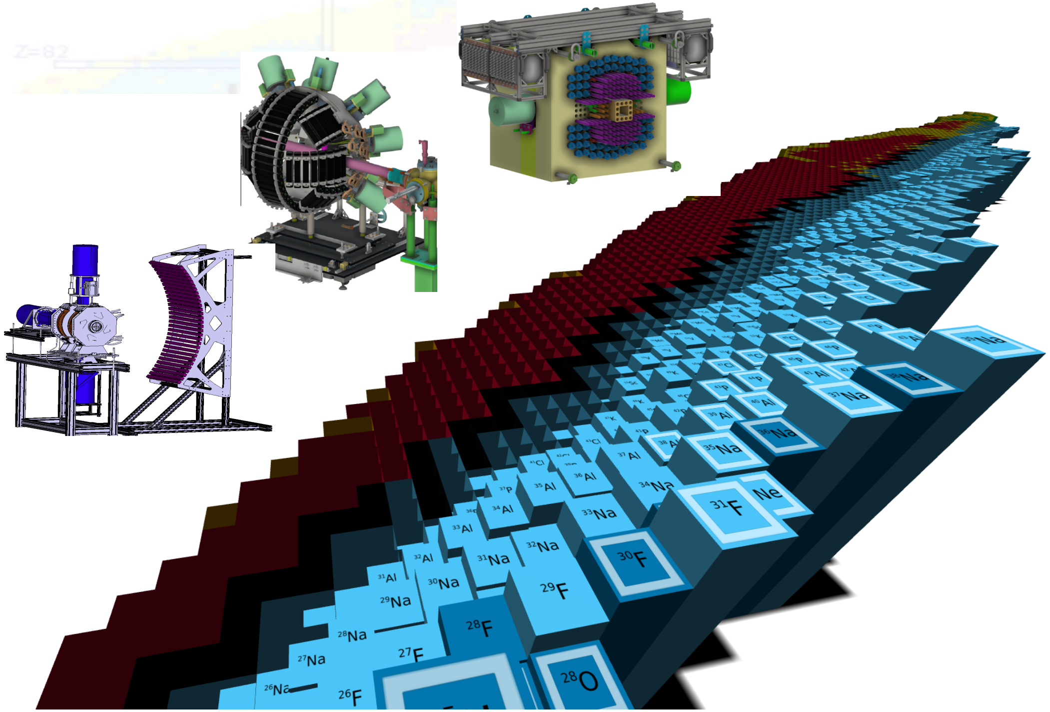
Neutron emission **strongly hindered** (10^3-10^6) → statistical emission.
The mechanism of forming C.N. after β-decay not understood.
Strong departures from C.N.-decay observed (^{53}K, ^{44}S, ^{134}In).





Theory collaborations:
T. Kawano (LANL), J. Esher (LLNL) – statistical model
J. Okolowicz (IFJ), M. Ploszajczak (GANIL) - Gamow-SM, continuum coupling
A. Ravlic, Y. Saito, W. Nazarewicz (FRIB) – QRPA, structure

- Explore neutron-gamma competition
  - Total absorption spectroscopy
  - High-resolution neutron and gamma detection
- Measure widths directly (lighter nuclei)
  - Direct measurements possible >10 keV with TOF
- Barely explored β2n
  - Data for astrophysics from neutron counters
  - First β2n emission study with TOF (^{134}In)
- Orientation studies
  - Spin assignments for beta decay
  - Confirm L-values for neutron emission
- Detector development
  - IDS and FDSi workhorse TOF detectors
  - Improvement of resolution and efficiency with NEXT
  - New-generation NEXT for FDS



Thank you !

PHYSICAL REVIEW LETTERS **135**, 152501 (2025)

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

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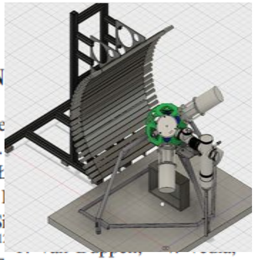
PHYSICAL REVIEW LETTERS **131**, 022501 (2023)

^{133}In: A Rosetta Stone for Decays of *r*-Process N…

Z. Y. Xu,[1] M. Madurga,[1] R. Grzywacz,[1,2] T. T. King,[1,2] A. Algora,[3,4] A. N. Andreye… M. J. G. Borge,[11] C. Costache,[12] H. De Witte,[13] A. Fijalkowska,[14,15] L. M. Fraile,[7] H.… C. Halverson,[1] L. J. Harkness-Brennan,[18] J. Heideman,[1] M. Huyse,[13] A. Illana,[13,19] … A. Korgul,[15] T. Kurtukian-Nieto,[21] I. Lazarus,[22] R. Lică,[23,12] R. Lozeva,[24] N. Marginean,[12] … C. Mihai,[12] R. E. Mihai,[12] A. I. Morales,[3] R. D. Page,[18] J. Pakarinen,[19,25] M. Piersa-Si… P. Sarriguren,[11] M. Singh,[1] Ch. Sotty,[12] M. Stepaniuk,[15] O. Tengblad,[11] A. Turturica,… S. Viñals,[11] N. Warr,[26] R. Yokoyama,[1] and C. X. Yuan[27]



PHYSICAL REVIEW LETTERS **132**, 152503 (2024)

Proton Shell Gaps in $N = 28$ Nuclei from the First Complete Spectroscopy Study with FRIB Decay Station Initiator

I. Cox,[1] Z. Y. Xu,[1] R. Grzywacz,[1,2] W.-J. Ong,[3] B. C. Rasco,[2] N. Kitamura,[1] D. Hoskins,[1] S. Neupane,[1,3] T. J. Ruland,[2,4] J. M. Allmond,[2] T. T. King,[2] R. S. Lubna,[5] K. P. Rykaczewski,[2] H. Schatz,[5,6] B. M. Sherrill,[5,6] O. B. Tarasov,[5] A. D. Ayangeakaa,[7,8] H. C. Berg,[5,6] D. L. Bleuel,[3] G. Cerizza,[5] J. Christie,[1] A. Chester,[5] J. Davis,[9] C. Dembski,[5,6] A. A. Doetsch,[5,6] J. G. Duarte,[3] A. Estrade,[10] A. Fijałkowska,[11] T. J. Gray,[2] E. C. Good,[5] K. Haak,[6] S. Hanai,[12] J. T. Harke,[3] C. Harris,[6] K. Hermansen,[5,6] D. E. M. Hoff,[3] R. Jain,[5,6] M. Karny,[11] K. Kolos,[3] A. Laminack,[2] S. N. Liddick,[5,13] B. Longfellow,[3] S. Lyons,[9] M. Madurga,[1] M. J. Mogannam,[13,5] A. Nowicki,[1] T. H. Ogunbeku,[3] G. Owens-Fryar,[5,6] M. M. Rajabali,[14] A. L. Richard,[3] E. K. Ronning,[13,5] G. E. Rose,[15] K. Siegl,[1] M. Singh,[1,16] A. Spyrou,[5,6] A. Sweet,[3] A. Tsantiri,[6,5] W. B. Walters,[17] and R. Yokoyama[12]

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Compound-Nucleus and Doorway-State Decays of β-Delayed Neutron Emitters ^{51,52,53}K

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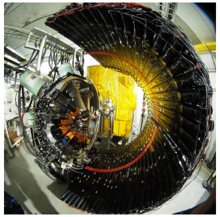
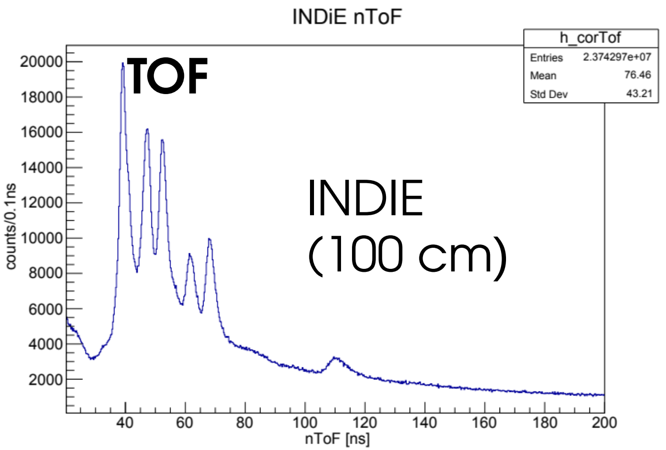
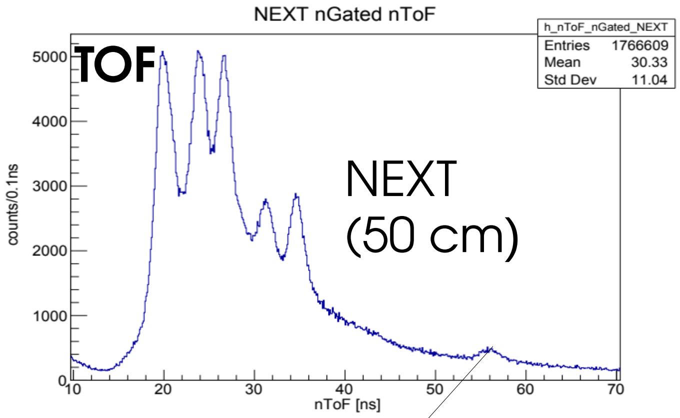
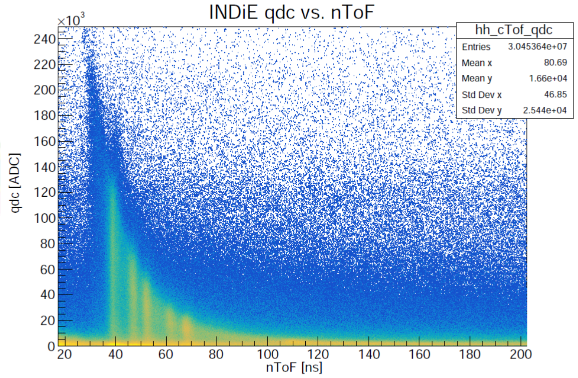
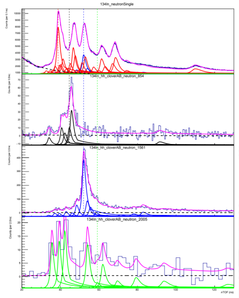


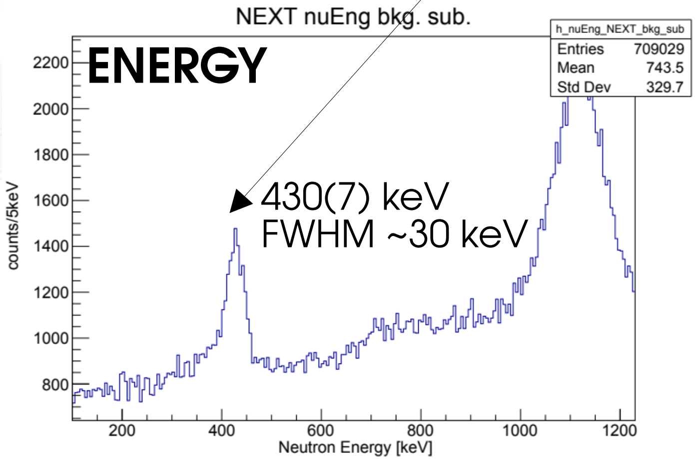
The 430 keV neutron transition

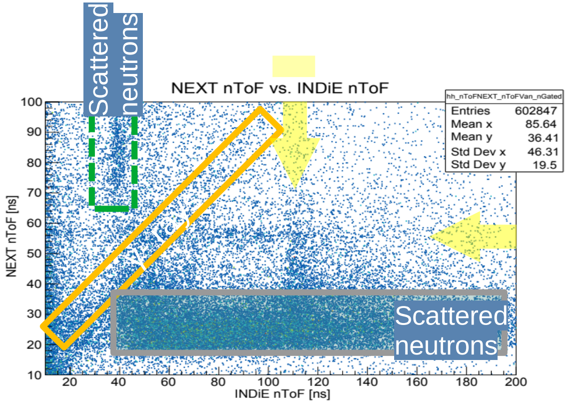












Energy calibration
From ^{133}In (Xu et al.)
With γ-rays and ^{17}N decay