The Reactor Antineutrino Anomaly and Pygmy Dipole Resonance in ^{92}Sr

A Comprehensive Spectroscopy Study with the GRIFFIN Spectrometer

or the β^-decay of ^{92}Rb into ^{92}Sr

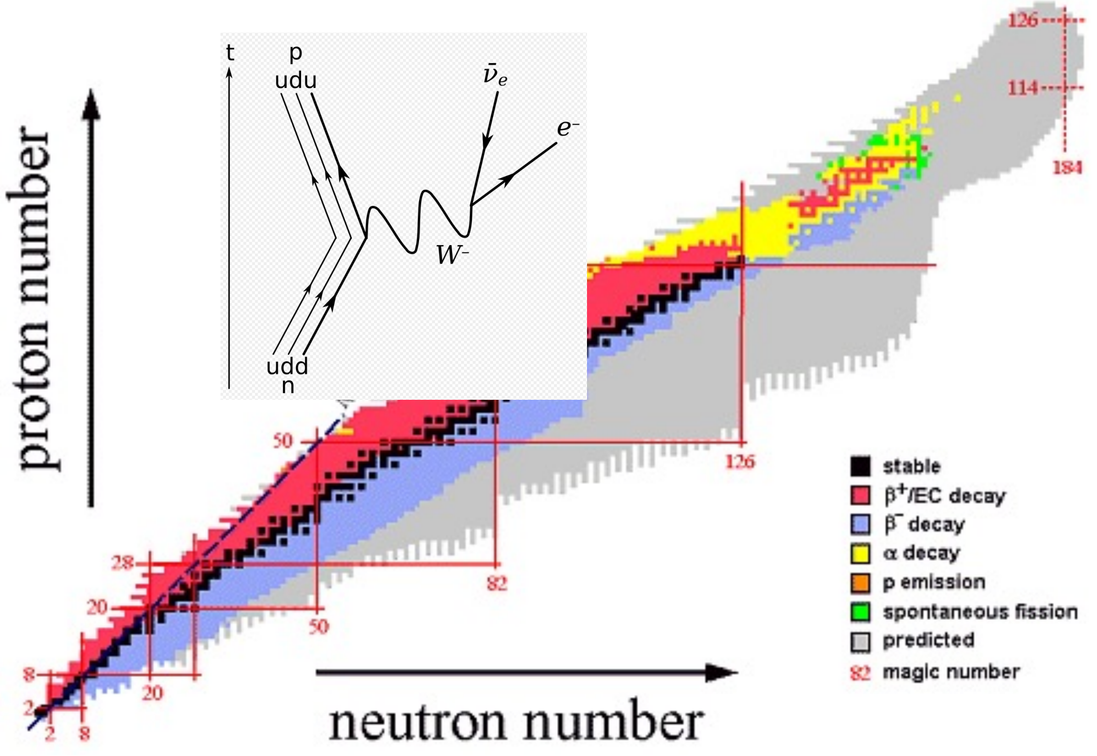
Corina Andreoiu
analysis by Pietro Spagnoletti
Simon Fraser University
SSNET 2025, Paris, November 2024

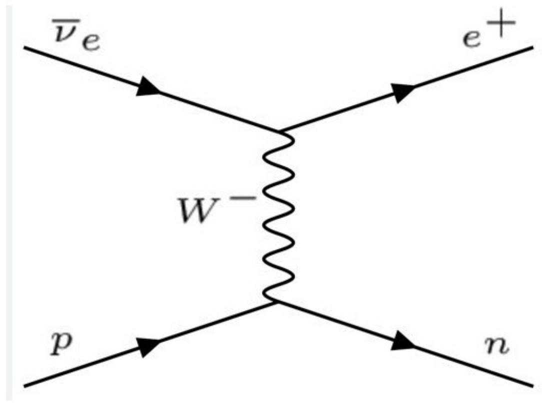
SFU

GRIFFIN

β decay

- Nuclear beta decay plays important roles in many aspects in nuclear physics, including the beta spectrum and anti-neutrino spectrum, the reactor anti-neutrino anomaly (RAA), the calculations of residual power or post-irradiation fuel management
- Two kinds of transitions are involved in nuclear decay: allowed and forbidden; **forbidden decays could influence the shape of the antineutrino spectra**
- Early studies of beta decaying nuclei suffered from the Pademonium effect, specially above 4.5 MeV





Gamma-ray- vs Total Absorption Spectroscopy

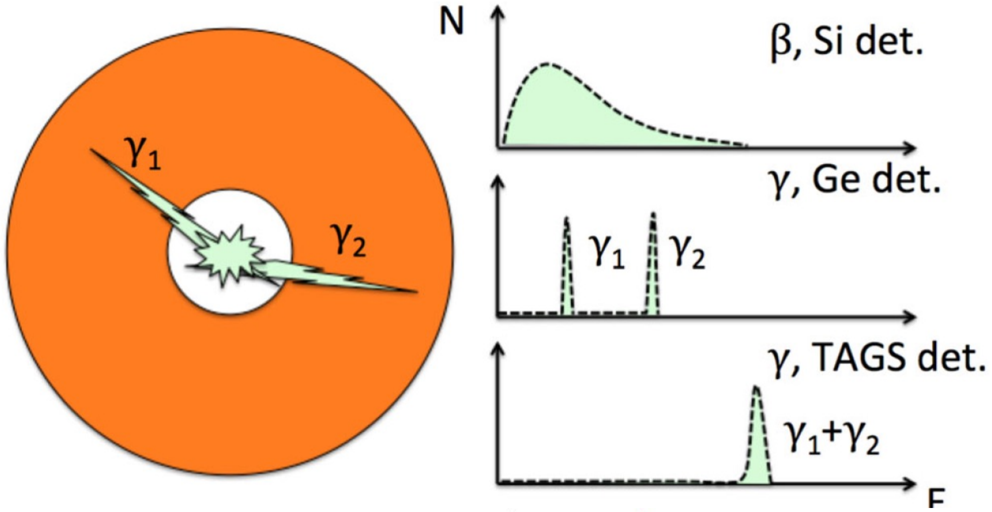
- Two different approaches are used to study fission products and beta decaying nuclear properties.

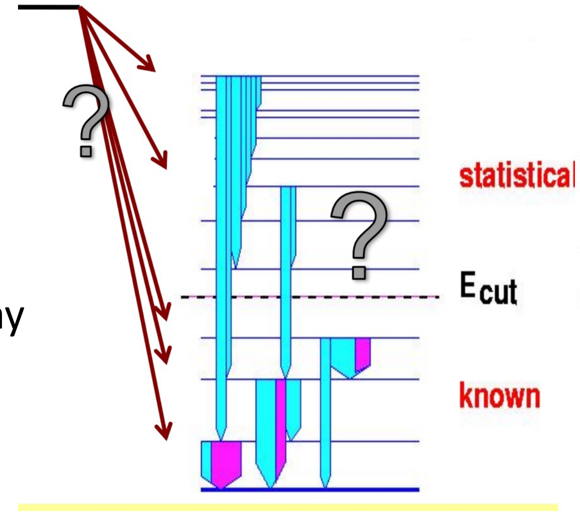
- One is based on discrete γ-ray spectroscopy with a limited number of high-resolution Ge counters. These studies had reduced efficiency for high-energy gamma ray, and suffer from absence of coincidence data.

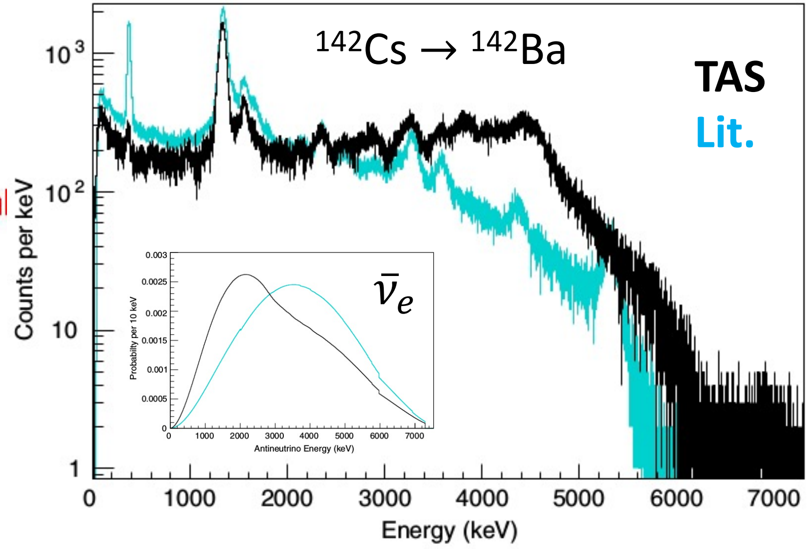
- The other is associated with a calorimetric technique utilizing low-resolution NaI detectors, known as Total Absorption Spectrometry (TAS). Poor energy resolution and lack of detailed knowledge of the level schemes. TAS data analysis results in large uncertainties deduced beta feeding distribution due to data manipulation (folding).

Total Absorption Spectroscopy

- Utilizes large volume scintillator detectors.
  - Calorimeter.
- Exploits high detection efficiency.
  - Free from *pandemonium*.
- Poor energy resolution.
  - Limited sensitivity to individual states.
- Analysis
  - Monte-Carlo simulations.
  - Level scheme split into two regions
  - Low energy with discrete states
    - Uses known branching ratios.
  - High energy bins
    - Statistical model for level densities, gamma-ray BR.
    - Gamma-ray multiplicity dependence.





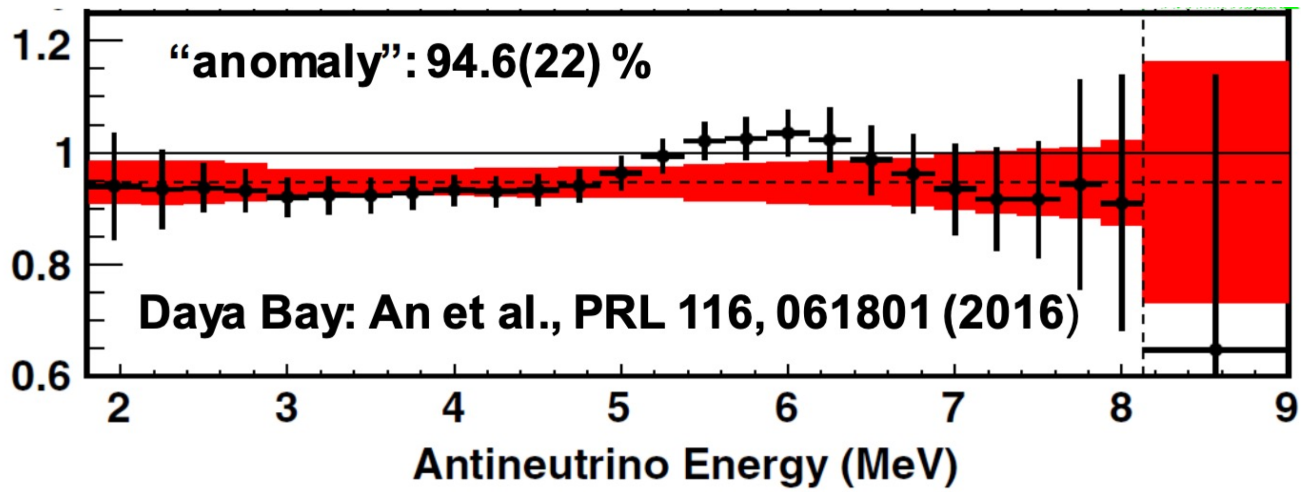


Rasco et al., PRL 117, 092501 (2016)

^{92}Rb – special nucleus

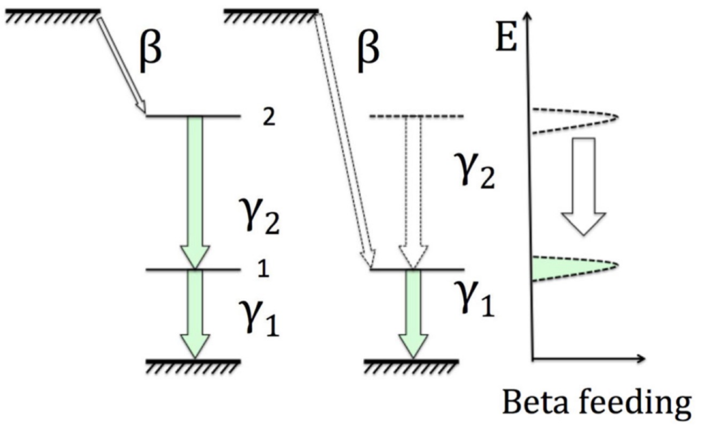
- ^{92}Rb is a major fission product with significant implications for **antineutrino production**, **spectrum distortion**, and the **reactor antineutrino anomaly**. Its role in high-energy antineutrino emissions and the "5 MeV bump" makes it a nucleus of interest in both nuclear physics and particle physics research.
- Rb-92, Y-96m, Cs-142 are the three β decays that contribute 43% of the antineutrino flux near 5.5 MeV emitted by nuclear reactors.

Surplus of detected antineutrinos in the energy range of **5 to 7 MeV** compared to theoretical predictions.

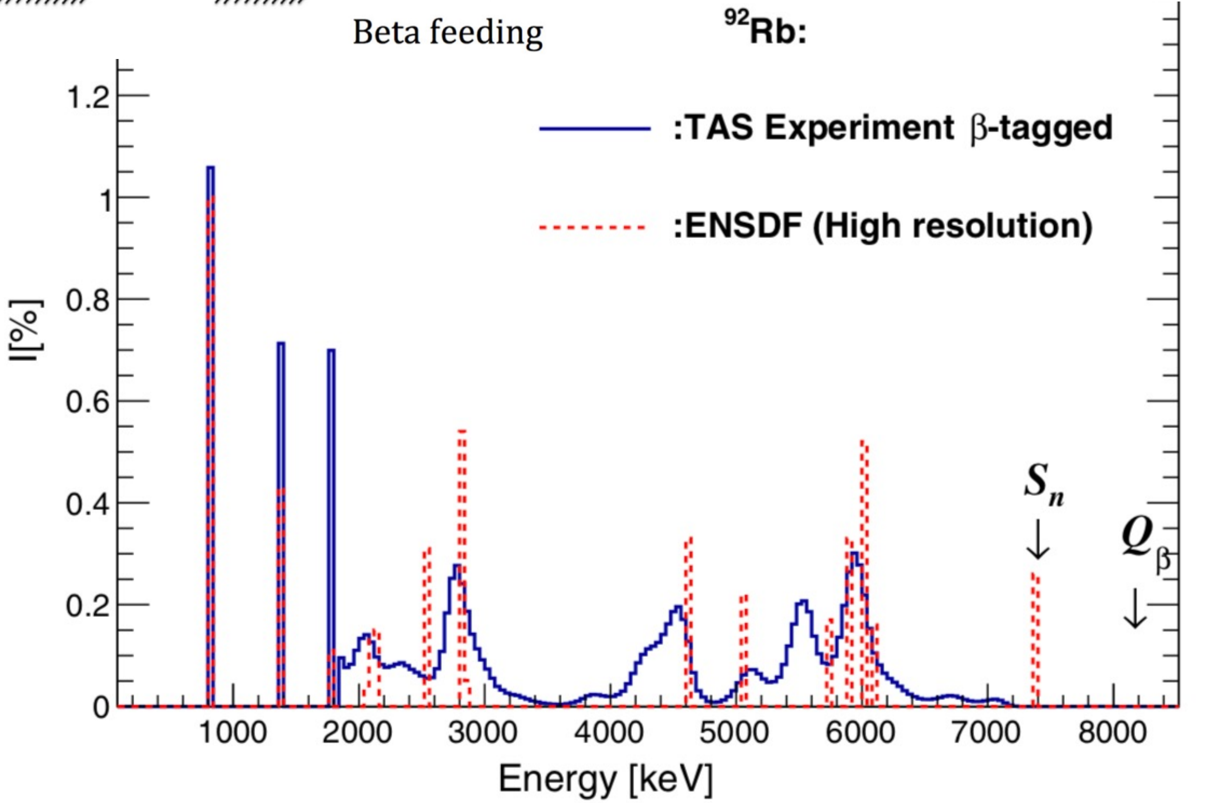


β^- data ^{92}Rb → ^{92}Sr

- ^{92}Rb (Z=37; N=55)
  - Q_β = 8095 keV
  - $J^\pi = 0^-$
- Dominant contributor of high-energy $\overline{\nu_e}$ flux
- ENSDF data from late 1970s.
  - High-Resolution Spectroscopy (HRS)
  - Using a few low-eff Ge(Li) detectors.
- Two new TAS studies
  - Zakari-Issoufou *et al.* (2015)
  - Rasco *et al.* (2016)
- Significant disagreement in β feeding
  - HRS: Pandemonium!
  - TAS: No fine structure information!
- Why is there large β feeding to high-energy levels?
  - B(GT) strength
  - $0^- \to 1^-$



A.-A. Zakari-Issoufou et al, Phys. Rev. Lett. 115, 102503 (2015)



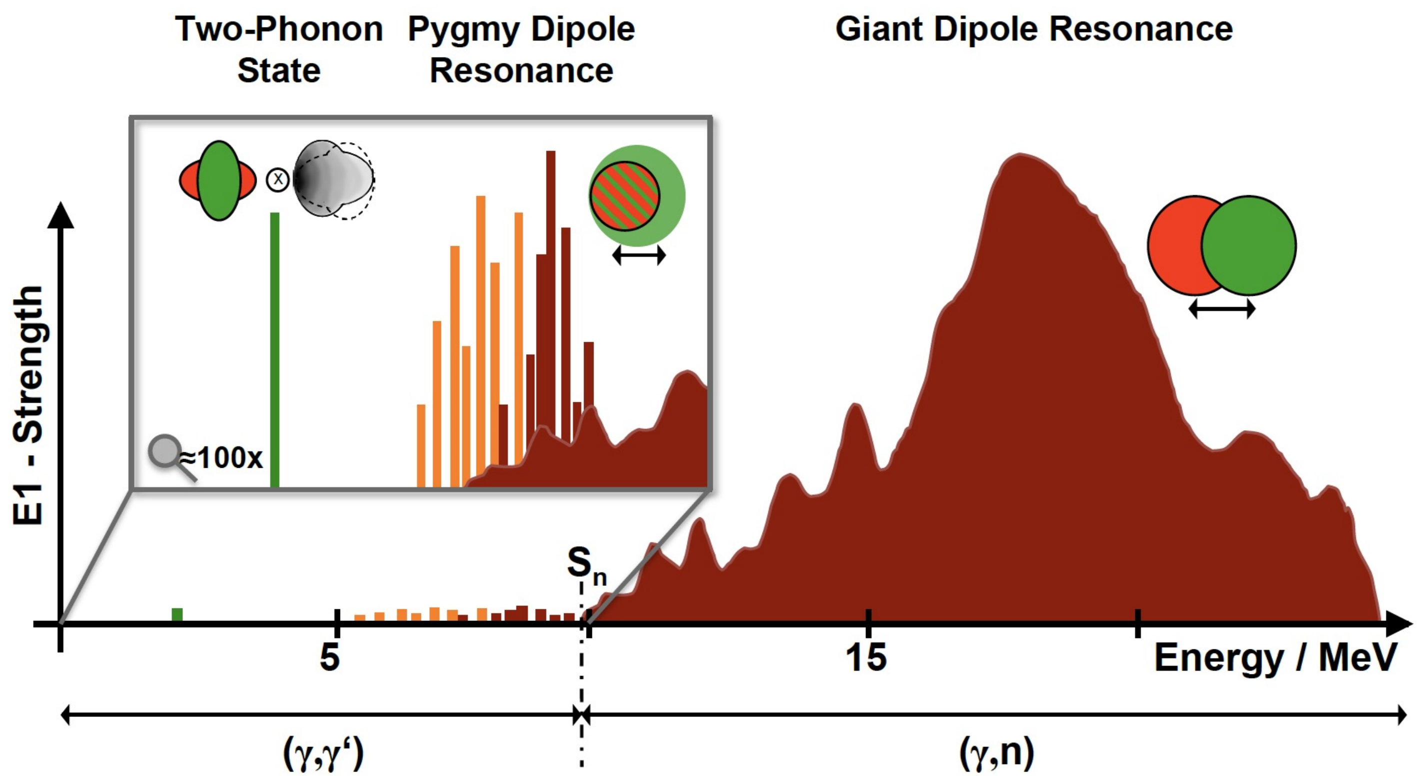
Pygmy Dipole Resonance

- Resonance-like structure of 1^- levels situated low energy tail of the GDR.
  - Neutron-rich nuclei

- Interpretation
  - GDR – oscillation between neutron and proton bodies.
  - PDR – neutron skin oscillation

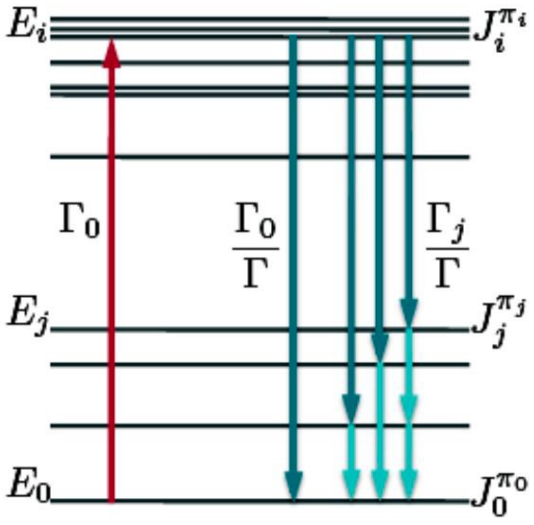
- What role do nuclear shell effects play?

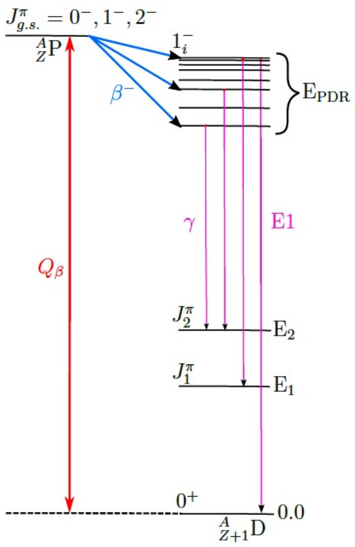
- Impacts.
  - Nucleosynthesis.
  - Nuclear Equation of State.
  - Neutron stars.

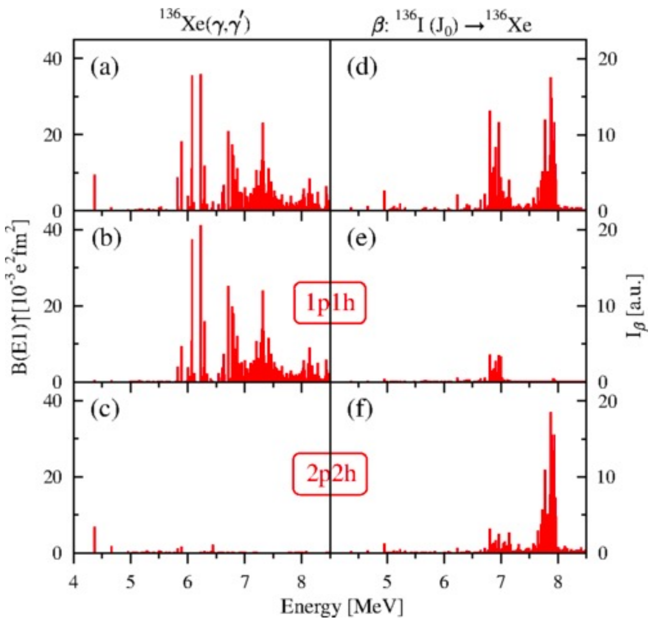


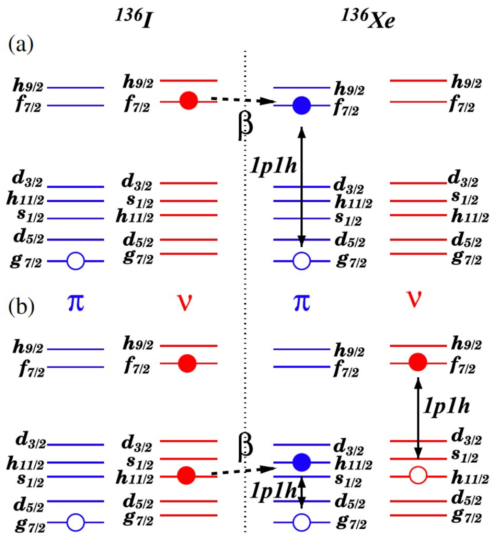
Probes for PDR

- Nuclear Resonance Fluorescence is the workhorse of PDR studies
  - Excellent excitation of 1^- levels.
  - Direct measurement of B(E1) values.
  - Only suitable for stable nuclei.
  - ^{92}Sr is not stable [$T_{1/2}$ = 2.66(4) h].
  - Preferentially excites 1p1h states.
- β decay offers alternative probe of PDR
  - ^{92}Rb: $J^\pi = 0^-$, Q_β = 8096 keV.
  - Strongly populates 2p2h states.
- Multi-messenger approach is best way to probe nuclear structure.







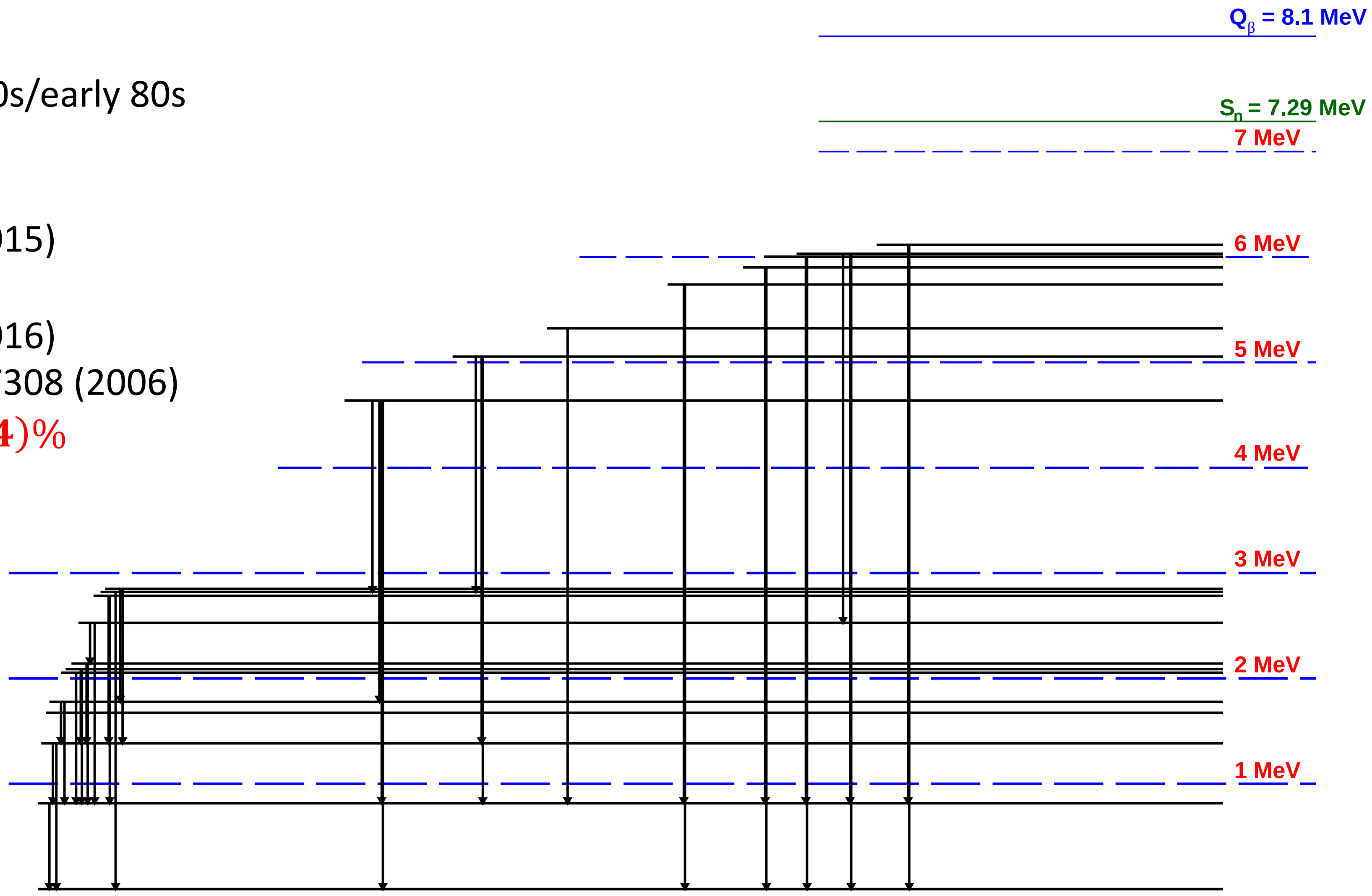


Scheck et al. Phys. Rev. Lett 116, 132501 (2016)

Previous studies

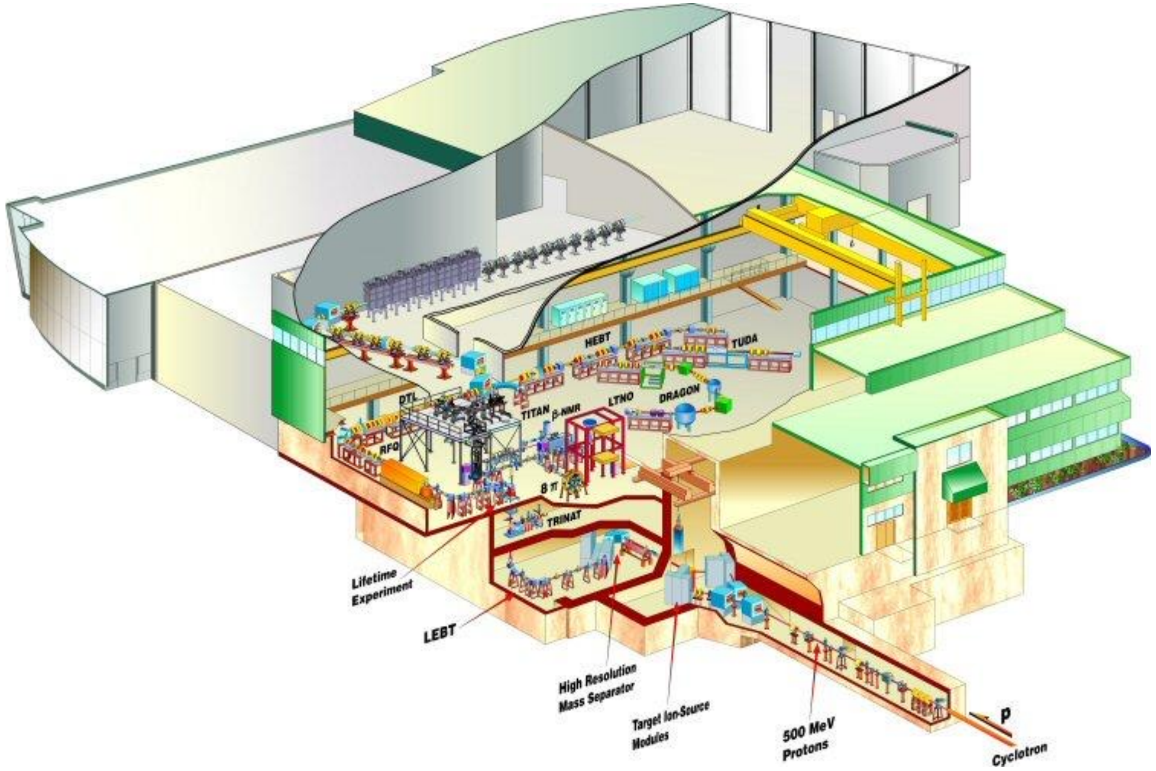
- Early beta-decay studies from late 70s/early 80s
  - 17 excited states.
- TAGS (BaF detectors) Zakari
  - Phys. Rev. Lett. 115, 102503 (2015)
- TAGS (NaI detectors) Rasco
  - Phys. Rev. Lett. 117, 092501 (2016)
- G. Lhersonneau, Phys. Rev. C 74, 017308 (2006)
  - **815 keV; $I_\gamma(2_1^+ \rightarrow 0_1^+) = 3.2(4)\%$**
- Argonne study (not yet published)
  - 52 Additional levels.

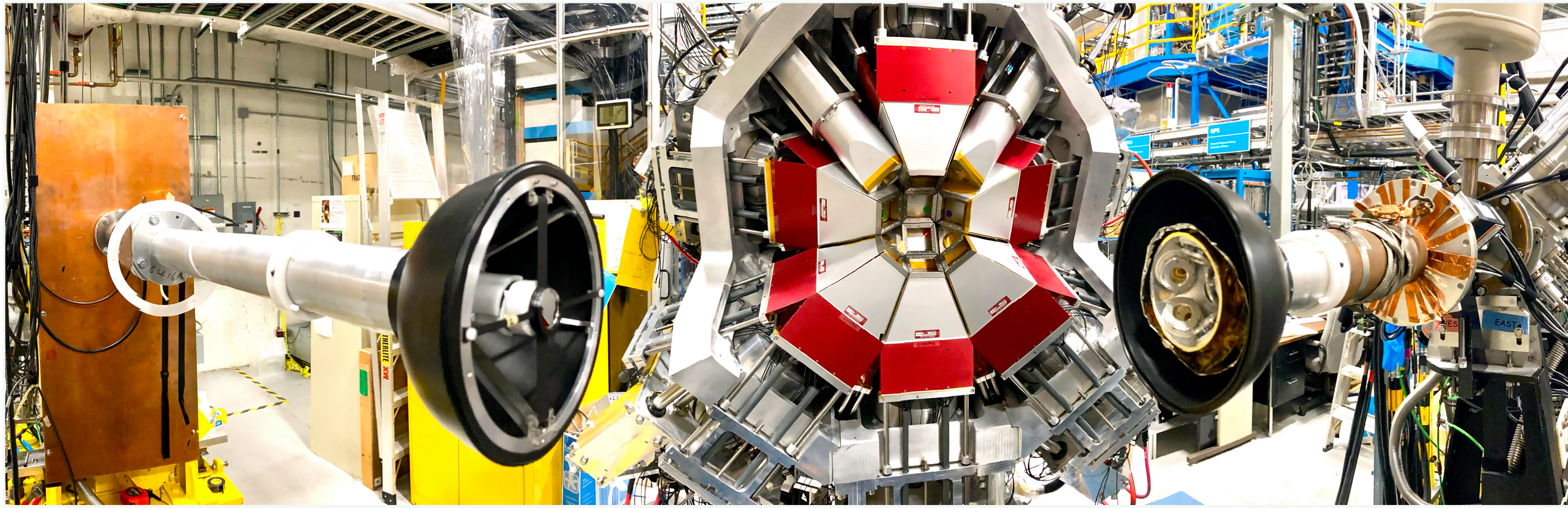
- I_β (g.s. → g.s.)
  - ENSDF: 95.2(7) %
  - Zakari: 87.5(25) %
  - Rasco: 91(3) %
  - Argonne: 91(2) %



Experiment 2130

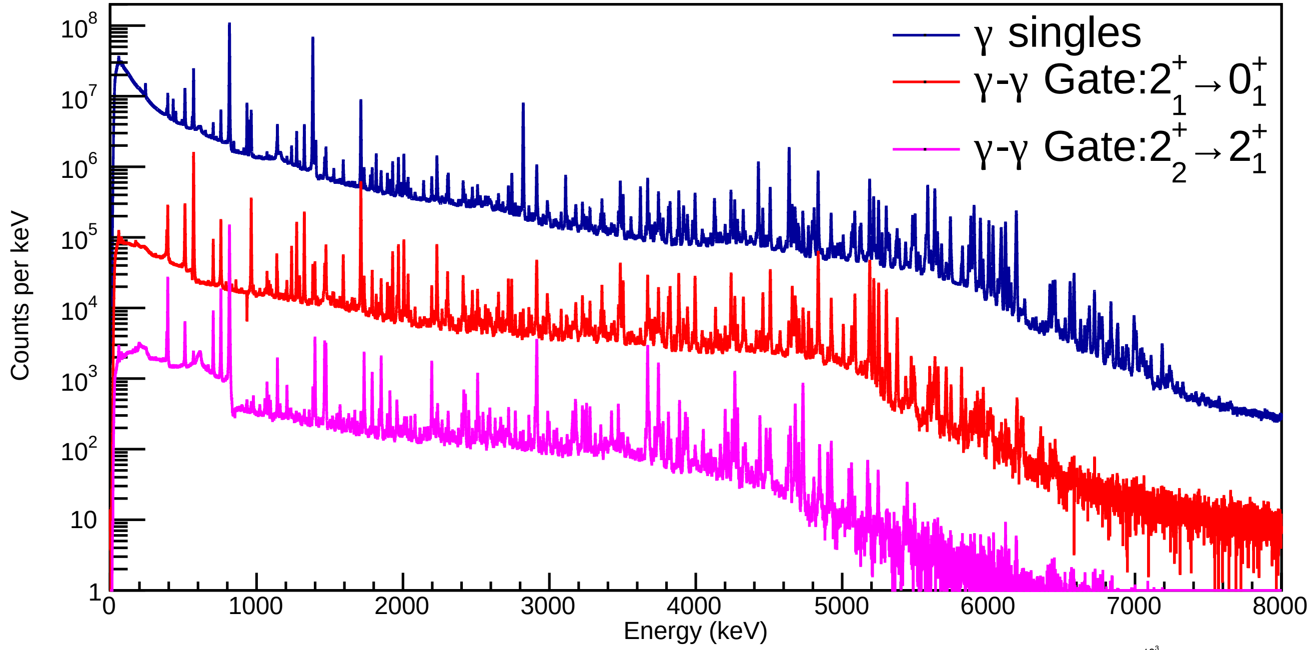
- Performed at ISAC, TRIUMF
- 480 MeV protons on UC_x target.
  - ^{92}Rb from Surface Ion Source (SIS)
  - Yield: $\sim 10^9$ pps
- Delivered to GRIFFIN
  - $\sim 10^6$ pps for $\sim$10 hours
  - 15 HPGe Clover detectors
    - Anti-Compton shielding
  - ZDS: β-tagging
  - PACES: Conversion electrons
  - LaBr: Fast-timing

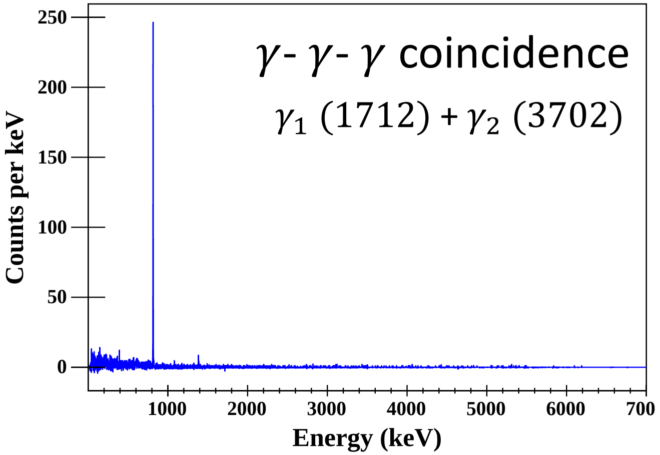


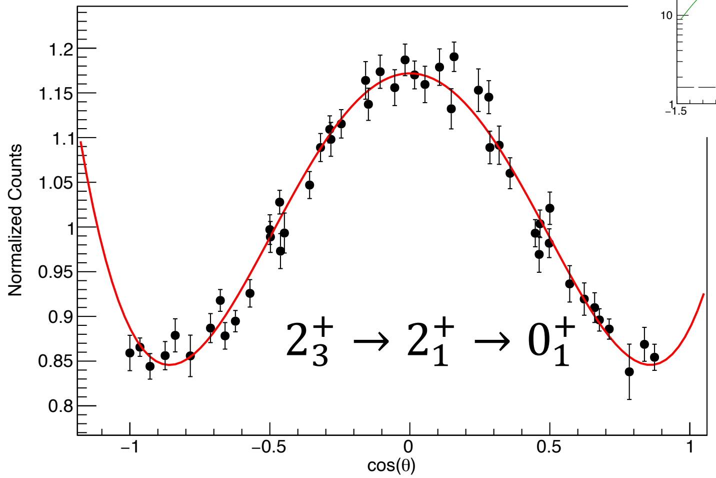


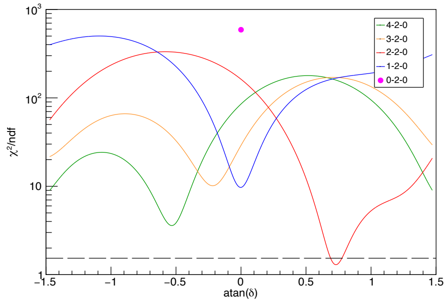
Results

- ~1.6 x 10^{11} decays occurred
  - Massive data set
- Analysis
  - γ-ray singles
  - γ-γ and γ-γ-γ coincidences.
  - γ-$\gamma(\theta)$ angular correlations
- Identify γ rays below 0.01% intensity
  - Relative to strongest transition



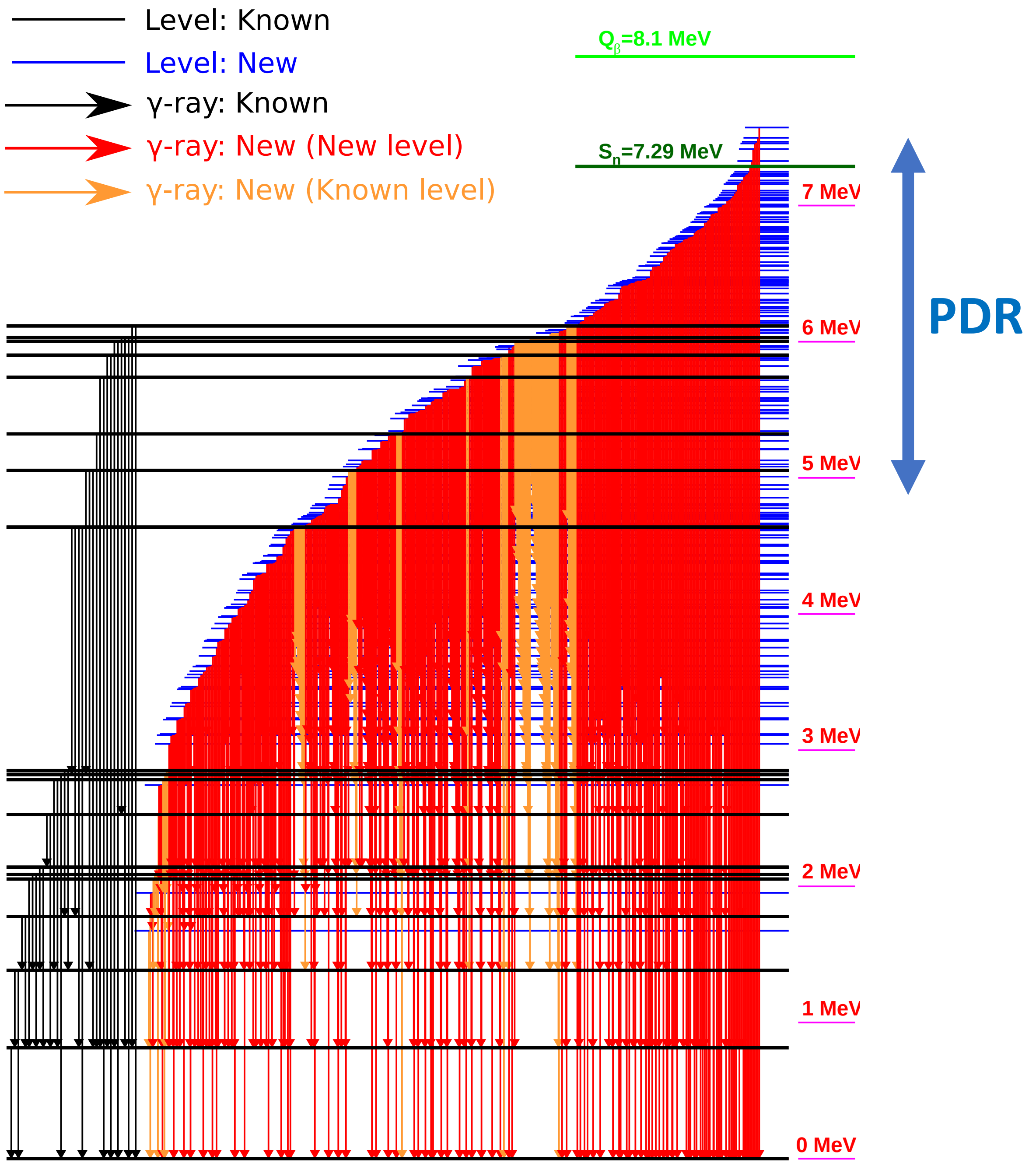






^{92}Sr Levels

- Early beta-decay studies from late 70s/early 80s
  - 17 excited states.
  - $\sim$ 50 γ-ray transitions
- GRIFFIN
  - $\sim$**170 excited states** populated!
  - Many levels in the PDR.
  - Strongly fragmented γ-decay strength.
  - $\sim$ **850 γ-ray transitions**!
  - Table of results
    - 15 pages
- May be the largest β-decay data collected.
  - Not verified.



Levels

- Early beta-decay studies from late 70s/early 80s
  - 17 excited states.
  - $\sim 50\ \gamma$-ray transitions
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  - $\sim$170 excited states populated!
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  - Table of results
    - 15 pages
- May be the largest β-decay data collected.
  - Not verified.

Level: Known

Level: New

Q_β=8.1 MeV

E_x (keV)	J^π	I_β^{Rel} (%)	I_β^{Abs} (%)	log ft	E_γ (keV)	E_f (keV)	J_f^π	I_γ^{Rel} (%)	BR_γ
6030.00(7)	$1^{\pm\ a,b,d}$	28.3(13)	0.21(3)	5.80(7)	931.0(3)	5098.9(2)	0,1,2	0.0141(15)	0.90(10)
					1081.7(3)	4948.45(15)	$1^\pm$	0.038(4)	2.5(3)
					1220.5(7)	4808.39(9)	$1^\pm$	0.017(3)	1.1(2)
					1233.6(3)	4796.36(15)	1,2	0.057(5)	3.7(3)
					1392.2(3)	4637.66(7)	$1^\pm$	0.048(5)	3.1(3)
					1415.9(4)	4614(3)	1,2	0.007(1)	0.48(7)
					1519.7(3)	4510.3(3)	1,2	0.0091(13)	0.6(8)
					1594.6(4)	4435.2(3)	1,2	0.0123(15)	0.80(10)
					1646.6(6)	4383.1(3)	1,2	0.0069(15)	0.50(10)
					1652.4(3)	4377.54(18)	1,2	0.058(5)	3.8(4)
					1873.1(4)	4156.9(3)	1,2	0.0087(12)	0.57(8)
					1977.9(6)	4051.3(12)	0,1,2	0.018(3)	1.2(2)
					1985.5(3)	4044.44(17)	1,2	0.027(4)	1.8(3)
					2044.6(4)	3985.16(18)	1,2	0.022(4)	1.5(3)
					2053.0(3)	3976.99(12)	1,2	0.14(12)	9.2(8)
					2135.8(4)	3894.09(11)	1,2	0.0071(16)	0.5(1)
					2218.8(3)	3811.06(11)	1,2	0.037(6)	2.4(4)
					2277.0(3)	3753.09(13)	1,2	0.042(4)	2.8(2)
					2337.6(4)	3692.27(13)	2^+	0.045(7)	2.9(5)
					2415.2(3)	3614.6(12)	0,1,2	0.092(7)	6(5)
					2449.2(3)	3580.7(1)	1,2	0.077(8)	5.1(6)
					2473.7(3)	3556.3(1)	$1^\pm$	0.29(2)	19.3(14)
					2496.4(3)	3533.87(11)	2^+	0.035(4)	2.3(3)
					2563.1(3)	3466.67(11)	1,2	0.142(16)	9.3(11)
					2682.2(3)	3347.8(1)	1,2	0.137(14)	9(9)
					2911.1(3)	3118.9(1)	2^+	0.89(9)	58(6)
					2920.1(3)	3110.14(8)	$1^\pm$	0.127(9)	8.3(6)
					2984.2(3)	3045.9(1)	2^+	0.201(13)	13.2(9)
					3180.7(3)	2849.51(9)	2^+	0.161(15)	11.0(10)
					3209.4(4)	2820.7(7)	$1^\pm$	0.034(4)	2.2(3)
					3247.2(4)	2783.44(8)	2^+	0.022(3)	1.42(19)
					3286.3(4)	2743.7(8)	2^+	0.067(6)	4.4(4)
					3503.1(2)	2526.87(8)	0^+	0.72(5)	47(3)
					3889.7(4)	2140.58(7)	1^+	0.096(8)	6.3(5)
					3942.1(3)	2088.16(7)	0^+	0.32(2)	20.7(16)
					3976.8(3)	2053.65(9)	2^+	0.064(5)	4.2(3)
					4251.4(4)	1778.02(7)	2^+	0.065(8)	4.3(5)
					4645.4(4)	1384.5(6)	2^+	0.144(13)	9.4(8)
					5215.2(6)	814.61(6)	2^+	1.53(12)	100(8)
					6030.0(5)	0	0^+	0.82(9)	54(6)

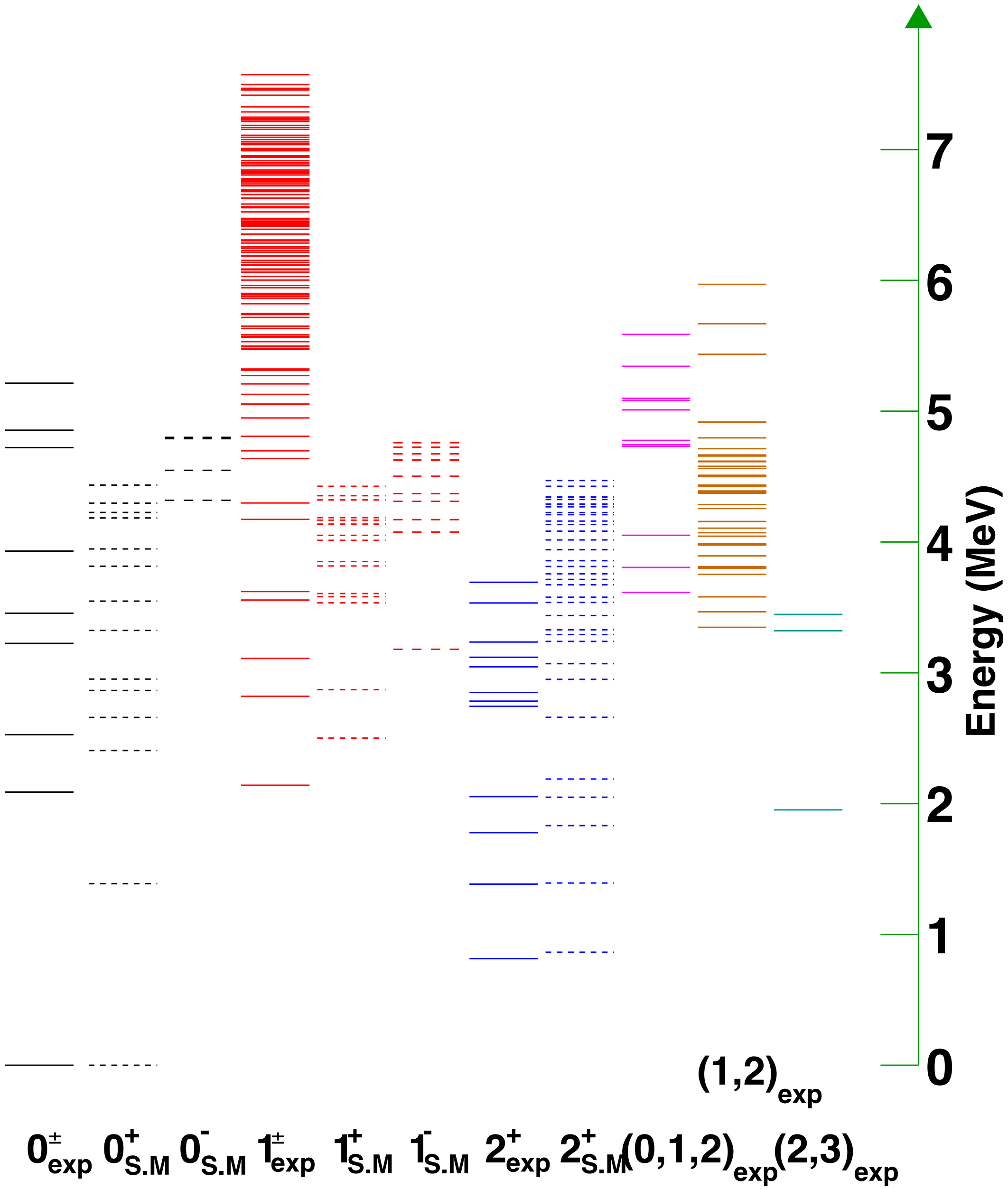
40 γ-ray transitions from one level!

$$\sum_{I_\gamma} BR_\gamma^{abs.}(I_\gamma < 1\%) = 11\ \%$$

$$\sum_{I_\gamma} BR_\gamma^{abs.}(I_\gamma < 5\%) = 40\ \%$$

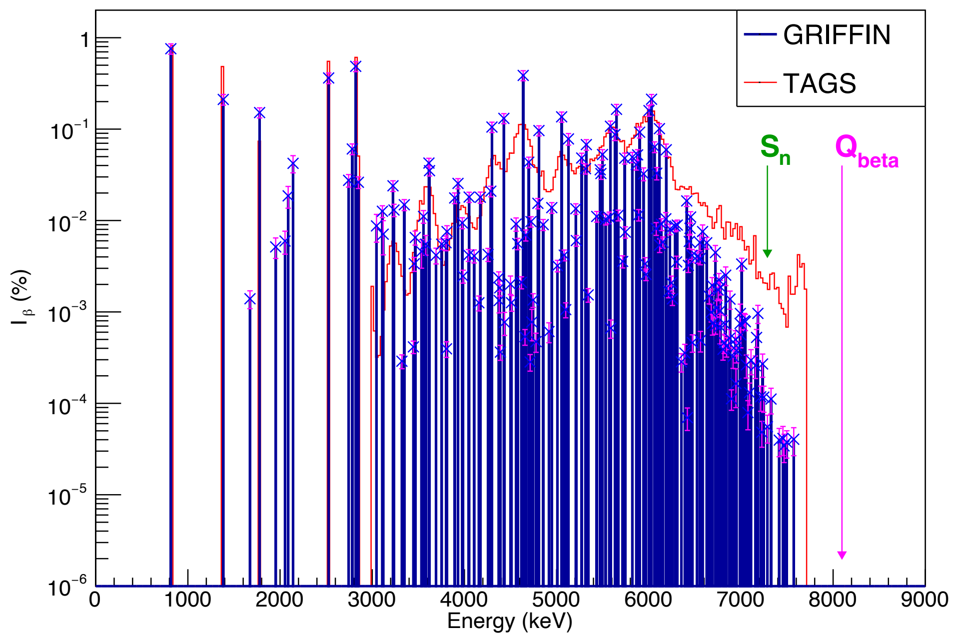
Shell-Model calculations

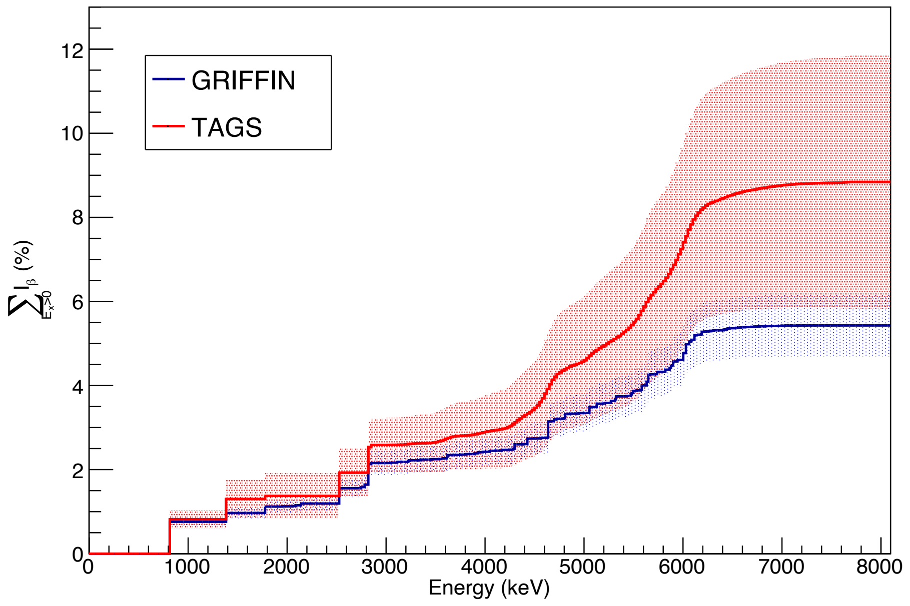
- Calculations by Marlom Ramalho
  - University of Jyväskylä
- ^{92}Sr (Z=38, N=54)
- ^{78}Ni closed core (Z=28,N=50)
  - 10 protons
  - π: $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$
  - 4 neutrons
  - ν: $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$
- 250 states up to 5 MeV
- Extrapolating to Q_β = 8095 keV window
  - 17,000 states



GRIFFIN vs TAS

- β-feeding compares favourably against MTAS result!
  - State-by-state comparison is difficult.
  - Cumulative feeding more appropriate.
- GRIFFIN data provides the fine-structure details.
  - Level energies
  - γ-ray branching ratios
  - Not possible with TAS.
- GRIFFIN data nearly free of Pandemonium.
  - Challenging given no. of levels populated.
  - Not completely.
  - Only possible with very large statistics.





Log*ft* values and selection rules

^{92}Rb; 0^-

$0^{\pm}$, $1^{\pm}$, 2^+

0^- are rare and high in energy

2^- would be second-forbidden

0 - 3 MeV

0^+ states via non-unique first-forbidden

2^+ states via unique first-forbidden

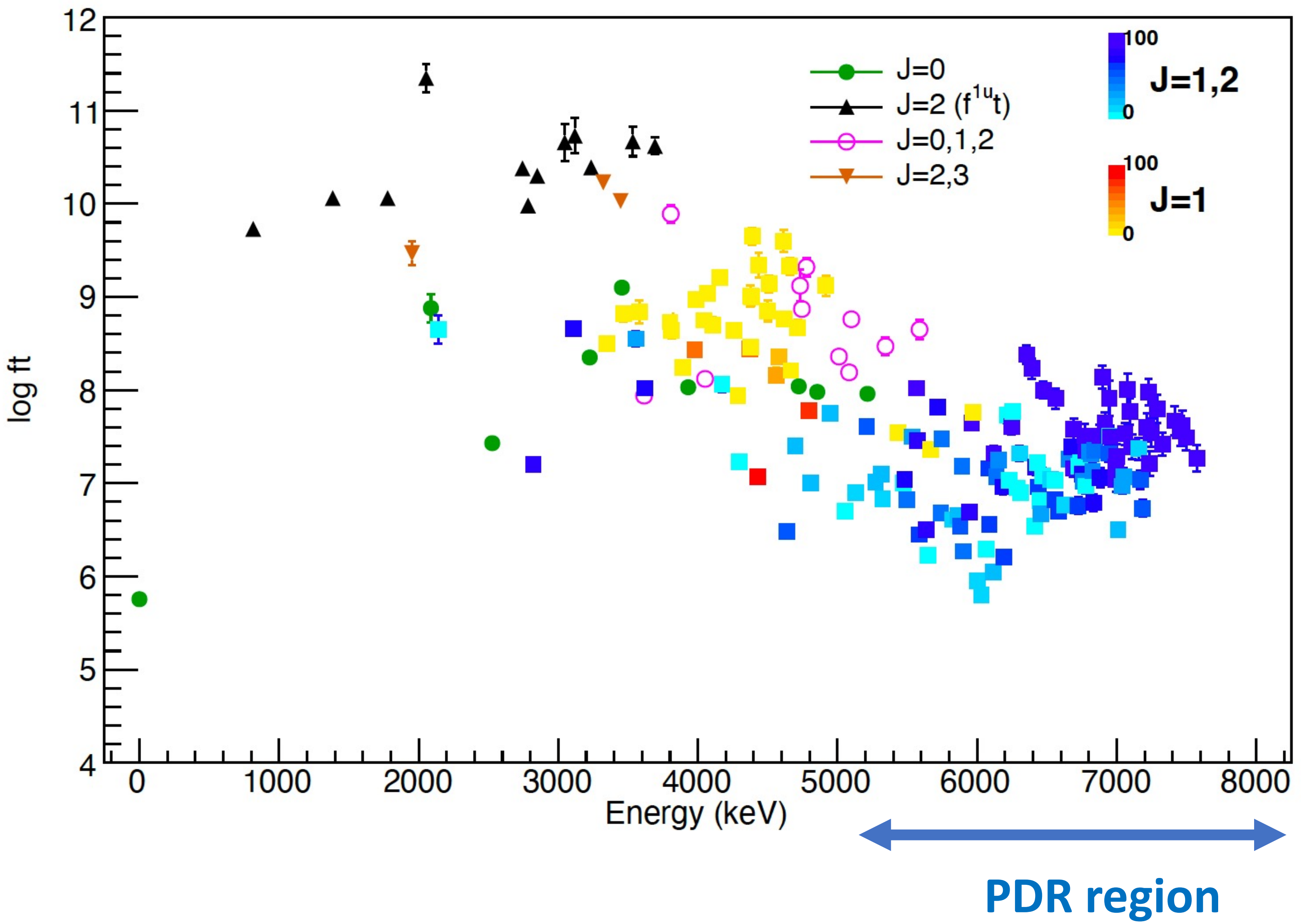
3 – 5 MeV

log*ft* consistent with non-unique first-forbidden

1^+ states? what character?

> 5 MeV Pygmy Dipole Region

lower log*ft*; allowed transitions; 1^-



Summary

- β^{-}-decay study of ^{92}Rb with GRIFFIN spectrometer at TRIUMF.
- Unprecedented level of detail for ^{92}Sr
  - $\sim$170 excited states populated.
    - Large number of J=1 levels in PDR region.
  - $\sim$ 850 γ-ray transitions.
- β-feeding measurements GRIFFIN vs TAS
  - Fine structure
    - Allowed, first-forbidden decays → ***β* spectrum shape**
  - Excellent agreement despite
    - High-level density.
    - Fragmented γ-decay.
  - Only possible thanks to high beam intensities and GRIFFIN capabilities.

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GRIFFIN

Thank you to all collaborators!

Exploring the origin of the reactor antineutrino anomaly: high-resolution β-decay study of ^{92}Rb

P. Spagnoletti,[1] M. Ramalho,[2] J. Suhonen,[2,3] C. Andreoiu,[1] M. Scheck,[4] Z. Ahmed,[5] D. Annen,[1] G. Ball,[6] G. Benzoni,[7] S.S. Bhattacharjee,[6] H. Bidaman,[5] V. Bildstein,[5] S. Buck,[5] R. Caballero-Folch,[6] R.J. Coleman,[5] S. Devinyak,[5] I. Dillman,[6] I Djianto,[1] F.H. Garcia,[8] A. Garnsworthy,[6] P.E. Garrett,[5] B. Greaves,[5] C. Griffin,[6] G. Grinyer,[9] E.G. Fuakye,[9] G. Hackman,[6] D. Hymers,[5] D. Kalaydjieva,[10] R. Kanungo,[11] K. Kapoor,[9] E. Kasanda,[5] W. Korten,[10] N. Marchini,[12] K. Mashtakov,[5] A. Nannini,[12] K. Ortner,[1] B. Olaizola,[13] C. Natzke,[6] C. Petrache,[10] M. Polettini,[12] A. Radich,[5] M. Rocchini,[5] N. Saei,[9] M. Satrazani,[14] M. Siciliano,[15] M. Singh,[11] C. Svensson,[5] D.A. Torres,[16] R. Umashankar,[6] V. Vedia,[6] E Wadge,[1] T. Zidar,[5] and M. Zielińska[10]

[1] *Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[2] *Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland*
[3] *International Centre for Advanced Training and Research in Physics (CIFRA), P.O. Box MG12, 077125 Bucharest-Magurele, Romania*
[4] *School of Computing, Engineering and Physical Sciences, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom*
[5] *Department of Physics, University of Guelph, Guelph N1G 2W1 Ontario, Canada*
[6] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada*
[7] *INFN Sezione di Milano, IT-20133 Milano, Italy*
[8] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[9] *Department of Physics, University of Regina, S4S 0A2 Regina, Canada*
[10] *IRFU/DPhN, CEA Saclay, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[11] *Astronomy and Physics Department, Saint Mary's University, Halifax, Nova Scotia, B3H 3C3, Canada*
[12] *INFN Sezione di Firenze, IT-50019 Firenze, Italy*
[13] *CERN, CH-1211 Geneva, Switzerland*
[14] *Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[15] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[16] *Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*

caa12@sfu.ca

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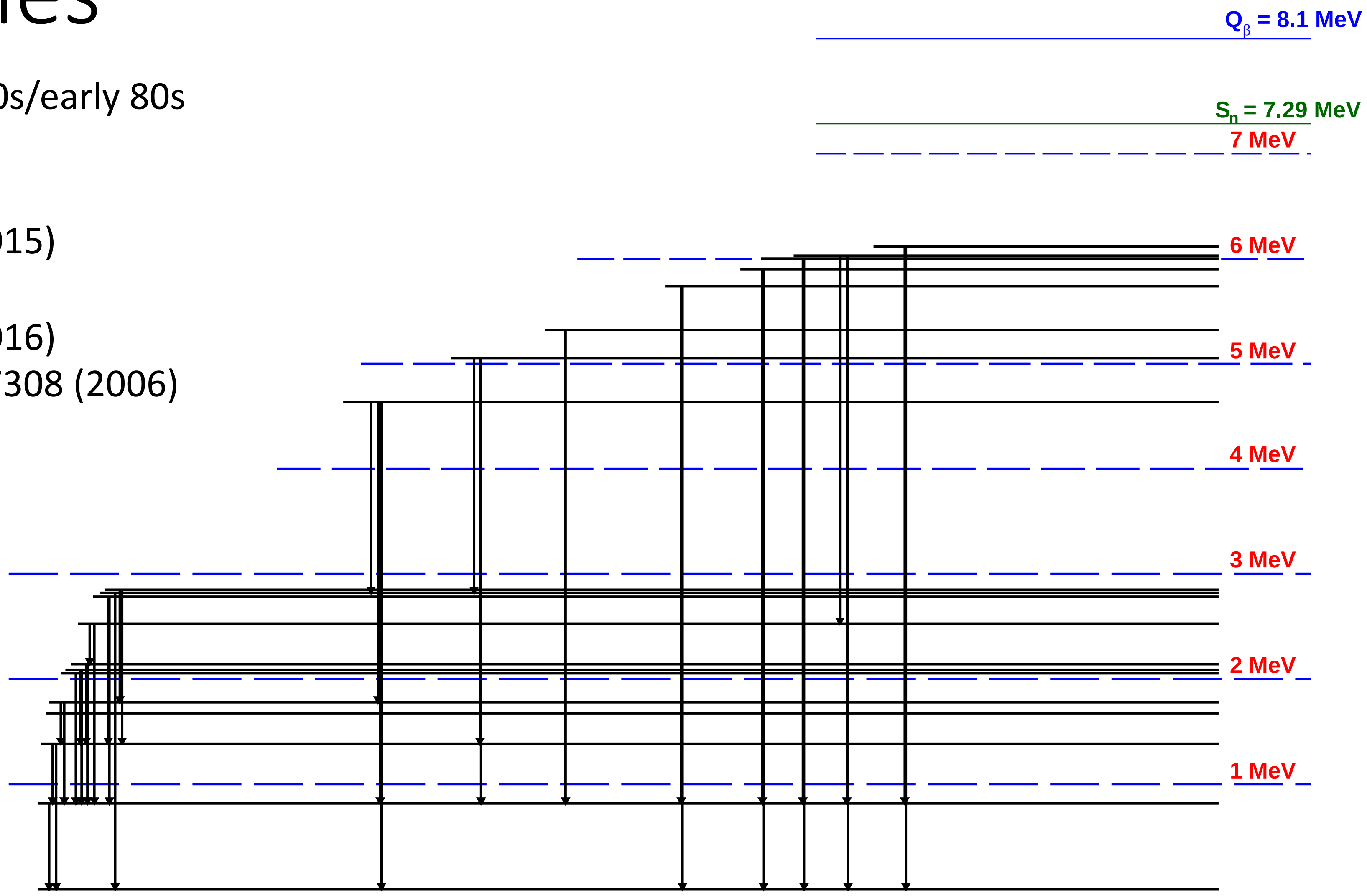


Current level scheme

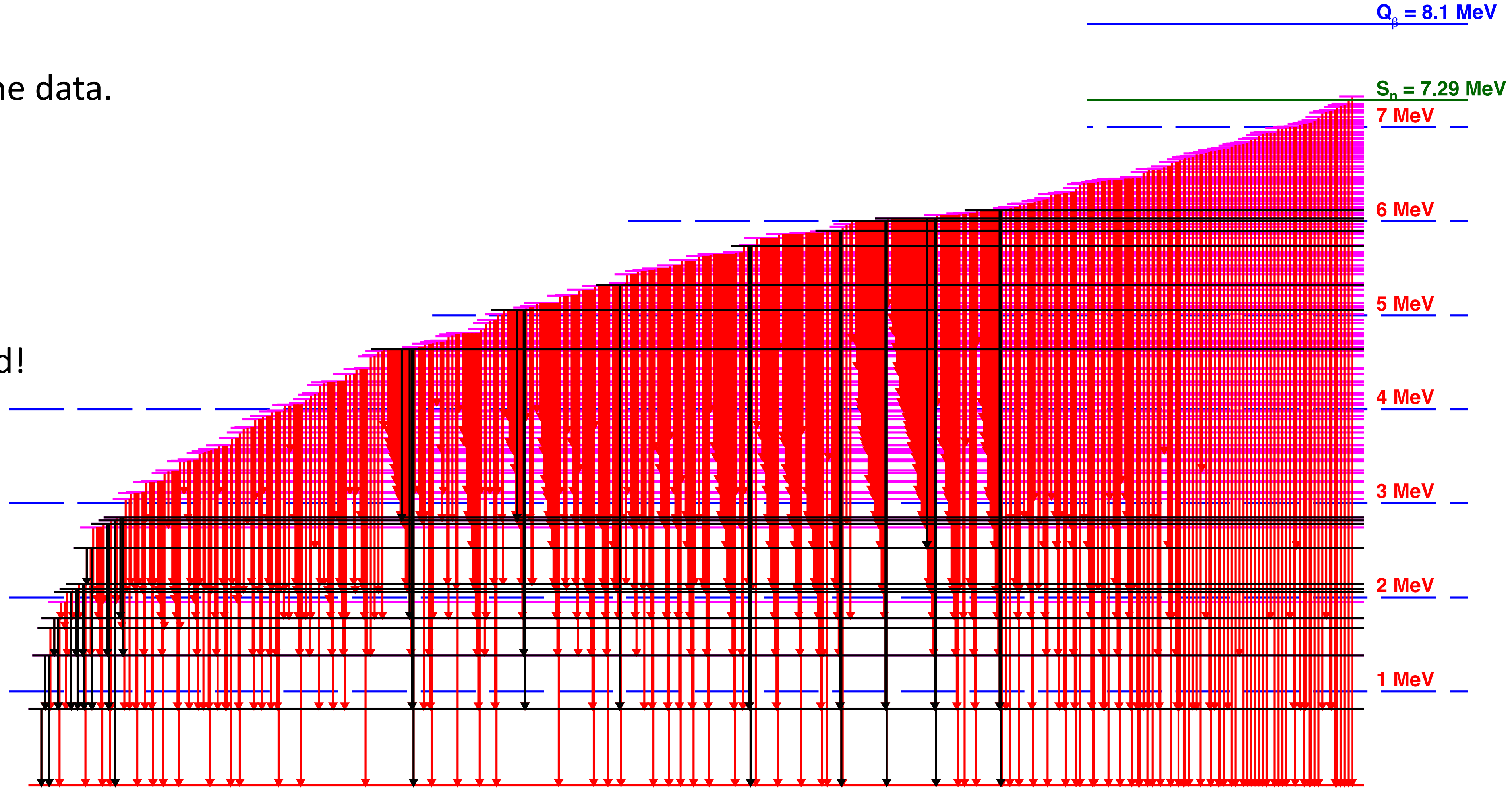
$\sim$170 levels observed in the data.

$\sim$680 γ-ray transitions.

There are errors!

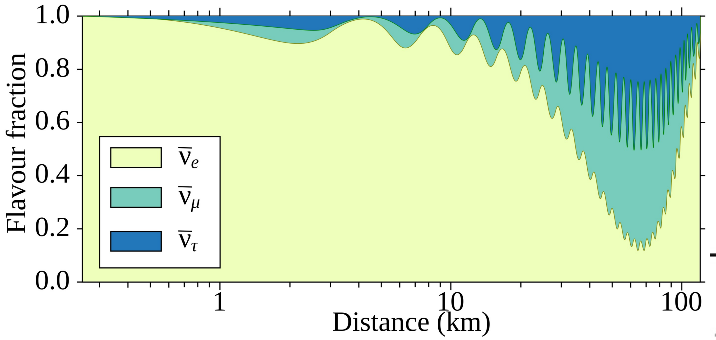
Some transitions misplaced!

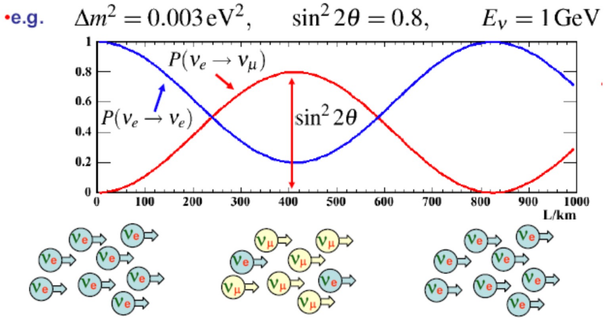
Some missing!

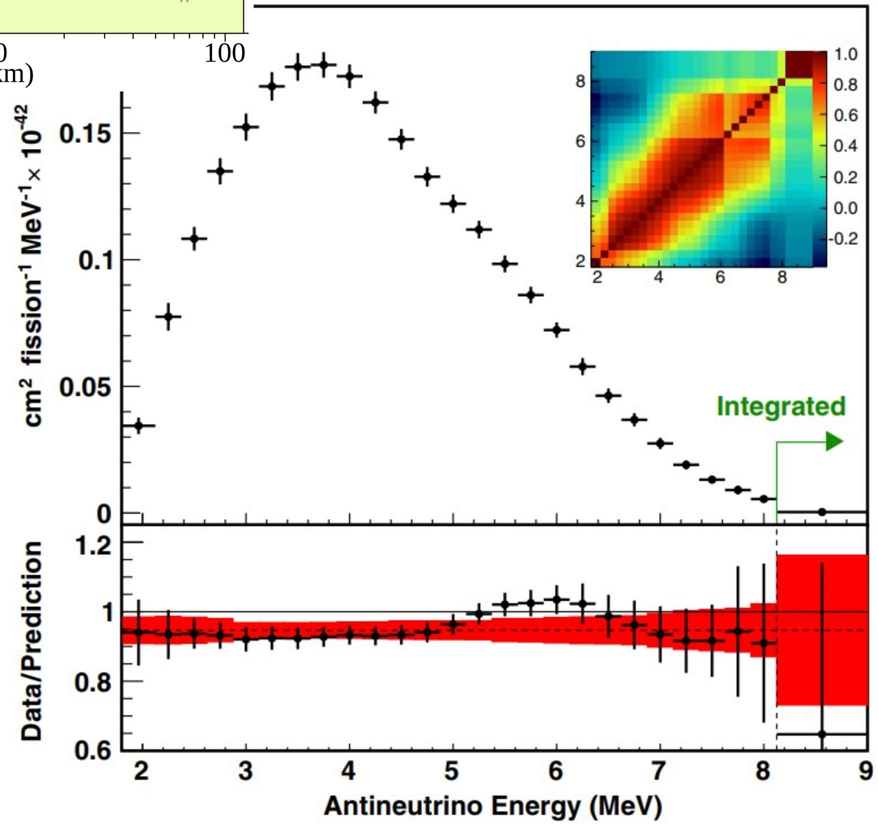


Reactor Antineutrino Anomaly (RAA)

- Nuclear Reactors play key role in neutrino physics
  - First Exp. observation of $\bar{\nu}_e$'s
  - Confirmed neutrino oscillation
    - Solution to the solar neutrino problem
  - Nonzero neutrino mixing angle θ_{13}
- RAA
  - Flux measurements disagree with improved theory calc.
    - Huber-Mueller Model (2011)
    - Summation method
  - "Missing" $\bar{\nu}_e$ flux → $\bar{\nu}_s$???
  - Excess of $\bar{\nu}_e$ at 5 MeV

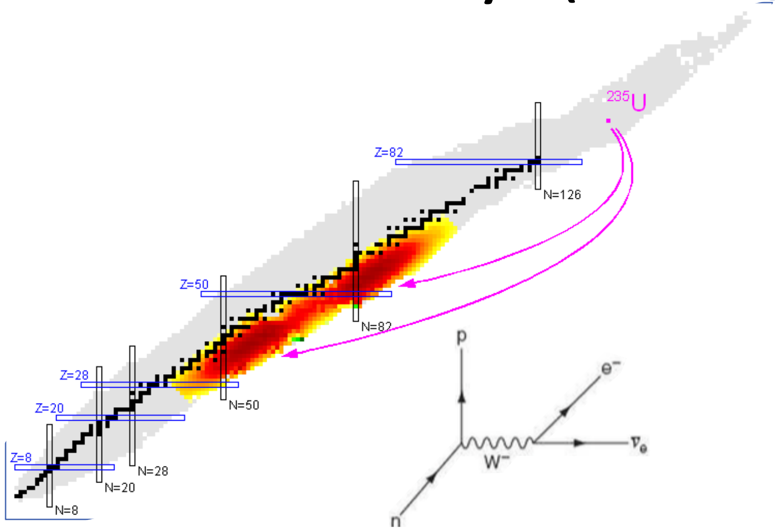


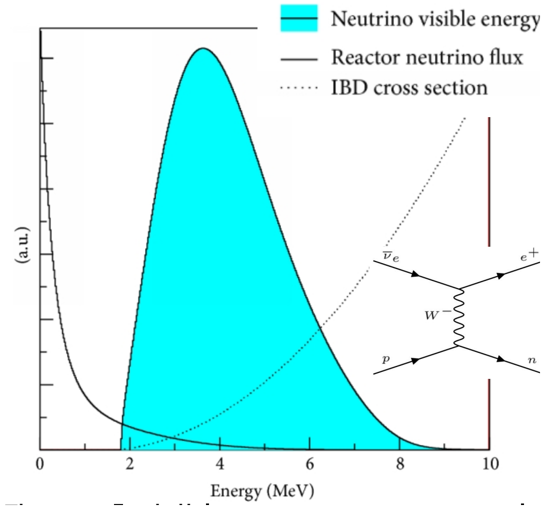




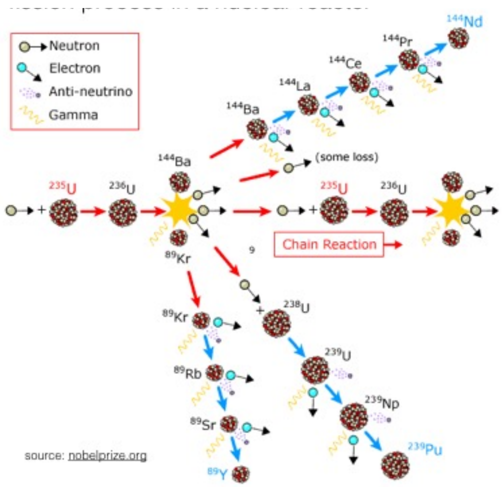
Reactor Antineutrino Anomaly (RAA)

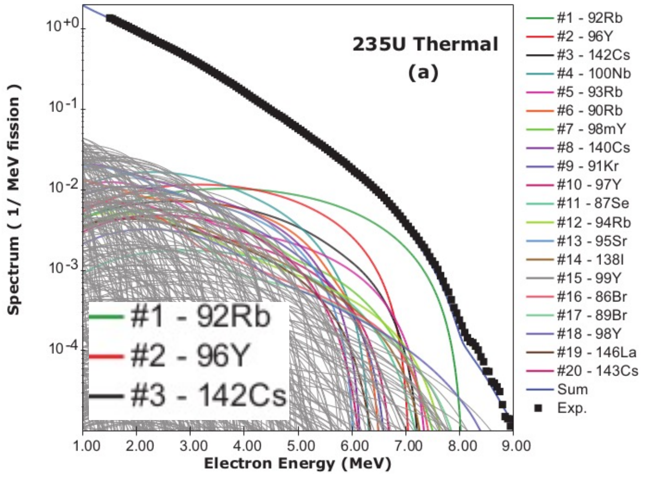
- $\bar{\nu}_e$ flux
  - measured via inverse β decay (IBD)
    - $p + \bar{\nu}_e \rightarrow n + e^+$ [E($\bar{\nu}_e$) > 1.8 MeV]
  - Produced via β decay of fission fragments
  - $\bar{\nu}_e$ energy spectrum
    - Dependent on β-decay properties





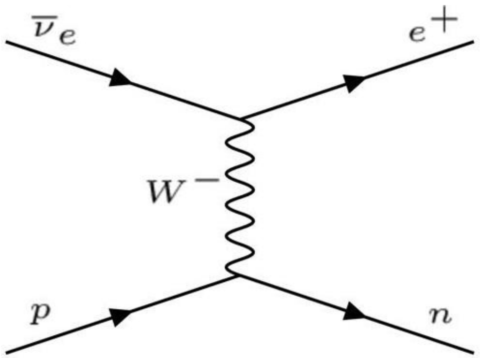
- $\bar{\nu}_e$ flux calculations
  - Requires robust β-decay data!
  - Much existing data is not.
    - Pandemonium effect!
  - Total Absorption Spectroscopy to the rescue.
- Decay Heat.
  - Reactor safety.

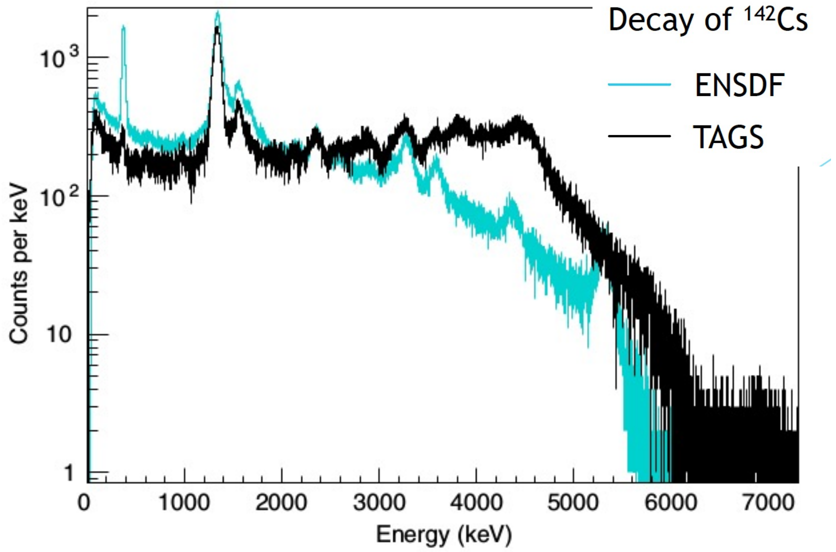


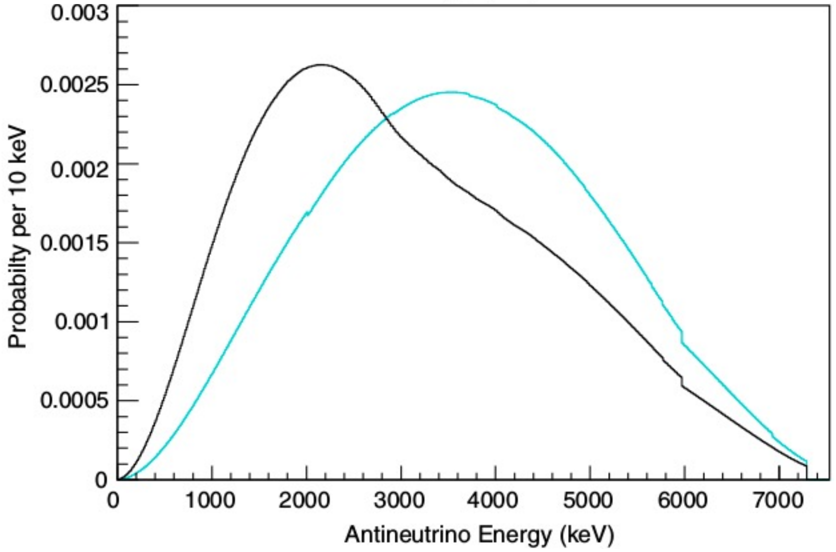


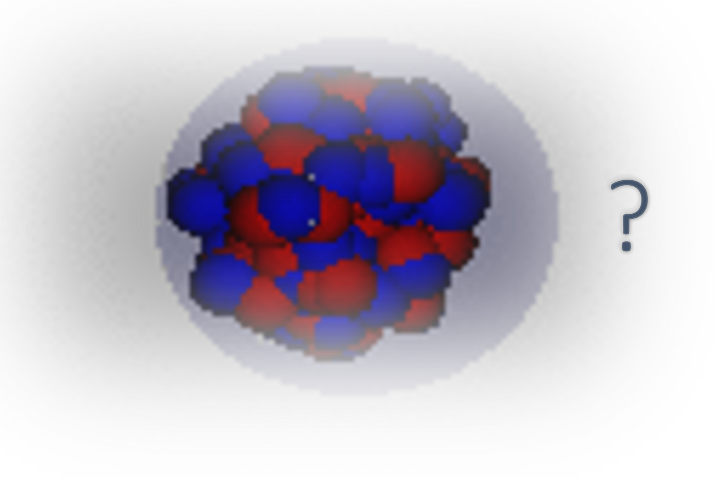
Antineutrino reactor anomaly

- The population of highly excited states means there is less energy shared between the electron antineutrino pair.
- More energy deposited in the reactor.
- The energy spectrum of the antineutrino is reduced.
- Fewer antineutrinos have required energy to induce inverse beta decay.
    - $p + \bar{\nu}_e \rightarrow n + e^+$



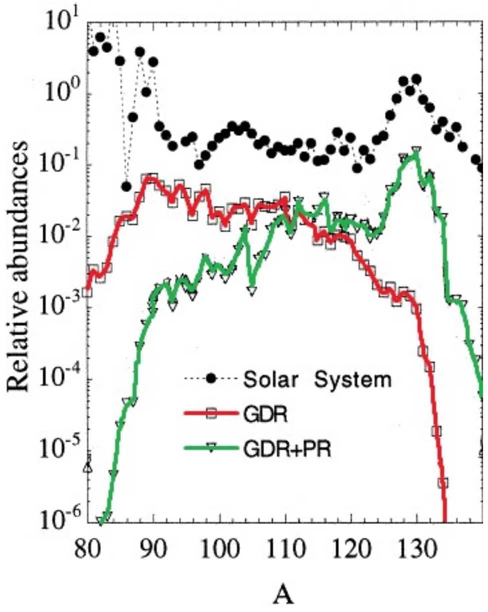




WHY  ?

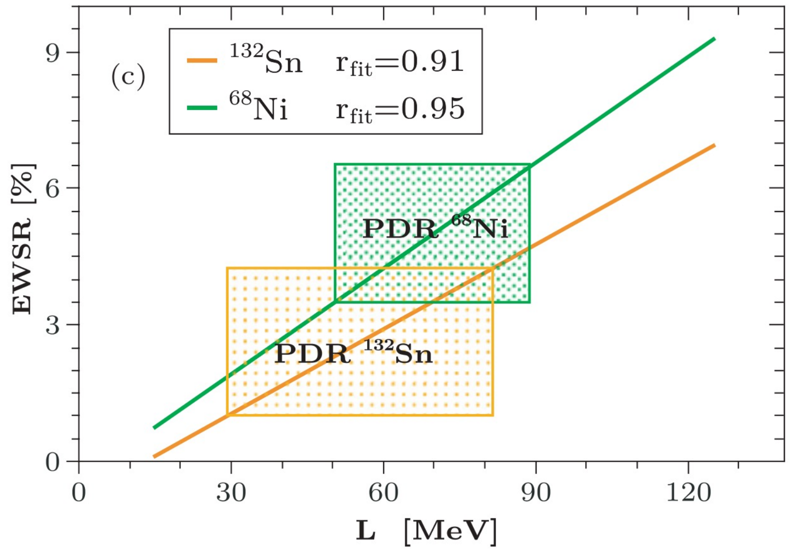
Review articles:
N.Paar et al., Rep Prog. Phys. **70** 691 (2007)
D. Savran et al., Prog. Part. Nucl. Phys. **70** 210 (2013)
A. Bracco et al., Prog. Part. Nucl. Phys. 106 **360** (2019)

Nucleosynthesis



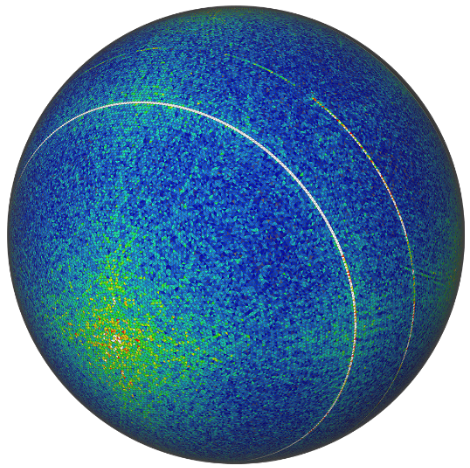
S.Goriely et al., Phys. Lett.B 436 (1998) 10

Nuclear EoS



A. Carbone et al., PRC 81, 041301(R) (2010)

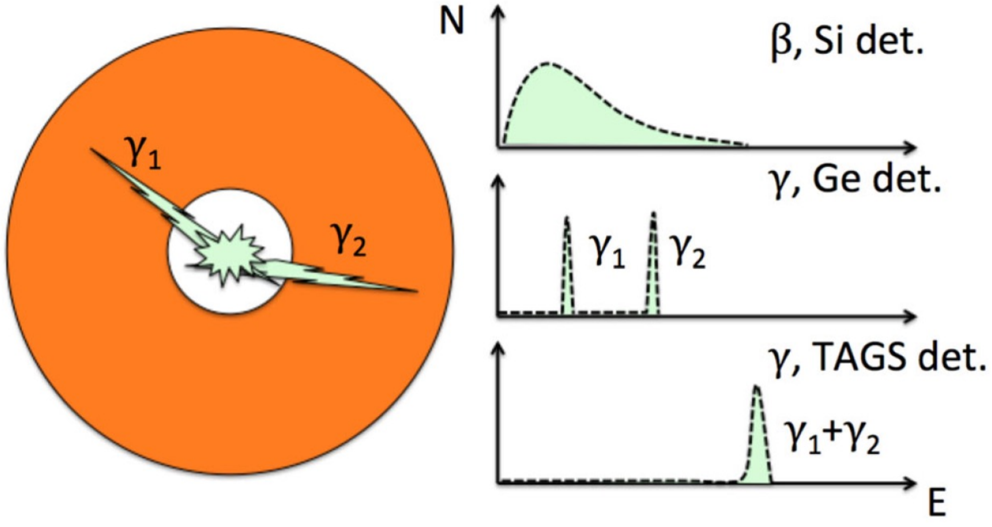
Neutron Stars

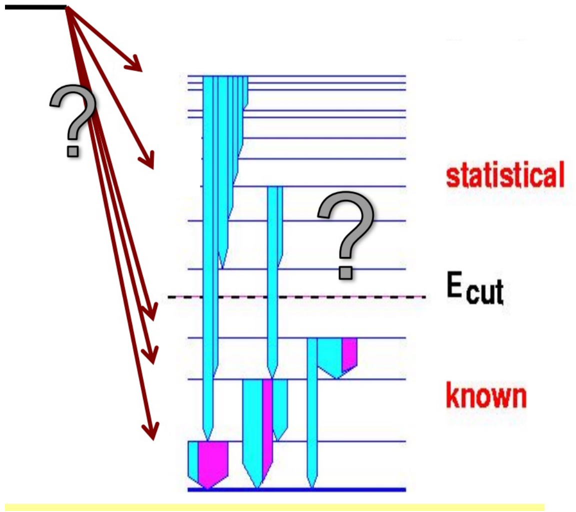


K. Sumiyoshi, Astrophys. J. 629, 922 (2005)
Lattimer et al., Phys. Rep. 442, 109 (2007)

Total Absorption Spectroscopy

- Utilizes large volume scintillator detectors.
- Exploits high detection efficiency.
  - Free from *pandemonium*.
- Poor energy resolution.
  - Limited sensitivity to individual states.
- Analysis
- Level scheme split into two regions
- Low energy with discrete states
  - Uses known branching ratios.
- High energy bins
  - Statistical model for level densities, gamma-ray BR.
  - Gamma-ray multiplicity dependence.

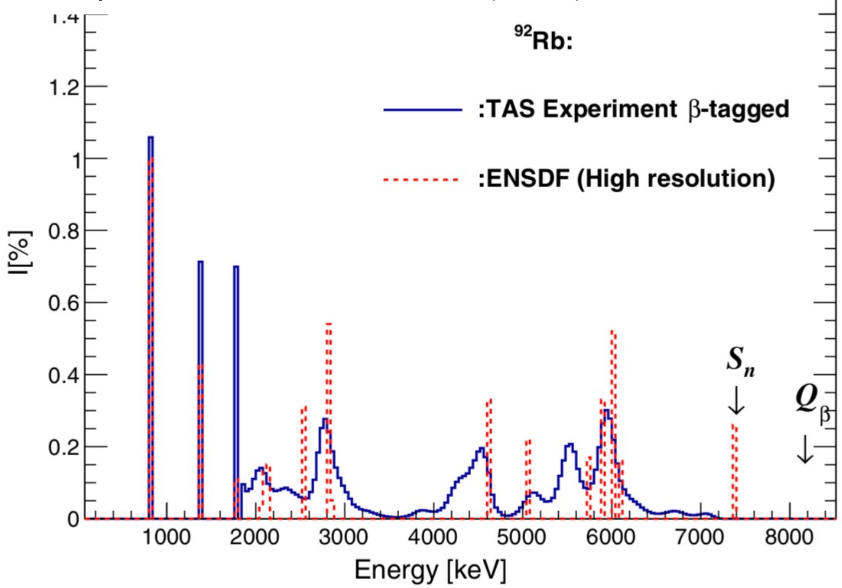


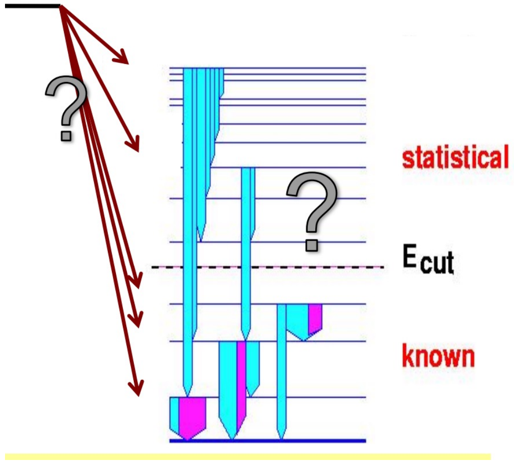


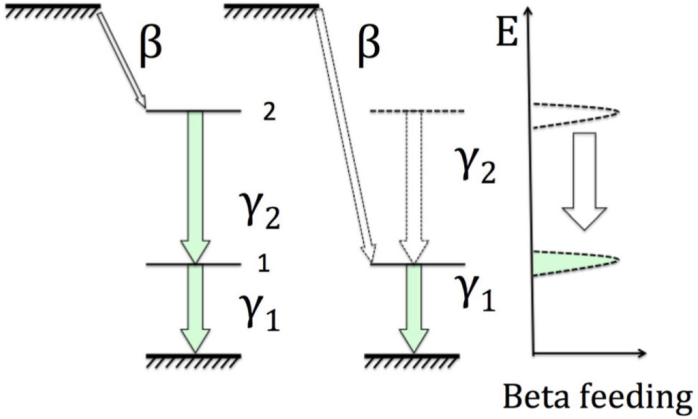
β^- data $^{92}Rb \rightarrow {}^{92}Sr$

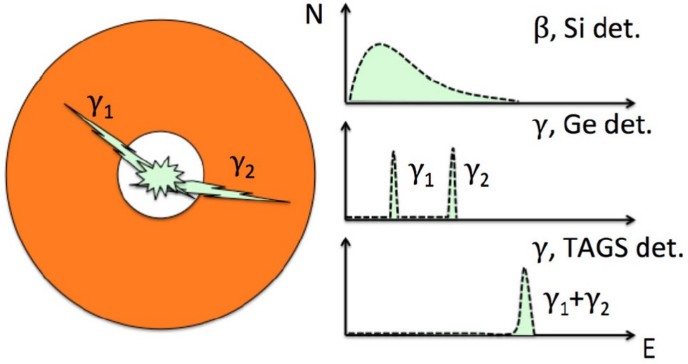
- Dominant contributor of high-energy $\bar{\nu}_e$ flux
- ENSDF data from late 1970s.
  - Using a few low-eff Ge(Li) detectors.
- Two new TAS studies
  - Zakari-Issoufou *et al* (2015)
  - Rasco *et al* (2016)
- Significant disagreement in β feeding
  - Pandemonium!
- ^{92}Rb
  - Q_β = 8095 keV
  - $J^\pi = 0^-$

A.-A. Zakari-Issoufou et al,
Phys. Rev. Lett. 115, 102503 (2015)

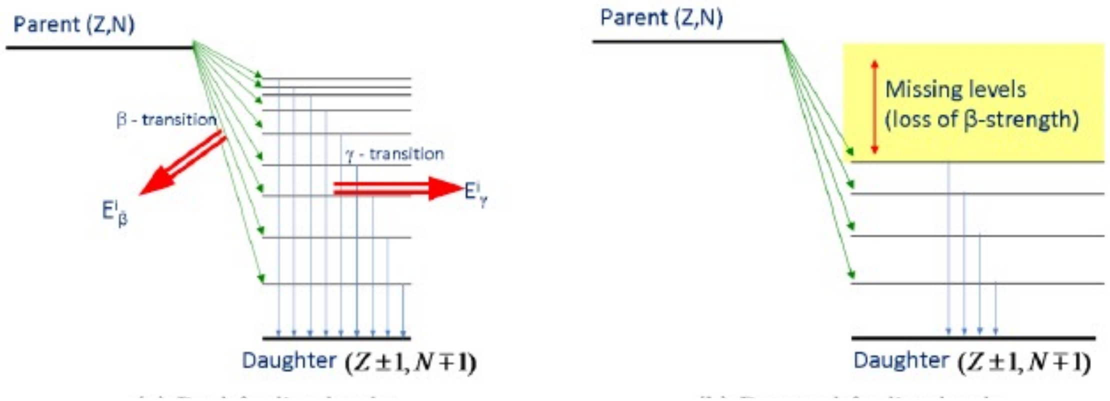


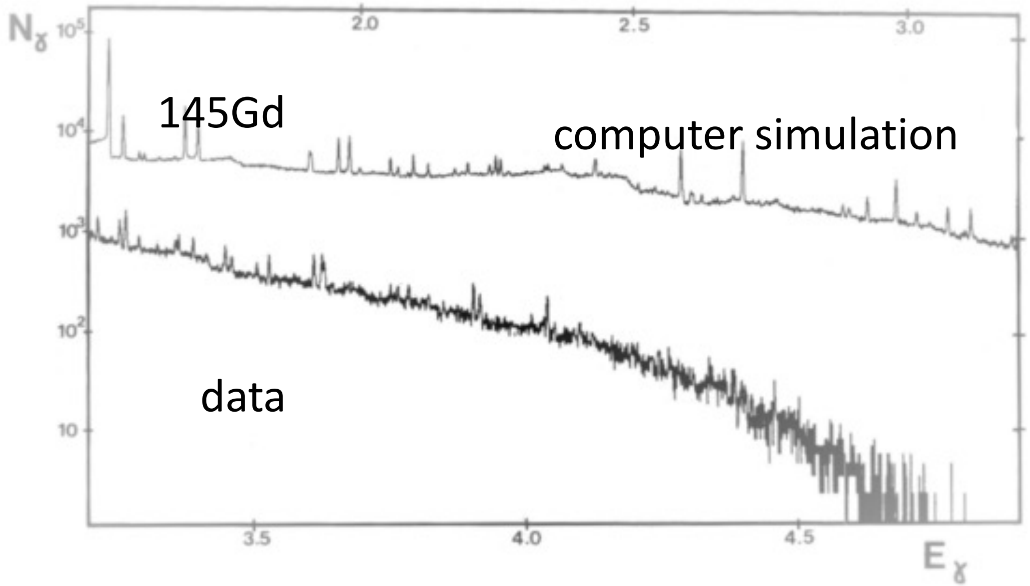






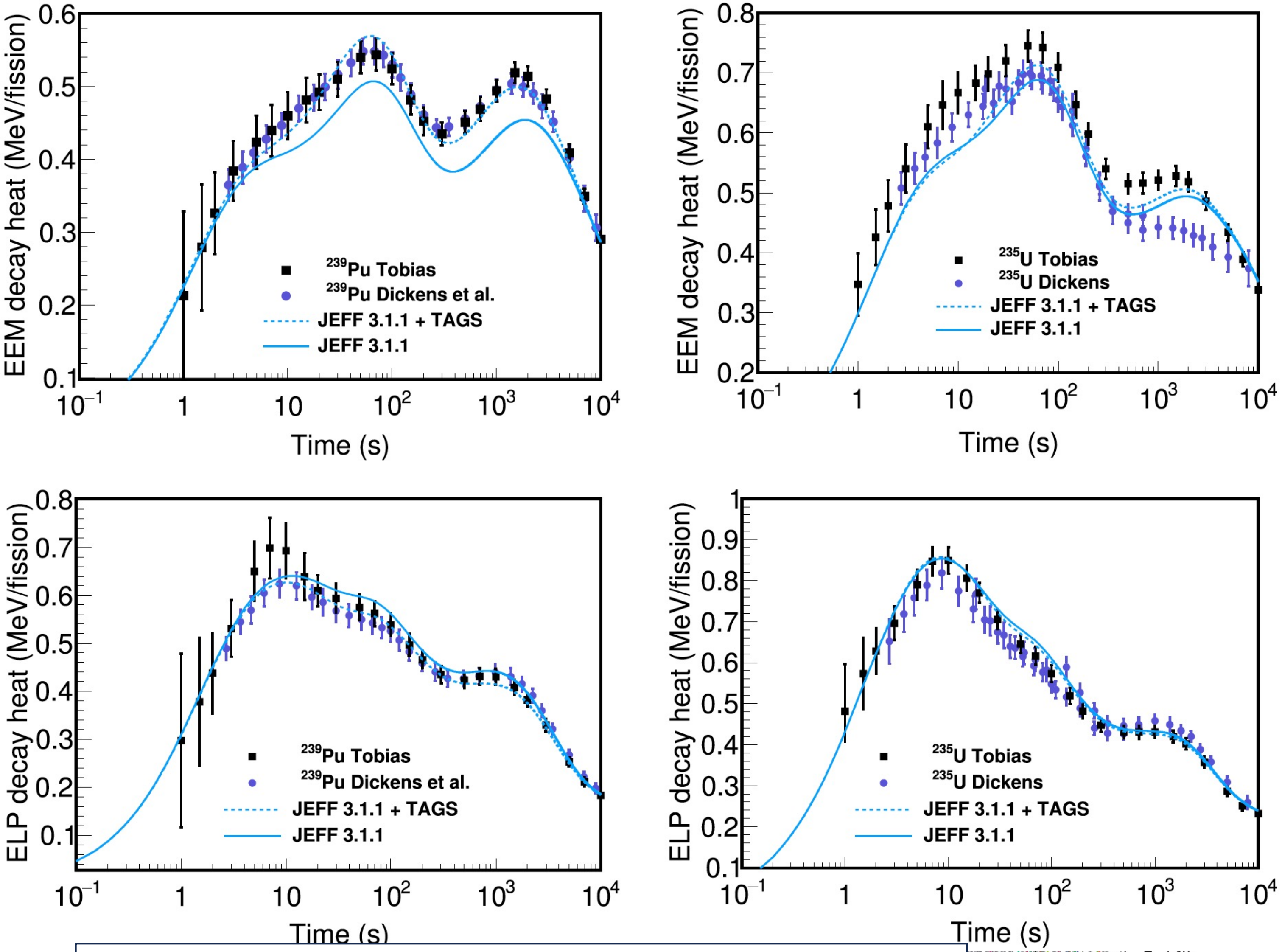
Pandemonium effect





Reactor decay heat

- Reactors produce energy via fission.
- Each fission is followed by ~6 β decays.
- β decay account for 7-8% energy released.
- Dominates after shut down.
  - Cooling times.
- Decay heat is important for both safety of present and design of future reactors.



^{86,87,88}Br, ^{91,92,94}Rb, ^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc