β^- decay of ^{92}Rb
Reactor Antineutrino Anomaly
and
Pygmy Dipole Resonance

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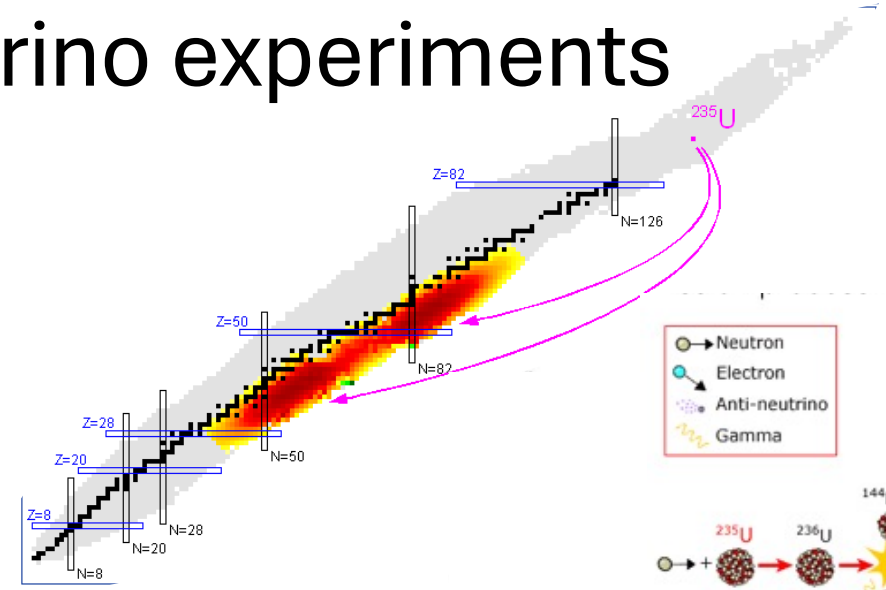
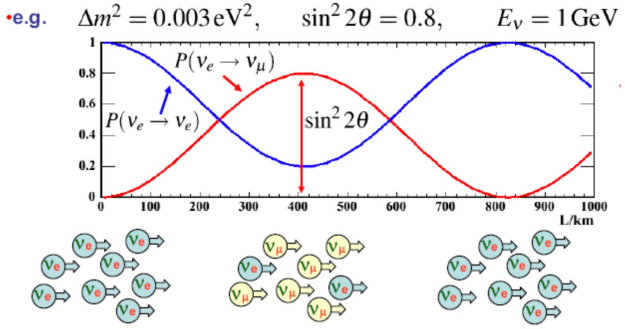
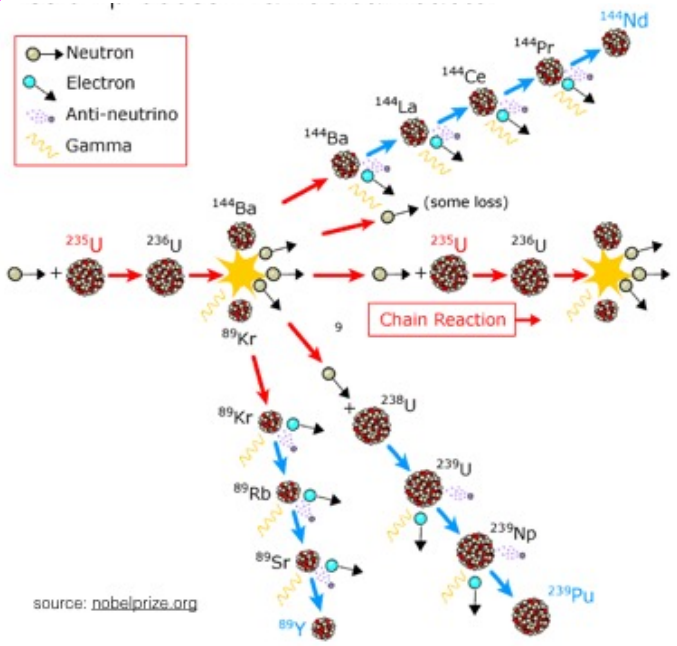
Reactor Antineutrino experiments

- Reactors produce energy via fission
- Neutron-rich fission fragments unstable against β^- decay
- $n \rightarrow p + e^- + \bar{\nu}_e$
- Provided first experimental observations of $\bar{\nu}_e$
  - 1956
- Confirmed neutrino oscillation
  - Solution to the solar neutrino problem
- Nonzero neutrino mixing angle
  - θ_{13}

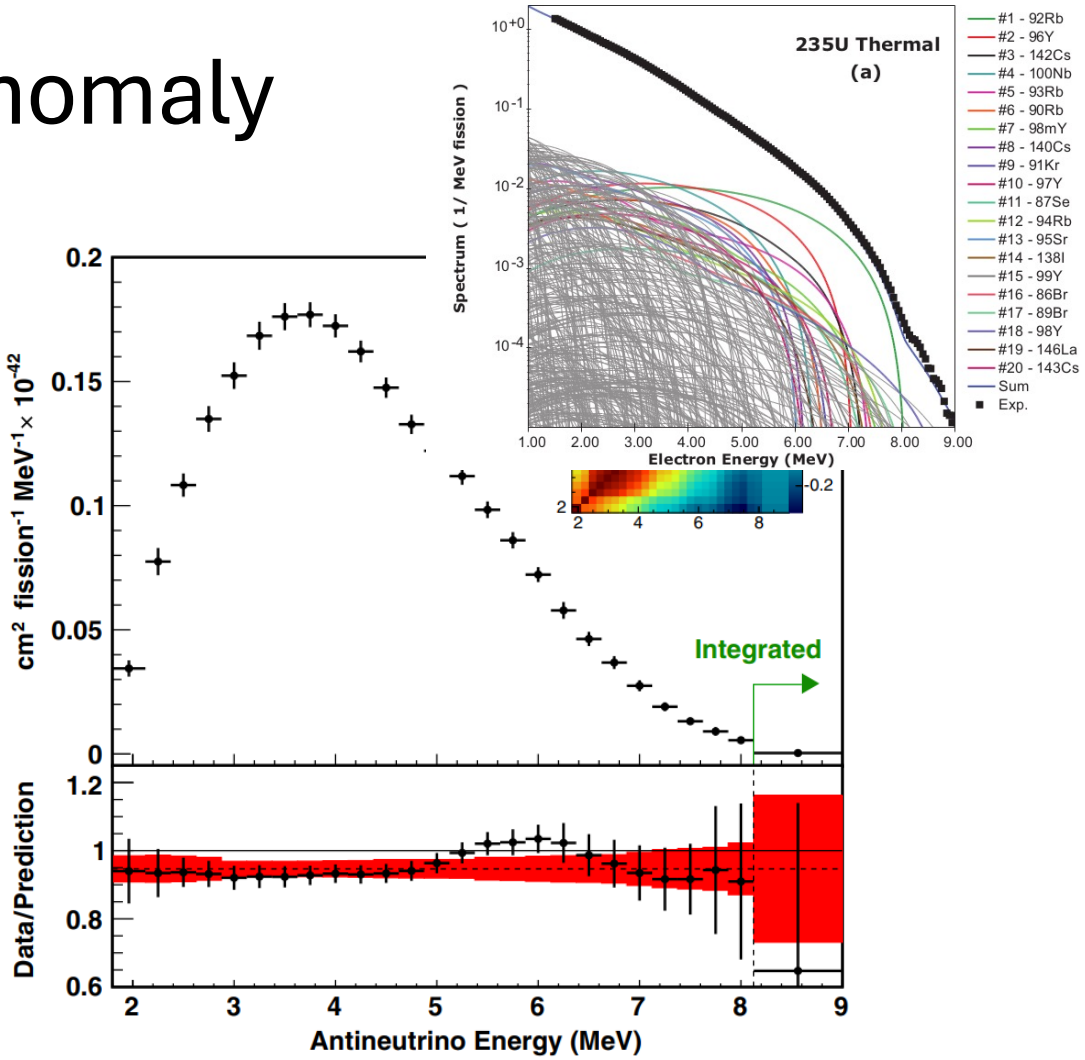






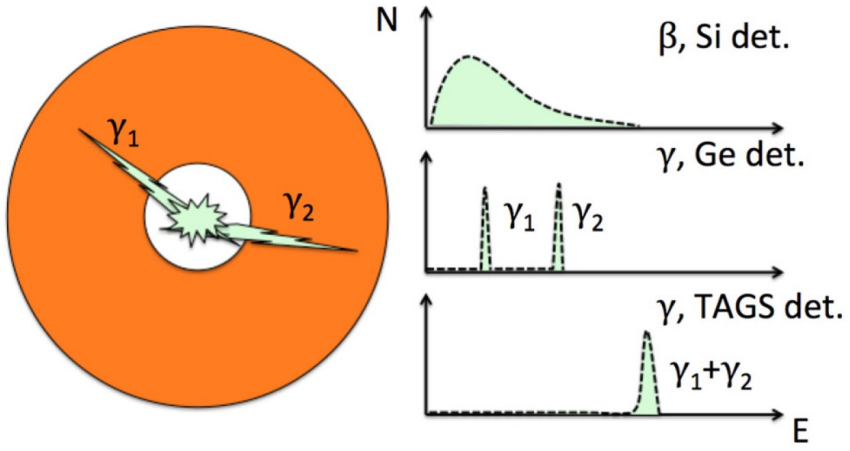
Reactor Antineutrino Anomaly

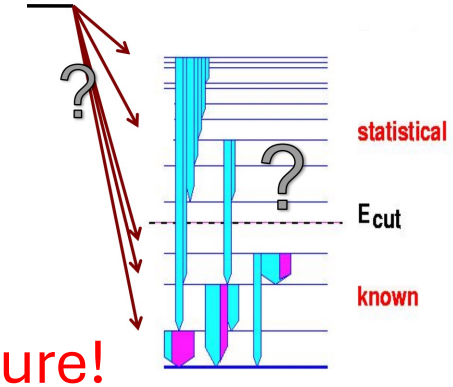
- Flux measurements disagree with improved theory calc.
  - Daya Bay, Double Chooz, RENO
  - Huber-Muller Model (2011)
- ~6% of neutrinos missing
- Excess of neutrinos at 5-7 MeV
- Summation Method
  - Alternative approach to H-M model
  - Sums all β-branches to calculate neutrino spectrum
  - Requires reliable β-decay data

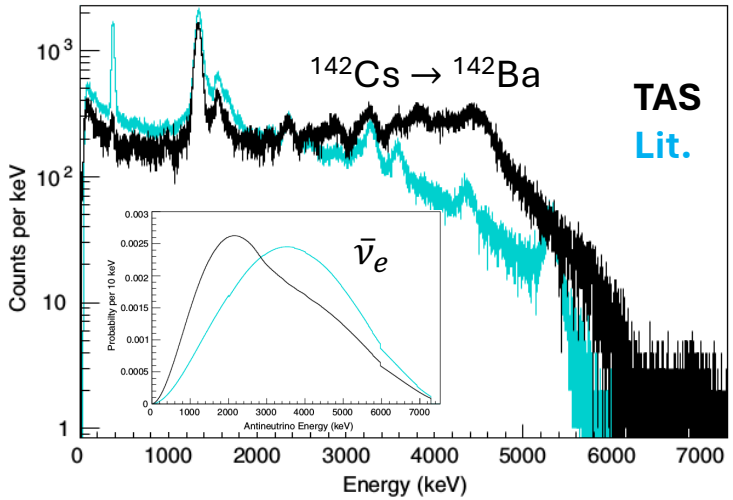


Total Absorption Spectroscopy

- Utilizes large volume scintillator detectors.
  - Calorimeter.
- Exploits high detection efficiency.
  - Free from *pandemonium*.
- Poor energy resolution.
- Limited sensitivity individual levels.
- Limited probe of nuclear structure!

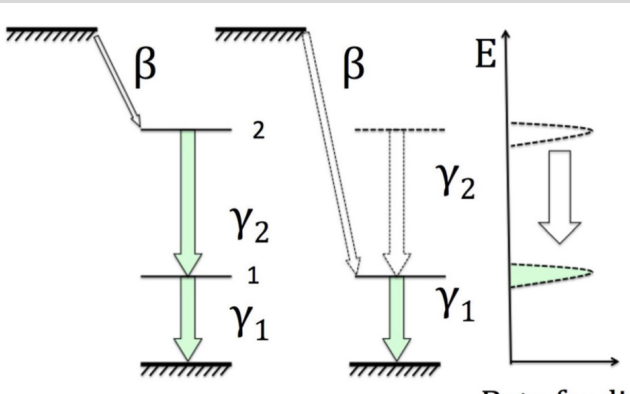




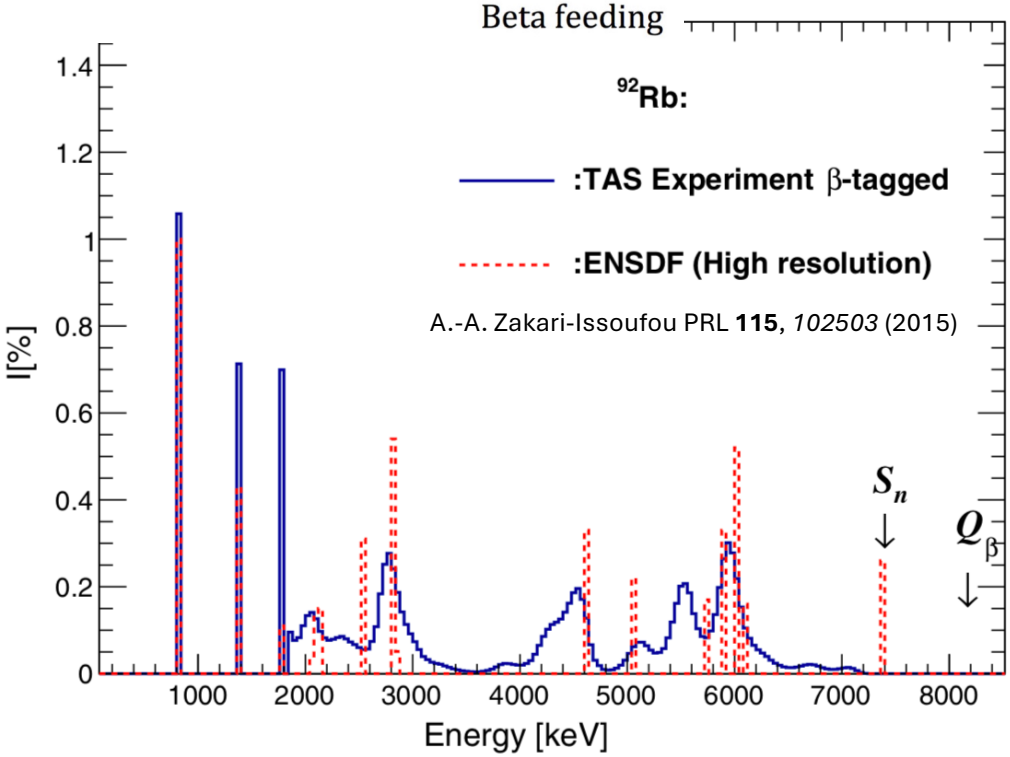


^{92}Rb β decay

- ^{92}Rb is a main contributor of high-energy $\bar{\upsilon}_e$
- High-Resolution Spectroscopy (HRS)
  - Early generation Ge detectors (1972)
  - *Pandemonium effect*
  - Missing β strength
  - → incorrect predictions for $\bar{\upsilon}_e$
- Total Absorption Spectroscopy
  - Alternative approach
  - Provides reliable β-feeding data
  - Impacts reactor decay heat calc.

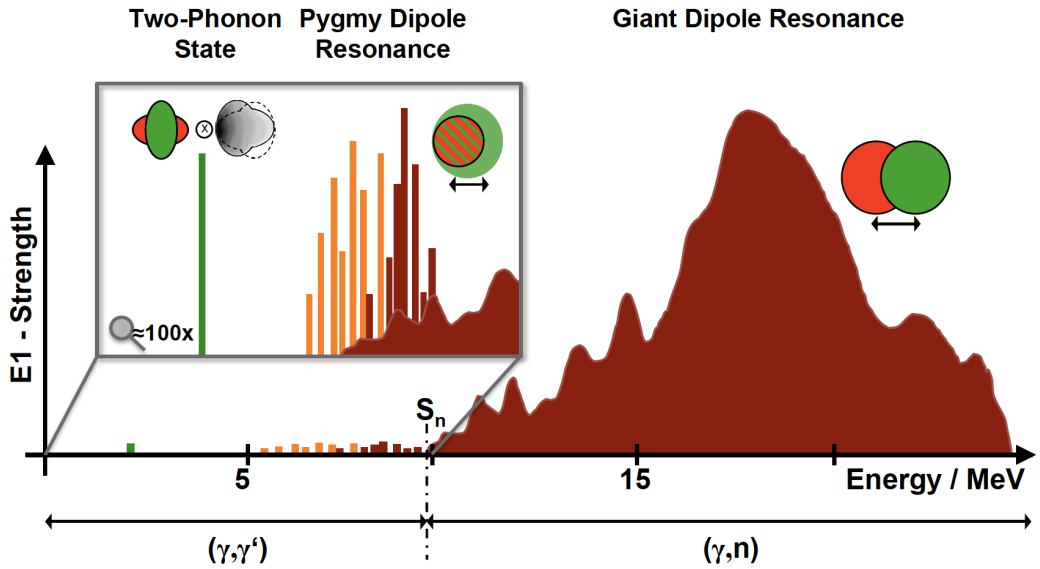


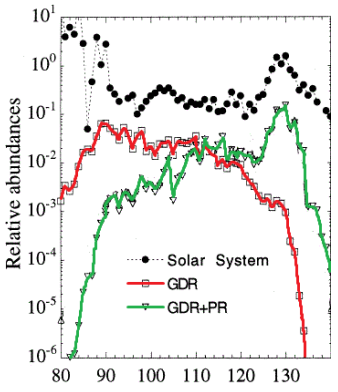
Beta feeding



β decay and Pygmy Dipole Resonance

- Resonance-like structure of 1^- levels situated low energy tail of the Giant Dipole Resonance.
  - Neutron-rich nuclei
- Exhausts few % of E1 strength of the EWSR.
- Split into Isoscalar and Isovector components.
- Impacts.
  - Nucleosynthesis.
  - Nuclear Equation of State.
  - Neutron stars.
- β offers alternative probe of PDR states.





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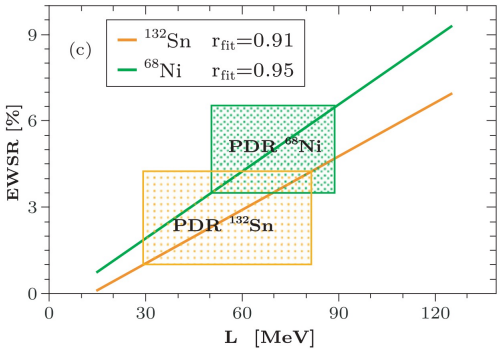
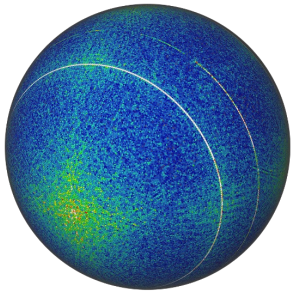


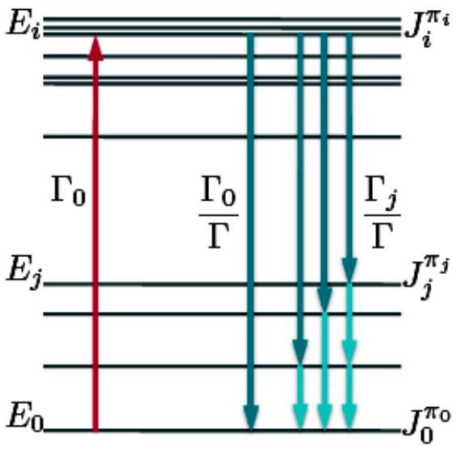
A. Carbone et al., PRC 81, 041301(R) (2010)

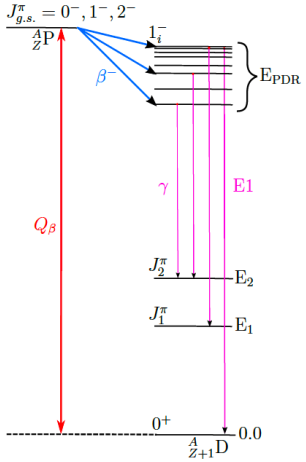


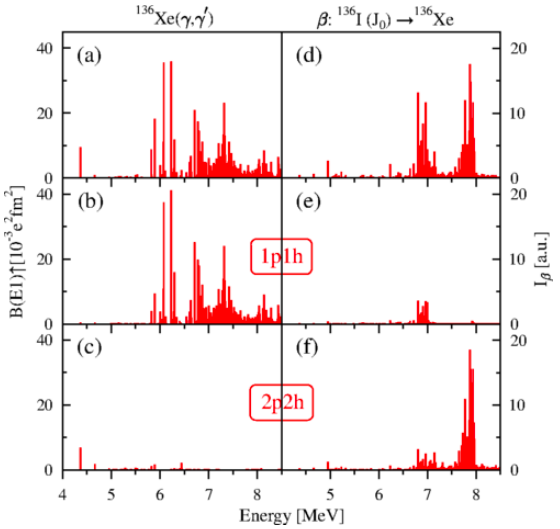
K. Sumiyoshi, Astrophys. J. 629, 922 (2005)
Lattimer et al., Phys. Rep. 442, 109 (2007)

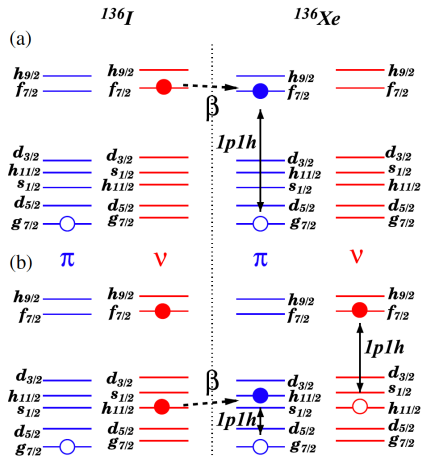
Probes for PDR

- Nuclear Resonance Fluorescence is the workhorse of PDR studies
  - Excellent excitation of $\mathbf{1}^-$ levels.
  - Direct measurement of B(E1) values.
  - Only suitable for stable nuclei.
  - ^{92}Sr is not [$T_{1/2}$ = 2.66(4) h].
  - Preferentially excites 1p-1h states.
- ^{92}Rb: $J^\pi = 0^-$, Q_β = 8096 keV.
- Transitions to ^{92}Sr (S_n = 7.3 MeV)
  - Allowed to 0^- and $\mathbf{1}^-$
  - First Forbidden to 0^+, 1^+ and 2^+





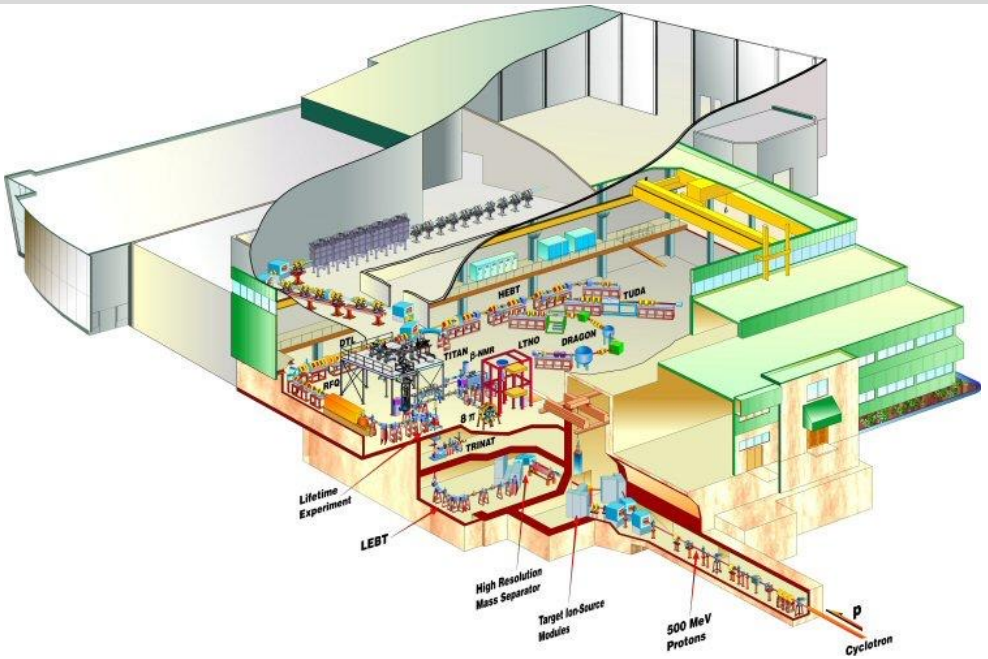


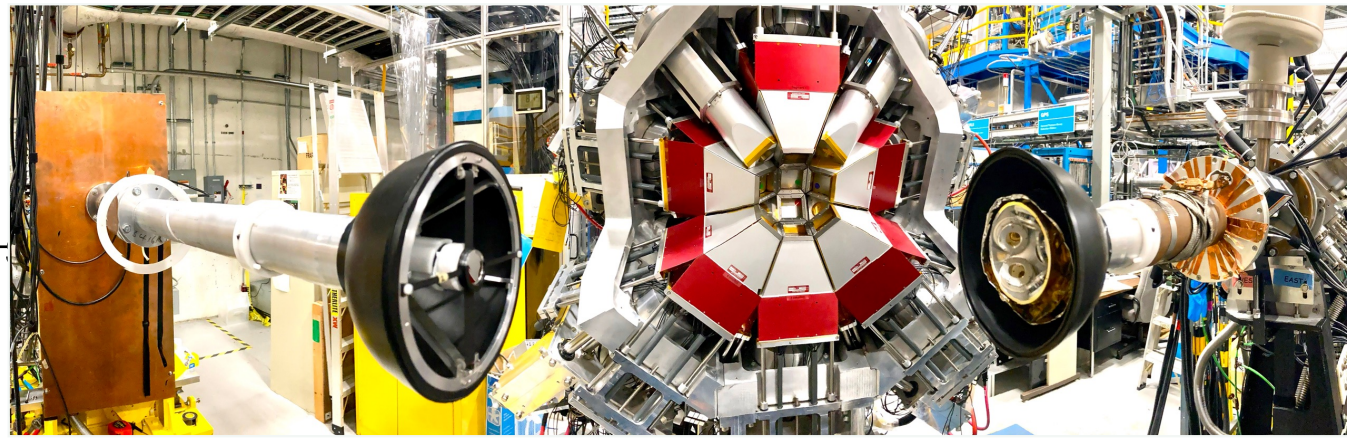


Scheck et al. Phys. Rev. Lett 116, 132501 (2016)

Experiment

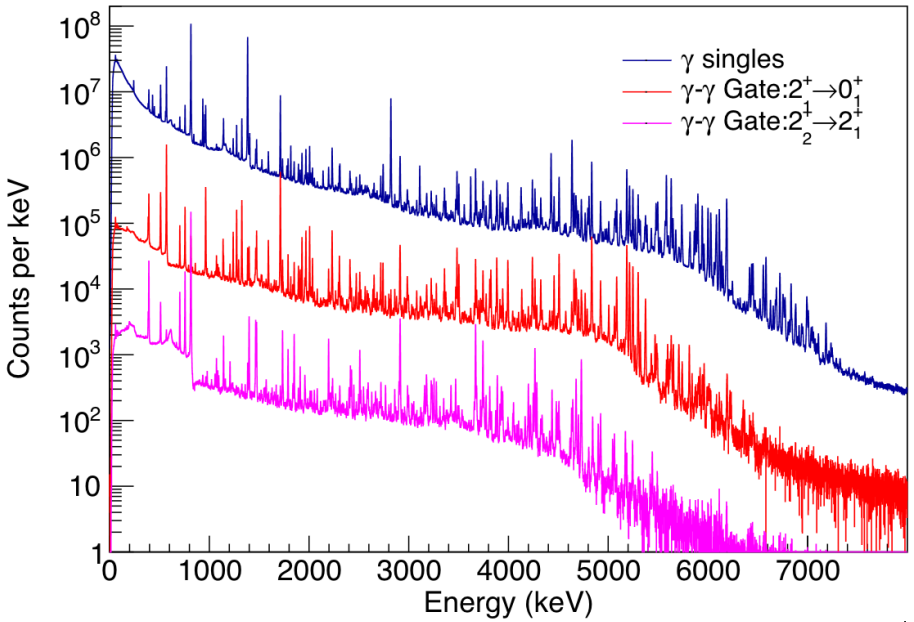
- Performed at ISAC, TRIUMF
- 480 MeV protons on UC_x target.
  - ^{92}Rb from Surface Ion Source
  - Yield: ~ 10^9 pps
- Delivered to GRIFFIN
  - ~10^6 pps for ~10 hours
  - 15 HPGe Clover detectors
    - Anti-Compton shielding
  - ~~ZDS: β-tagging~~
  - ~~PACES: Conversion electron~~
  - $LaBr_3$(Ce): Fast-timing

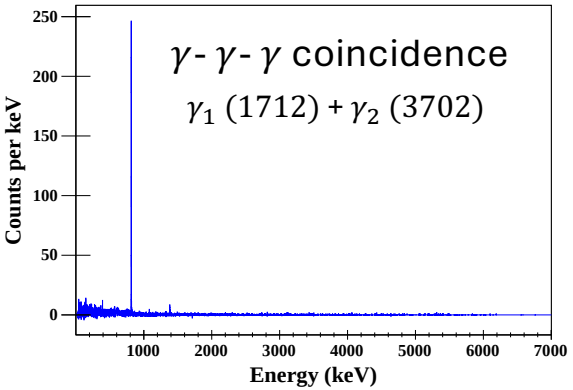


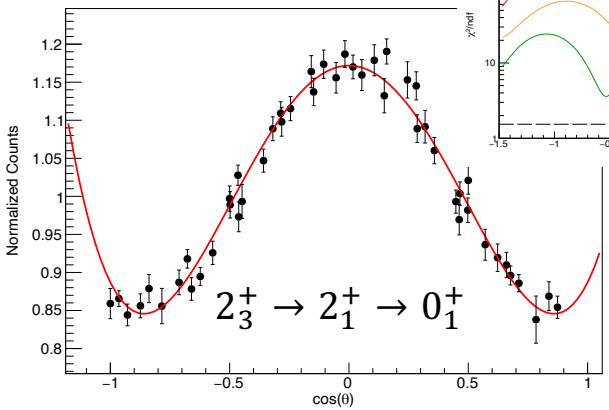


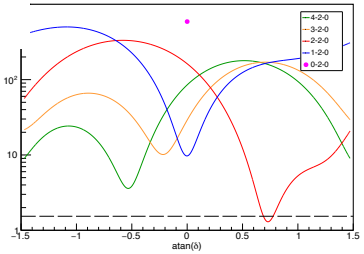
Results

- ~1.6 x 10^{11} decays occurred
  - Massive data set
  - Many, many, many γ rays
- 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



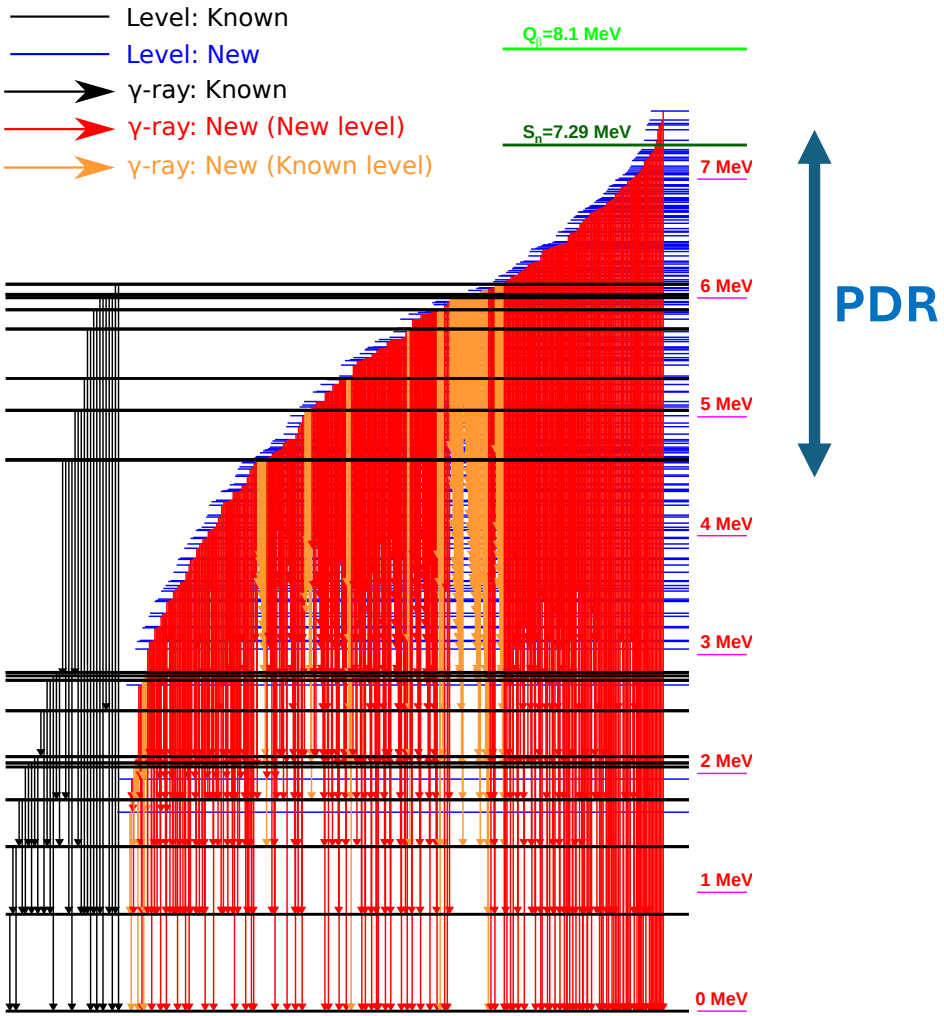






^{92}Sr Levels

- Early β-decay studies from late 70s/early 80s.
  - 17 excited states.
  - ~ 50 γ-ray transitions.
- GRIFFIN
  - **~190 excited states** populated!
  - Many levels in the PDR.
  - Strongly fragmented γ-decay strength.
  - **~ 864 γ-ray transitions!**

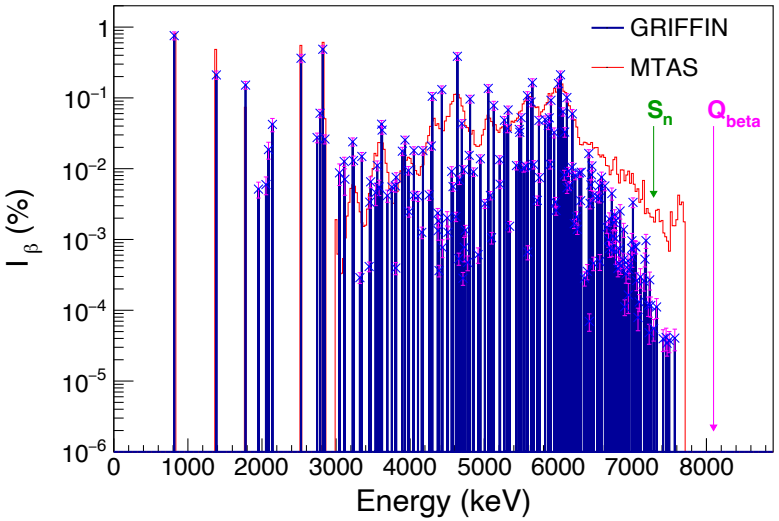


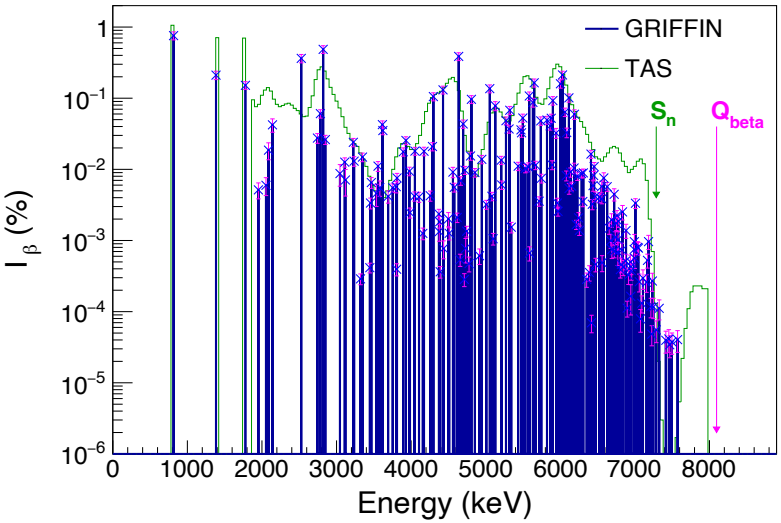
GRIFFIN vs. TAS

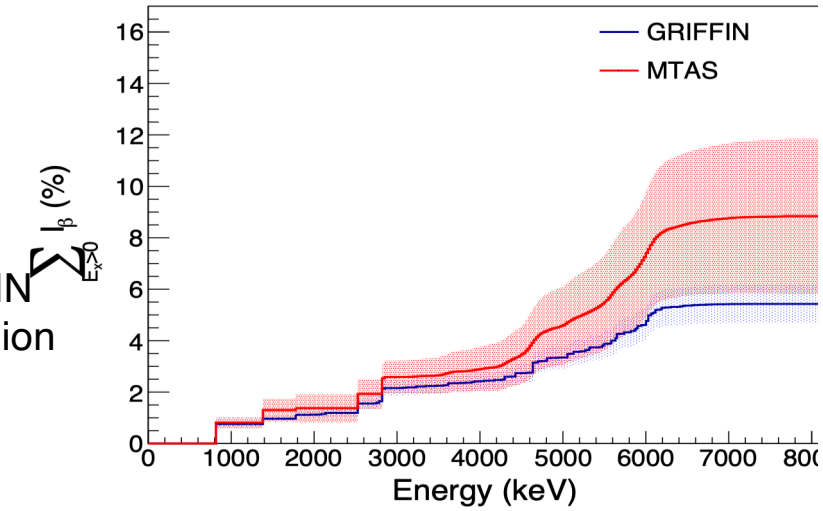
TAS (Green): A.-A. Zakari-Issoufou
PRL **115**, *102503* (2015)
MTAS (Red) : C. Rasco, PRL **117**, *092501* (2016).

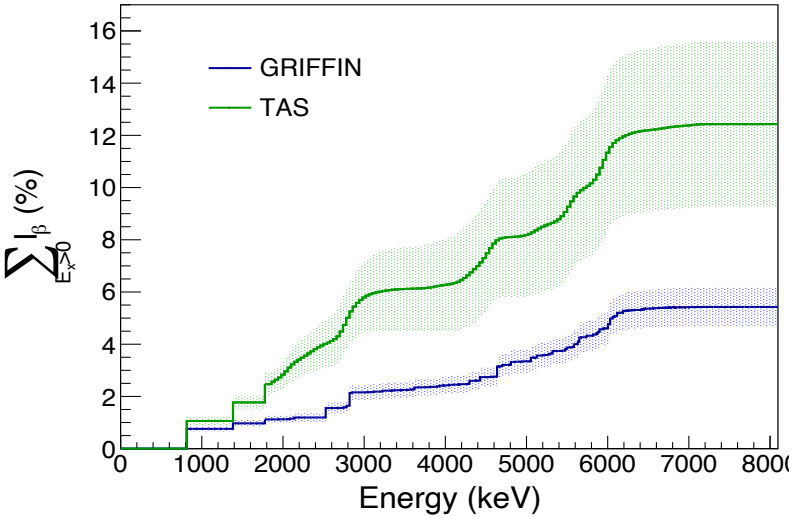
Direct β-feeding
- Examine structure.

Cumulative β-feeding
- Examine ***Pandemonium***.
- New Results from GRIFFIN show significant suppression of *Pandemonium*.









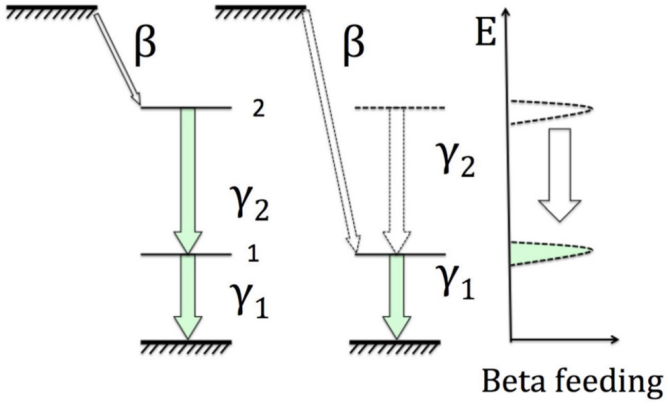
Pandemonium

- Misplaced β-feeding originates from unobserved or misplaced γ rays.
- Lots of weak transitions can add up.
- 6030-keV Level
  - ENSDF: 3 transitions
  - GRIFFIN: 40 transitions
  - **Missing transitions 54% I_β**

E_x (keV)	J^π	I_β^{Rel} (%)	I_β^{Abs} (%)	log ft
6030.00(7)	$1^{\pm}$ [a,b,d]	28.3(13)	0.21(3)	5.80(7)

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

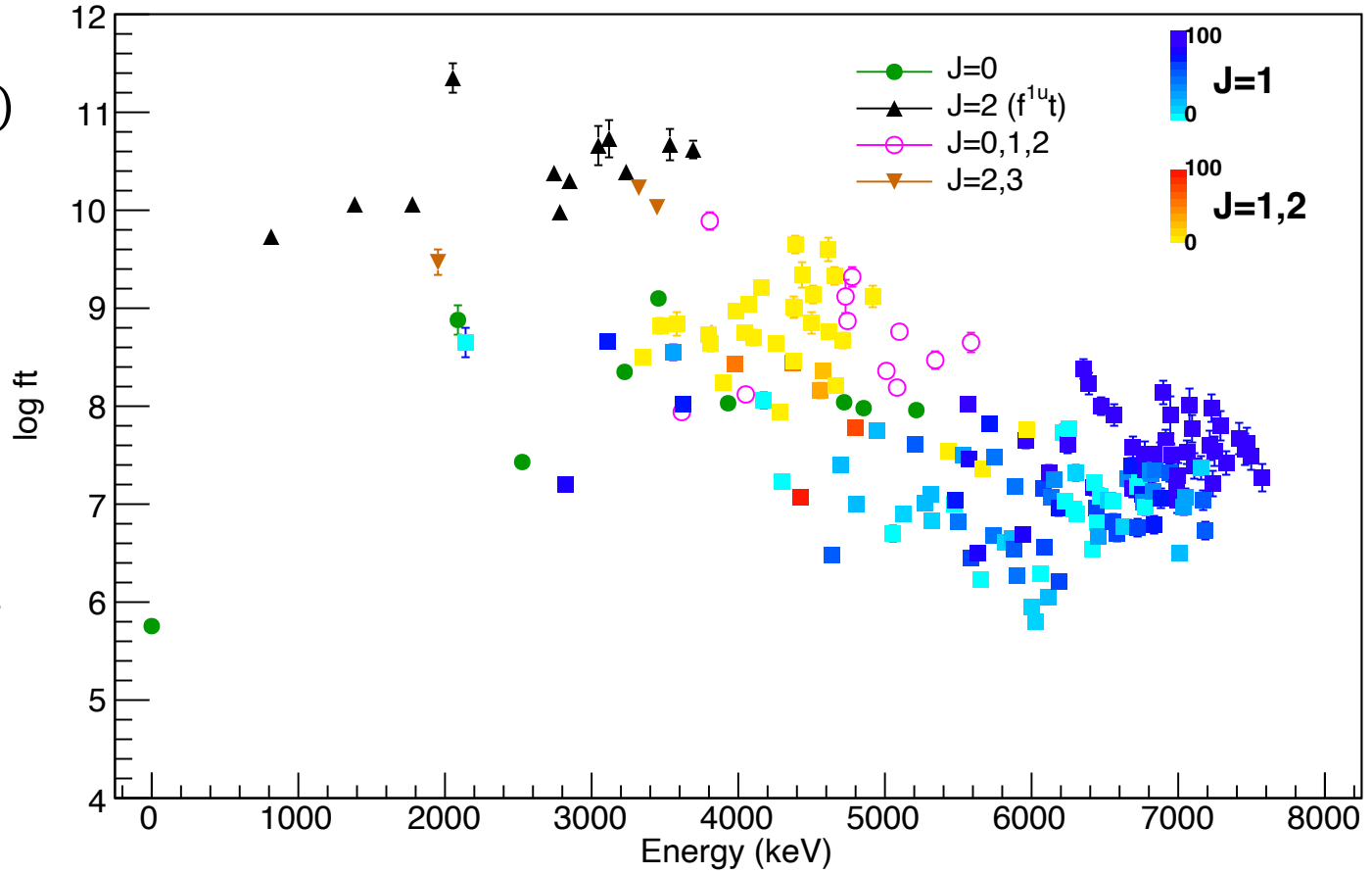
$$\sum_{I_\gamma} BR_\gamma^{abs.}(I_\gamma < 5\%) = 40\ \%$$

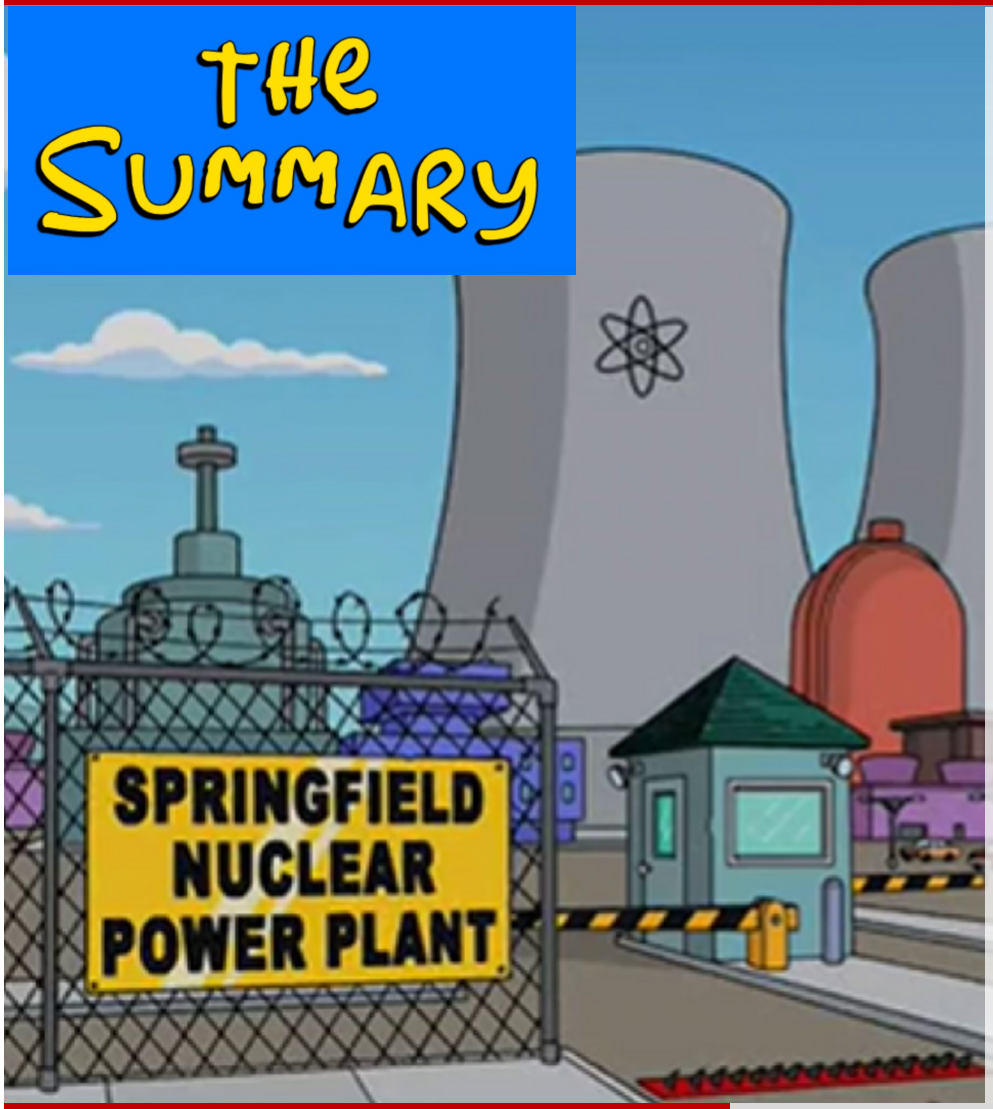


E_γ (keV)	E_f (keV)	J_f^π	I_γ^{Rel} (%)	BR_γ
931.0(3)	5098.9(2)	0,1,2	0.0141(15)	0.90(10)
1081.7(3)	4948.45(15)	$1^{\pm}$	0.038(4)	2.5(3)
1220.5(7)	4808.39(9)	$1^{\pm}$	0.017(3)	1.1(2)
1233.6(3)	4796.36(15)	1,2	0.057(5)	3.7(3)
1392.2(3)	4637.66(7)	$1^{\pm}$	0.048(5)	3.1(3)
1415.9(4)	4614(3)	1,2	0.007(1)	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)

^{92}Rb $(0^-) \rightarrow$ ^{92}Sr *log ft* values

- ^{92}Rb $(0^-) \rightarrow$ ^{92}Sr $(0^+, E_x = 0)$
  - I_β = 94.6(8) %
  - log *ft* = 5.755(5)
  - Very fast FF transition!
- Below 4.5 MeV
  - First-Forbidden transitions.
- Above 4.5 MeV
  - Allowed transitions to 1^- levels.
  - PDR!





- Reactor Antineutrino experiments have played a pivotal role in neutrino physics.
- Reliable β-decay data is essential for future reactor experiments and to improve decay-heat calculations.
- State-of-the-art HPGe arrays can suppress Pandemonium to obtain results consistent with TAS.
  - Excellent agreement despite
  - High-level density.
  - Fragmented γ-decay.
  - Provides highly complementary data.
- ^{92}Rb decay is examined in unparalleled detail.
  - 190 levels populated + 864 γ-ray transitions observed.
  - Many 1^- levels in PDR region populated.
  - β decay offers alternative probe for PDR studies!

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

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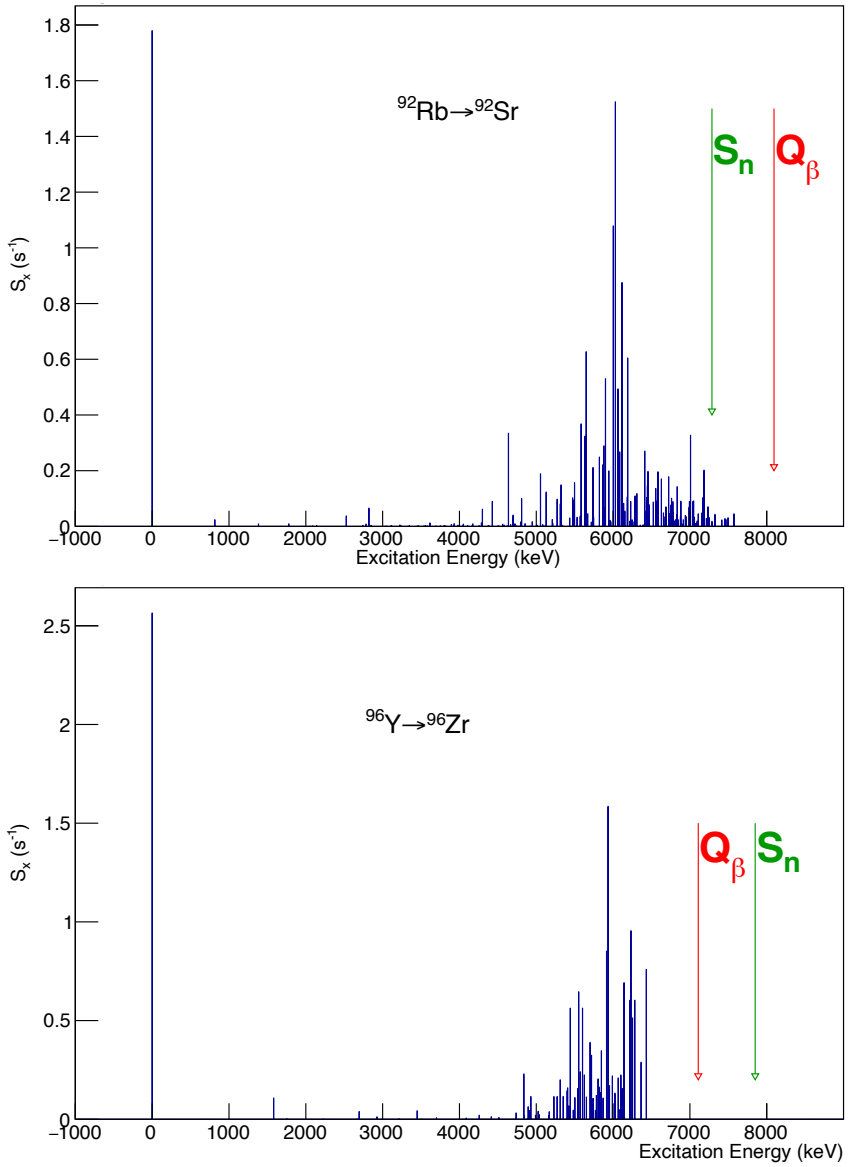
^{92}Rb→^{92}Sr
S_n
Q_β
S_x (s^{-1})
Excitation Energy (keV)
^{96}Y→^{96}Zr
Q_β
S_n
S_x (s^{-1})
Excitation Energy (keV)