$\boldsymbol{\beta^-}$ decay of ^{92}Rb
Reactor Antineutrino Anomaly
and
Pygmy Dipole Resonance

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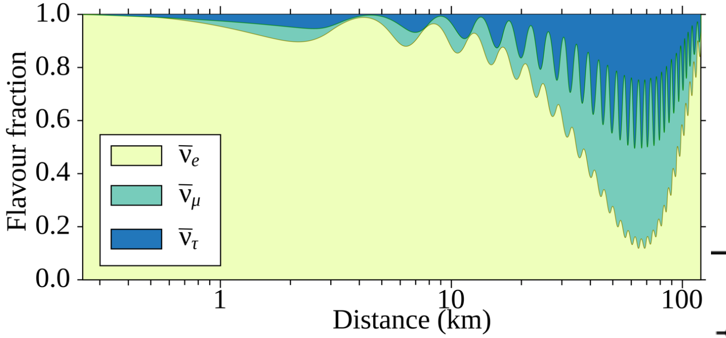
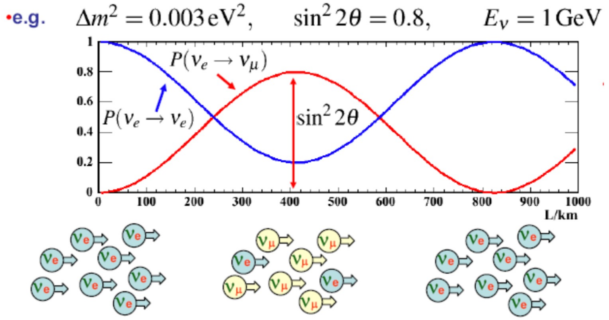
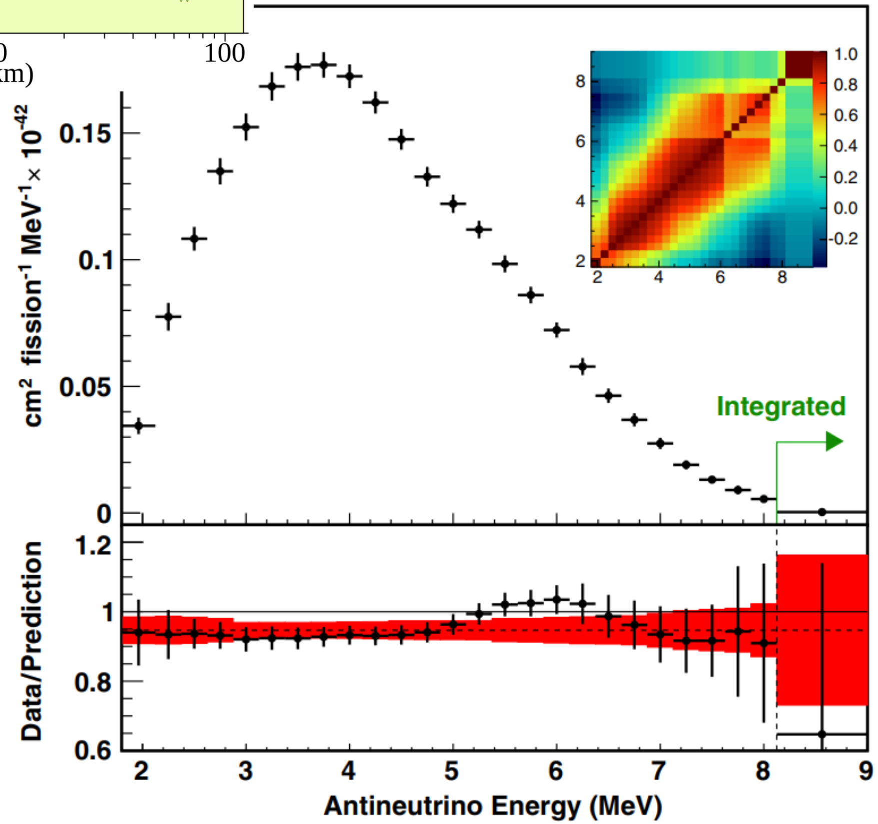
SFU TRIUMF GRIFFIN

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

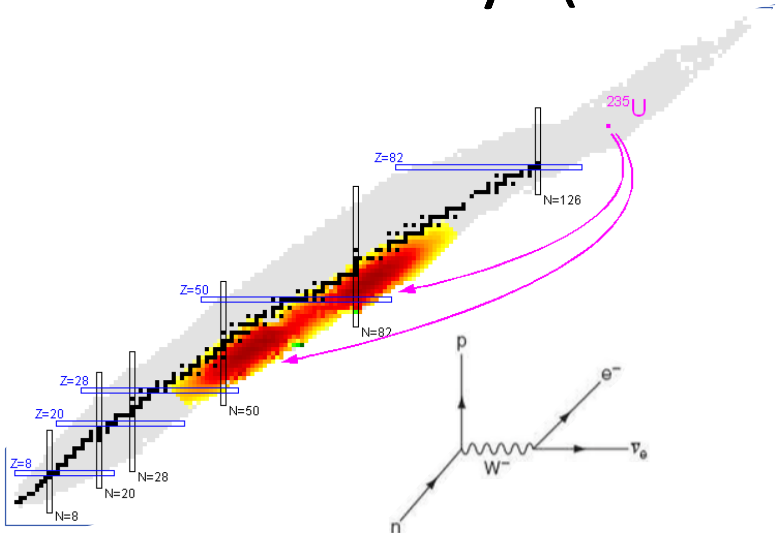


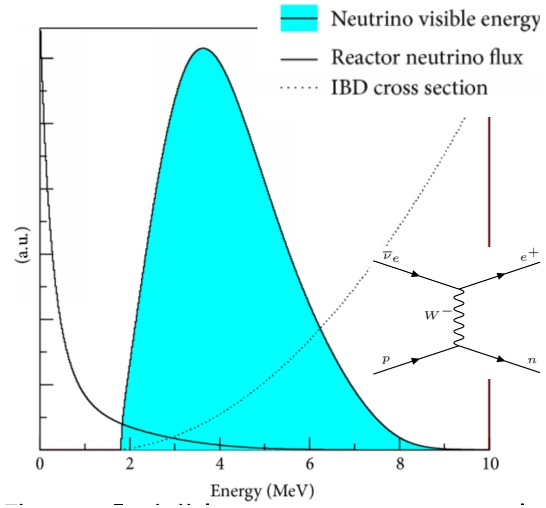




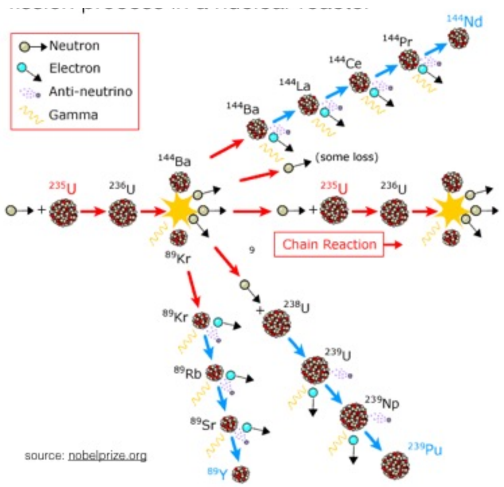
Reactor Antineutrino Anomaly (RAA)

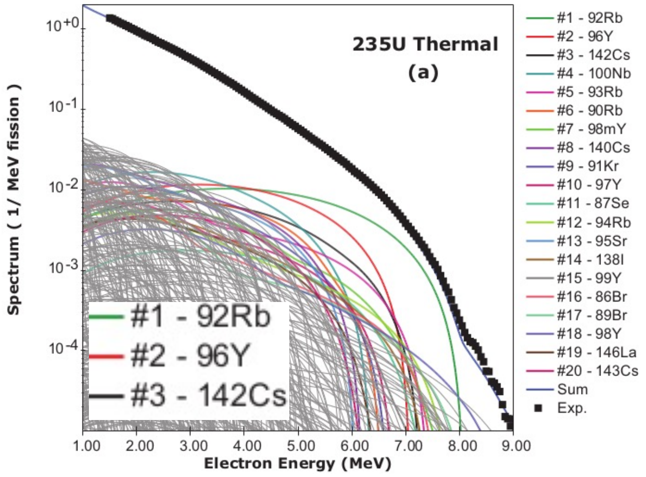
- $\bar{\nu}_e$ flux
  - measured via inverse β decay (IBD)
    - $p + \bar{\nu}_e \rightarrow n + e^+$ [E($\bar{\nu}_e$) > 1.8 MeV]
  - Produced via β decay of fission fragments
  - $\bar{\nu}_e$ energy spectrum
    - Dependent on β-decay properties





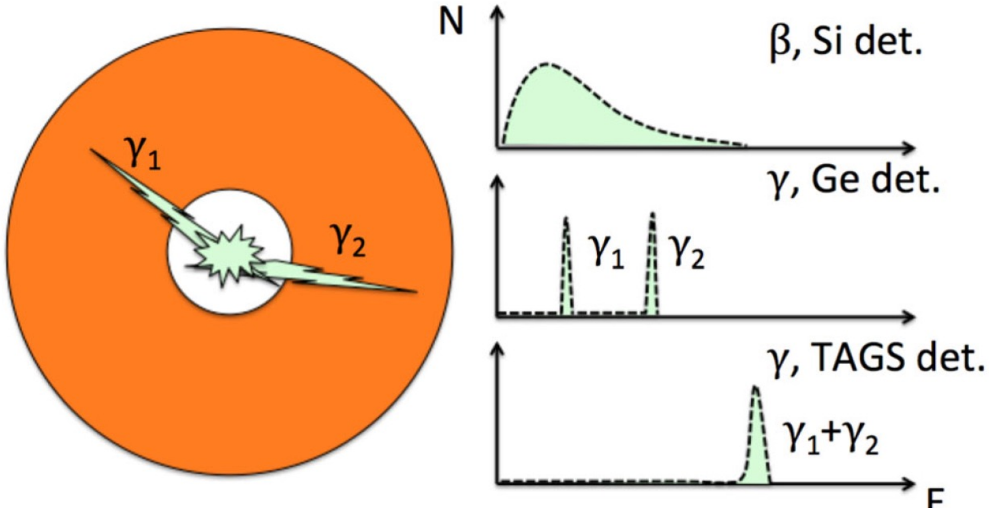
- $\bar{\nu}_e$ flux calculations
  - Requires robust β-decay data!
  - Much existing data is not.
    - Pandemonium effect!
  - Total Absorption Spectroscopy to the rescue.
- Decay Heat.
  - Reactor safety.

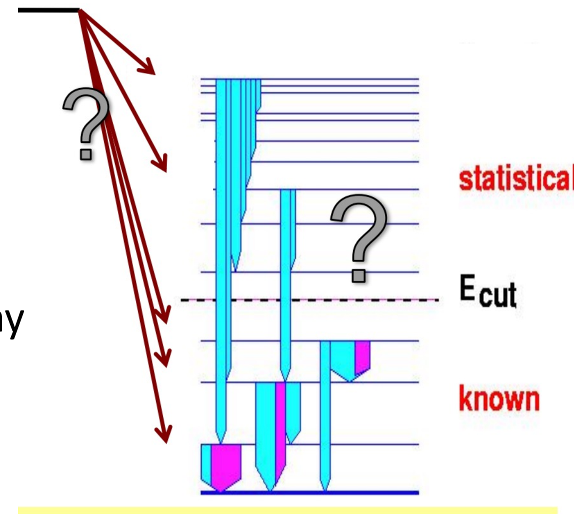


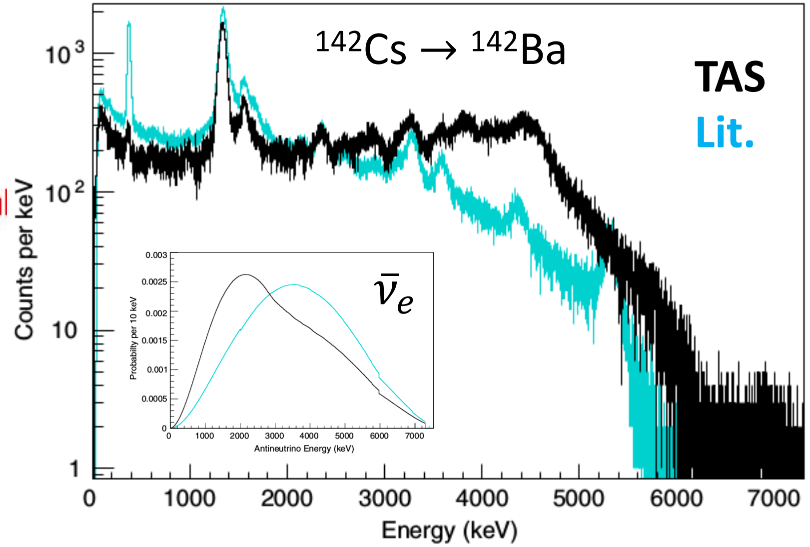


Total Absorption Spectroscopy

- 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.

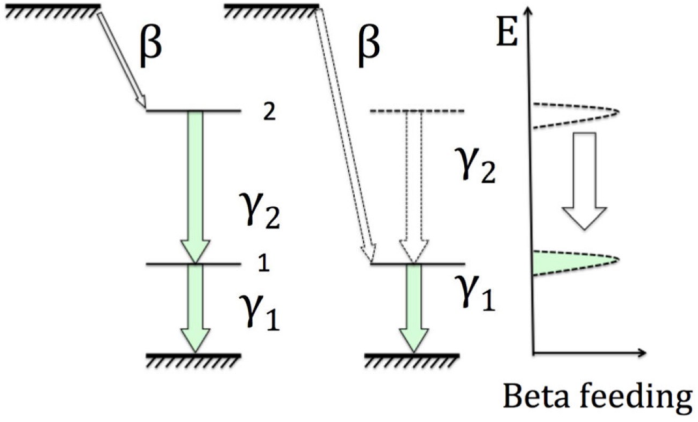




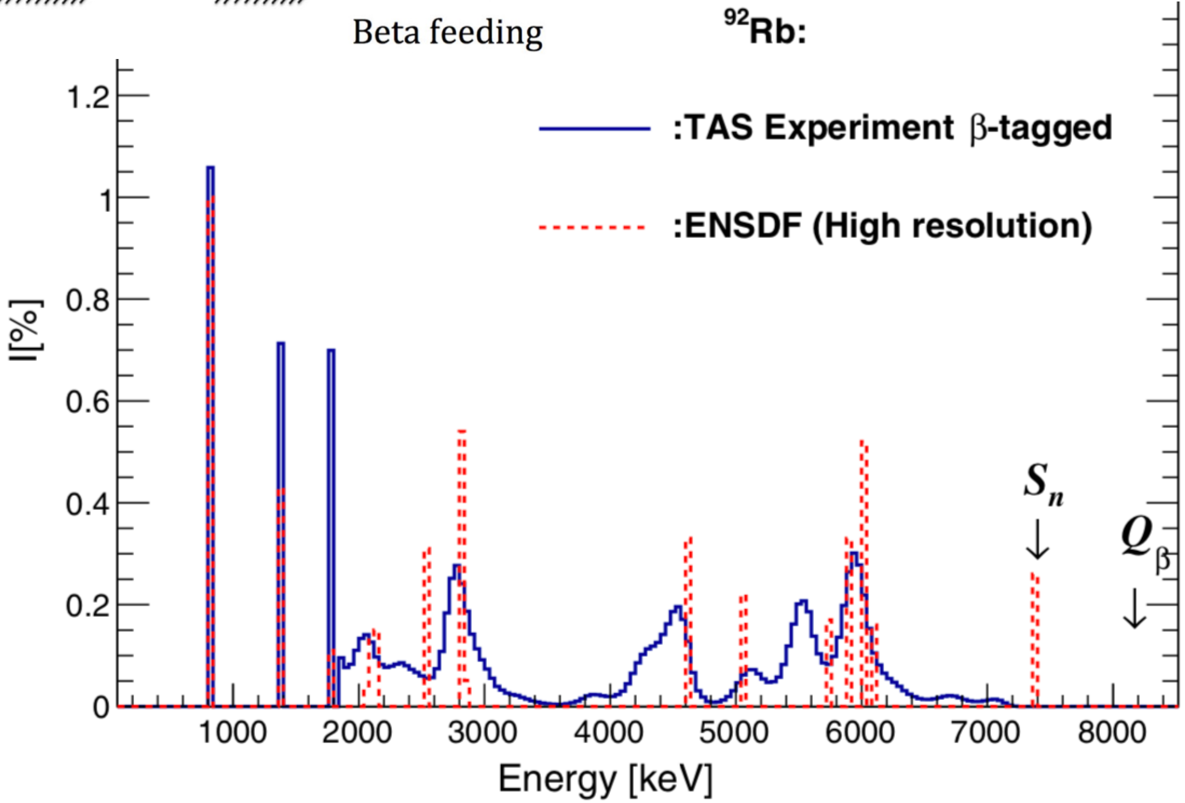


β^- data ^{92}Rb $\rightarrow$ ^{92}Sr

- ^{92}Rb
  - 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
  - $0^- \rightarrow 1^-$

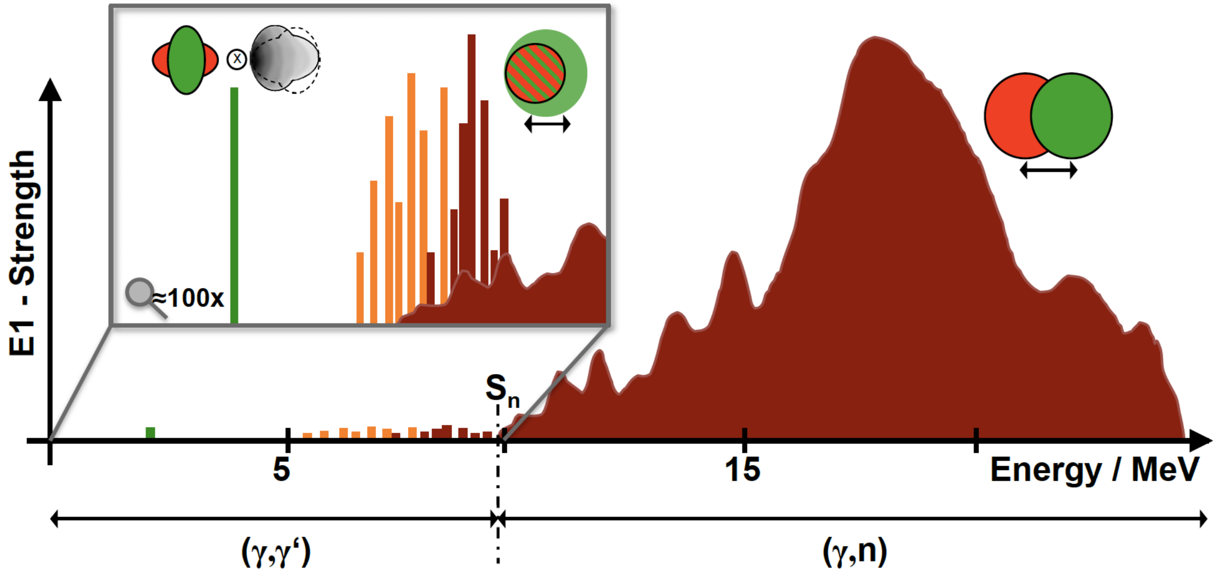


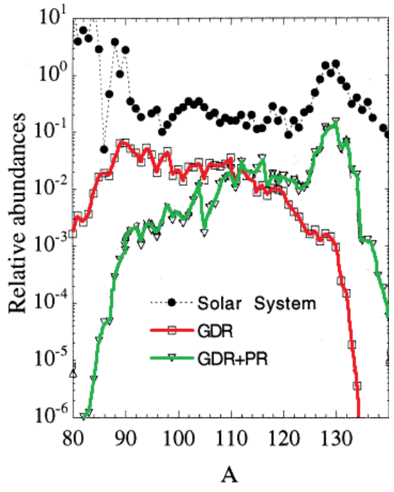
A.-A. Zakari-Issoufou et al, Phys. Rev. Lett. 115, 102503 (2015)



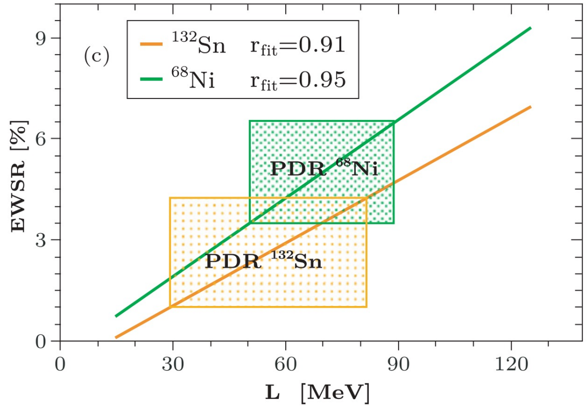
Pygmy Dipole Resonance

- Resonance-like structure of 1^- levels situated low energy tail of the GDR.
    - Neutron-rich nuclei
- Exhausts few % of E1 strength of the EWSR.
- Split into Isoscalar and Isovector components.
- 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.

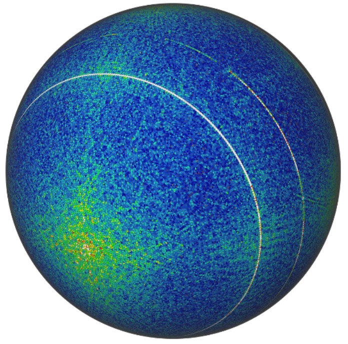




S.Goriely et al., Phys. Lett.B 436 (1998) 10



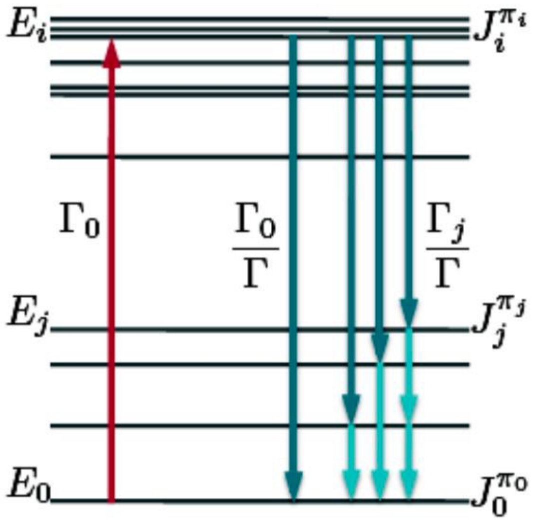
A. Carbone et al., PRC 81,
B. 041301(R) (2010)

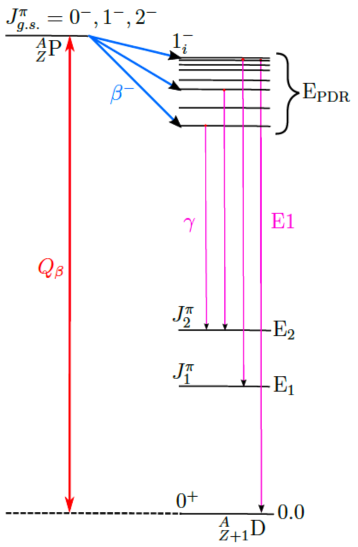


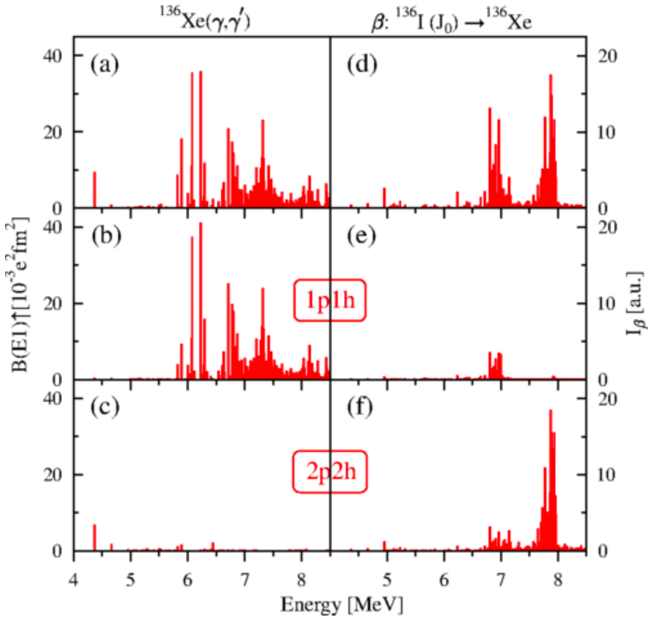
K. Sumiyoshi, Astrophys. J. 629, 922 (2005)
Lattimer et al., Phys. Rep. 442, 109 (2007)

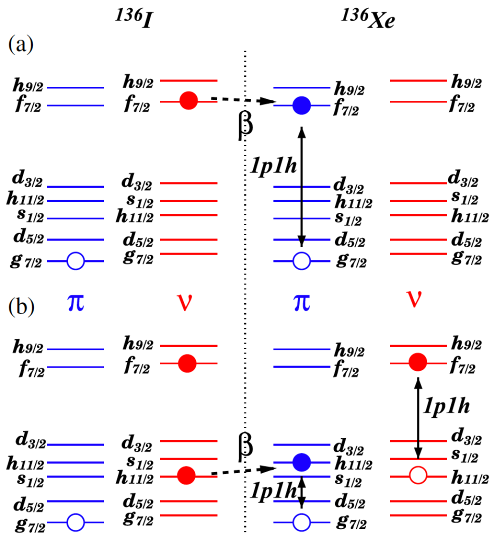
Probes for PDR

- Nuclear Resonance Fluorescence is the workhorse of PDR studies
  - Excellent excitation of 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 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.





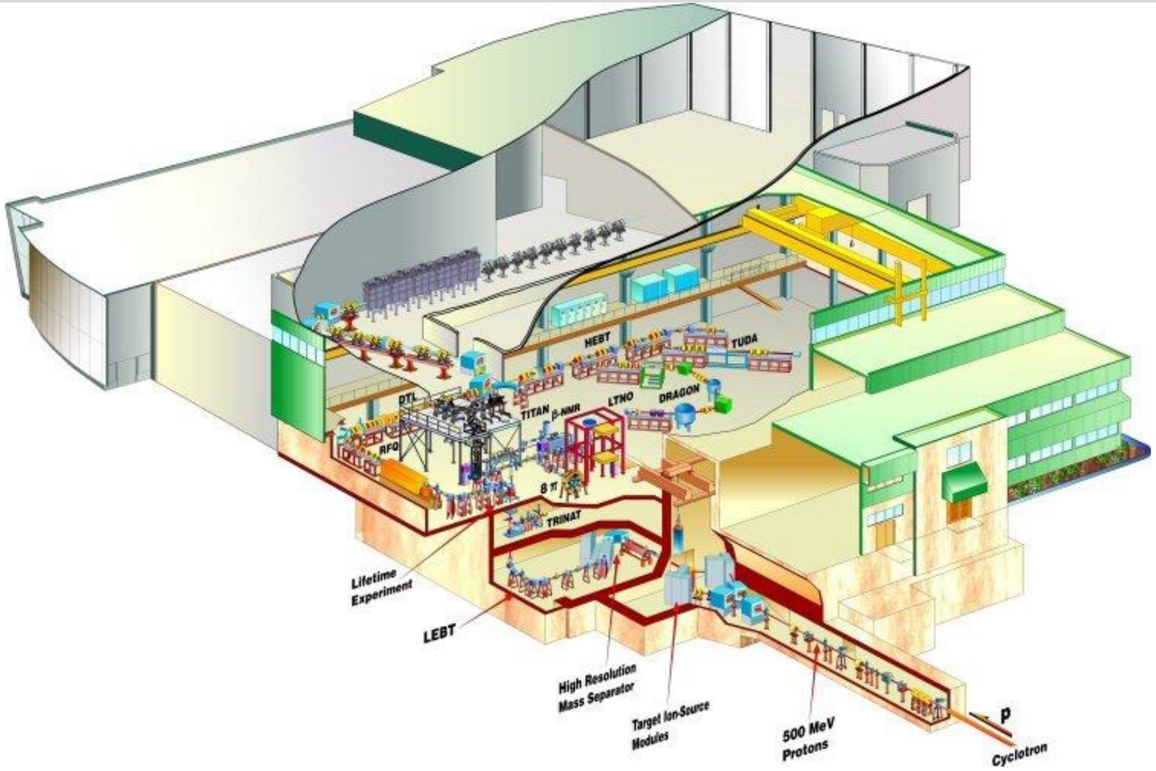


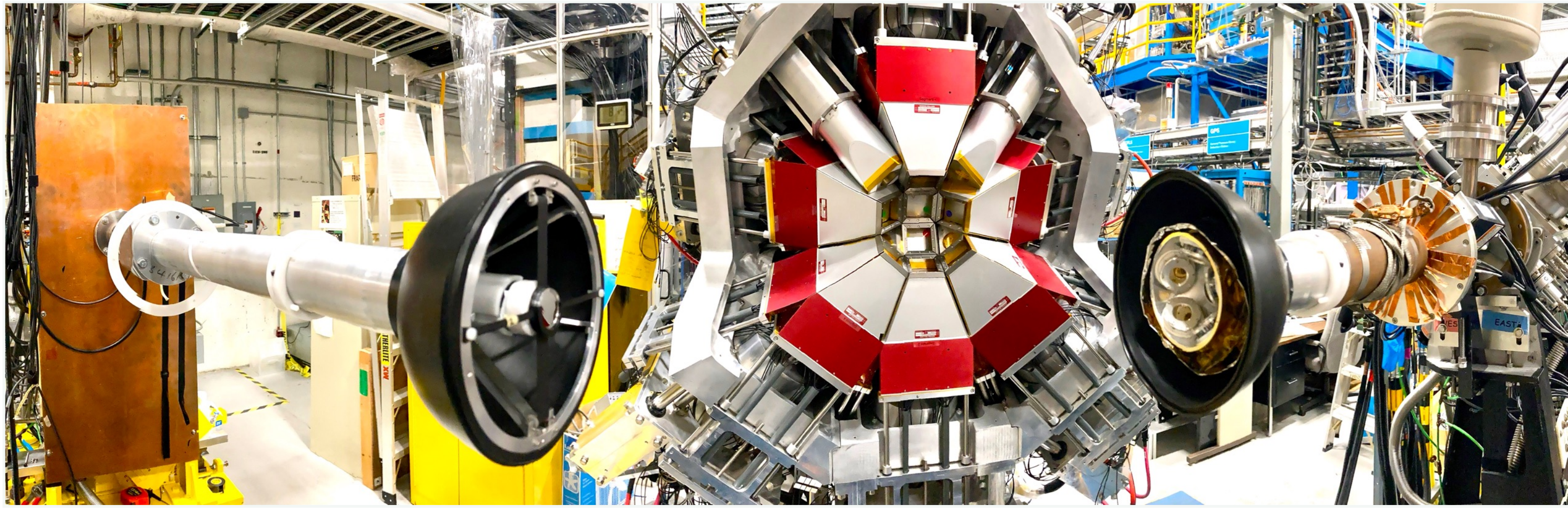


Scheck et al. Phys. Rev. Lett 116, 132501 (2016)

Experiment

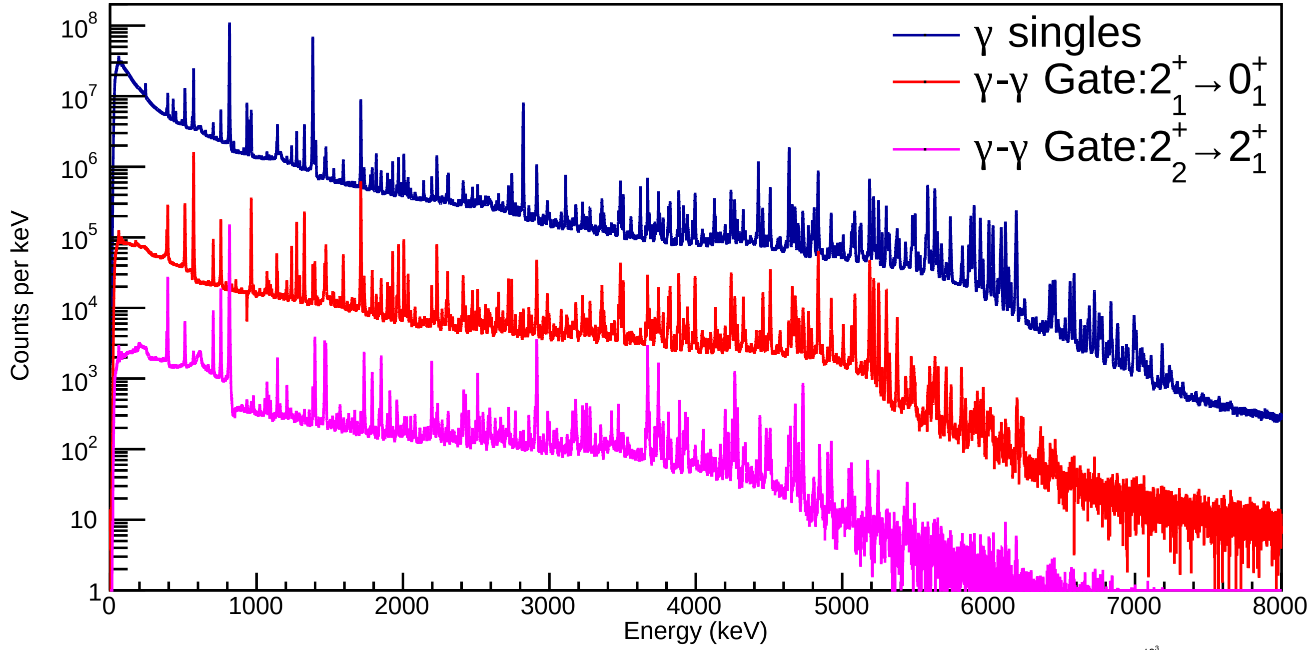
- Performed at ISAC, TRIUMF
- 480 MeV protons on UC_x target.
  - ^{92}Rb from Surface Ion Source (SIS)
  - Yield: $\sim 10^9$ pps
- Delivered to GRIFFIN
  - $\sim 10^6$ pps for ~ 10 hours
  - 15 HPGe Clover detectors
    - Anti-Compton shielding
  - ZDS: β-tagging
  - PACES: Conversion electrons
  -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

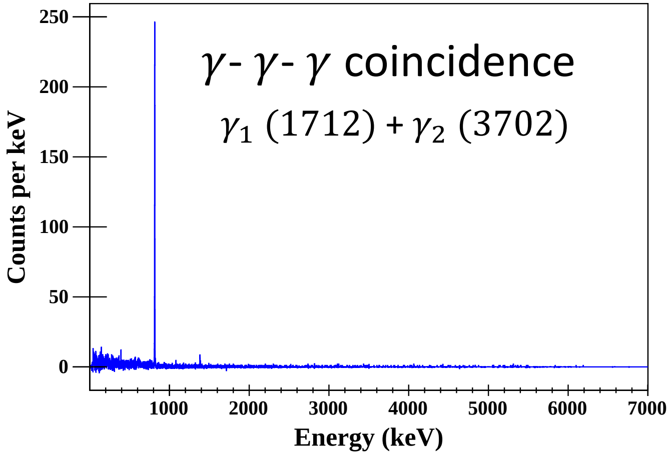


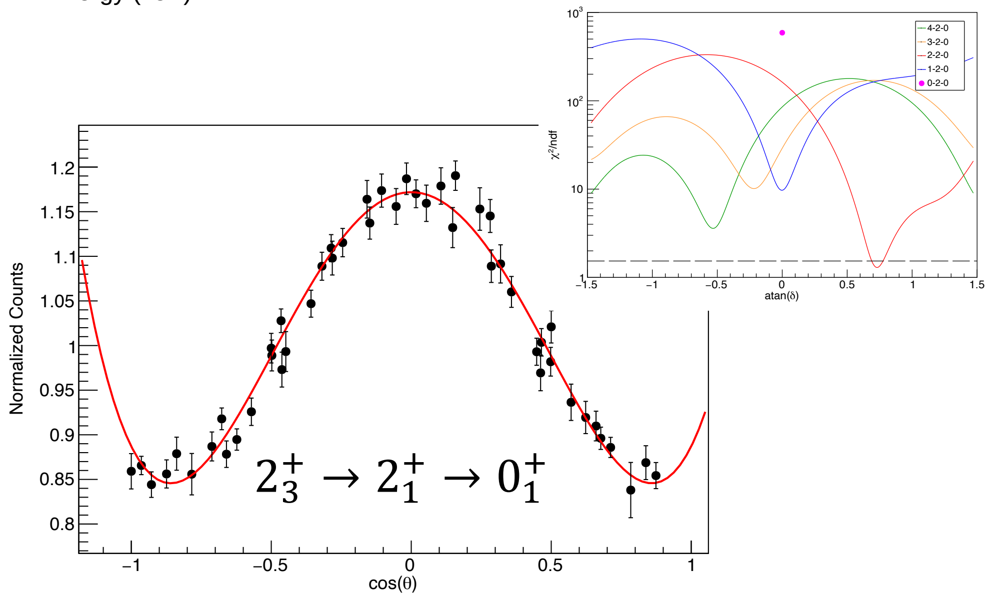


Results

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

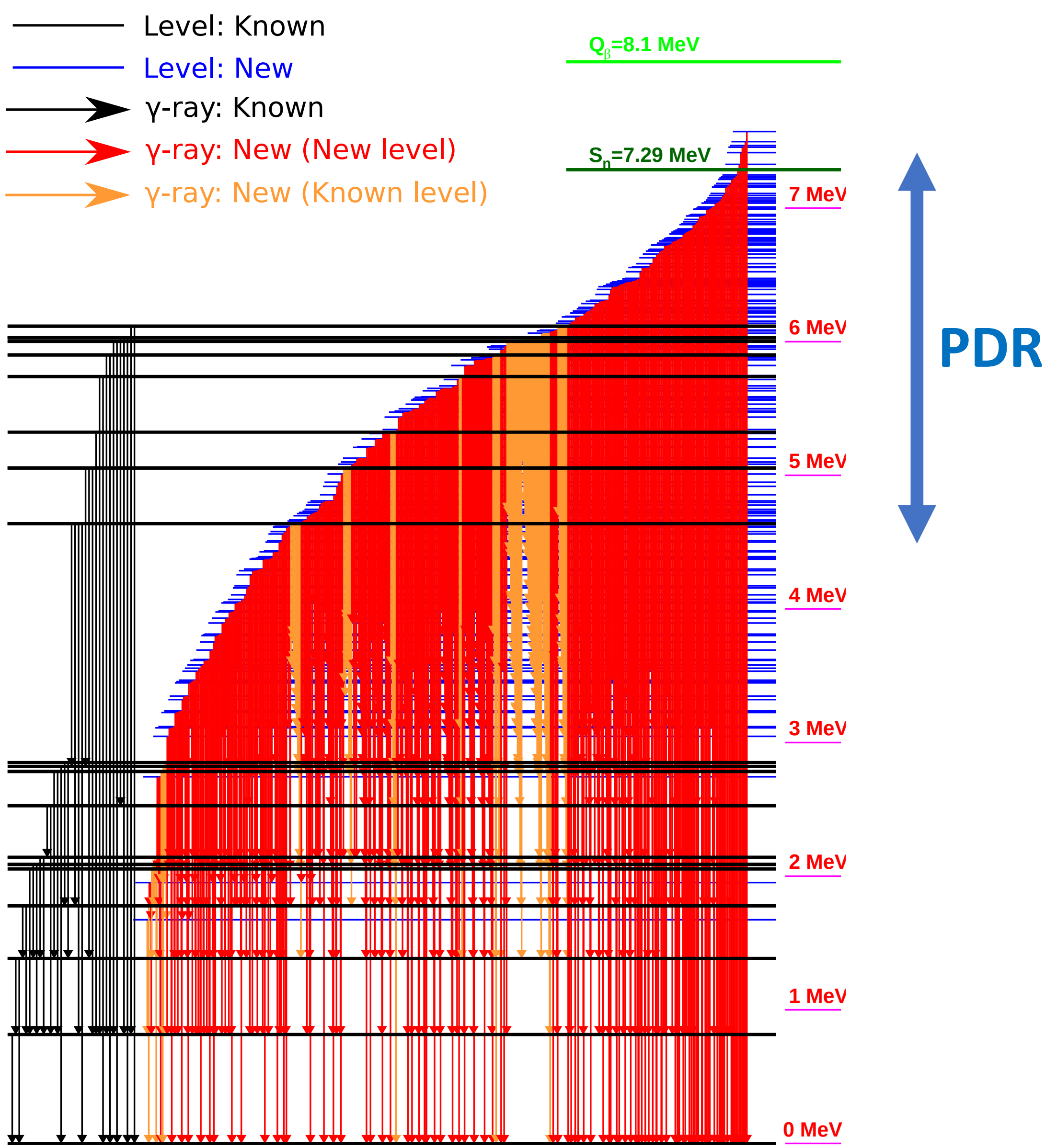






^{92}SR Levels

- Early 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

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- 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)

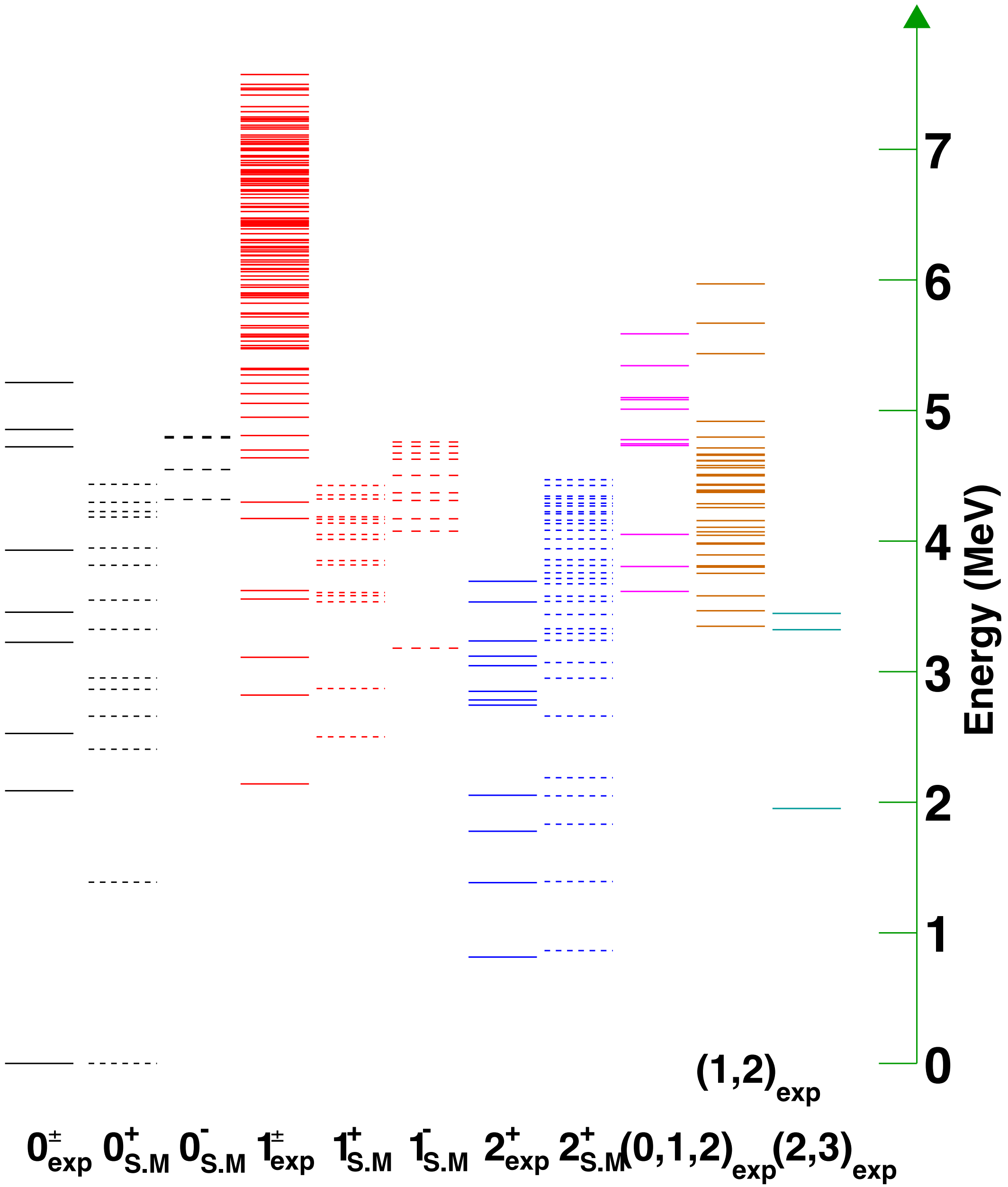
40 γ-ray transitions from one level!

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

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

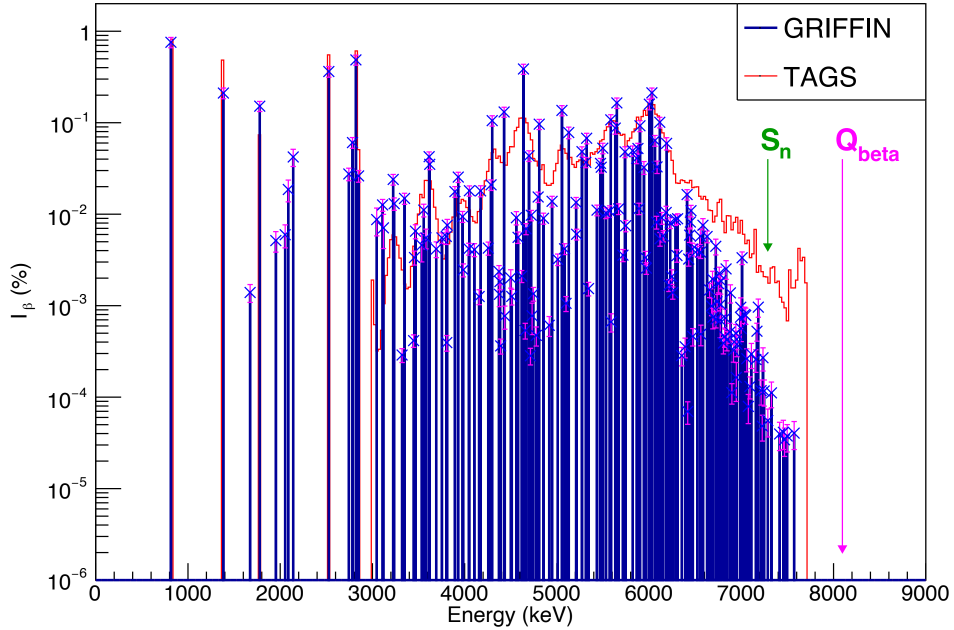
Shell-Model calculations

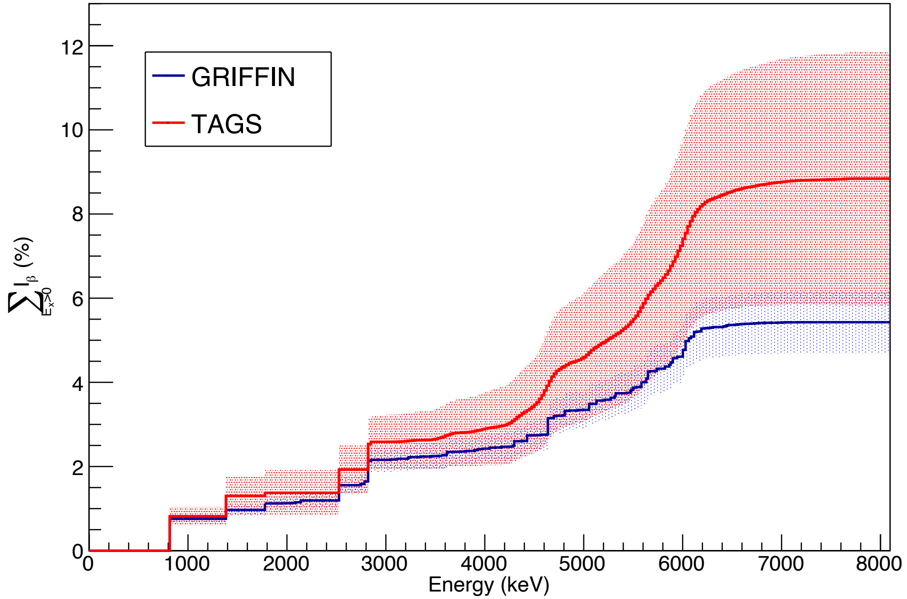
- Calculations by Marlom Ramalho
  - University of Jyväskylä
- ^{92}Sr (Z=38, N=54)
- ^{78}Ni closed core (Z=28,N=50)
  - 10 protons
  - π: $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$
  - 4 neutrons
  - ν: $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$
- 250 states up to 5 MeV
- Extrapolating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





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 $\rightarrow$ β spectrum shape
  - Excellent agreement despite
    - High-level density.
    - Fragmented γ-decay.
  - Only possible thanks to high beam intensities and GRIFFIN capabilities.

Thank you to my Collaborators!

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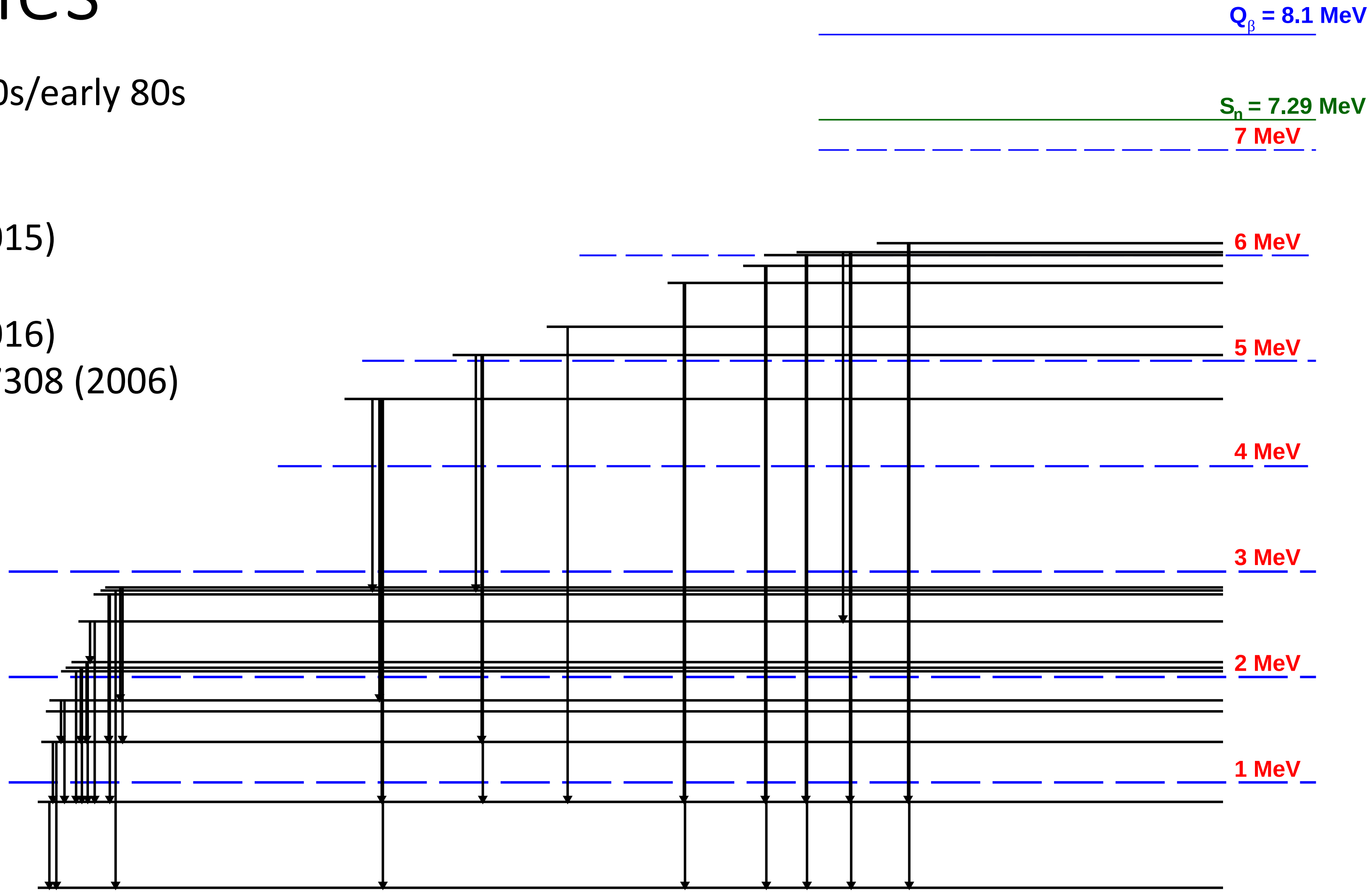
Previous studies

- 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)
  - $\boldsymbol{I_\gamma(2_1^+ \rightarrow 0_1^+) = 3.2(4)\%}$
- 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) %



Current level scheme

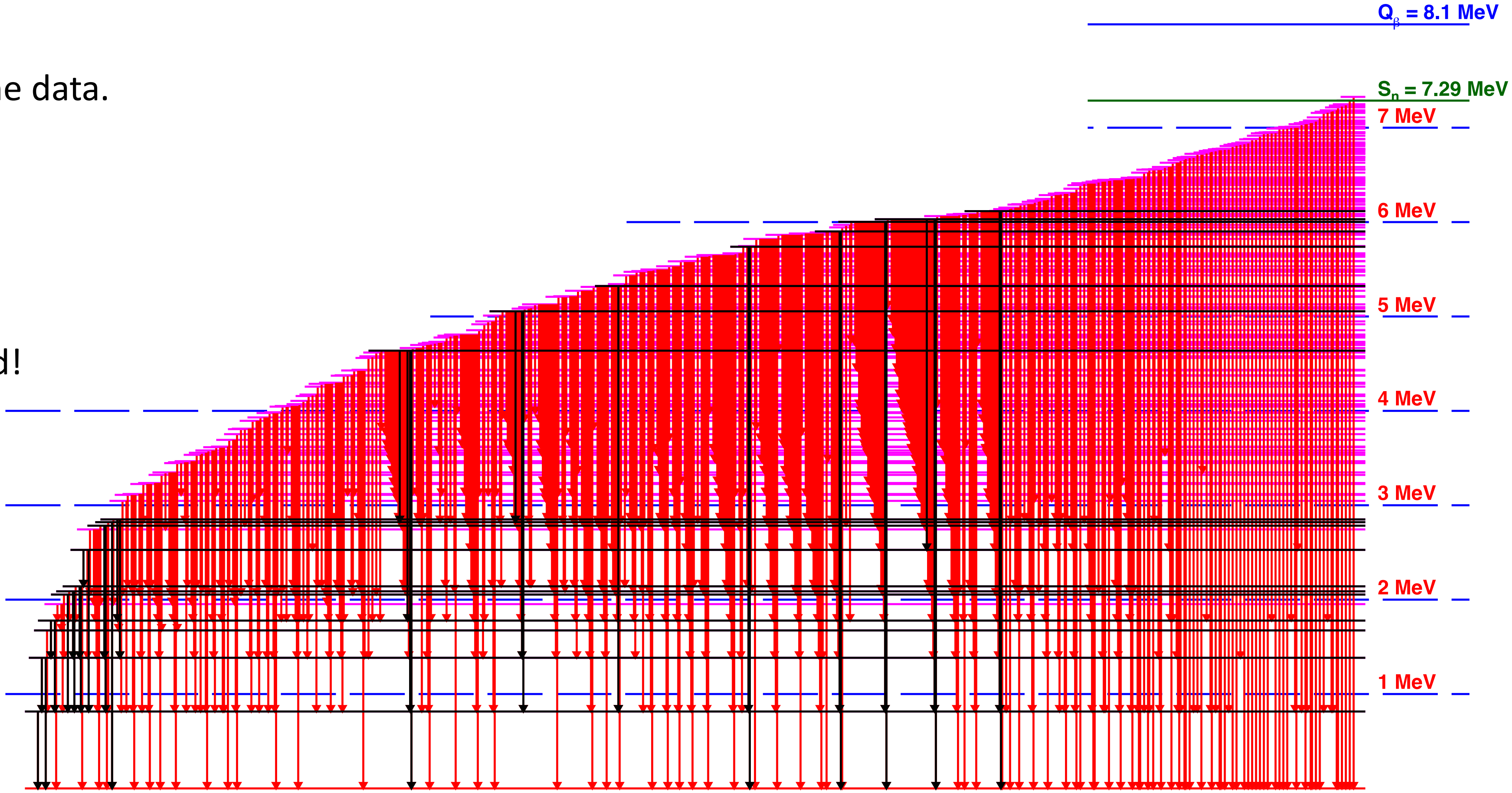
$\sim$170 levels observed in the data.

$\sim$680 γ-ray transitions.

There are errors!

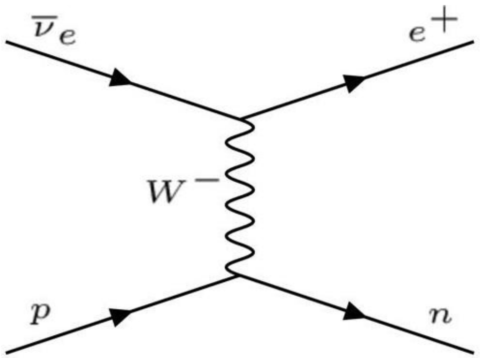
Some transitions misplaced!

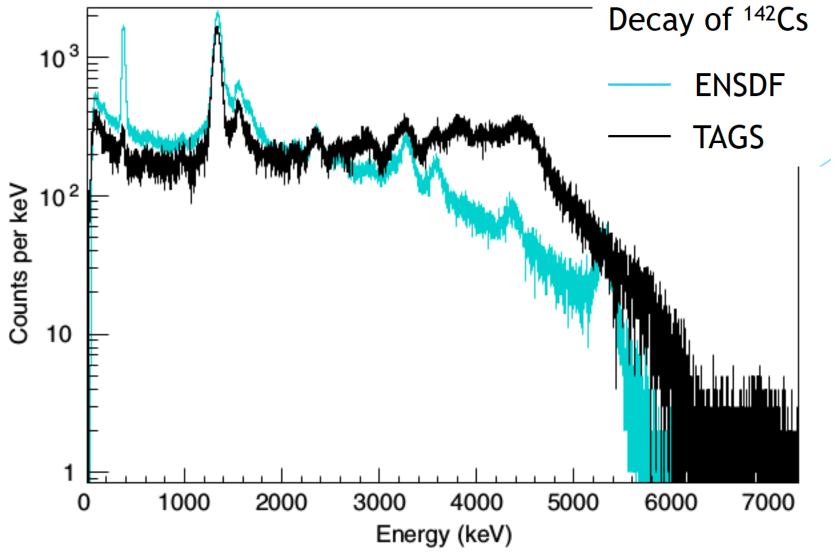
Some missing!

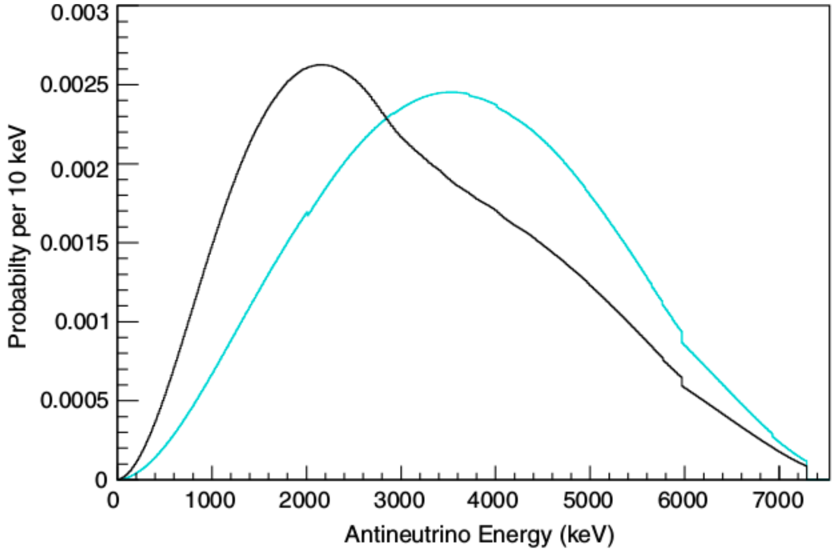


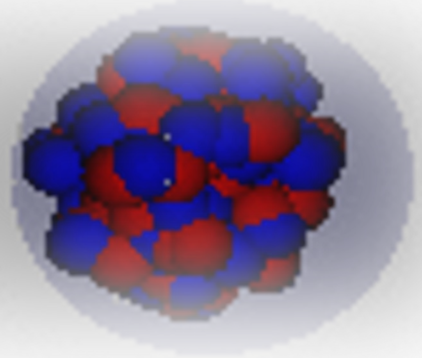
Antineutrino reactor anomaly

- 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.
  - $p + \bar{\nu}_e \rightarrow n + e^+$



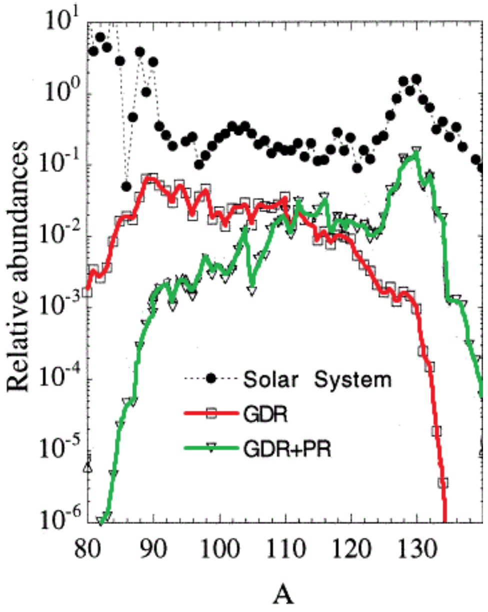




WHY  ?

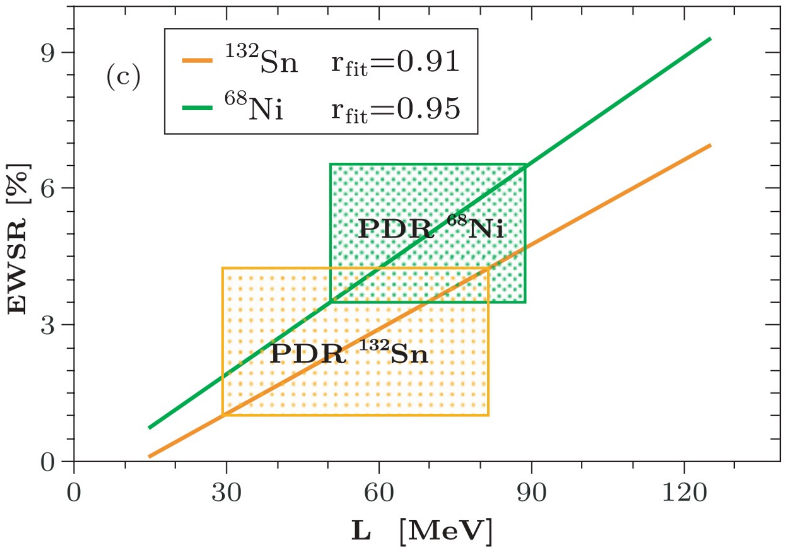
Review articles:
N.Paar et al., Rep Prog. Phys. **70** 691 (2007)
D. Savran et al., Prog. Part. Nucl. Phys. **70** 210 (2013)
A. Bracco et al., Prog. Part. Nucl. Phys. 106 **360** (2019)

Nucleosynthesis



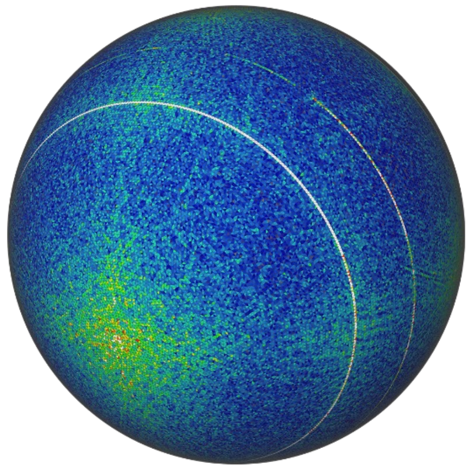
S.Goriely et al., Phys. Lett.B 436 (1998) 10

Nuclear EoS



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

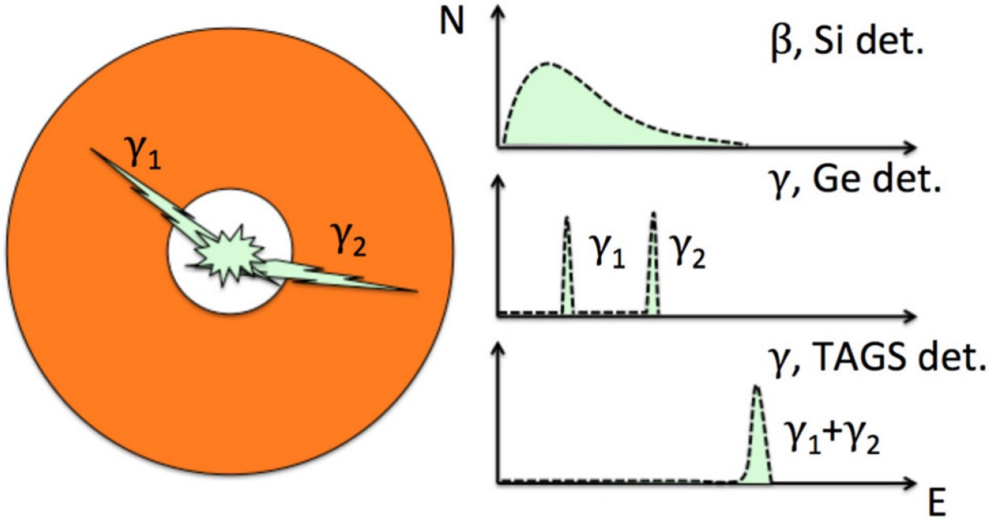
Neutron Stars

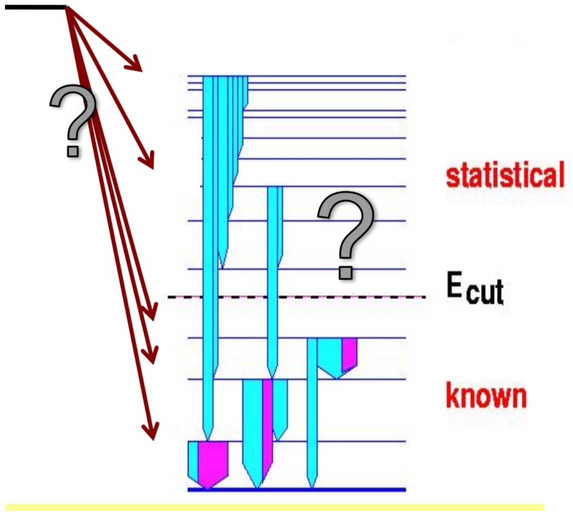


K. Sumiyoshi, Astrophys. J. 629, 922 (2005)
Lattimer et al., Phys. Rep. 442, 109 (2007)

Total Absorption Spectroscopy

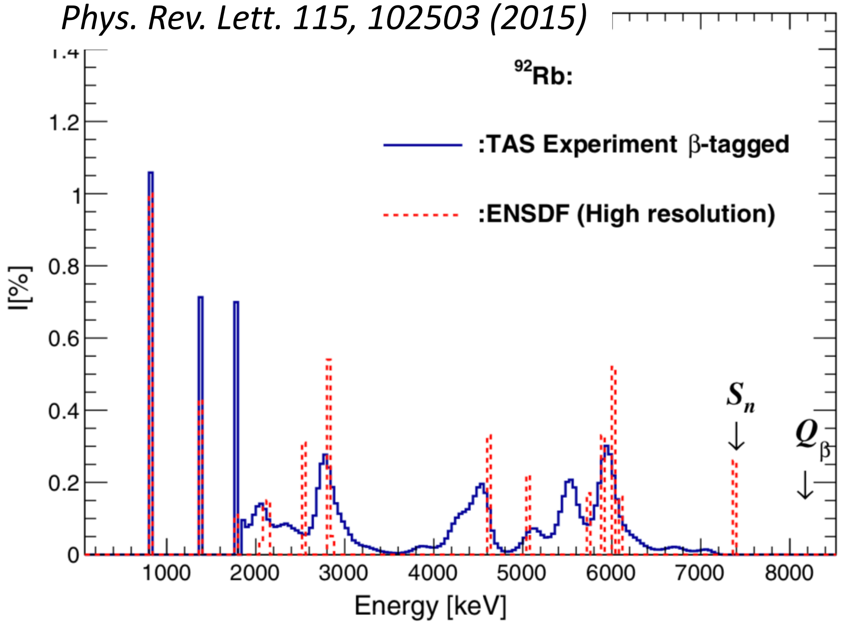
- Utilizes large volume scintillator detectors.
- Exploits high detection efficiency.
  - Free from *pandemonium*.
- Poor energy resolution.
  - Limited sensitivity to individual states.
- Analysis
- Level scheme split into two regions
- Low energy with discrete states
  - Uses known branching ratios.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

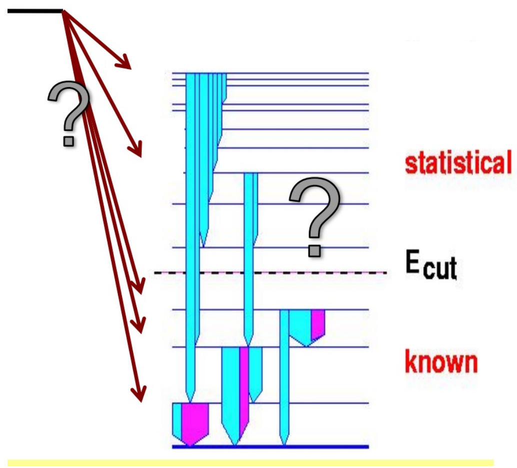




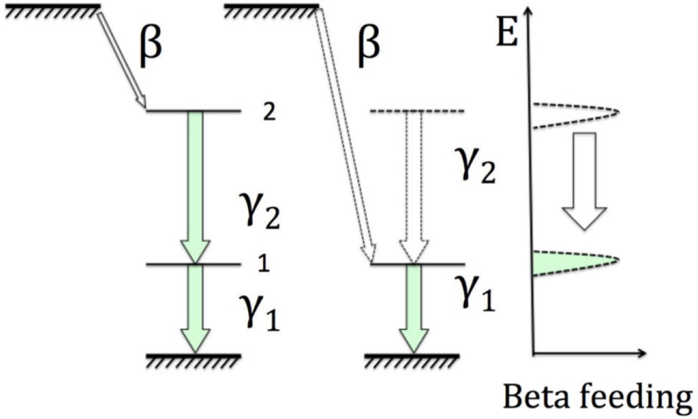
β^- data $^{92}\text{Rb} \rightarrow {}^{92}\text{Sr}$

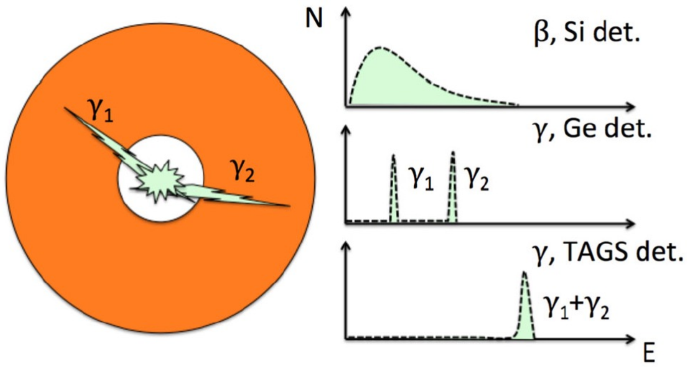
A.-A. Zakari-Issoufou et al,
Phys. Rev. Lett. 115, 102503 (2015)





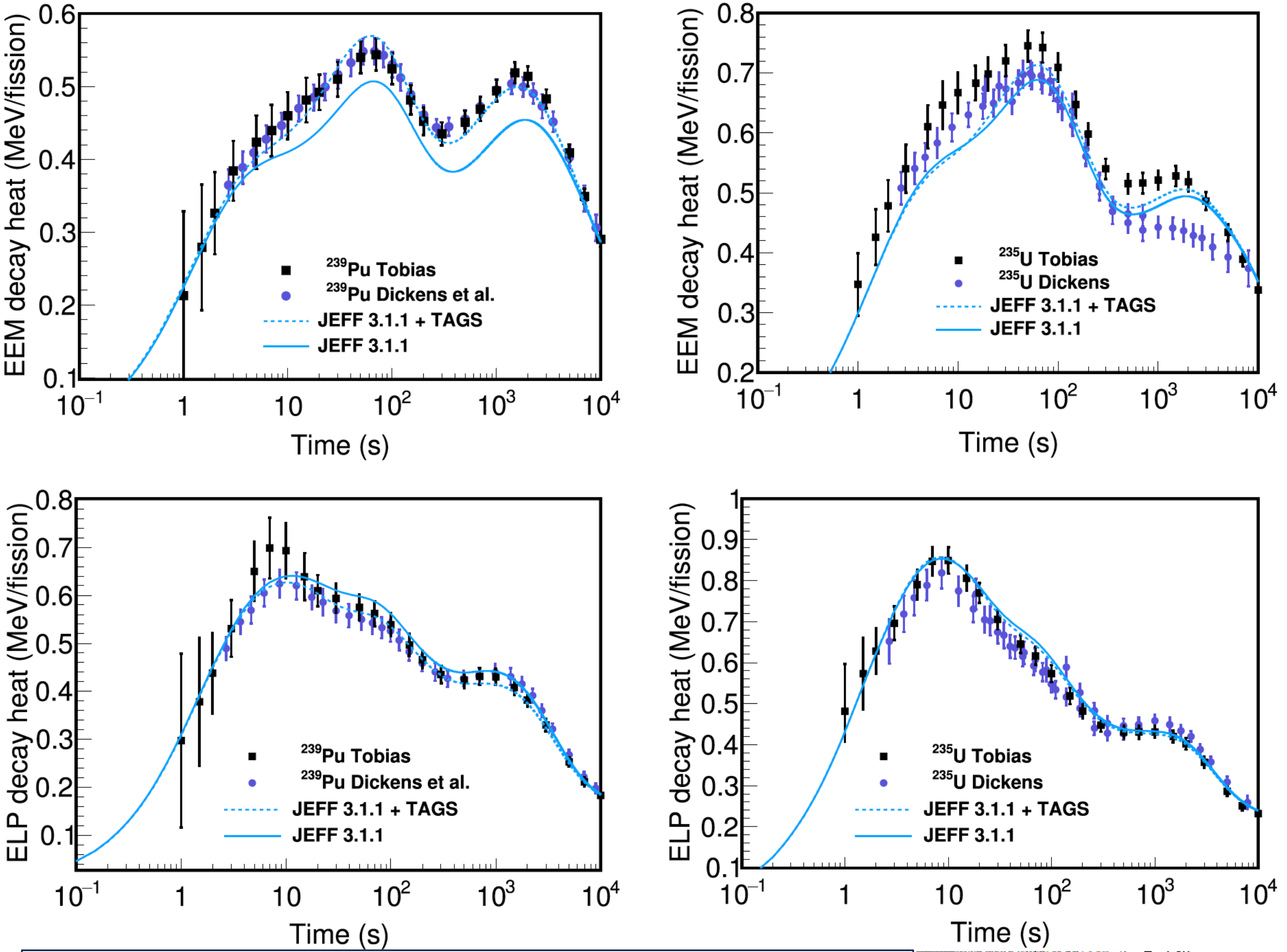
- Dominant contributor of high-energy $\bar{\nu}_e$ flux
- ENSDF data from late 1970s.
  - Using a few low-eff Ge(Li) detectors.
- Two new TAS studies
  - Zakari-Issoufou *et al* (2015)
  - Rasco *et al* (2016)
- Significant disagreement in β feeding
  - Pandemonium!
- ^{92}Rb
  - Q_β = 8095 keV
  -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





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