**β-decay Phenomenology of Nuclear Fission Products**

Behr and Vogel  
My 1982 summer research  
Nucl Phys A411 199 (1983)  
Summed database 100 fission products  
Hints that nuclear giant resonances are fed  
Higher energy ν’s dominated by a few cases with large energy release
Reactor $\nu$ energies with an atom trap

- Nuclear reactors produce a lot of $\nu$'s
- (Total # measured)/(calculated) = 0.92 ± 0.04
A remarkable success— but what is missing?
- Discrepancy is worse between 5 and 7 MeV
How well is the source understood?
- We measure the energy spectrum of $\nu$'s
produced by a particular type of $\beta$ decay, to
test theory understanding

TRIUMF Neutral Atom Trap (TRINAT)
How atom traps work
How we can measure $\nu$ energy
First results for $^{92}$Rb decay
TRIumf Neutral Atom Trap collaboration:

D. Melconian
A. Gorelov
J.A. Behr
Undergrad
not this term

J. McNeil

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\( \nu \) was invented to solve an experimental puzzle

\[ \nu \rightarrow \alpha \]

\[ \alpha \rightarrow 144\text{Sm} \]

\[ p_\alpha = p_{144\text{Sm}} \]

\[ E_\alpha = 3.183 \text{ MeV}, \text{ always} \]

"Controversy and Consensus: Nuclear \( \beta \) decay 1911-1934" Springer 2000, eds. Hiebert, Knobloch, Scholz (C. Jensen)

\( \beta \) decay: A continuous \( E_e \) spectrum, not a discrete peak!

Meitner and Hahn 1911, Danysz 1913, experimentally resolved:

- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!)

sought to power stars...?

- 1930 Pauli postulated a new particle (??!!)

How to test?

Probability to interact in a detector follows from the neutron decay rate (Bethe and Peierls, Nature 133 532 (1934); Robson Phys Rev 83 349 (1951))

Pauli: “I have done a terrible thing... postulated a particle that cannot be detected.”

Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick’s experiment of 1914. Source: Chadwick and Ellis, “Preliminary Investigation” (note 82), p. 277.
Reactor $\nu$’s: first direct confirmation by “Inverse $\beta$ decay”

1995 Nobel Prize

Fredrick Reines

Reactor $\nu$’s: first direct confirmation by “Inverse $\beta$ decay”

1st plan: put a detector next to a nuclear bomb
Pulsed source, get above natural backgrounds 😊
Must calibrate detector well before experiment 😞
Reactor worked better:
1956 Science 124 103
C. Cowan, F. Reines, Harrison, Kruse, McGuire (Los Alamos)
They thought they could predict the number to $\sim 30\%$ →

Reactor ν’s

traps

trinat

xtras

sketch of the equipment used at Savannah River. The

200 liters

$4 \times 10^{-6}$ SuperK’s

compared to the expected$^a$

$\sigma_{\text{exp}} = (12^{+3}_{-1}) \times 10^{-44} \text{ cm}^2$

$\sigma_{\text{th}} = (5^{+1}_{-1}) \times 10^{-44} \text{ cm}^2$
Two reactor $\nu$ ‘anomalies’

- total $\nu$ flux is $92\pm4\%$ of expected $\rightarrow$ extra $\nu$?

Update Hayes et al. PRL 120 022503 (2018):

Fuel composition changes with time

Still room for $\sim 5\%$ discrepancy and a sterile $\nu$

Flux[distance] measurements (PROSPECT) may clarify this

- Disagreement between detectors and computation at $\nu$ energy 5-7 MeV

The 5-7 MeV $\nu$’s are a fair fraction of the detected $\nu$’s
The ‘bump’ is now well-measured, but not explained

- Experimental excess over models $E_\nu$ 5-7 MeV
  Seen in reactor experiments RENO and Daya Bay
  Still consistent with PROSPECT first result
- Understanding is needed for ambitious neutrino hierarchy measurement with reactor $\nu$ oscillations (thus a near detector planned for JUNO)
- There are models with ‘new physics’ to explain the ‘bump’ (Barryman, Brdar, Huber PRD 99 055045)
- Nuclear theory generally is now estimating larger uncertainties for weak magnetism and 1st-forbidden decays, making the bump more consistent with less precise theory.
- Nearly half of these 5-7 MeV $\nu$’s come from $0^- \rightarrow 0^+$ decays
The TRIUMF logo is shown, indicating a connection to TRIUMF, a facility known for nuclear research.

The text discusses Reactor $\nu$ ‘anomalies’ and $^{92}$Rb decay. The decay scheme of $^{92}$Rb is shown, with a $Q$ value of 8104 MeV and a half-life of 4.48 s.

$^{92}$Rb decays into ground state (g.s.) with a 95.2% probability, based on Lhersonneau et al. (PRC 74, 017308, 2006). First excited state $2^+$ decays into $0^+ \gamma$ with 3.2% probability.

Two total absorption spectrometer results are mentioned: 87.5% (Zakari-Issoufou et al., PRL 115, 102503, 2015) and 91% (Rasco et al., PRL 117, 092501, 2016). A conventional thick scintillator + Ge done at ANL is in between (E. McCutchan, Apr 2018 APS), indicating branching ratio likely under control.

The text concludes with a summary of the anomalies and their implications in reactor neutrino studies.
Non-allowed $\nu$ spectrum from $^{92}\text{Rb}$ decay?

Corrections beyond Gamow-Teller allowed energy spectra are thought to be important for reactor $\nu$ spectra.

Sonzogni, McCutchan, and Hayes PRL 119 112501 (2017) “precisely measured electron spectra for about 50 relevant fission products are needed” to pin down weak magnetism and forbidden correction terms.

Historically, $E_\beta$ spectra in $0^- \rightarrow 0^+$ decay disagree with theory: worth new technique.

$0^- \rightarrow 0^+$ correction to allowed $\beta$ spectrum is theoretically possible [Hayes, Friar, Garvey et al. PRL 2014], removing 0-10% $\nu$ at highest energy.
Other experiments permit $^{92}$Rb to be ‘non-allowed’

- Reviews typically say $^{92}$Rb beta spectrum is consistent with an allowed shape. This is based on the spectrum from Rudstam et al. ADNDT 45 239 (1990). Theory expects one matrix element to dominate, producing an allowed spectrum shape.

  Yet experiments can accommodate the deviations our measurements imply →

- $^{134}$Sb with a Paul trap at ANL. Siegl et al. PRC 97 035504 (2018): average $a_{\beta\nu} = 0.47 \pm 0.16$, attributed to excited state feeding $3\% \rightarrow 17\%$. 

![Diagram of experiment setup]
Reactor ν’s traps trinat xtras on TRINAT’s wall (from co-op H. Norton)
Magneto-optical trap: damping

For a trap, we want a damped harmonic oscillator.
’Red-detuned’ beams provide the “damping”

‘Optical molasses’

We still need a position-dependent force
“Light sabers’ would make atom traps easy” (H. Norton)

\[ \nabla \cdot \mathbf{S} \neq 0 \]

But light sabers violate Poynting’s theorem

“Optical Earnshaw Theorem”
(Ashkin + Gordon 1983)
Magneto-optical trap: perturb atoms

Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

\[ \varepsilon = \hat{\mathbf{s}} \cdot \mathbf{k} \]
What elements can be laser cooled?
TRIumf Neutral Atom trap at ISAC

37K 8x10^7/s  TiC target  1750°C  70 µA protons

main TRIUMF cyclotron
‘world’s largest’
500 MeV H^- (0.5 Tesla)
TRINAT plan view

- Isotope/isomer selective
- Avoid untrapped atom background with 2nd trap
- 75% transfer
- 0.7 mm cloud for $\beta$-$\text{Ar}^+ \rightarrow \nu$ momentum
- Spin-polarized $99.1 \pm 0.1\%$
Neutralizer and Collection trap
TRINAT lab: “tabletop experiment”
$^{92}$Rb Decay geometry

$^{92}$Rb \rightarrow \beta^- + 92$Sr + $\nu_e$ - $\nu_e$
ion MCP assembly

14 inch CF flange
Electrostatic field
delay-line anode for position info
No stray wires
Low-Z (glassy carbon, titanium) and open structure to minimize $\beta^+$ scattering
Data $^{92}$Rb (10% of total)

Three experiments (two T.A.S., one careful $\beta$-$\gamma$) now concur on $\approx$10% excited state feeding

Scatter plot of recoil TOF vs. recoil radius.

We can separate the decay to the ground state cleanly from the reconstructed total energy.
Preliminary: Reactor $\bar{\nu}$'s from $0^- \rightarrow 0^+ {}^{92}\text{Rb}$ decay

Determine $a_{\beta\nu}$ from the recoil energy spectrum:

Warburton PRC 1982:

$$P(E, \theta_{\beta\nu}) = 1 + a \frac{v}{c} \cos(\theta_{\beta\nu})$$

$$a = \frac{1 - \frac{\omega^2}{9\xi_0^2}}{1 + \frac{\omega^2}{9\xi_0^2} - \frac{2\omega m_\beta \gamma}{3\xi_0 E_\beta}}$$

Nuclear matrix elements:

$$\langle i | \sigma \cdot r | f \rangle / R_{\text{nucleus}} = \omega$$

$$\langle i | \gamma_5 | f \rangle \rightarrow \xi_0$$

Which $\Rightarrow \beta$ spectrum distorted by:

$$1 + \frac{\omega^2}{9\xi_0^2} - \frac{2\omega m_\beta \gamma}{3\xi_0 E_\beta}$$

We see that $a$ changes with $E_\beta$ Should be able to determine $\omega/\xi_0$
Reactor $\nu$ energies with your atom trap

- Nuclear reactors produce a lot of $\nu$’s
- Discrepancy between calculation and experiment is worse between 5 and 7 MeV

We measure the energy spectrum of $\nu$’s produced by $0^- \rightarrow 0^+ \beta$ decay, to test theory understanding.

**TRIUMF Neutral Atom Trap (TRINAT)**
Measured $\beta$-$\nu$ correlation to test theory
First results for $^{92}$Rb decay next week at DNP
“Why Optical Traps Can’t Work”

Earnshaw Theorem: $\nabla \cdot \vec{E} = 0 \Rightarrow$
no electrostatic potential minimum for charge-free region

"Optical Earnshaw Theorem" (Ashkin + Gordon 1983):

$\Rightarrow$ no 3-D traps from spontaneous light forces with static light fields

Using Poynting’s theorem:

$\nabla \cdot \vec{S} = \frac{c}{4\pi} \nabla \cdot (\vec{E} \times \vec{B}) = -\vec{J} \cdot \vec{E} - \frac{\partial u}{\partial t} = 0$

Dodges!

- Time-dependent forces (pulsed lasers)
- Dipole Force traps (“optical tweezers”)
- Modify internal structure of atom with external fields
Why atom traps are shallow

\[ |e> \quad \begin{array}{c} \Omega \\
\text{absorption} \end{array} \quad \Omega \quad \begin{array}{c} \text{stimulated} \\
\text{emission} \end{array} \quad \gamma = 1/\tau \quad \begin{array}{c} \text{spontaneous} \\
\text{emission} \end{array} \]

\[ |g> \quad \text{"Einstein B"} \quad \Omega \quad \text{"Einstein A"} \]

\[ \frac{dN_g}{dt} = -\Omega N_g + \Omega N_e + \gamma N_e = -\frac{dN_e}{dt} \]

Steady-state \( \Rightarrow \quad =0 \quad \Rightarrow \quad N_e = \frac{\Omega N_g}{\gamma + \Omega} \]

Limits:

- \( N_e \overset{\Omega < \gamma}{\longrightarrow} \frac{\gamma}{\Omega} N_g \text{ (sure)}; \quad N_e \overset{\Omega > \gamma}{\longrightarrow} N_g \text{ !!} \)

- At high intensity, same # in ground, excited state
- Atomic transition “saturates”

Maximum scattering rate = \( \frac{\gamma N_e}{N} \rightarrow \gamma/2 \)

So radiation pressure traps are shallow IF they rely on spontaneous emission
‘No stray wires’

Nested insulators: E no longer falls across dielectric surfaces

- Argon conditioning
- 1.2 kV/cm reached
- Improved ion MCP mount (as in Hong et al. NIM Seattle-Argonne) in progress
- More compact shakeoff $e^-$ MCP and wedge-and-strip readout to allow simultaneous ion and $e^-$ detection.

- Remove $A_\beta$ background
- Adds $A_{\text{recoil}}$
- All detectors together for trap diagnostics and for $\rho$-independent $\beta$-recoil observable