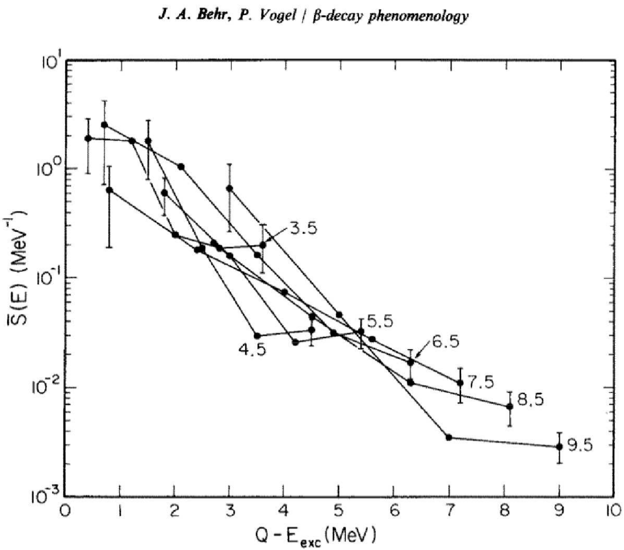
β-decay Phenomenology of Nuclear Fission Products



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

trinat.triumf.ca/publications-1/reactor_nus_2021.pdf

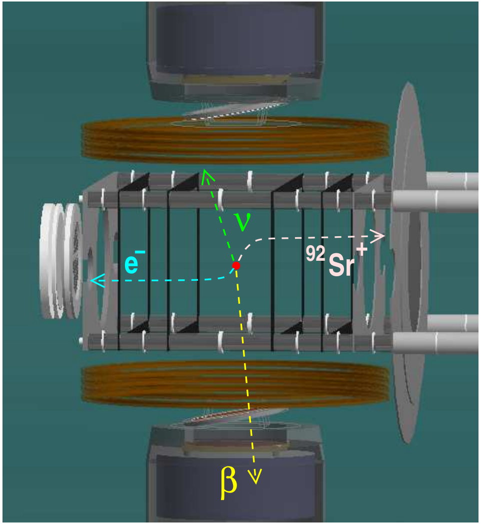
Reactor ν energies with an atom trap

• Nuclear reactors produce a lot of ν's

• (Total # measured)/(calculated) = 0.92 $\pm$ 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 ν's produced by a particular type of β decay, to test theory understanding



TRIUMF Neutral Atom Trap (TRINAT)
How atom traps work
How we can measure ν energy
First results for ^{92}Rb decay

TRIumf Neutral Atom Trap collaboration:

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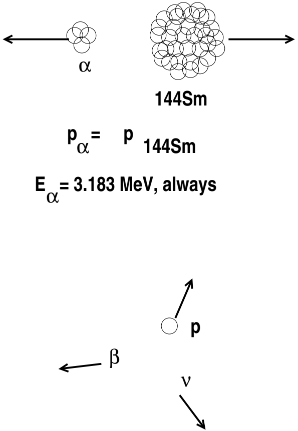
Support: NSERC, NRC through TRIUMF, DOE, State of Texas

ν was invented to solve an experimental puzzle



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

β decay: A continuous $\boldsymbol{E_e}$ spectrum, not a discrete peak!

Meitner and Hahn 1911, Danysz 1913, experimentally resolved:

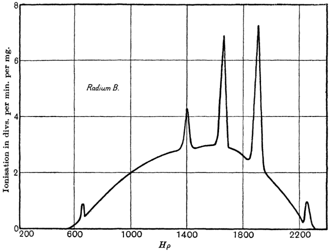


Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick's experiment of 1914. Source: Chadwick and Ellis, "Preliminary Investigation" (note 82), p. 277.

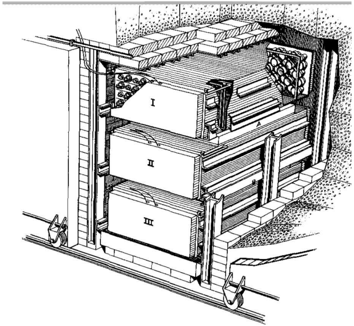
- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!) sought to power stars...?
- 1930 Pauli postulated a new particle (??!!)

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."

Reactor ν's: first direct confirmation by "Inverse β decay"



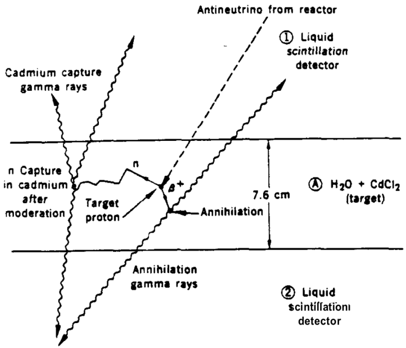
sketch of the equipment used at Savannah River. The

200 liters

4x10^{-6} SuperK's

1995 Nobel Prize

Nobel Lecture 1995 *Fredrick Reines*



$$\bar{\sigma}_{exp} = (12^{+7}_{-4}) \times 10^{-44}\ cm^2$$

compared to the expected[2]

$$\bar{\sigma}_{th} = (5 \pm 1) \times 10^{-44}\ cm^2$$

With parity violation (1957) prediction is 2x bigger :)

1st plan: put a detector next to a nuclear bomb

Pulsed source, get above natural backgrounds ☺

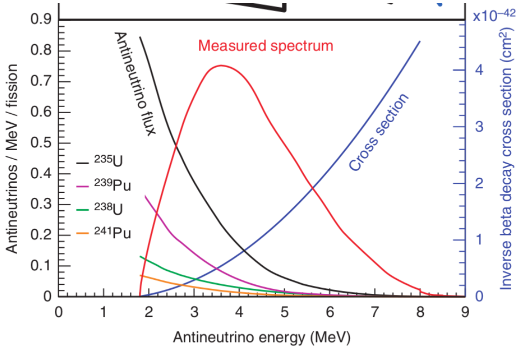
Must calibrate detector well before experiment ☹

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% $\rightarrow$

TRIUMF Two reactor ν 'anomalies'

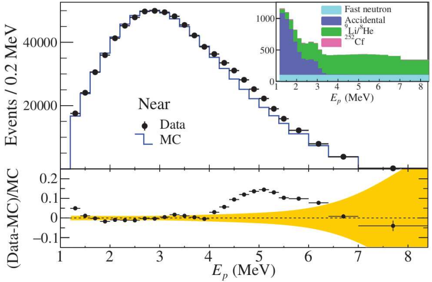
- total ν flux is 92$\pm$4% of expected $\rightarrow$ extra ν?
  Update Hayes et al. PRL 120 022503 (2018):
  Fuel composition changes with time
  Still room for $\sim$ 5% discrepancy and a sterile ν
  Flux[distance] measurements (PROSPECT) may clarify this
- Disagreement between detectors and computation at ν energy 5-7 MeV



P. Vogel, L.J. Wen, C. Zhang, Nature Comm 6 6935 (2015)
The 5-7 MeV ν's are a fair fraction of the detected ν's

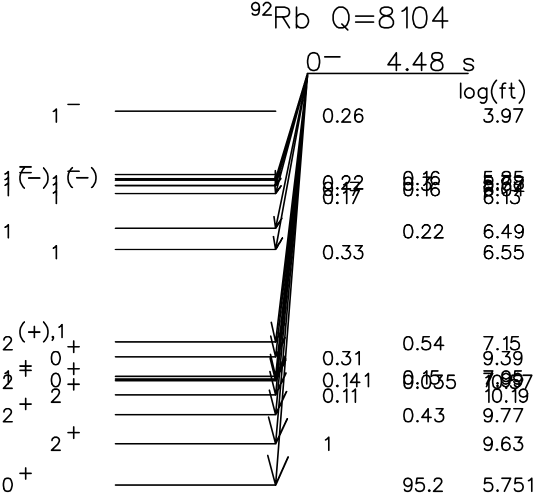
TRIUMF The 'bump' is now well-measured, but not explained

- Experimental excess over models E_ν 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 ν 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 ν's come from $0^- \rightarrow 0^+$ decays



RENO PRL 121 201801 (2018)

Reactor ν 'anomalies' and ^{92}Rb decay



^{92}Rb $\sim$10% of reactor ν's 5-7 MeV

2012 NDS compilation: g.s. $\rightarrow$ g.s. branch 95.2$\pm$.7%, based on Lhersonneau et al. PRC 74 017308 (2006) feeding of first $2^+ \rightarrow 0^+$ γ 3.2$\pm$4%

- **Total absorption spectrometer results: Zakari-Issoufou et al. PRL 115 102503 (2015) 87.5$\pm$2.5%**
  Rasco et al. PRL 117 092501 (2016) 91$\pm$3%
- **Conventional thick scintillator + Ge done at ANL is in between (E. McCutchan, Apr 2018 APS)**

Branching ratio likely under control

Is the energy spectrum of ν's predictable?
β energy spectrum for allowed decay:

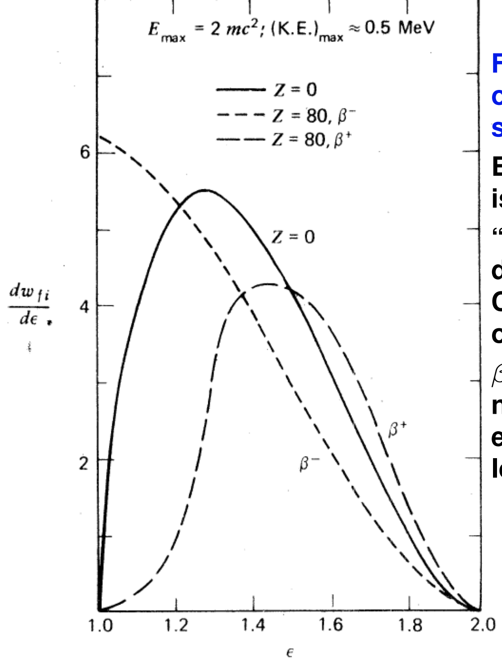
Assuming the outgoing leptons are plane waves,
Integrate $p_e^2 dp_e p_\nu^2 dp_\nu \delta(Q - K_e - E_\nu)$ over p_ν,

$$W(p_e)dp_e = \frac{1}{2\pi^3\hbar^3 c^3} \sum_{\mu\ m_f} |\langle J_f m_f r | O_{\lambda\mu}(\beta) | J_i m_i r' \rangle|^2 F(Z, K_e) p_e^2 (Q - K_e) \sqrt{(Q-K_e)^2 - m_\nu^2}\, dp_e$$

with $O_{\lambda\mu} = \sum_{j=1}^{A} (G_V \tau_\pm(j) + G_A \vec{\sigma}(j)\tau_\pm(j))$. Differentiating $E^2 = p^2 + m^2 \Rightarrow pdp = EdE$,

$$W(E_e)dE_e \propto F(Z, E_e) E_e p_e (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_\nu^2}\, dE_e$$

(Most forbidden decay operators produce large changes in this energy spectrum)



Fermi function effect on β energy spectrum

But the outgoing β is not a plane wave

"Coulomb function" distorted by the Coulomb potential of the nucleus.

β^- is 'pulled into' nucleus... a big effect for high Z and low E_β

Selection rules

Fermi

G-T

γ_5 dominates $0^- \rightarrow 0^+$

$\sigma \cdot r$ suppressed by r/λ
but that r dependence distorts the E_ν spectrum

'1st forb. unique' $2^\pm \leftrightarrow 0^\mp$
One operator $\Rightarrow$ calculable correlations from a.m.

TABLE I. Allowed and first-forbidden nuclear matrix elements and their selection rules (K designates the rank of the transition operator, when regarded as a tensor).

	Matrix element	K	ΔJ	$\Delta\pi$
Allowed	$C_V\int 1$	0	0	+1
	$C_A\int \boldsymbol{\sigma}$	1	0, ±1 (no 0→0)	+1
First forbidden	$C_A\int \gamma_5$, $C_A\int(\boldsymbol{\sigma}\cdot\mathbf{r}/i)$	0	0	−1
	$C_V\int \mathbf{r}i$, $C_V\int \boldsymbol{\alpha}$, $C_A\int(\boldsymbol{\sigma}\times\mathbf{r})$	1	0, ±1 (no 0→0)	−1
	$C_A\int iB_{ij}$	2	0, ±1, ±2 (no 0→0, no 1→0, no 0→1)	−1

Weidenmüller Rev Mod Phys 33 574 (1961)

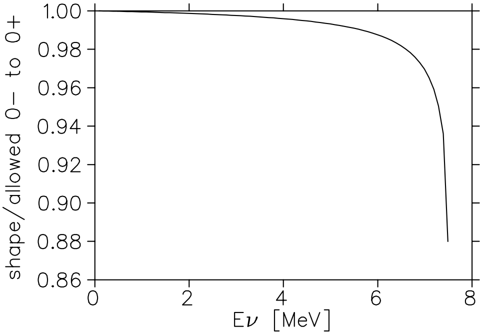
TRIUMF

Non-allowed ν spectrum from ^{92}Rb decay?

Corrections beyond Gamow-Teller allowed energy spectra are thought to be important for reactor ν 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_β spectra in $0^- \rightarrow 0^+$ decay disagree with theory: worth new technique



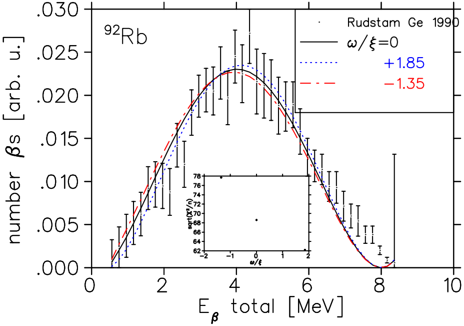
$0^- \rightarrow 0^+$ correction to allowed β spectrum is theoretically possible [Hayes, Friar, Garvey et al. PRL 2014], removing 0-10% ν at highest energy.

TRIUMF Other experiments permit ^{92}Rb to be 'non-allowed'

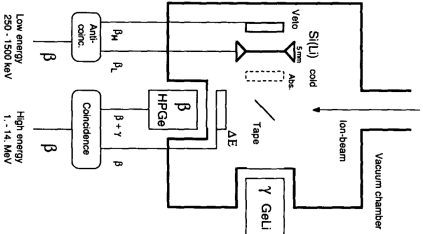
- Reviews typically say ^{92}Rb beta spectrum is consistent with an allowed shape. This is based on the spectrum from Rudstam et al. ADNDT 45 239 (1990)

Theory expects one matrix element to dominate, producing an allowed spectrum shape

Yet experiments can accomodate the deviations our measurements imply $\rightarrow$



- ^{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%.



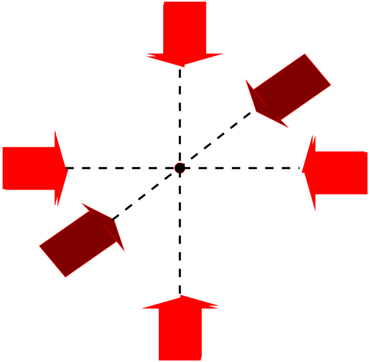
O. Tengblad et al. / Integral ν-spectra

TRIUMF

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"

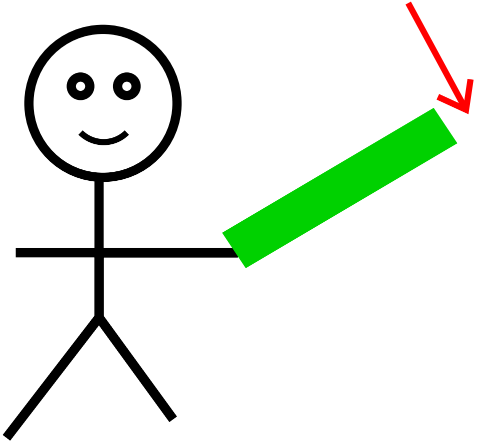


'Optical molasses'

We still need a position-dependent force

"'Light sabers' would make atom traps easy" (H. Norton)

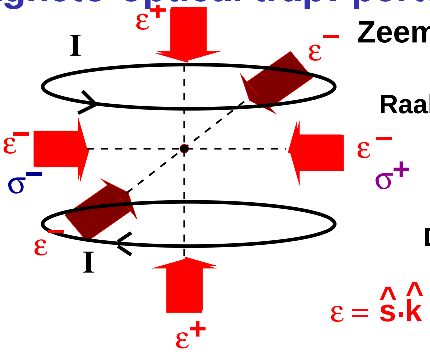
$$\vec{\nabla} \cdot \vec{S} \neq 0$$



"Optical Earnshaw Theorem"
(Ashkin + Gordon 1983)

But light sabers violate Poynting's theorem

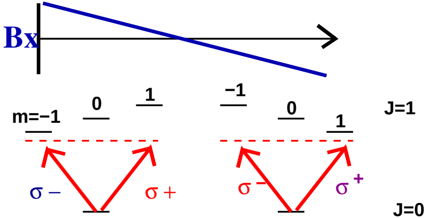
Magneto-optical trap: perturb atoms



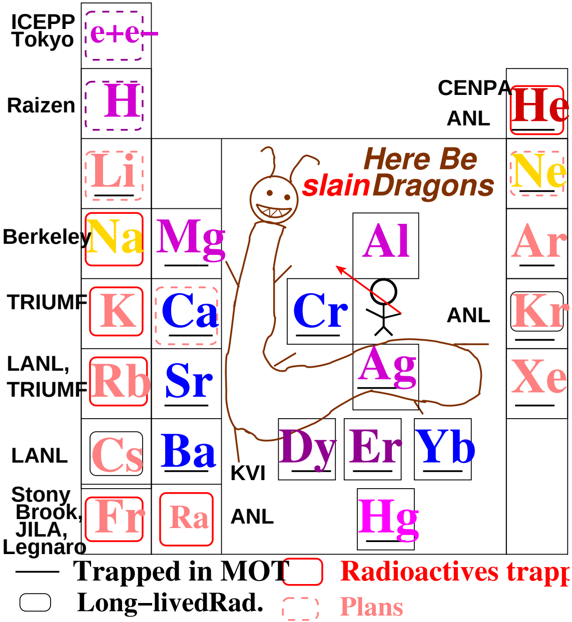
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

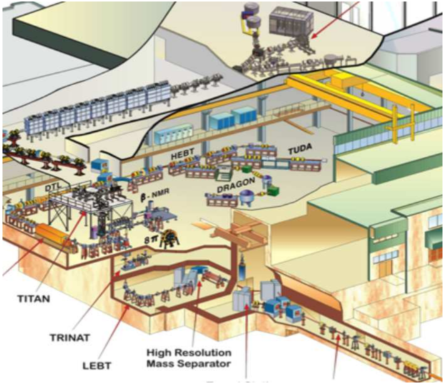
Damped harmonic oscillator



What elements can be laser cooled?



TRIumf Neutral Atom trap at ISAC

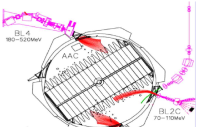


^{37}K 8x10^{7}/s

TiC target
1750^{o}C

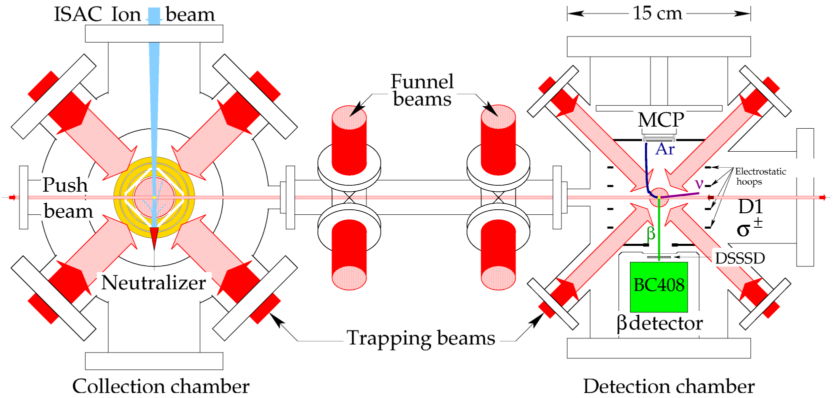
70 μA
protons

main TRIUMF cyclotron
'world's largest'
500 MeV H^- (0.5 Tesla)



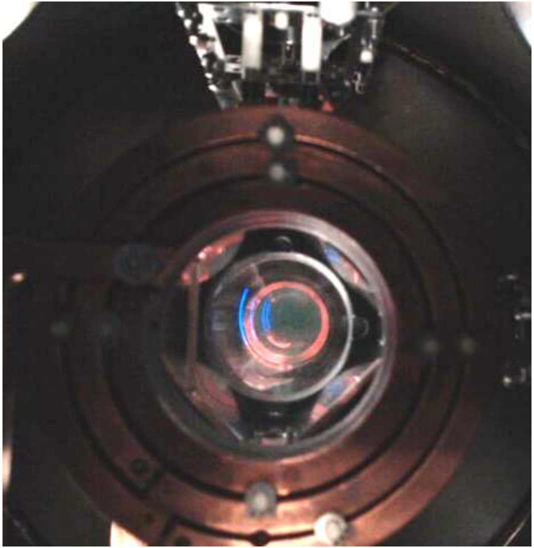
TRINAT plan view

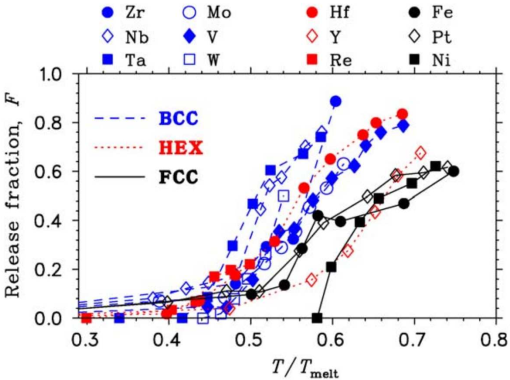
- Isotope/Isomer selective
- 75% transfer
- Avoid untrapped atom background with 2nd trap
- 0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum

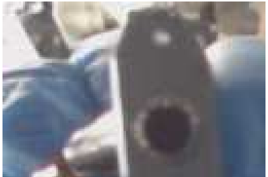


- Spin-polarized 99.1±0.1%

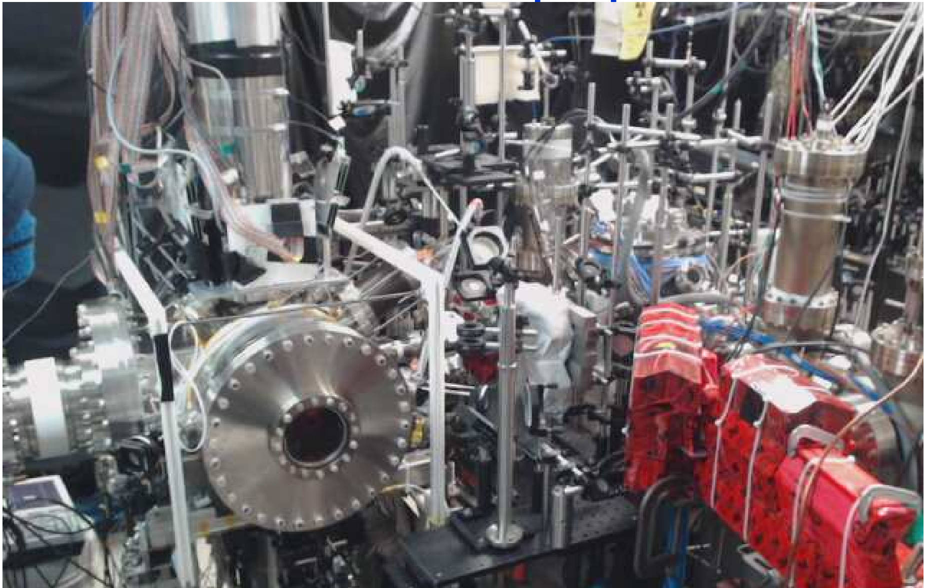
Neutralizer and Collection trap







TRINAT lab: "tabletop experiment"



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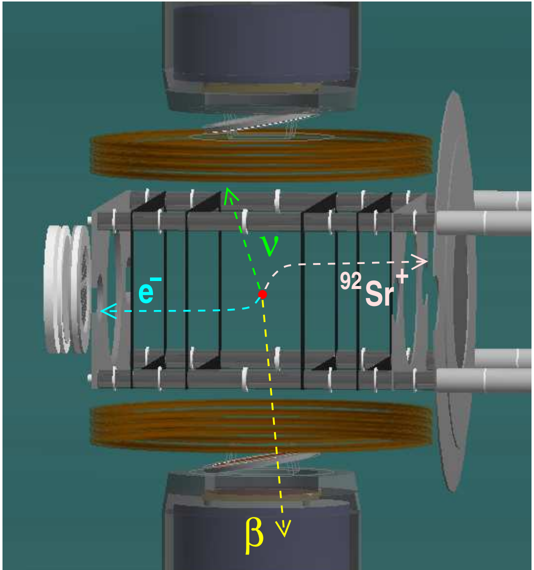
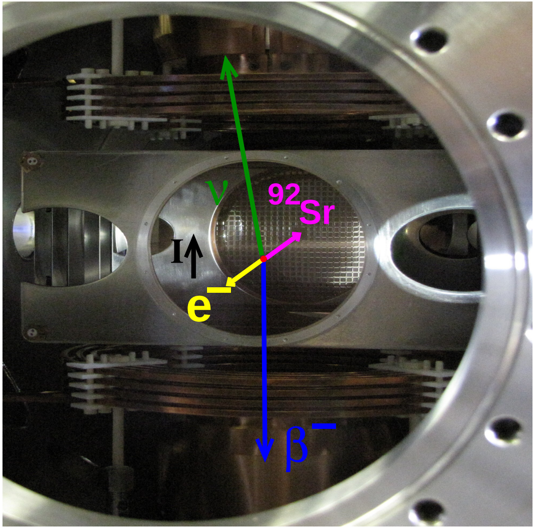
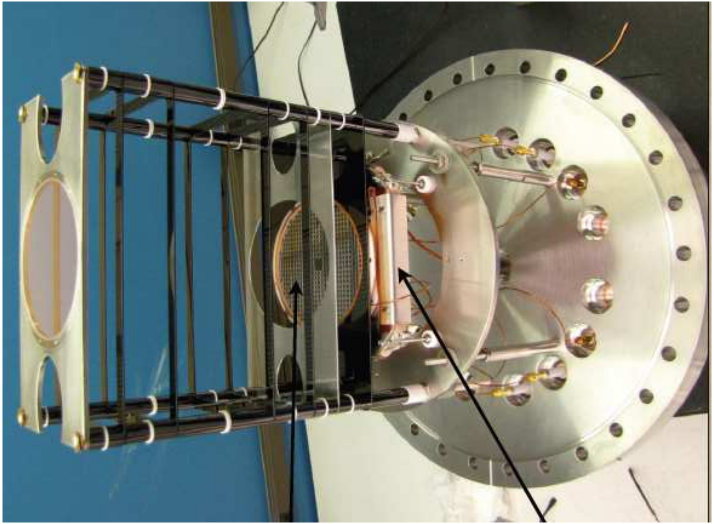
^{92}Rb Decay geometry

TEXAS A&M UNIVERSITY





ion MCP assembly



14 inch CF flange

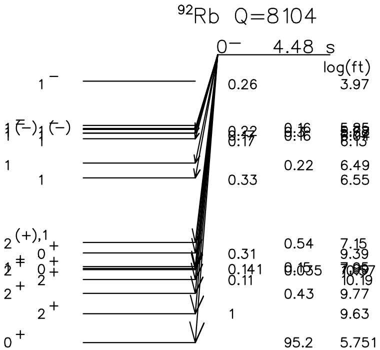
Electrostatic field

delay-line anode for position info

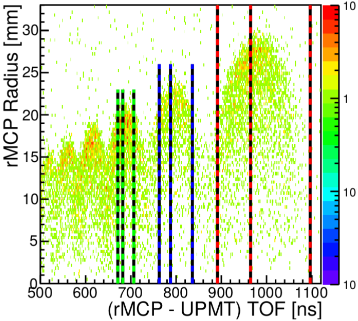
No stray wires

Low-Z (glassy carbon, titanium) and open structure to minimize β^+ scattering

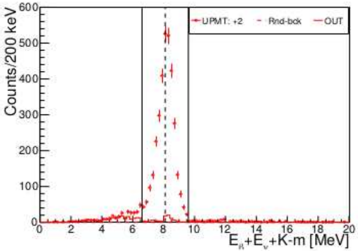
TRIUMF Data ^{92}Rb (10% of total)



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



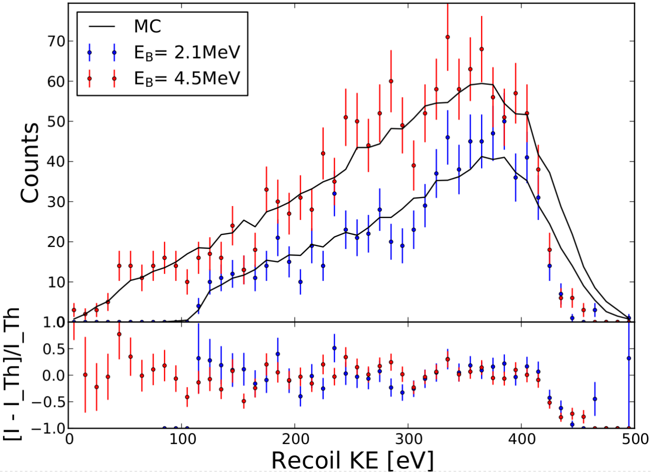
Scatter plot of recoil TOF vs. recoil radius.



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}Rb decay

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



James McNeil, APS DNP 2020 RF.00004

Warburton PRC 1982:

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

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

Nuclear matrix elements:

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

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

Which $\Rightarrow$ β 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_β

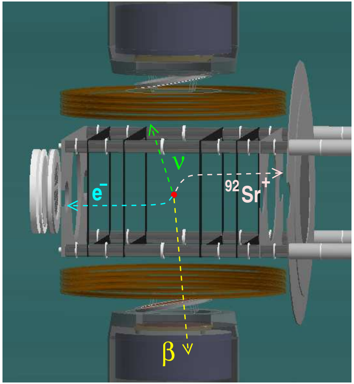
E_ν spectrum changed by $\lesssim$ 10%

Reactor ν energies with your atom trap

- Nuclear reactors produce a lot of ν's
- Discrepancy between calculation and experiment is worse between 5 and 7 MeV

We measure the energy spectrum of ν's produced by $0^- \rightarrow 0^+$ β decay, to test theory understanding

TRIUMF Neutral Atom Trap (TRINAT)
Measured β-ν correlation to test theory
First results for ^{92}Rb decay shown at 2020 DNP

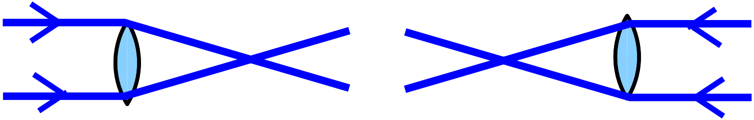


"Why Optical Traps Can't Work"

Earnshaw Theorem: $\vec{\nabla} \cdot \vec{E} = 0 \Rightarrow$

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:

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

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> —

|g> —

Ω
absorption

Ω
stimulated
emission

"Einstein B"

$\gamma = 1/\tau$
spontaneous
emission

"Einstein A"

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

Steady-state $\Rightarrow$ **=0** $\Rightarrow N_e = \frac{\Omega N_g}{\Omega+\gamma}$

Limits: $N_e \xrightarrow{\Omega << \gamma} \frac{\Omega}{\gamma} N_g$ **(sure);** $N_e \xrightarrow{\Omega >> \gamma} N_g$ **!!**

- **At high intensity, same # in ground, excited state**

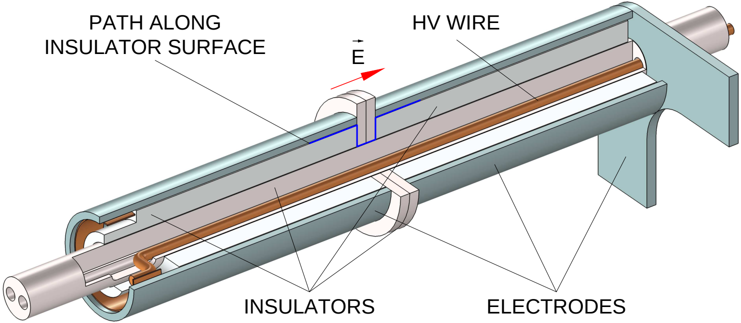
Atomic transition "saturates"

Maximum scattering rate = $\gamma N_e / N \rightarrow \gamma / 2$

So radiation pressure traps are shallow IF they rely on spontaneous emission

TRIUMF ‘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 simulataneous ion and e^- detection.**

- **Remove A_β background**
- **Adds $A_{\rm recoil}$**
- **All detectors together for trap diagnostics and for ρ-independent β-recoil observable**