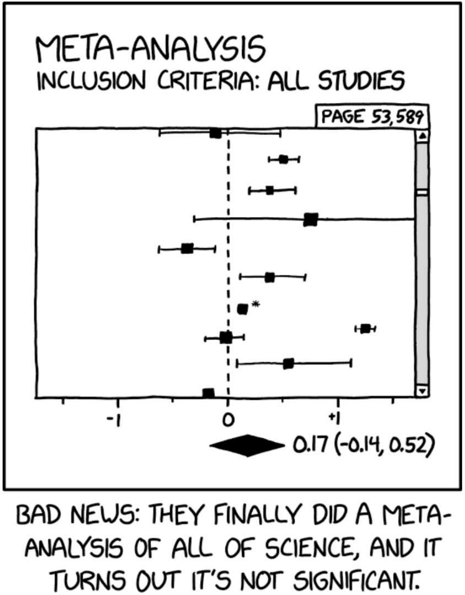
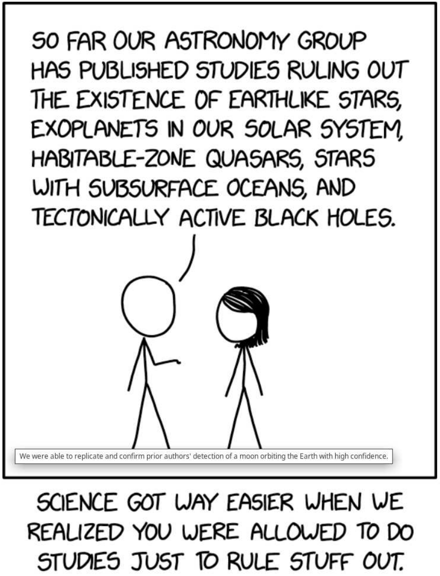
xkcd.com/2755/



xkcd.com/2783/



Engineering ν spin with atom traps

- ν intro

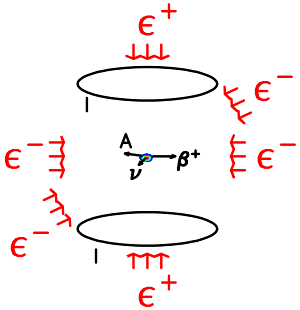
  Direct measurements of ν handedness

  All ν's are left-handed so far

- How atom traps work

  How we polarize nuclei by direct optical pumping (very similar to Ruohong Li's methods, but we have more time)

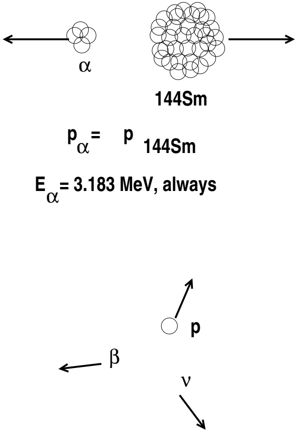
  Our proposal to measure ν handedness



TRIUMF acknowledges centuries of ongoing stewardship by the Musqueam people.

https://trinat.triumf.ca/talks/engineering_nu_spin_summer2023

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:

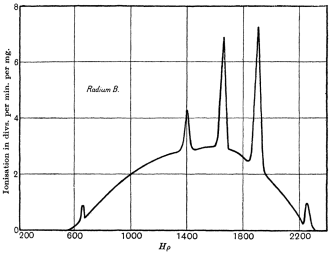


Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick's experiment of 1914. Source: Chadwick and Ellis, "Preliminary Investigation" (note 82), p. 277.

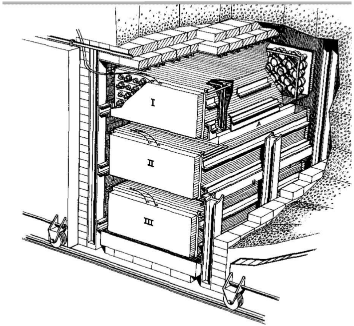
- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!) sought to power stars...?
- 1930 Pauli postulated a new particle (??!!)

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"



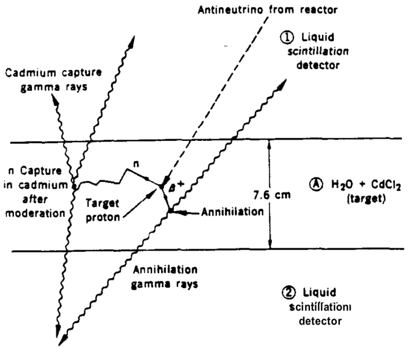
sketch of the equipment used at Savannah River. The

200 liters

4x10^{-6} SuperK's

1995 Nobel Prize

Nobel Lecture 1995 *Fredrick Reines*



compared to the expected[2]

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

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

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% $\rightarrow$

Intrinsic spin: a conceptual difficulty for e$-$ and ν

Physically, we can add the intrinsic spin of the e^- to its orbital angular momentum

so we'll treat instrinsic spin of e^- and ν like any other angular momentum, and think about it with classical pictures.

We should remember that trying to build a classical picture is pretty tricky.

An e^- with Bohr radius $4\pi\hbar^2/e^2 m_e$ must rotate about 2 orders faster than the speed of light to have one $\hbar$ of angular momentum.

JB should draw a picture on the board or wave his hands in obvious ways

More on spin:

Eugene Commins, "Electron Spin and Its History," Ann Rev Nucl Part Science 62 133 (2012)

Derek FJ Kimball, "Testing Gravity's Effect on Quantum Spins," Physics 16 80 (2023).

'PD'Op: Can one write a 'Bohr radius' for the ν?

Parity

(From A. Zee "Fearful Symmetry")

As of 1956, we thought all interactions respected parity

Parity operator

$$\boldsymbol{P}\ \psi(\vec{r}) \rightarrow \pm\ \psi(-\vec{r})$$

1957:

$\tau - \theta$ Puzzle

+ μ decay

+ ^{60}Co decay $\Rightarrow$

P

$=$

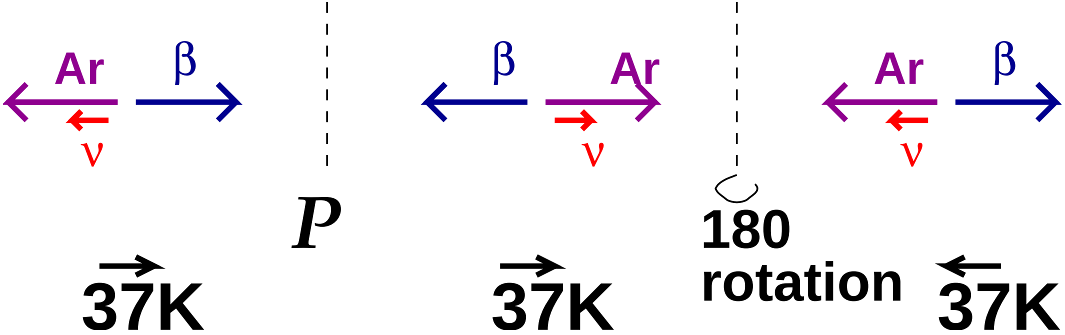
P

$\neq$

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

$\vec{r} \to -\vec{r}$ $\quad\quad$ $\vec{p} \sim \frac{d\vec{r}}{dt} \to -\vec{p}$ $\quad\quad$ $\vec{J} = \vec{r} \times \vec{p} \to +\vec{J}$



⇒ A spin flip corresponds exactly to *P* reversal

Decays don't exactly test *T*-reversal symmetry

One experimental discovery of parity violation

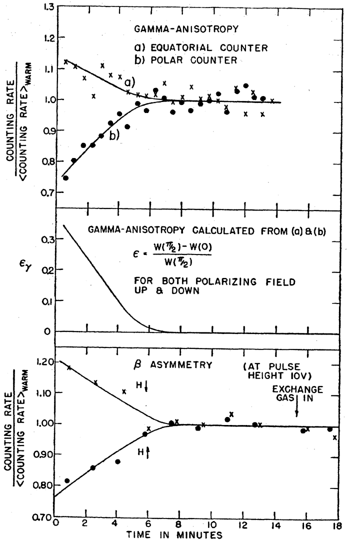
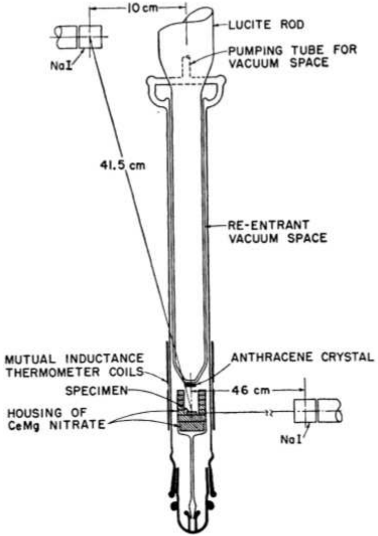


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



Wu, Ambler, Hayward, Hopper, Hobson, PR 105 1413 Feb '57

Dilution Refrigerator to spin-polarize

^{60}Co $\rightarrow$ ^{60}Ni + β^- + $\bar{\nu}$

$$W[\theta] = 1 + PA\hat{I} \cdot \frac{\vec{p_\beta}}{E_\beta}$$

$$= 1 + A\frac{v}{c}\cos[\theta]$$

$A_{\beta-} \approx -1.0$

Followup:

^{58}Co $\rightarrow$ ^{58}Fe + β^+ + ν

$A_{\beta+} > 0$

CP conserved?

This tells us nothing about the ν's helicity

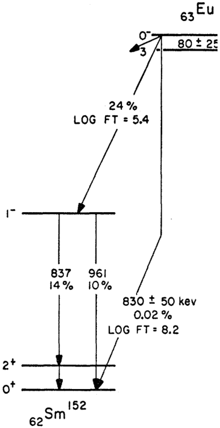
Measure ν helicity $\epsilon=\hat{s}_\nu \cdot \hat{k}_\nu$ directly: transfer $\hat{s}_\nu$ to γ circular polarization; boost $\vec{k}_\gamma$ by $\pm\vec{k}_\nu$

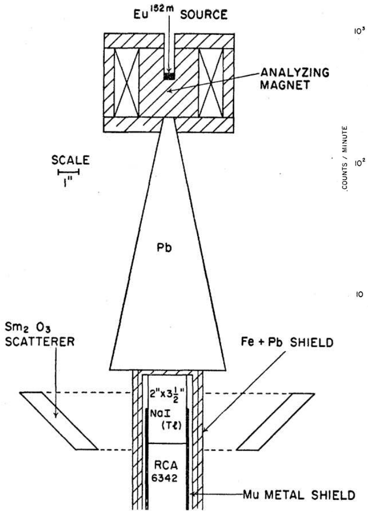
Goldhaber, Grodzins, Sunyar Phys Rev 109 1015 (Dec 1957)

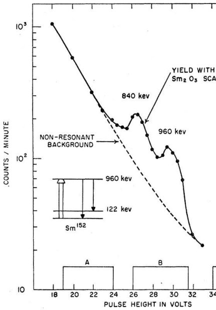
$e^- + {}^{152m}\mathrm{Eu} \rightarrow \nu + {}^{152}\mathrm{Sm}$

- **Upward-going ν populates $\langle I_z \rangle = 0, +1$ not -1**
- **So γ is circularly polarized– transmission through magnet depends on iron polarization:** $\frac{N_+ - N_-}{N_+ + N_-}$=0.017±0.003
- **Upward ν boosts γ momentum so it can be absorbed on-resonance**

$\Rightarrow$ ν helicity -1 $\pm$ 10%

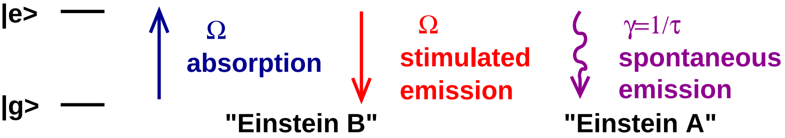






Surprisingly enough, this is the best direct measurement of ν helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$

Why atom traps are shallow



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

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

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

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

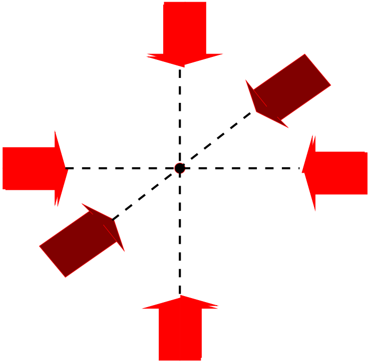
Atomic transition "saturates"

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

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

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

"Why Optical Traps Can't Work"

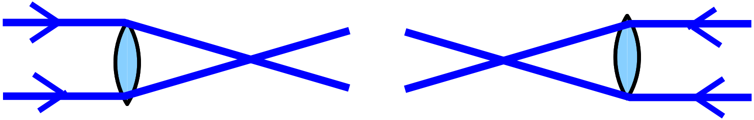
Earnshaw Theorem: $\vec{\nabla} \cdot \vec{E} = 0 \Rightarrow$

no electrostatic potential minimum for charge-free region

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

Using Poynting's theorem:

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



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

Dodges !

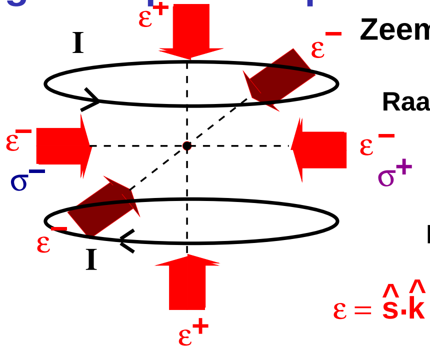
- Time-dependent forces (pulsed lasers)
- Dipole Force traps ("optical tweezers")
- Modify internal structure of atom with external fields

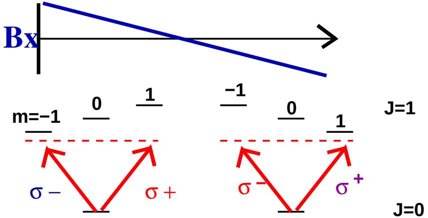
Magneto-optical trap: restoring force must perturb atoms

Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator



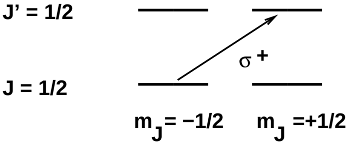


How to spin-polarize a nucleus with a laser

Polarization of nuclei by Optical Pumping

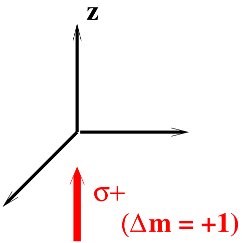
Biased random walk

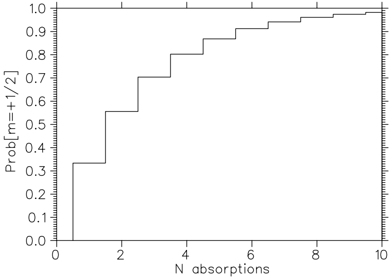
Simple example:



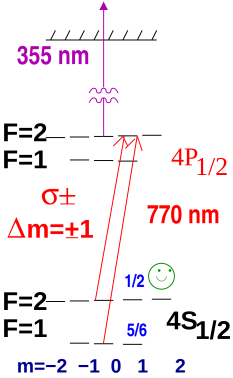
P(m=1/2) = 1 - $(2/3)^N$ after N steps

Need 12 cycles to get to 99% of maximum.





Optical pumping and probing ^{37}K



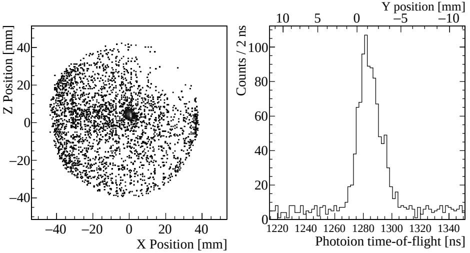
Photoionize 1%

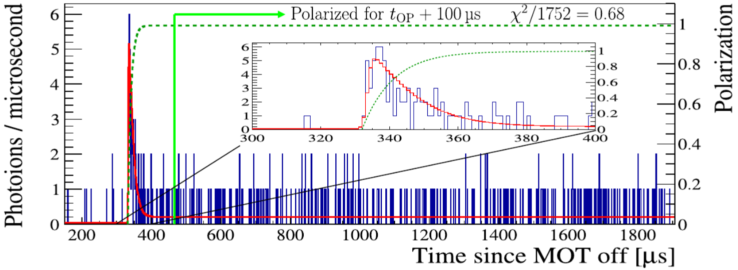
***in situ* probe**

P_+=+0.9913(8)

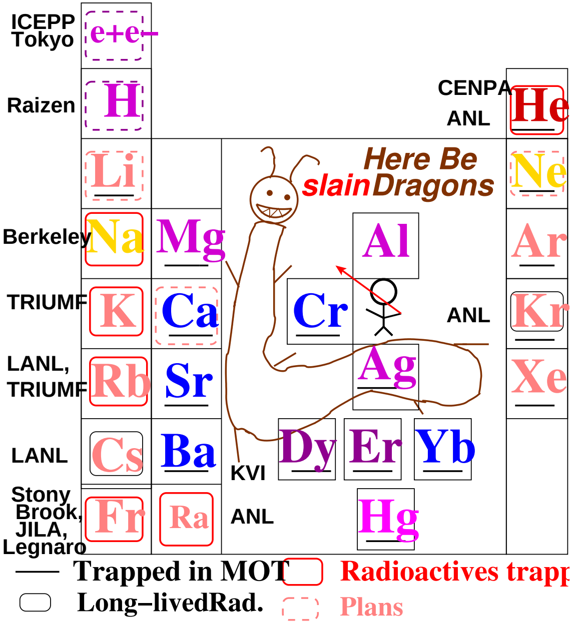
P_-=−0.9912(9)

Fenker NJP 2016

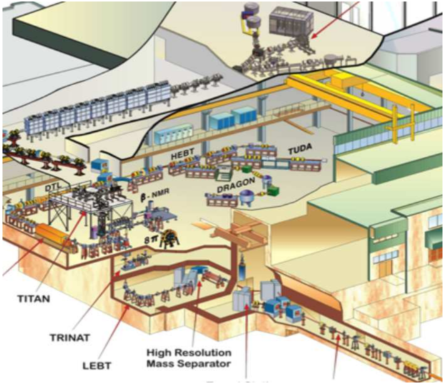




What elements can be laser cooled?



TRIumf Neutral Atom trap at ISAC

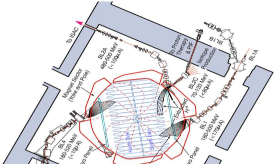


^{37}K 8x10^7/s

TiC target 1750^{o}C

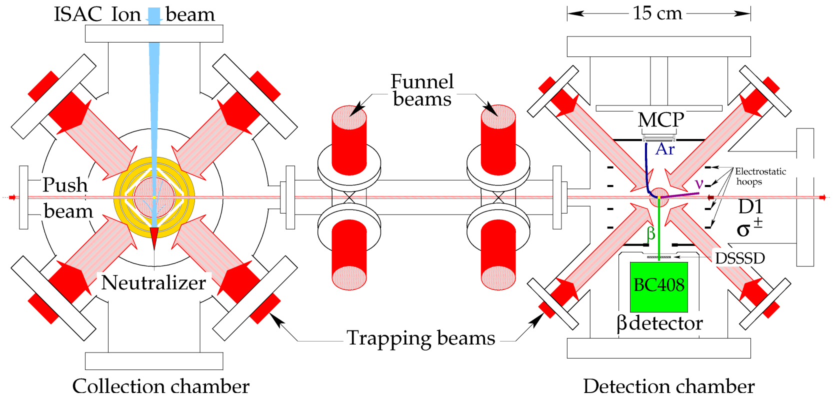
70 μA protons

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



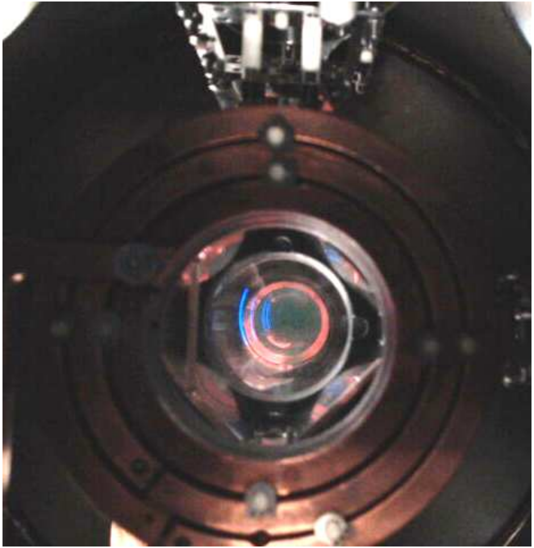
TRINAT plan view

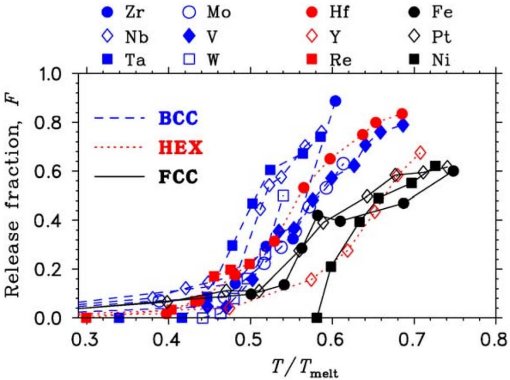
- Isotope/Isomer selective
- 75% transfer
- Avoid untrapped atom background with 2nd trap
- 0.7 mm cloud for β-Ar^{+} $\rightarrow$ ν momentum

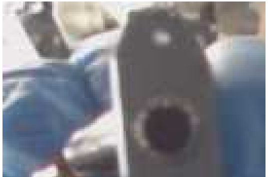


- Spin-polarized 99.1±0.1%

Neutralizer and Collection trap

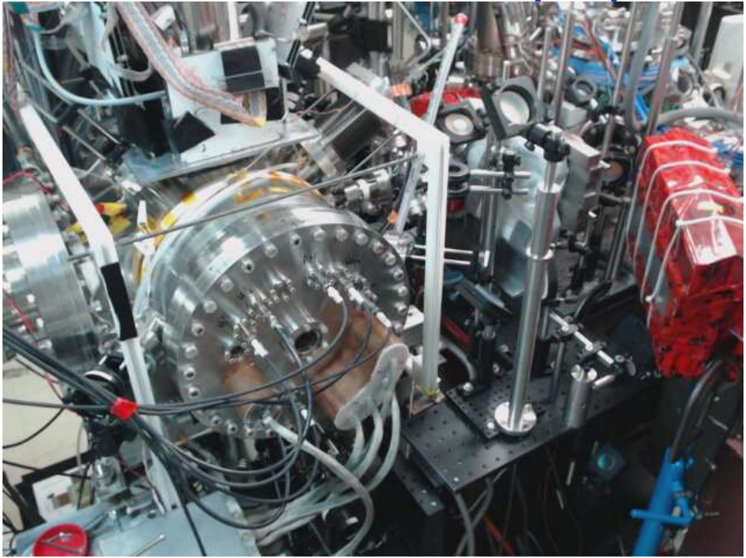




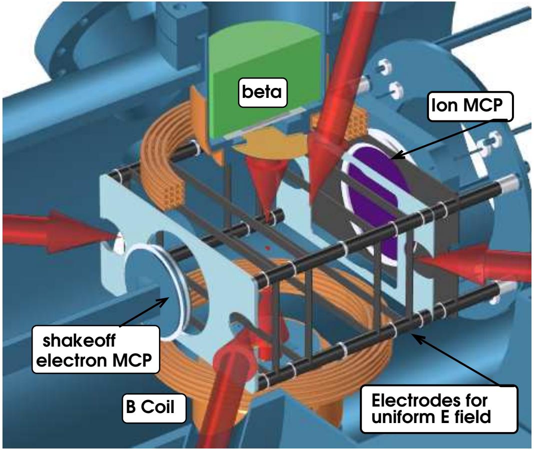


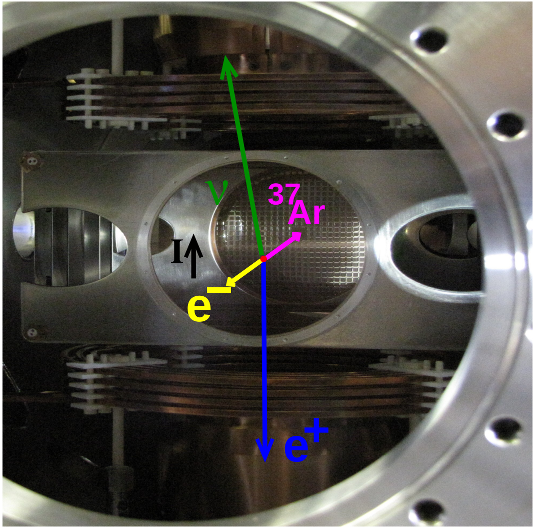
TRIUMF

TRINAT lab: “tabletop experiment”



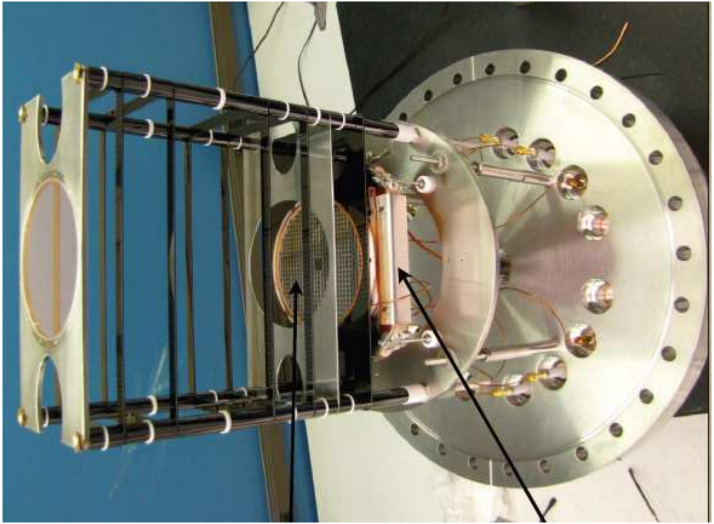
^{37}K decay geometry





- β, recoil nucleus
- shakeoff e^- for TOF trigger
  The decay pattern shown on the right is helicity-forbidden if the ν goes straight up

ion MCP assembly



14 inch CF flange

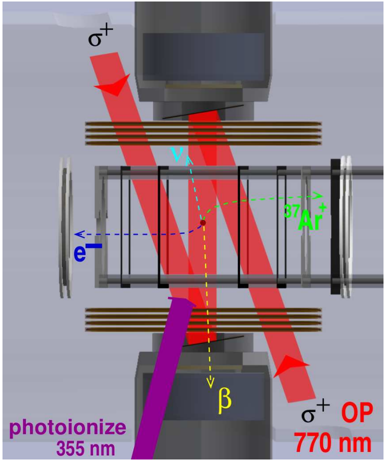
Electrostatic field

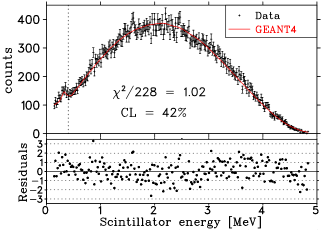
delay-line anode for position info

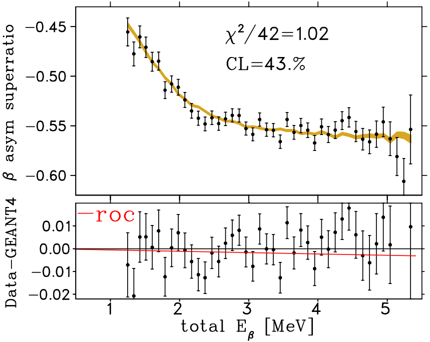
no stray wires

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

β^+ asymmetry ^{37}K data







Fenker et al. Phys Rev Lett 120, 062502 (2018)

A_β[experiment]= -0.5707 $\pm$ 0.0019

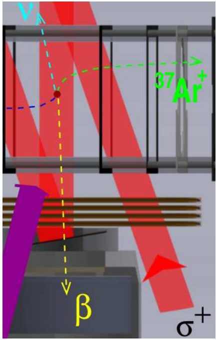
A_β[theory] = -0.5706 $\pm$ 0.0007

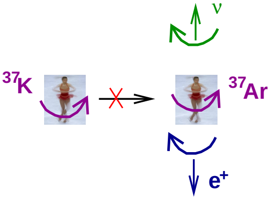
The best fractional accuracy achieved in nuclear or neutron β decay

TRIUMF

A different isospin mirror-decay spin-polarized observable

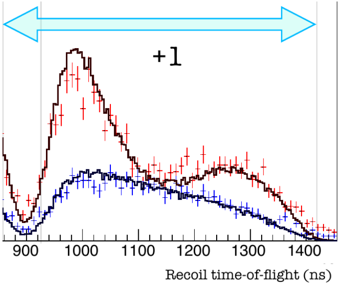
Isobaric mirror decay has helicity-driven null





Nearly direct ν helicity measurement (assuming the β^+ helicity)

2014 polarized β-recoil



$I^\pi = 3^+ \rightarrow 2^+$ decay of ^{38g}K or $I^\pi = 1^+ \rightarrow 0^+$ ^{80}Rb would complete a direct ν helicity determination

$$W(\theta, P) \approx 1 + a_{\rm pol} \cos(\theta_{\beta\nu})$$

where $a_{\rm pol} = (A_\beta - B_\nu)P - a_{\beta\nu} + 2c/3$ = 1 or 0, independent of $\frac{M_{GT}}{M_F}$

The neutron community checks this combination of observables for consistency

Mostovoi+Frank Pis'ma Zh. Eksp. Teor. Fiz. 24 45 (1976)

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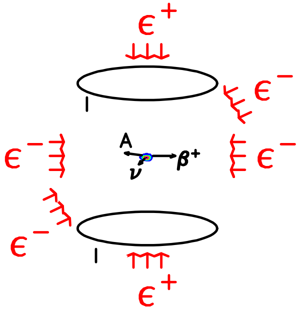
  Direct measurements of ν handedness

  All ν's are left-handed so far

- How atom traps work

  How we polarize nuclei by direct optical pumping (very similar to Ruohong Li's methods, but we have more time)

  Our proposal to measure ν handedness



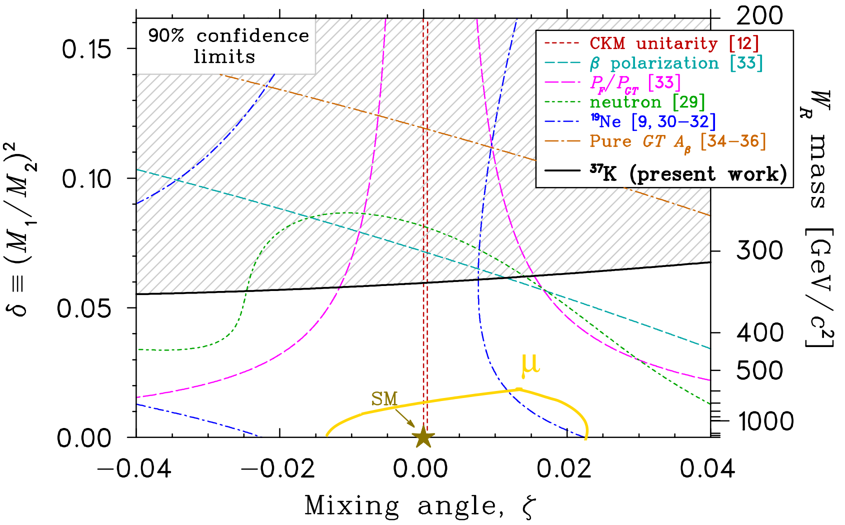
TRIUMF
A. Gorelov
B. Kootte
J.A. Behr

UBC
J. McNeil*
Undergrad:
H. Gallop, Waterloo
F. Klose, UBC
M. Ozen, Ottawa

University of Manitoba
M. Anholm*
finished
G. Gwinner

Texas A&M University
D. Melconian
J. Klimo
M. Vargas-Calderon

Still no wrong-handed ν's



Extra W' with heavier mass, couples to wrong-handed ν_R

We can evade TWIST limits by assuming the muon ν_R is heavy

LHC $M'_W > 3.7$ TeV 90%