Fermilab's "Broken Symmetry" sculpture

Slightly broken symmetry in abstract spaces drives a lot of modern particle (and condensed matter) physics

If quarks were massless, their helicity $\widehat{\text{spin}} \cdot \hat{\text{v}}$ would be well-defined $\Rightarrow$ chiral symmetry

The π's mass comes from: binding energy of quarks;
the π is the Goldstone boson of the broken chiral symmetry

Axion mass comes from a broken global U(1) symmetry hypothesized to keep a time-reversal-breaking term in the strong interaction zero.
This could still be all the dark matter.

W, Z exchange bosons of the weak interaction get mass from a broken symmetry

https://trinat.triumf.ca/talks/BrokenSymmetryWrongHandedNeutrinos.pdf

Broken symmetry and wrong-handed ν's

- ν intro

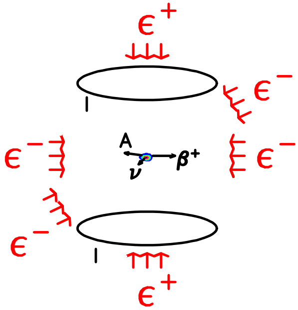
  Direct measurements of ν handedness

  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 is located on the traditional, ancestral, and unceded territory of the Musqueam people

UBC Museum of Anthropology shares a Reciprocal Research Network cultural heritage online tool with the Musqueam Indian Band, the Stolo Nation/Tribal Council, and the Umista Cultural Society

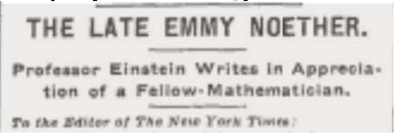
Senator Pastore: Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?

Robert Wilson (Fermilab): No, sir... It has to do with the respect with which we regard one another, the dignity of people, our love of culture.

Symmetries: Continuous, Discrete

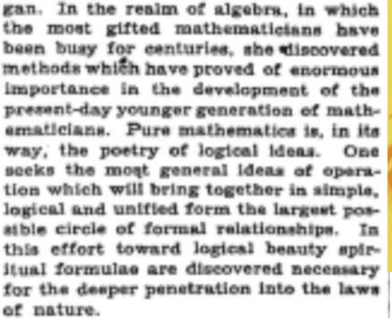
- **Noether's theorem (1915):**

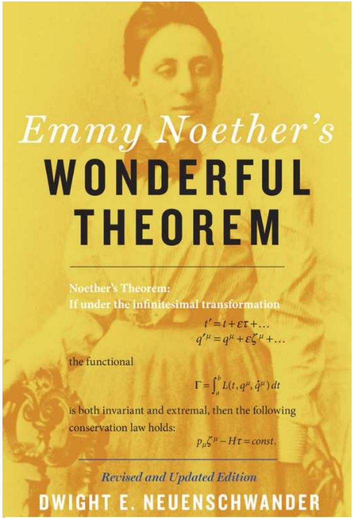
Continuous symmetry	$\rightarrow$	Conserved quantity
Time-translational invariance	$\rightarrow$	Energy
Space-translational invariance	$\rightarrow$	Momentum
Rotational invariance	$\rightarrow$	Angular momentum
(Laplace-Runge-Lenz vector)	$\rightarrow$	name?


THE LATE EMMY NOETHER.

Professor Einstein Writes in Apprecia- tion of a Fellow-Mathematician.

To the Editor of The New York Times:

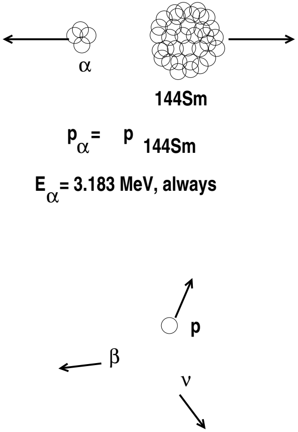

gan. In the realm of algebra, in which the most gifted mathematicians have been busy for centuries, she discovered methods which have proved of enormous importance in the development of the present-day younger generation of mathematicians. Pure mathematics is, in its way, the poetry of logical ideas. One seeks the most general ideas of operation which will bring together in simple, logical and unified form the largest possible circle of formal relationships. In this effort toward logical beauty spiritual formulae are discovered necessary for the deeper penetration into the laws of nature.



In Ted Chiang's "Story of Your Life" [Movie "Arrival"]: aliens think in terms of the action, not position and momentum

- **Discrete symmetries in quantum mechanics: Parity, Time reversal $\rightarrow$**

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:

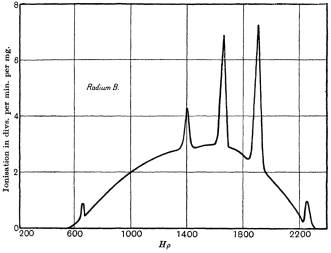


Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick's experiment of 1914. Source: Chadwick and Ellis, "Preliminary Investigation" (note 82), p. 277.

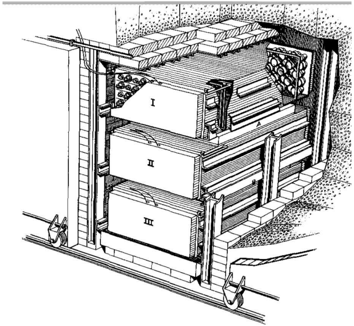
- 1915 Noether's theorem
- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!) sought to power stars...?
- 1930 Pauli postulated a new particle (??!!)

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"



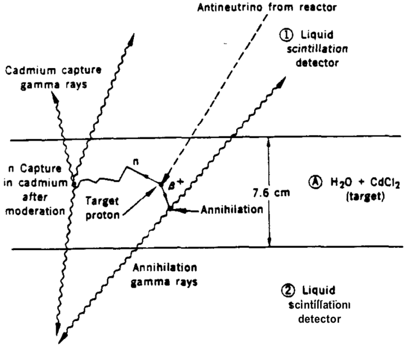
sketch of the equipment used at Savannah River. The

200 liters

4x10^{-6} SuperK's

1995 Nobel Prize

Nobel Lecture 1995 *Fredrick Reines*



compared to the expected[2]

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

$$\bar{\sigma}_{th} = (5\pm1) \times 10^{-44}\ cm^2$$

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).

Can one write a 'Bohr radius' for the ν?

Parity

As of 1956, we thought all interactions respected parity

Parity operator
$$P\,\psi(\vec{r}) \rightarrow \pm\,\psi(-\vec{r})$$

1957:
$\tau - \theta$ Puzzle
+ μ decay
+ ^{60}Co decay $\Rightarrow$

(From A. Zee "Fearful Symmetry")

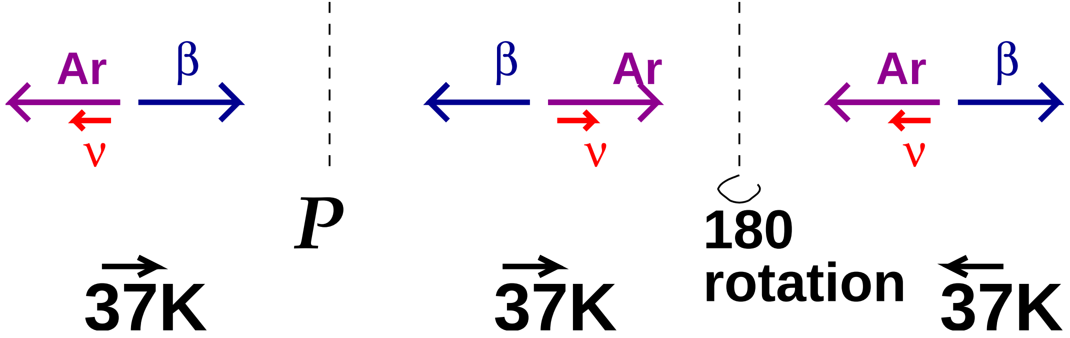
P  $=$ 

P  $\neq$ 

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

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



$\Rightarrow$ **A spin flip corresponds exactly to *P* reversal**

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

One experimental discovery of parity violation

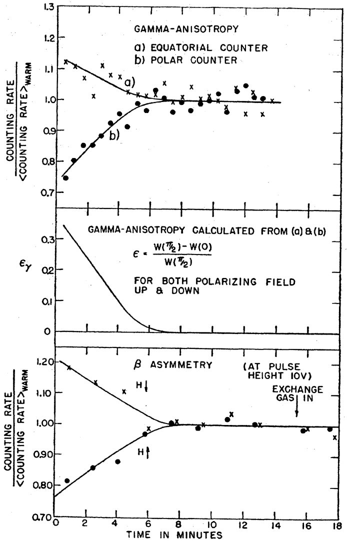
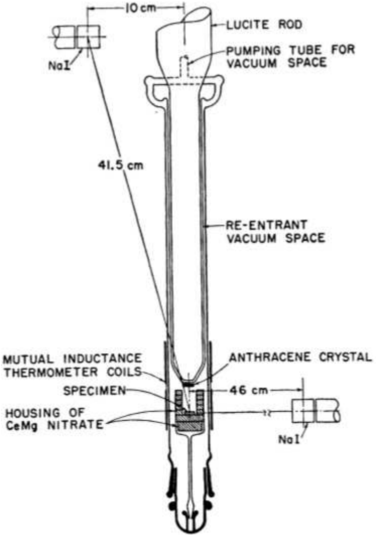


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



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 does not tell us directly about the ν's helicity

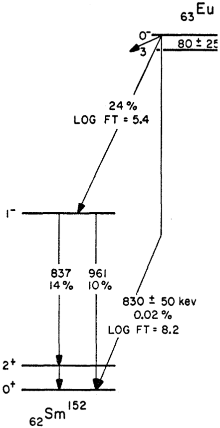
Measure ν helicity $\epsilon = \hat{s}_\nu \cdot \hat{k}_\nu$ directly: transfer $\hat{s}_\nu$ to γ circular polarization; boost $\vec{k}_\gamma$ by $\pm\vec{k}_\nu$

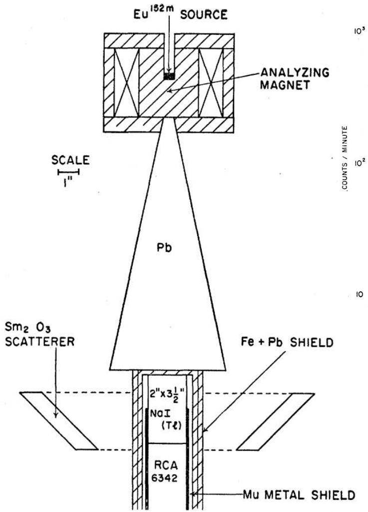
Goldhaber, Grodzins, Sunyar
Phys Rev 109 1015 (Dec 1957)

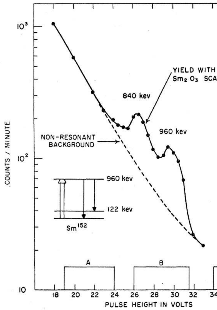
$e^- + {}^{152m}\mathrm{Eu} \rightarrow \nu + {}^{152}\mathrm{Sm}$

- **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%



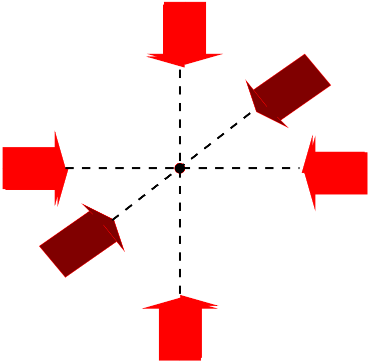




Surprisingly enough, this is the best direct measurement of ν helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$

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"

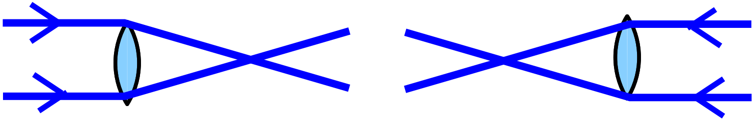
Earnshaw Theorem: $\vec{\nabla} \cdot \vec{E} = 0 \Rightarrow$

no electrostatic potential minimum for charge-free region

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

Using Poynting's theorem:

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

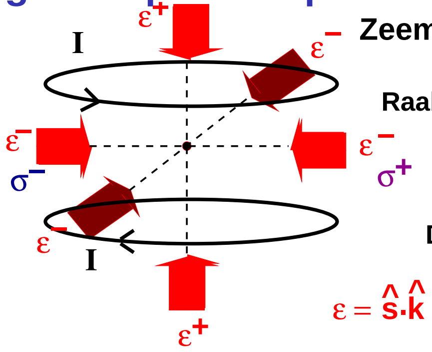


$\Rightarrow$ no 3-D traps from spontaneous light forces with static light fields

Dodges !

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

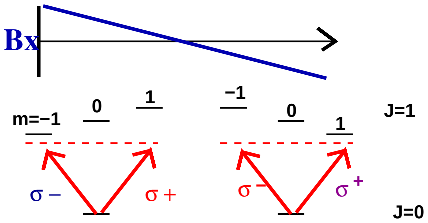
Magneto-optical trap: restoring force must perturb atoms



Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

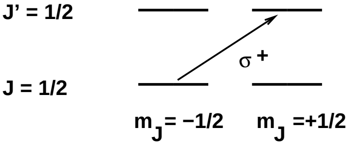


How to spin-polarize a nucleus with a laser

Polarization of nuclei by Optical Pumping

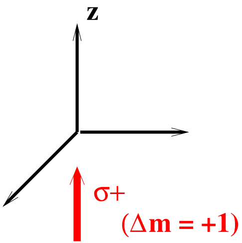
Biased random walk

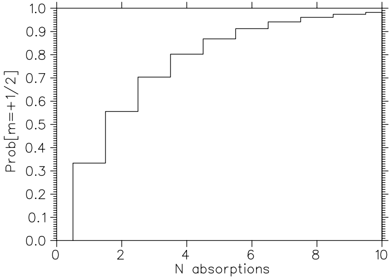
Simple example:

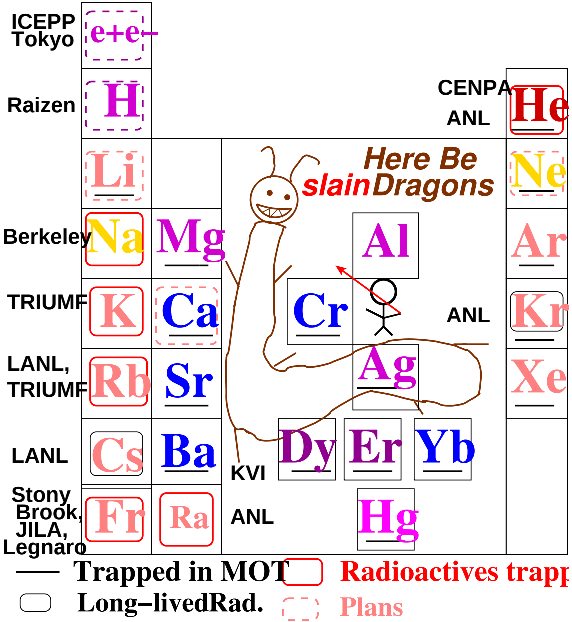


P(m=1/2) = 1 - $(2/3)^N$ after N steps

Need 12 cycles to get to 99% of maximum.

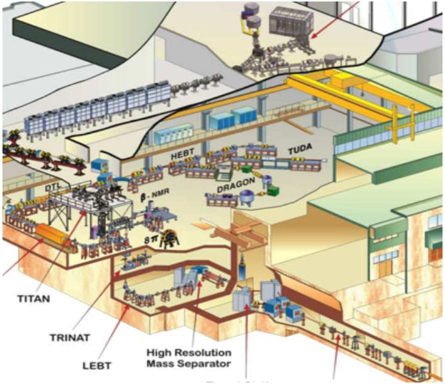






What elements can be laser cooled?

TRIumf Neutral Atom trap at ISAC

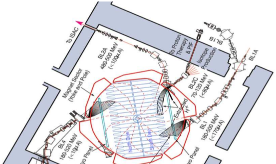


^{37}K 8x10^{7}/s

TiC target
1750^{o}C

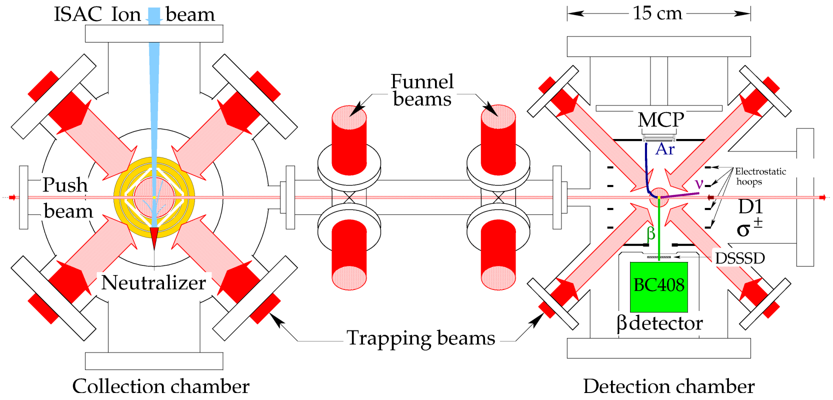
70 μA
protons

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



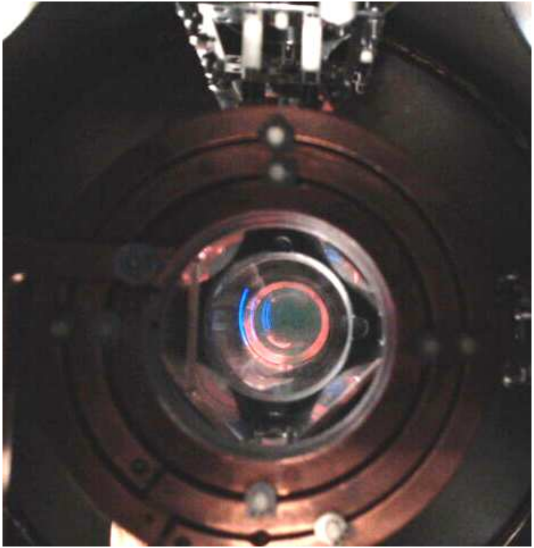
TRINAT plan view

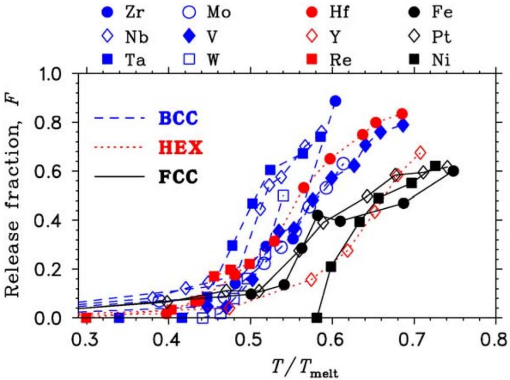
- **Isotope/Isomer selective**
- **75% transfer**
- **Avoid untrapped atom background with 2nd trap**
- **0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum**

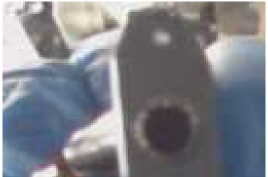


- **Spin-polarized 99.1±0.1%**

Neutralizer and Collection trap

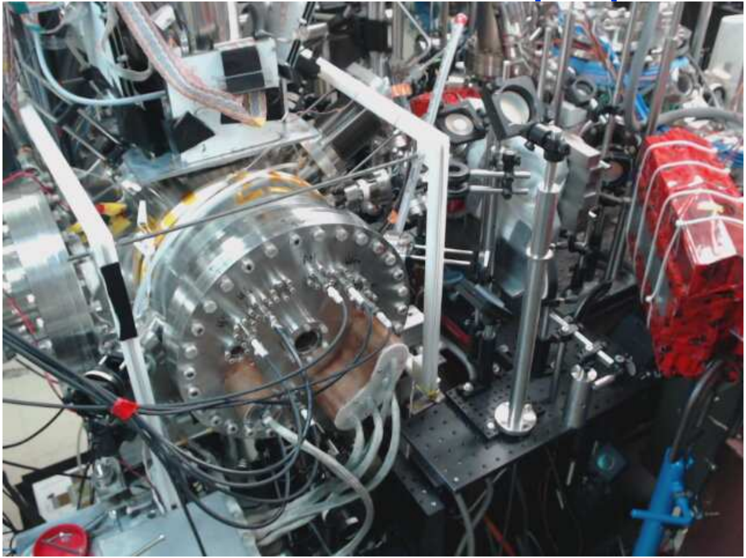




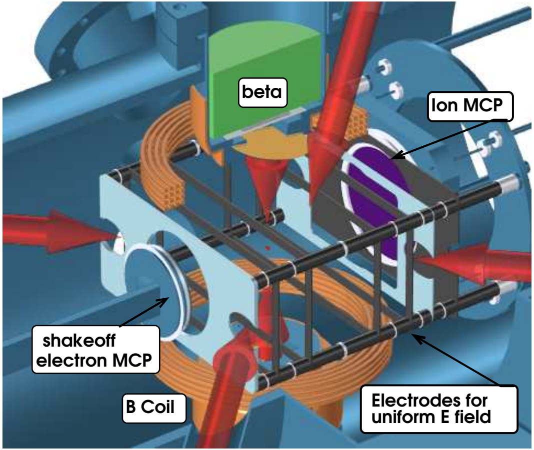


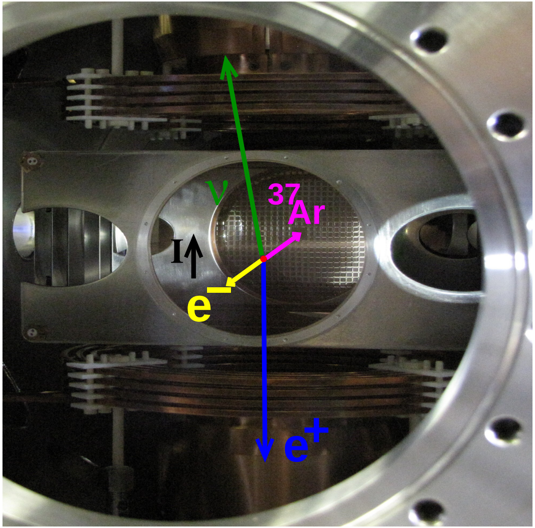
TRIUMF

TRINAT lab: "tabletop experiment"



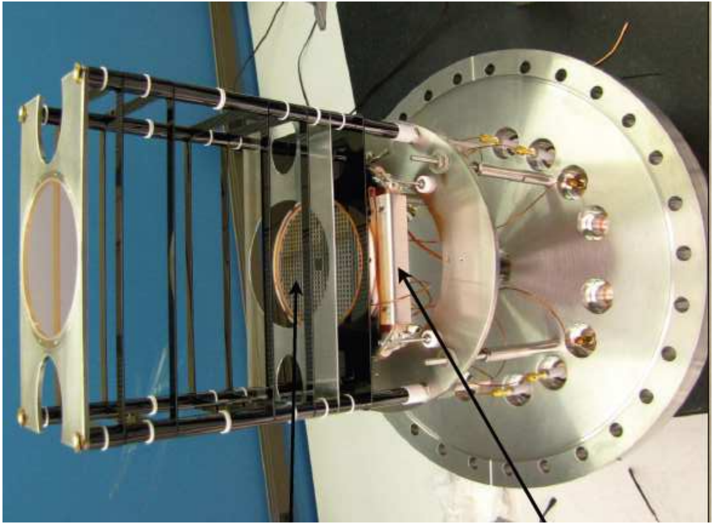
^{37}K decay geometry





- 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

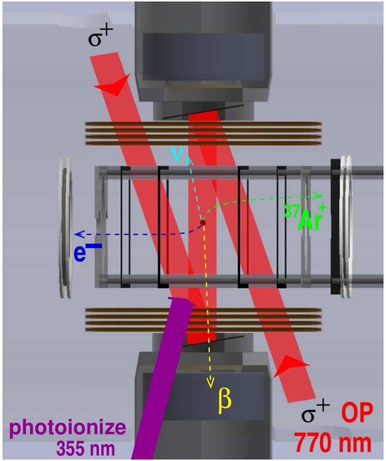
Electrostatic field

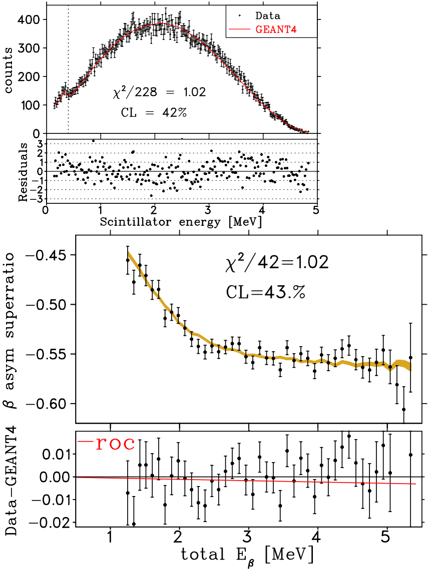
delay-line anode for position info

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

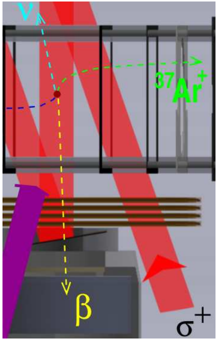
A_β[theory] = -0.5706 $\pm$ 0.0007

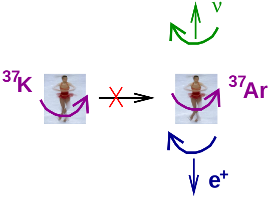
The best fractional accuracy achieved in nuclear or neutron β decay

TRIUMF

A different isospin mirror-decay spin-polarized observable

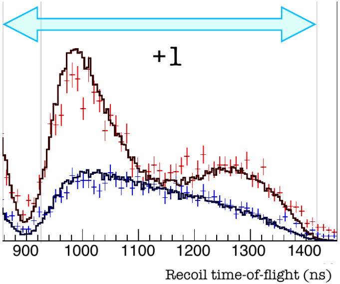
Isobaric mirror decay has helicity-driven null





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)

Broken Symmetry and Wrong-handed ν's

- ν intro

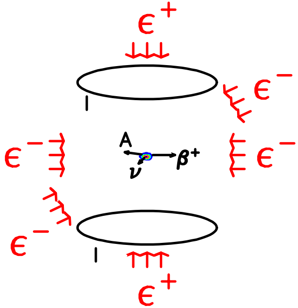
  Direct measurements of ν handedness

  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

A. Gorelov
B. Kootte
J.A. Behr

UBC

J. McNeil*
Undergrad:
L. Kawasme, UBC

University of Manitoba
G. Gwinner

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

"...since the π is both a Nambu-Goldstone boson and a $q\bar{q}$ bound state, it holds a unique position in nature" Horn, Roberts JPG 43 2016 073001

Continuous symmetry leaving a Lagrangian invariant $\rightarrow$ spin-0 $m = 0$ boson

Goldstone Salam Weinberg PR 127 965 (1961)

Breaking that symmetry generates a pseudo Nambu Goldstone boson with $m \neq 0$

JB is ignoring sublety here– the Lagrangian can stay symmetric while a vacuum expectation value of a field can break the symmetry...

- The π can be treated as a Goldstone boson acquiring m from broken chiral symmetry.

(Remember chiral symmetry means m_q's = 0, so q's then have well-defined handedness.)

Remembering that $m_\rho \approx 4/5\ m_{\rm nucleon}$, and constituent q's work for μ_ρ, but $m_\pi \approx 1/7\ m_{\rm nucleon}$

Gell-Mann Oakes Renner PR 175 2195 (1968)
(note this pre-dates QCD)

$m_\pi^2 \propto \langle \pi | U_{ECSB} | \pi \rangle$

U_{ECSB} is interactions breaking chiral symmetry

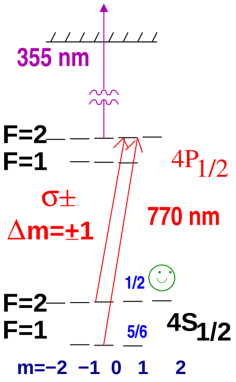
(also $m_\pi^2 + 3m_\eta^2 - 4m_K^2 = 0$)

π as a $q\bar{q}$ bound state of constituent q's leads instead to $m_\pi \propto \langle \pi | U_{ECSB} | \pi \rangle$
(to get $m_\pi = 135$ MeV needs fine tuning)

- If m_q's = 0, then for a Goldstone boson π, m_π = 0, and its interactions also vanish (!)
  Restoring chiral symmetry in nuclei was a possible solution to the Gamow-Teller strength deficit (below).

- We saw that chiral EFT of N-N interaction is based on $\approx$ chiral symmetry of the q's.
  So is chiral perturbation theory, which quantifies a QCD-induced weak decay (below).
  The axion is another Goldstone boson from $\not{T}$ in QCD (below)

TRIUMF Optical pumping and probing ^{37}K TEXAS A&M UNIVERSITY



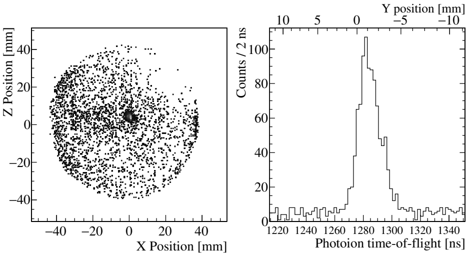
Photoionize 1%

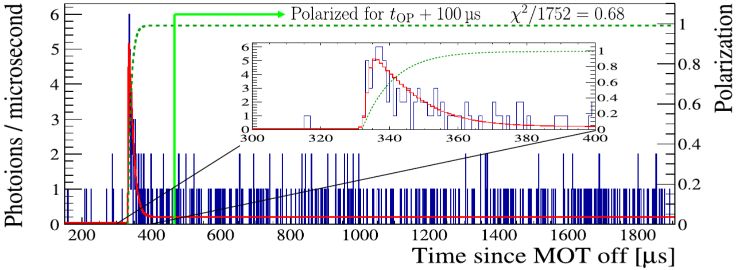
***in situ* probe**

$\boldsymbol{P_+ = +0.9913(8)}$

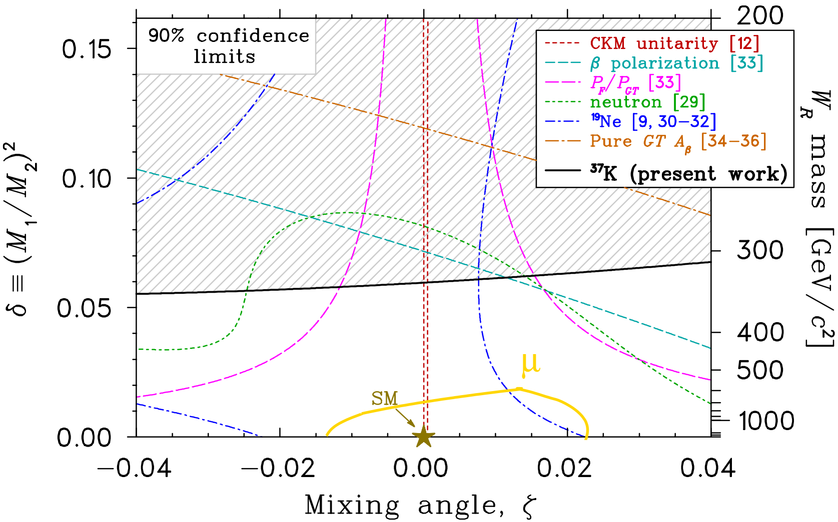
$\boldsymbol{P_- = -0.9912(9)}$

Fenker NJP 2016





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%