Fermilab's "Broken Symmetry" sculpture



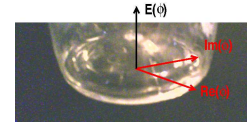




Slightly broken symmetry in abstract spaces drives a lot of modern particle (and condensed matter) physics

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

$L_{QCD} = \bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R - \bar{q}_L m q_R - \bar{q}_R m q_L - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$

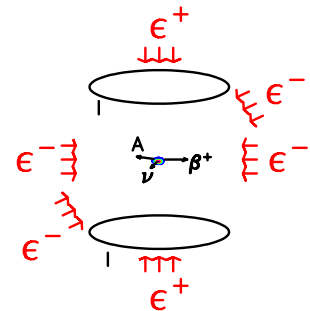


if $m = 0$, L_{QCD} is invariant under applying different phases to q_L, q_R, a continuous symmetry. Then a constructed scalar field $\phi = \bar{q}_L q_R$ varies under this continuous symmetry $\rightarrow$ an $m = 0$ goldstone boson, the π.

The chiral symmetry is **also** broken by $m \neq 0$ in $L_{QCD} \rightarrow$ a mass to π by subtly changing the scalar field $\bar{q}_L q_R$ (for 1 quark 'the H_2O bottle gets tilted') making the π a "pseudo"-Nambu-Goldstone boson (also from the evident binding $q\bar{q}$, and from m_q itself in L_{QCD}). The π was suspected to be a Goldstone boson before quarks

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	→	**Conserved quantity**
Time-translational invariance	→	**Energy**
Space-translational invariance	→	**Momentum**
Rotational invariance	→	**Angular momentum**
(Laplace-Runge-Lenz vector)	→	**name?**

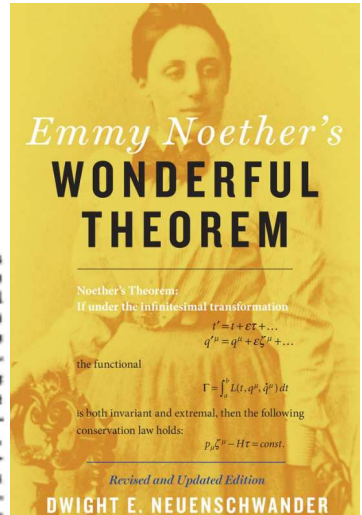


THE LATE EMMY NOETHER.

Professor Einstein Writes in Appreciation 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 →**

- Wigner considered implications of P, T symmetry conservation in atomic spectra 1926-28. Showed $\langle T\psi_i, T\psi_f\rangle = \langle \psi_f, \psi_i\rangle^*$

"In quantum theory, invariance principles permit even further reaching conclusions than in classical mechanics." (D. Gross, Physics Today 48 46 (1995))

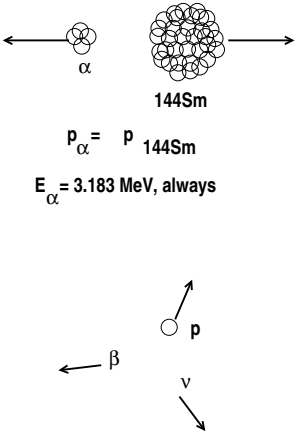
- Weyl 1931 considered C, P, T and CPT in "Maxwell-Dirac theory": C $\Rightarrow$ Dirac eq. negative energy states had to have same mass as the e^- plato.stanford.edu
- From "CP Violation Without Strangeness" Khriplovich and Lamoreaux:

1949 Dirac "I do not believe there is any need for physical laws to be invariant under reflections in space and time although the exact laws of nature so far known do have this invariance."

Apr 1956 Asimov "The Dead Past" ν travels backwards in time

- Oct 1956 Lee and Yang proposed $\not{P}$ in weak decays to fix the θ-τ puzzle
- Feynman gives Ramsey 50:1 odds $\not{P}$ would not be observable
  Ramsey experiment starting at ORNL gets derailed by fission experiments...
  it's OK, Ramsey won 1989 Nobel for his fringes
- 1957 3 simultaneous experimental measurements of $\not{P} \rightarrow$

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 E_e spectrum, not a discrete peak!

Meitner and Hahn 1911, Danysz 1913, experimentally resolved:

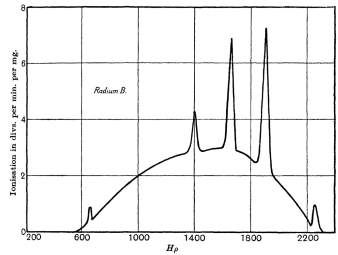


Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick's experiment of 1914. Source: Chadwick and Ellis, "Preliminary Investigation" (note 82), p. 277.

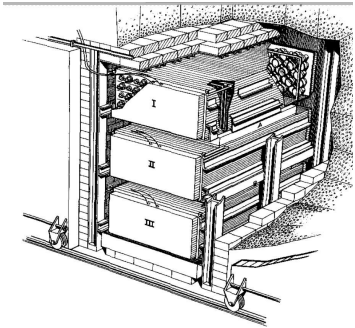
- 1915 Noether's theorem
- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!) sought to power stars...?
- 1930 Pauli postulated a new particle (??!!)

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"

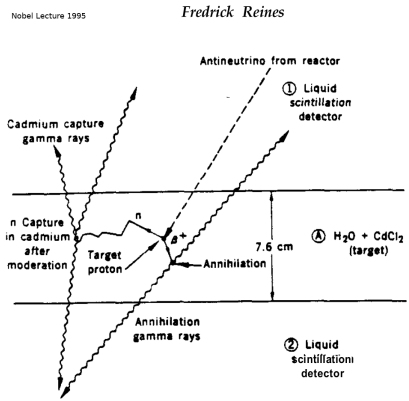


sketch of the equipment used at Savannah River. The

200 liters

4x10^{-6} SuperK's

1995 Nobel Prize



compared to the expected[2]

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

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

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

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

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?

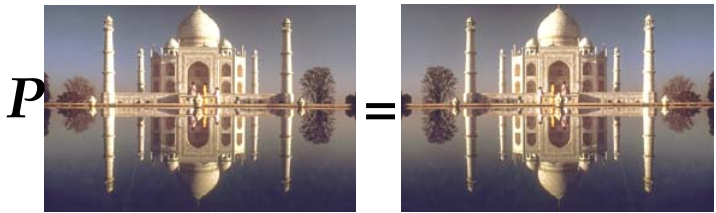
Parity

(From A. Zee "Fearful Symmetry")

As of 1956, we thought all interactions respected parity

Parity operator

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

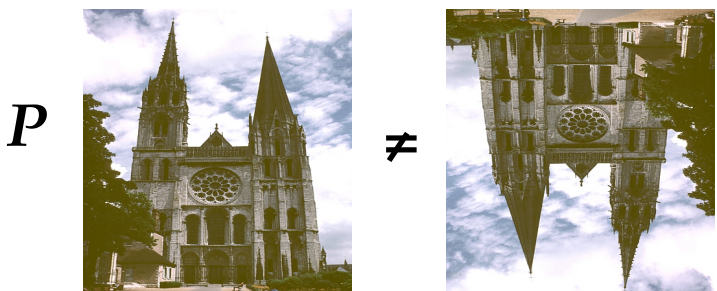


1957:

$\tau - \theta$ Puzzle

+ μ decay

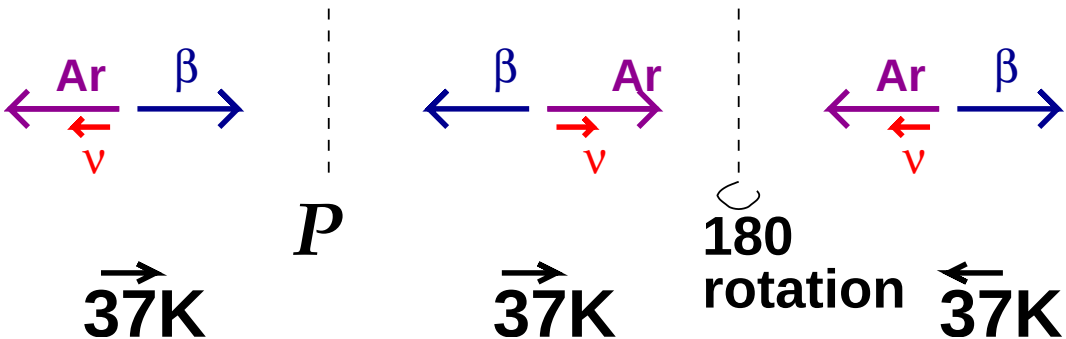
+ ^{60}Co decay $\Rightarrow$



Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

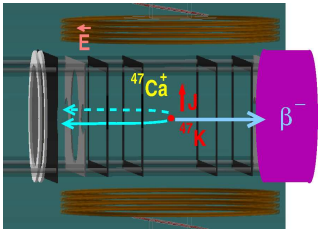
$\vec{r} \rightarrow -\vec{r}$ $\quad \vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$ $\quad \vec{J}=\vec{r} \times \vec{p} \rightarrow +\vec{J}$



⇒ **A spin flip corresponds exactly to *P* reversal**

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

Summary: T-odd P-even NN from isospin-hindered ^{47}K β decay



Any $\not T$ decay experiment should answer:

- **Does interaction between outgoing particles mimic $\not T$?**

'We wish': with upgrades we can reach $D_{\text{false}} \sim 10^{-4}$

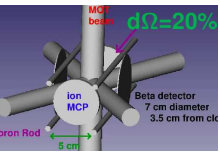
- **Have null ToPo EDM's ruled you out?**

Given 10x enhancement, not if we reach $D < 10^{-3}$

- **Has your experiment been done better? Our 1st goal is 3x better than Calaprice et al. ^{56}Co, complementary to NOPTREX n scattering for ToPe**

- **Isospin-hindered β decay enhances sensitivity to $\not T$ $D\,\vec{I}\cdot\vec{v}_\beta\times\vec{v}_\nu$**

☺Measured systs for B_ν in ^{37}K $\rightarrow$ ^{47}K $D \lesssim 0.001 \Rightarrow \frac{h_{\rho NN}[ToPe]}{h_{\rho NN}} \lesssim 10^{-4}$, complementarity to ToPo n EDM and NOPTREX's n ToPe scattering. 2 weeks



Upgrades in $d\Omega_\beta$, trap stability, collection $\rightarrow D \lesssim 0.0001 \Rightarrow \frac{h_{\rho NN}[ToPe]}{h_{\rho NN}} \lesssim 10^{-5}$

Would inspire Sakharov-driving ToPe models if we found something 10 weeks

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J.A. Behr

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UBC
O. Tijani
J. McNeil

UNIVERSITY OF MANITOBA
G. Gwinner

TEXAS A&M UNIVERSITY
D. Melconian
M. Vargas-Calderon

EDM in a fundamental particle breaks T: this is exact

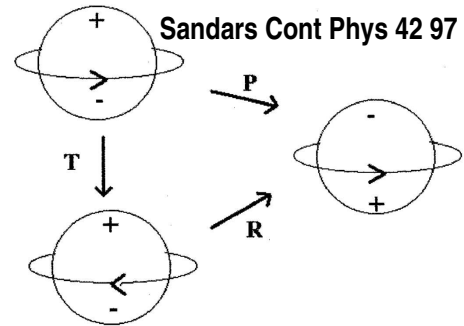
Landau, Nucl. Phys. 3 (1957) p. 127

Electric Dipole moment $\vec{d} = \sum q_i \vec{r}_i$

Since the angular momentum is the only vector in the problem, $\vec{d} = a\vec{J}$

Under T, $\vec{J} \overset{t\to -t}{\to} -\vec{J}$ $\quad \vec{d} \overset{t\to -t}{\to} +\vec{d}$

If the physics is invariant under T, this is a contradiction, $\Rightarrow a = 0$



[• The other logical possibility: there are 2 states, with opposite sign of the EDM, and T just formally changes one state to the other.
For most fundamental particles, we know there aren't 2 states
Why do we know the electron doesn't have 2 states?
E.g. some polar molecules have a dipole moment listed in tables, which produces degenerate states and does not break T ...]

One experimental discovery of parity violation

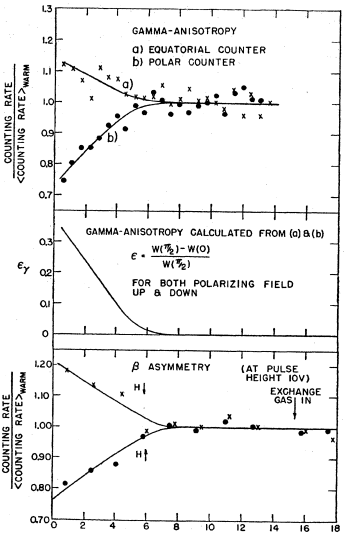
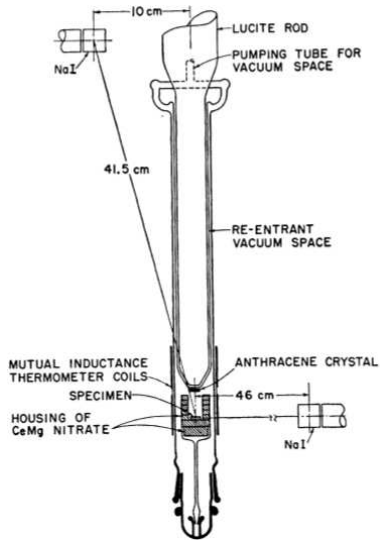


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



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

Dilution Refrigerator to spin-polarize

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

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

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

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

Followup:

$$^{58}\mathrm{Co} \rightarrow {}^{58}\mathrm{Fe} + \beta^+ + \nu$$

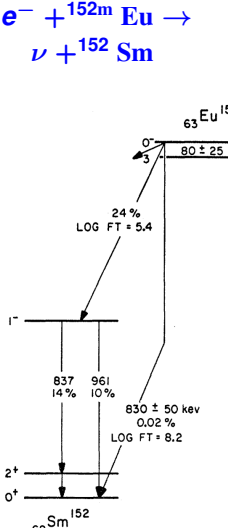
$$A_{\beta+} > 0$$

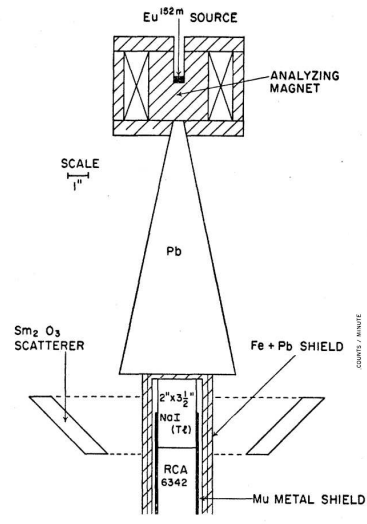
CP conserved?

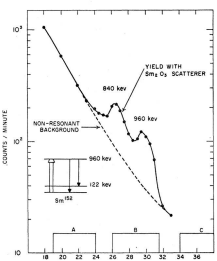
This does not tell us directly about the ν's helicity

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 $\pm\vec{k}_\nu$

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







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

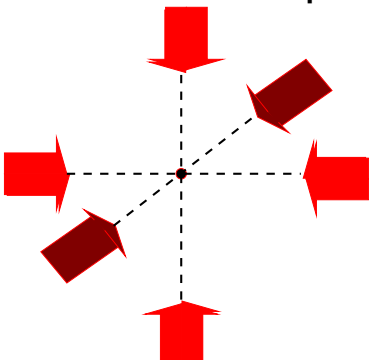
- Upward-going ν populates $\langle I_z \rangle = 0, +1$ not -1
- So γ is circularly polarized– transmission through magnet depends on iron polarization: $\frac{N_+ - N_-}{N_+ + N_-} = 0.017 \pm 0.003$
- Upward ν boosts γ momentum so it can be absorbed on-resonance

$\Rightarrow$ 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

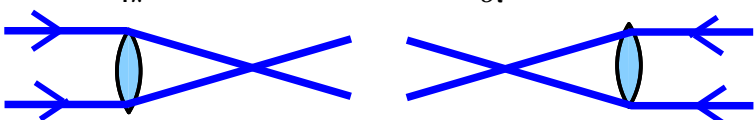
"Why Optical Traps Can't Work"

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:

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

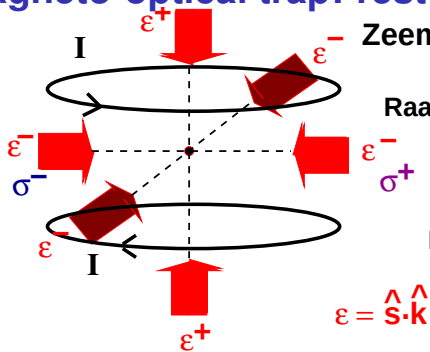


$\Rightarrow$ no 3-D traps from spontaneous light forces
with static light fields

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

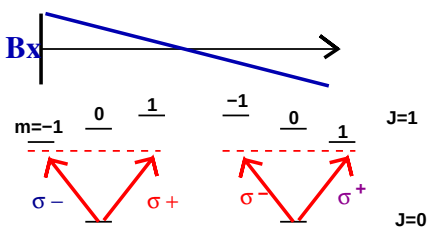


Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

$$\varepsilon = \hat{s}\cdot\hat{k}$$

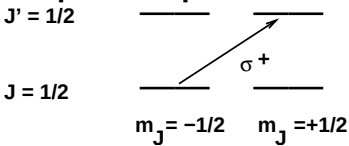


How to spin-polarize a nucleus with a laser

Polarization of nuclei by Optical Pumping

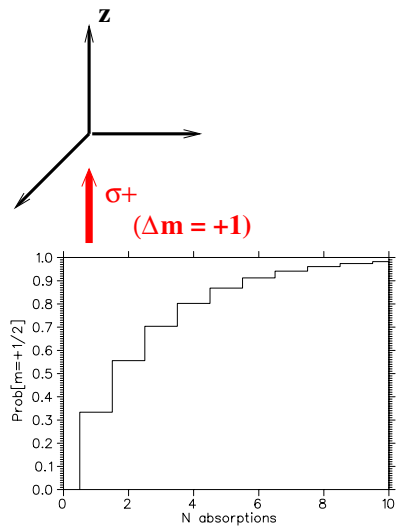
Biased random walk

Simple example:

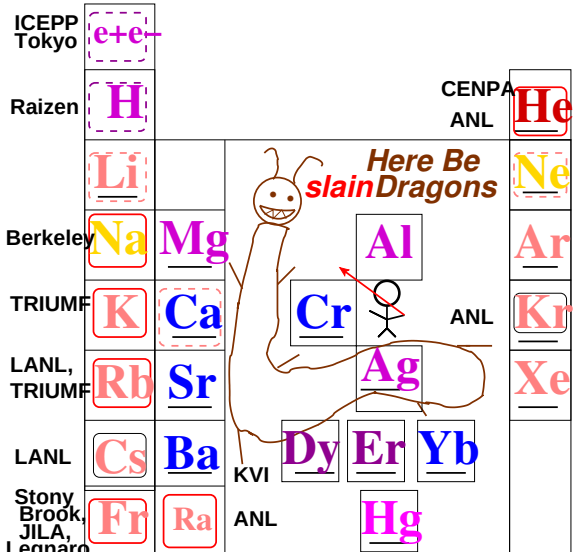


$P(m=1/2) = 1 - (2/3)^N$ after N steps

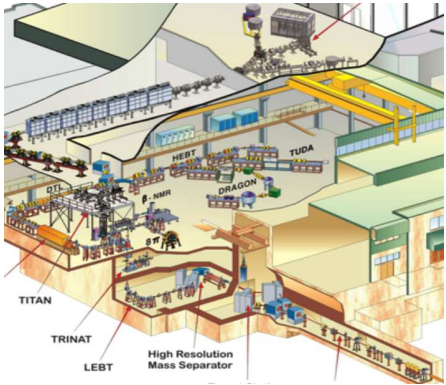
Need 12 cycles to get to 99% of maximum.



What elements can be laser cooled?

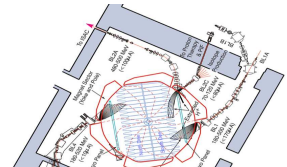


TRIumf Neutral Atom trap at ISAC



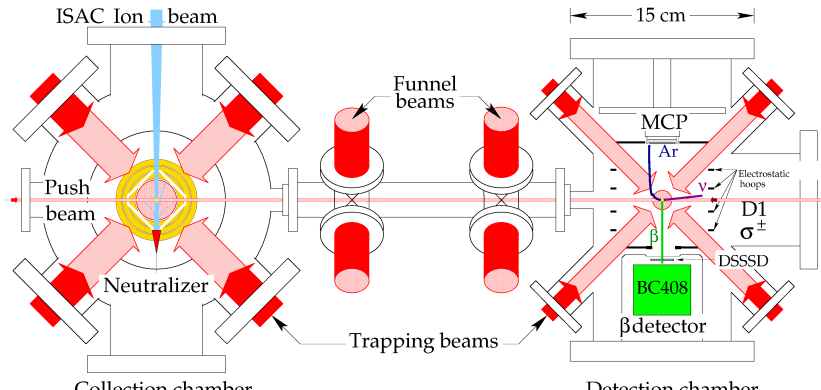
^{37}K 8x10^{7}/s TiC target 1750^{o}C 70 μA protons

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



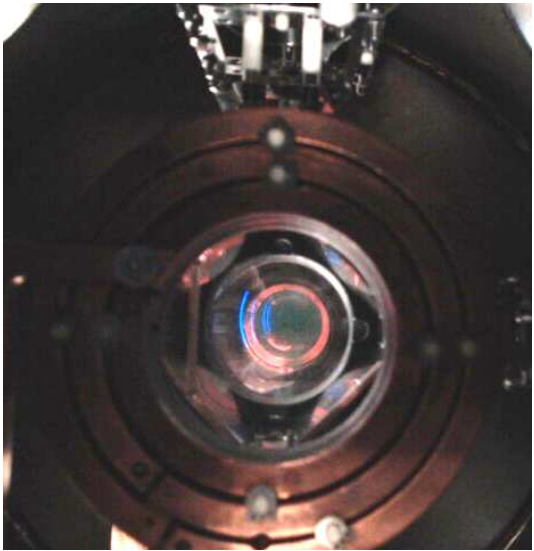
TRINAT plan view

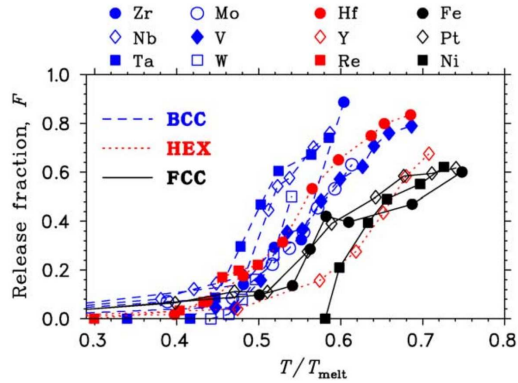
- Isotope/Isomer selective
- 75% transfer
- Avoid untrapped atom background with 2nd trap
- 0.7 mm cloud for β-Ar$^+ \rightarrow \nu$ momentum



- Spin-polarized 99.1$\pm$0.1%

Neutralizer and Collection trap

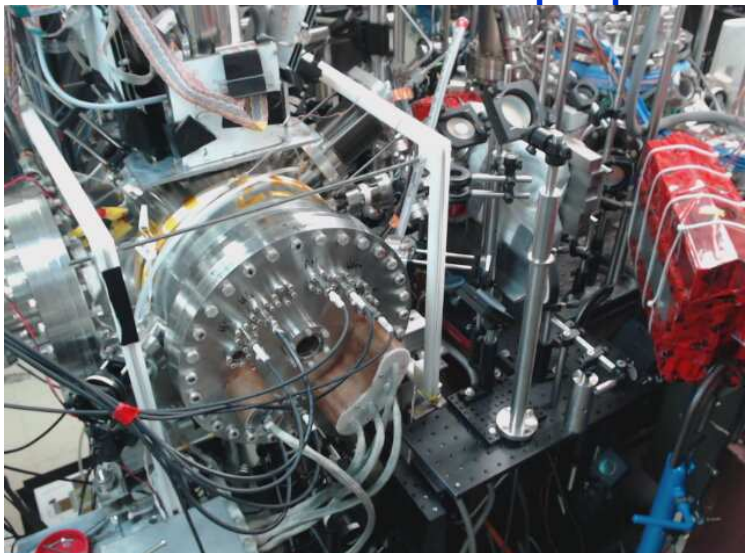




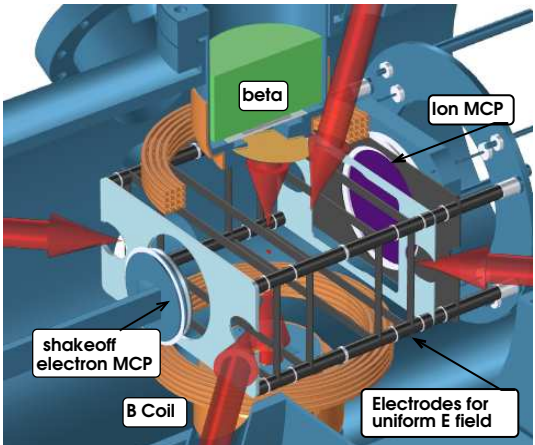


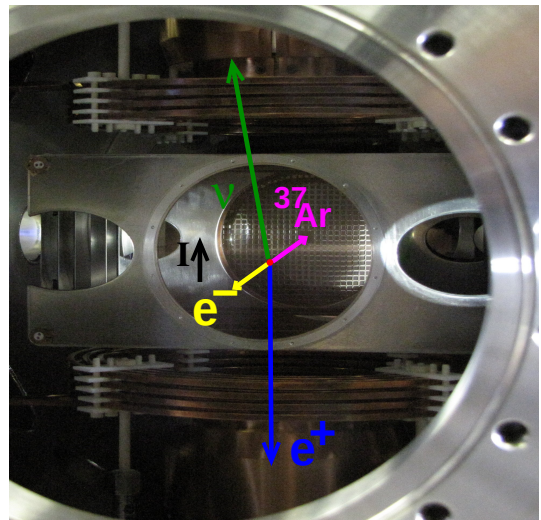
TRIUMF

TRINAT lab: “tabletop experiment”



^{37}K decay geometry

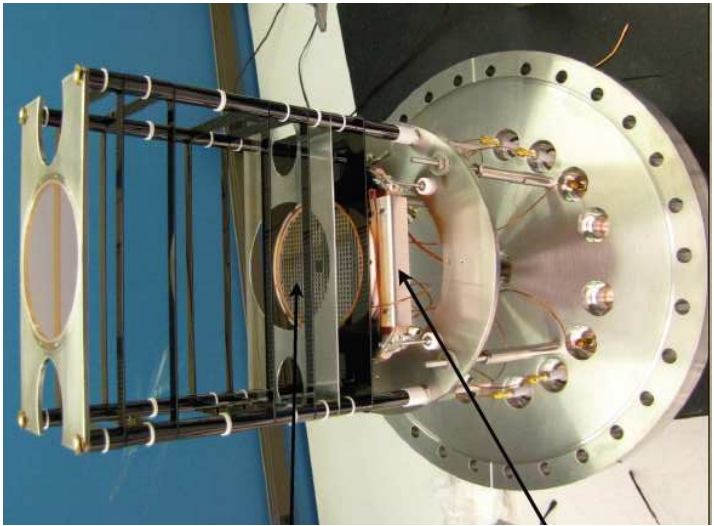




- β, recoil nucleus
- shakeoff e^- for TOF trigger

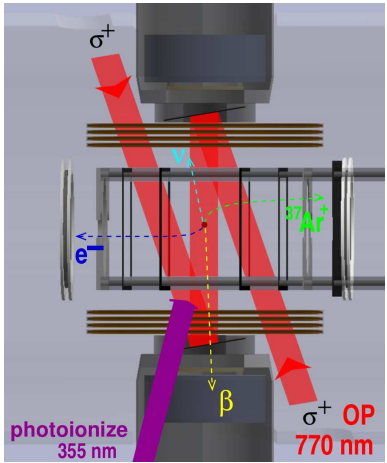
The decay pattern shown on the right is helicity-forbidden if the ν goes straight up

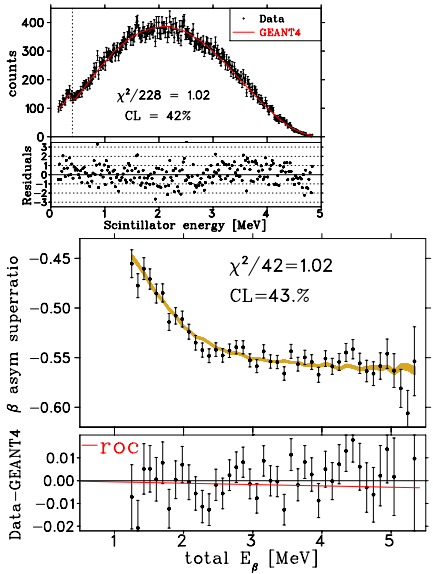
ion MCP assembly



- 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)

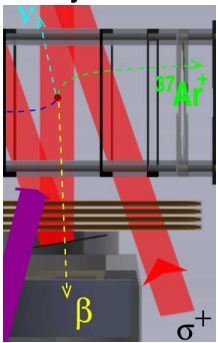
A_β[experiment]= -0.5707 $\pm$ 0.0019

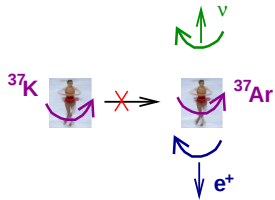
A_β[theory] = -0.5706 $\pm$ 0.0007

The best fractional accuracy achieved in nuclear or neutron β decay

A different isospin mirror-decay spin-polarized observable

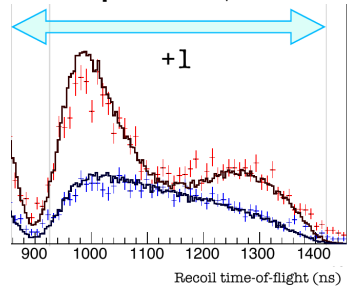
Isobaric mirror decay has helicity-driven null





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

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

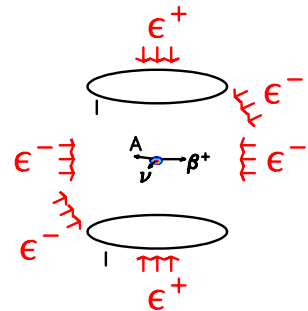
where $a_{pol} = (A_\beta - B_\nu)P - a_{\beta\nu} + 2c/3 = 1$ or 0, independent of $\frac{M_{GT}}{M_F}$

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



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Chiral symmetry of QCD Lagrangian: what does this mean? Needs QFT

Rewrite $L_{QCD} = \bar{q}(i\not{D} - m)q - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$

in terms of left- and right- handed chirality components of the quark fields $q_L = \frac{1}{2}(1+\gamma_5)q$; $q_R = \frac{1}{2}(1-\gamma_5)q$:

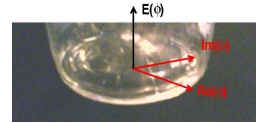
$$L_{QCD} = \bar{q}_L i\not{D} q_L + \bar{q}_R i\not{D} q_R - \bar{q}_L m q_R - \bar{q}_R m q_L - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

For a massive particle with chirality $\hat{s}\cdot\hat{k}$, you can boost to a frame where $\hat{k}\rightarrow -\hat{k}$, so the particle appears to have opposite chirality.

Definitive chirality needs $m = 0$

Still considering $m = 0$, L_{QCD} is invariant under applying different phases to q_L, q_R, a continuous symmetry.

Keeping $m = 0$, a constructed scalar field ϕ=$\bar{q}_L q_R$ which varies under this continuous symmetry $\rightarrow$ an $m = 0$ goldstone boson, the π.

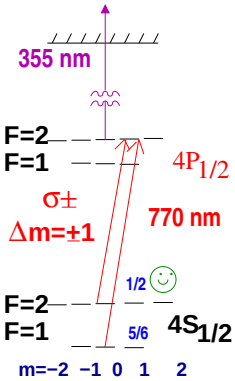


The chiral symmetry is also broken by $m \neq 0$ in L_{QCD}! But this symmetry breaking in L can't produce any Goldstone boson. It does give mass to that Goldstone boson, by subtly changing the scalar field $\bar{q}_L q_R$ (for 1 quark 'the wine bottle gets tilted') making the π a "pseudo"-Nambu-Goldstone boson (also from the evident binding $q\bar{q}$, and from m_q itself in L_{QCD}). The π was suspected to be a Goldstone boson before quarks

Note $m_u \sim 5$ MeV and $m_d \sim 9$ MeV $<< \Lambda \sim 1$ GeV

TRIUMF Optical pumping and probing ^{37}K

TEXAS A&M UNIVERSITY



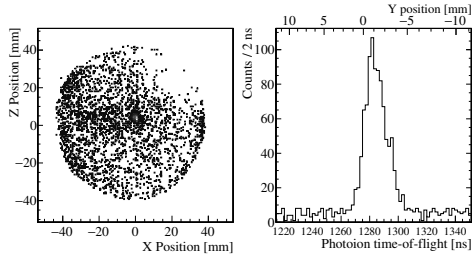
Photoionize 1%

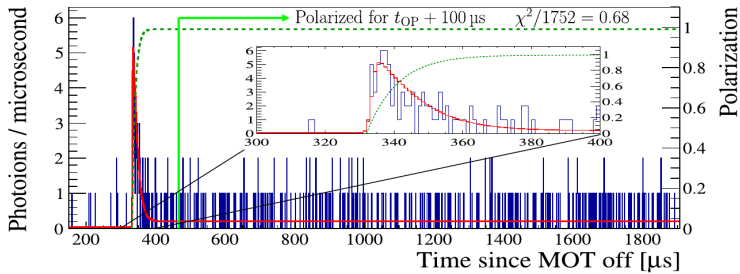
in situ **probe**

P_+=+0.9913(8)

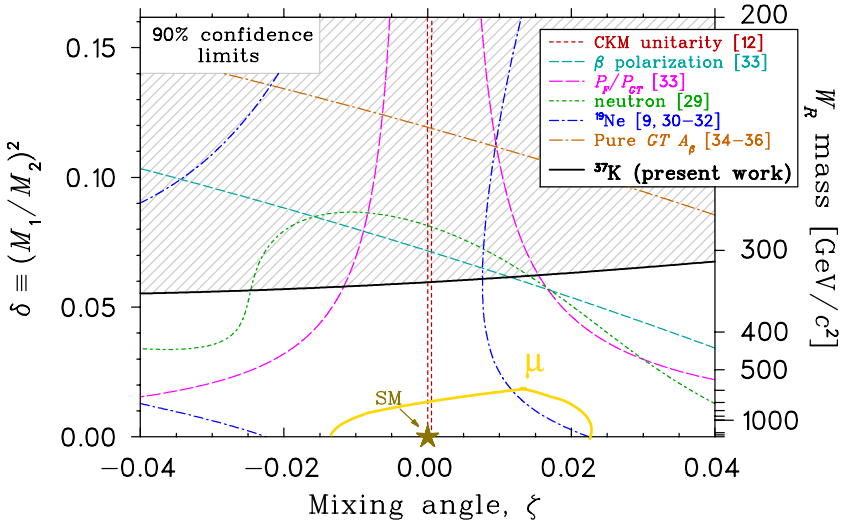
P_-=–0.9912(9)

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%