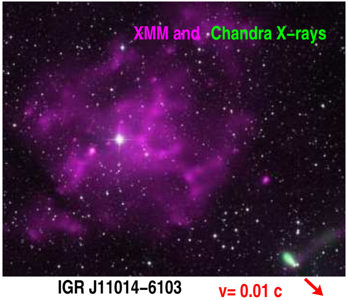
Preview: Weak interaction breaks parity: Consequences?

'Pulsar kicks'



Fuller PRD 2003

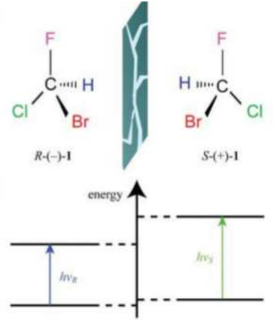
Forced $p + e^- \rightarrow n + \nu$

$W(\theta) = 1 + \frac{\langle m_I \rangle}{I} A_\nu \cos(\theta_{\hat{I}})$

B field polarizes p's

Need ν_e to include 10^{-8} admixture of $m_\nu \sim$ keV

Earthling's amino acids are all left-handed



Letokhov PLA'75

Darquie CHIRALITY 2010

$\Delta E \sim 10^{14-16}$eV

Not Enough for left-handed bugs to win, so $\rightarrow$

Spin-polarized SN ν's could preferentially zap wrong-handed amino acids

Finding the right environment for spin-polarized amino acids? e.g. :

Astrobiology 18 (2018) Selection of Amino Acid Chirality via ν Interactions with ^{14}N in $\vec{E} \times \vec{B}$ Fields M.A. Famiano, R.N. Boyd

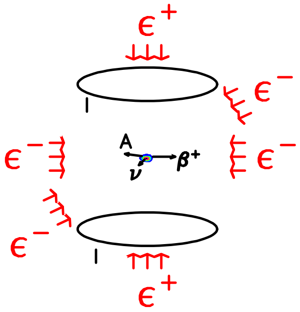
(TRIUMF EEC 90's)...

ν's, Fun Sym, and Atom Traps

- **Parity *P* symmetry**

  How to test *P* symmetry experimentally

  Only left-handed ν so far: how do we know this?



- **How atom traps work**
- **$\not{P}$ with TRIUMF Neutral Atom trap for β decay**

If there's time:

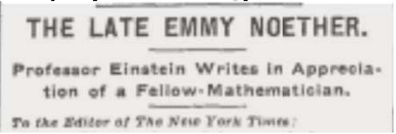
- **$\not{P}$ in Fr atoms**
- **$\not{T}$ experiments**

https://trinat.triumf.ca/talks/nus-funsym-fall2022

Symmetries: Continuous, Discrete

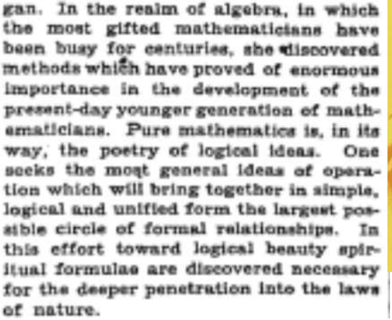
- Noether's theorem (1915):

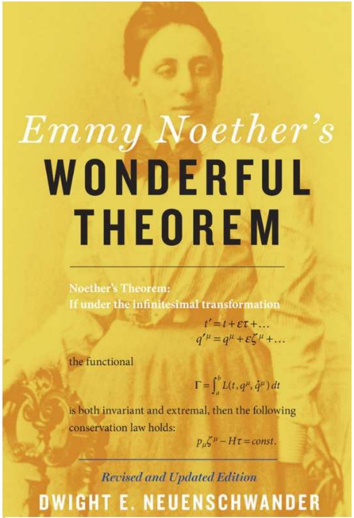
Continuous symmetry	$\rightarrow$	Conserved quantity
Time-translational invariance	$\rightarrow$	Energy
Space-translational invariance	$\rightarrow$	Momentum
Rotational invariance	$\rightarrow$	Angular momentum
(Laplace-Runge-Lenz vector)	$\rightarrow$	name?


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 $\rightarrow$

Historical Ideas about P, T breaking

- 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 $\not{P}$ $\rightarrow$

Parity (From A. Zee "Fearful Symmetry")

As of 1956, we thought all interactions respected parity

Parity operator

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

P  $=$ 

1957:

$\tau - \theta$ Puzzle

+ μ decay

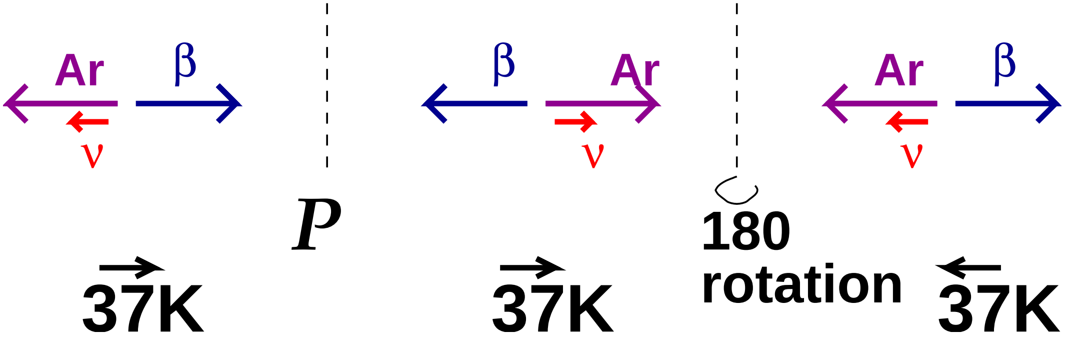
+ ^{60}Co decay $\Rightarrow$

P  $\neq$ 

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

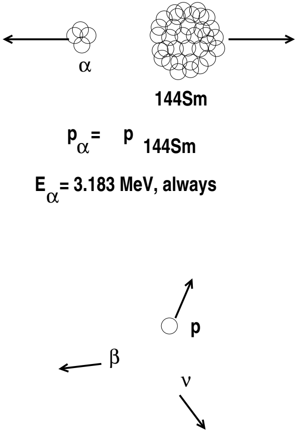
$\vec{r} \to -\vec{r}$ $\vec{p} \sim \frac{d\vec{r}}{dt} \to -\vec{p}$ $\vec{J} = \vec{r} \times \vec{p} \to +\vec{J}$



⇒ A spin flip corresponds exactly to *P* reversal

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

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:

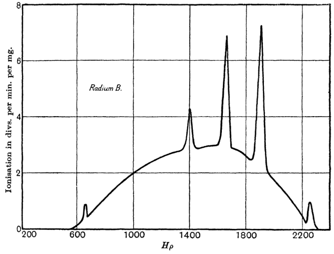


Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick's experiment of 1914. Source: Chadwick and Ellis, "Preliminary Investigation" (note 82), p. 277.

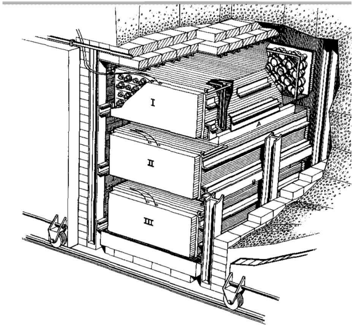
- 1915 Noether's theorem
- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!) sought to power stars...?
- 1930 Pauli postulated a new particle (??!!)

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

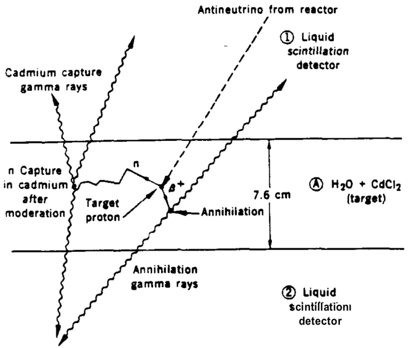
200 liters

4x10^{-6} SuperK's

1995 Nobel Prize

Nobel Lecture 1995

Fredrick Reines



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

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 ∼ 30%

One experimental discovery of parity violation

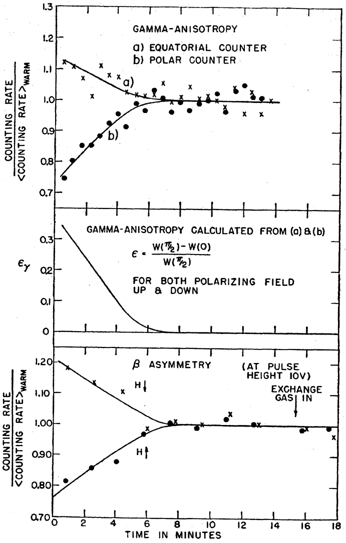
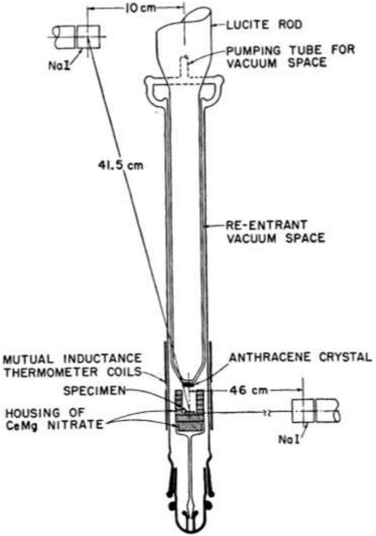


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



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

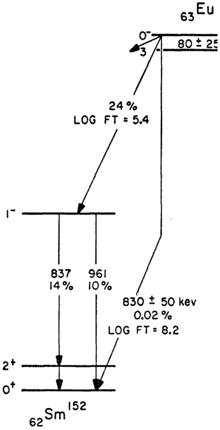
Goldhaber, Grodzins, Sunyar Phys Rev 109 1015 (Dec 1957)

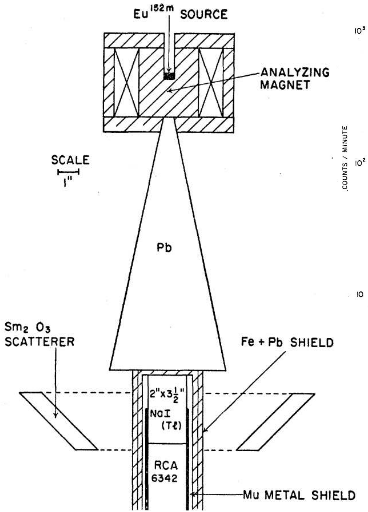
$$e^- + {}^{152m}\text{Eu} \rightarrow \nu + {}^{152}\text{Sm}$$

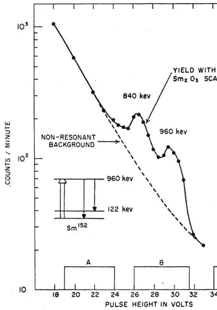
- **Upward-going ν populates $\langle I_z \rangle = 0, +1$ not -1**
- **So γ is circularly polarized– transmission through magnet depends on iron polarization:** $\frac{N_+ - N_-}{N_+ + N_-} = 0.017 \pm 0.003$
- **Upward ν boosts γ momentum so it can be absorbed on-resonance**

$\Rightarrow$ ν helicity -1 $\pm$ 10%

($\bullet$ $\bar{\nu}$ helicity $\sim$ +1 Palathingal PRL 524 24 '69)



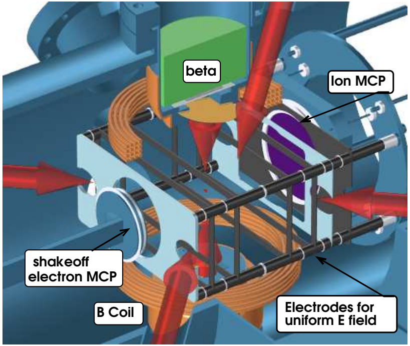




Surprisingly enough, this is the best direct measurement of ν helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$

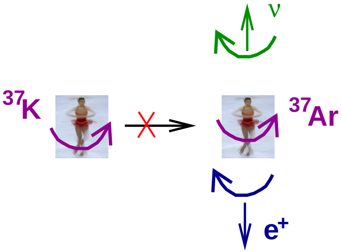
TRIUMF

a different isospin mirror-decay spin-polarized observable



- 10,000 atoms trapped
- P measured in-situ on ^{37}K by atomic method
- ion + shakeoff e^- for A_{recoil}

Isobaric mirror decay has helicity-driven null

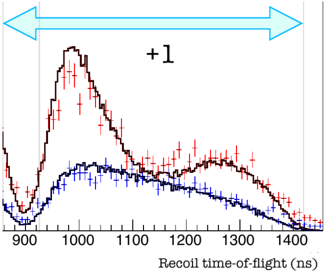


$W(\theta,P) \approx 1 + a_{pol} \cos(\theta_{\beta\nu})$

with $a_{pol} = (A_\beta - B_\nu)P - a_{\beta\nu} + 2c/3$

$= 1$ or 0, indep of $\frac{M_{GT}}{M_F}$

2014 polarized β-recoil



a_{pol} is an elegant observable, but we may always be statistics-limited– we push upgrades of singles A_β and A_{recoil}

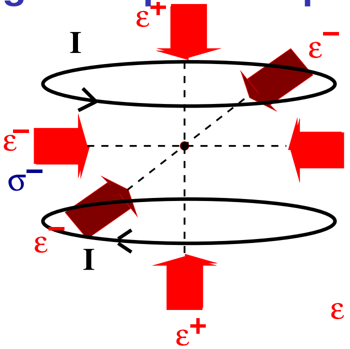
The neutron community checks this combination of observables for consistency

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

Magneto-optical trap: perturb atoms

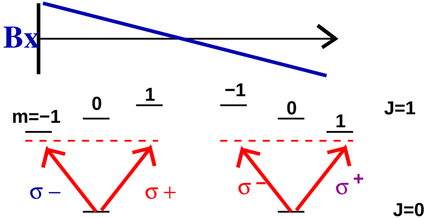
Zeeman Optical Trap (MOT)

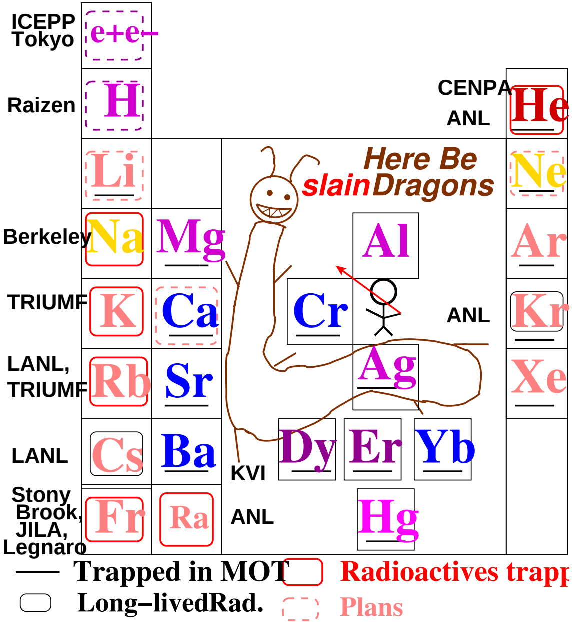
Raab et al. PRL 59 2631 (1987)



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

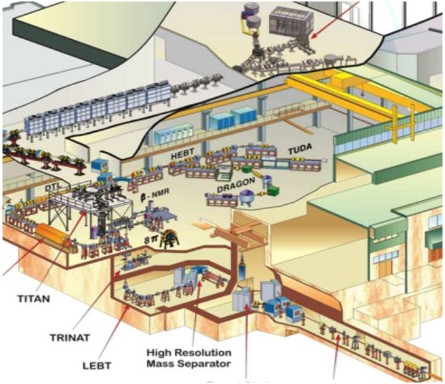
Damped harmonic oscillator





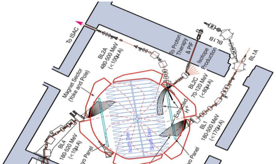
What elements can be laser cooled?

TRIumf Neutral Atom trap at ISAC



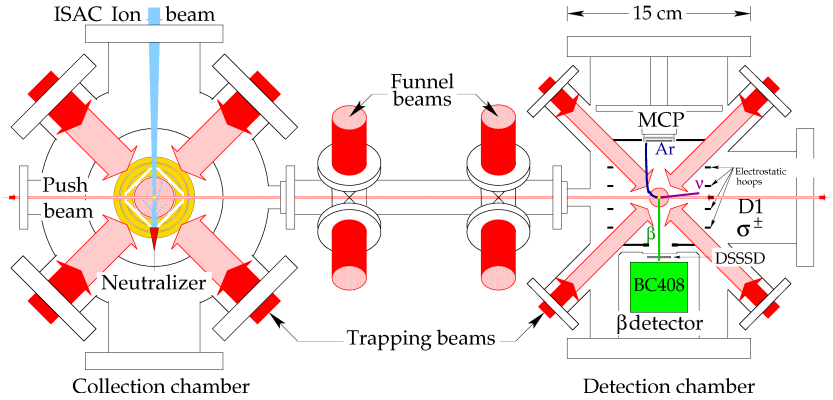
^{37}K 8x10^7/s TiC target 1750^{o}C 70 μA protons

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



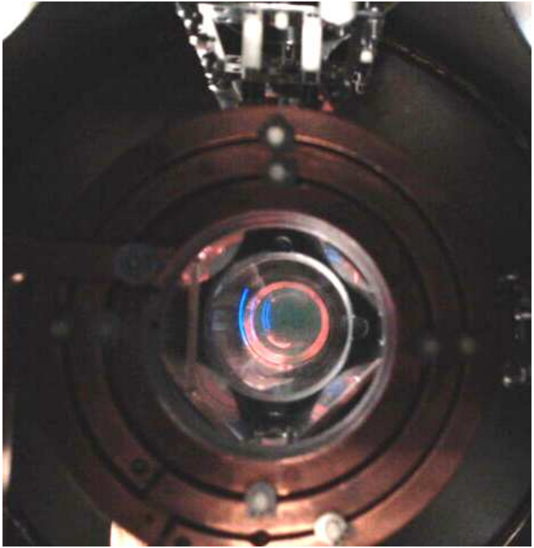
TRINAT plan view

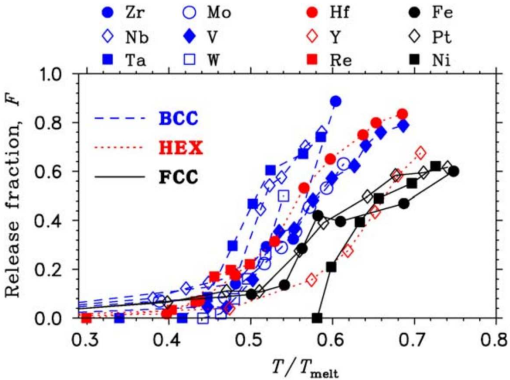
- Isotope/Isomer selective
- 75% transfer
- Avoid untrapped atom background with 2nd trap
- 0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum

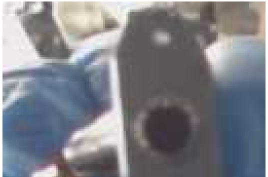


- Spin-polarized 99.1±0.1%

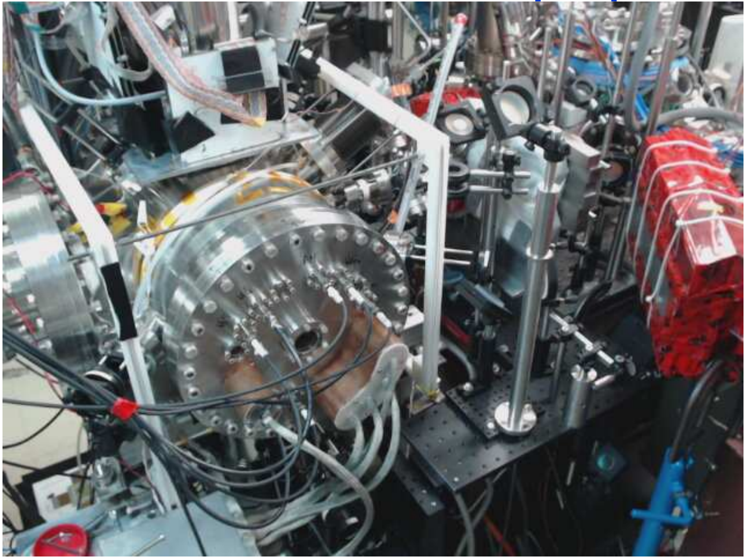
Neutralizer and Collection trap



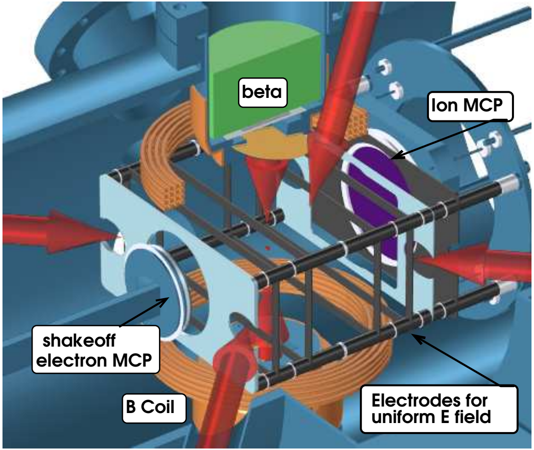


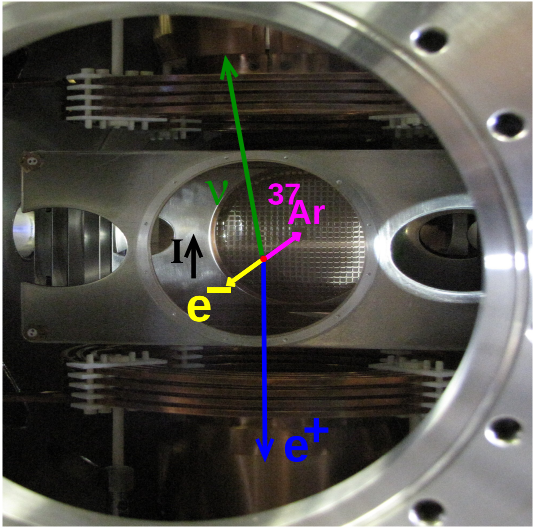


TRINAT lab: "tabletop experiment"



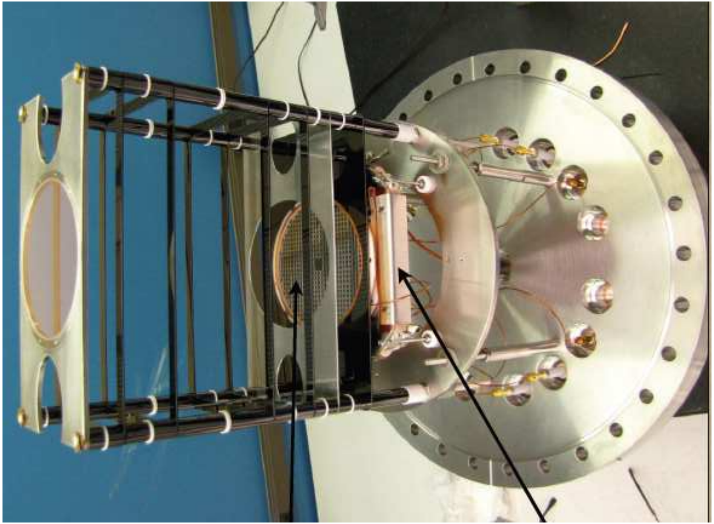
^{37}K decay geometry





- 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

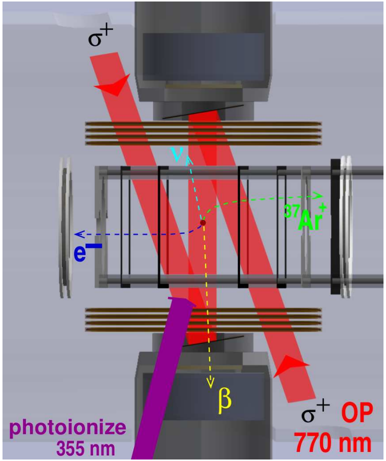
delay-line anode for position info

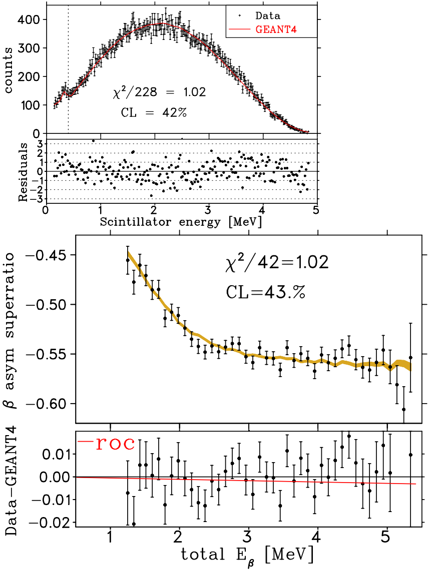
no stray wires

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

β^+ asymmetry ^{37}K data

TEXAS A&M UNIVERSITY — TRIUMF





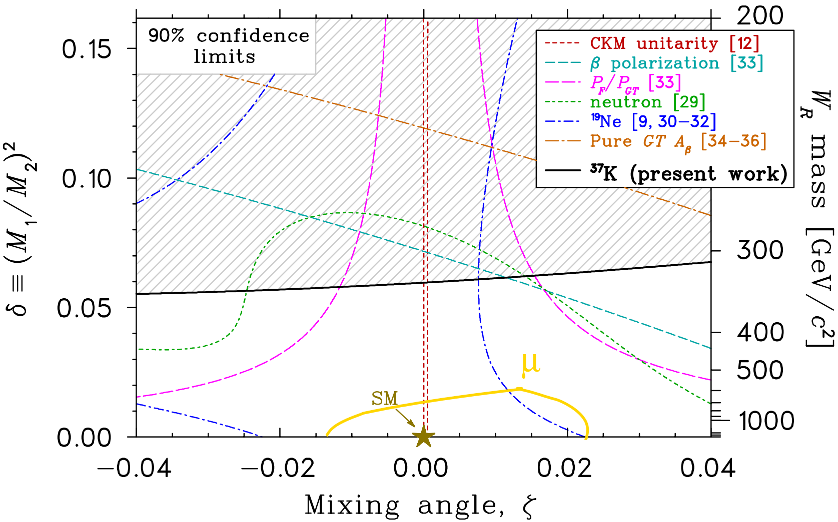
Fenker et al. Phys Rev Lett 120, 062502 (2018)

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

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

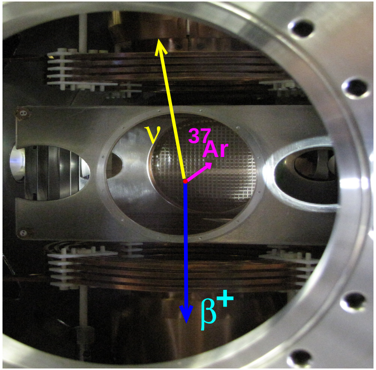
LHC $M'_W > 3.7$ TeV 90%

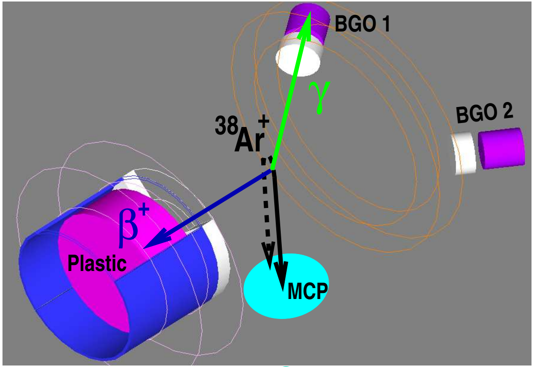
TRIUMF $\not{T}$ correlation of 3 of 4 momenta

$\mathbf{t} \rightarrow \mathbf{-t} \Rightarrow \vec{\mathbf{p}} \propto \frac{d\vec{r}}{dt} \rightarrow \mathbf{-}\vec{\mathbf{p}}$

but $\vec{p}_{\mathrm{recoil}} \cdot \vec{p}_\beta \times \vec{p}_\nu \equiv 0$ ☹

$$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma = -\vec{p}_{\mathrm{recoil}} \cdot \vec{p}_\beta \times \vec{p}_\gamma \xrightarrow{t \rightarrow -t} \vec{p}_{\mathrm{recoil}} \cdot \vec{p}_\beta \times \vec{p}_\gamma$$





- We can test symmetry of apparatus with coincident pairs ☺
- Not exact. Outgoing particles interact → fake $\not{T}$

TRIUMF

The nucleon: a special place for γ's

Harvey Hill Hill PRL 99 261601 (2007);

EFT with SM interactions combined in the nucleon:

goal was extra γ production by medium-energy ν's

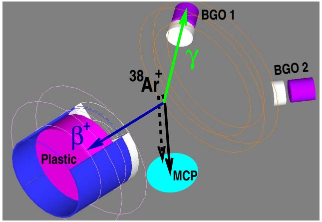
QCD Weak E&M

$$\mathcal{L} = \frac{-4c_5}{m_{\text{nucleon}}^2} \frac{eG_F V_{ud}}{\sqrt{2}} \epsilon^{\sigma\mu\nu\rho} \bar{p}\gamma_\sigma n \bar{\psi}_{eL}\gamma_\mu\psi_{\nu L} F_{\nu\rho}$$

Gardner, He PRD 2013: looked for contributions to radiative n decay. Noticed QCD antisymmetry led to a scalar triple product of momenta ☺:

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{M^2} \frac{E_e}{p_e k} (\vec{p}_e \times \vec{k}_\gamma) \cdot \vec{p}_\nu$$

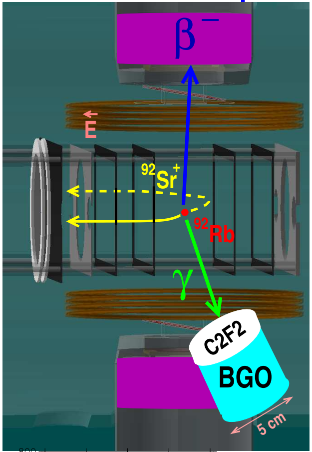
Needs non-SM QCD-like physics, scale $M \sim$ 10's of MeV

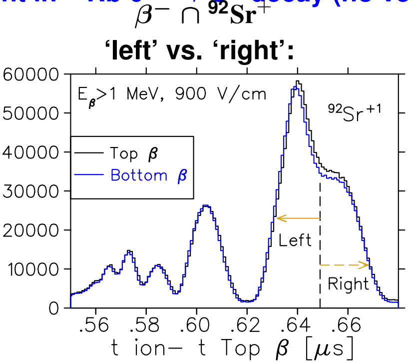


Particles strongly interacting with themselves
but weakly interacting with us
are also possible dark matter candidates

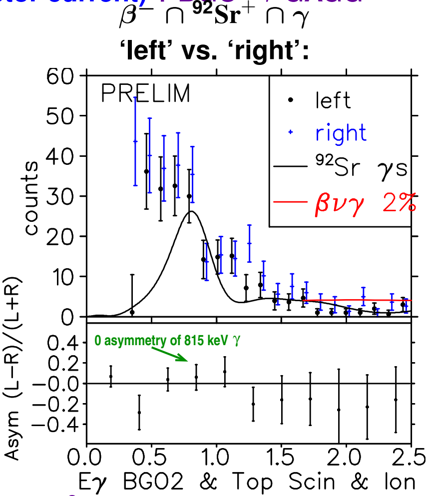
See the 'SIMP miracle' Hochberg et al. arXiv:1402.5143

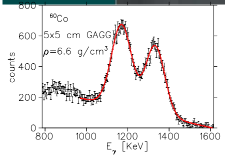
TRIUMF Test experiment in ^{92}Rb $0^- \rightarrow 0^+$ decay (no vector current) + BGO $\rightarrow$ GAGG





(other γ detector sees background from upstream)





BGO $\rightarrow$ GAGG (Ce:$Gd_3Al_2Ga_3O_{12}$)

- better E_γ resolution and timing, ρ= 6.6 g/cm^3
- Good photopeak efficiency (55% at 1 MeV)
- not radioactive like LYSO

Sensitivity to $\sim$ 0.05 to 0.10 asymmetries of few percent branches

University of Manitoba

FrPNC Discovery potential: Weak neutral current

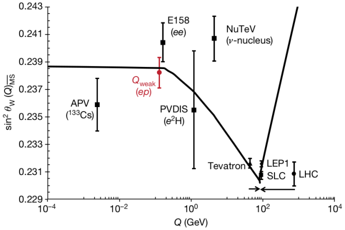
TRIUMF

Best prediction of SM: weak neutral current

$\leftarrow$ Seen 1973 by Gargamelle in ν scattering

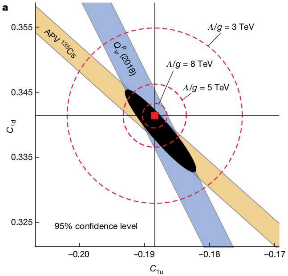
- **Could have been 1st measured in ^{18}F γ asymmetry (CSULA, INFN, Mainz, Queens) but isovector/isoscalar $\propto \sin^2(\theta_W)/N_c$**

Manitoba @ TRIUMF Fr trap: 10^6 atoms $\Rightarrow < 1\%$ stats in < 1 day



Androic Nature 2018 (Qweak)

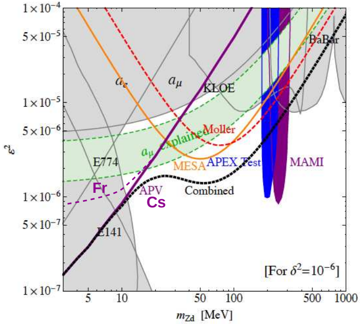
(Recent M_W CDF Science 376 170 2022 would move APV prediction 1 σ down 2204.11991v3)



Sensitivity to new bosons at mass scale 5 to 8 TeV

- **Fr/Cs$\propto$(rel)$Z^2/N \approx 20$ FrPNC goal: exceed Cs**

lower-mass Z' Davoudiasl PRL 109 031802 2012

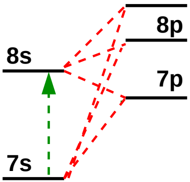


q_{Cs} = 2.4 MeV/c, q_{Fr} = 10 MeV/c $\Rightarrow$ different sensitivity to $m_{Z'} \sim$ MeV

UNIVERSITY OF MANITOBA

FrPNC: Recent results

TRIUMF



Weak interaction mixes

s, p

Claude & Marie-Anne Bouchiat
Used in Cs by Wieman. In Fr:

$$|A_{7s\to 8s}|^2 = |E1_{\rm Stark} + E1_{\rm PNC} + \overset{\text{in PBC}}{M1}|^2$$

$$\approx |E1_{\rm stark}|^2 + 2E1_{\rm Stark}E1_{\rm PNC}$$

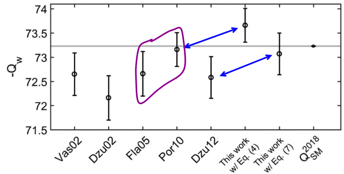
$E1_{\rm PNC} \sim 10^{-9}$ of an allowed $E1$ transition amplitude

By picking an E field one can make the asymmetry $\sim 10^{-3}$

Measurement of $|M1|^2$ with PBC $\sim 10^{-13}$ of an allowed $|E1|^2$

T.Hucko, A.Sharma, Kalita, Orozco, Gorelov, Gwinner...

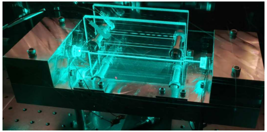
Toh Damitz Tanner Johnson Elliott PRL 2019



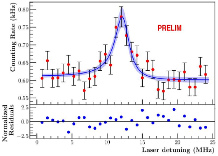
Cs: $E1_{PNC} \overset{\text{theory}}{\rightarrow} Q_W$ disagrees $\sim 1.5\ \sigma$
Cs: Asym $\rightarrow E1_{PNC}$ using measured $M1/\beta$ differs from using other observables

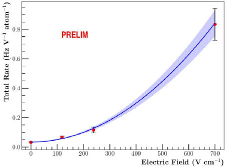
- 8% accuracy differentiates between calculations (theory - exp. ~10% in Cs, only other M1 measured)
- Interference (without PBC) will measure $M1/\beta$ better (Goal 2022) $M1$ Fr/Cs ≈ 3, so goal is $M1/\beta$ to deterministic accuracy

Power buildup cavity
UHV
$Q \approx 4{,}000$



T. Hucko, ACOT 2021

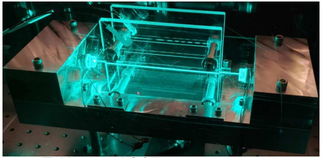




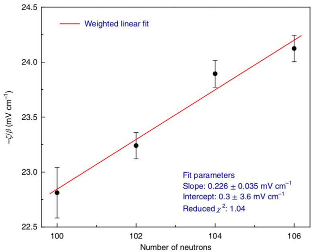
An example of university-driven precision measurement, backed by NSERC using TRIUMF-ISAC unique isotope delivery, patiently producing physics

University of Manitoba **FrPNC: goals and needs** TRIUMF

- **Atomic parity-violating signal 2024**
- **Competitive electron-quark neutral weak coupling 2025+**
- **Nuclear anapole also extracted 2025+ (parity-violating E&M moment induced by nucleon-nucleon weak interaction). Only measured in ^{133}Cs, ^{205,207}Tl : more cases needed**
- **Needs: Maximum yield and long beamtimes $^{208-213}$Fr to beat down systematic uncertainties**
- **Further needs: $^{220-226}$Fr would provide greater lever arm to test SM dependence on N, in competition with Yb $\sim$1% atomic PNC measurements $\rightarrow$**



T. Hucko, ACOT 2021



Antypas Budker Nat Phys 15 120 2019

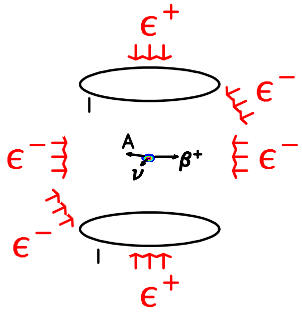
S2139LOI DeMille, Behr, Teigelhöfer would measure Fr_2 dimers in FrPNC trapping facility, to determine s-wave scattering and other properites for high-density Fr. A full ^{223}FrAg EDM (nuclear $\not{T}$ Schiff moment) exp. needs to laser-cool Ag elsewhere

ν's, Fun Sym, and Atom Traps

- **Parity *P* symmetry**

  How to test *P* symmetry experimentally

  Only left-handed ν so far:
  how do we know this?



- **How atom traps work**
- **$\not{P}$ with TRIUMF Neutral Atom trap for β decay**

If there's time:
- **$\not{P}$ in Fr atoms**
- **$\not{T}$ experiments**

https://trinat.triumf.ca/talks/nus-funsym-fall2022

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Physics and time reversal

When t $\rightarrow$ -t, does anything change?

- Wave Equ. is 2nd-order in t: $\nabla^2 u = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2}$ symmetric in t
- Heat Equ. is 1st-order in t: $\nabla^2 u = -\frac{\partial u}{\partial t}$ t$\rightarrow$ -t, boom?

'Dissipation', like friction... The arrow of time remains a research problem in stat mech, but it's not from (known) particle physics

- Schroedinger Equation is 1st order: $i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}$

'Take the complex conjugate'
(but see Dressel et al. PRL 119 220507 (2017)
"Arrow of Time for Continuous Quantum Measurements")

Microscopic physics was thought to be symmetric in t

Simulating $\not{T}$ in decays?

We've constructed an angular correlation, a scalar observable, by a dot product of two vectors

$1 + \hat{p} \cdot \hat{J}$

which is odd under P as we need

($\vec{p}$ is even, $\vec{J} = \vec{r} \times \vec{p}$ is odd)

But $\vec{J}$ is odd under T, not even

So we need at least 3 vectors to have a T-odd scalar observable,
the scalar triple product $\vec{v1} \cdot (\vec{v2} \times \vec{v3})$

An example $\rightarrow$

EDM in a fundamental particle breaks T: this is exact

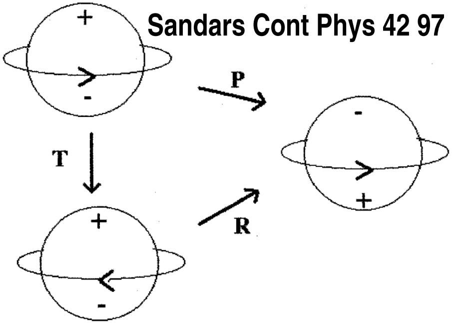
Landau, Nucl. Phys. 3 (1957) p. 127

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

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

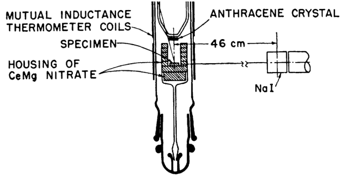
Under T, $\vec{J} \overset{t \to -t}{\longrightarrow} -\vec{J} \quad \vec{d} \overset{t \to -t}{\longrightarrow} +\vec{d}$

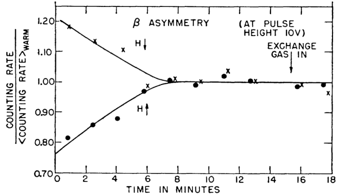
If the physics is invariant under T, this is a contradiction, $\Rightarrow a = 0$



[• 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 ...]

Parity broken, why not $\not{T}$ime?





Immediately after $\not{P}$arity was seen to be totally broken in β decay ('ν left-handed')

Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413

Many T-odd observables were proposed:

PHYSICAL REVIEW VOLUME 106, NUMBER 3

Possible Tests of Time Reversal Invariance in Beta Decay

J. D. JACKSON,* S. B. TREIMAN, AND H. W. WYLD, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received January 28, 1957)

Need scalar triple products of 3 vectors: observables involving spin

$$D\hat{J}\cdot\frac{\vec{p_\beta}}{E_\beta}\times\frac{\vec{p_\nu}}{E_\beta} \qquad R\vec{\sigma}_\beta\cdot\hat{\mathrm{J}}\times\frac{\vec{\mathrm{p}}_\beta}{E_\beta}$$

TRINAT has *D* ideas

are consistent with $\not{T} < 0.001$

(We're looking for $\not{T}$ that could still be big:) but some has been found $\rightarrow$

PHYSICAL REVIEW VOLUME 106, NUMBER 3

Possible Tests of Time Reversal Invariance in Beta Decay

J. D. Jackson,* S. B. Treiman, and H. W. Wyld, Jr.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received January 28, 1957)

$\not{CP}$ discovered in $K\bar{K}$ meson decays in 1963, though not much (Cronin and Fitch Nobel prize 1980)

Quark eigenstates in the weak interaction:

To explain some weak decays,

$|u\rangle \rightarrow |d\rangle + \epsilon|s\rangle$ **i.e.** $|u\rangle \rightarrow \cos(\theta_C)|d\rangle + \sin(\theta_C)|s\rangle$

For 3 families of particles,

$\rightarrow$ 3x3 unitary "CKM" matrix between $|d\rangle, |s\rangle, |b\rangle$

There is one complex phase, which leads to this type of $\not{CP}$

A reason for 3 generations of particles?

That one phase is consistent with $\not{CP}$ in $K\bar{K}$ and $B\bar{B}$ systems

There have been hints in $K\bar{K}$ and $B\bar{B}$ of more $\not{CP}$ than in the standard model,

$p\bar{p} \to \mu^+\mu^+$ or $\mu^-\mu^-$ $\not{CP}$ at 3.6 σ Abazov PRD 2014 Fermilab;
so this 2001 cartoon was a little premature $\to$

J. Fabergé, CERN Courier, 6, No. 10, 193 (October 1966). [Courtesy of Madame Fabergé.]

T2K ν_μ oscillations different from $\bar{\nu}_\mu$ at 2 to 3 σ Nature 580 339 (2020)

$\not{CP}$ could have some utility for cosmology $\to$

The excess of matter over antimatter can come from $\not{CP}$

Sakharov JETP Lett 5 24 (1967) used $\not{CP}$ to generate the universe's excess of matter over antimatter:

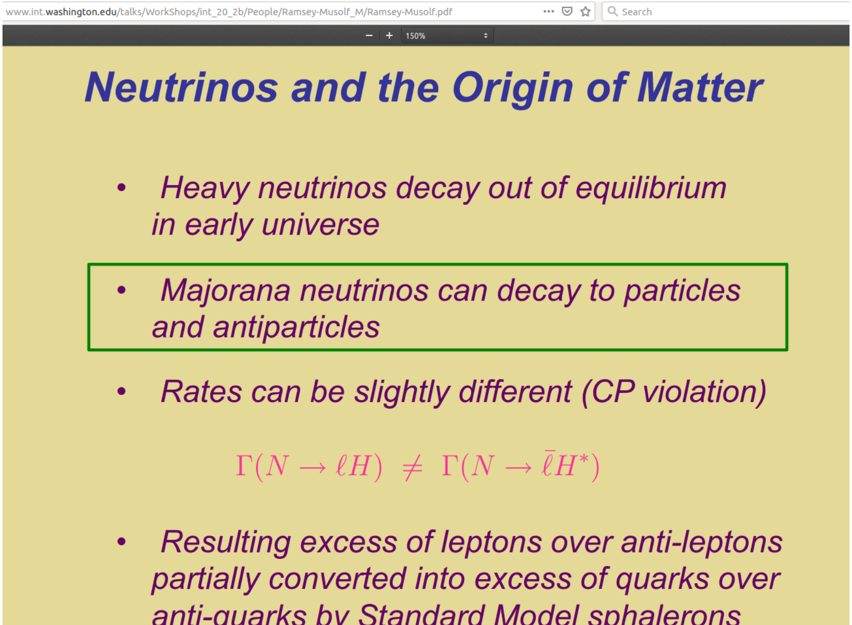
- **$\not{CP}$,**
- **baryon nonconservation, and**
- **nonequilibrium.**

But known $\not{CP}$ is too small by 10^{10}, so 'we' need more to exist. **Caveats:**

- **You could use $\not{CPT}$ [Dolgov Phys Rep 222 (1992) 309]**
- **We need $\not{CP}$ in the early universe, not necessarily now**

So we look for more $\not{CP}$. How is this related to $\not{T}$?

that seems a little abstract
concrete demonstrative example (Ramsey-Musolf at INT 2020
$\not{CP}$ explaining T2K's ν vs. $\bar{\nu}$ result lets heavy *N* decay this way in some models



$\not{T}$ is related to $\not{CP}$ by the "CPT Theorem"

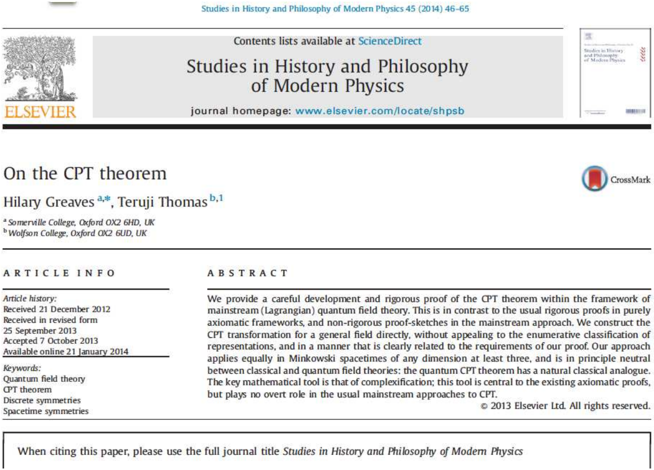
"All local Lorentz invariant QFT's are invariant under CPT"
Schwinger Phys Rev 82 914 (1951)
Lüders, Pauli, Bell 1954

- **Gravity $\rightarrow$ not flat:**

K meson experiments Adler PhysLettB 364 (1995) 239 test $\not{CPT}$ to within 1000x expected from quantum gravity

- **Strings not 'local'**

Proofs still pursued $\rightarrow$


Studies in History and Philosophy of Modern Physics 45 (2014) 46–65

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

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On the CPT theorem

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ARTICLE INFO

Article history:
Received 21 December 2012
Received in revised form 25 September 2013
Accepted 7 October 2013
Available online 21 January 2014

Keywords:
Quantum field theory
CPT theorem
Discrete symmetries
Spacetime symmetries

ABSTRACT

We provide a careful development and rigorous proof of the CPT theorem within the framework of mainstream (Lagrangian) quantum field theory. This is in contrast to the usual rigorous proofs in purely axiomatic frameworks, and non-rigorous proof-sketches in the mainstream approach. We construct the CPT transformation for a general field directly, without appealing to the enumerative classification of representations, and in a manner that is clearly related to the requirements of our proof. Our approach applies equally in Minkowski spacetimes of any dimension at least three, and is in principle neutral between classical and quantum field theories: the quantum CPT theorem has a natural classical analogue. The key mathematical tool is that of complexification; this tool is central to the existing axiomatic proofs, but plays no overt role in the usual mainstream approaches to CPT.

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When citing this paper, please use the full journal title *Studies in History and Philosophy of Modern Physics*

Assuming CPT, $\not{CP} \Leftrightarrow \not{T}$ in most physics theories
The matter excess then motivates $\not{T}$ searches

$\not{T}$, $\not{C}\not{P}$, and popular culture

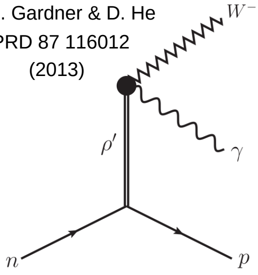
CPT theorem has made pop culture

'It's never been tested... a theoretical relationship between time and antimatter'
Spock, 1966

Though $\vec{p_\nu} \cdot \vec{p_\beta} \times \vec{p_\gamma}$ doesn't involve spin, EDM's indirectly constrain:

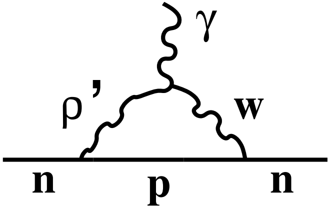
Some *TRV* $\gamma\beta\nu$ interactions, e.g. :

S. Gardner & D. He PRD 87 116012 (2013)



make neutron EDM at "1-loop" order

(D. McKeen, private comm):



"Naive Dimensional Analysis"

$c_5 \frac{e^2 G_F M_W^3}{16\pi^2 m_{\rho'}^2}$ suggests nEDM larger than experiment by $\sim 10^8$.

$\rightarrow$ *TRV* $\beta\nu\gamma$ from such interactions likely too tiny to measure ☹

- **Other interactions (e.g. leptoquarks) need "2 loops" so generate comparatively tiny nEDM so are less constrained, could generate *TRV* $\beta\nu\gamma$ large enough to measure ☺**

Other constraints

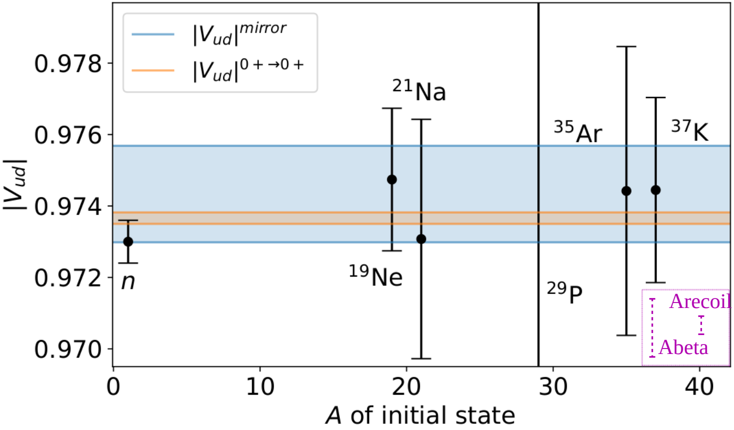
- **Direct constraint from n $\rightarrow$ p $\beta\nu\gamma$ branch $\propto |c_5|^2$**

Bales PRL 2016: $3.4 \pm 0.2 \times 10^{-3}$ (theory 3.1×10^{-3})

$\Rightarrow \frac{\mathrm{Im}(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ ^{37}K *TRV* asym can be ~ 1 ☺

Weak interaction: same strength, all nuclei?

TEXAS A&M UNIVERSITY



Hayen and Severijns, arXiv:1906.09870 (June 2019)

Deduced V_{ud} from mirror decays

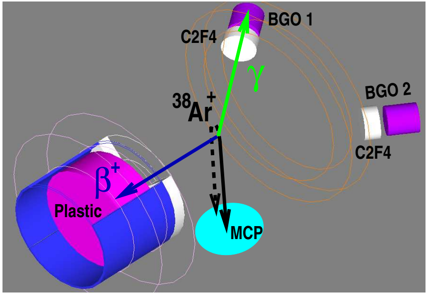
Are people overestimating their uncertainties? We aren't ☺

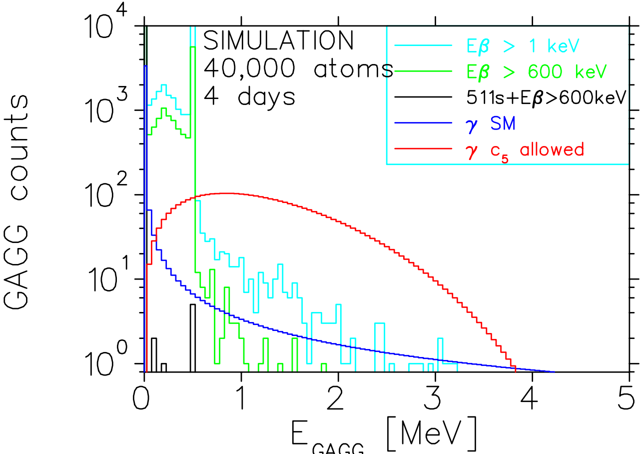
We project to reach 0.0005 accuracy, as good as any $0^+ \to 0^+$ except ^{26m}Al.

Assumes 5% isospin breaking calculation.

Simulations: E_γ signature and backgrounds

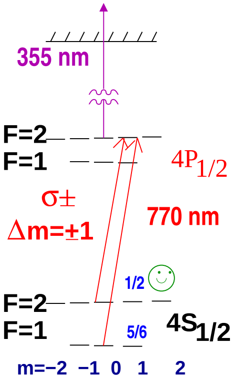
- **Classical bremsstrahlung $\propto 1/E_\gamma$**
- **Any time-reversal violating interaction involves β, ν and $\gamma \Rightarrow$ 4-body phase space $\propto E_\gamma(Q - E_\gamma)^3$** Bernard PLB 593 (2004)

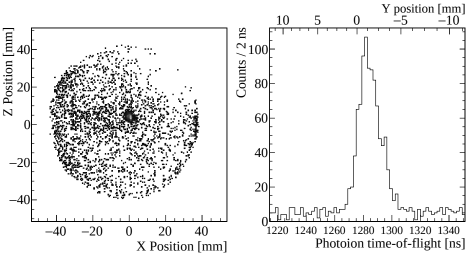


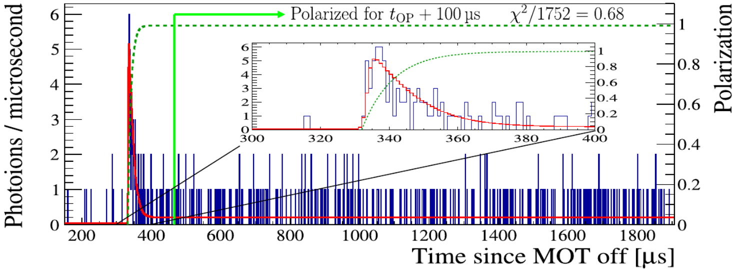


We are concentrating on:
- **$E_\gamma > 511$ keV**
- **the β^+ in the opposite detector**

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