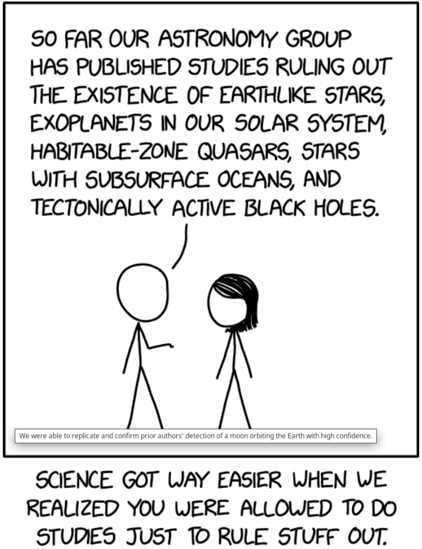
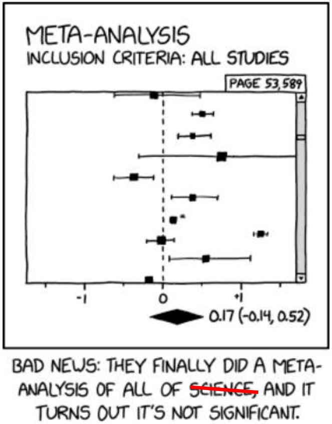
xkcd.com/2783/



xkcd.com/2755/

Effect Size

|< < Prev Random Next > >|



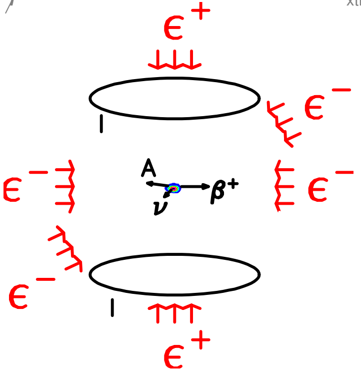
Fun Sym

ν's, Fun Sym, and Atom Traps

- **Parity P symmetry**

  How to test P symmetry experimentally

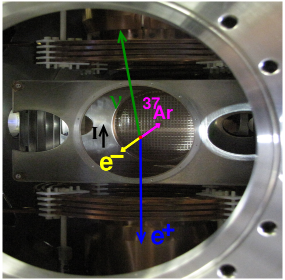
  Only left-handed ν so far: how do we know?
- **$\not P$ with TRIUMF Neutral Atom trap for β decay**
- **$\not P$ in Francium atoms**
- **How atom traps work**
- **$\not T$ experiments** *so much time, so little to do*



TRIUMF
A. Gorelov
J.A. Behr
J. McNeil
P. Miri

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

UNIVERSITY OF MANITOBA
A. Sharma
T. Morshed
I. Halilovic
G. Arrowsmith-Kron
G. Gwinner



Symmetries: Continuous vs Discrete

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

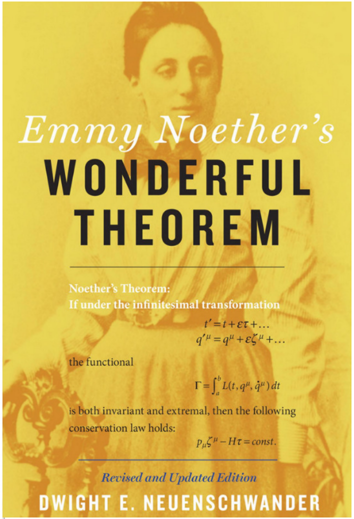
Continuous symmetry	$\rightarrow$	Conserved quantity
Time-translational invariance	$\rightarrow$	Energy
Space-translational invariance	$\rightarrow$	Momentum
Rotational invariance	$\rightarrow$	Angular momentum
(Laplace-Runge-Lenz vector)	$\rightarrow$	name?

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" aliens think in terms of the action, not position and momentum [Movie "Arrival"]

- **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

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

P  $=$ 

1957:

$\tau - \theta$ Puzzle

+ μ decay

+ ^{60}Co decay $\Rightarrow$

P  $\neq$ 

Preview: Weak interaction breaks parity: Consequences?

'Pulsar kicks'

IGR J11014–6103 v= 0.01 c ↘

Fuller PRD 2003

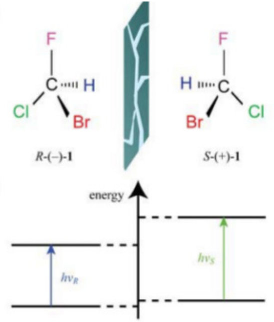
Forced $\boldsymbol{p} + \boldsymbol{e}^- \rightarrow \boldsymbol{n} + \nu$

$$\boldsymbol{W}(\theta) = \mathbf{1} + \frac{\langle \boldsymbol{m_I} \rangle}{\boldsymbol{I}} \boldsymbol{A}_\nu \cos(\theta_{\hat{\mathrm{I}}})$$

B field polarizes $\boldsymbol{p}$'s

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

Earthling's amino acids are all left-handed



Letokhov PLA'75

Darquie CHIRALITY 2010

$\Delta \boldsymbol{E} \sim \mathbf{10}^{\mathbf{14-16}}$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. :

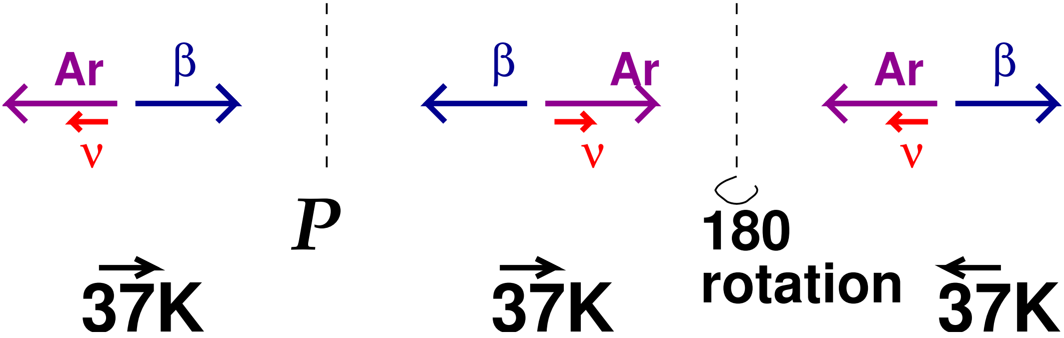
Astrobiology 18 (2018) Selection of Amino Acid Chirality via ν Interactions with ^{14}N in $\vec{\boldsymbol{E}} \times \vec{\boldsymbol{B}}$ Fields M.A. Famiano, R.N. Boyd

(TRIUMF EEC 90's)...

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

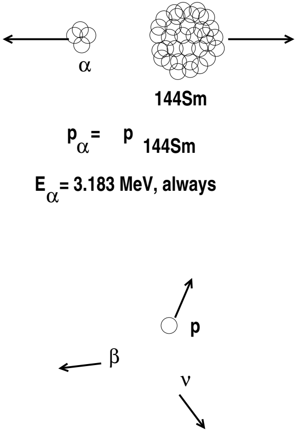
$\vec{\mathbf{r}} \longrightarrow -\, \vec{\mathbf{r}}$ $\quad$ $\vec{\mathbf{p}} \sim \frac{d\vec{\mathbf{r}}}{dt} \longrightarrow -\vec{\mathbf{p}}$ $\quad$ $\vec{\mathbf{J}} = \vec{\mathbf{r}} \times \vec{\mathbf{p}} \longrightarrow +\vec{\mathbf{J}}$



⇒ A spin flip corresponds exactly to *P* reversal

Most 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:

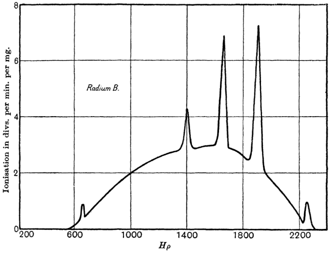


Figure 3.12: The beta spectrum of radium B, obtained by Chadwick and Ellis when they repeated Chadwick's experiment of 1914. Source: Chadwick and Ellis, "Preliminary Investigation" (note 82), p. 277.

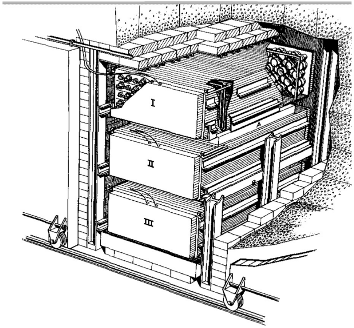
- 1915 Noether's theorem
- 1923 Ellis+Wooster: statistical energy conservation
- 1929 Niels Bohr: non-conservation of energy (?!) sought to power stars...?
- 1930 Pauli postulated a new particle (??!!)

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"



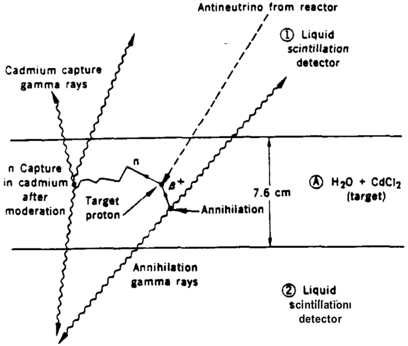
sketch of the equipment used at Savannah River. The

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

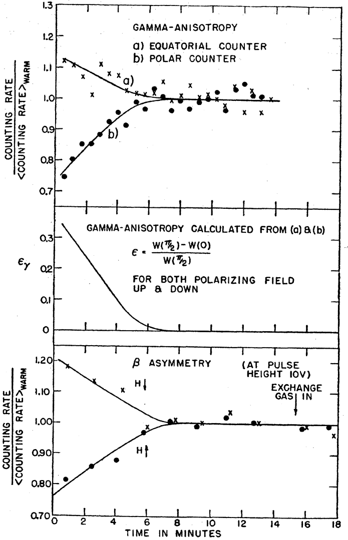
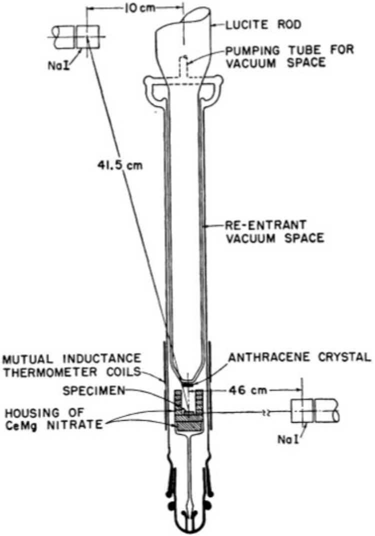


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



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?

You said you were going to talk about the ν 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 $\pm\vec{k}_\nu$

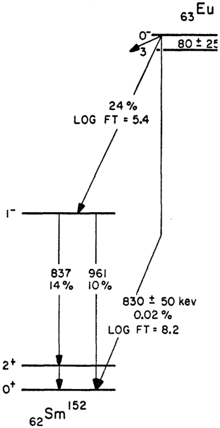
Goldhaber, Grodzins, Sunyar Phys Rev 109 1015 (Dec 1957)

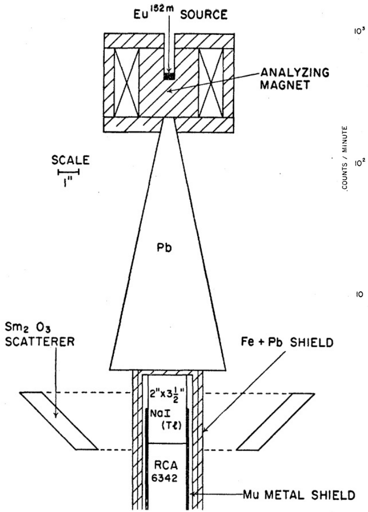
$e^- + {}^{152m}\mathrm{Eu} \rightarrow \nu + {}^{152}\mathrm{Sm}$

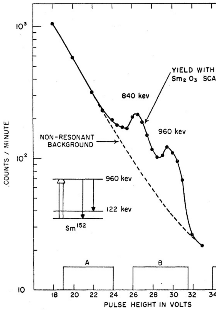
- **Upward-going ν populates $\langle I_z \rangle = 0, +1$ not -1**
- **So γ is circularly polarized– transmission through magnet depends on iron polarization: $\frac{N_+ - N_-}{N_+ + N_-}$=0.017$\pm$0.003**
- **Upward ν boosts γ momentum so it can be absorbed on-resonance**

$\Rightarrow$ ν helicity -1 $\pm$ 10%

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





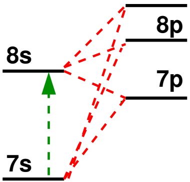


Surprisingly enough, this is the best direct measurement of ν helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$

UNIVERSITY OF MANITOBA

FrPNC: Recent results

TRIUMF



Weak interaction mixes

s, p

Claude & Marie-Anne Bouchiat

Used in Cs by Wieman. In Fr:

in PBC

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

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

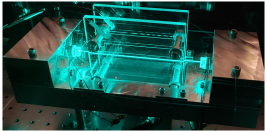
$E1_{\rm PNC} \sim 10^{-9}$ of an allowed $E1$ transition amplitude

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

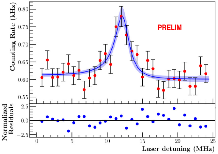
Measurement of $|M1|^2$ with PBC $\sim 10^{-13}$ of an allowed $|E1|^2$

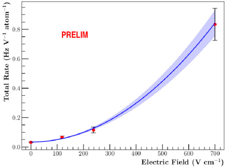
T.Hucko, A.Sharma, Kalita, Orozco, Gorelov, Gwinner...

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

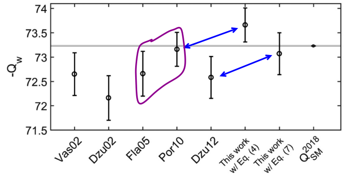


T. Hucko, ACOT 2021





Toh Damitz Tanner Johnson Elliott PRL 2019



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

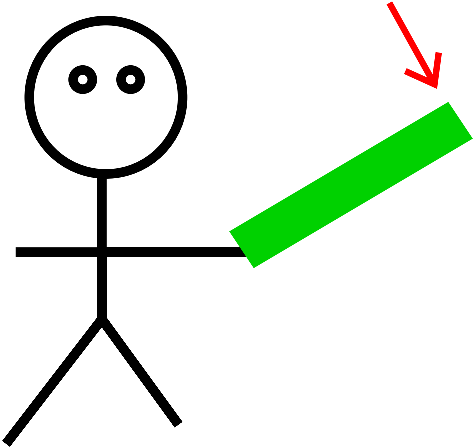
- 8% accuracy differentiates between calculations (theory - exp. ~10% in Cs, only other M1 measured)
- Interference (without PBC) will measure $M1/\beta$ better (Goal 2022)

$M1$ Fr/Cs ≈ 3,

so goal is $M1/\beta$ to deterministic accuracy

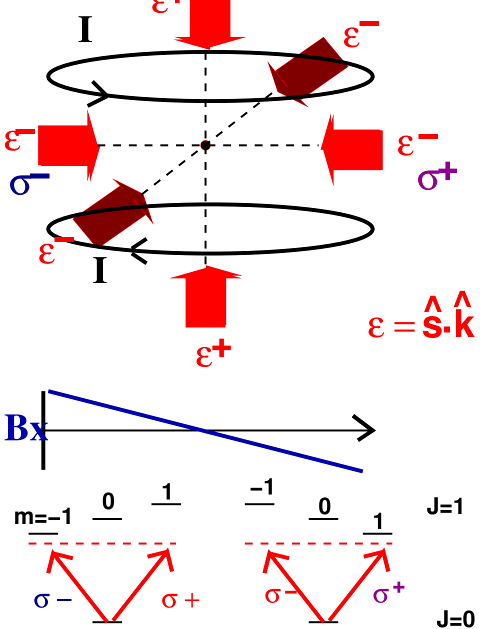
"“Light sabers would make atom traps easy” (H. Norton)

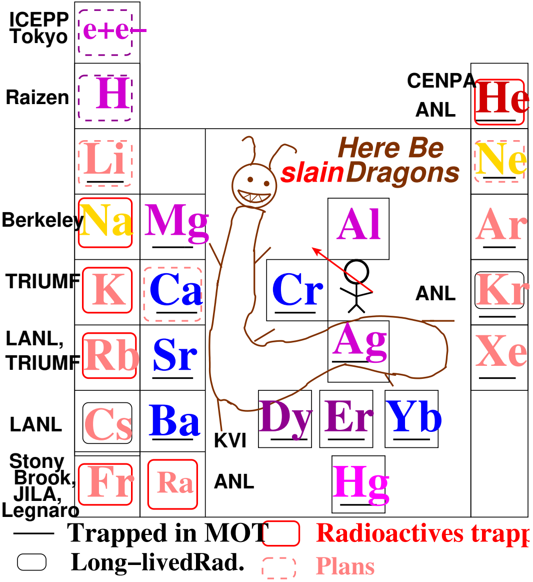
$$\vec{\nabla} \cdot \vec{S} \neq 0$$



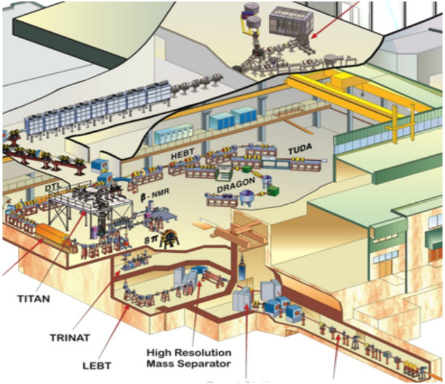
But light sabers violate Poynting's theorem

Magneto-optical trap: damped HO



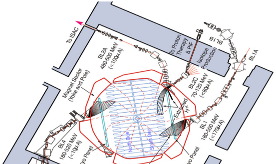


TRIUMF TRIumf Neutral Atom trap at ISAC

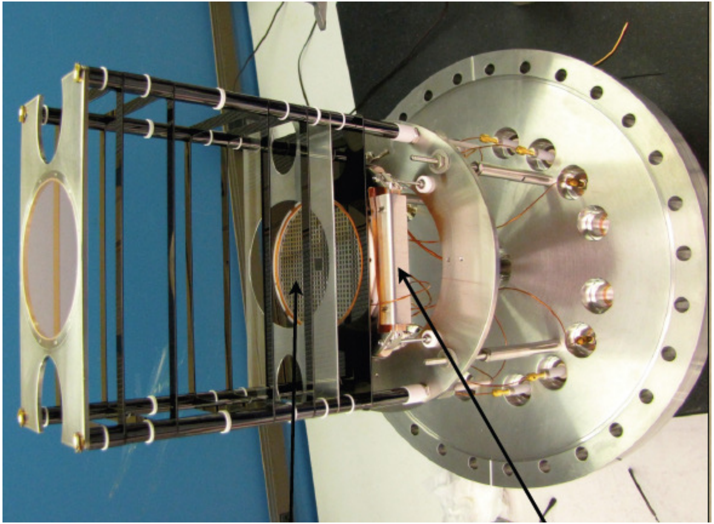


^{37}K 8x10^7/s TiC target 1750^{o}C 70 μA protons

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



ion MCP assembly



14 inch CF flange

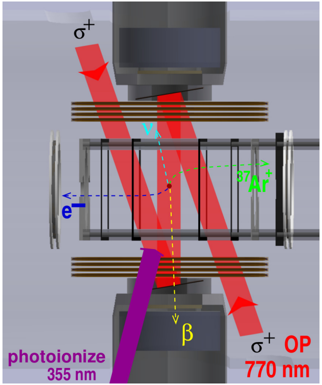
Electrostatic field

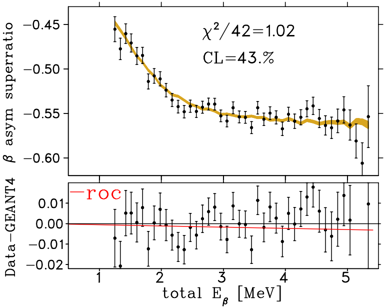
delay-line anode for position info

no stray wires

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

β^+ asymmetry ^{37}K



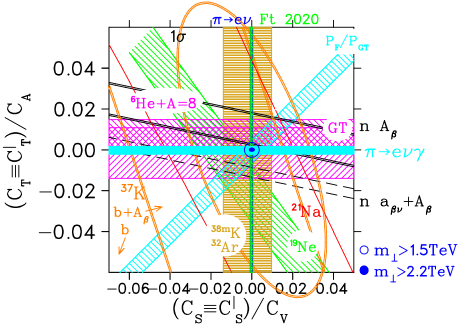


Fenker et al. Phys Rev Lett 120, 062502 (2018)

A_β[experiment]= -0.5707 $\pm$ 0.0019

A_β[theory] = -0.5706 $\pm$ 0.0007

Good agreement: only left-handed ν's and right-handed β^+

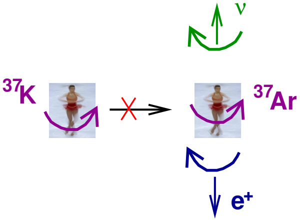


Dependence of the β asymmetry on m_β / E_β also constrains new physics competing with π decay and LHC p+p $\rightarrow$ e + ν

Anholm thesis 2022, arXiv:2509.11502

We want to do 5x better to be competitive

A spin-polarized angular distribution sensitive to ν helicity



If I_z = I_{initial} and I_{initial} = I_{final}, the leptons can't increase $I_{z\ \mathrm{final}}$

If β^+ down, the ν can't go up, unless either β or ν have wrong helicity

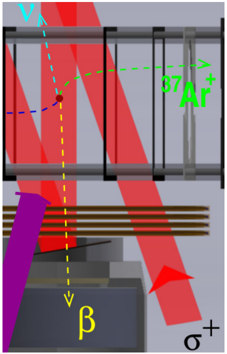
Any imperfect I_z/I mimics a wrong-handed ν

^{38}K G.T. $3^+ \rightarrow 2^+$ needs both ν and β^+ helicities wrong:

would be most direct ν helicity measurement

since Goldhaber 1957

Helicity-driven null



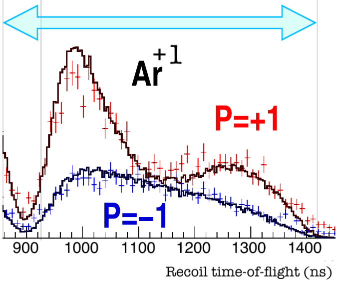
Fenker et al. PRL 2018

A_β= -0.5707$\pm$ 0.001913 in agreement with SM

achieved I_z/I = 0.991 $\pm$ 0.001

0.993 to 0.994 in 2024

2014 polarized β-recoil



$v_{\mathrm{TOFaxis}} = 0$ suppressed. Dip would be deeper with ion MCP position cut or $\cos(\theta_{\beta-\nu})$ determination

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

$$a_{\mathrm{pol}} = \frac{a_{\beta\nu} - 2c/3T + PB_\nu}{1 + PA_\beta + bm/E}$$

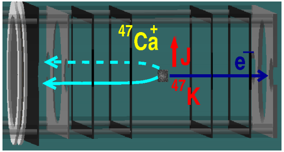
$$= 1 \text{ or } 0\text{, independent of } \frac{M_{GT}}{M_F}$$

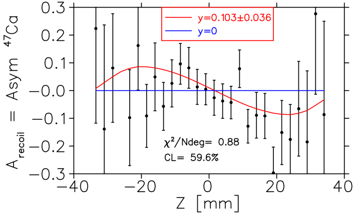
Analog-Antianalog isospin mixing in ^{47}K β^- decay and $\not{T}$

Measuring ~~isospin~~ in $^{47}_{19}$K^{28} decay determines sensitivity to parity-even ~~isospin~~ $\not{T}$ N-N interactions via future $D\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$

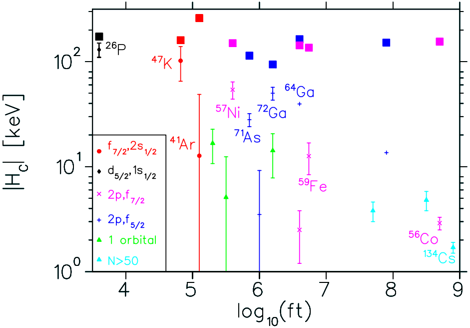
B. Kootte et al. PRC 109 L052501 (2024)

A_{recoil} = 0 for pure G-T



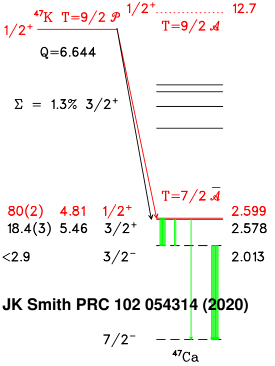


so there's a large M_F



I=1/2$^+$ ^{47}K β^- decay has **large:**

- $H_C = \langle \bar{\mathcal{A}} | V_{\rm Coul} | \mathcal{A} \rangle$ = 101 $\pm$ 37 keV
- fraction of $\mathcal{A} - \bar{\mathcal{A}}$ mixing prediction Auerbach, Loc NPA 1027 122521 (2022)

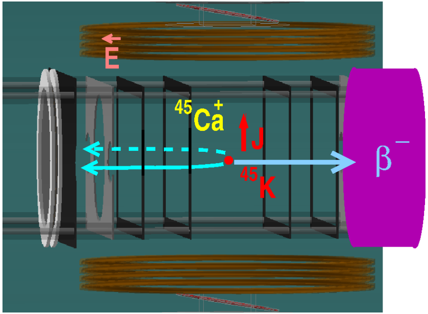


JK Smith PRC 102 054314 (2020)

$^{47}_{20}$Ca^{27}'s single 1/2$^+$ state contains most of the $\bar{\mathcal{A}}$ config

$y = g_V M_F / g_A M_{GT}$ = 0.098$\pm$0.037 large enough to be favorable for D, enhanced by $\sim 10^2$ in isospin-suppressed β decay. Microscopic $\not{T}$ can be deduced from the simple structure.

D $\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$ in atom trap: Features, Systematics



- **Collect recoils going into 4 pi with electric field of 1 kV/cm**
- **Full reconstruction of recoil and beta momenta**
- **Point source: we know where it is (by sampling photoionization) and it doesn't move when we flip the polarization**

D Uncertainties / 100 scaling from Melconian PLB 649 270 (2007)

	B_ν	Improvements	Projected
Cloud position $\sigma^\pm$	1.3	$\pm 500\mu$m $\rightarrow \pm 20\mu$m	0.05
Cloud size/Temp	0.3	" "	0.03
MCP Position cal	1.0	DLA+ mask	$\lesssim 0.1$
$\hat{x}$-OP alignment	0.25	Geometry is $\perp$	$\lesssim 0.02$
E field	0.2		$\lesssim 0.1$

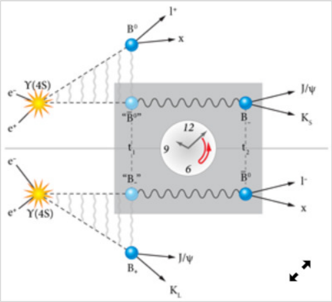
- **Any stray polarization along wrong axis is deadly, a lowest-order fake D: Measure with singles asymmetry for recoils and β's**

Any $\not{T}$ decay experiment should answer: Does interaction between outgoing particles mimic time reversal?; Is your experiment better; Have null EDM's ruled you out?

Entanglement in decays

There exists microscopic true $\cancel{T}$ in nature! independent of assumptions about QFT, CPT theorem, unitarity...

- **BABAR PRL 2012: Entanglement of B meson pairs enables $\psi_{\text{initial}} \leftrightarrow \psi_{\text{final}}$ also seen in K's KLOE-2 PLB 2023**



APS/Alan Stonebraker

Figure 1: Electron-positron collisions at SLAC produce a $\Upsilon(4s)$ resonance that results in an entangled pair of B mesons. When one meson decays at time t_1 , the identity of the other is "tagged" but not measured specifically. In the top panel, the tagged meson is a "$\overline{B}^0$". This surviving meson decays later at t_2 , encapsulating a time-ordered event, which in this case corresponds to "$\overline{B}^0$" $\rightarrow B_-$. To study time reversal, the BaBar collaboration compared the rates of decay in one set of events to the rates in the time-reversed pair. In the present case, these would be the "B_-" $\rightarrow \overline{B}^0$ events, shown in the bottom panel.

M. Zeller Physics 2012

EDM in a fundamental particle breaks T: this is exact

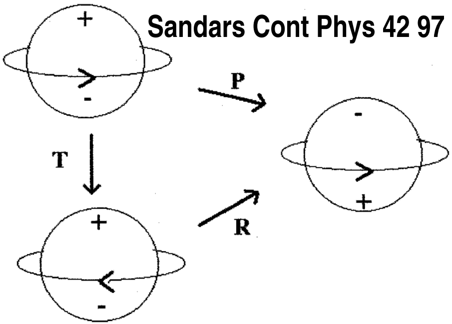
Landau, Nucl. Phys. 3 (1957) p. 127

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 ...]

No EDM's have been seen. The $\not{T}$ (and related $\not{CP}$) seen is in K and B mesons, explained by one standard model parameter

T2K ν oscillations have 3σ evidence for $\not{CP}$, modelled by a similar complex phase in the ν mass matrix

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

K_L decays more often to $\pi^- e^+ \bar{\nu}$ than to $\pi^+ e^- \nu$ by 0.3%.

Quark eigenstates in the weak interaction:
Cabibbo explained some weak decays by:

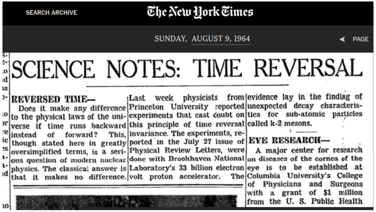
$|u\rangle \rightarrow |d\rangle + \epsilon|s\rangle$ **i.e.** $|u\rangle \rightarrow \cos(\theta_C)|d\rangle + \sin(\theta_C)|s\rangle$

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

There is one complex phase, which leads to this type of $\not{CP}$
Any 2x2 unitary matrix, one can define away the phase as trivial
Maybe one reason for 3 families of particles ?

$\cancel{T}$, $\cancel{CP}$, and everything

$\cancel{CP}$ discovery in $K\bar{K}$ got a paragraph in NY Times



SEARCH ARCHIVE The New York Times

SUNDAY, AUGUST 9, 1964 PAGE

SCIENCE NOTES: TIME REVERSAL

REVERSED TIME— Does it make any difference to the physical laws of the universe if time runs backward instead of forward? This, though stated here in greatly oversimplified terms, is a serious question of modern nuclear physics. The classical answer is that it makes no difference.

Last week physicists from Princeton University reported experiments that cast doubt on this principle of time reversal invariance. The experiments, reported in the July 27 issue of Physical Review Letters, were done with Brookhaven National Laboratory's 33 billion electron volt proton accelerator. The evidence lay in the finding of unexpected decay characteristics for sub-atomic particles called k-2 mesons.

EYE RESEARCH— A major center for research on diseases of the cornea of the eye is to be established at the Columbia University's College of Physicians and Surgeons with a grant of $1 million from the U. S. Public Health

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

Sending the Enterprise back in time 3 days must have needed $\cancel{CP}$ well beyond Standard Model ☺

Sakharov immediately laid out ways to use $\cancel{CP}$ at early times to generate the excess of matter observed in the universe ("everything"), but the known amount makes about a billion times less matter than we see

Evidence for $\cancel{CP}$ in accelerator ν's may make more T2K Nature 580 339 (2020)

$\cancel{CPT}$ can also do it (Dolgov Phys Rep 222 309 (1992) also mentions Dine-Affleck topological defects)

$\not{T}$ 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

ELSEVIER

Studies in History and Philosophy of Modern Physics

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

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.

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

ν's, Fun Sym and Atom Traps

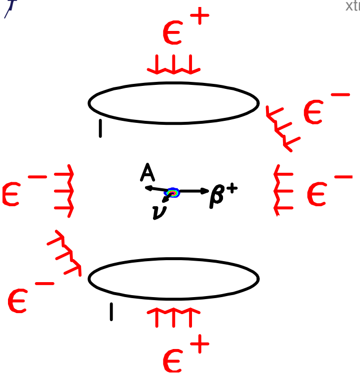
Truth loves its limits, for there it meets the beautiful
Rabindranath Tagore, "Fireflies"

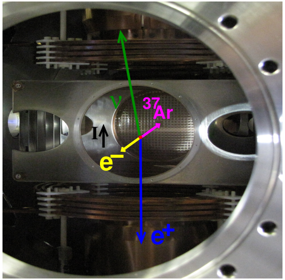
- **Parity *P* symmetry**

  How to test *P* symmetry experimentally

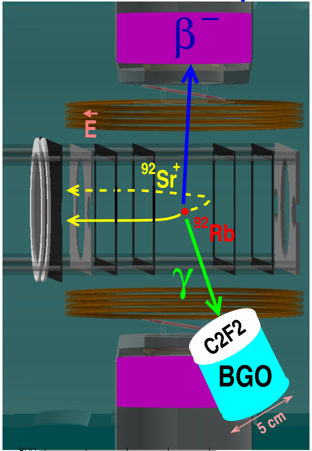
  Only left-handed ν so far: how do we know?
- **$\not{P}$ with TRIUMF Neutral Atom trap for β decay**
- **$\not{P}$ in Francium atoms**
- **How atom traps work**
- **$\not{T}$ experiments**

Left out ν mass matrix phase:
T2K accelerator-produced ν oscillations show
nearly 3σ nonzero CP violation



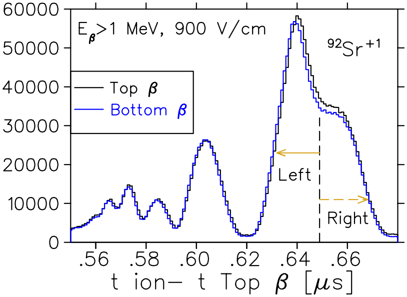


TRIUMF Test experiment in ^{92}Rb $0^- \rightarrow 0^+$ decay (no vector current) + BGO $\rightarrow$ GAGG



$\beta^- \cap {}^{92}\mathrm{Sr}^+$

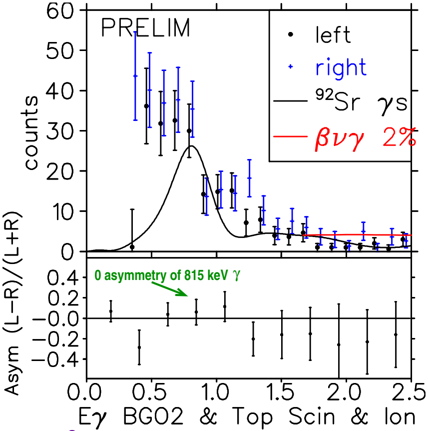
'left' vs. 'right':

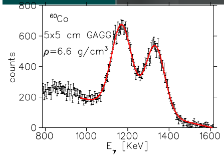


(other γ detector sees background from upstream)

$\beta^- \cap {}^{92}\mathrm{Sr}^+ \cap \gamma$

'left' vs. 'right':





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**

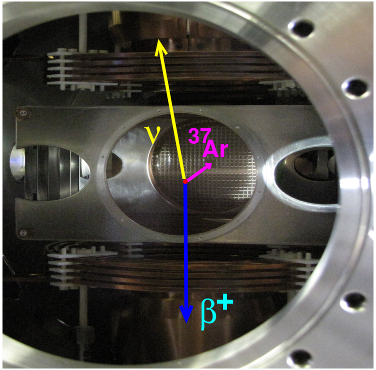
Sensitivity to $\sim$ 0.05 to 0.10 asymmetries of few percent branches

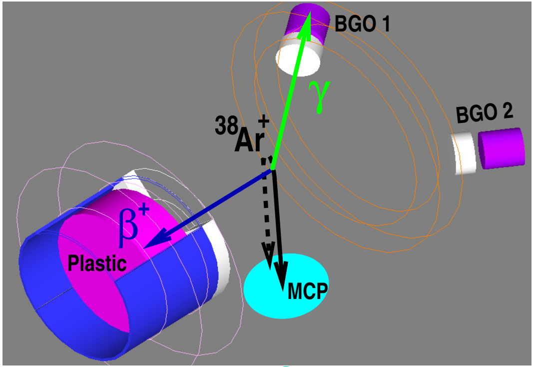
$\not T$ correlation of 3 of 4 momenta

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

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

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



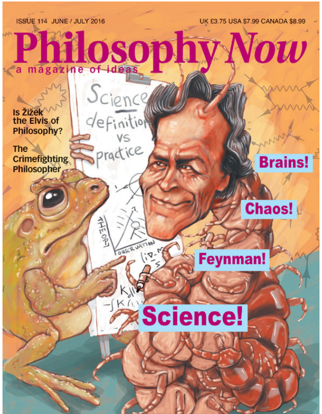


- We can test symmetry of apparatus with coincident pairs ☺
- Not exact. Outgoing particles interact → fake $\not T$

Mirrors are not really reversing x,y,z and are kinda confusing

Plato's 'mirror problem':

"Mirror, Mirror"
T. Wilkinson,
PhilNow 114 (2016)



Plato: Why do mirrors reverse L-R but not U-D?

JB: You gotta look at this diagram. See,
Up stuff stays Up, and Left stuff stays Left.
Nothing's actually reversing.
I'd say your interpretation of 'left' is not quite right ☺

Plato: 'explains what I'm missing, but still too abstract for JB'

JB thinks Plato and other philosophy is critical to humans, but there's not much deep about mirrors.