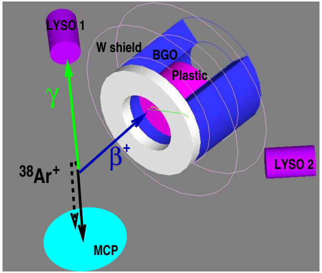
Time-reversal violation in radiative β decay

- **Time-reversal symmetry violation**
- **Our plans for $\beta\nu\gamma$ correlation**
- **Constraints from other experiments**



TRIumf Neutral Atom Trap:

A. Gorelov
J.A. Behr
J. McNeil

B. Fenker
D. Melconian

M. Anholm

D. Ashery

Support: NSERC, NRC through TRIUMF, Israel Science Foundation, DOE, Texas

TRIUMF

$\not{T}$, $\not{CP}$, and ‘Us’

CP and T symmetry are related by the ‘CPT Theorem’:
All local Lorentz invariant QFT’s are invariant under CPT.

Then $\not{CP} \Rightarrow \not{T}$

$\not{CP}$ discovered in $K\bar{K}$ meson decays in 1963

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.

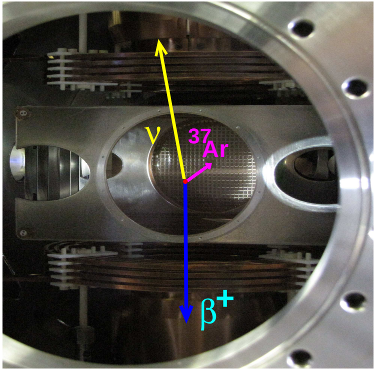
But known $\not{CP}$ is too small by 10^{10}, so ‘we’ need more to exist

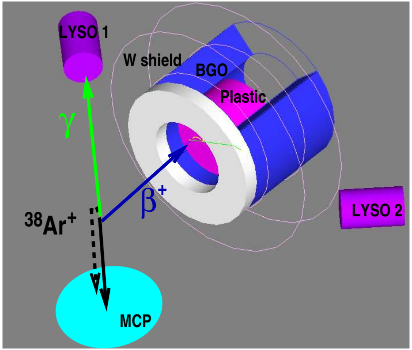
3-momentum T̸ correlation

When t → -t :

$\vec{r} \rightarrow \vec{r} \qquad \vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$

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





BUT flipping t is not the same thing as running the decay backwards.
Particles interact on the way out, and you don't reverse that part.

TRIUMF $\gamma\beta\nu\not{T}$ Experiment

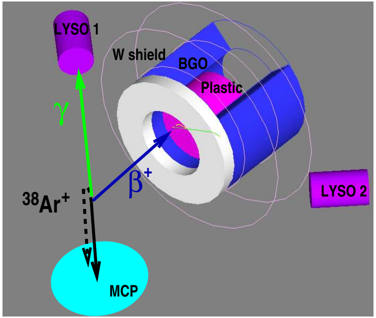
Harvey Hill Hill PRL 99 261601 combine QCD+electroweak interaction in the nucleon's $\mathcal{L}$

Gardner, He PRD 87 116012 (2013) reduce this to

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

which upon interference with S.M. gives $\not{T}$ decay contribution $\rightarrow$

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



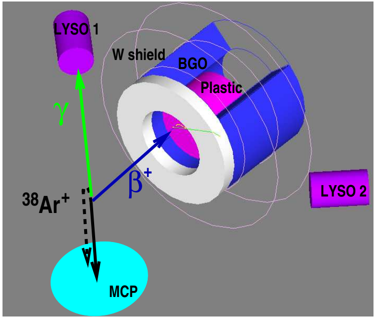
new physics $M \sim$ MeV

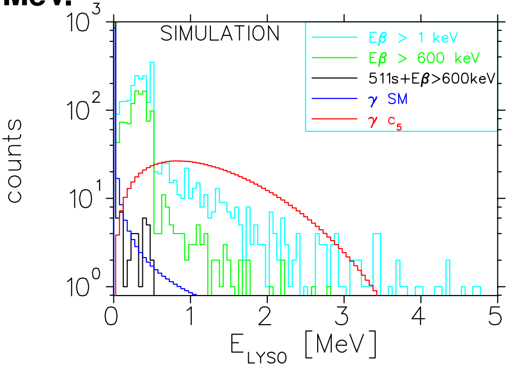
- $\not{T}$ 250x larger in $^{38\mathrm{m}}$K decay than neutron
- final state fake effect 8x10^{-4}
- $^{38\mathrm{m}}$K 40,000 atoms, 30,000 events/week $\Rightarrow \sigma \sim 0.02$
- Test asymmetry of apparatus with coincidence pairs
- n $\rightarrow$ p $\beta\nu\gamma$ branch (Nico Nature 06, Bales PRL 16) $\Rightarrow$

$\frac{\mathrm{Im}(c_5)}{M^2} \leq 8MeV^{-2} \Rightarrow$ Asym can be ~ 1

GEANT4 simulation of $\gamma\beta\nu\not{T}$

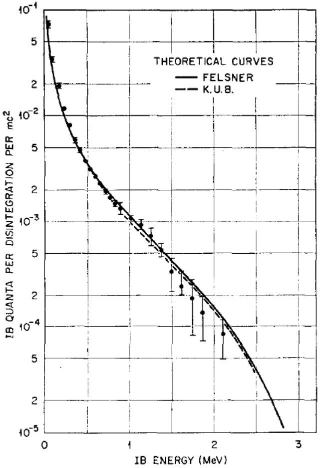
- the new 'c5' term needs Fermi or Fermi+GT transition $\Rightarrow$ neutron, tritium, or β^+ emitters
- background from β 'external bremsstrahlung' suppressed by requiring β^+ to hit plastic
- Require two 511's in BGO, so we know they didn't go to γ detector, enables measurements at $E_\gamma < 0.2$ MeV.





Radiative nuclear β^- decay experiments have been done

^{6}He Bienlein and Pleasonton NP 1965



^{35}S

vector current $\mathcal{O}(10^{-2})$

Boehm and Wu PR 93 518 (1954)

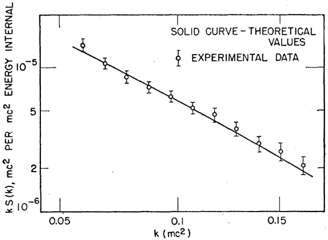
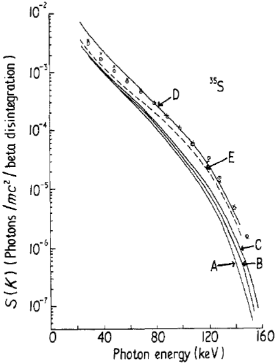


FIG. 3. Internal bremsstrahlung of S^{35}.

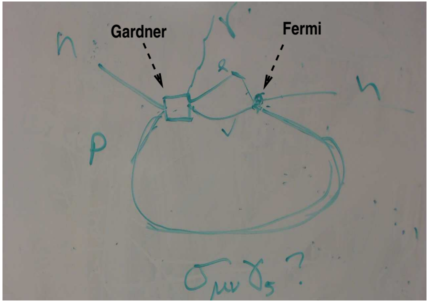
Powar and Singh JPG 2 43 (1976)



TRIUMF

EDMs and $\not T$ radiative β decay

No spin involved, so different physics at lowest order, but



Ng, Vos on my office whiteboard:
'Im(c_5)' interaction
+ s.m. β decay
$\rightarrow$ n EDM at 2 loops

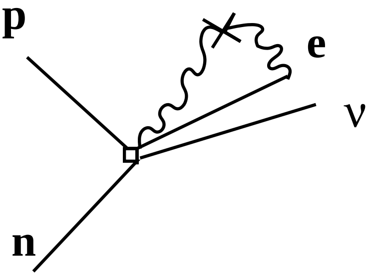
'Naive Dimensional Analysis':

$$d_n \sim \frac{Im(c_5) G_F e}{M^2} \frac{G_F m_n^5}{(16\pi^2)^2} \sim \frac{10^{-22} e{-}cm}{M^2} [\mathrm{MeV}^{-2}]$$

$d_n[\exp] < 3 \times 10^{-26}$ **e-cm**
(Baker 2006 PRL)

null n EDM $\Rightarrow \frac{Im(c_5)}{M^2} < 3 \times 10^{-4} [\mathrm{MeV}^{-2}] \rightarrow 10^{-3}$ asym
We can still reach this sensitivity at higher $E\gamma$

TRIUMF D $\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$ and $\gamma\beta\nu$TRV



K. Vos, W. Dekens (private communication)
One loop correction produces large D observable

'Naive Dimensional Analysis'

$D_{c5} \approx \mathcal{I}\frac{\alpha}{4\pi}4M_N^2\frac{\mathrm{Im}(c_5)}{M^2} \Rightarrow$

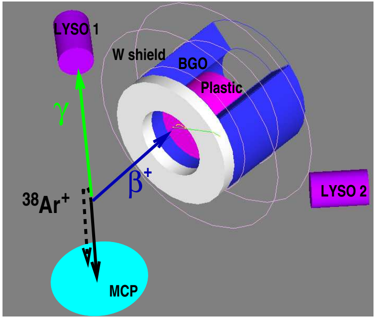
$\frac{\mathrm{Im}(c_5)}{M^2} \lesssim 1/\mathcal{I}\ \ D_{c5} \times 10^{-3}[MeV^{-2}]$

^{37}K wins by p$^2 \sim$ 25 w.r.t neutron, and if M^2 is tuned we could win by 25 more

But this is still a tight constraint, depending on whether $\mathcal{I}$ is 0 or infinity

TRIUMF Outlook: $\gamma\beta\nu$ $\not{T}$

- New observable, sensitive to MeV-scale $\not{T}$
- 'Final-state effects' from allowed processes $< 10^{-3}$
- EDMs indirect constraints (2-loop) are reachable



- Experiment Plans

Add low-Eγ detectors to TRINAT

Sensitivity $\sim$ 0.02 is possible, similar to

$K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$

Would be 1st measurement in 1st generation of particles

Physics and time reversal

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

- **Wave Equation is 2nd-order in t:**

$\nabla^2 u = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2}$ **symmetric in t**

- **Heat Equation is first-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

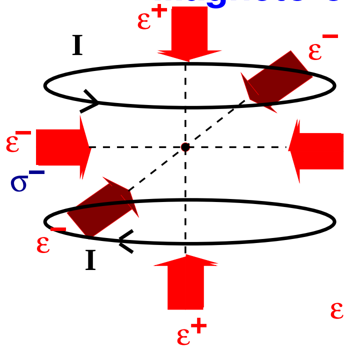
- **Schroedinger Equation is first order:**

$i\hbar\frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2}$ **'Take the complex conjugate'**

Microscopic physics was thought to be time-reversal symmetric, until $\rightarrow$

TRIUMF

Magneto-optical trap

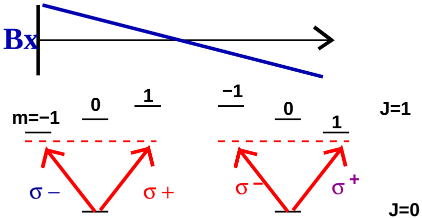


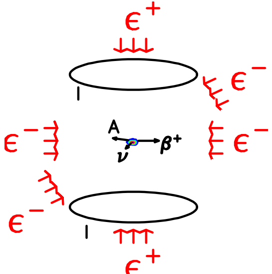
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

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





Other 3-momentum TRV correlations

- **Medium and high-energy TRV 3-momentum correlations:**

$K^- \to \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$
Three progressively better calculations of the final-state effects were done
(Khriplovich+Rudenko 1012.0147 Phys Atomic Nuclei 2011)

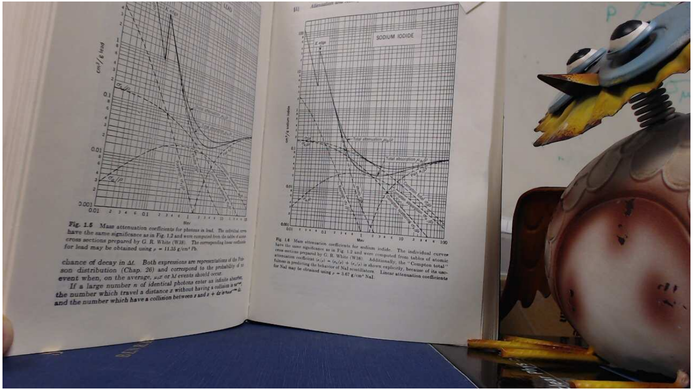
3-momentum correlations (no γ) at LHCb and BABAR, $\sigma \sim 0.003$
(Martinelli arXiv 1411.4140

General formalism for triple product momentum asymmetries Bevan 1408.3813

Note that same-sign dimuon asymmetry is at 3.6 σ
Abazov PRD 2014

TRIUMF

γ Wisdom (before running GEANT4)



Cardboard has less 'outer bremsstrahlung' background

but not as good as stainless steel for UHV

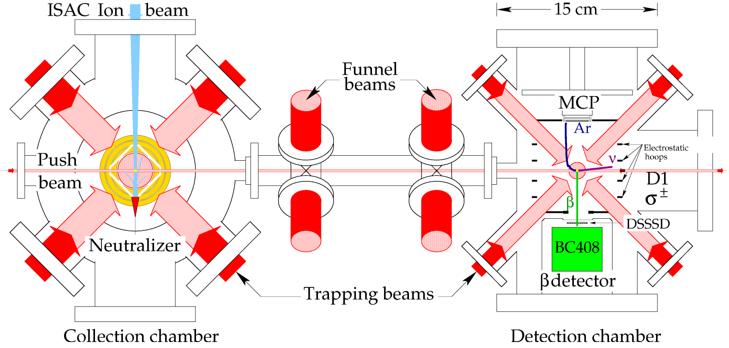
511 keV γs from β^+ annihilation are a challenge

history and $\not{T}$

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

TRIUMF's β decay Neutral Atom Trap

- Isotope/Isomer selective
- Evade 1000x untrapped atom background by $\rightarrow$ 2nd MOT
- 75% transfer (must avoid backgrounds!); 10^{-3} capture
- 0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum $\rightarrow$ β-ν correlation
- 99.1 $\pm$ 0.1% polarized, known atomically



TRIumf Neutral Atom Trap collaboration

TEXAS A&M UNIVERSITY

**B. Fenker
D. Melconian

TRIUMF

*A. Gorelov
J.A. Behr
M.R. Pearson
K.P. Jackson
J. McNeil**

UNIVERSITY OF MANITOBA

**M. Anholm
G. Gwinner

TEL AVIV UNIVERSITY

D. Ashery
I. Cohen

Undergrad / 1 at a time

** Grad student   * PDF

Supported by NSERC, NRC through TRIUMF, WestGrid, Israel Science Foundation, DOE, State of Texas

$\not{T}$ in radiative β decay and EDMs

Dekens, Vos 1502.04629: dim 6 operators at TeV scale

$$\mathcal{L}_6^{\rm eff} = -\frac{8ic_w}{gv^2} V_{ud}\,{\rm Re}\,C_{\varphi\tilde{W}B}(\Lambda)\,\varepsilon^{\mu\nu\alpha\beta}(\bar{u}_L\gamma_\mu d_L)(\bar{e}_L\gamma_\nu\nu_L)F_{\alpha\beta}$$

$\rightarrow 10^{-10}$ asymmetries if constants $\sim$ 1.

Also generates EDMs $\Rightarrow$ constants $\sim$ 0.01

So TeV-scale general dim 6 ops can make $\not{T}$ $\gamma\nu\beta$ and EDMs, but don't make measureable nuclear radiative β decay; effects $\sim p^2_{\rm lepton}/{\rm scale}^2$.

The QCD-like MeV-scale example of Gardner and He is tuned to maximize contribution to neutron β decay and avoid other experiments. E.g. direct searches by colliders are masked by jets.

EDMs constrain the Gardner term anyway $\rightarrow$

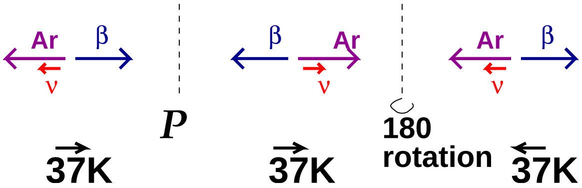
Vector current needs β^+ emitter

- β^- decays with vector current:
n, ^{3}H, (not easy)
'isospin-forbidden Fermi' amplitudes with $log(ft) \sim 5-6$ (e.g. ^{35}S)
But isobaric analogs usually lie high in excitation for β^-
E.g. ^{24}Na $4^+ \rightarrow$ ^{24}Mg 4^+, $log(ft) = 6$ (famous for the analog transition from ^{24}Al), feeds 2 subsequent γs so does not help.
^{92}Rb is 'first-forbidden G-T'
- The interference with SM term requires this vector current to produce the Gardner-He term.

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

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



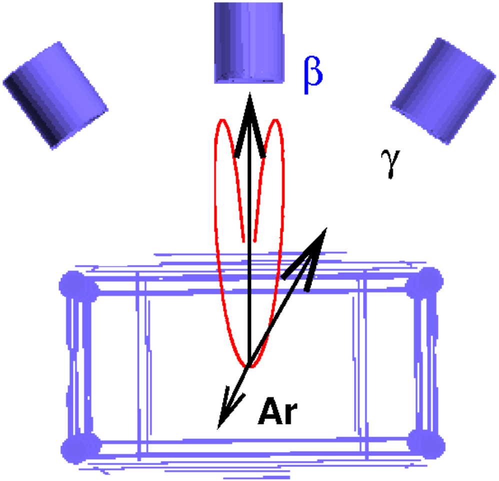
$\not{T}$, $\not{CP}$ Experiments

$\not{CP}$: $B\bar{B}$ mesons; ν T2K; K decay TREK; many EDMs
$p\bar{p}$ $\mu^+\mu^+$ or $\mu^-\mu^-$ $\not{CP}$ at 3.6 σ Abazov PRD 2014 Fermilab;
- Two types at TRIUMF:

- β Decay: construct an observable from 3 (or 5) vectors that change sign when t $\rightarrow$ -t. (e.g. $\vec{p}$, or spin)
flip a vector, see if rate changes $\rightarrow$
mimics T reversal

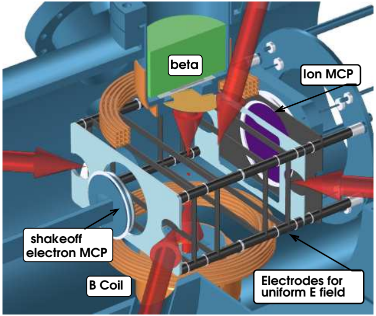
- A permanent electric dipole moment in the ground state of a system violates time reversal symmetry
[People have reversed nuclear reactions at $\sim 10^{-3}$ accuracy]
[Wigner distribution: GOE of nuclear levels]

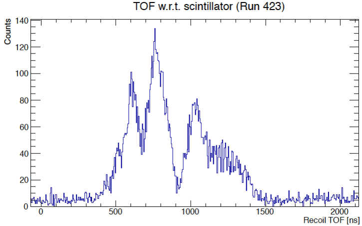
Bremsstrahlung is forward-peaked



You don't have to cover all solid angle with detectors to see the photons

^{37}K spin-polarized experiments





- 10,000 atoms trapped at a time
- AC MOT for fast switching of Bquad of MOT
- Spin polarization measured in-situ on ^{37}K by atomic method
- Position-sensitive electron detector shows shakeoff electrons contained