**Time-reversal violation in radiative $\beta$ decay**

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

**TRIumf Neutral Atom Trap:**

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$\mathcal{CP}$ and $T$ symmetry are related by the ‘CPT Theorem’: All local Lorentz invariant QFT’s are invariant under CPT. Then $\mathcal{CP} \Rightarrow T$

$\mathcal{CP}$ discovered in $K\bar{K}$ meson decays in 1963

Sakharov JETP Lett 5 24 (1967) used $\mathcal{CP}$ to generate the universe’s excess of matter over antimatter:

- $\mathcal{CP}$,
- baryon nonconservation, and
- nonequilibrium.

But known $\mathcal{CP}$ is too small by $10^{10}$, so ‘we’ need more to exist.
When $t \to -t$:

$\vec{r} \to \vec{r} \quad \vec{p} \sim \frac{d\vec{r}}{dt} \to -\vec{p}$

$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma = -\vec{p}_{\text{recoil}} \cdot \vec{p}_\beta \times \vec{p}_\gamma$

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

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

$$\mathcal{L} = -\frac{4c_5}{m_{\text{nucleon}}^2} \frac{e G_F V_{ud}}{\sqrt{2}} \sigma_{\mu\nu\rho} \bar{p}_\sigma n_{\overline{\psi} e L} \gamma_\mu \psi L F_{\nu\rho}$$

which upon interference with S.M. gives $T$ decay contribution

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

- $T$ 250x larger in $^{38m}$K decay than neutron
- final state fake effect $8 \times 10^{-4}$
- $^{38m}$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) $\Rightarrow \frac{\text{Im}(c_5)}{M^2} \leq 8 \text{MeV}^{-2} \Rightarrow$ Asym can be $\sim 1$
GEANT4 simulation of $\gamma\beta\nu\tau$

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

![Diagram of GEANT4 simulation setup]

![Simulation graph showing counts vs $E_{LYSO}$]
Radiative nuclear $\beta^-$ 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)

Powar and Singh
JPG 2 43 (1976)

Fig. 3. Internal bremsstrahlung of $^3$He.
EDMs and radiative $\beta$ decay

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

Ng, Vos on my office whiteboard:
‘$\text{Im}(c_5)$’ interaction
+ s.m. $\beta$ decay
→ n EDM at 2 loops

‘Naive Dimensional Analysis’:
$$d_n \sim \frac{\text{Im}(c_5) G_F e}{M^2} \frac{G_F m_n^5}{(16\pi^2)^2} \sim \frac{10^{-22}\text{e-cm}}{M^2}$$

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

null n EDM $\Rightarrow \frac{\text{Im}(c_5)}{M^2} < 3 \times 10^{-4}[\text{MeV}^{-2}] \rightarrow 10^{-3}$ asym

We can still reach this sensitivity at higher $E_\gamma$
One loop correction produces large $D$ observable

‘Naive Dimensional Analysis’

$$D_{c5} \approx \frac{\mathcal{I}}{4\pi} 4M_N^2 \frac{\text{Im}(c_5)}{M^2} \Rightarrow \frac{\text{Im}(c_5)}{M^2} \leq \frac{1}{\mathcal{I}} D_{c5} \times 10^{-3}[\text{MeV}^{-2}]$$

$^{37}$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
**Outlook: $\gamma \beta \nu \mathcal{T}$**

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

**Experiment Plans**

Add low-$E_\gamma$ detectors to TRINAT

Sensitivity $\sim 0.02$ is possible, similar to $K^- \to \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$

Would be 1st measurement in 1st generation of particles
Physics and time reversal

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

- Wave Equation is 2nd-order in $t$:
  \[ \nabla^2 u = \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} \text{ symmetric in } t \]

- Heat Equation is first-order in $t$:
  \[ \nabla^2 u = -\frac{\partial u}{\partial t} \text{ t} \to -t, \text{ boom?} \]
  ‘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:
  \[ i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} \text{ ‘Take the complex conjugate’} \]

Microscopic physics was thought to be time-reversal symmetric, until \rightarrow
Magneto-optical trap

Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

\[ \epsilon = \hat{s} \cdot \hat{k} \]

\[ B_x \]

\[ m = -1, 0, 1 \quad J = 0 \]

\[ \sigma^- \quad \sigma^+ \]

\[ J = 0 \]

\[ \epsilon^+ \quad \epsilon^- \]

\[ \beta^+ \]
Other 3-momentum TRV correlations

- Medium and high-energy TRV 3-momentum correlations:
  \( K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma \) 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 \( \gamma \)) 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 \( \sigma \)
Abazov PRD 2014
Cardboard has less ‘outer bremsstrahlung’ background but not as good as stainless steel for UHV. 511 keV $\gamma$-rays from $\beta^+$ annihilation are a challenge.
history and Τ

TRIUMF’s $\beta$ 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 $\beta$-$\text{Ar}^+ \rightarrow \nu$ momentum $\rightarrow$ $\beta$-$\nu$ correlation
- $99.1 \pm 0.1\%$ polarized, known atomically
**TRIumf Neutral Atom Trap collaboration**

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\[ \mathcal{L}_6^{\text{eff}} = -\frac{8i c_w}{g v^2} V_{ud} \text{Re} C \varphi \bar{W}_B(\Lambda) \varepsilon^{\mu \nu \alpha \beta} (\bar{u}_L \gamma_\mu d_L)(\bar{e}_L \gamma_\nu \nu_L) F_{\alpha \beta} \]

\[ \rightarrow 10^{-10} \text{ asymmetries if constants } \sim 1. \]
Also generates EDMs \( \Rightarrow \) constants \( \sim 0.01 \)
So TeV-scale general dim 6 ops can make \( \mathcal{J} \gamma \nu \beta \) and EDMs, but don’t make measurable nuclear radiative \( \beta \) decay; effects \( \sim p_{\text{lepton}}^2 / \text{scale}^2 \).
The QCD-like MeV-scale example of Gardner and He is tuned to maximize contribution to neutron \( \beta \) 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 $\beta^+$ emitter

- $\beta^-$ 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 $\beta^-$

  E.g. $^{24}$Na $^4_+ \rightarrow ^{24}$Mg $^4_+$, $\log(ft) = 6$ (famous for the analog transition from $^{24}$Al), feeds 2 subsequent $\gamma$s 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 $P$:
\[\vec{r} \rightarrow -\vec{r}, \quad \vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}, \quad \vec{J} = \vec{r} \times \vec{p} \rightarrow +\vec{J}\]
\( \mathcal{T}, \mathcal{CP} \) Experiments

\( \mathcal{CP} \): B\( \bar{B} \) mesons; \( \nu \) T2K; K decay TREK; many EDMs
\( p\bar{p}, \mu^+\mu^+ \) or \( \mu^-\mu^- \) \( \mathcal{CP} \) at 3.6 \( \sigma \) Abazov PRD 2014 Fermilab;

- Two types at TRIUMF:
  - \( \beta \) 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