**TRIUMF**

**Time-reversal violation** $\mathcal{T}$ in radiative $\beta$ decay: experimental progress

- **$\mathcal{T}$ Motivation**
- Our geometry and simulation for $\beta\nu\gamma$ correlation
- Parasitic test $^{92}\text{Rb} 0^- \rightarrow 0^+$

**TRIUMF Neutral Atom Trap:**

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$T$, $CP$, and baryon asymmetry

Sakharov JETP Lett 5 24 (1967) used $CP$ to generate the universe’s excess of matter:

- $CP$,
- baryon nonconservation, and
- nonequilibrium.

But known $CP$ in the standard model is too small by $10^{10}$ to generate us.

Caveats: can use $CPT$

(Dolgov Phys Rep 222 (1992) 309)

We need more $CP$ in the early universe, not necessarily now.

→ ● We should look for $CP$ i.e. $T$ violation where we can
3-momentum $T$ correlation: Our example

When $t \rightarrow -t$:

$\vec{r} \rightarrow \vec{r}$  \hspace{1cm} $\vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$

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

$t \rightarrow -t$

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

- We can test symmetry of apparatus with coincident pairs
- Not exact: outgoing particles interact $\rightarrow$ ‘final-state’ fake $T$
3-momentum $T$ correlations: Other examples

Don’t depend directly on spin,
so only generate EDM’s in higher order

- **Medium energy $T$ 3-momentum correlation:**

  $K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma$ 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, $0 \pm 0.003$ (Martinelli arXiv 1411.4140)**

- **General formalism for triple product momentum asymmetries Bevan 1408.3813**

  Proposed $T$ in $\pi^\pm \rightarrow e^\pm \nu_e e^+ e^-$ [Flagg Phys Rev 178 2387 (1969)] never done:

  Ours would be unique measurement in 1st generation of particles
$\gamma\beta\nu\mathcal{T} : A$ model

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

Gardner, He, PRD 2013 $\mathcal{L} \rightarrow \begin{array}{c} \frac{-4c_5}{m_{\text{nucleon}}} \frac{eG_F V_{ud}}{\sqrt{2}} \epsilon^{\sigma \mu \nu \rho} \bar{p} \gamma_\sigma n \bar{\psi}_e \gamma_\mu \psi_\nu L F_{\nu \rho} \\
\end{array}$

interference with SM vector current gives $\mathcal{T}$ decay contribution

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

- $\mathcal{T}$ 250x larger in $^{38m}\text{K}$ decay than neutron
- final state fake effect $8 \times 10^{-4}$

- $n \rightarrow p \beta\nu\gamma$ branch (Nico Nature 06, Bales PRL 16)

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

Bales b.r. = $(3.35 \pm 0.16) \times 10^{-3}, 1.7 \sigma$ higher than theory $3.08 \times 10^{-3}$
radiative $\beta$ decay and EDMs

No spin $\rightarrow$ different physics at lowest order, but Ng, Vos private comm.: ‘$\text{Im}(c_5)$’ interaction + S.M. $\beta$ decay $\rightarrow$ n EDM at 2 loops

‘Naive Dimensional Analysis’:

$$d_n \sim \frac{\text{Im}(c_5) G_F e}{M^2} \frac{G_F m_n^5}{(16\pi^2)^2}$$

$$\sim \frac{10^{-22} e\text{-cm}}{M^2} \text{[MeV}^{-2}]$$

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

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

We can still reach this sensitivity

Since $n_{\text{edm}}$ usually targets other physics, it would be good to know independently if this is there

[Some $\gamma\beta\nu$ interactions make at 1 loop a $n_{\text{EDM}}$]
Geometry: simplest addition to TRINAT

- Added BGO detectors with SiPM readout
- Tested parasitic to $^{92}\text{Rb }\nu$ spectrum
- Sep 2018
- [J. McNeil CN.00005 now Kohala 4]

**Total, photopeak efficiency:**

<table>
<thead>
<tr>
<th>Material</th>
<th>815 keV</th>
<th>2.17 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 KHz LYSO</td>
<td>0.59</td>
<td>0.28</td>
</tr>
<tr>
<td>Best Z BGO</td>
<td>0.60</td>
<td>0.34</td>
</tr>
<tr>
<td>Bright, low Z NaI</td>
<td>0.26</td>
<td>0.10</td>
</tr>
<tr>
<td>90ns, 50K $\gamma$/MeV GAGG</td>
<td>$&gt;$ NaI</td>
<td>$&gt;&gt;$ NaI</td>
</tr>
</tbody>
</table>
Generic phase space for $\gamma\beta\nu\Upsilon$

- Classical bremsstrahlung $\propto 1/E_\gamma$
- Any time-reversal violating interaction involves $\beta, \nu$ and $\gamma$ and produces a 4-body phase space $\propto E_\gamma (Q - E_\gamma)^3$

Sensitivity to $\sim 5\%$ of SM bremsstrahlung rate

We are concentrating on $E_\gamma > 511$ keV and the ‘opposite’ $\beta^+$
Test with $^{92}\text{Rb} \ 0^- \rightarrow ^{92}\text{Sr} \ 0^+ + \beta^- \nu\gamma$

Online $\beta-\gamma$ doubles:
511 keV from E&M showers
Shoulder of 3-6% 815 keV $\gamma$ from $^{92}\text{Rb}$ decay

East and west-going ions
Ion TOF spectrum similar for top and bottom $\beta$
Test with $^{92}\text{Rb} \, 0^- \rightarrow ^{92}\text{Sr} \, 0^+ + \beta^- \nu \gamma$

- $\gamma$ spectrum & $\beta^-$ & ions ‘west’ vs. ‘east’.
- $5 \times 10^6$ ion-$\beta$ coincidences: Sensitivity to few % $\gamma$ branch

- Top and bottom $\beta$ + GEANT4 may disentangle radiative $\gamma$, showers (511!), discrete 815 keV $\gamma$’s and new $\gamma\beta\nu$

No vector current, so no $c_5$ interaction: Sensitive to pseudoscalar $T$? Pseudoscalar quark $\rightarrow$ nucleon form factor is 350 (Gonzalez-Alonso and Camalich PRL 2014)
\textbf{T} \gamma\beta\nu: Experimental progress

- Unique to 1st generation of particles
- Sensitive to MeV-scale \( T \)
- Complementary to \( K^- \to \pi^0 e^- \bar{\nu}_e \gamma \)

INR Moscow 2007,
\( A_{TRV} = -0.015 \pm 0.021 \)

- Adding \( \gamma \)'s to TRINAT's \( \beta\nu \) detection
  Focus on \( E_\gamma > 0.511 \) MeV and 'opposite' \( \beta^+ \)

\( ^{92}\text{Rb} \ 0^- \to 0^+ \) test: possible sensitivity to \( T \) pseudoscalar

- Vector current mechanism of Gardner and He:
  Projection for 40,000 atoms \( ^{37,38}\text{mK} \) trapped and a week:
  If new physics has 3\% branch, 5 days for 1\% on \( T \) asym.
  Sensitivity to 5\% of SM bremsstrahlung \( \to 10\% \) on \( T \) asym
TRIUMF Neutral Atom Trap at ISAC

- Main TRIUMF cyclotron
  - ‘world’s largest’
  - 500 MeV H⁻ (0.5 Tesla)

- $^{37}$K 8x10⁷/s
- TiC target
- 1750°C
- 70 µA protons
TRINAT efficiency, ISAC yields for $\gamma\beta\nu X$

ISAC $8 \times 10^7$/s $^{37}$K from TiC 2014
0.5 Zr catcher release $900^\circ$C
$5 \times 10^{-4}$ Collection
0.65 Decay before transfer
0.75 Transfer efficiency
→ 10,000 atoms $^{37}$K demonstrated

0.01 $\beta$ detection $\epsilon$
0.15 Ar ion fraction
0.5 MCP ion $\epsilon$
0.8 Counting duty cycle
(Polarized+Unpolarized)
ISAC 4x more $^{38m}$K

Behr et al.
HI 225 115 (2014)
Swanson
JOSA B 15 2641 (1998)
Past radiative nuclear $\beta^-$ decay experiments

$^6$He Bienlein and Pleasanton NP 1965

$^{35}$S vector current $\mathcal{O}(10^{-2})$
Boehm and Wu
PR 93 518 (1954)

Fig. 3. Internal bremsstrahlung of $^{35}$S.

For axial vector current

Powar and Singh
JPG 2 43 (1976)

5-10% discrepancies allowed
**$\mathcal{T}$ in radiative $\beta$ decay and EDMs**

Dekens, Vos 1502.04629: dim 6 operators at TeV scale

$$\mathcal{L}_{\text{eff}}^6 = -\frac{8i c_w}{g v^2} V_{ud} \text{Re} C_k \bar{W}_B (\Lambda) \varepsilon^{\mu \nu \alpha \beta} (\bar{u}_L \gamma_\mu u_L) (\bar{e}_L \gamma_\nu e_L) F_{\alpha \beta}$$

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

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

So TeV-scale general dim 6 ops can make $\mathcal{T} \gamma \nu \beta$ 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 \( 0^- \rightarrow 0^+ \) is ‘first-forbidden G-T’ which does not have the vector current,

nor does first-forbidden unique \( ^{42}\)K \( 2^- \rightarrow 0^+ \)

Other first-forbidden can have vector current contributions times some other operator (\( ^{93}\)Rb) but these have a lot of \( \gamma \)s

- The interference with SM term requires this vector current to produce the Gardner-He term.