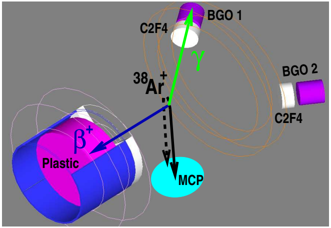
TRIUMF Time-reversal violation ~~T~~ in radiative β decay: experimental progress

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



TRIumf Neutral Atom Trap:

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$\not{T}$, $\not{CP}$, and baryon asymmetry

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

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

But known $\not{CP}$ in the standard model is too small by 10^{10} to generate us

Caveats: **can use $\not{CPT}$**

(Dolgov Phys Rep 222 (1992) 309)

We need more $\not{CP}$ in the early universe,

not necessarily now

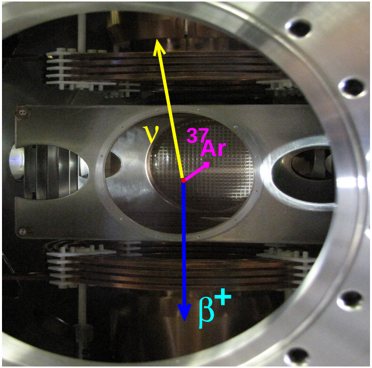
→ • We should look for $\not{CP}$ i.e. $\not{T}$ violation where we can

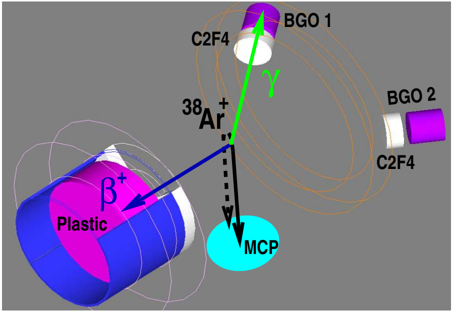
3-momentum $\not{T}$ correlation: Our example

When t $\rightarrow$ -t :

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

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





- We can test symmetry of apparatus with coincident pairs
- Not exact: outgoing particles interact $\rightarrow$ ‘final-state’ fake $\not{T}$

3-momentum $\not{T}$ correlations: Other examples

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

- **Medium energy $\not{T}$ 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 γ) at LHCb and BABAR, 0 ± 0.003 (Martinelli arXiv 1411.4140)**

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

Proposed $\not{T}$ in $\pi^\pm \rightarrow e^\pm \nu e^+ e^-$ [Flagg Phys Rev **178** 2387 (1969)] never done:

Ours would be unique measurement in 1st generation of particles

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$\gamma\beta\nu\not{T}$: A model

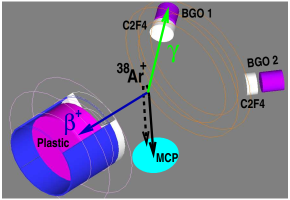
Harvey Hill Hill PRL 99 261601
combine in SM QCD+electroweak
interaction in the nucleon's $\mathcal{L}$

Gardner, He PRD 2013 $\mathcal{L} \rightarrow$

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

interference with SM vector current
gives $\not{T}$ decay contribution

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



new physics
$M \sim$ MeV

- $\not{T}$ 250x larger in ^{38m}K decay than neutron
- final state fake effect 8x10^{-4}

- 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 $\sim$ 1

Bales b.r. = $(3.35 \pm 0.16) \times 10^{-3}$, 1.7 σ higher than theory 3.08×10^{-3}

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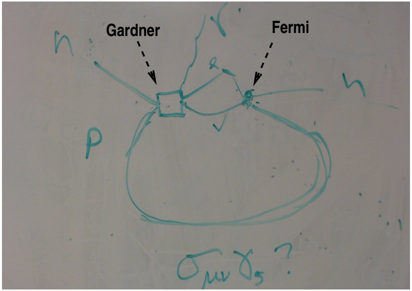
$\not T$ radiative β decay and EDMs

No spin $\rightarrow$ different physics at lowest order, but



Ng, Vos private comm.:
'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

Since n_{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_{EDM}]

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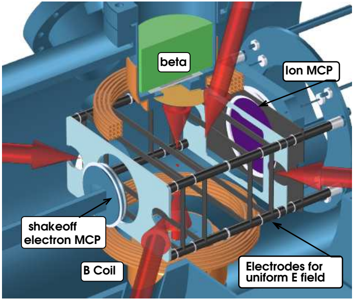
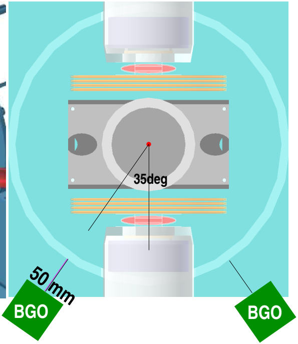
Geometry: simplest addition to TRINAT





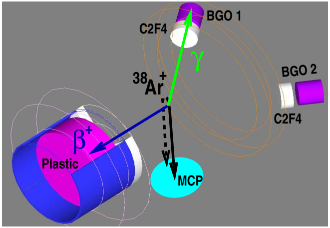
- **Added BGO detectors with SiPM readout**

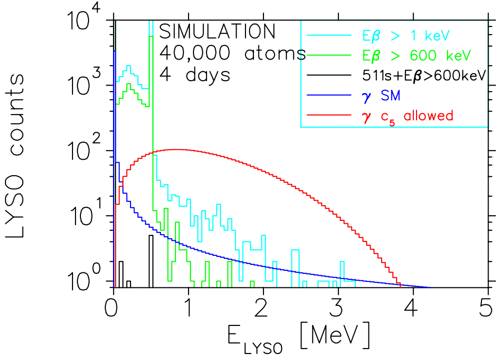
Tested parasitic to ^{92}Rb ν spectrum Sep 2018 [J. McNeil CN.00005 now Kohala 4]

Total, photopeak efficiency:	**material**	**815 keV (3% ^{92}Rb)**	**2.17 MeV (2% ^{37}K)**
10 KHz	**LYSO**	**0.59**	**0.28**
Best Z	**BGO**	**0.60**	**0.34**
Bright, low Z	**NaI**	**0.26**	**0.10**
90ns, 50K γ/MeV	**GAGG**	**$>$ NaI**	**$>>$ NaI**

Generic phase space for $\gamma\beta\nu\not{T}$

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

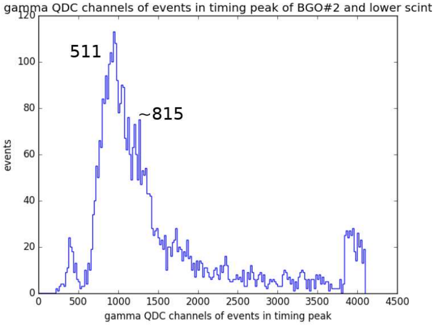




Sensitivity to $\sim$ 5% of SM bremsstrahlung rate

We are concentrating on $E_\gamma > 511$ keV and the 'opposite' β^+

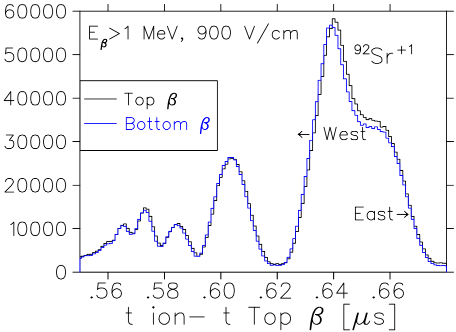
Test with ^{92}Rb $0^- \rightarrow {}^{92}$Sr $0^+ + \beta^-\nu\gamma$



Online β-γ doubles:

511 keV from E&M showers

Shoulder of 3-6% 815 keV γ from ^{92}Rb decay

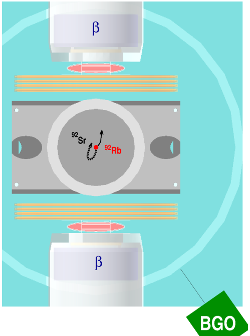


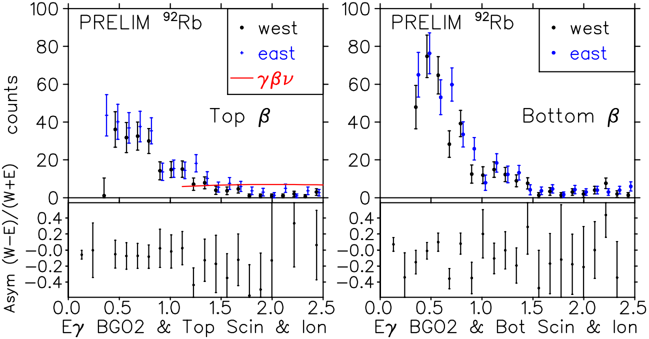
East and west-going ions

Ion TOF spectrum similar for top and bottom β

TRIUMF Test with ^{92}Rb $0^- \rightarrow$ ^{92}Sr $0^+ + \beta^-\nu\gamma$

- γ spectrum & β^- & ions 'west' vs. 'east'.
- 5x10^6 ion-β coincidences: Sensitivity to few % γ branch



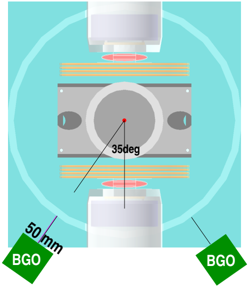


- Top and bottom β + GEANT4 may disentangle radiative γ, showers (511!), discrete 815 keV γ's and new $\gamma\beta\nu$

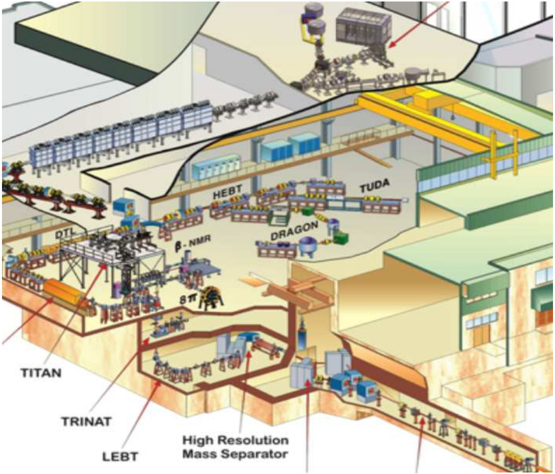
No vector current, so no c_5 interaction: Sensitive to pseudoscalar T̸ ? Pseudoscalar quark $\rightarrow$ nucleon form factor is 350 (Gonzalez-Alonso and Camalich PRL 2014)

TRIUMF $\not T$ $\gamma\beta\nu$: Experimental progress

- **Unique to 1st generation of particles**
- **Sensitive to MeV-scale $\not T$**
- **Complementary to $K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$**



- **Adding γ's to TRINAT's $\beta\nu$ detection**
Focus on $E_\gamma > 0.511$ MeV and 'opposite' β^+
^{92}Rb $0^- \rightarrow 0^+$ test: possible sensitivity to $\not T$ pseudoscalar
- **Vector current mechanism of Gardner and He:**
Projection for 40,000 atoms ^{37,38m}K trapped and a week:
If new physics has 3% branch, 5 days for 1% on $\not T$ asym.
Sensitivity to 5% of SM bremsstrahlung $\rightarrow$ 10% on $\not T$ asym



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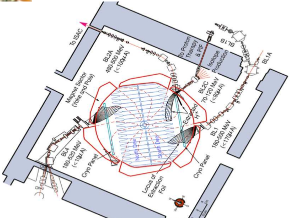
TRIumf Neutral Atom Trap at ISAC

^{37}K 8x10^{7}/s

TiC target 1750^{o}C

70 μA protons

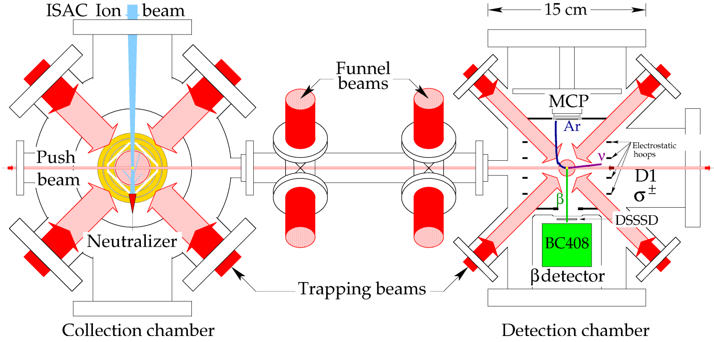
main TRIUMF cyclotron ‘world’s largest’ 500 MeV H^{-} (0.5 Tesla)



TRINAT efficiency, ISAC yields for $\gamma\beta\nu \not{T}$

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

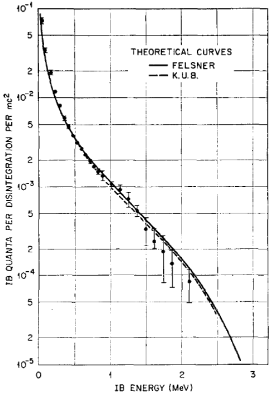
0.01 β detection ϵ
0.15 Ar ion fraction
0.5 MCP ion ϵ
0.8 Counting duty cycle
(Polarized+Unpolarized)
ISAC 4x more $^{38\mathrm{m}}$K



Behr et al.
HI 225 115
(2014)
Swanson
JOSA B 15
2641 (1998)

Past radiative nuclear β^- decay experiments

^{6}He Bienlein and Pleasonton NP 1965



^{35}S vector current $\mathcal{O}(10^{-2})$

Boehm and Wu PR 93 518 (1954)

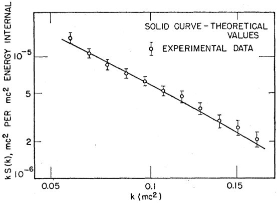
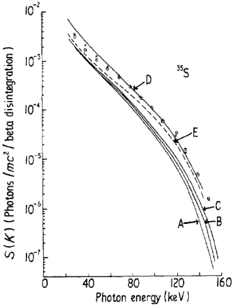


FIG. 3. Internal bremsstrahlung of S^{35}.

For axial vector current

Powar and Singh JPG 2 43 (1976)



5-10% discrepancies allowed

$\not{T}$ 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 $0^- \rightarrow 0+$ 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 γs

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