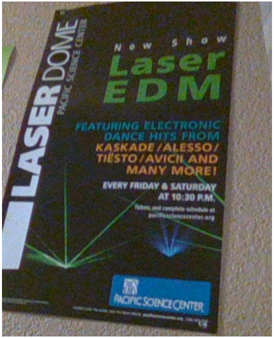
trv

slides 14 and 22 have corrections after the talk.
Phase space for new interaction produces γs and TRV asymmetries at higher $\boldsymbol{E_\gamma}$ that is not yet in the GEANT4 simulations

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



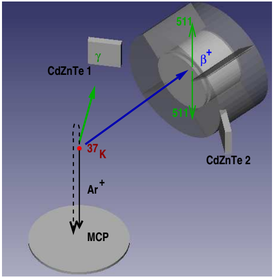
Time reversal in radiative β decay

- **Motivation for TRV in general**
- **Motivation for $\gamma\beta\nu$TRV**

3 momenta (no spin)

EDMs and *D* are known to be small: maybe a good idea to look somewhere else, too

Gardner and He PRD 87 116012 (2013): 'hidden' QCD-like MeV-scale interactions



- **Other constraints on $\gamma\beta\nu$TRV**
- **Experiments with TRIUMF Neutral Atom trap for β decay**

Thanks to QCD community for g_S

Adding γ detection for $\gamma\beta\nu$TRV in ^{38m}K

D in ^{37}K

Time reversal violation: motivation

$\not{CP}$ discovered in $K\bar{K}$ meson decays in 1963 (Cronin and Fitch Nobel prize 1980)
Consistent with a phase in the CKM quark weak/mass mixing matrix

Sakharov JETP Lett 5 24 (1967) used $\not{CP}$ to generate the universe's excess of matter over antimatter:
but known $\not{CP}$ is too small by $10^{9 \text{ or } 10}$
D0: $p\bar{p} \rightarrow$ same sign dimuon asym $\not{CP}$ at 3.6 σ (Abazov PRD 2014)

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

'CPT Theorem': All local Lorentz invariant QFT's are invariant under CPT then $\not{CP} \Leftrightarrow \not{T}$ in most situations
so we look for new sources of $\not{T}$

TRV Experiments with and without corrections

- Two types (of several):
- A permanent electric dipole moment in the ground state of a system violates time reversal symmetry– no theory corrections
- Decays and reactions: 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 (Must correct theoretically for ‘final state’ effects)

Other searches for $\not{C}\not{P}$: B mesons; $\mu\bar{\mu}$ in $p\bar{p}$ (Abazov PRD 2014); ν oscillation community; K decay TREK; orthopositronium decay TUNL and Krakow

permanent EDMs violate time reversal

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

because the angular momentum is the only vector in the problem.

$\vec{d} = a\vec{J}$ **where a is a constant**

$$\vec{J} \stackrel{t\to -t}{\longrightarrow} -\vec{J}$$

$$\vec{d} = \sum q_i \vec{r}_i \quad \Rightarrow \quad \vec{d} \stackrel{t\to -t}{\longrightarrow} +\vec{d}$$

If the physics is invariant under T, this is a contradiction, $\Rightarrow$ $a = 0$.

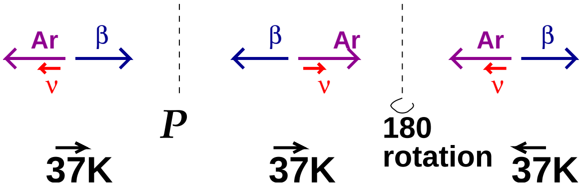
This has no theory corrections

[unless of course you want to calculate the neutron EDM from QCD :)
"the pion has too many quarks" John Ng, TRIUMF]

Decays: Parity Operation can be simulated exactly by Spin Flip

Under Parity operation *P*:

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



Time reversal tests in decays

Under Time reversal operation *T* :

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

Can construct observables odd in time like $\vec{J} \cdot \vec{p_\beta} X \vec{p_\nu}$
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.

(Nuclear reactions can be and have been reversed)

Many experiments flip $\vec{J} \rightarrow$

TRV in radiative β decay: 3 momenta

One SM physics term from QCD+electroweak (Harvey Hill Hill PRL 99 261601; Hill PRD 81 0138008 2010):

$$\mathcal{L}^{(3)} = \frac{c_5}{M^2}\bar{N}i\epsilon^{\mu\alpha\beta\sigma}\gamma_\sigma\tau^a \mathrm{Tr}(\tau^a\{\tilde{A}_\mu, [i\tilde{D}_\alpha, i\tilde{D}_\beta]\})N$$

M nucleon mass; N nucleon doublet; A,D gauge fields; c_5 undoable nonperturbative QCD calculation

Gardner, He PRD 87 116012 (2013)

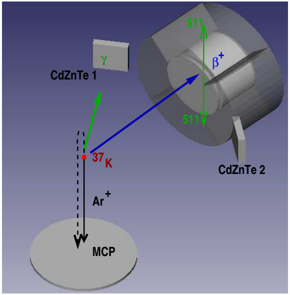
$$-\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\alpha\beta}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu L}F_{\alpha\beta}$$

interference with S.M. vector current

$\rightarrow$ decay rate contribution

$$256e^2 G_F V_{ud}\, Im(c_5 g_V)\frac{E_e}{p_e k}(\vec{p_e}\times\vec{k_\gamma})\cdot\vec{p_\nu}$$

the form of the term comes from SM physics



Requires new physics for TRV

e.g., QCD-like hidden sector with scale $\sim$ MeV.

Few constraints

Could supply TRV for baryogenesis and dark matter together, but details not worked out (Gardner priv. comm.)

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

Radiative neutron β decay

again from Gardner and He PRD 2013

• Neutron β decay radiative branch agrees with S.M. to 10% (Nico 2005)

$\Rightarrow$ TRV asymmetry < 0.1 in n$\rightarrow$ p+$\beta\nu\gamma$

Measurements of the radiative branch in higher-*Z* nuclei also agree at 10% accuracy

The TRV asymmetry can still be $\sim$ unity in ^{37}K at higher E_γ

TRV in radiative β decay and EDMs

Dekens, Vos 1502.04629: dim 6 operators at TeV scale

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

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

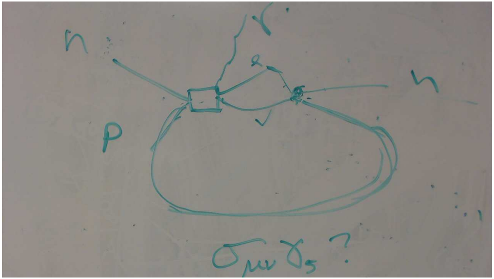
Also generates EDMs $\Rightarrow$ constants $\sim$ 0.01

So TeV-scale general dim 6 ops can make TRV $\gamma\nu\beta$ 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 $\rightarrow$

EDMs and TRV radiative β decay



Ng, Vos left this diagram on my office whiteboard

Gardner's low-energy interaction between nucleons+ standard model β decay interaction $\rightarrow$ n EDM at 2 loops

Dimensional analysis:

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

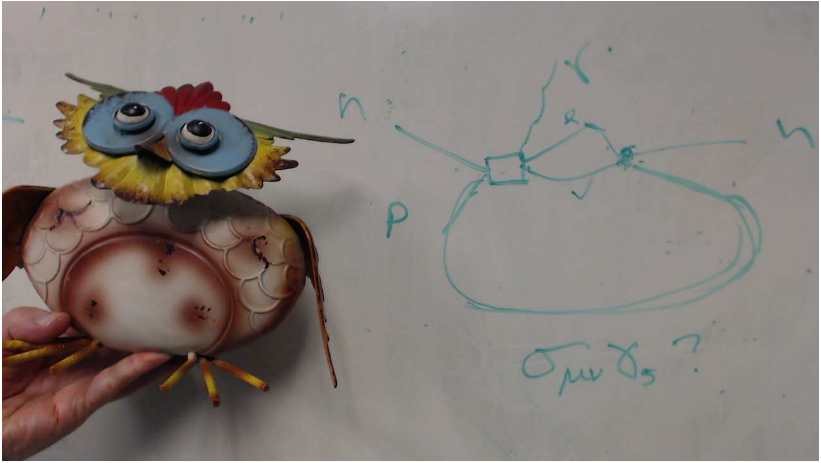
$d_n[\exp] < 3 \times 10^{-26}$e-cm (Baker 2006 PRL)

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

if this physics is the only n EDM source

We can still reach this sensitivity at higher $E\gamma$

Not a penguin diagram



D $\vec{J} \cdot \vec{p_\beta} \times \vec{p_\nu}$ and $\gamma\beta\nu$TRV

Gardner and He worked out contribution to radiative TRV from Lee-Yang Lagrangian + radiative correction and found the contribution very small, given sensitive null measurements of D and R

Dekens and Vos [private comm] have noticed that the c_5 interaction + one loop corrections makes the D observable order of magnitude estimate is very large. Details remain to be worked out.

~~**If so, this should scale with Z; makes ^{37}K an attractive candidate for a measurement of D ([JB, private comm with himself]) even considering the null measurements in the neutron and ^{19}Ne**~~

nothing in the problem scales with Z (neither the c_5 interaction, nor classical bremsstrahlung...)

Experimental considerations

from Gardner and He PRD 87 116012 (2013):

- **the new 'c5' term needs Fermi operator**
- **$^{38\mathrm{m}}$K or ^{37}K A $\sqrt{B.R.} \sim$ 200x neutron**
- **Final state false TRV 0.8-2.6x10^{-3} from 10-300 keV for ^{35}Ar**

(much smaller for ^{19}Ne because of accidental cancellation of Fermi and Gamow-Teller contributions)

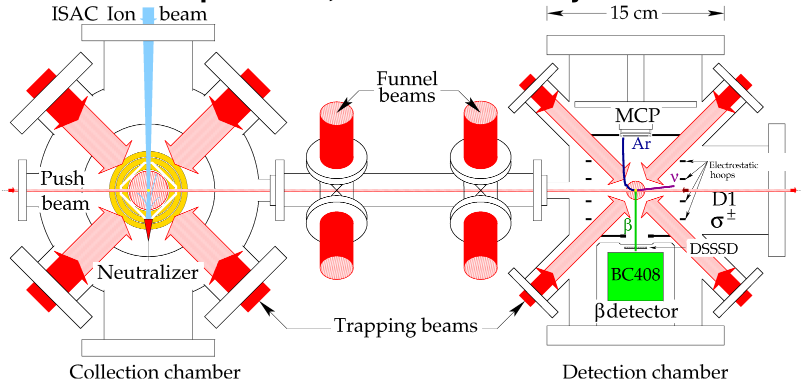
- **Lee-Yang interactions make Asym TRV $\sim 10^{-6}$**
- **$^{38\mathrm{m}}$K 40,000 atoms $\rightarrow$ TRV A_γ to 0.01 per 10 days**

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.

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

B. Fenker
D. Melconian

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

****M. Anholm**
G. Gwinner

D. Ashery
I. Cohen
Undergrad
1 at a time

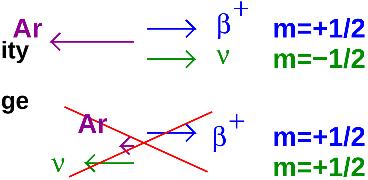
** Grad student * PDF

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

Lepton helicity → angular distribution

For ^{38m}K, $0^+ \rightarrow 0^+$ decay:

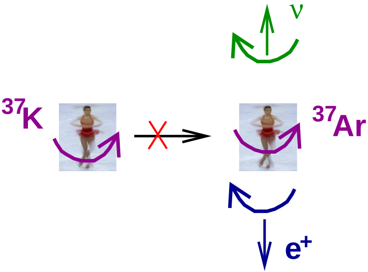
leptons have opposite helicity for W (vector) boson exchange



$$W[\theta_{\beta\nu}] = 1 + b\frac{m}{E} + a\,\frac{v_\beta}{c}\cos\theta_{\beta\nu}$$

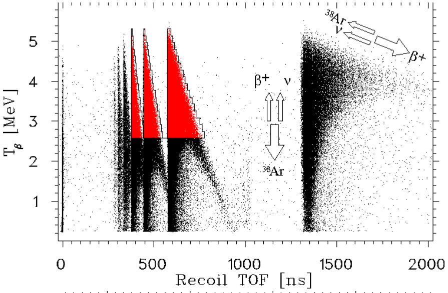
$\Rightarrow$ **a = +1, b = 0** $a = -1$ for scalar

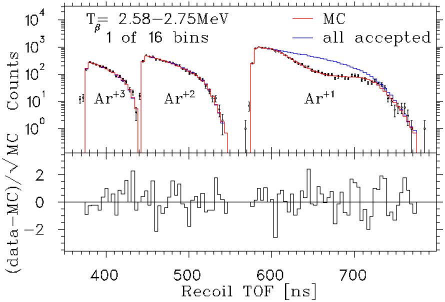
- **independent of isospin mixing and nuclear structure**
- **Radiative corrections 2x10^{-3}, recoil order term is 3x10^{-4}**



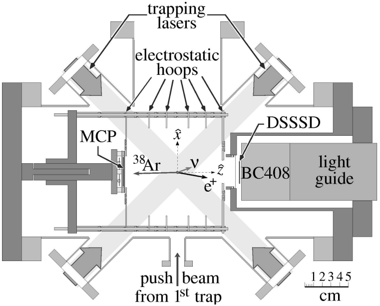
← This decay pattern needs non-S.M. chirality

^{38m}K β-ν correlation





$$W[\theta] = 1 + \tilde{a}\cos[\theta]$$

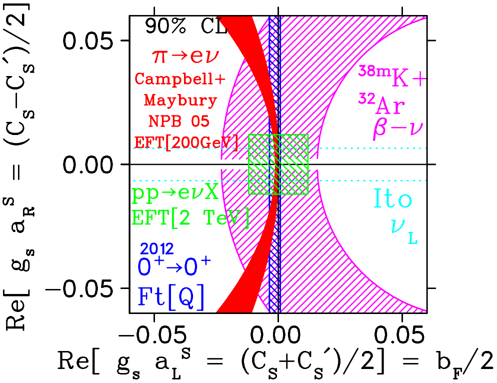


Gorelov PRL 2005

$\tilde{a} = 0.9981 \pm 0.0030 \pm^{0.0032}_{0.0037}$

- **New geometry goal is to collect all recoils**
- **To go to lower E_β, reconstruct it**

Direct and indirect sensitivity to scalars



- **LHC constraints**

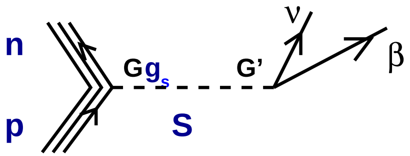
σ [p p $\rightarrow$ e ν X]
Cirigliano, González-Alonso, Graessler JHEP02(2013)046
limits scalars coupling to wrong-handed ν

- **$\pi \rightarrow e\nu$ (Campbell Murray NPB 04)**
  PIENU has improved 2x (PRL 2015)

- **contributions to m_ν from $C_S - C_s'$ should be understood**

Assuming g_S=1.02$\pm$0.10 (Gonzalez-Alonso, Camalich PRL 112 042501 (2014) (0.8$\pm$0.4 Bhattacharya et al PRD 2013)

personalized History of g_S



Propagator+vertices: T $\propto g_S \frac{G_S^2}{M_S^2}$

Nucleon scalar form factor $|g_S|$= $|\langle p|\bar{u}d|n\rangle|$ = ? 0.25 to 1.0 (Herczeg ProgParNucPhys 46/2 413 (2001));

'but that's a factor of 16 in counting time'

0.6 (quark model Adler et al. PRD 11 3309 (1975));

~~0.63(9) (Lattice gauge Liu et Woloshyn et al. PRD 59 (1999))~~ (uncertainty does not include known systematics);

0.8(4) Bhattacharya et Lin et al. PRD 2013

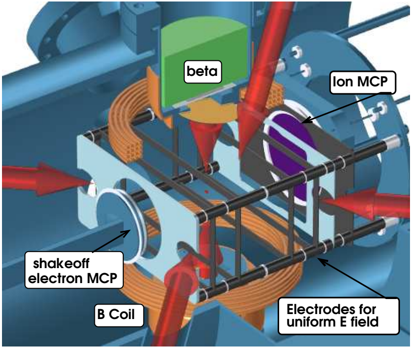
1.02(10) Gonzalez-Alonso, Camalich PRL 112 042501 (2014)

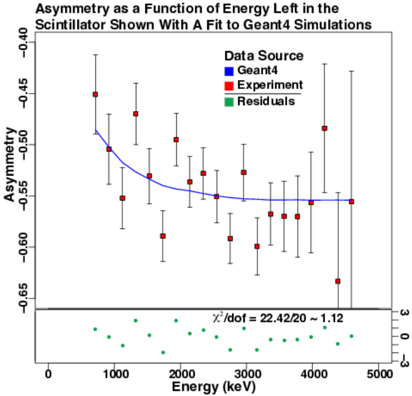
Theorists have told me things 'everyone knows'

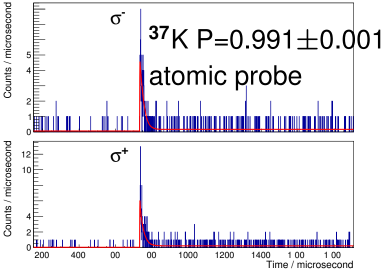
'You also need a nucleon-nucleus form factor, about 1.1 or 1.2'

'g_S runs with momentum. You win over high-energy by 1.2.'

$^{37}\vec{\mathrm{K}}$ A_β, A_{recoil}: scalar, tensor, V+A





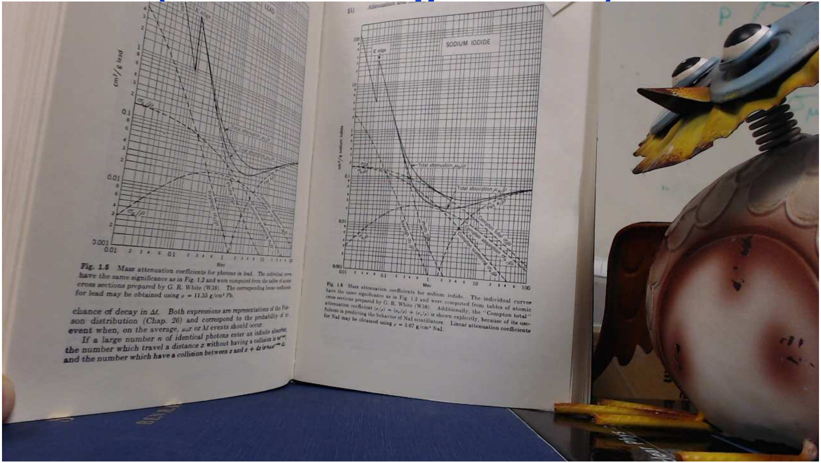


A_β = -0.5635(63)(71)

S. Behling, Ph.D. thesis, TAMU, 2012 data

2014 data: $\sigma_{A\beta} \sim 0.002$ (stat) and β-recoil coincidences

γ Wisdom (before running GEANT4)

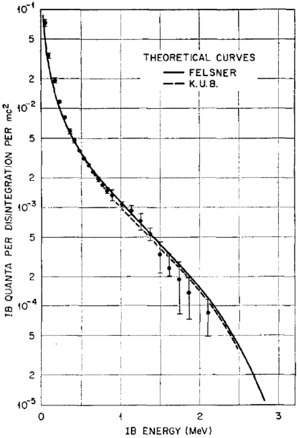


Cardboard has less ‘outer bremsstrahlung’ background

but not as good as stainless steel for UHV

You want to use positrons?

Radiative nuclear β^- decay experiments e.g.



^{6}**He Bienlein and Pleasonton NP 1965 (low energy 1.5x disagreement from lineshape folding?)**

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

Boehm and Wu PR 1954

Powar and Singh JPG (1976)

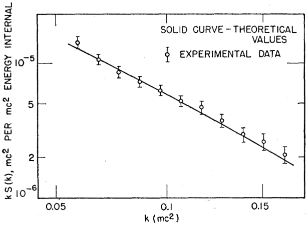
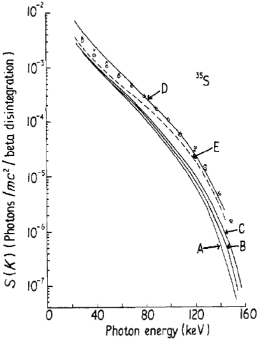
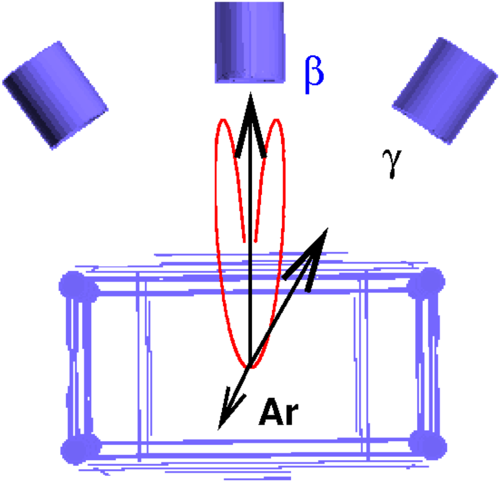


FIG. 3. Internal bremsstrahlung of S^{35}.



S.M. Bremsstrahlung is forward-peaked



Existing ports at 35 degrees, $\beta - \gamma$ is larger by 3x compared to uniform distribution

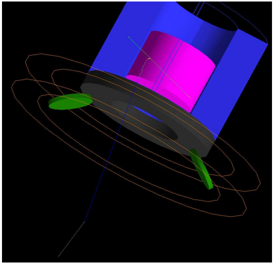
sin(35^o) = 0.57 (Triple scalar product)

Will test apparatus symmetry with β-γ and with recoil-γ doubles

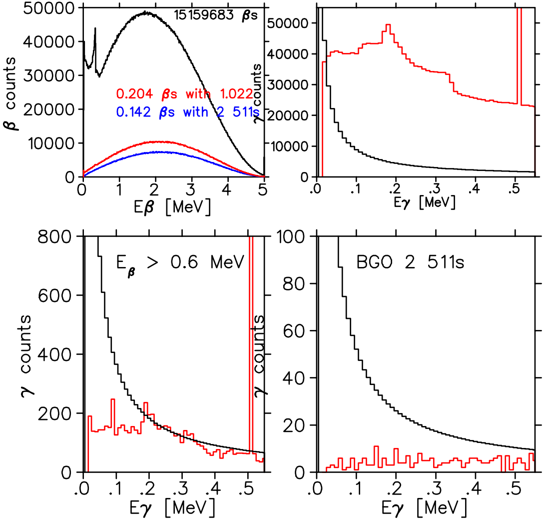
GEANT4: Actively excluding 511s

The experiment is possible at low $E\gamma$ with a β^+ emitter.

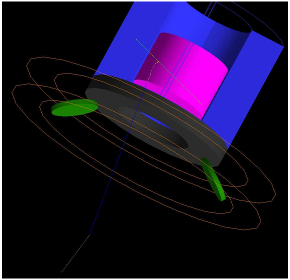
Plastic core (β^+) + BGO segmented cylinder (511s)



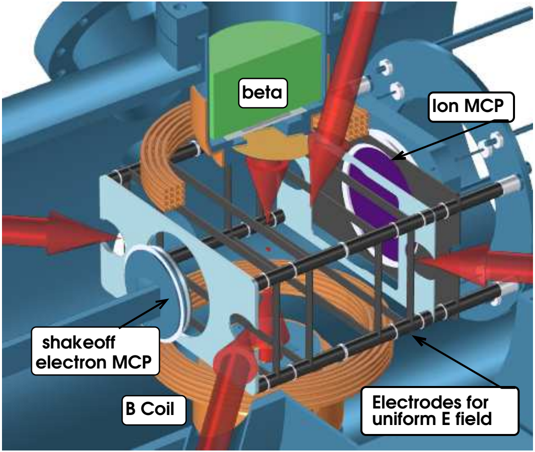
This detector is not compatible with ^{37}K and ^{38}K angular correlations →



Location of plastic+BGO 511 detector



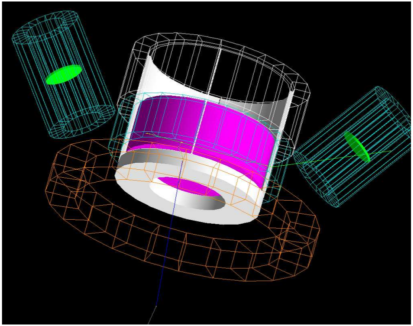
In place of present β detectors

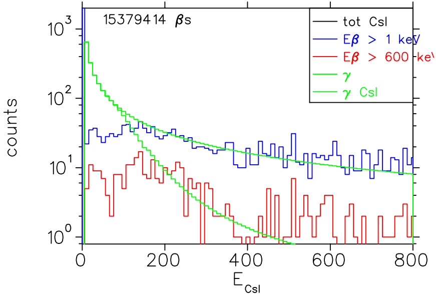


Adding γ detectors to present TRINAT can work

at lowest energies (so far)

- W shielding
- 1.5mm thick CsI(Tl) for γs High-Z: Photoabsorption dominates, $\sim 1/E\gamma^3$; 90% for 100 keV and 7% for 500 keV
- Needs readout insensitive to B fields (e.g. SiPM)





Predicted TRV asym $\sim \propto E_\gamma$

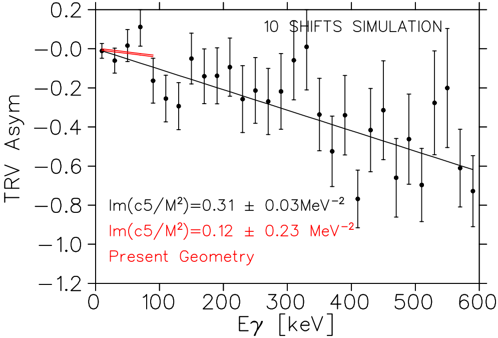
Neutron radiative β decay branch measured to 10% accuracy (Nico 2006)

$\Rightarrow$

$Im(c5/M^2) < 12\mathrm{MeV}^{-2}$

Present geometry + γs

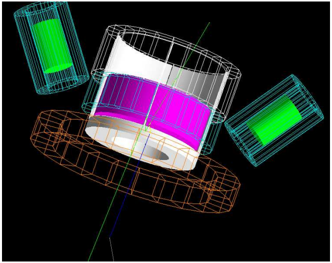
Dedicated geometry with BGO 511 detection

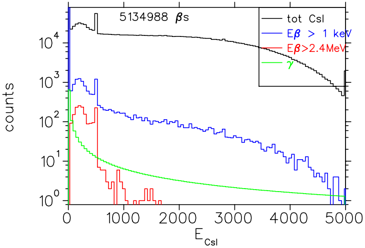


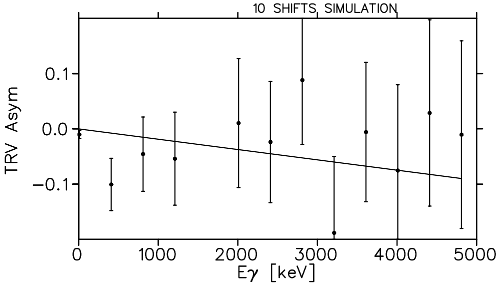
Present TRINAT + γs running parasitic to ^{37}K experiments would have better sensitivity than direct limits by $\sim$ 50

To reach sensitivity suggested by null n EDM experiments, thicker γ detectors, measure higher $E\gamma$ closer to 5 MeV endpoint $\rightarrow$

TRV asym $\propto$ higher E_γ ?





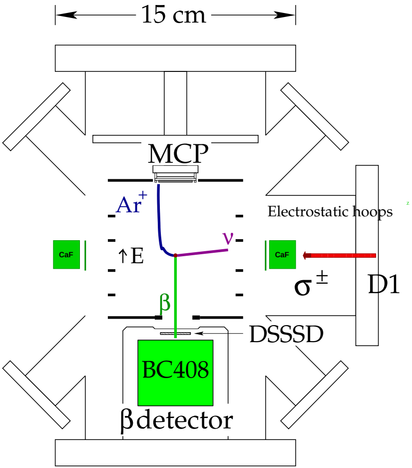


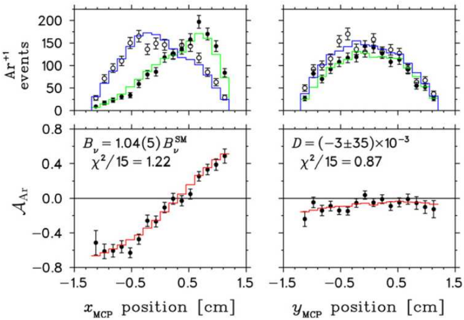
Asym=−.0197 ± 0.0148

$\mathrm{Im}(c5/M^2)$=0.0012 ± 0.0009MeV^{-2}

To reach sensitivity of null n EDM experiments: thicker γ detectors, measure higher $E\gamma$ closer to 5 MeV endpoint. Considering LSO and GSO (density, Z, speed, not hygroscopic)

TRINAT has measured D in ^{37}K





Melconian PLB 649 370 (07)

D $\vec{J} \cdot \vec{p_\beta} X \vec{p_\nu}$

All angles of nuclear recoils collected by electric field

Larger β efficiency is needed

TRINAT and D: future?

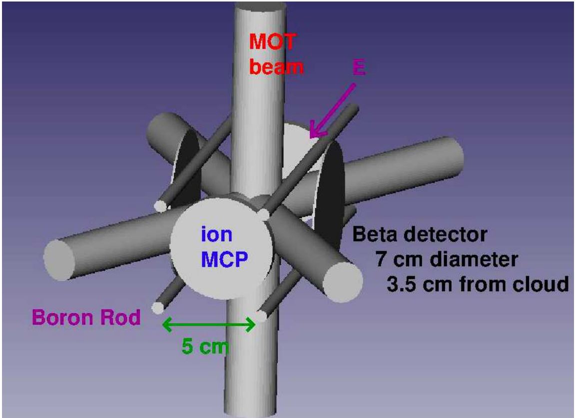
To do better would require a dedicated geometry

emiT (neutron) 2011: D= -0.96 $\pm$ 1.89 $\pm$ 1.01 $\times$ 10^{-4}

Do observables evade EDM constraints?

Ng,Tulin PRD 2012 D could still be 10^{-4} to 10^{-5}

Dedicated geometry: statistics 2x10^{-4} in 2 weeks



Add transparent β detectors? Kapton $>$ 85% transmission

g_p for Pseudoscalar quark-lepton interaction is 350

Gonzalez-Alonso and Camalich PRL 112 042501 (2014)
Is that enough enhancement to motivate $0^+ \rightarrow 0^-$ β-ν correlation?

JB's Open questions

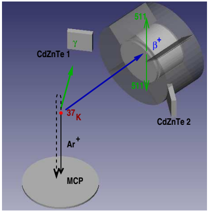
- **Final state effects as a function of β-γ angle and lepton energy**
- **TRV asymmetry as a function of lepton energy and γ angle**
- **Constraints and/or incentives:**
EDMs
D

Is there a mechanism for MeV-scale strongly interacting sectors to have TRV couplings with SM particles? Can they have their own version of θ_{QCD}? Is there a connection with 'SIMP Miracle'?

- **Is the $\gamma\beta\nu$TRV experiment feasible at higher E_γ ?**

(• g_P in nuclei is 350?)

$\gamma\beta\nu$ TRV in ^{38m} conclusion



- **Motivations**

New observable, sensitive to MeV-scale TRV
'Final-state effects' from allowed processes are small
EDMs indirect constraints (2-loop) are reachable
Constraints from D might motivate D in ^{37}K:)

- **Experiment**

Add conventional low-Eγ detectors to TRINAT;
Sensitivity $\sim$ few % is possible. To do better requires a redesign.
GEANT4: Actively excluding β^+s works OK

not the *E* coefficient

β decay feeding excited nuclear states, look at γ correlation with nuclear alignment

$E_1(\hat{J}\cdot\hat{k})(\hat{J}\cdot\hat{p}\times\hat{k})$

Sensitive to interference between Fermi and Gamow-Teller (similar to D)

• ^{56}Co Calaprice, Freedman, Osgood, Thomlinson PRC 15 381 (1977)

$E_1 = -0.011 \pm 0.022$

• proposal by Young in ^{36}K PRC 52 R464 (1995); Minamisono MSU/NSCL

^{38m}K β-recoil error budget

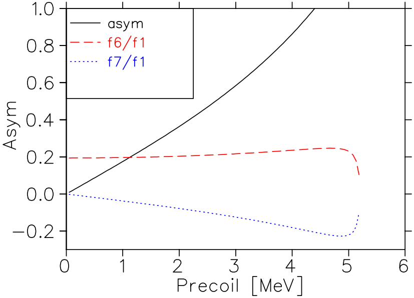
Error	PRL	Future
$\vec{E}$ field/trap width :	0.17%	0.04%
E field nonuniformity	0.14%	0.03%
β^+ backscattering bkgd	None	None
$E_{\beta+}$ Detector Response:		
Lineshape tail/total	0.06%	0.03%
511 keV Compton sum	0.09%	0.04%
Calibration, nonlinearity	0.17%	0.08%
MCP Eff[E_{Ar+}]	0.07%	0.03%
MCP Eff[θ]/XY position	0.08%	0.04%
e^- shakeoff [E_{recoil}]	0.18%	0.08%
Sum systematics	0.37%	0.14%
Total error	0.48%	0.19%

Planned Improvements:

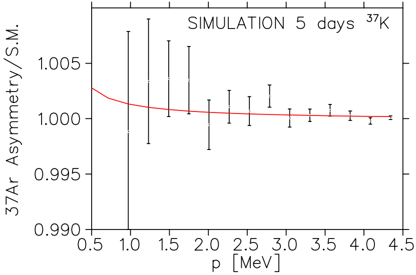
- Larger MCP and $\vec{E}$ field
- larger ISAC yields $1/\sqrt{5}$ statistical error
- E_β calibration from interwoven background-free ^{37}K

- **Most systematic errors determined by statistics-limited data evaluation.**

^{37}K decay recoil asymmetry



recoil singles asymmetry



Simulation for 5 days
10,000 atoms trapped

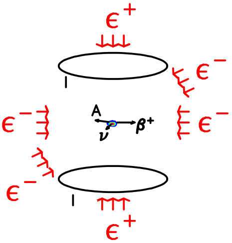
Would extract $C_t + C_t'$= 0.0018+-0.0008, possible from SUSY [Profumo PRD 75 075017] with uncertainty smaller than world average in nuclear β decay

TRIUMF Neutral Atom Trap 2016+

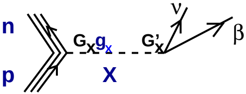
Angular correlations of products for polarized and unpolarized β decays are sensitive to separate terms of:

$$H_{\rm int} = \sum_X (\bar{\psi}_p O_X \psi_n)(C_X \bar{\psi}_e O_X \psi_\nu + C'_X \bar{\psi}_e O_X \gamma_5 \psi_\nu)$$

'X': Lorentz vector, axial vector, scalar, tensor



- **Spin-polarized experiments in progress**
  Goal 0.001 accuracy $\rightarrow$ sensitivity to $M_x/G_x \sim M_W/\sqrt{0.001} \sim 2$ TeV



- **^{38m}K β-ν upgrade is sensitive to 'scalar' only and is complementary to other experimental constraints**
  - **Time reversal violation in radiative β decay** is not produced this way; is sensitive e.g. to MeV-scale QCD-like hidden sector models; TRV asymmetry 0.1 is allowed
  - **The E_ν spectrum of ^{92}Rb and reactor ν anomalies**