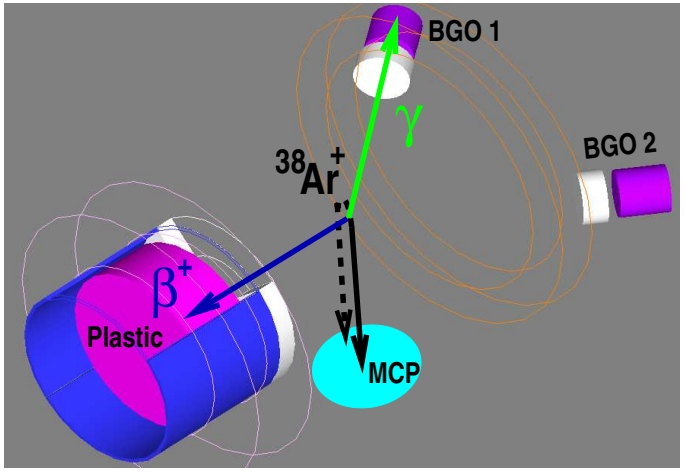
TRIUMF Time-reversal violation $\not{T}$ in radiative β decay: experimental progress

- $\not{T}$ Motivation
- Our geometry and simulation for $\beta\nu\gamma$ correlation
- Test run with ^{92}Rb $0^- \rightarrow 0^+$



TRIumf Neutral Atom Trap:

TRIUMF
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We are looking for a grad student for this project

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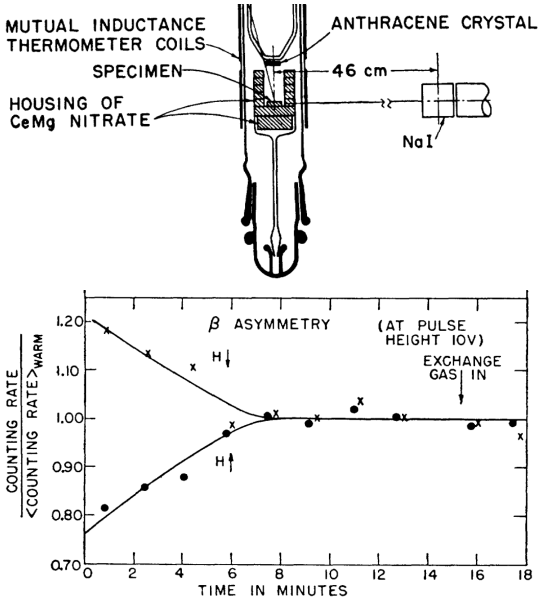
Parity broken, why not Time?



Immediately after Parity was seen to be totally broken in β decay ('ν left-handed')

Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413

Many T-odd observables were proposed:

PHYSICAL REVIEW VOLUME 106, NUMBER 3

Possible Tests of Time Reversal Invariance in Beta Decay

J. D. JACKSON,* S. B. TREIMAN, AND H. W. WYLD, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received January 28, 1957)

Need scalar triple products of 3 vectors: observables involving spin

$$D\hat{J} \cdot \frac{\vec{p}_\beta}{E_\beta} \times \frac{\vec{p}_\nu}{E_\beta} \qquad R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} \times \frac{\vec{\mathbf{p}}_\beta}{E_\beta}$$

are consistent with $T < 0.001$

So we're looking for something that could still be big: →

TRIUMF $\not{T}$ correlation of 3 of 4 momenta

$t \rightarrow -t \Rightarrow \vec{p} \propto \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$

We routinely measure

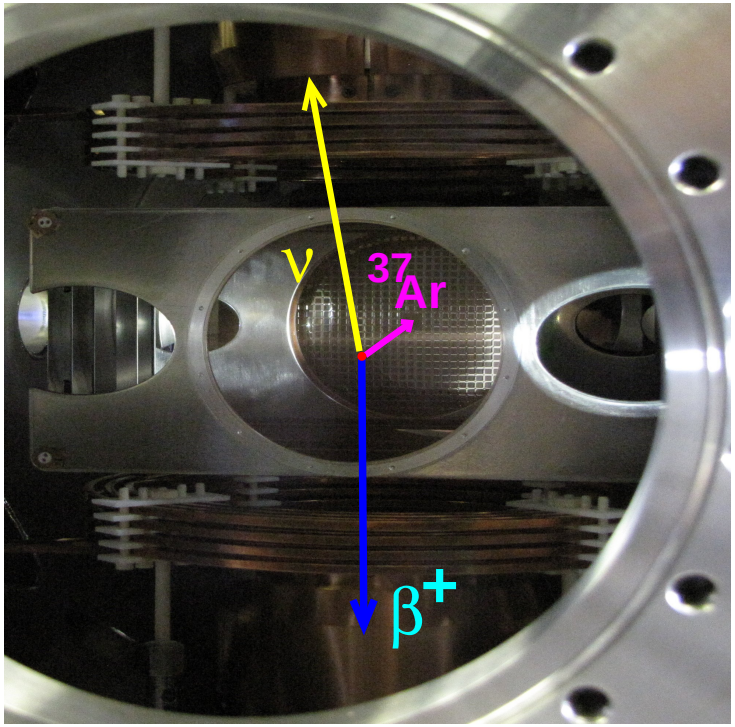
$\vec{p}_\nu = -\vec{p}_\beta - \vec{p}_{recoil}$

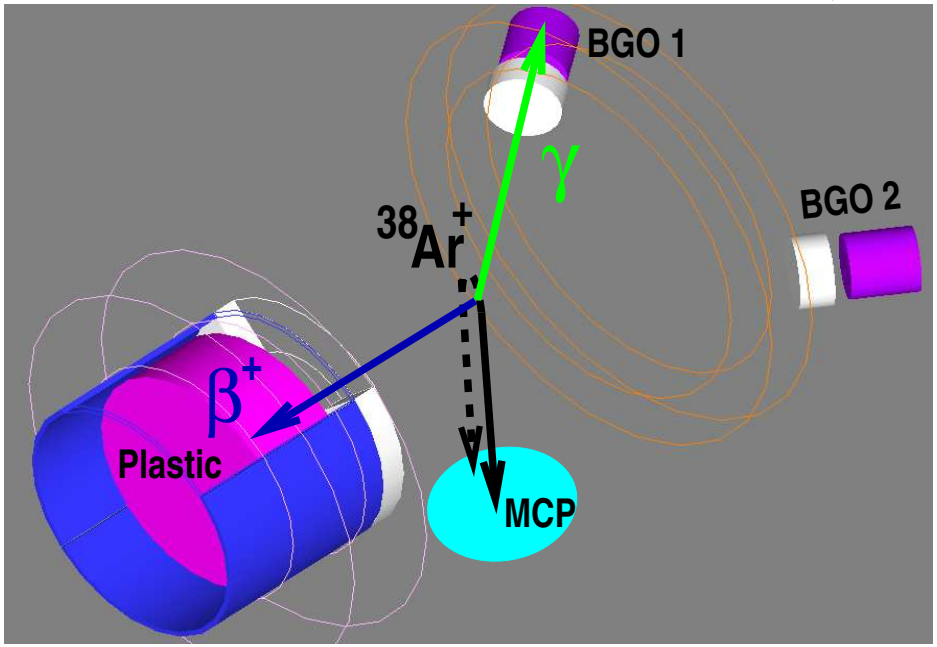
but $\vec{p}_{recoil} \cdot \vec{p}_\beta \times \vec{p}_\nu \equiv 0$ ☹

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

$\xrightarrow{t \rightarrow -t}$

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





- We can test symmetry of apparatus with coincident pairs ☺
- Not exact. Outgoing particles interact →
  'final-state' fake $\not{T} \leq 10^{-3}$ for ^{37}K ☺(Gardner,He 2013)

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The nucleon: a special place for γ's

S.M. interactions combined in the nucleon:

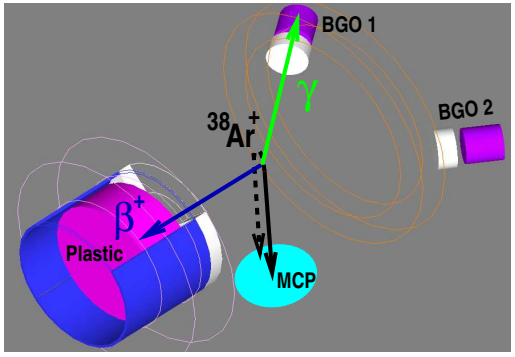
Harvey Hill Hill PRL 2007 Gardner He PRD 2013

QCD Weak decay E&M

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

Interference with S.M. β decay 'vector current' gives $\beta\nu\gamma$ decay contribution with the scalar triple product we want:

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



$\not T$ needs new physics with scale $M \sim$ MeV

- **This source of $\not T$ scales with p^2_{lepton}, so is $\sim 10^2$ larger in ^{37}K decay than neutron**

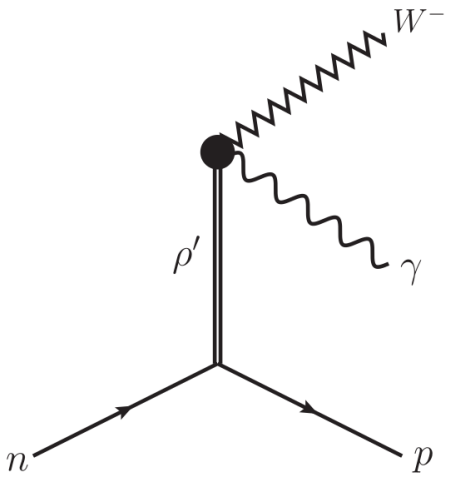
- **Direct constraint from n $\to$ p $\beta\nu\gamma$ branch $\propto |c_5|^2$**

Bales PRL 2016: $3.4 \pm 0.2 \times 10^{-3}$ (theory 3.1×10^{-3})

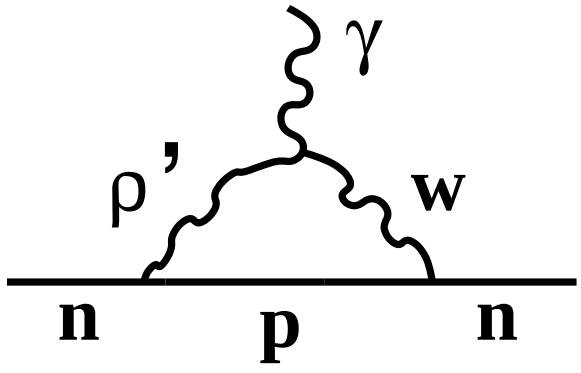
$\Rightarrow \frac{\text{Im}(c_5)}{M^2} \leq 8MeV^{-2} \Rightarrow$ **^{37}K $\not T$ asym can still be ~ 1 ☺**

Constraint from neutron EDM on $\not{T}\ \beta\nu\gamma$

Some $\not{T}\ \gamma\beta\nu$ interactions, e.g. :



make neutron EDM at "1-loop" order (D. McKeen, private comm):



"Naive Dimensional Analysis"

$$c_5 \frac{e^2 G_F M_W^3}{16\pi^2 m_{\rho'}^2}$$

suggests nEDM larger than experiment by $\sim 10^8$.

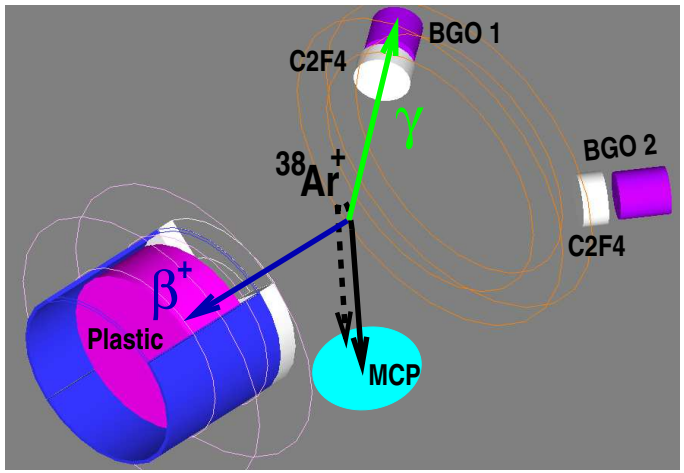
[Gardner and He, PRD 2013]

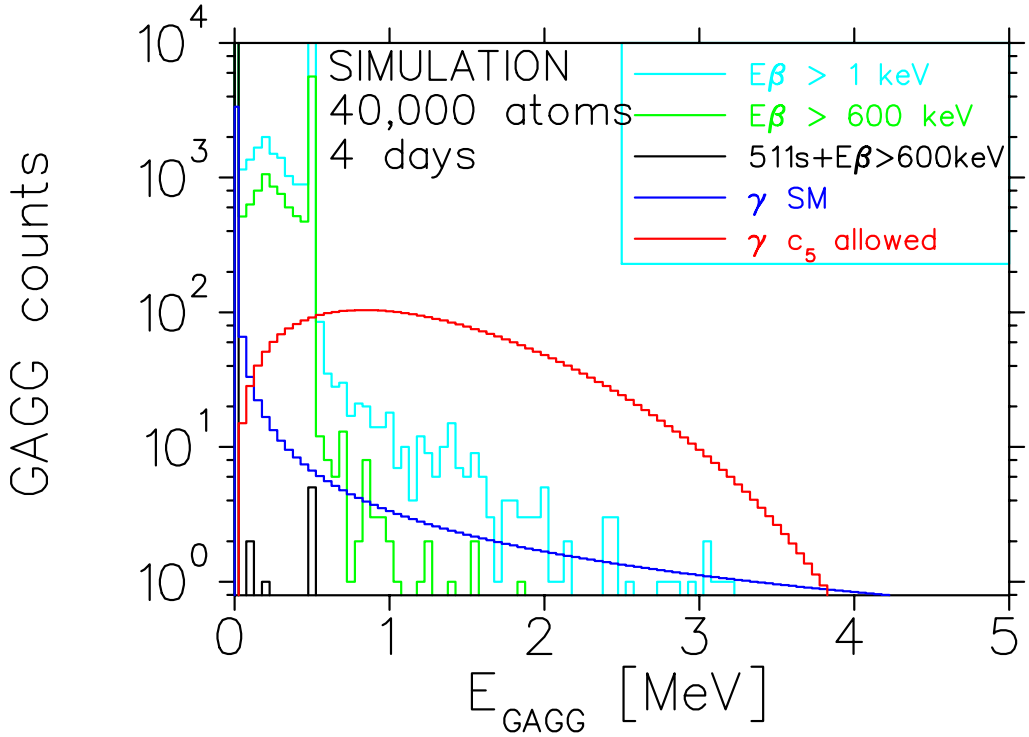
- **So $\not{T}\ \beta\nu\gamma$ from such interactions would likely be too tiny to measure ☹**
- **Other interactions (e.g. leptoquarks) need "2 loops" so generate comparatively tiny nEDM so are unconstrained and can generate $\not{T}\ \beta\nu\gamma$ large enough to measure ☺**

Simulations: E_γ signature and backgrounds

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

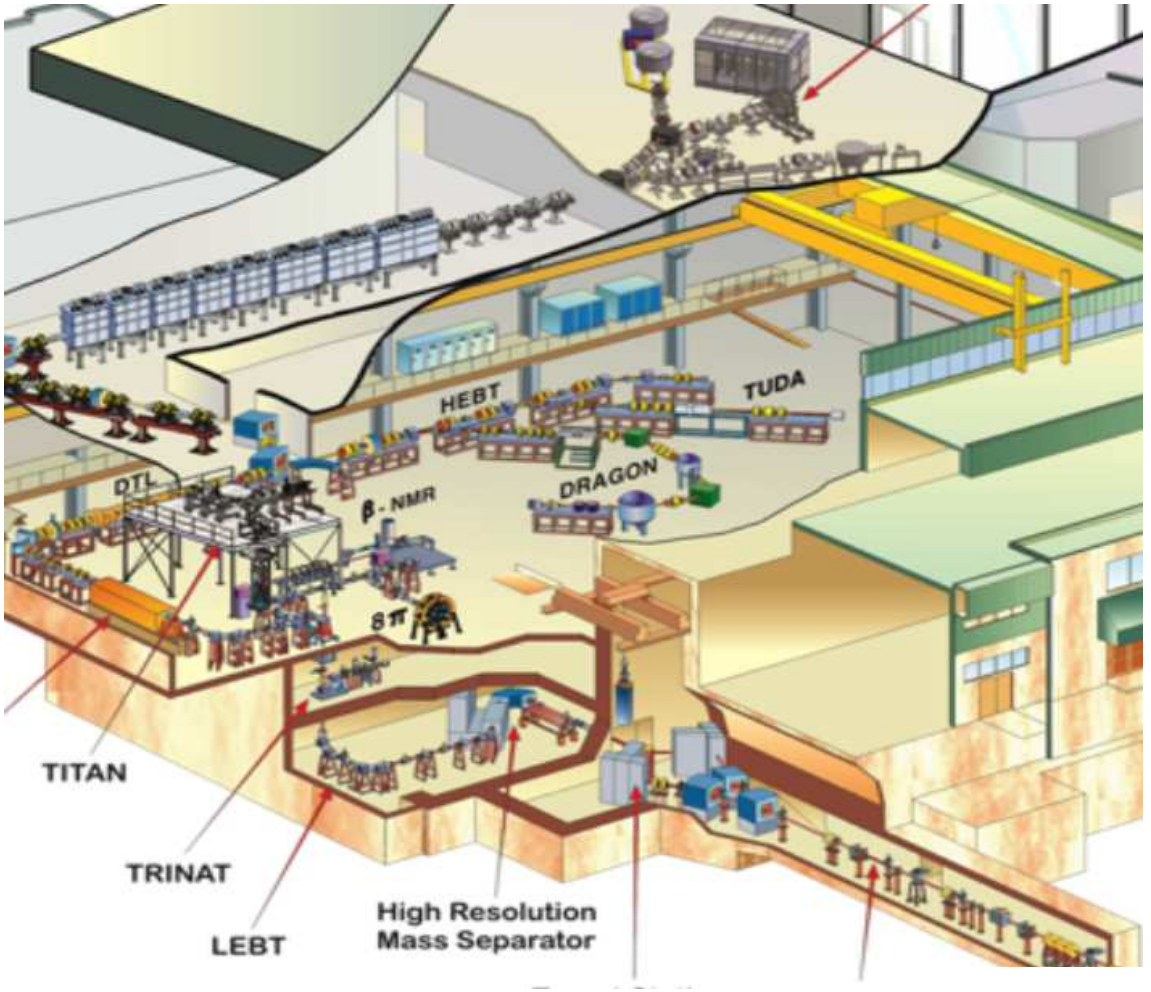
Bernard PLB 593 (2004)

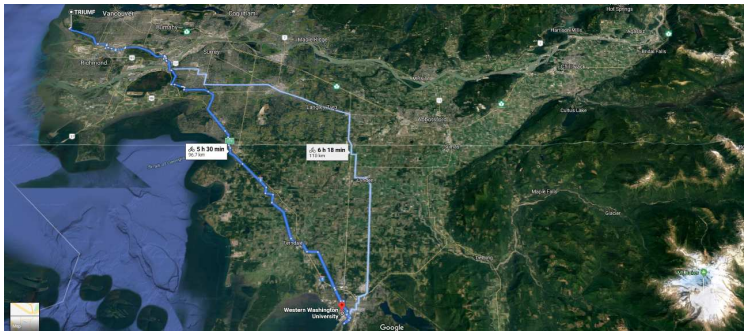




We are concentrating on:

- **$E_\gamma > 511$ keV**
- **the β^+ in the opposite detector**





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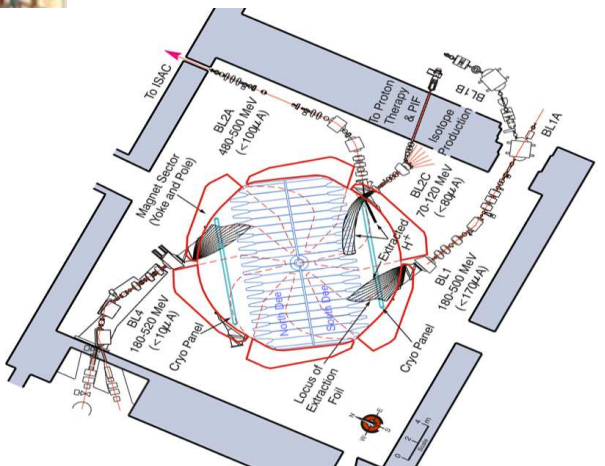
TRIumf Neutral Atom Trap at ISAC

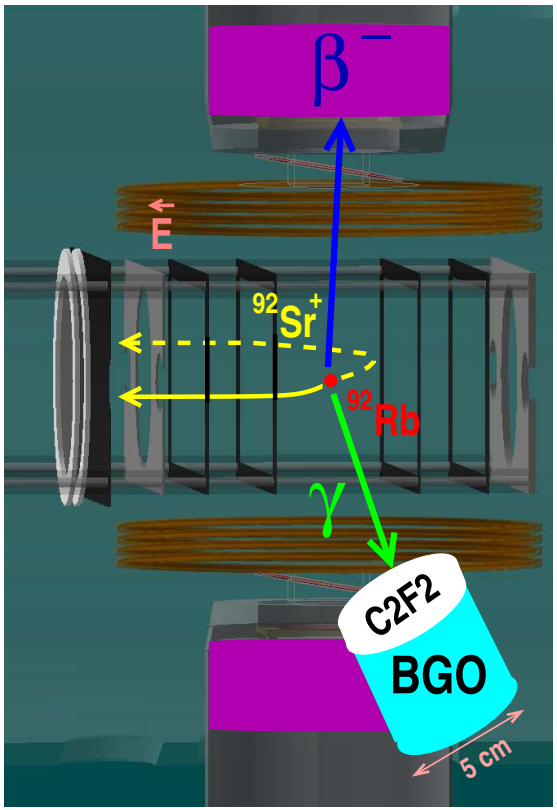
main TRIUMF cyclotron
'world's largest'
500 MeV H^-
(0.5 Tesla)

^{37}K 8x10^7/s TiC target 1750^{o}C 70 μA protons

^{92}Rb 6x10^8/s UC_x target

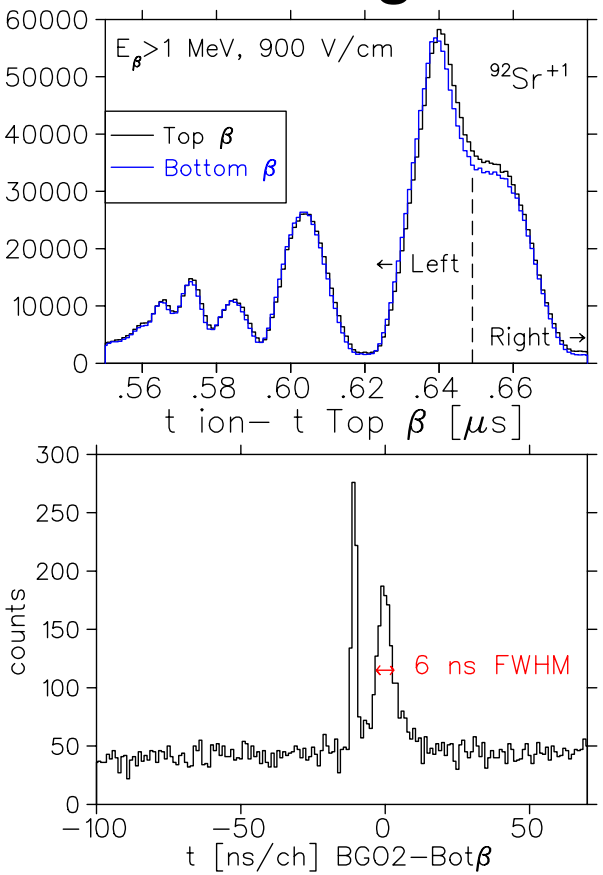


$\not T$ test with ^{92}Rb $0^- \rightarrow$ ^{92}Sr 0^+ + $\beta^-\nu\gamma$



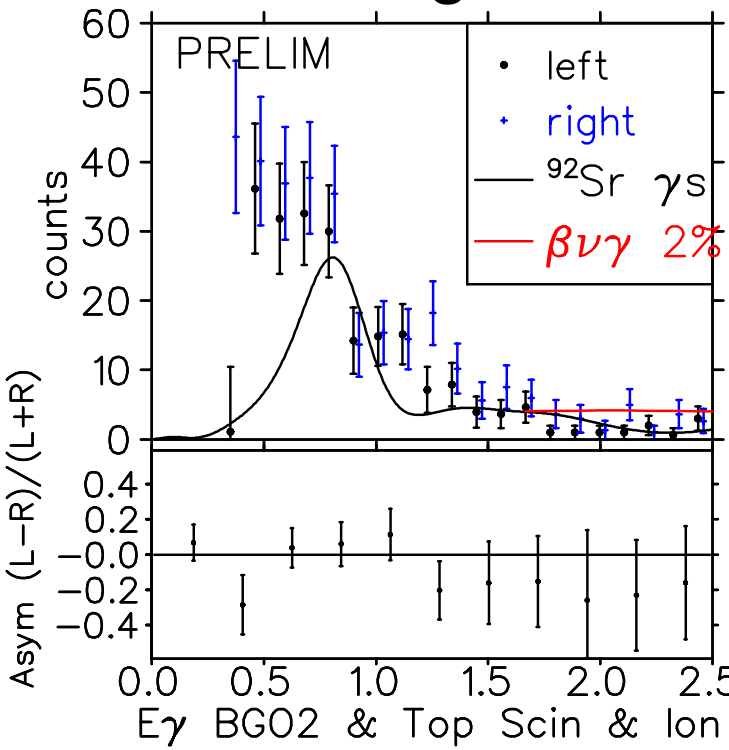
$\beta^- \cap {}^{92}\mathrm{Sr}^+$

'left' vs. 'right':



$\beta^- \cap {}^{92}\mathrm{Sr}^+ \cap \gamma$

'left' vs. 'right':



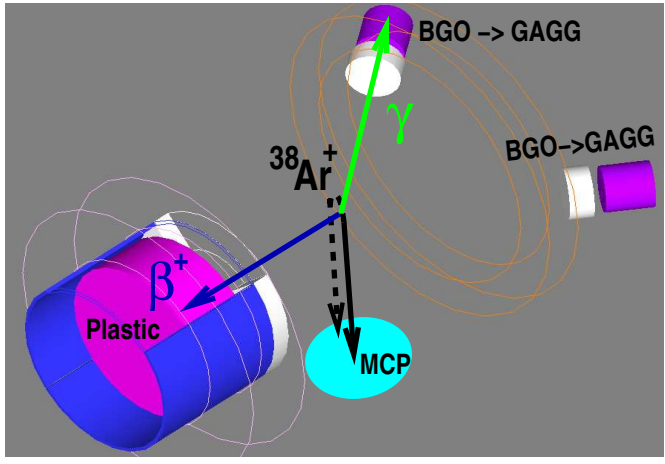
Sensitivity to
$\lesssim$ 2 % $\beta\nu\gamma$ branch
Asym of bkg is tricky

BGO $\rightarrow$ GAGG ($Ce:Gd_3Al_2Ga_3O_{12}$)

- **better E_γ resolution and timing, ρ= 6.6 g/cm^3**
- **not radioactive like LYSO**

Summary $\not{T}$ $\beta\nu\gamma$

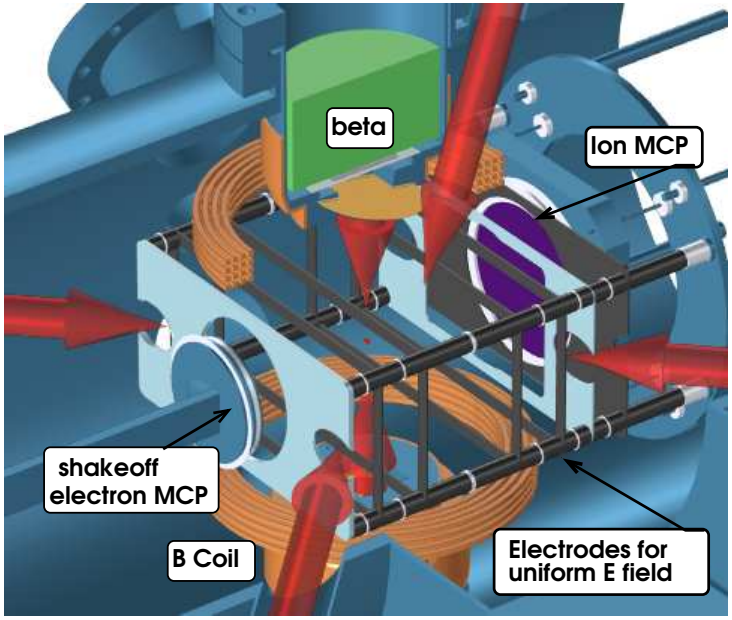
- Few direct constraints from other observables
- Unique to 1st generation of particles, complementary to
  $K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma$
  INR Moscow 2007,
  $A_{TRV} = -0.015 \pm 0.021$

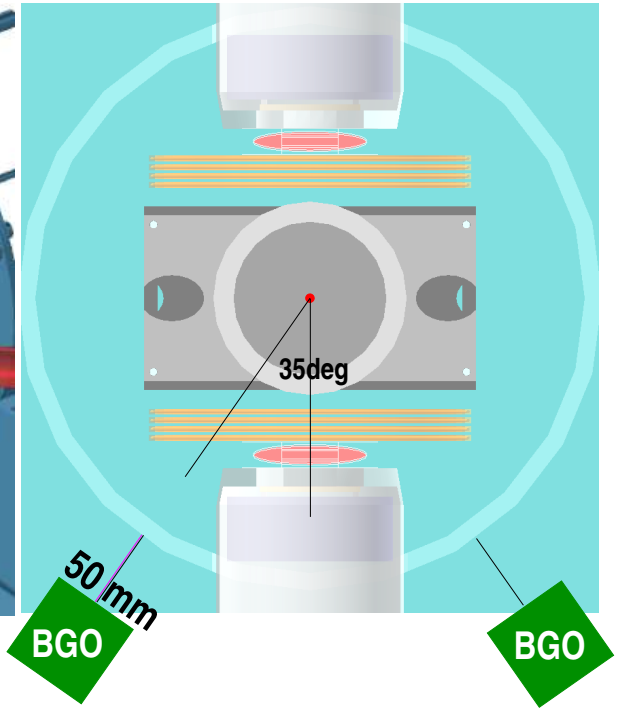


- We're adding γ's to TRINAT's $\beta\nu$ detection
  ^{92}Rb $0^- \rightarrow 0^+$ test:
  Possible sensitivity to $\not{T}$ pseudoscalar
  A dedicated geometry may be justified

Vector current mechanism of Gardner, He:
Projected: sensitivity to $\sim$ 5% of SM bremsstrahlung
$\rightarrow \sim$ 5 to 10% on $\not{T}$ asym for ^{37}K

Geometry: simplest addition to TRINAT





- **Added BGO detectors with SiPM readout**

Tested symbiotic with ^{92}Rb ν spectrum Sep 2018

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	$LaBr_3$	0.26	0.13
Bright, low Z	NaI	0.26	0.10
90ns, 50K γ/MeV	GAGG	$\sim$0.4	$\sim$0.2

GAGG is not naturally radioactive

$\not{T}$ 3-momentum correlations: 2nd, 3rd generation

- $K^- \to \pi^0 e^- \bar{\nu}_e \gamma$ **INR Moscow 2007,**
$A_{TRV} = -0.015 \pm 0.021$
final-state effects small Khriplovich+Rudenko
1012.0147 Phys Atomic Nuclei 2011

- **3-momentum correlations (no γ) at LHCb and BABAR, 0 ± 0.003 (Martinelli arXiv 1411.4140)**

Proposed $\not{T}$ in $\pi^\pm \to e^\pm \nu e^+ e^-$ [Flagg Phys Rev **178** 2387 (1969)] never done:
Ours would be unique measurement in 1st generation of particles

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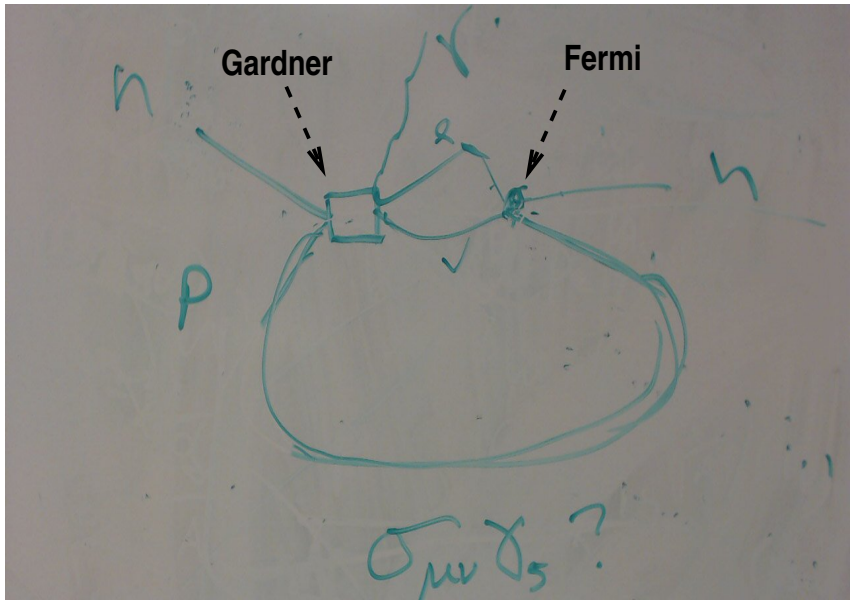
$\not{T}$ radiative β decay and EDMs amend **

No spin → different physics at lowest order, but



Ng, Vos private comm.:
'Im(c_5)' interaction
+ S.M. β decay
→ n EDM at 2 loops

'Naive Dimensional Analysis':

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

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

$d_n[\mathrm{exp}] < 3 \times 10^{-26}$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

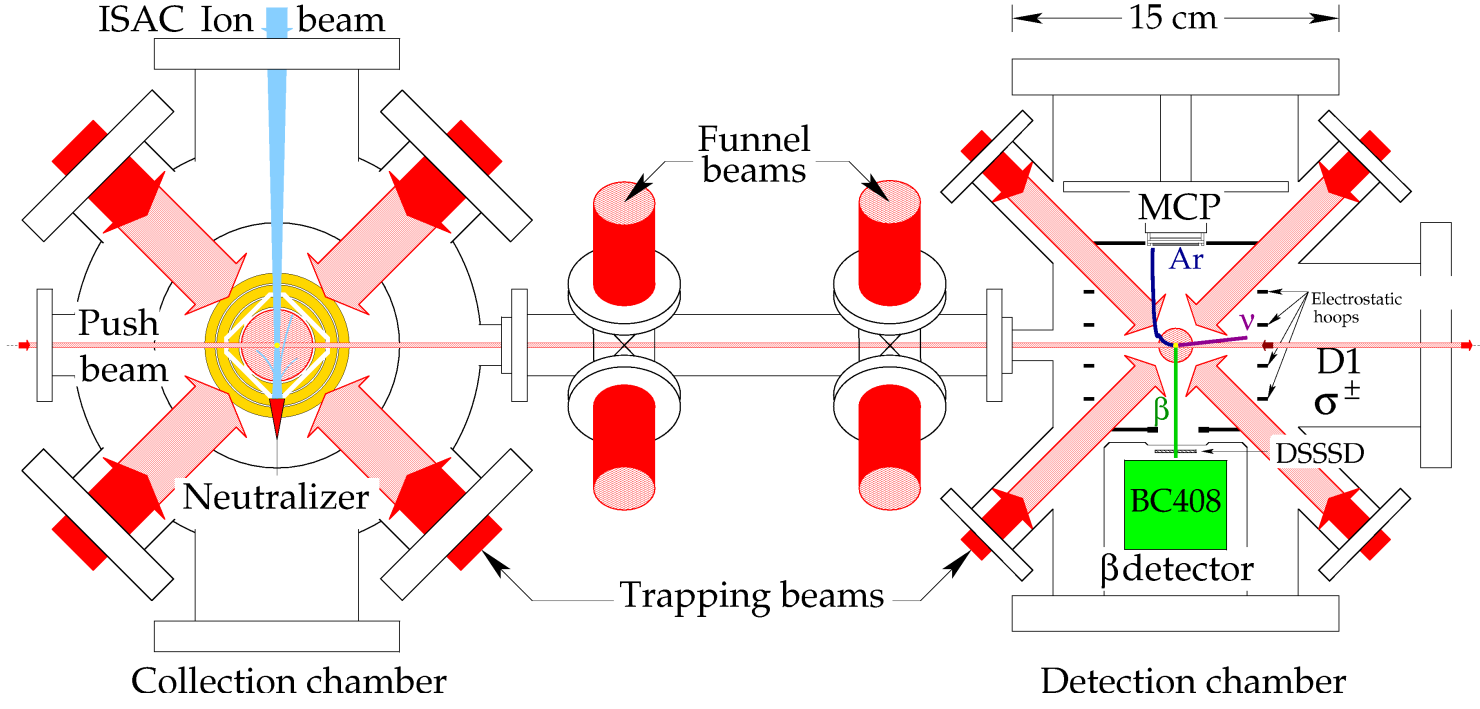
Since n_{edm} usually targets other physics, it would be good to know independently if this is there

** Loop integral momenta must stay below EFT scale M, so using m^5_{nucleon} likely overestimates by orders of magnitude

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

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

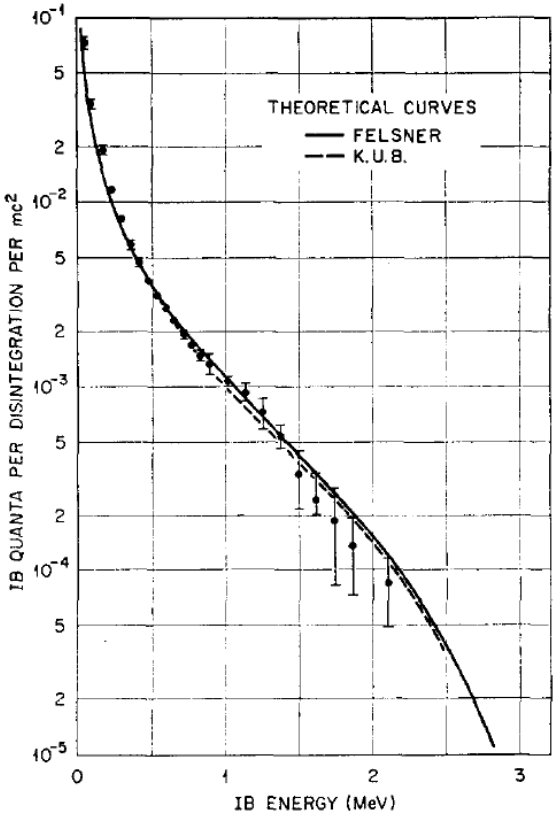
0.01 β detection ϵ
0.15 Ar ion fraction
0.5 MCP ion ϵ
0.8 Counting duty cycle (Polarized+Unpolarized)
ISAC 4x more ^{38m}K



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)

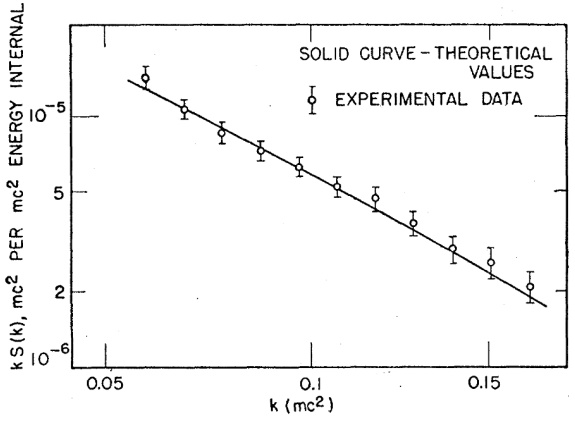
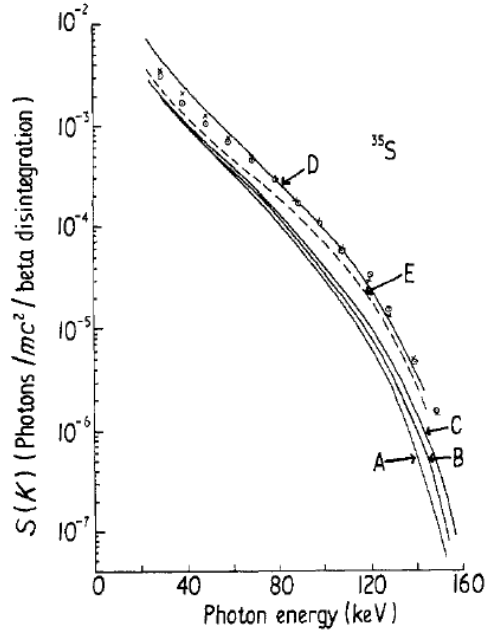


FIG. 3. Internal bremsstrahlung of S^{35}.

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

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

$\rightarrow 10^{-10}$ asymmetries if constants ~ 1.
Also generates EDMs $\Rightarrow$ constants ~ 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 $\sim p^2_{\text{lepton}}/\text{scale}^2$.

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.

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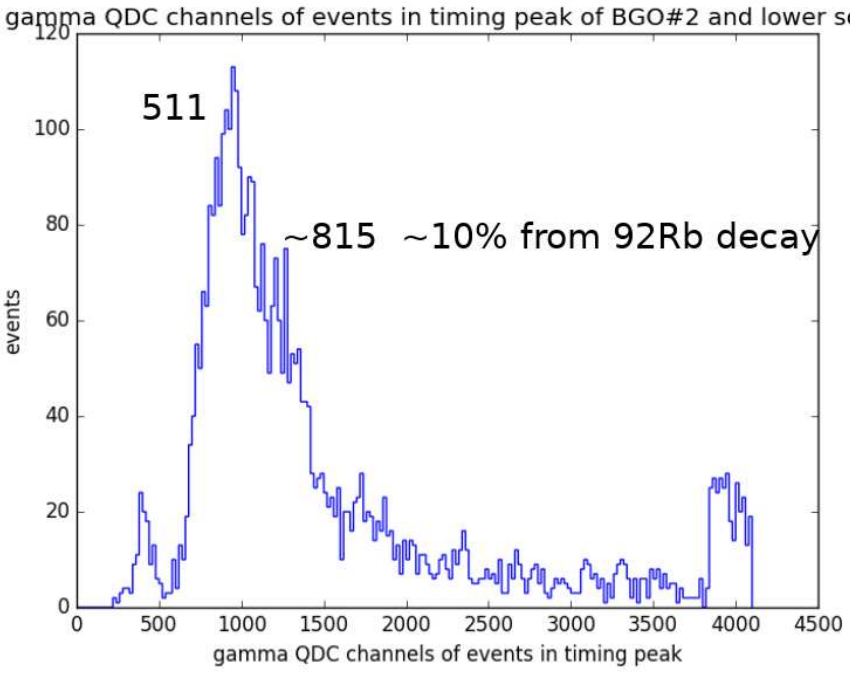
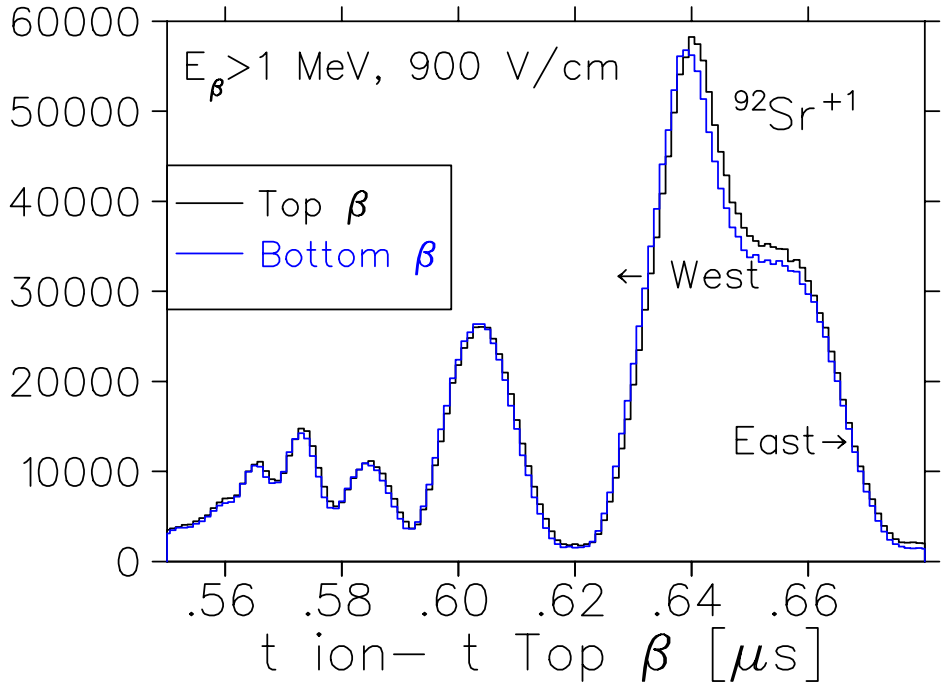
Test with ^{92}Rb $0^- \rightarrow$ ^{92}Sr $0^+ + \beta^- \nu \gamma$





Online analysis β-γ doubles:

511 keV from E&M showers

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

Left and right-going ions

Ion TOF spectrum similar for top and bottom β