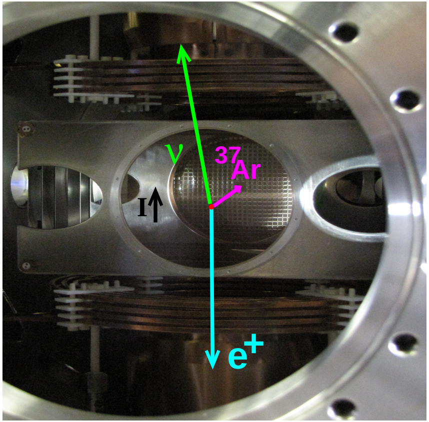
$\not T$ with TRIUMF's Neutral Atom Trap for β decay

- $\vec{p_\nu} \cdot \vec{p_\beta} \times \vec{p_\gamma}$ in $^{37 \text{ or } 38m}$K $\beta\nu\gamma$ decay
  Low-E, Weakly coupled strongly interacting $\not T$
- $D\, \hat{I} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta}$ in isospin-hindered ^{45,47}K decay
  Parity even, isospin-breaking $\not T$ in final nucleus
- Technical: optical pumping of ^{37}K
  99.1$\pm$0.01% + Thin mirrors, improved σ^+...
- ~~A_β, A_{recoil} in ^{37}K decay~~



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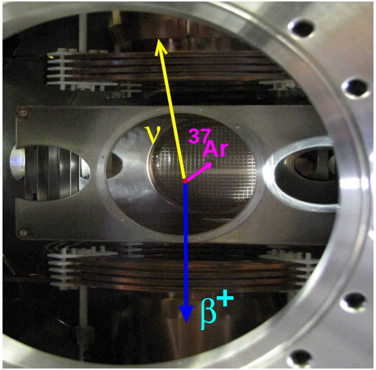
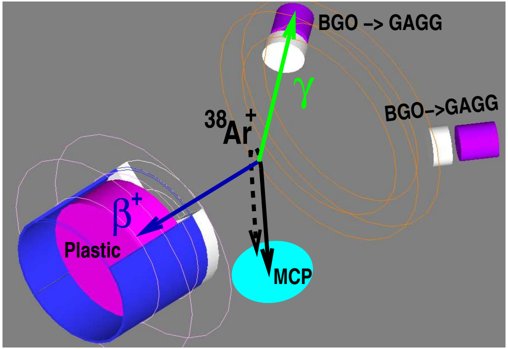
3-momentum $\not T$ correlation: Our example

When t → -t :

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

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





- **We can test symmetry of apparatus with coincident pairs**
- **Not exact: outgoing particles interact → 'final-state' fake $\not T$**

3-momentum $\not{T}$ correlations in 2nd, 3rd generations

- **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 γ) at LHCb and BABAR, 0 ± 0.003 (Martinelli arXiv 1411.4140)**
- **General formalism for triple product momentum asymmetries Bevan 1408.3813**

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

Ours would be unique measurement in 1st generation of particles

TRIUMF

Motivation $\not{T}$ in $\beta\nu\gamma$ decay

- Once P was found to be maximally broken, many spin-dependent T-odd observables were proposed and measured to be $\lesssim 10^{-3}$ like

$$D\hat{\mathrm{I}} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta} \quad R\vec{\sigma}_\beta \cdot \hat{\mathrm{I}} \times \frac{\vec{\mathrm{p}}_\beta}{E_\beta}$$

- In contrast, our type of $\not{T}$ needs 3 independent momenta. E.g. proposed $\not{T}$ in $\pi^\pm \rightarrow e^\pm \nu e^+ e^-$ [Flagg Phys Rev 178 2387 (1969)] was never done:
- Our exp. would be unique to 1st generation of particles

Harvey Hill Hill PRL 99 261601 (2007);

EFT with SM interactions combined in the nucleon: goal was extra γ production by medium-energy ν's

QCD Weak E&M

$\downarrow$ $\downarrow$ $\downarrow$

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

Gardner, He PRD 2013: looked for contributions to radiative n decay. Noticed QCD antisymmetry led to a scalar triple product of momenta 🙂:

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

Needs non-SM QCD-like physics, scale $M \sim$ 10's of MeV

Gardner further considered explicit models with new particles weakly coupled to SM, strongly interacting among themselves

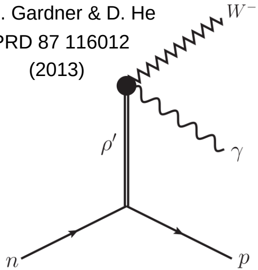
Gardner's interaction needs Vector current $\Rightarrow$ β^+ emitter

- 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.

Though $\vec{p_\nu} \cdot \vec{p_\beta} \times \vec{p_\gamma}$ doesn't involve spin, EDM's indirectly constrain:

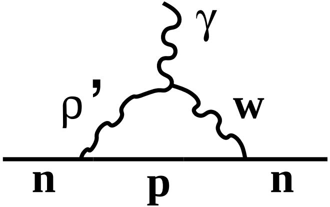
Some *TRV* $\gamma\beta\nu$ interactions, e.g. :

S. Gardner & D. He PRD 87 116012 (2013)



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 $\sim 10^8$.**

$\rightarrow$ ***TRV* $\beta\nu\gamma$ from such interactions likely too tiny to measure** ☹

- **Other interactions (e.g. leptoquarks) need "2 loops" so generate comparatively tiny nEDM so are less constrained, could generate *TRV* $\beta\nu\gamma$ large enough to measure** ☺

Other constraints

- **Direct constraint from n $\rightarrow$ 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})

$\Rightarrow \frac{\mathrm{Im}(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ **^{37}K *TRV* asym can be ~ 1** ☺

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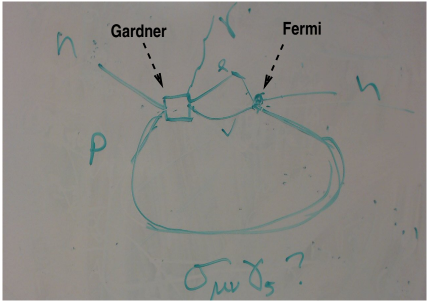
More general 2-loop: EDMs and $\not{T}$ radiative β decay

No spin involved, so again 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 **

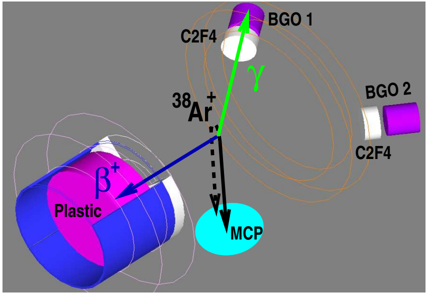
We could still reach this sensitivity and measure this physics directly

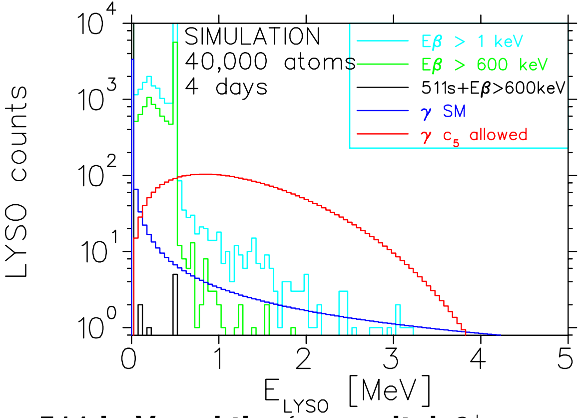
[Some $\gamma\beta\nu$ interactions make at 1 loop a neutron EDM]

** Loop integral momenta must stay below EFT scale M, so if $M \sim$ 100MeV, using m^5_{nucleon} likely overestimates by orders of magnitude

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 $\propto E_\gamma(Q - E_\gamma)^3$ Bernard PLB 593 105 (2004)**





Sim suggests sensitivity to $\sim$ 5% of classical bremsstrahlung rate

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

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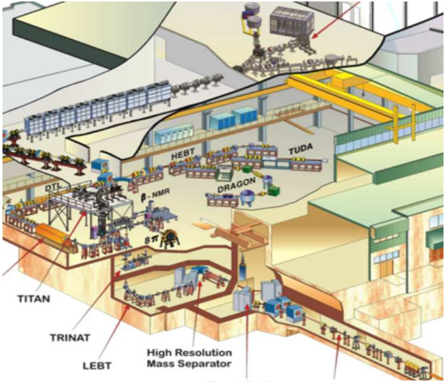
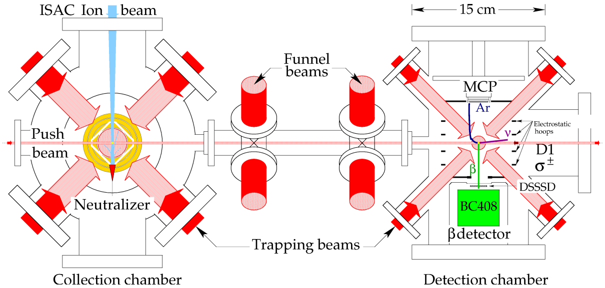
TRIumf Neutral Atom trap at ISAC

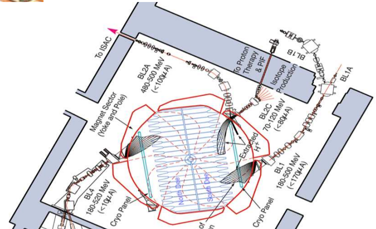




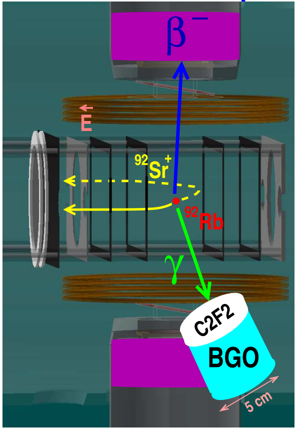
900°C Zr catcher release 0.5, 5×10^{-4} Collection
0.75 Transfer efficiency $\rightarrow$ 10^4 atoms ^{37}K

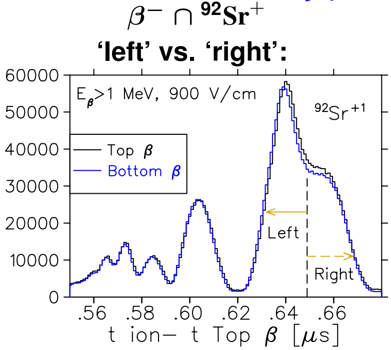
^{37}K TiC target 70 μA
8x10^7/s 1750^{o}C protons

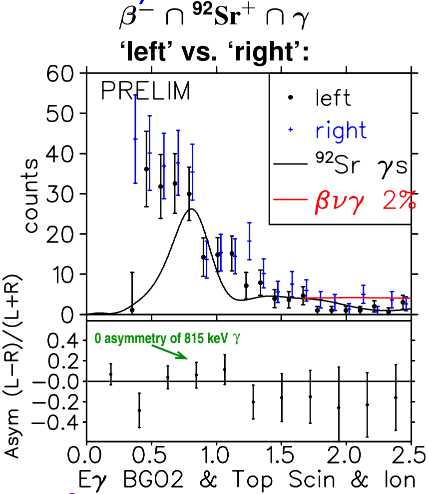
main TRIUMF cyclotron
'world's largest' 18 m
500 MeV H^- (0.5 Tesla)



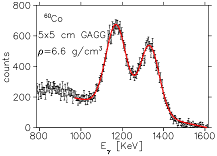
TRIUMF Test experiment in ^{92}Rb $0^- \to 0^+$ decay (no vector current) + BGO → GAGG







(other γ detector sees background from upstream)



BGO → GAGG (Ce:$Gd_3Al_2Ga_3O_{12}$)

- better E_γ resolution and timing, ρ= 6.6 g/cm^3
- Good photopeak efficiency (55% at 1 MeV)
- not radioactive like LYSO

Sensitivity to ∼ 0.05 to 0.10 asymmetries of few percent branches

Constrains T̸ pseudoscalar? (g_P = **350** (Gonzalez-Alonso+Camalich PRL 2014))

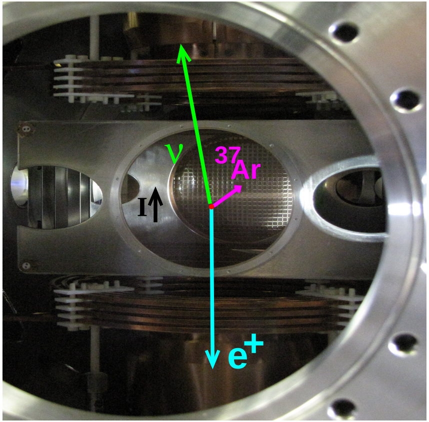
TRIUMF $\not{T}$ in isospin-hindered $^{45}_{19}$K β^- decay

Enhancements to some sources of *TRV* for observables "*D*" and "E_1":
Barroso and Blin-Stoyle PLB 1973

One E_1 measurement: ^{56}Co Calaprice, Freedman 1977

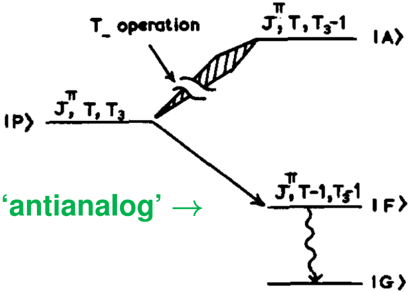
This is pre-proposal. Our goal: find an enhanced D measurement case for

TRIumf Neutral Atom Trap (TRINAT):



Enhancement of $\not{T}$ in isospin-hindered β^- decay

Barroso and Blin-Stoyle, PL 45B 178 (1973):



'antianalog' $\rightarrow$

Observables:

$D\ \hat{I} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta}$

$E_1\ (\hat{I} \cdot \hat{k_\gamma})(\hat{I} \cdot \hat{p_\beta} \times \hat{k_\gamma})$

D, E_1 are both $\propto$

$$K = \frac{Im(G_V G_A^* M_V M_A^*)}{|G_V|^2|M_V|^2 + |G_A|^2|M_A|^2}$$

$$K = \frac{y}{(1+y^2)} \sin(\alpha_V - \alpha_A)$$

with $y = \frac{g_V|M_V|}{g_A|M_A|}$

In this system,

$$\tan \alpha_V = -i \frac{\langle F|V_{\not{T}}|A\rangle}{\langle F|V_{\mathrm{Coul}}|A\rangle}$$

So for *TRV* physics mixing $|F\rangle$ with $|A\rangle$, then $V_{\not{T}}$ is only competing with V_{Coul}, not V_{strong},

enhancing α_V by $\sim 10^3$ ☺

M_A can't be too small (want $y \approx 0.1$) or α_A can cancel

Simplest I.M.: $M_V \sim \sqrt{2T} \frac{\langle F|V_{\mathrm{coul}}|A\rangle}{\Delta E_{\mathrm{FA}}} \Rightarrow K \overset{y \to 0}{\sim} \frac{\langle F|V_{\not{T}}|A\rangle}{\Delta E_{\mathrm{FA}}} \frac{\sqrt{2T}}{M_A}$ **independent of $\langle F|V_{\mathrm{coul}}|A\rangle$ ☹?**

so we should choose good $\frac{y}{1+y^2}$ so α_V remains the figure of merit ☺

TRIUMF

*P*arity even, N-N isospin-breaking $\not{T}$: complementary to Parity odd EDM's or $\not{T}$ neutron resonance experiments?

Volume 45B, number 3 PHYSIC

The following simple phenomenological form is assumed for the T-violating potential [e.g., 19]

$$V_{\mathrm{t.v.}} = G_{\mathrm{t.v.}} \tfrac{1}{2}[f(r)\hat{r}\cdot p + \mathrm{h.c.}]$$

$$\times [1 + a\,\sigma^{(1)}\cdot\sigma^{(2)})(\tau_3^{(1)} + \tau_3^{(2)}) \qquad (11)$$

$$+ (b + c\,\sigma^{(1)}\cdot\sigma^{(2)})\tau_3^{(1)}\tau_3^{(2)}]$$

- **Other physics:** When GT is weak, 2nd-class induced semileptonic $\not{T}$ tensor d_{II} can disproportionately interfere (Kim+Primakoff PR 180 1502 (1969); J. Mortara Ph.D. thesis 1992)

“Test of time-reversal invariance in the beta decay of ^{56}Co”

Asymmetry of the 45° γ detectors with nuclear alignment

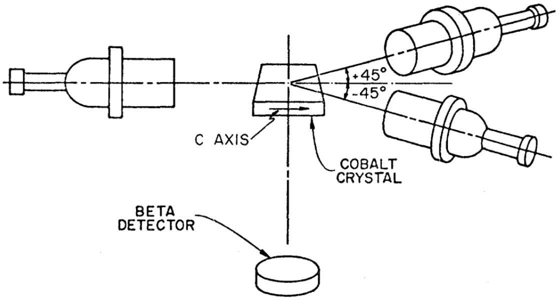


FIG. 3. A schematic representation of the detector geometry showing the three NaI γ detectors in the horizontal plane of crystal at angles of $-45°+45°$, and 180° to the c axis of the cobalt crystal. The β detector is located below the crystal.

Calaprice, Freedman, (Princeton); Osgood, Thomlinson (BNL)

PRC 15 381 (1977)

E_1 = -0.01 $\pm$ 0.02

log(ft) = 8.7 (E_β spectrum, no β-γ correlation $\Rightarrow$ still allowed!)

y = -0.13$\pm$0.02 just right

Markey and Boehm PRC 26 287R (1982)

V_{Coul}= 2.9 keV, $V_{TRV} = 54 \pm 110$eV

(J.L. Mortara Ph.D. thesis 1992 UCB $E_1 = -0.001 \pm 0.006$)

JB can’t find theory papers citing these results ☹

A dozen measurements of M_V, $\langle F|V_{\rm coul}|A\rangle$

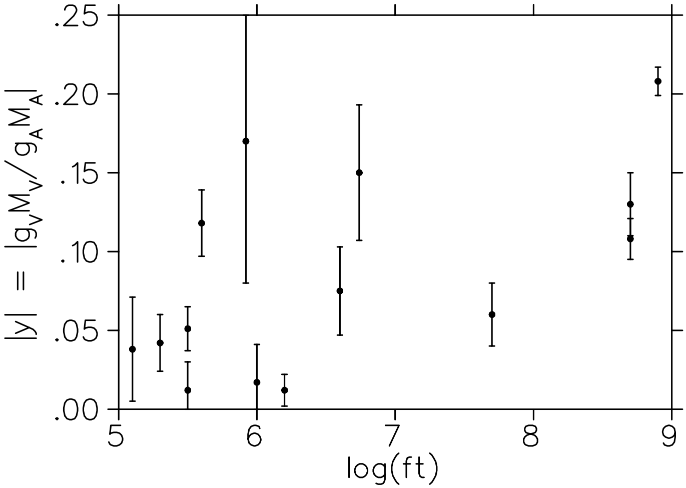
Physics community has pushed to find good $\not{T}$ cases

Mostly β-γ circular polarization correlation

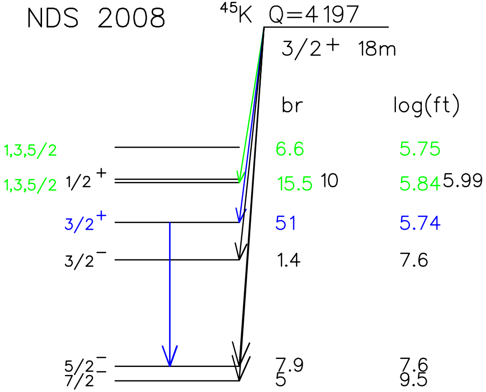
Atkinson NPA114 143 (1968);
Mann PR 137 B1 (1965) ;
Behrens ZfP 201 153 (1967)

Hints of a correlation between $|M_V|$ and $|M_A|$ for these 'antianalog' configurations: $|M_V|/|M_A|$ not changing much as $|M_A|$ falls

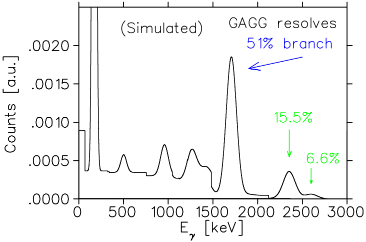
^{57}Fe $V_{\rm Coul}$= 54$\pm$10 keV,
^{56}Co $V_{\rm Coul}$= 2.9$\pm$0.5 keV

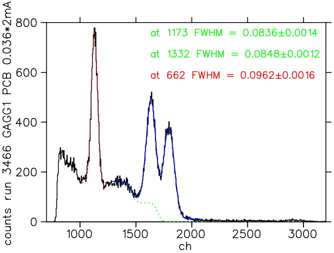


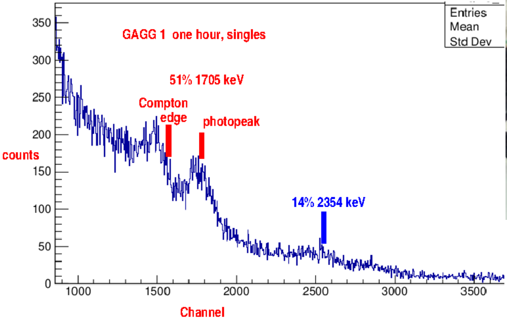
Some ^{45}K details

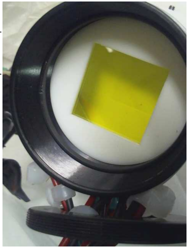


51% branch to 3/2+ state in ^{45}Ca.
Could have a large ‘antianalog’ component,
$\langle F|V_{\mathrm{coul}}|A\rangle \sim$ 5 to 50 keV ?









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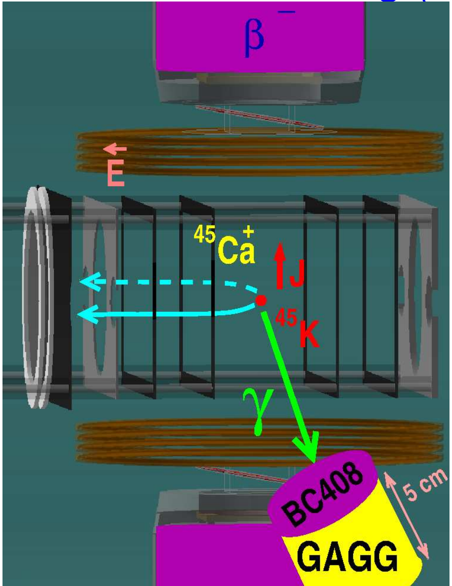
Measuring $\langle F|V_{\mathrm{Coul}}|A\rangle$ in ^{45}K



- $A_{\mathrm{recoil}} \propto A_\beta + B_\nu$

$$A_{\mathrm{recoil}} \overset{p_{\mathrm{recoil}} \gg m_\beta}{=} 5/8(A_\beta + B_\nu)$$

(Depends on recoil energy via predicted kinematics) S. Treiman Phys Rev 1958

- So A_{recoil} = 0 for pure Gamow-Teller

$$A_{\mathrm{recoil}} = 2\sqrt{\frac{J}{J+1}} G_V M_V / G_A M_A$$

linear in M_V / M_A

- Recoil-γ coincidences to select the antianalog

Determination of y with uncertainty $\sim$ 0.02 or better should be possible

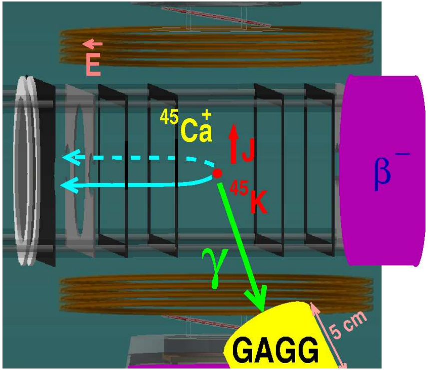
β asymmetry to determine 1/2,3/2,5/2$^+$

(see Pitcairn PRC 79 015501 (2009)

We measured $A_T = 0.015(29)(19)$ for G-T decay of ^{80}Rb)

TRINAT and D

Have considered D in $^{37}\vec{\mathrm{K}} \rightarrow$ ^{37}Ar + β^{+} + ν
5x10^{-4} statistical uncertainty per week of counting is possible.



Hard to compete with n and with ^{19}Ne on the G_V/G_A interference physics
(constrained by Ng-Tulin PRD 2012)

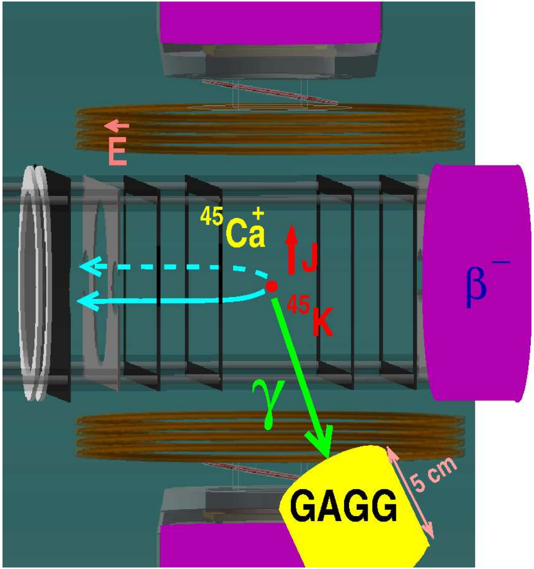
We can get better statistics in ^{45}K, an isospin-hindered case: β^{-} decay always makes a charged recoil for efficient detection.

Uncertainty Projection:
Losing by 10x in sensitivity by $1/M_A$,
given E_1 = -0.01 $\pm$ 0.02 in ^{56}Co,
and winning by isospin sqrt(7/2),
we can get a limit on K by this effect 4x better per week of counting.

How that translates into sin(α_V) and $V_{\not{T}}$ depends on V_{Coul} (2.9 keV in ^{56}Co).

TRIUMF

D in atom trap: Features, Systematics



- Collect recoils going into 4 pi with electric field of 1 kV/cm
- Full reconstruction of recoil and beta momenta
- Point source: we know where it is (by sampling photoionization) and it doesn't move when we flip the polarization
- Any stray polarization along wrong axis is deadly, a lowest-order fake D: Measure with singles asymmetry for recoils and β's

TRIUMF ^{47}K vs. ^{45}K

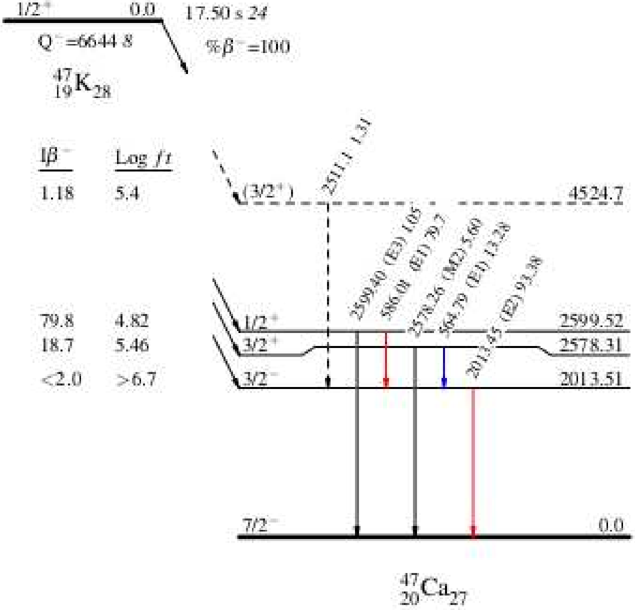
y (Fermi/GT ratio) must be measured

80% branch $1/2^+ \to 1/2^+$

Likely more reliable calculation of final-state D_{EM} is possible

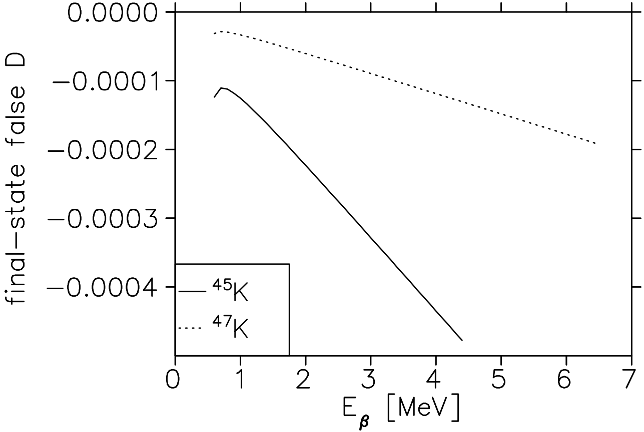
Shorter $t_{1/2}$ → less background from untrapped atoms

10x Faster G-T (s.p. s1/2 5x faster GT than d3/2) may be problematic



TRIUMF

Final-state (false) *D*



Holstein PRC 5 1529 (1972)

- **Assumes weak magnetism *b* and induced tensor *d* are single-particle values, not suppressed like M_A ⇒ Should be an upper limit**
- **Needs a calculation, but should be OK**

For ^{56}Co final-state E_1=0.0002 (Calaprice 1977)

Summary $\not T$ in isospin-hindered $^{45}_{19}$K, $^{47}_{19}$K decay

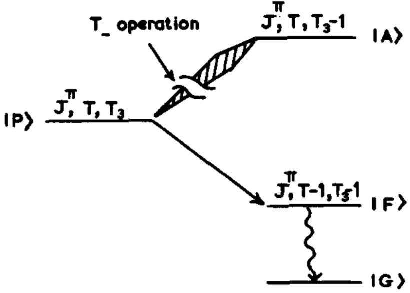
Implementing Barroso and Blin-Stoyle PLB 1973 with TRINAT,

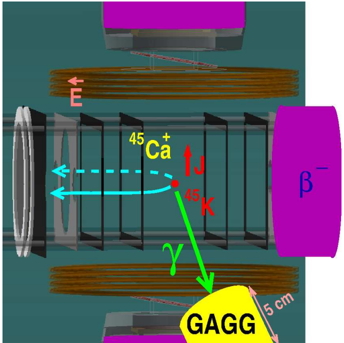
We would measure $D\, \hat{\mathrm{J}} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta}$

Project 5x10^{-4} statistics per week, 4x better precision on observable K than ^{56}Co Calaprice and Freedman

Extracting V_{TRV} needs M_V/M_{GT} to extract V_{coul}, which we would do by the recoil asymmetry wrt spin

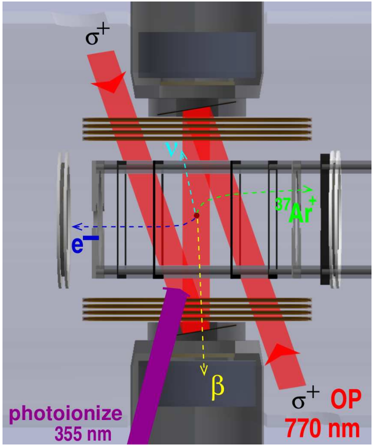
Complementary to other *TRV*:
***P* even, Isovector/tensor N-N *TRV* (evades Ng-Tulin 2012);**
or Semileptonic 2nd-class d_{II} *TRV*





TRIUMF Precision measurement of the nuclear polarization of laser-cooled, optically pumped ^{37}K

- **Motivation: spin-polarized β decay**
- **Direct Optical pumping**
  Our polarization method also provides a continuous probe
  Complication: Coherent population trapping. Easy to kill.
- **Measurement of ^{37}K polarization**



New J. Phys. **18** (2016) 073028

B Fenker[1,2,7], J A Behr[3], D Melconian[1,2,7], R M A Anderson[3], M Anholm[3,4], D Ashery[5], R S Behling[1,6], I Cohen[5], I Craiciu[3], J M Donohue[3], C Farfan[3], D Friesen[3], A Gorelov[3], J McNeil[3], M Mehlman[1,2], H Norton[3], K Olchanski[3], S Smale[3], O Thériault[3], A N Vantyghem[3] and C L Warner[3]

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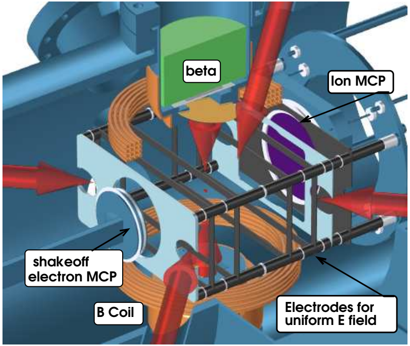
[4] Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2, Canada
[5] School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[6] Department of Chemistry, Texas A&M University, 3012 TAMU, College Station, TX 77842-3012, USA

Our first use: ^{37}K A_{β} Fenker PRL 120 062502 (2018)

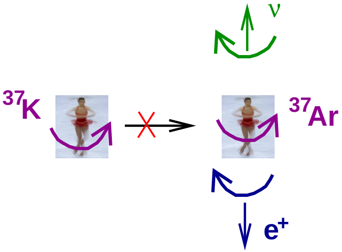
TRIUMF

a different isospin mirror-decay spin-polarized observable



- 10,000 atoms trapped
- *P* measured in-situ on ^{37}K by atomic method
- ion + shakeoff e$^-$ for $A_{\rm recoil}$

Isobaric mirror decay has helicity-driven null

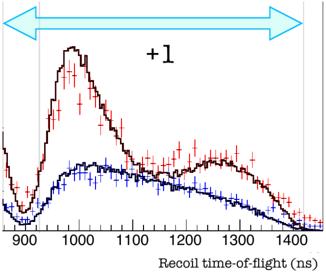


$W(\theta,P) \approx 1 + a_{\rm pol} \cos(\theta_{\beta\nu})$

with $a_{\rm pol} = (A_\beta - B_\nu)P - a_{\beta\nu} + 2c/3$

$= 1$ or 0, indep of $\frac{M_{GT}}{M_F}$

2014 polarized β-recoil



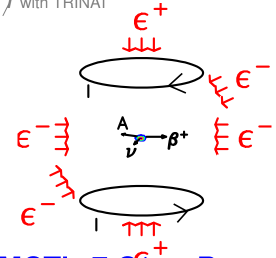
a_{pol} is an elegant observable, but we may always be statistics-limited– we push upgrades of singles A_β and A_{recoil}

The neutron community checks this combination of observables for consistency

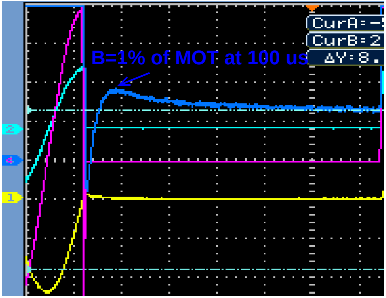
Mostovoi+Frank Pis'ma Zh. Eksp. Teor. Fiz. 24 45 (1976)

TRIUMF

AC MOT to turn off Bquad

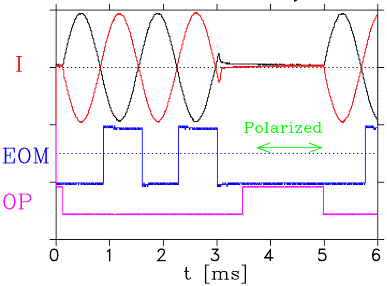


MOT's 7 G/cm Bquad off to 1% of its value in 100 μs:



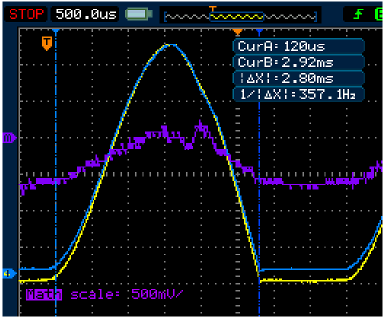
M. Anholm M.Sc. UBC 2011

Turn off MOT of 2 ms, OP:



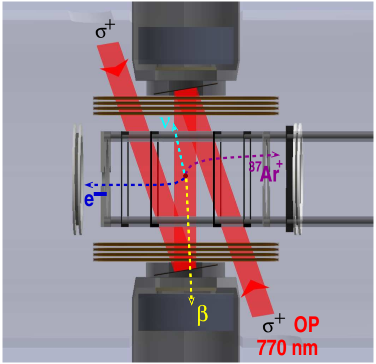
Inductively heats detectors to 40-60 °C

Presently trying $\omega/2$ →



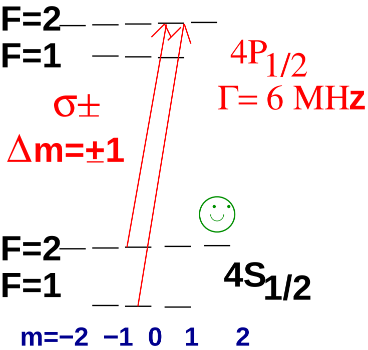
To remove longer-time eddy current buildup, need to invert this once

Direct Optical Pumping, I=3/2



- **Biased random walk**
- **$\sigma^{\pm}$ light $4S_{1/2} \to 4P_{1/2}$ transition**

The same light creates the polarization and probes it nondestructively



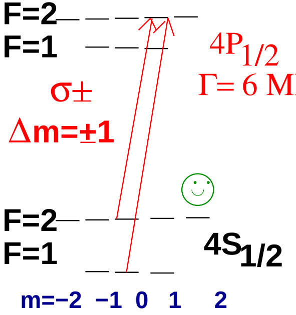
- **optimize with ^{41}K, almost same hyperfine splitting as ^{37}K**

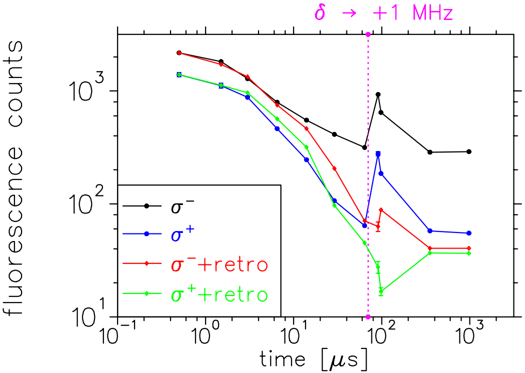
$\vec{F} = \vec{J}_{\mathrm{atom}} + \vec{I}_{\mathrm{nucleus}}$ $\quad H_{\mathrm{hyperfine}} = - \vec{\mu}_N \cdot \vec{B}_e = A\, \vec{I} \cdot \vec{J}$

Spin flips: $\sigma^+ \to \sigma^-$;
small frequency shift (-2 MHz) to compensate Zeeman shift

TRIUMF

Coherent Population Trapping is bad for us

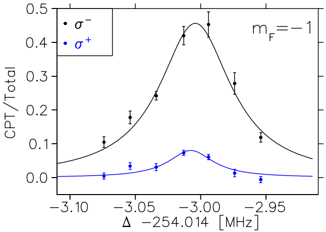


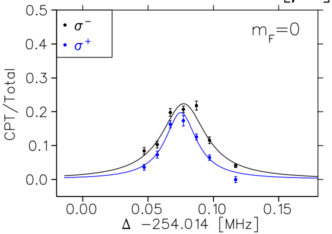


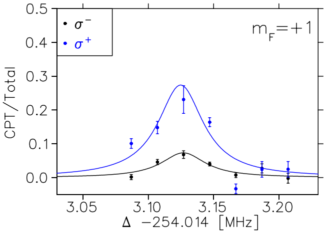
But easy to remove by counter-propagating beams and by RF detuning

⇒

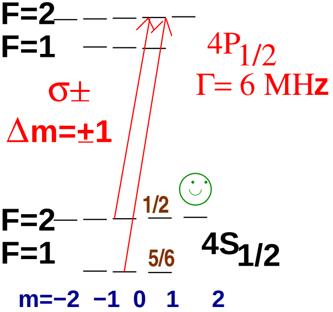
B_z = 2.339(10) G







Quantifying ^{41}K polarization from excited state population



Same centroid P 2 ways:

Rate eqs for populations

$$\frac{dN_i}{dt} = -R_{ji}N_i + R_{ij}N_j + \lambda N_j$$

Optical Bloch Eqs include $B_\perp$ rigorously

$$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H,\rho] + \lambda$$

Tail ∼ few % of peak ⇒

We need tail/peak to ∼ 10% accuracy to extract P to ∼ 0.1%

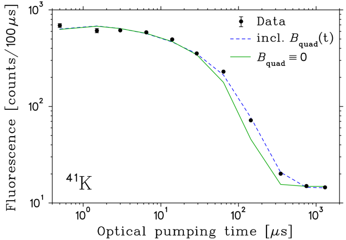
We can't quite extract P by inspection:

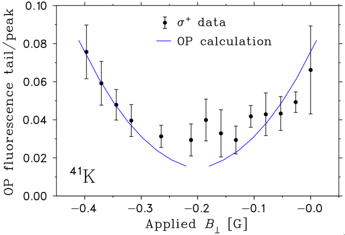
- **Nuclear polarization is different in $F = 2, m_F = 1$ vs. $F = 1, m_F = 1$**

$\Delta F = 0$ for Larmor precession

We measure S_3 and float $B_\perp$ (S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5))

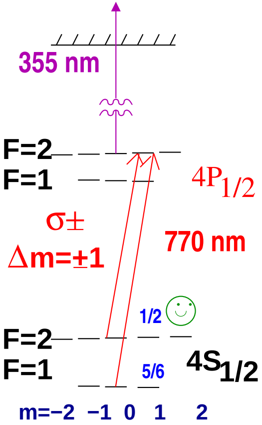
Fenker PRL 2018 Suppl Mat





Optical pumping and probing ^{37}K

TEXAS A&M UNIVERSITY

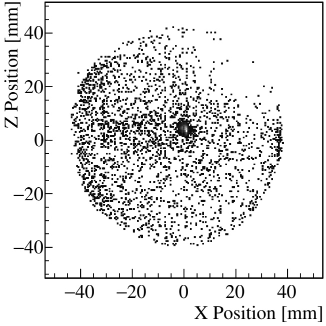


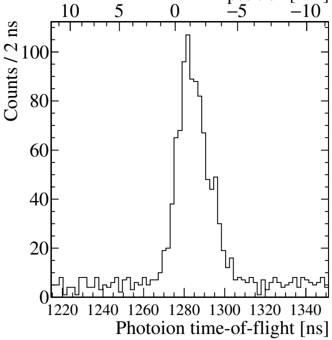
1 of 10 data sets

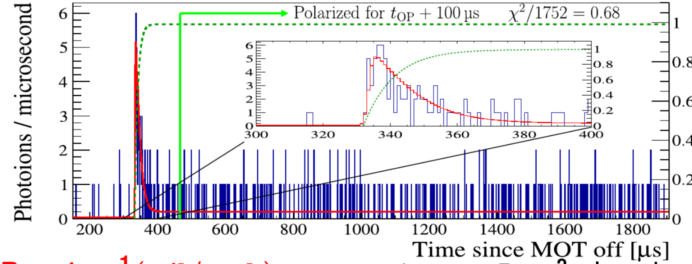
Photoionize 1% *in situ* **probe**

P_+=+0.9913(8) P_-=−0.9912(9)

Fenker NJP 2016

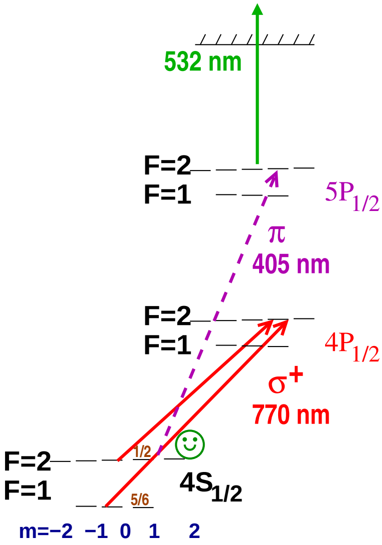






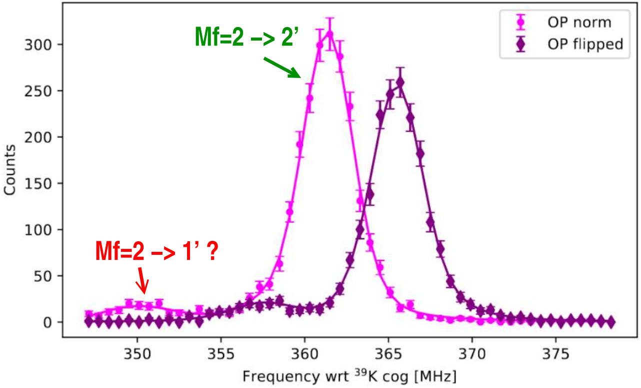
$P \approx 1 - \frac{1}{3}(\text{tail}/\text{peak})$ unpumped atoms $P \sim \frac{2}{3}$ already

In progress: More direct probe of ^{41}K population



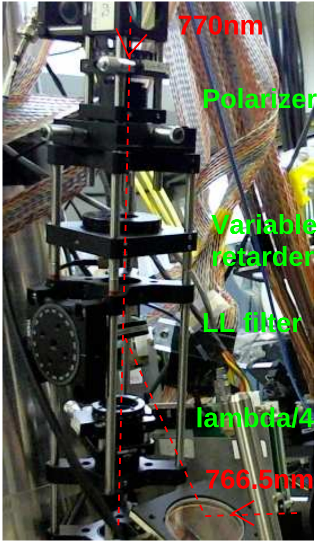
Our ^{37}K probe is in situ and nondestructive, but as a 1-parameter fit could use confirmation.

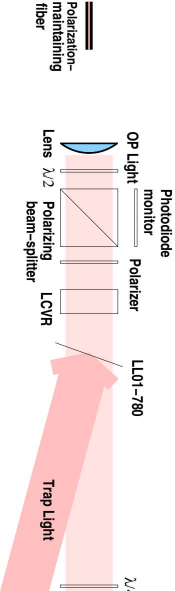
- **$4S_{1/2} \to 5P_{1/2}$ has 1.1 Mhz FWHM, so resolves m_F levels split by our 2 Gauss Bz holding field**
- **Destructive and alters *P* but still provides useful info**



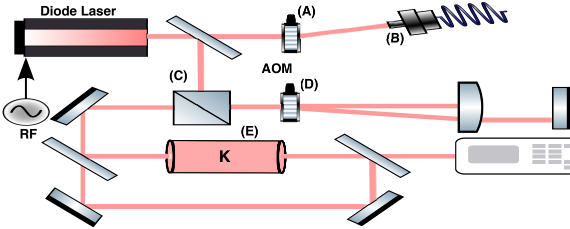
TRIUMF

Optics Techniques





- Combine 769.9nm D1 and 766.49 D2 with angle-tuned 780 nm laser-line filter
- Flip spin state with liquid crystal variable retarder $\rightarrow$ twisted nematic l.c.
- Relieve stress-induced birefringence with PCTFE (Neoflon) viewport seals
- RF injection to generate the two ν's $\rightarrow$ fiber-coupled EOM



Polarization Improvements

SYST $\times 10^{-4}$	ΔP σ^-	ΔP σ^+	ΔT σ^-	ΔT σ^+	Fixes
Initial T	3	3	10	8	Measure it
Global fit v. ave	2	2	7	6	More 355nm
S_3^{out} Uncertainty	1	2	11	5	Better: TnLC
Cloud temp	2	0.5	3	2	
Binning	1	1	4	3	More 355nm
B_z Uncertainty	0.5	3	2	7	
Initial P	0.1	0.1	0.4	0.4	
Require $\mathcal{I}_+ = \mathcal{I}_-$	0.1	0.1	0.1	0.2	
Total SYSTEMATIC	5	5	17	14	
STATISTICS	7	6	21	17	More 355nm

B. Fenker New J. Phys 18 073028 2016

$P(\sigma^+) = +0.9913(8)$ $T(\sigma^+) = -0.9770(22)$

$P(\sigma^-) = -0.9912(9)$ $T(\sigma^-) = -0.9761(27)$

0.25 mm SiC-backed mirrors $\rightarrow$ pellicles for less β^+ scattering

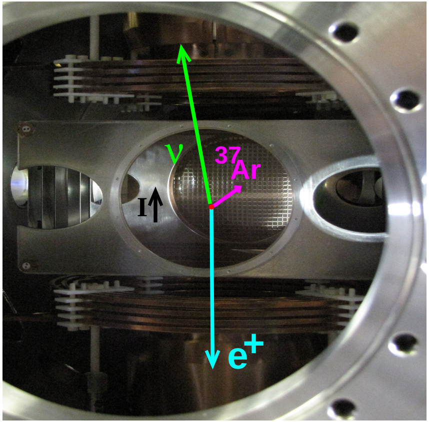
Stern Family of National Photocolor

70nm Au + 4μ Kapton 5λ flatness

- PCTFE viewport seals
- Lower-frequency AC-MOT
- Double OP power: fight Larmor precession
- Uncertainty $\propto (1 - P)$ so the better we make P, the smaller its uncertainty

$\not{T}$ with TRIUMF's Neutral Atom Trap for β decay

- $\vec{p_\nu} \cdot \vec{p_\beta} \times \vec{p_\gamma}$ in $^{37 \text{ or } 38\text{m}}$K $\beta\nu\gamma$ decay
  Low-E, Weakly coupled strongly interacting $\not{T}$
- $D\, \hat{\mathrm{I}} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta}$ in isospin-hindered ^{45,47}K decay
  Parity even, isospin-breaking $\not{T}$ in final nucleus
- Technical: optical pumping of ^{37}K
  99.1$\pm$0.01% + Thin mirrors, improved σ^+...
- ~~A_β, A_{recoil} in ^{37}K decay~~



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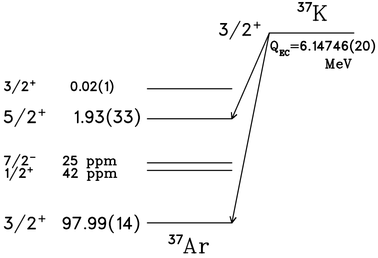
Support: NSERC, NRC through contribution agreement with TRIUMF, US DOE

^{37}K: isobaric mirror decays minimize nuclear uncertainties



$\mathcal{F}t$ (Shidling PRC 2014) $\Rightarrow$

$\rho = C_A M_{GT} / C_V M_F$ = 0.5768±0.0021

$\Rightarrow A_\beta[theory]$ = -0.5706±0.0007

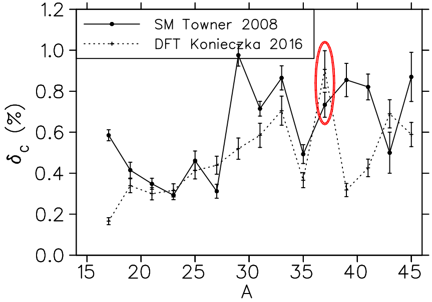
main uncertainty is experimental branching ratio

CVC $\Rightarrow$ most important corrections:

- $\mu \Rightarrow b_{WM}$ (small for $\pi d_{3/2}$)
- Induced tensor $d_1 \approx 0$ for isobaric mirror
- $Q \Rightarrow$ largest 2nd-order recoil + Coulomb + finite-size $\Rightarrow$

$\Delta A_\beta \approx -0.0028\,(E_\beta / E_0)$ Holstein RMP 1975

Deduced V_{ud} from exp A_β agrees with Hayen Severijns arXiv 1906.09870 using Behrens and Bühring



Shell model for isospin mixing $\Rightarrow$ 0.0004 uncertainty

DFT for isospin mixing has improved functional for A∼37

Using weighted average for δ_C would $\Rightarrow$ 0.0004 $\rightarrow$ 0.0005

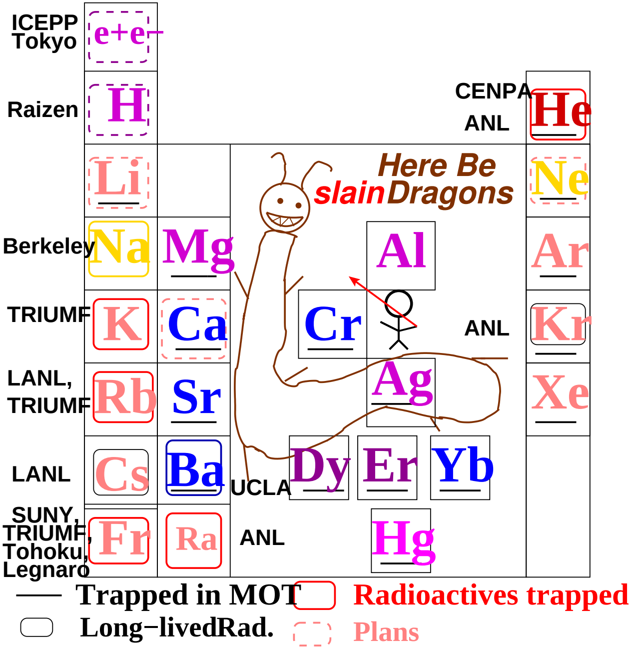
This could use modern theory

Many elements can now be laser trapped

Atoms with simple transitions (allowing ∼10,000 photon momentum transfers to cool) are easiest

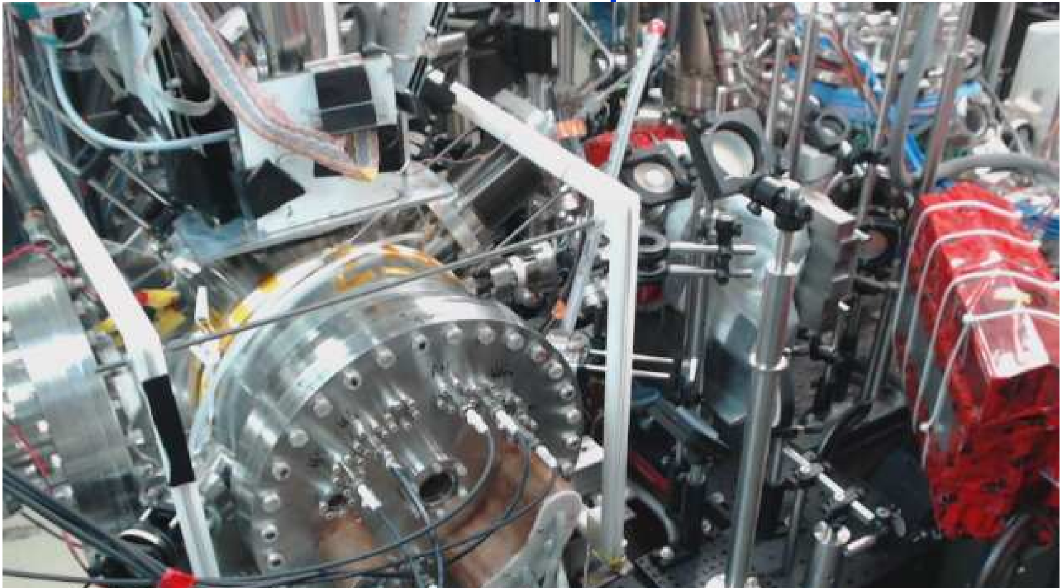
But many are now possible, if you add enough lasers, depending on what efficiency one can accept

Molecules like SrF, CaF, YO have been laser-cooled



TRIUMF

TRINAT lab: “tabletop experiment”



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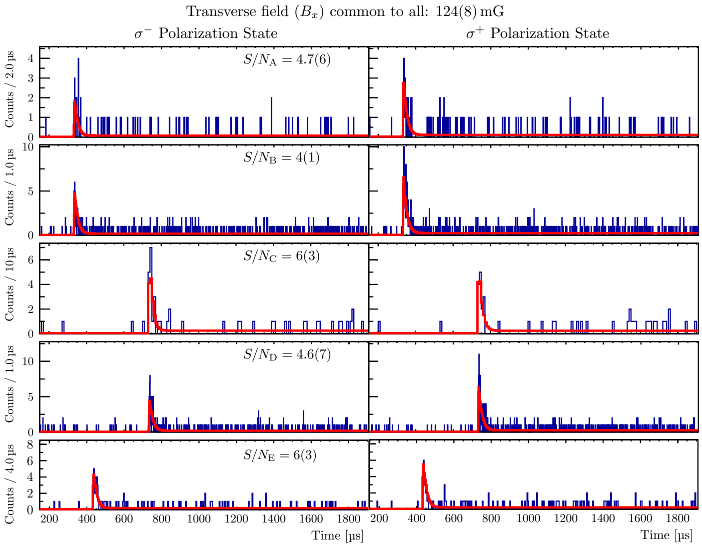
Polarization fit to all ^{37}K data



- **The small unpumped population is pretty well polarized**