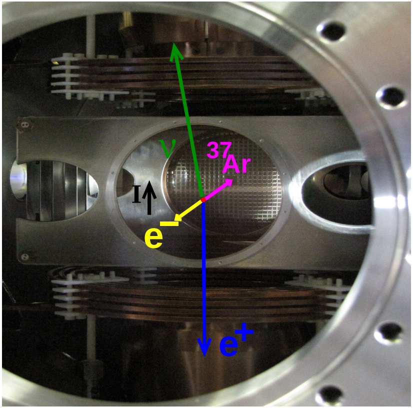
TRIUMF β decay correlations with TRIUMF's neutral atom trap

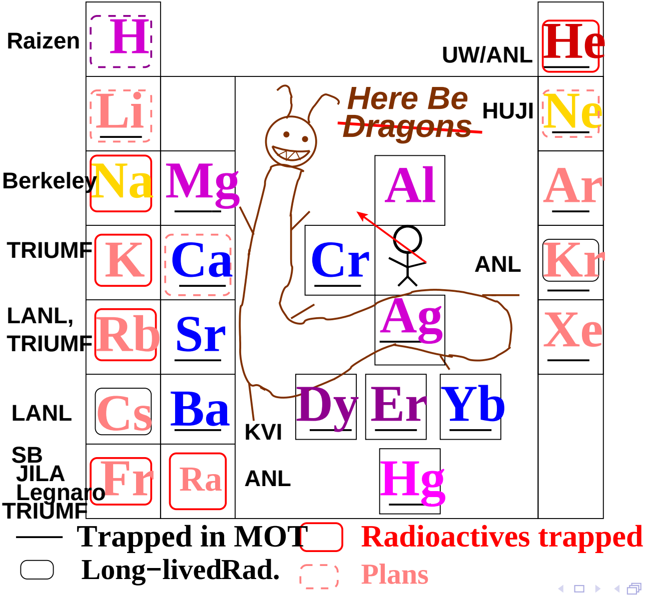
- ^{38m}K β-ν correlation plans
- Polarized atoms and their in-situ measurement (Melconian will detail $^{37}\vec{K}$ correlations)
- Detection of shakeoff electrons



Possible Futures:

- Gardner's $\cancel{T}$ in ^{37}K and $\cancel{^{92}\mathrm{Rb}}$
- D correlation in ^{37}K

What elements can be laser cooled?



TRIumf Neutral Atom Trap collaboration

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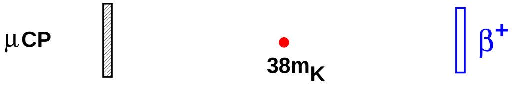
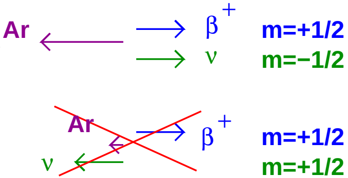
$a_{\beta\nu}$ and Scalar bosons

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



leptons have opposite helicity for W (vector) boson exchange



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

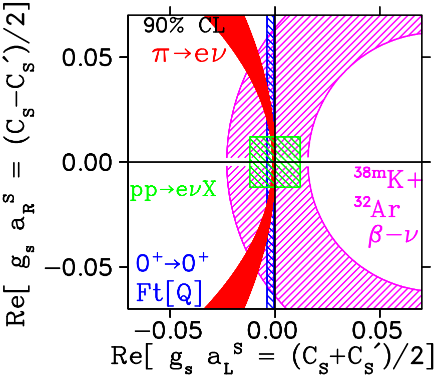
$\Rightarrow$ a = +1, b = 0

- helicity argument independent of isospin mixing
- Radiative corrections (Glück) $2\text{x}10^{-3}$
- recoil order term is $3\text{x}10^{-4}$

$\Rightarrow$ S.M. prediction for *a* does not depend on nuclear structure

For scalar exchange, lepton helicities are same: a= -1

Constraints on scalar interactions



- The best constraints on scalars coupling to ν with standard helicity are from the superallowed *Ft* values.

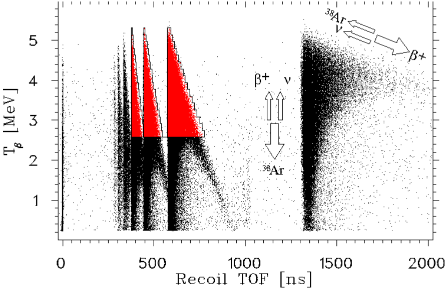
  One goal is to achieve similar sensitivity within one experiment

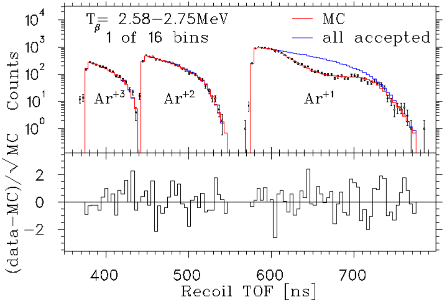
- LHC constraints (p p $\to$ e ν X Cirigliano, González-Alonso, Graessler JHEP02(2013)046 have improved on scalars coupling to wrong-handed ν

  $\pi \to e\nu$ (Campbell Murray NPB 04) will have more accuracy from TRIUMF and PSI soon.

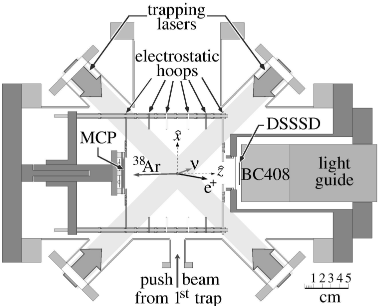
Lighter boson with weaker coupling evades EFT?

TRIUMF ^{38m}K β-ν correlation





β-recoil coincidences



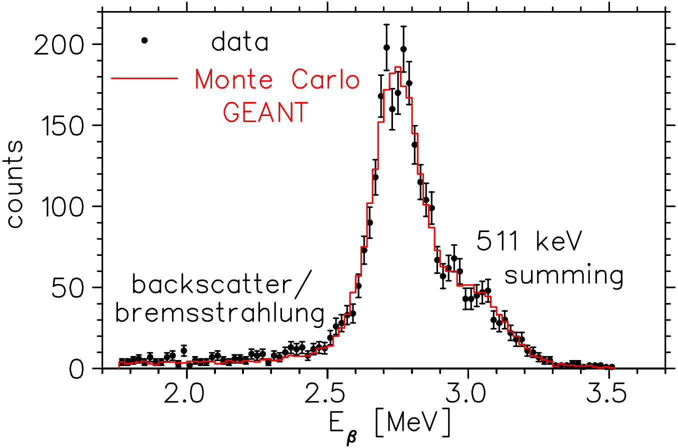
Gorelov PRL 2005

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

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

In-situ calibrations

E_β detector response for "monoenergetic" β's from kinematics of other observables (β-recoil angle and recoil momentum)



TRIUMF

^{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%

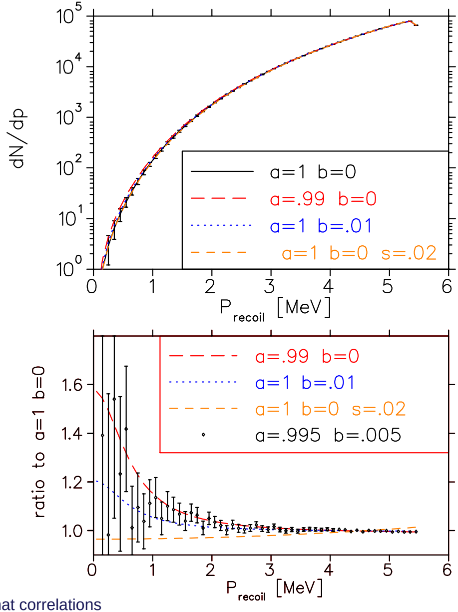
Planned Improvements:

- 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.**

TRIUMF

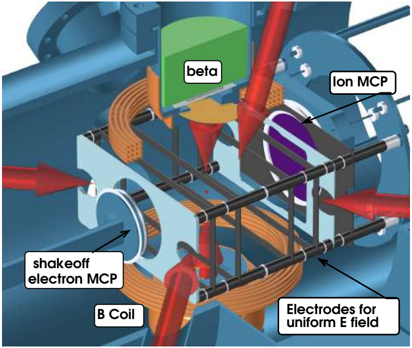
^{38m}K recoil – shakeoff e$-$

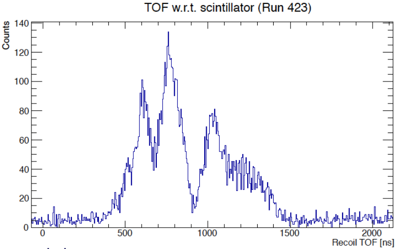


SIMULATION
Recoil momentum spectrum
Sensitive to a or b (highly correlated)
Can extract momentum-dependent shakeoff separately

$\sigma_b \sim$ 0.003 per day
High statistics, though
$\Delta a/a$ is smaller
Look for dimers, as Vetter PRC (2008)

^{37}K spin-polarized experiments

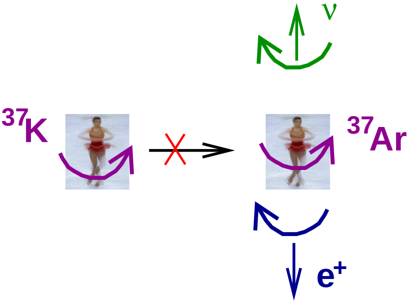


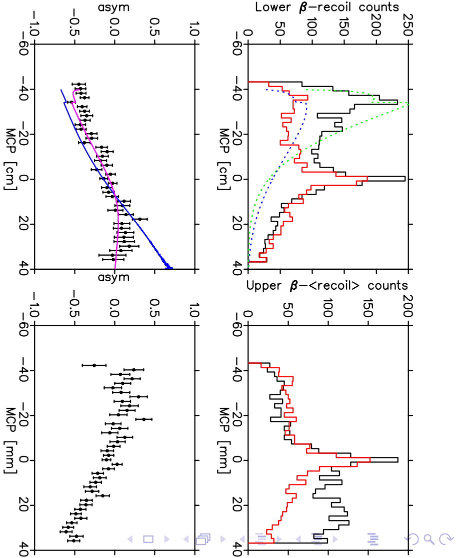


- 10,000 atoms trapped at a time
- AC MOT for fast switching of Bquad of MOT
- Spin polarization measured in-situ on ^{37}K by atomic method
- Position-sensitive electron detector shows shakeoff electrons contained

Helicity-driven null in mirror decay

ν can't go with I if β is against; 2 hrs data 'online' cut





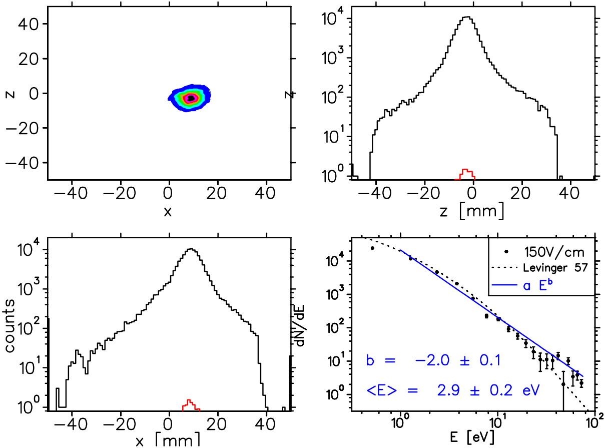
which is why

$$1-(A_\beta - B_\nu) - a_{\beta\nu} + 2c/3 = 0$$

Reconstructing ν direction will help

^{37}K shakeoff e^- energy

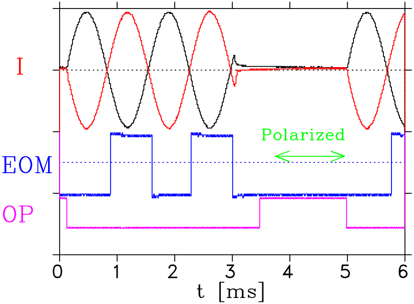
- $|\vec{E}|$=150 V/cm (B_z= 2G), $E_{\rm shakeoff} \to$ radius distribution
- $\sim$1% above 25 eV threshold for double DNA strand breaks
- average energy makes $< 10^{-5}$ contribution to Ft value



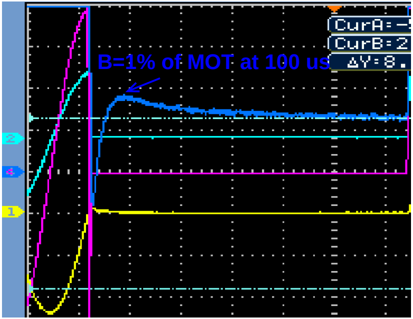
AC MOT

Adapted from Harvey and Murray PRL **101** 173201 (2008)

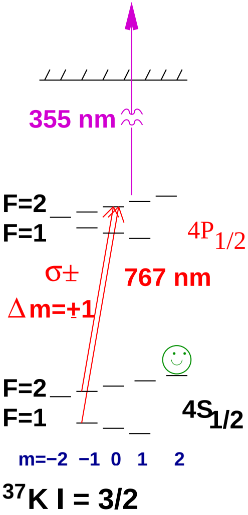
Turns off MOT's 7G/cm Bquad field quickly, with eddy currents near 0

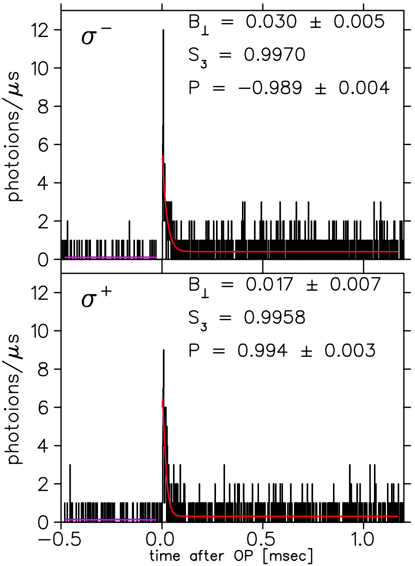


B quad off to 1% of its value in 100 μs:



Optical pumping and probing ^{37}K

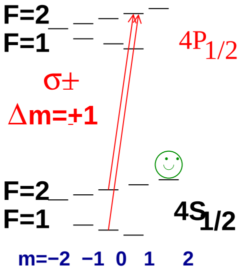




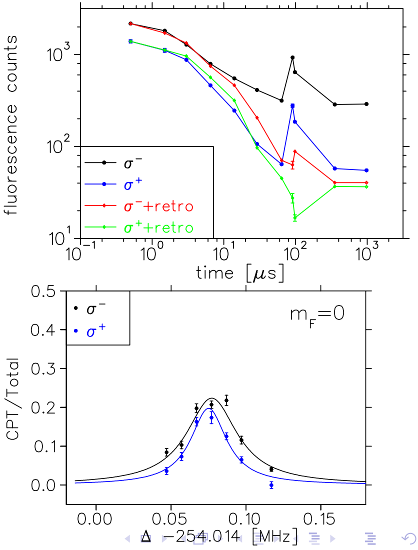
PRELIM (e.g. we know 1st 2 of 100 cycles is hurt by a transient $B_\perp$)

TRIUMF Coherent Population Trapping in ^{41}K

We test such systematics with ^{41}K



- Atoms trapped in the coherent dark state have $P \sim 0$
- Can trap $\sim$ 30% on purpose, but easy to eliminate by detuning + retroreflected beams



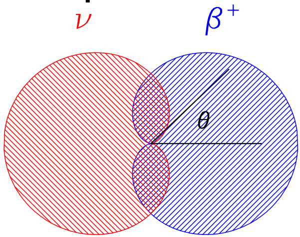
A new method for an old observable (Treiman '58)

Final nuclei angular distribution wrt initial spin

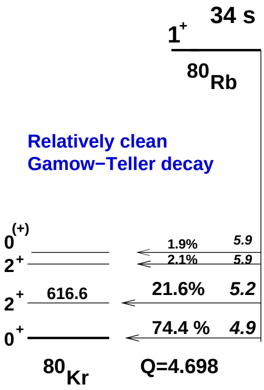
$$W[\theta] = (1 + \tfrac{1}{3}cTx_2) - x_1(A_\beta + B_\nu)P\cos\theta - x_2 cT\cos^2\theta$$

$$x_1 \overset{Q>>m}{\longrightarrow} 5/8;\ P = \frac{\langle M\rangle}{I};\ T = \frac{I(I+1) - 3\langle M^2\rangle}{I(2I-1)}$$

- **For pure Gamow-Teller, A_{recoil}= 0 in SM**



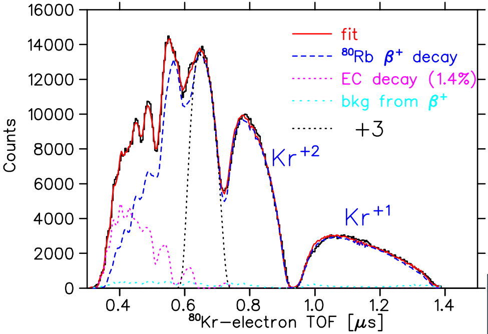
$\models\Rightarrow$



$$A_\beta + B_\nu = \lambda_{J'J}(-2C_T C_T' + \langle\frac{m}{E_\beta}\rangle(C_T + C_T'))$$

Challenge: constrain $\sim$ 0.01 recoil-order correction

TOF of ^{80}Kr daughter, atomic e$^-$ trigger

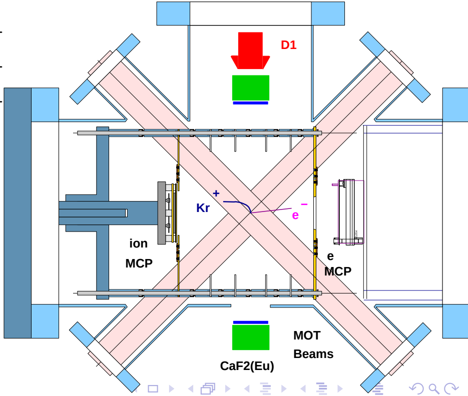


- like Vetter LBL PRC'08

Measure:

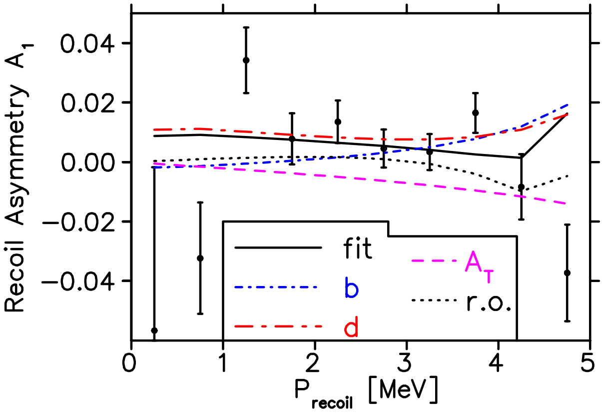
$\theta_{\rm recoil}$ **wrt** $\vec{I}$**,**

$|p_{\rm recoil}|$



High statistics, low backgrounds

Distinguishing new tensors from S.M. corrections



$A_1[p_{\mathrm{recoil}}]$ differs for new tensor C_T,C'_T vs. SM higher-order

***b* weak magnetism**

b/A = $g_M M_{GT}$ +

$\langle \boldsymbol{f} || \sum \tau_i^+ \vec{l} || \boldsymbol{i} \rangle$

***d* QCD-induced tensor**

d_I/A = g_A

$\langle \boldsymbol{f} || \sum \tau_i^+ i\vec{\sigma} \times \vec{l} || \boldsymbol{i} \rangle$

- **Effects of *d* can be separated this way**

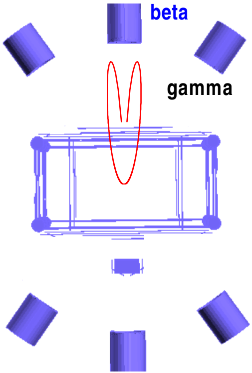
Non-SM contribution to the asymmetry:

$\boldsymbol{A_T} = \mathbf{0.015 \pm 0.029 \pm 0.019}$

(Systematics from b/AM_{GT}=4.7±4.7, nucleon value)

^{38g}K I = 3 → 2 but is in SD shell

TRIUMF $\not{T}$ no spin, no EDM constraints



Gardner and He PRD 87 116012 (2013)

$\xi\ (\vec{I_e} \times \vec{k_\gamma}) \cdot \vec{I_\nu}$

- **inner bremss Z=18**

3% $>$ 100 keV; 6% $>$ 10 keV

- **Bremsstrahlung is forward-peaked. sin(35^o)=0.57**
- **^{37}K 10,000 atoms, 7000 events/week $\Rightarrow \sigma_\xi \sim$ 0.02**
  - **the new 'c5' term needs Fermi or Fermi+GT transition**

  $\not{T}$ increases with E_0

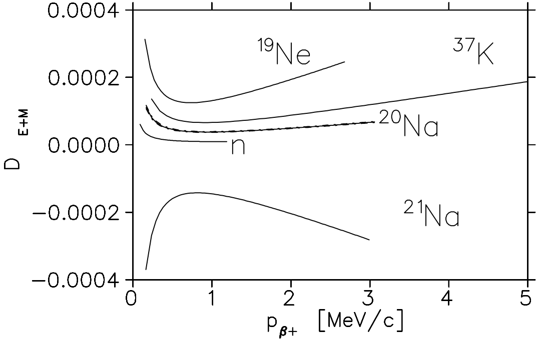
  - **Final state effects $\propto$ 1-$\lambda^2/3$**

  σ_{SYST}? No spins to flip... $\sim$ 0.5% like $a_{\beta\nu}$?

TRIUMF $D\ \vec{I} \cdot \vec{v_\beta} X \vec{v_\nu}$ Constraints

- **^{19}Ne (Hallin et al. Princeton): D = $(1 \pm 6) \times 10^{-4}$**
- n (TRINE) PLB 2004 **D = $(-2.8 \pm 6.4 \pm 3.0) \times 10^{-4}$**
- **n (emiT)** PRL 2011: **D = $(-1.0 \pm 1.9 \pm 1.0) \times 10^{-4}$**

- **'Final state' effects for ^{37}K are smaller than ^{19}Ne, weak magnetism is smaller [Holstein PRC 1972]**

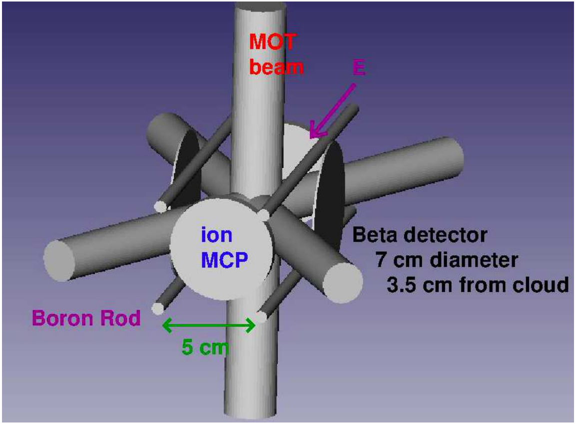


EDM constraints:

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

TRIUMF TRINAT and D

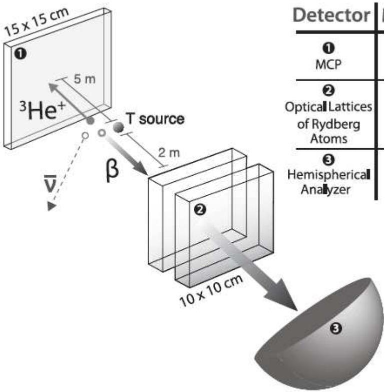
P is not along β detection axis, so dedicated geometry: statistics $\sim$ 2x10^{-4} in 2 weeks



Transparent β detectors?
Kapton $>$ 85% transmission to NIR

4π β^+ detector passing 100 eV nuclear recoils

M. Jerkins,
J.R. Klein,
J.H. Majors,
F. Robicheaux,
M. G. Raizen
New Journal of Physics 12 (2010) 043022

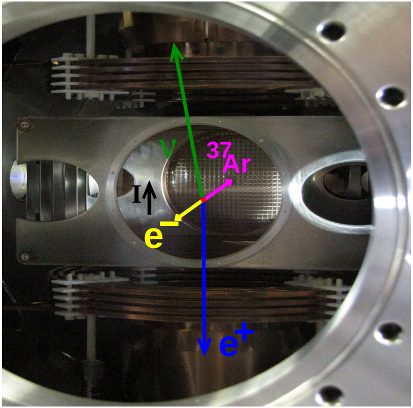


β excites optical lattice of Rydberg atoms from N=53 to a state that gets field ionized and swept out

1 keV β has v= 0.06c; need N$\sim$160, $|\vec{E}|$=0.4 V/cm to get 10 ions/cm for MeV βs

TRIUMF β decay correlations with TRIUMF's neutral atom trap

- Tools for β-ν include reconstruction of lower E_βs
- Polarization measured in-situ: old and new observables
- Shakeoff e$^-$ are useful
- considering time reversal in future



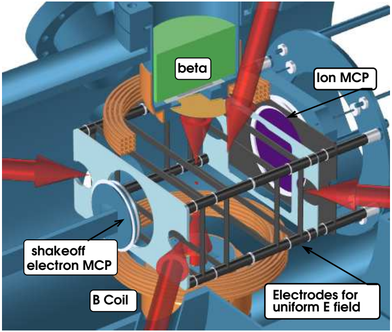
Theory: constraints from EDM's

- Ng+Tulin PRD 2012 EFT approach to constraints from other experiments $\rightarrow$ D $\leq 10^{-5}$
- most terms contributing to D are constrained by null neutron EDM experiments
- leptoquark exchange was thought to be unconstrained by EDM null results, and it is still true: Ng and Tulin constrained this possibility by combining other experiments like atomic PNC
- In EFT all terms $\sim$1; since more than 1 term contributes, there can always be cancellations

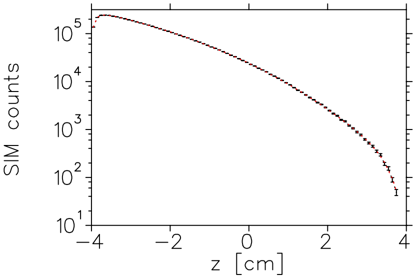
Systematic errors for D in atom trap

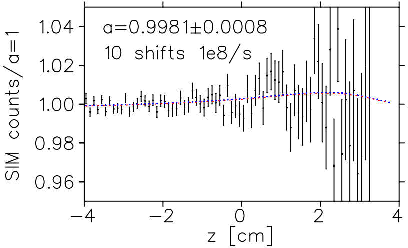
- **Point source: we know where it is (by sampling photoionization) and it doesn't move when we flip the polarization**
- **Polarization along wrong axis is deadly: Measure with singles asymmetry for recoils and β's**
- **Collect recoils going into 4 pi with electric field of 1 kV/cm**
- **Full reconstruction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

$a_{\beta\nu}$ in spin-polarized geometry



- **Position info ∼ TOF in Gorelov 2005 →**
- **Cloud size is critical for position resolution**
- **β-recoil + e$^-$-recoil**





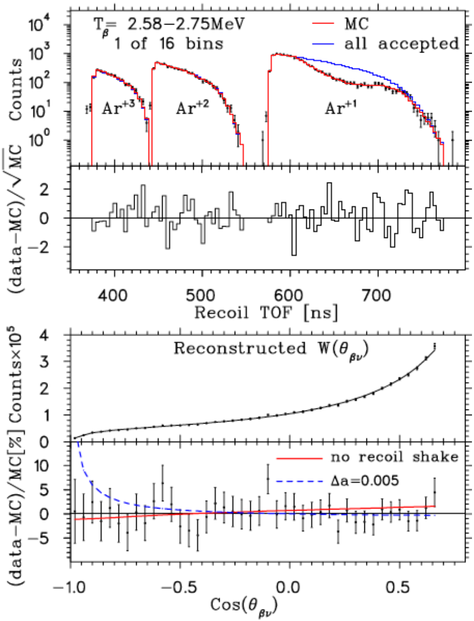
- Reconstruct $\theta_{\beta\nu}$ → 3x better sensitivity.

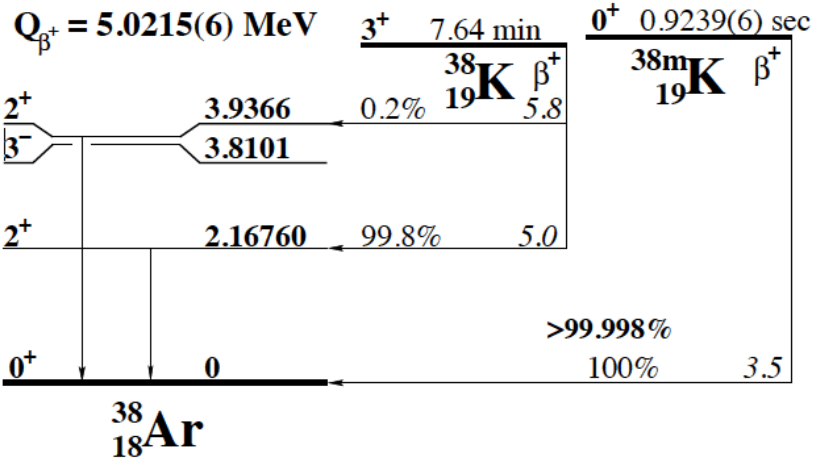
Methods I and II agree:
I: recoil TOF[T_β],
T_β>2.6 MeV
C.L. of total fit is 52%

II: Angular distribution determined from other observables (except E_β).
Can simultaneously fit E_{recoil}-dependent shakeoff

$\tilde{a}$=0.9981 ± 0.0030(stat) ± 0.0037(syst)

(Adelberger ^{32}Ar PRL 1999
$\tilde{a}$=0.9989 ± 0.0052(stat) ± 0.0039(syst)
still being re-evaluated)





Excited-state branch known to be negligible

(Ground state makes a background in β singles: we can deal with this better)

Theory: SUSY contributions to β decay

PHYSICAL REVIEW D 75, 075017 (2007)

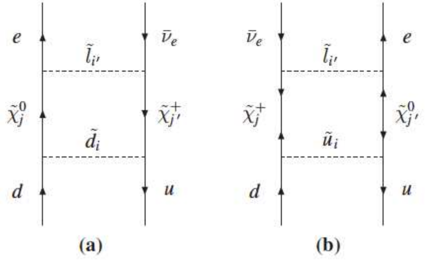


FIG. 2. Feynman diagrams relative to supersymmetric contributions giving rise to anomalous amplitudes in β decay processes.

SUSY can produce up to 0.001 changes in nuclear β decay observables.
Not direct exchange of leptoquarks
but higher-order 'box' diagram with two particles exchanged at once.

This corner of SUSY is hard to constrain and hard to eliminate. Profumo et al. considered $\tilde{d}, \tilde{u}$ masses 1-10 times the lightest SUSY particle mass, not actually using Tevatron constraints. Some such masses are ruled out by LHC but a full reanalysis would have to be done.

Sub-Doppler cooling of I=0 alkali

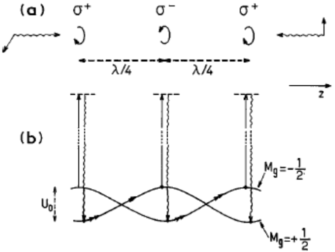


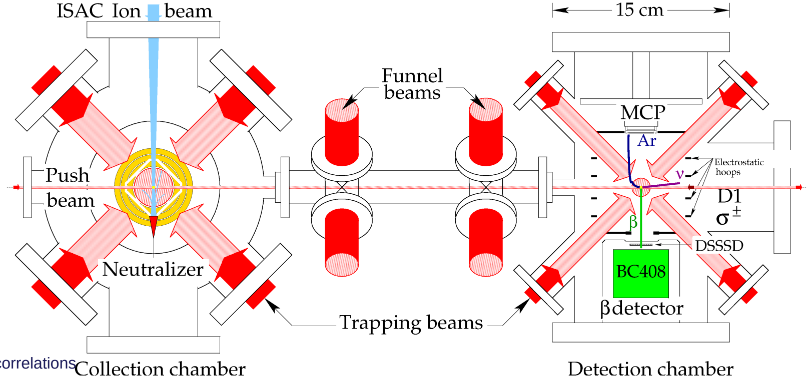
FIG. 2. Sisyphus cooling. Laser configuration formed by two

Cohen-Tannoudji Nobel lecture
"Lin ⊥ Lin" molasses.
Order of magnitude lower T
The textbook example has never been done. Needs I=0 alkali.
A MOT does NOT use Lin ⊥ Lin molasses.

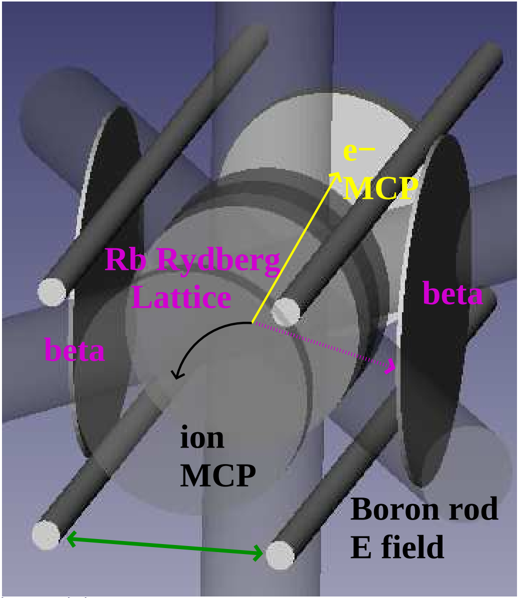
σ^+ σ^- molasses $\to$ linear polarization rotation in space, needs AC Stark shift dependence on m^2. No effect for m=1/2
So we used Doppler-limited cooling in 38mK before, achieving poor temperatures but tight 0.7 mm cloud with high power.
We have since achieved 0.25 mm ^{85}Rb like everyone else.
We want a) smaller cloud; b) less intensity to minimize dimers
1) Add optical pumping light for Lin ⊥ Lin molasses
2) Flip between trapping and Lin ⊥ Lin with the MOT beams

TRIUMF's Neutral Atom Trap(s)

- Isotope/Isomer selective
- Evade 1000x untrapped atom background by $\to$ 2nd MOT
- 75% transfer; 5×10^{-4} capture
- 0.7 mm cloud for ^{38m}K
- 99.X% polarized, known atomically (in progress)
- manipulate atoms separately from capture
  (reduce intensity $\to$ fewer dimers)



TRIUMF 'TRINAT3D'



- Shakeoff e$^-$ triggers optical lattice dump

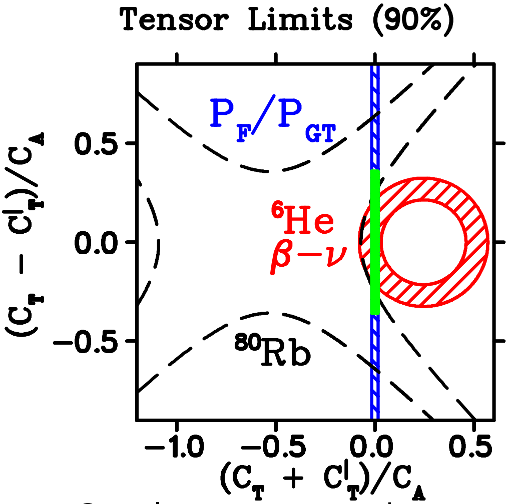
Switch $\sim$ ~~50V/cm~~ 0.5 V/cm field on in $\sim$ 100 ns

TPC for β without straggling

$\hat{p}_\beta, \vec{p}_{\mathrm{recoil}} \Rightarrow \vec{p}_{beta}$

- $\to$ 1x10^{-4} stat error on D in 1 week

$^{80}\vec{\mathrm{Rb}}$ decay: Tensor constraints



- Dash:
  C_T, C_T', b, d all float
  limits not competitive
- Green bar:
  set b/AM_{GT}=4.7±4.7,
  assume $C_T + C_T'$=0
  (Carnoy ^{14}O/^{10}C 1991)
  $\rightarrow$
  $A_T = 0.015 \pm 0.029$ (stat)
  $\pm\, 0.019$ (syst) $\Rightarrow$

$|(C_T - C_T')/C_A| <$ **0.36**
R. Pitcairn PRC 2009

- Complementary constraints to tensor couplings to ν_R compared to ^{6}He β-ν correlation (Johnson ORNL PR 1963)

^{38g}K I = 3 $\rightarrow$ 2 but is in SD shell

Nice things to have

Ion detection independent of angle and energy

SiPM readout of plastic

Elastomer-sealed windows to minimize birefringence (PCTFE)

Thinner mirror substrates than 0.25 mm SiC

UHV-compatible gas detector

β detectors transparent to NIR

Resistive rods for electric fields

Heavimet conflat flanges