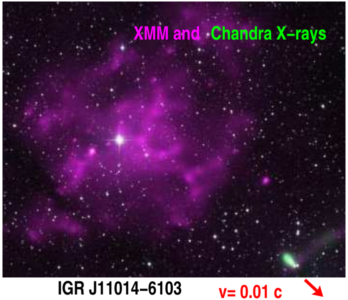
Weak interaction breaks parity: Consequences?

'Pulsar kicks'



Fuller PRD 2003

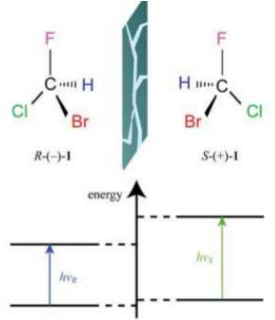
Forced $p + e^- \rightarrow n + \nu$

$W(\theta) = 1 + \frac{\langle m_I \rangle}{I} A_\nu \cos(\theta_{\hat{I}})$

B field polarizes p's

Need ν_e to include 10^{-8} admixture of $m_\nu \sim$ keV

Earthling's amino acids are all left-handed



Letokhov PLA'75

Darquie CHIRALITY 2010

$\Delta E \sim 10^{14-16}$eV

Not Enough for left-handed bugs to win, so →

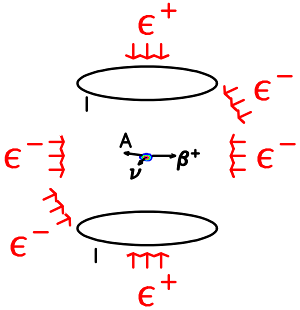
Spin-polarized SN ν's could preferentially zap wrong-handed amino acids

Finding the right environment for spin-polarized amino acids? e.g. :

Astrobiology 18 (2018)
Selection of Amino Acid Chirality via ν Interactions with ^{14}N in $\vec{E} \times \vec{B}$ Fields
M.A. Famiano, R.N. Boyd
(TRIUMF EEC 90's)...

Still no wrong-handed νs

- ν helicity and Parity *P* symmetry
  How to test *P* symmetry experimentally
  Only left-handed ν so far
- How 'magneto-optical' atom traps work
- ~~The most accurate~~ β asymmetry
  What we learn from it
  How much better we want to do



TRIumf Neutral Atom Trap collaboration:

TEXAS A&M UNIVERSITY
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B. Fenker
M. Mehlman
P. Shidling
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TRIUMF
A. Gorelov
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Undergrad
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UBC
J. McNeil

UNIVERSITY OF MANITOBA
M. Anholm
G. Gwinner

Parity (From A. Zee “Fearful Symmetry”)

As of 1955, we thought all interactions respected parity

Parity operator

$P\,\psi(\vec{r}) \rightarrow \pm\,\psi(-\vec{r})$

‘$\tau - \theta$ Puzzle’

$\tau \rightarrow 2\pi$

$\theta \rightarrow 3\pi$

Same lifetime and mass!

but $P\pi = -\pi$

Lee, Yang Phys Rev 104 254 Jun ’56: same particle, but parity broken $\Rightarrow$

Predicted asymmetries in μ and ^{60}Co decay $\Rightarrow$

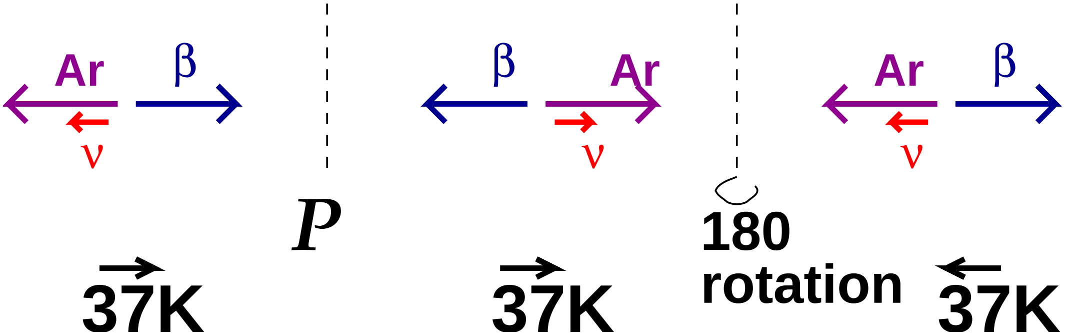
P  $=$ 

P  $\neq$ 

Decays: Parity Operation can be simulated by Spin Flip

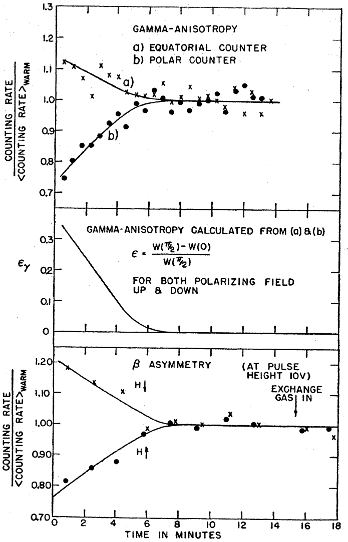
Under Parity operation *P*:

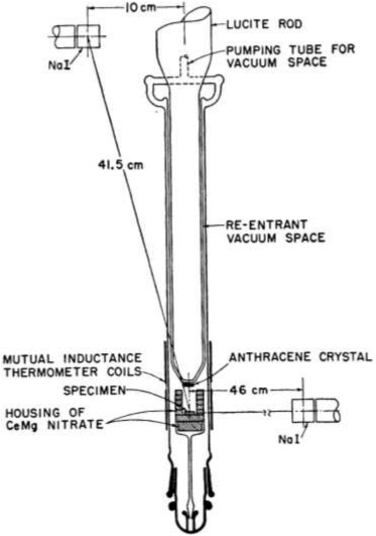
$\vec{r} \rightarrow -\vec{r}$ $\quad \vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$ $\quad \vec{J} = \vec{r} \times \vec{p} \rightarrow +\vec{J}$



⇒ A spin flip corresponds exactly to *P* reversal

One experimental discovery of parity violation





Wu, Ambler, Hayward, Hopper, Hobson, PR 105 1413 Feb '57

Dilution Refrigerator to spin-polarize

^{60}Co $\rightarrow$ ^{60}Ni + β^- + $\bar{\nu}$

$$W[\theta] = 1 + PA\hat{I}\cdot\frac{\vec{p_\beta}}{E_\beta}$$

$$= 1 + A\frac{v}{c}\cos[\theta]$$

$A_{\beta-} \approx -1.0$

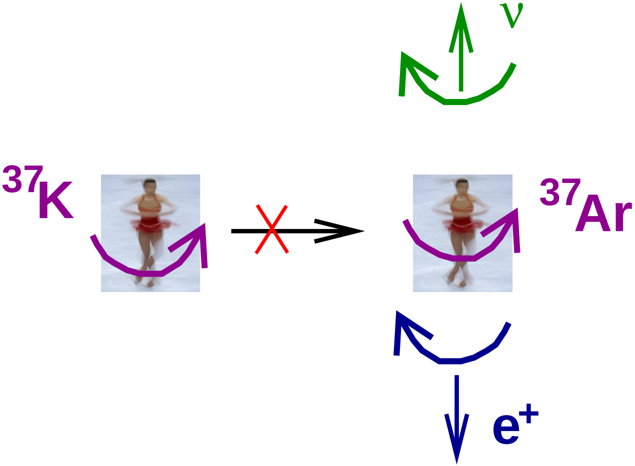
April followup:

^{58}Co $\rightarrow$ ^{58}Fe + β^+ + ν

$A_{\beta+} > 0$

CP conserved?

Further sensitivity to wrong-handed leptons



So far: ν is left-handed, $\bar{\nu}$ is right-handed

I'll show you data on this One can measure the ν helicity more directly $\rightarrow$

Measure ν helicity: transfer to γ circular polarization

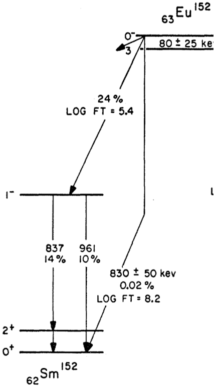
Goldhaber, Grodzins, Sunyar
Phys Rev 109 1015 (Dec 1957)

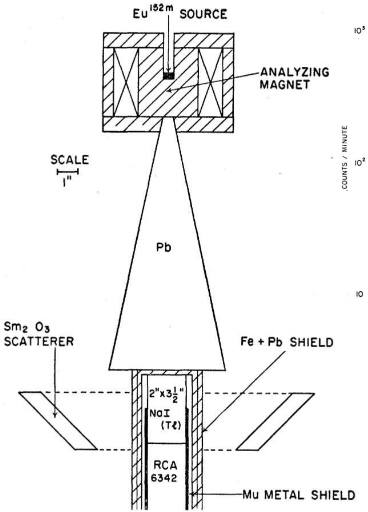
$$e^- + {}^{152m}\mathrm{Eu} \rightarrow \nu + {}^{152}\mathrm{Sm}$$

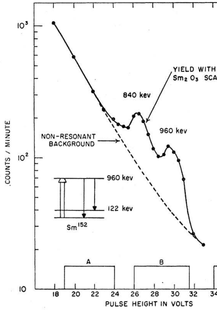
- **Upward-going ν populates $\langle I_z \rangle = 0, +1$ not -1**
- **So γ is circularly polarized– transmission through magnet depends on iron polarization:** $\frac{N_+ - N_-}{N_+ + N_-}$**=0.017±0.003**
- **Upward ν boosts γ momentum so it can be absorbed on-resonance**

$\Rightarrow$ ν helicity -1 $\pm$ 10%

(• $\bar{\nu}$ helicity $\sim$ +1
Palathingal PRL 524 24 ’69)



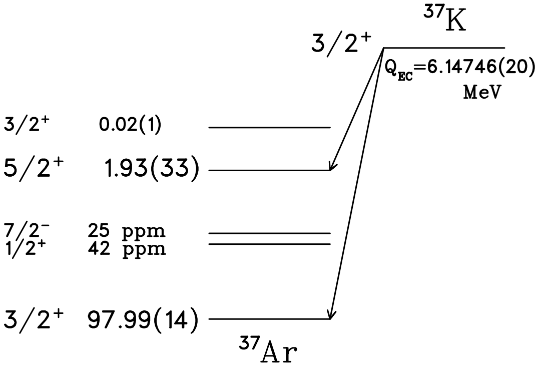




^{37}K isobaric mirror decay: a 'heavy neutron' ?

Here there are 2 operators, so A_β isn't 1 or -1 or a clean fraction

'Fermi' operator changes n to p;
'Gamow-Teller' changes n to p and flips nucleon spin



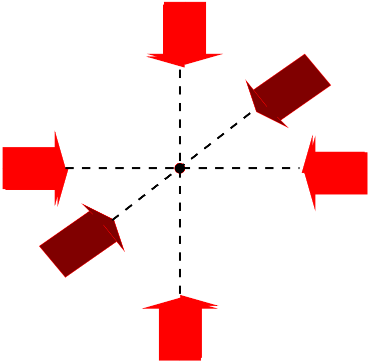
τ, Q and branch $\Rightarrow$ decay strength $\mathcal{F}t$
We know the Fermi $\mathcal{F}t_0$ from the $0^+ \rightarrow 0^+$ decays, so from $\mathcal{F}t$ we can get the Gamow-Teller strength:
$\mathcal{F}t$ (Shidling PRC 2014) $\Rightarrow$

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

Implies $A_\beta[SM]$ = -0.5706 ± 0.0007

Magneto-optical trap: damping

For a trap, we want a damped harmonic oscillator
’Red-detuned’ beams provide the “damping”



‘Optical molasses’

We still need a position-dependent force

"Why Optical Traps Can't Work"

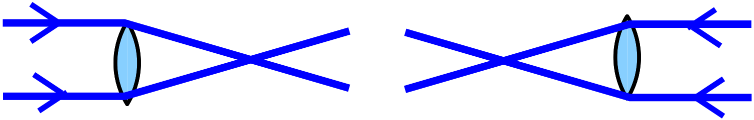
Earnshaw Theorem: $\vec{\nabla} \cdot \vec{E} = 0 \Rightarrow$

no electrostatic potential minimum for charge-free region

"Optical Earnshaw Theorem" (Ashkin + Gordon 1983):

Using Poynting's theorem:

$$\vec{\nabla} \cdot \vec{S} = \frac{c}{4\pi} \vec{\nabla} \cdot (\vec{E} \times \vec{B}) = -\vec{J} \cdot \vec{E} - \frac{\partial u}{\partial t} = 0$$

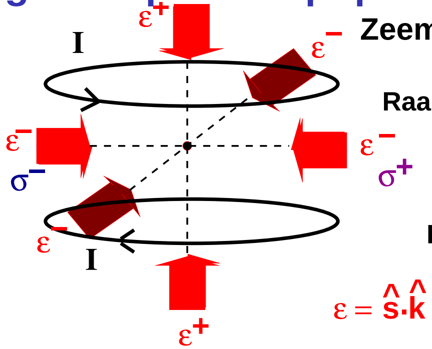


$\Rightarrow$ no 3-D traps from spontaneous light forces with static light fields

Dodges !

- Time-dependent forces (pulsed lasers)
- Dipole Force traps ("optical tweezers")
- Modify internal structure of atom with external fields

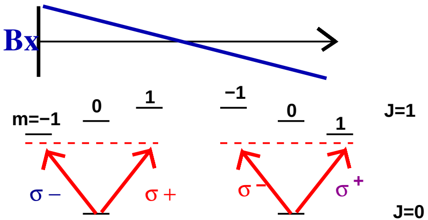
Magneto-optical trap: perturb atoms



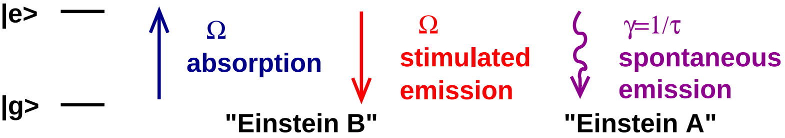
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator



Why atom traps are shallow



$$\frac{dN_g}{dt} = -\Omega N_g + \Omega N_e + \gamma N_e = -\frac{dN_e}{dt}$$

Steady-state $\Rightarrow$ **=0** $\Rightarrow N_e = \frac{\Omega N_g}{\Omega+\gamma}$

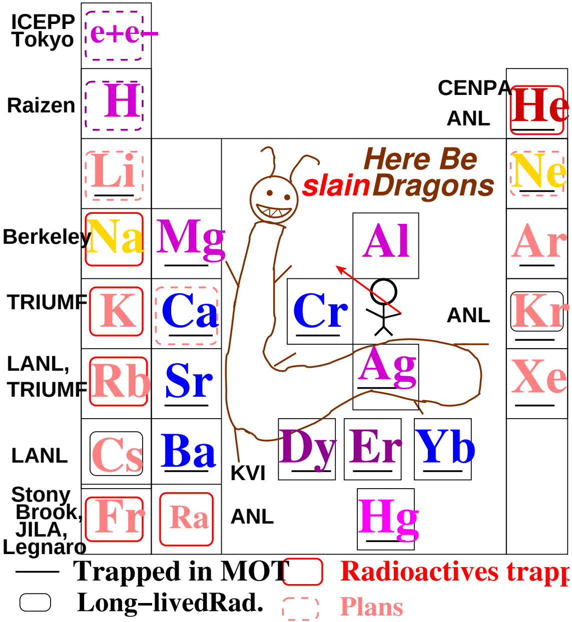
Limits: $N_e \overset{\Omega<<\gamma}{\longrightarrow} \frac{\Omega}{\gamma} N_g$ **(sure);** $N_e \overset{\Omega>>\gamma}{\longrightarrow} N_g$ **!!**

- **At high intensity, same # in ground, excited state**

Atomic transition "saturates"

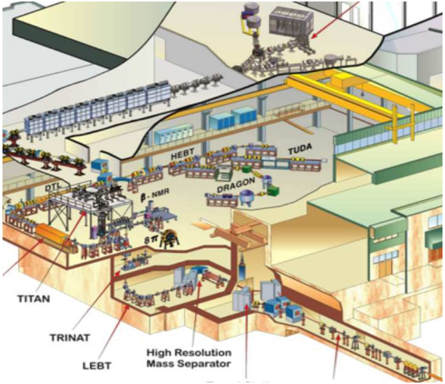
Maximum scattering rate = $\gamma N_e/N \rightarrow \gamma/2$

So radiation pressure traps are shallow IF they rely on spontaneous emission



What elements can be laser cooled?

TRIumf Neutral Atom trap at ISAC

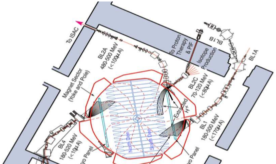


^{37}K 8x10^{7}/s

TiC target
1750^{o}C

70 μA
protons

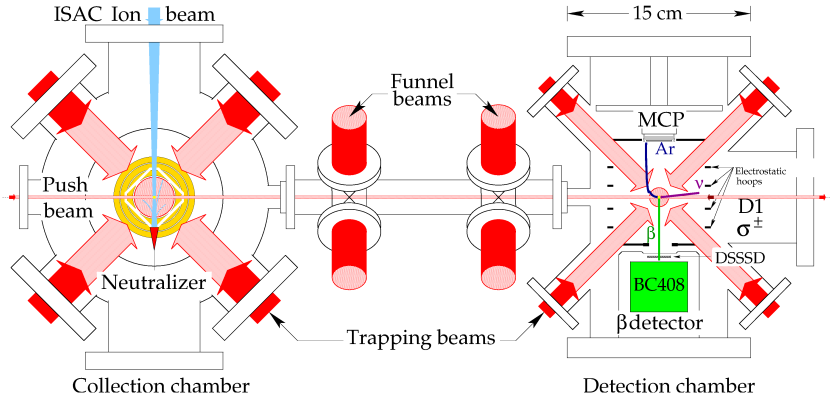
main TRIUMF cyclotron
'world's largest'
500 MeV H^{-} (0.5 Tesla)



TRIUMF

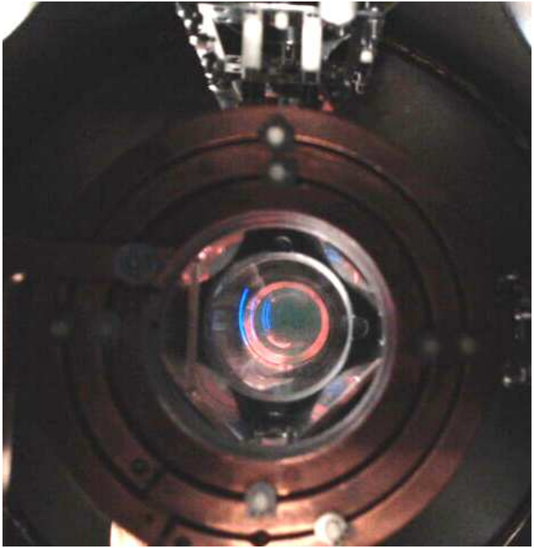
TRINAT plan view

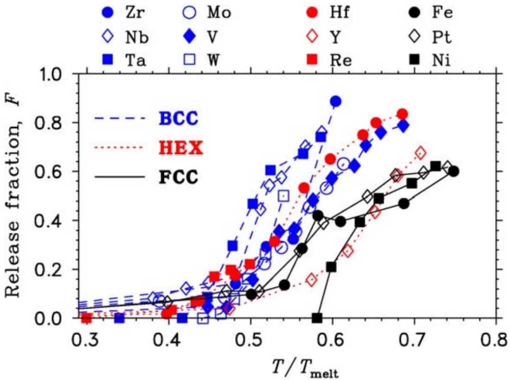
- Isotope/Isomer selective
- 75% transfer
- Avoid untrapped atom background with 2nd trap
- 0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum

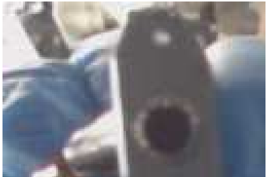


- Spin-polarized 99.1±0.1%

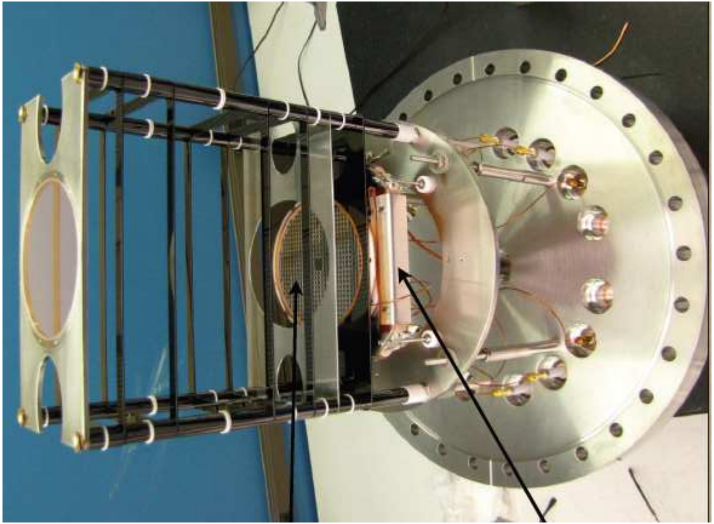
Neutralizer and Collection trap







ion MCP assembly



14 inch CF flange

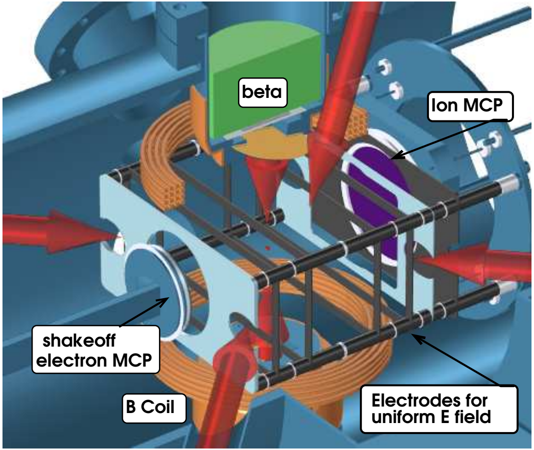
Electrostatic field

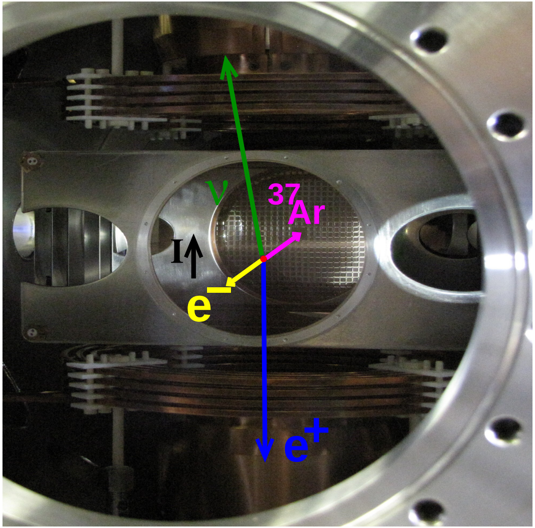
delay-line anode for position info

no stray wires

Low-Z (glassy carbon, titanium) to minimize β^+ scattering

^{37}K decay geometry

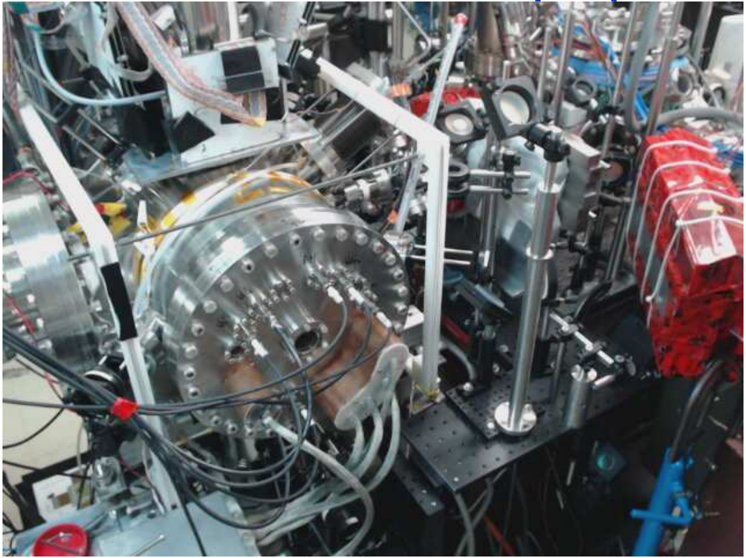




- β, recoil nucleus
- shakeoff e^- for TOF trigger
  The decay pattern shown on the right is helicity-forbidden if the ν goes straight up

TRIUMF

TRINAT lab: “tabletop experiment”

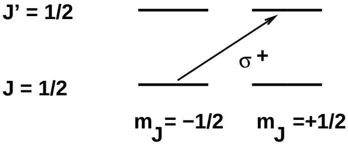


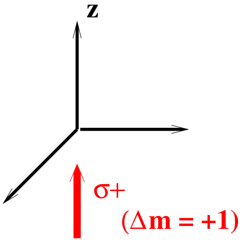
How to spin-polarize a nucleus with a laser

Polarization of nuclei by Optical Pumping

Biased random walk

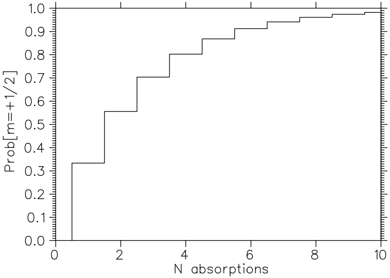
Simple example:





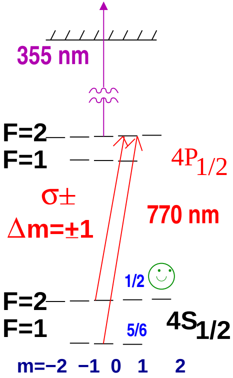
P(m=1/2) = 1 - $(2/3)^N$ after N steps

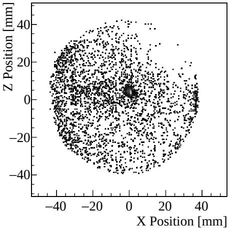
Need 12 cycles to get to 99% of maximum.

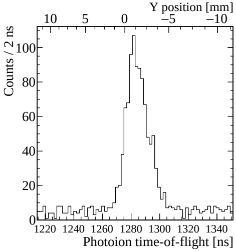


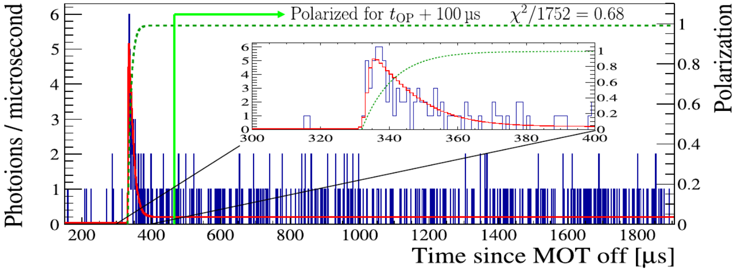
TRIUMF Optical pumping and probing ^{37}K

TEXAS A&M UNIVERSITY









Photoionize 1%

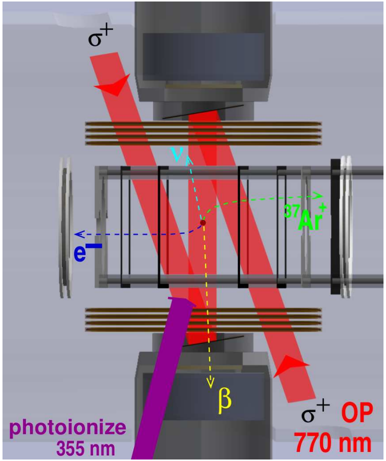
***in situ* probe**

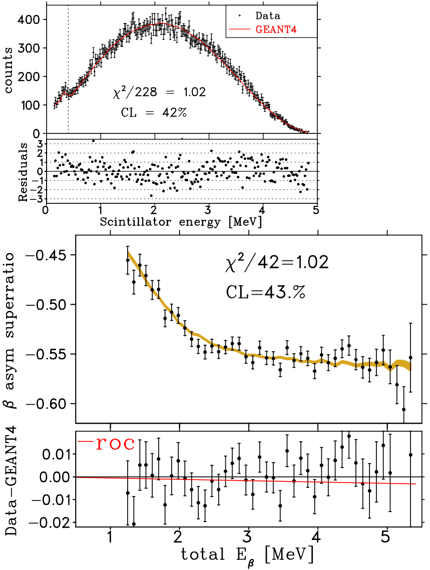
P_+=+0.9913(8)

P_-=−0.9912(9)

Fenker NJP 2016

β^+ asymmetry ^{37}K data





Fenker et al. Phys Rev Lett 120, 062502 (2018)

A_β[experiment]= -0.5707 $\pm$ 0.0019

A_β[theory] = -0.5706 $\pm$ 0.0007

The best fractional accuracy achieved in nuclear or neutron β decay

TEXAS A&M UNIVERSITY

Best fractional A_β

TRIUMF

^{37}K $A_\beta = -0.5707 \pm 0.0018$
agrees with standard model -0.5706 $\pm$ 0.0007

Better absolute uncertainties from:
^{19}Ne $A_\beta = -0.0360 \pm 0.0008$

neutron A_β = -0.11985 $\pm$ 0.00017 $\pm$ 0.00012 PERKEO III 2019
lifetime must still be settled

What physics can we probe? $\rightarrow$

Weak interaction and quark eigenstates

To explain some weak decays:

$|u\rangle \rightarrow |d\rangle + \epsilon|s\rangle$

i.e.

$|u\rangle \rightarrow \cos(\theta_C)|d\rangle + \sin(\theta_C)|s\rangle$

For 3 families of particles,

$|u\rangle \rightarrow \cos(\theta_C)|d\rangle + \sin(\theta_C)|s\rangle + \epsilon'|b\rangle$

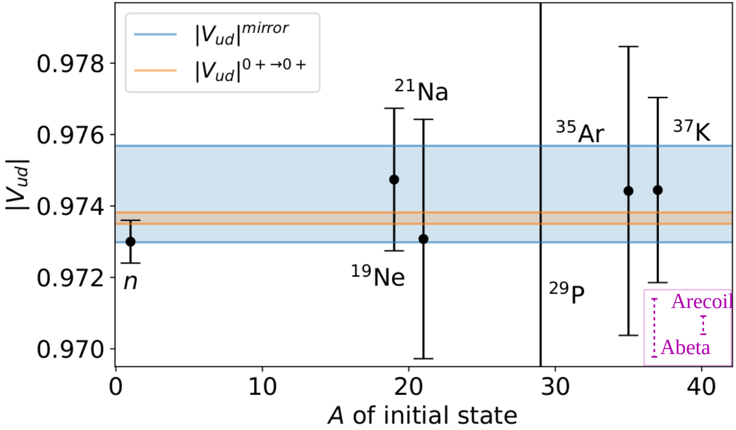
3x3 matrix. Unitarity $\Rightarrow |V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = 1$

Models exist to explain the value of θ_C

Such models can invoke 'spontaneous symmetry breaking' and then maybe restore the symmetry under some conditions

We interpret our measurement to measure $\theta_{\mathrm{Cabibbo}}$ i.e. V_{ud}

Weak interaction: same strength, all nuclei?



Hayen and Severijns, arXiv:1906.09870 (June 2019)

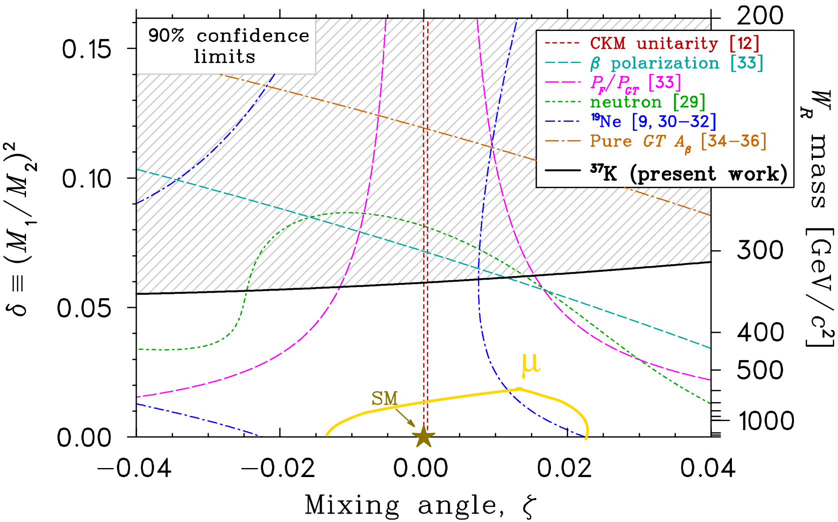
Deduced V_{ud} from mirror decays

Are people overestimating their uncertainties? We aren't ☺

We project to reach 0.0005 accuracy, as good as any $0^+ \rightarrow 0^+$ except ^{26m}Al.

Assumes 5% isospin breaking calculation.

Still no wrong-handed ν's



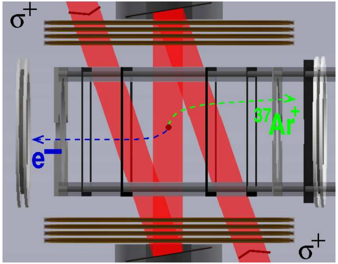
Extra W' with heavier mass, couples to wrong-handed ν_R

We can evade TWIST limits by assuming the muon ν_R is heavy

LHC $M'_W > 3.7$ TeV 90%

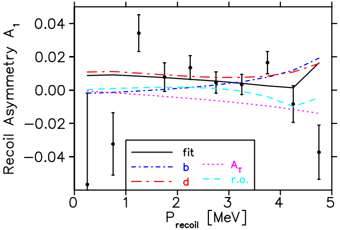
TRIUMF

$A_{recoil} \propto A_\beta + B_\nu$ in ^{37}K decay

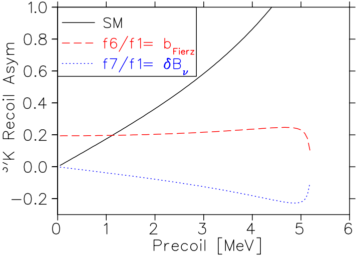


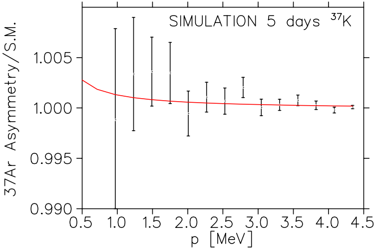
see ^{80}Rb Pitcairn PRC09

$A_T = 0.015(29)(19)$

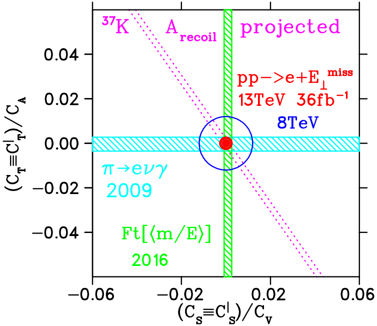


$A_{recoil}[p_{recoil}]$ independent of M_{GT}/M_F





Discovery potential, assuming known M_{GT}/M_F 90%

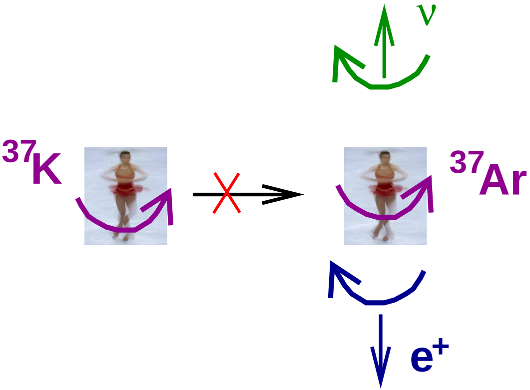


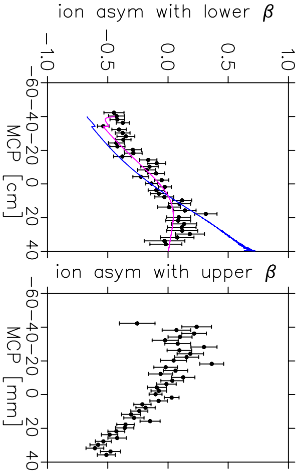
Completed upgrade to 1 kV/cm, fine-tuning polarization: plan to be ready in October 2020.

TRIUMF

Helicity-driven null in mirror decay

ν can't go with I if β is against





$$W(\theta) \approx 1 + a\cos(\theta_{\beta\nu})$$

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

Looking for wrong-handed νs

- ν helicity and Parity ***P*** symmetry

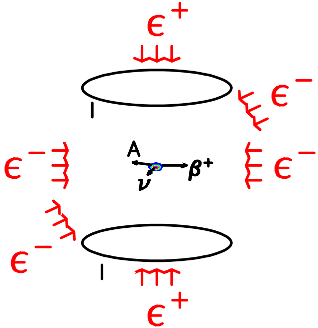
  P symmetry can be tested by flipping spins

  The standard model violates ***P*** 'maximally' so far

- 'Magneto-optical' atom traps and optical pumping provide ν-β coincidence experiments

We have made the most fractionally accurate A_β measurement (0.32%)
Fenker et al. PRL 120 062502 (2018)

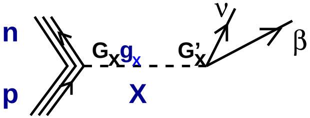
We want to reach 0.1% accuracy to complement high-energy collider searches



Why the weak interaction is 'weak' at low energy

'more massive virtual particles are created for shorter times'

Propagator+vertices:



$$T \propto \frac{G_X(-g^{\mu\nu}+p^\mu p^\nu/M_X^2)G_X}{p^2-M_X^2} \xrightarrow{p<<M_X}$$

$$T \propto \frac{G_X^2}{M_X^2} \Rightarrow$$

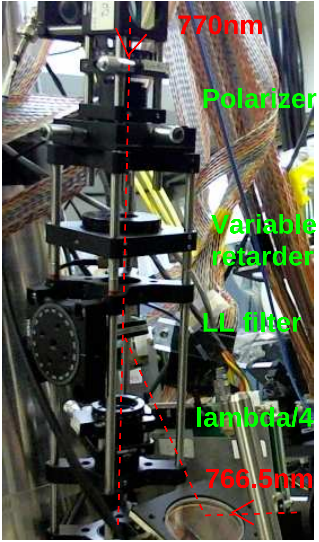
Decay rates $\propto \frac{G_X^4}{M_X^4}$

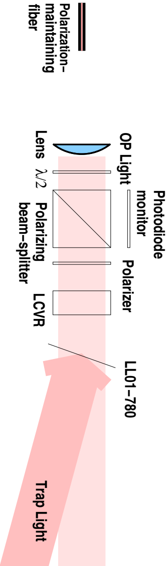
Decay rate $\propto \frac{G^2}{M_W^2}\frac{G_X^2}{M_X^2}$ **if process interferes with W (couples to left-handed ν)**

- **IF $G_X \sim$ electroweak coupling, then absence of 0.1% changes in angular correlations $\Rightarrow M_X >$ 6 or 30 M_W**

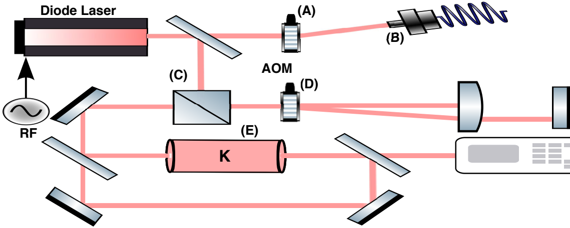
TRIUMF

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
- Relieve stress-induced birefringence with PCTFE (Neoflon) viewport seals (S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5))



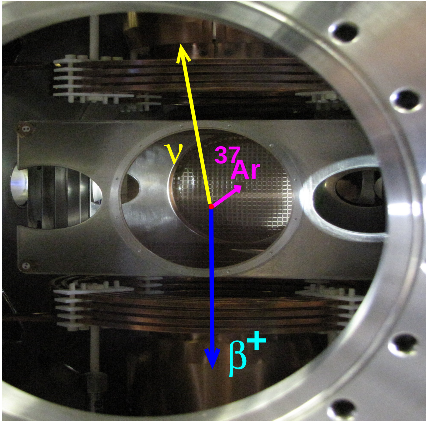
optics and detectors

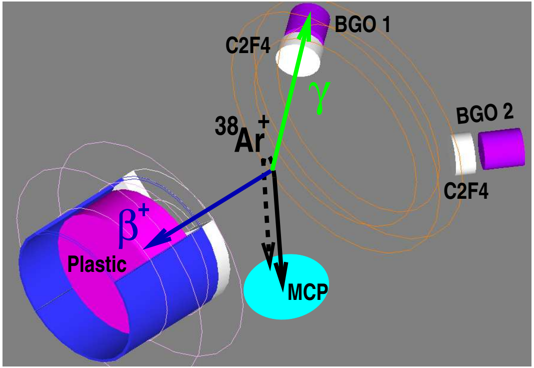
What about $\not{T}$? 3-momentum correlation

When t → -t :

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

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





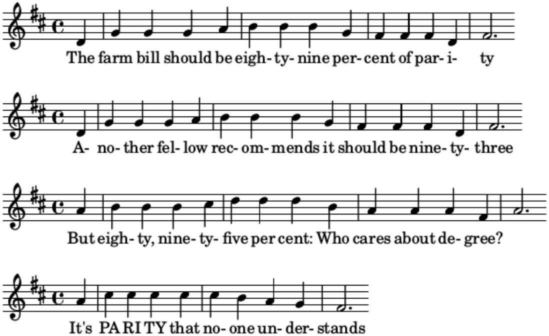
BUT flipping t is not the same thing as running the decay backwards.

Particles interact on the way out, and you don't reverse that part.

Parity: influences? 1956 Broadway Musical Lil' Abner

20 minutes by public transit

Timeless Lyrics: Gene de Paul, music Johnny Mercer



Lee and Yang, theory of parity violation published Oct 1956;
Opening night Lil' Abner Nov '56 (any free rehearsals?);
β experiment Wu et al. Jan '57; μ Garwin et al. Jan '57
(Mom, an admin asst at Columbia, thinks this is unrelated)
Theory won Nobel; experiment, music did not ☹