Parity and time-reversal symmetry in β decay

- **Parity *P* symmetry**

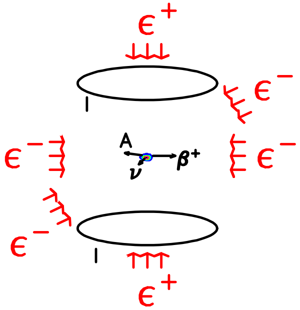
  How to test *P* symmetry experimentally

  Only left-handed ν so far

- **There is time-reversal symmetry violation**

  $\not{T}$ in nature

There should? be more: 'baryogenesis'



$\not{P}$, $\not{T}$ experiments at/with TRIUMF

- TRIUMF Neutral Atom trap (me ☺) β decay
- Laser-polarized beamline at TRIUMF

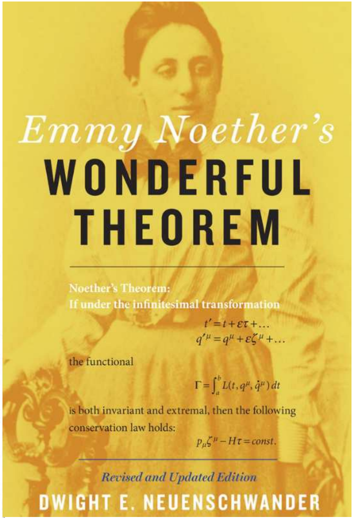
[Non-decays: • ν mixing,
- $\not{P}$ in Fr atoms; Searches for electric dipole moments;
- Using ultra-cold neutrons;
- hopefully atomic fountain of francium atoms]

https://trinat.triumf.ca/talks/triumf-summer-undergrad-talk-2021-jb

Symmetries: Continuous, Discrete

- Noether's theorem (1915):

Continuous symmetry	$\rightarrow$	Conserved quantity
Time-translational invariance	$\rightarrow$	Energy
Space-translational invariance	$\rightarrow$	Momentum
Rotational invariance	$\rightarrow$	Angular momentum
(Laplace-Runge-Lenz vector)	$\rightarrow$	name?



THE LATE EMMY NOETHER.

Professor Einstein Writes in Appreciation of a Fellow-Mathematician.

To the Editor of The New York Times:

...gan. In the realm of algebra, in which the most gifted mathematicians have been busy for centuries, she discovered methods which have proved of enormous importance in the development of the present-day younger generation of mathematicians. Pure mathematics is, in its way, the poetry of logical ideas. One seeks the most general ideas of operation which will bring together in simple, logical and unified form the largest possible circle of formal relationships. In this effort toward logical beauty spiritual formulae are discovered necessary for the deeper penetration into the laws of nature.

In Ted Chiang's "Story of Your Life" [Movie "Arrival"]: aliens think in terms of the action, not position and momentum

- Discrete symmetries in quantum mechanics: Parity, Time reversal $\rightarrow$

Historical Ideas about *P*, *T* breaking

- Wigner considered implications of P, T symmetry conservation in atomic spectra 1926-28. Showed $\langle T\psi_i, T\psi_f \rangle = \langle \psi_f, \psi_i \rangle^*$
“In quantum theory, invariance principles permit even further reaching conclusions than in classical mechanics.” (D. Gross, Physics Today 48 46 (1995))
- Weyl 1931 considered *C*, *P*, *T* and *CPT* in “Maxwell-Dirac theory”: C $\Rightarrow$ Dirac eq. negative energy states had to have same mass as the e^- plato.stanford.edu
- From “CP Violation Without Strangeness” Khriplovich and Lamoreaux:
1949 Dirac “I do not believe there is any need for physical laws to be invariant under reflections in space and time although the exact laws of nature so far known do have this invariance.”
- 1956 Lee and Yang proposed $\not{P}$ in weak decays to fix the θ-τ puzzle
- Feynman gives Ramsey 50:1 odds $\not{P}$ would not be observable
  Ramsey experiment starting at ORNL gets derailed by fission experiments...
  it’s OK, Ramsey won 1989 Nobel for his fringes
- 1957 3 simultaneous experimental measurements of $\not{P}$ $\rightarrow$

Parity (From A. Zee “Fearful Symmetry”)

As of 1956, we thought all interactions respected parity

Parity operator

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

P  $=$ 

1957:

$\tau - \theta$ Puzzle

+ μ decay

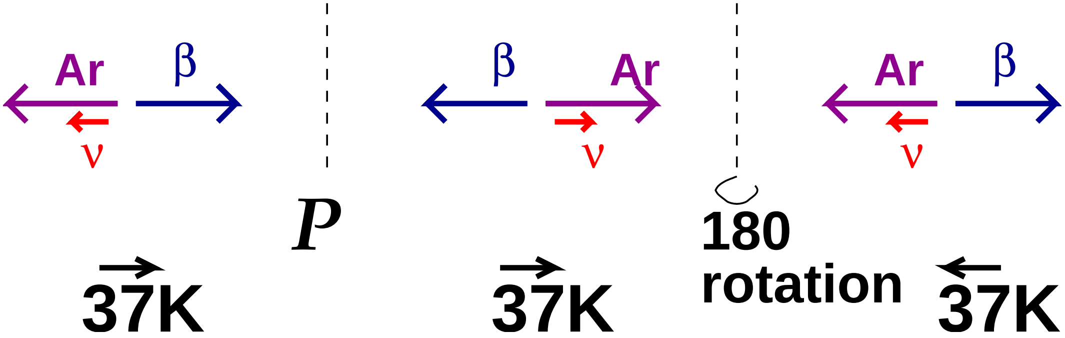
+ ^{60}Co decay $\Rightarrow$

P  $\neq$ 

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

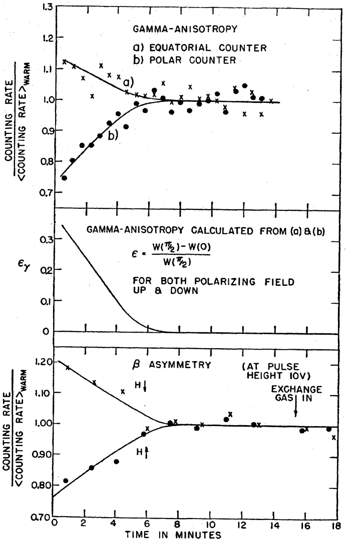
$\vec{r} \to -\vec{r}$ $\quad \vec{p} \sim \frac{d\vec{r}}{dt} \to -\vec{p}$ $\quad \vec{J} = \vec{r} \times \vec{p} \to +\vec{J}$

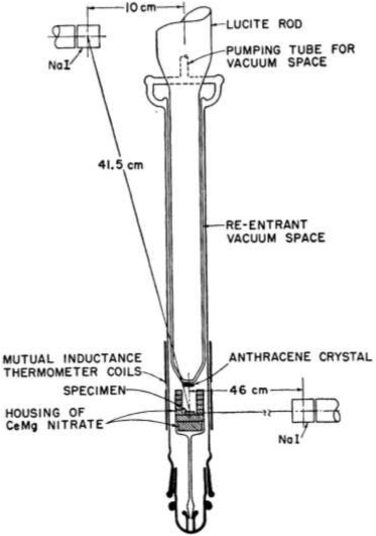


⇒ A spin flip corresponds exactly to *P* reversal

Decays don't exactly test *T*-reversal symmetry

One experimental discovery of parity violation





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

Dilution Refrigerator to spin-polarize

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

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

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

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

Followup:

$^{58}\mathrm{Co} \rightarrow {}^{58}\mathrm{Fe} + \beta^+ + \nu$

$A_{\beta+} > 0$

CP conserved?

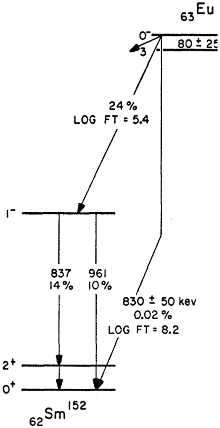
Measure ν helicity $\epsilon=\hat{s}_\nu \cdot \hat{k}_\nu$ directly: transfer $\hat{s}_\nu$ to γ circular polarization; boost $\vec{k}_\gamma$ by $\pm\vec{k}_\nu$

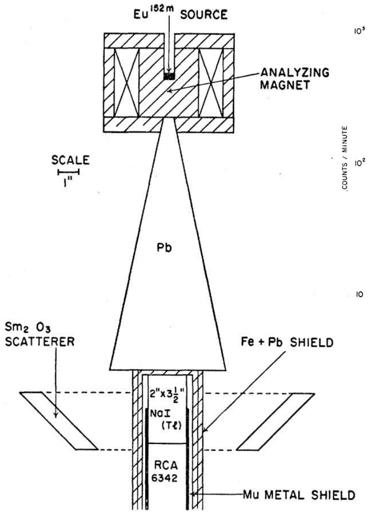
Goldhaber, Grodzins, Sunyar Phys Rev 109 1015 (Dec 1957)

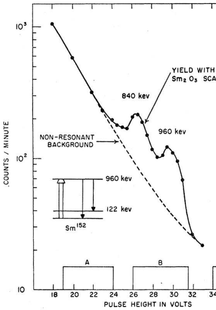
$e^- + {}^{152m}\mathrm{Eu} \rightarrow \nu + {}^{152}\mathrm{Sm}$

- **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$\pm$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)







Surprisingly enough, this is the best direct measurement of ν helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$

TRIUMF

Physics and time reversal

When t $\rightarrow$ -t, does anything change?

- **Wave Equ. is 2nd-order in t:** $\nabla^2 u = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2}$ **symmetric in t**
- **Heat Equ. is 1st-order in t:** $\nabla^2 u = -\frac{\partial u}{\partial t}$ **t$\rightarrow$ -t, boom?**

'Dissipation', like friction... The arrow of time remains a research problem in stat mech, but it's not from (known) particle physics

- **Schroedinger Equation is 1st order:** $i\hbar\frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2}$

'Take the complex conjugate'
(but see Dressel et al. PRL 119 220507 (2017)
"Arrow of Time for Continuous Quantum Measurements")

Microscopic physics was thought to be symmetric in t

Simulating $\not{T}$ in decays?

We've constructed an angular correlation, a scalar observable, by a dot product of two vectors

$1 + \hat{p} \cdot \hat{J}$

which is odd under *P* as we need

($\vec{p}$ is even, $\vec{J} = \vec{r} \times \vec{p}$ is odd)

But $\vec{J}$ is odd under *T*, not even

So we need at least 3 vectors to have a T-odd scalar observable,
the scalar triple product $\vec{v1} \cdot (\vec{v2} \times \vec{v3})$

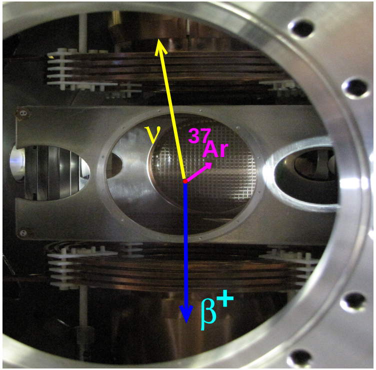
An example $\rightarrow$

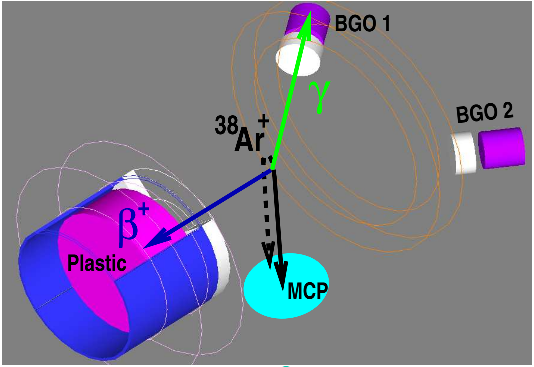
TRIUMF $\not{T}$ correlation of 3 of 4 momenta

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

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

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





- We can test symmetry of apparatus with coincident pairs ☺
- Not exact. Outgoing particles interact → fake $\not{T}$

EDM in a fundamental particle breaks T: this is exact

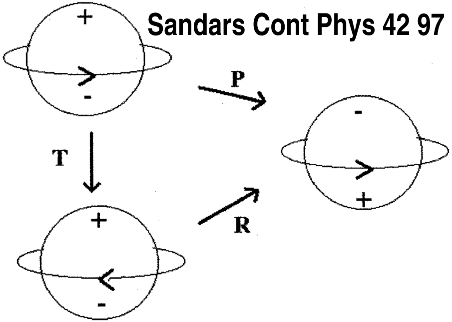
Landau, Nucl. Phys. 3 (1957) p. 127

Electric Dipole moment $\vec{d} = \sum q_i \vec{r}_i$

Since the angular momentum is the only vector in the problem, $\vec{d} = a\vec{J}$

Under T, $\vec{J} \stackrel{t\to -t}{\to} -\vec{J} \quad \vec{d} \stackrel{t\to -t}{\to} +\vec{d}$

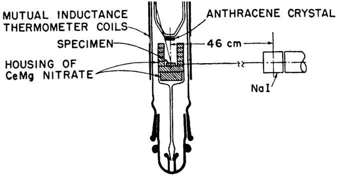
If the physics is invariant under T, this is a contradiction, $\Rightarrow a = 0$

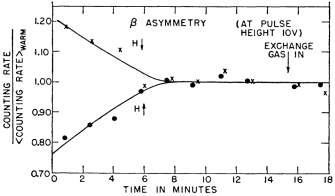


[• The other logical possibility: there are 2 states, with opposite sign of the EDM, and T just formally changes one state to the other.
For most fundamental particles, we know there aren't 2 states
Why do we know the electron doesn't have 2 states?
E.g. some polar molecules have a dipole moment listed in tables, which produces degenerate states and does not break T ...]

TRIUMF

Parity broken, why not $\not{T}$ime?





Immediately after $\not{P}$arity 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

$D\hat{J}\cdot\frac{\vec{p}_\beta}{E_\beta}\times\frac{\vec{p}_\nu}{E_\beta}$ $\quad R\vec{\sigma}_\beta\cdot\hat{\mathbf{J}}\times\frac{\vec{\mathbf{p}}_\beta}{E_\beta}$ **TRINAT has *D* ideas**

are consistent with $\not{T} < 0.001$

(We’re looking for $\not{T}$ that could still be big:) but some has been found $\rightarrow$

PHYSICAL REVIEW VOLUME 106, NUMBER 3

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J. D. Jackson,* S. B. Treiman, and H. W. Wyld, Jr.
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$\not{CP}$ discovered in $K\bar{K}$ meson decays in 1963, though not much (Cronin and Fitch Nobel prize 1980)

Quark eigenstates in the weak interaction:

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,

$\rightarrow$ 3x3 unitary "CKM" matrix between $|d\rangle, |s\rangle, |b\rangle$

There is one complex phase, which leads to this type of $\not{CP}$

A reason for 3 generations of particles?

That one phase is consistent with $\not{CP}$ in $K\bar{K}$ and $B\bar{B}$ systems

There have been hints in $K\bar{K}$ and $B\bar{B}$ of more $\not{CP}$ than in the standard model,

$p\bar{p} \rightarrow \mu^+\mu^+$ or $\mu^-\mu^-$ $\not{CP}$ at 3.6 σ Abazov PRD 2014 Fermilab;
so this 2001 cartoon was a little premature $\rightarrow$

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

T2K ν_μ oscillations different from $\bar{\nu}_\mu$ at 2 to 3 σ Nature 580 339 (2020)
$\not{CP}$ could have some utility for cosmology $\rightarrow$

The excess of matter over antimatter can come from $\not{CP}$

Sakharov JETP Lett 5 24 (1967) used $\not{CP}$ to generate the universe's excess of matter over antimatter:

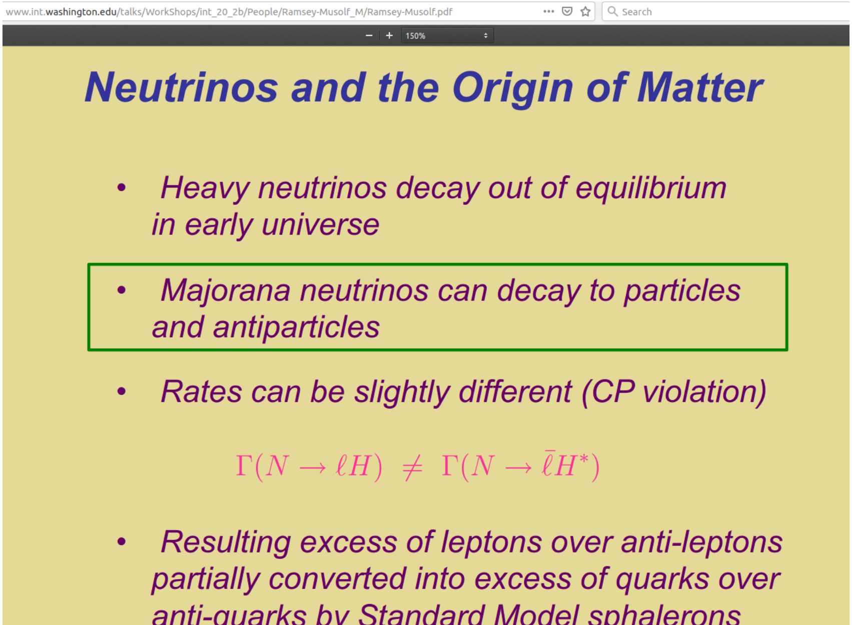
- **$\not{CP}$,**
- **baryon nonconservation, and**
- **nonequilibrium.**

But known $\not{CP}$ is too small by 10^{10}, so 'we' need more to exist. **Caveats:**

- **You could use $\not{CPT}$ [Dolgov Phys Rep 222 (1992) 309]**
- **We need $\not{CP}$ in the early universe, not necessarily now**

So we look for more $\not{CP}$. How is this related to $\not{T}$?

that seems a little abstract
concrete demonstrative example (Ramsey-Musolf at INT 2020
$\not{CP}$ explaining T2K's ν vs. $\bar{\nu}$ result lets heavy *N* decay this way in some models



$\not{T}$ is related to $\not{CP}$ by the "CPT Theorem"

"All local Lorentz invariant QFT's are invariant under CPT"
Schwinger Phys Rev 82 914 (1951)
Lüders, Pauli, Bell 1954

- Gravity $\rightarrow$ not flat:

K meson experiments Adler PhysLettB 364 (1995) 239 test $\not{CPT}$ to within 1000x expected from quantum gravity

- Strings not 'local'

Proofs still pursued $\rightarrow$

Studies in History and Philosophy of Modern Physics 45 (2014) 46–65

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On the CPT theorem

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ABSTRACT

We provide a careful development and rigorous proof of the CPT theorem within the framework of mainstream (Lagrangian) quantum field theory. This is in contrast to the usual rigorous proofs in purely axiomatic frameworks, and non-rigorous proof-sketches in the mainstream approach. We construct the CPT transformation for a general field directly, without appealing to the enumerative classification of representations, and in a manner that is clearly related to the requirements of our proof. Our approach applies equally in Minkowski spacetimes of any dimension at least three, and is in principle neutral between classical and quantum field theories: the quantum CPT theorem has a natural classical analogue. The key mathematical tool is that of complexification; this tool is central to the existing axiomatic proofs, but plays no overt role in the usual mainstream approaches to CPT.

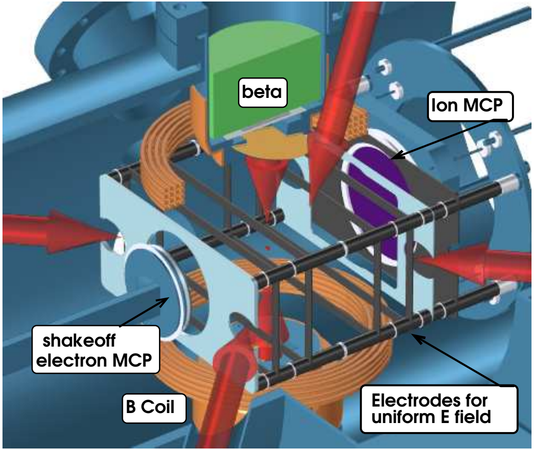
When citing this paper, please use the full journal title *Studies in History and Philosophy of Modern Physics*

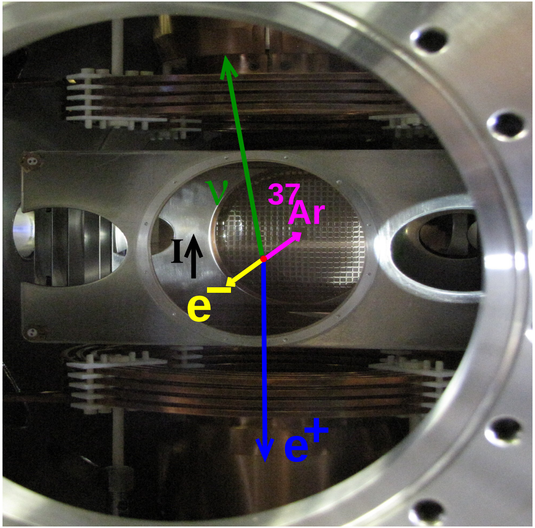
Assuming CPT, $\not{CP} \Leftrightarrow \not{T}$ in most physics theories
The matter excess then motivates $\not{T}$ searches

TRIUMF

^{37}K decay geometry

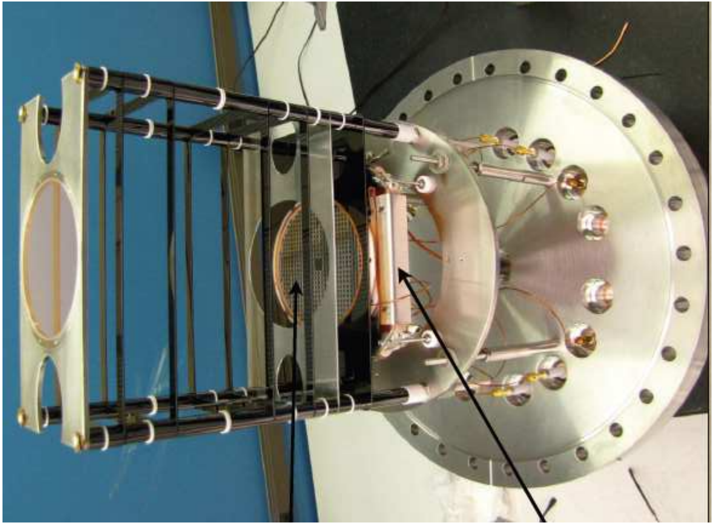
TEXAS A&M UNIVERSITY





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

ion MCP assembly



14 inch CF flange

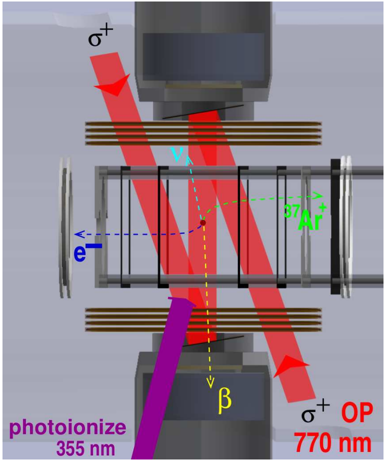
Electrostatic field

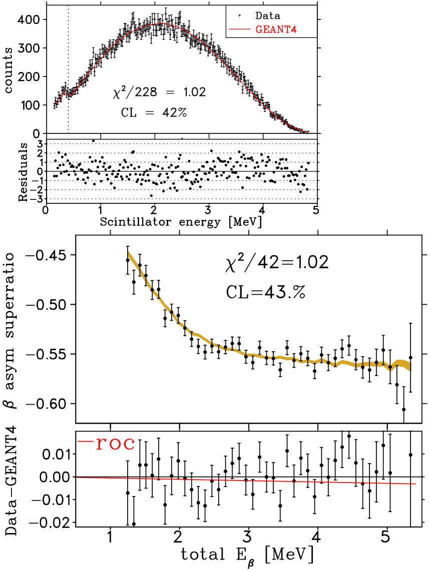
delay-line anode for position info

no stray wires

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

β^+ asymmetry ^{37}K data





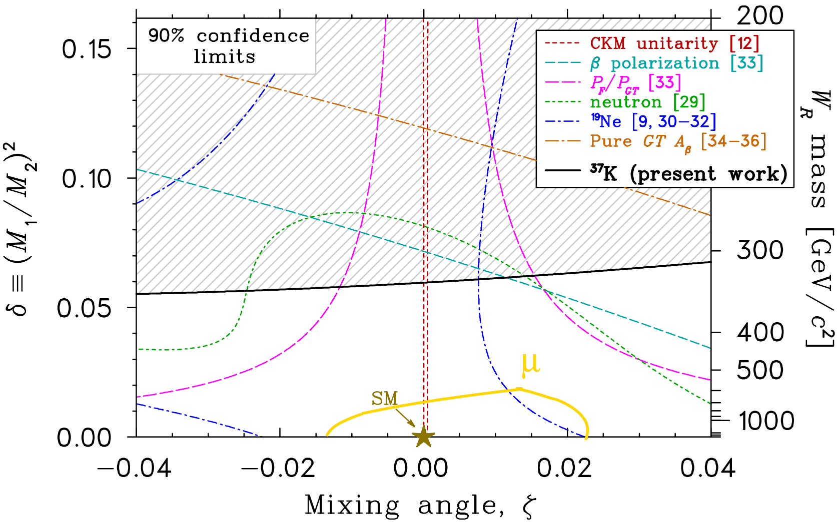
Fenker et al. Phys Rev Lett 120, 062502 (2018)

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

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 The nucleon: a special place for γ's

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

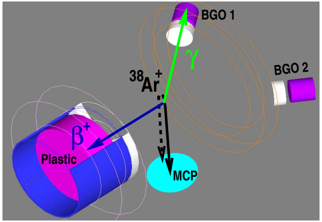
$$\mathcal{L} = \frac{-4c_5}{{m_{\rm nucleon}}^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu L}F_{\nu\rho}$$

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

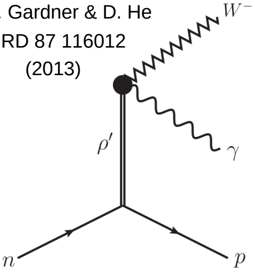
Particles strongly interacting with themselves
but weakly interacting with us
are also possible dark matter candidates
See the 'SIMP miracle' Hochberg et al. arXiv:1402.5143



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

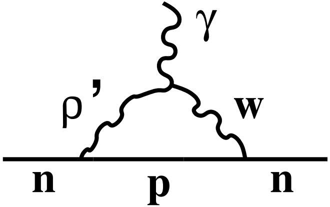
Some *TRV* $\gamma\beta\nu$ interactions, e.g. :

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 $\sim 10^8$.

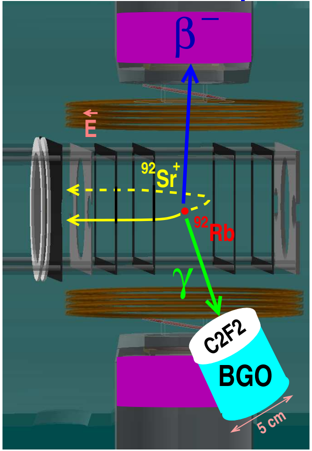
→ *TRV* $\beta\nu\gamma$ from such interactions likely too tiny to measure ☹

• 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

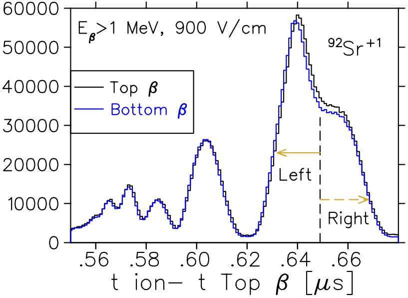
• Direct constraint from n → p $\beta\nu\gamma$ branch $\propto |c_5|^2$
Bales PRL 2016: $3.4 \pm 0.2 \times 10^{-3}$ (theory 3.1×10^{-3})
$\Rightarrow \frac{\mathrm{Im}(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ ^{37}K *TRV* asym can be ~ 1 ☺

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



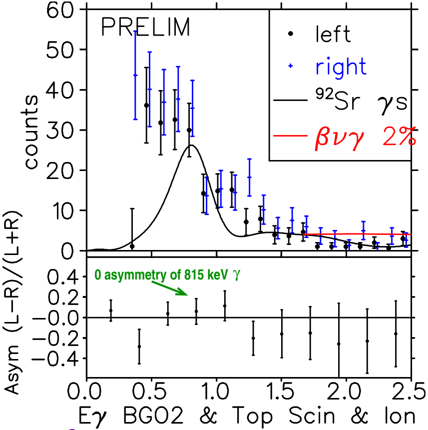
$\beta^- \cap {}^{92}\mathrm{Sr}^+$

'left' vs. 'right':

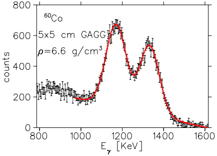


$\beta^- \cap {}^{92}\mathrm{Sr}^+ \cap \gamma$

'left' vs. 'right':



(other γ detector sees background from upstream)



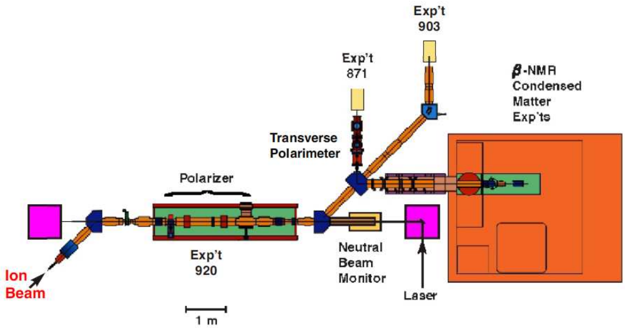
BGO → GAGG ($Ce:Gd_3Al_2Ga_3O_{12}$)

- **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

Laser-Polarized beam at TRIUMF/ISAC

C.D.P. Levy et al. / Nuclear Physics A 746 (2004) 206c–209c

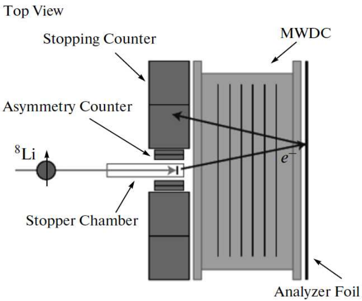


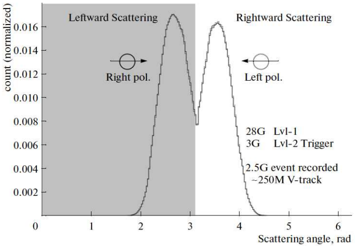
- **50-70% polarization, 20-50% efficient Re-stripped +1 beam deliverable to several beamlines**
- **Used for aligned ^{20}Na β correlation (2nd-class current comparison with ^{20}F) K. Minamisono PRC 84 055501 (2011)**

^{8}Li *R*, Jiro Murata, Rikkyo U.

TRV possibilities include ^{36}K *E* and ^{20}Na β-delayed α energy shift (Clifford PRL 50 (1983) 23)

Mott scattering Time reversal Violation progress





$$R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} \times \vec{\mathbf{v}}_\beta \xrightarrow{t \to -t} -R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} \times \vec{\mathbf{v}}_\beta$$

Totsuka et al Phys Part Nuclei 45 244 (2014)

Small false asymmetry in rectangular geometry

→ a more symmetric cylindrical geometry, finished data-taking Dec 2017

$\not P$ in atoms is tiny

P  = 

A "chargeless" weak interaction: the biggest Standard Model prediction

1973 ν scattering Gargamelle CERN

Atoms are mostly chemistry,
i.e. electromagnetism, which respects Parity

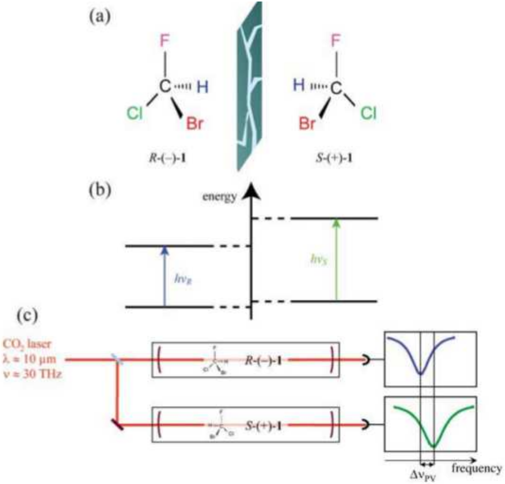
Some $\not P$ effects are ppb

Consider 2 signatures:

Molecular enantiomer energies;

Controlled Stark-$\not P$ interference

Molecule binding energy depends on handedness



Letokhov, Difference of energy-levels of left and right molecules due to weak interactions. Phys Lett A (1975) 53 275

Darquie <u>et al.</u> CHIRALITY 22 870 (2010) Progress Toward the 1st Observation of $\not{P}$ in Chiral Molecules by High-Resolution Laser Spec

- **Very small $\sim 10^{-16}$ to 10^{-14} energy shifts.**

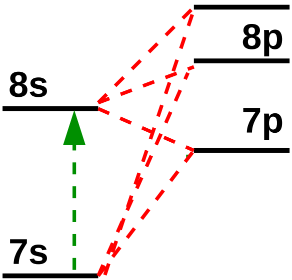
Astrobiology 18 (2018) Selection of Amino Acid Chirality via ν Interactions with ^{14}N in $\vec{E} \times \vec{B}$ Fields M.A. Famiano, R. N. Boyd...

Forbidden transition in an atom

Consider an E1 "electric dipole" transition between S states.
This is $\not{P}$ and forbidden.
(M1 "magnetic dipole" transition is allowed... I avoid a lot of neat physics by setting it to zero.)

Populate the 8S state, wait for it to decay by a single blue photon to the 7S. Rate $\sim$ interaction^2, lifetime $\sim$ 10^{10} sec (300 yr). With 10^9 trapped atoms, you get about 6 per minute $\rightarrow$.
9 months for ppt accuracy (a million events).

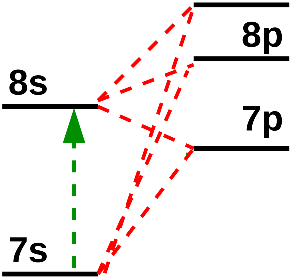
Instead we want something linear in the weak interaction:



Stark - Weak interference: flip E field

This idea is credited to the Bouchiat's (theorist-experimentalist couple)
Wieman in Boulder made the best 'chargeless weak interaction" measurement in Cesium atoms in 1999.
Emulating Boulder Cs scheme in Fr:

$$|A_{7s\to 8s}|^2 = |E1_{\rm Stark} + E1_{\rm PNC}|^2 \approx |E1_{\rm stark}|^2 + 2E1_{\rm Stark}E1_{\rm PNC}$$

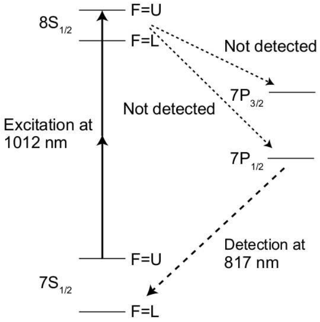


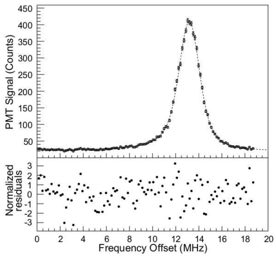
The interference term is $\sim 10^{-9}$ of an allowed E1 transition amplitude (rather than 10^{-18}).
By picking an E field one can make the asymmetry about 10^{-3}

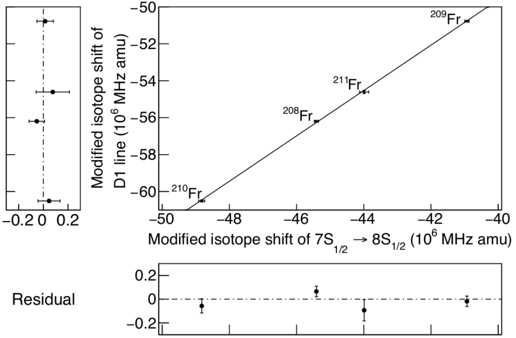
- Then calculate (or, preferably, measure) $E1_{\rm Stark}$ to extract $E1_{\rm PNC}$

FrPNC Excitation of parity-violating transition

M. Kalita et al. Phys Rev A 97 042507 (2018)
Field shift(8s)/(7s) 1.228±0.019 exp. vs. 1.234±0.010 atomic theory



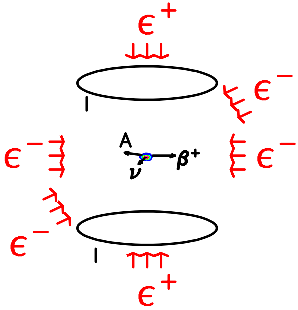




Discrete symmetries in β decay

- **Parity *P* symmetry**
  How to test *P* symmetry experimentally
  Only left-handed ν so far
- **There is time-reversal symmetry violation**
  $\not{T}$ in nature

There should? be more: 'baryogenesis'



$\not{P}$, $\not{T}$ experiments at/with TRIUMF

- TRIUMF Neutral Atom trap (me ☺) β decay
- Laser-polarized beamline at TRIUMF

[Non-decays: • ν mixing Nature 580 339 (2020)
- $\not{P}$ in Fr atoms; Searches for electric dipole moment;
- Using ultra-cold neutrons;
- hopefully atomic fountain of francium atoms]

https://trinat.triumf.ca/talks/triumf-summer-undergrad-talk-2021-jb

Preview: Weak interaction breaks parity: Consequences?

'Pulsar kicks'

IGR J11014–6103 v= 0.01 c ↘

Fuller PRD 2003

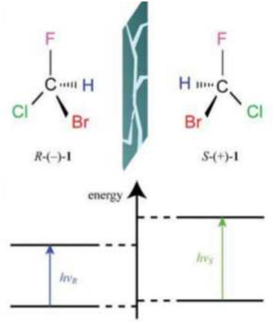
Forced $p + e^- \rightarrow n + \nu$

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

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. :

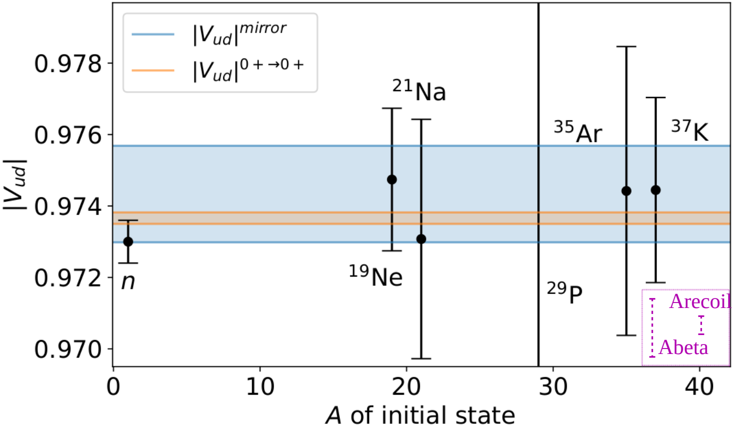
Astrobiology 18 (2018) Selection of Amino Acid Chirality via ν Interactions with ^{14}N in $\vec{E} \times \vec{B}$ Fields

M.A. Famiano, R.N. Boyd

(TRIUMF EEC 90's)...

Weak interaction: same strength, all nuclei?

TEXAS A&M UNIVERSITY



Hayen and Severijns, arXiv:1906.09870 (June 2019)

Deduced V_{ud} from mirror decays

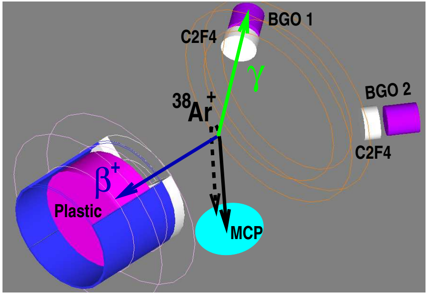
Are people overestimating their uncertainties? We aren't ☺

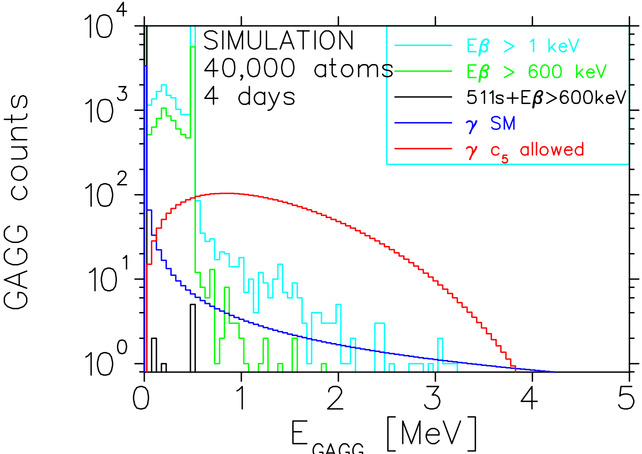
We project to reach 0.0005 accuracy, as good as any $0^+ \to 0^+$ except ^{26m}Al.

Assumes 5% isospin breaking calculation.

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)

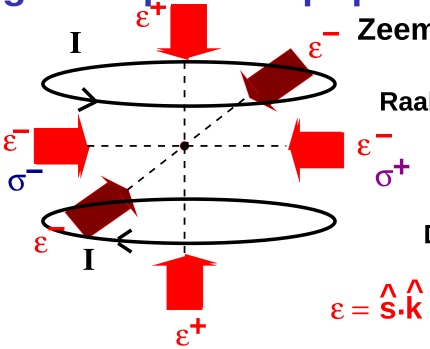




We are concentrating on:

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

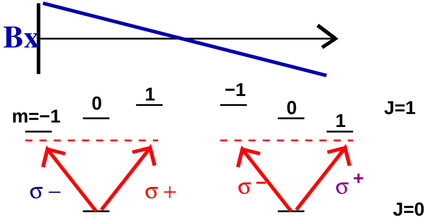
Magneto-optical trap: perturb atoms



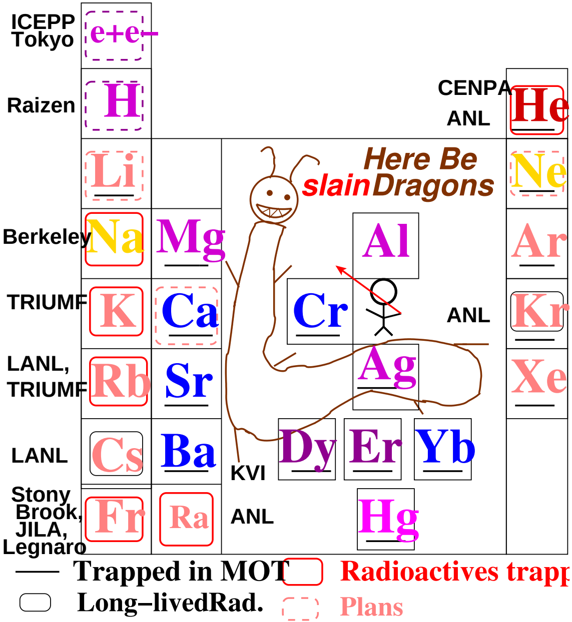
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

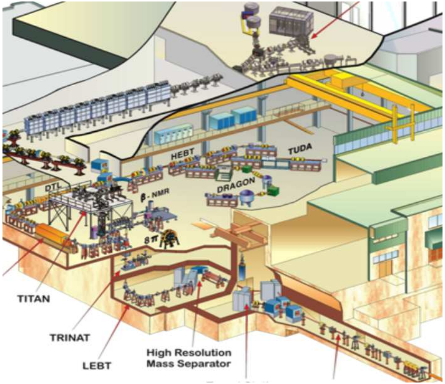
Damped harmonic oscillator



What elements can be laser cooled?



TRIumf Neutral Atom trap at ISAC

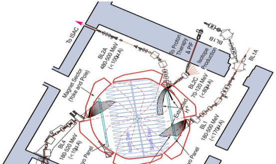


^{37}K 8x10^{7}/s

TiC target 1750^{o}C

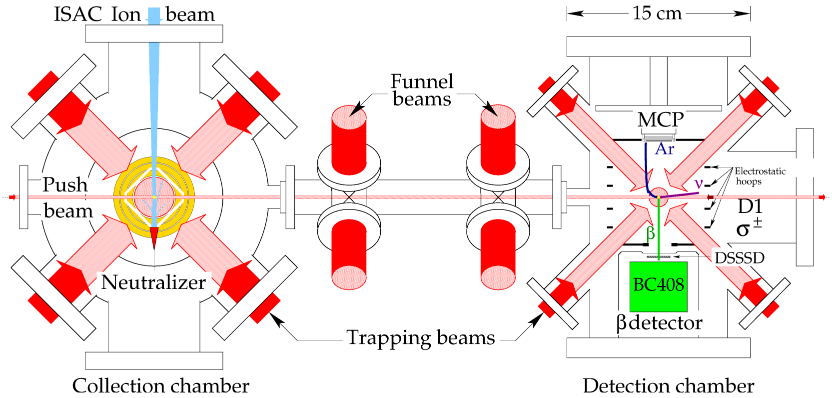
70 μA protons

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



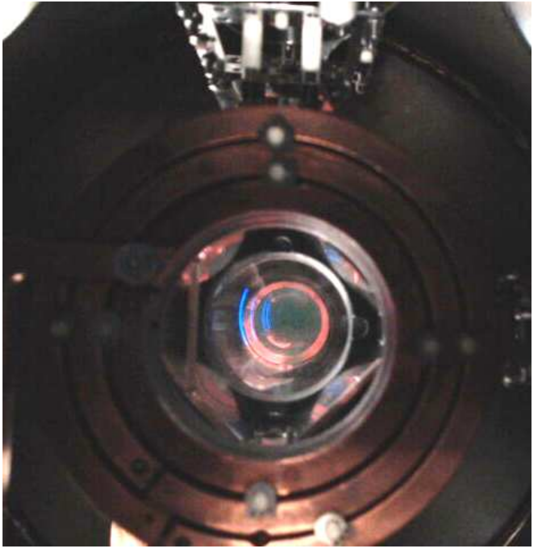
TRINAT plan view

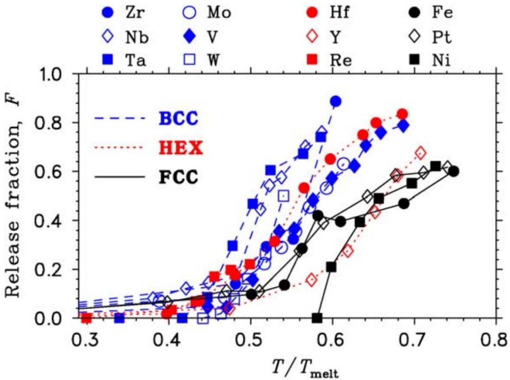
- **Isotope/Isomer selective**
- **75% transfer**
- **Avoid untrapped atom background with 2nd trap**
- **0.7 mm cloud for β-Ar$^+$ $\rightarrow \nu$ momentum**

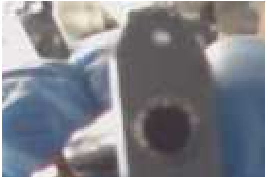


- **Spin-polarized 99.1±0.1%**

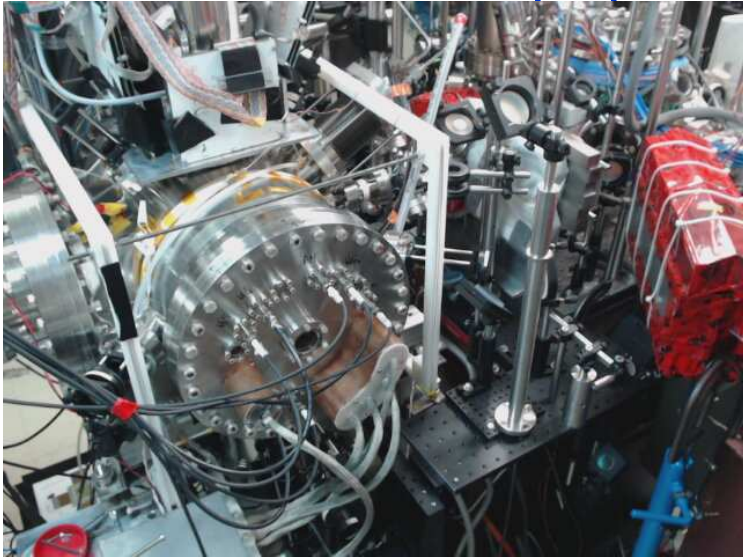
Neutralizer and Collection trap



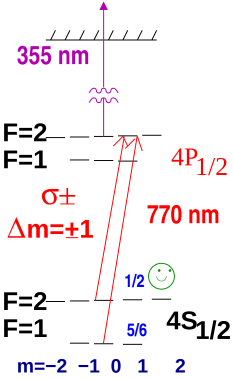


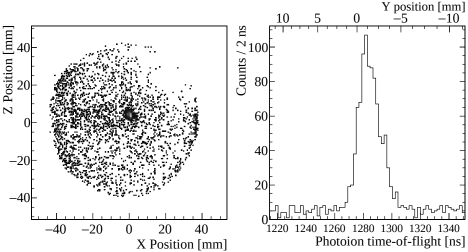


TRIUMF TRINAT lab: "tabletop experiment"



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