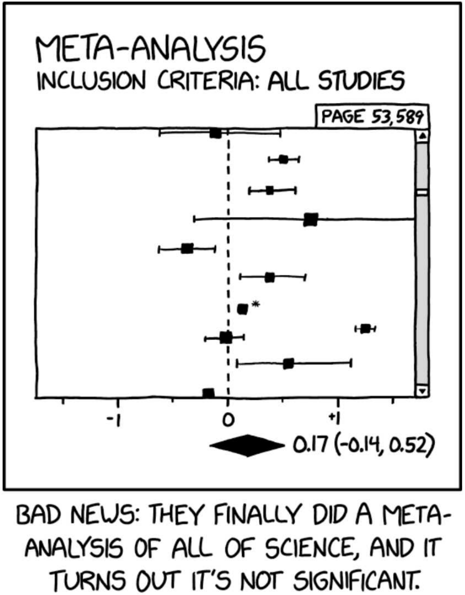
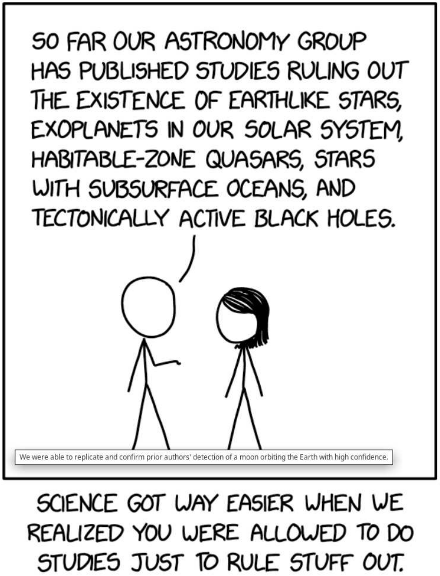
xkcd.com/2755/



xkcd.com/2783/



Laser Atom Traps at TRIUMF

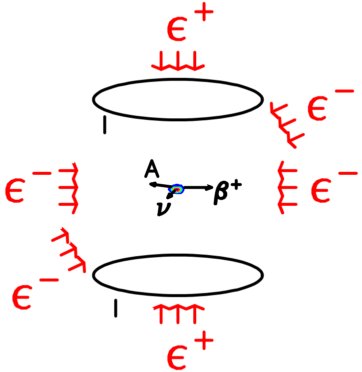
- How atoms traps don't work, and how they do
- Intro to Parity:
  Its signatures in decays and in atoms
- TRIUMF Atom Trap for Beta Decay

Deduce ν momentum from the other products

Test standard model predictions for angular distributions: so far all ν's are left-handed

- Francium Trapping Facility

Measuring the weak interaction in atoms by parity violation



Collaborations

TRIumf Neutral Atom Trap collaboration:

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D. Melconian

TRIUMF

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J.A. Behr
Undergrad
P. Miri

UBC

J.C. McNeil

UNIVERSITY OF MANITOBA

M. Anholm
G. Gwinner

Support: NSERC, NRC through TRIUMF, U.S. DOE, State of Texas

FrPNC collaboration

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UNIVERSITY OF MARYLAND 1856

L. Orozco

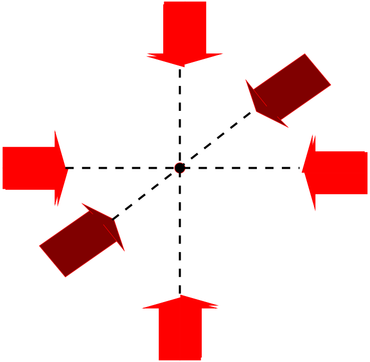
TRIUMF

J.A. Behr
A. Gorelov

Support: NSERC, NRC through TRIUMF, U.S. NSF

Magneto-optical trap: damping

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

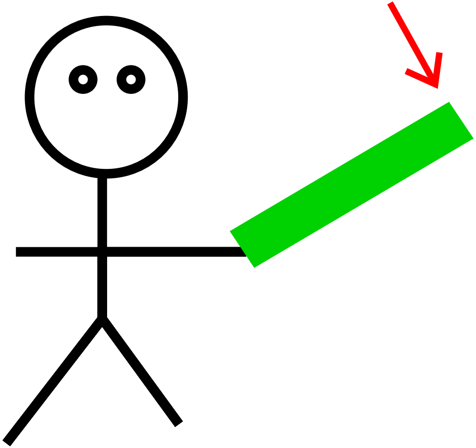


‘Optical molasses’

We still need a position-dependent force

"'Light sabers' would make atom traps easy" (H. Norton)

$$\vec{\nabla} \cdot \vec{S} \neq 0$$



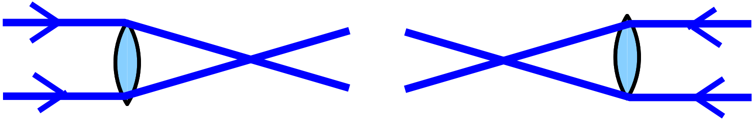
But light sabers violate Poynting's theorem

“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):



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

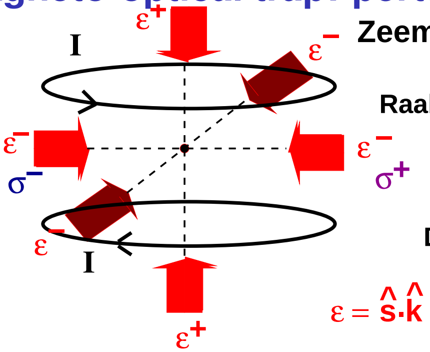
Using Poynting’s theorem:

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

Dodges !

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

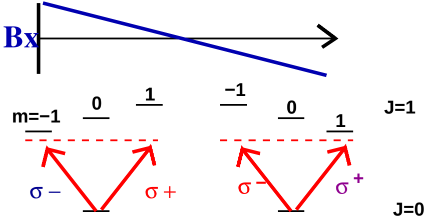
Magneto-optical trap: perturb atoms



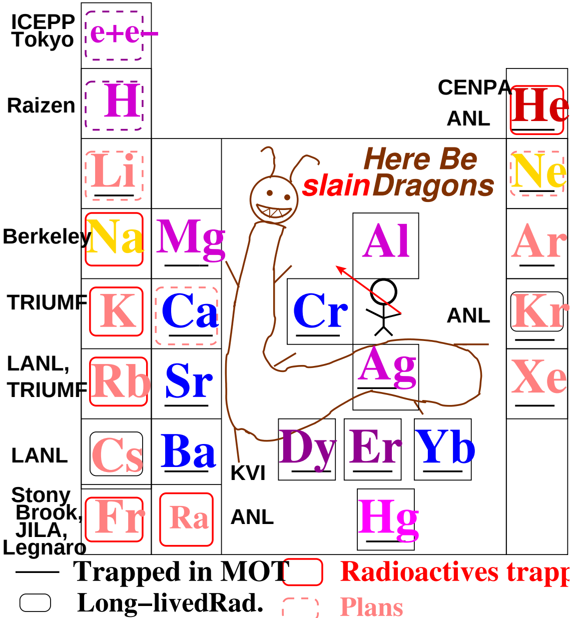
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator



What elements can be laser cooled?

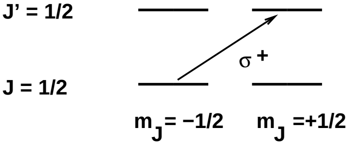


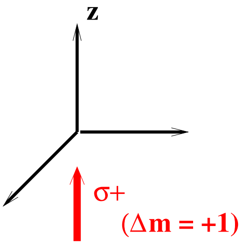
How to spin-polarize a nucleus with a laser

Polarization of nuclei by Optical Pumping

Biased random walk

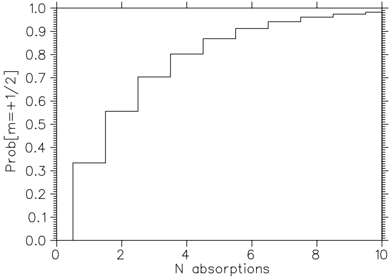
Simple example:





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

Need 12 cycles to get to 99% of maximum.



Parity (From A. Zee "Fearful Symmetry")

As of 1956, we thought all interactions respected parity

Parity operator

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

P  $=$ 

1957:

$\tau - \theta$ Puzzle

+ μ decay

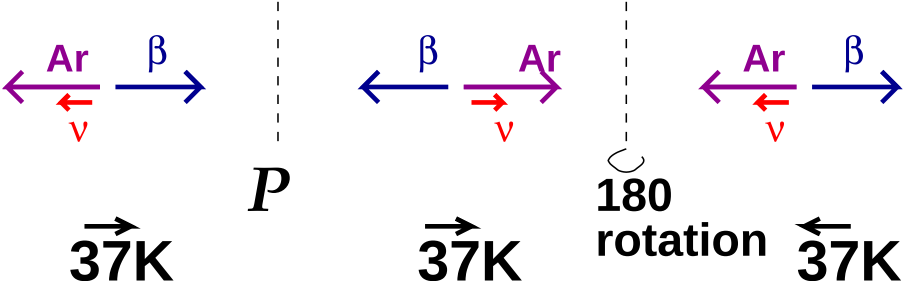
+ ^{60}Co decay $\Rightarrow$

P  $\neq$ 

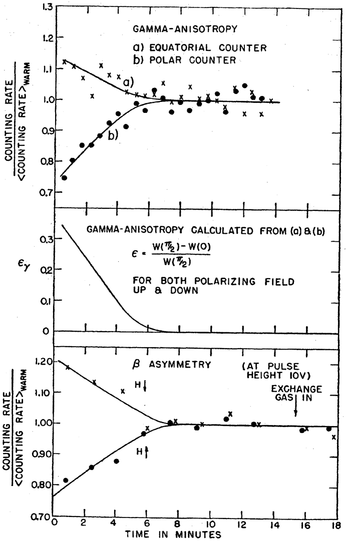
Decays: Parity Operation can be simulated by Spin Flip

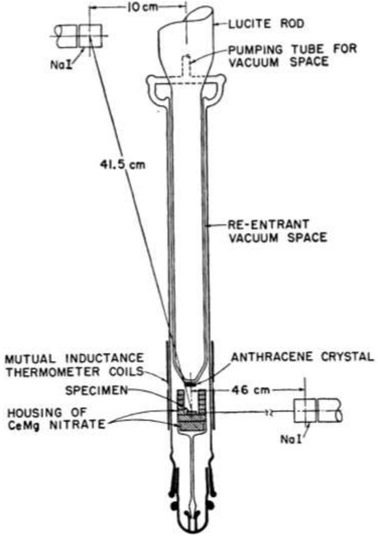
Under Parity operation *P*:

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



One experimental discovery of parity violation





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

Dilution Refrigerator to spin-polarize

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

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

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

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

Followup:

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

$$A_{\beta+} > 0$$

$\not{P}$ in atoms is tiny

P  = 

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

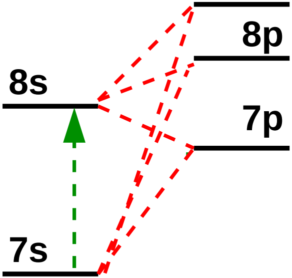
A “chargeless” weak interaction: the biggest Standard Model prediction

1973 ν scattering
Gargamelle CERN

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:

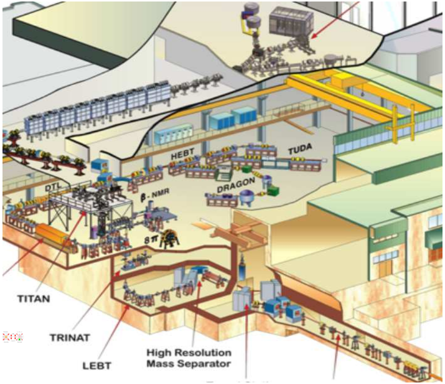
$$|A_{7s\rightarrow 8s}|^2 = |E1_{\mathrm{Stark}} + E1_{\mathrm{PNC}}|^2$$
$$\approx |E1_{\mathrm{stark}}|^2 + 2E1_{\mathrm{Stark}}E1_{\mathrm{PNC}}$$



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) $E1_{\mathrm{Stark}}$ to extract $E1_{\mathrm{PNC}}$

TRIumf Neutral Atom trap at Isotope Separator + ACcelerator

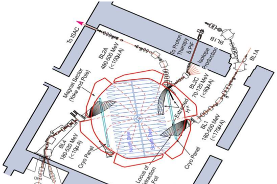


^{47}K 8x10^6/s

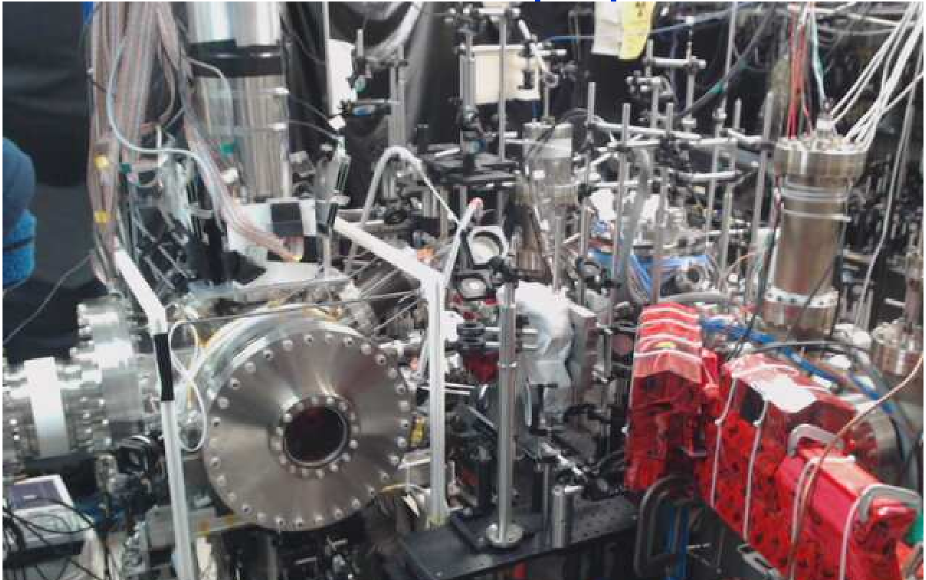
UC target $\sim$ 2000^{o}C

20 μA protons

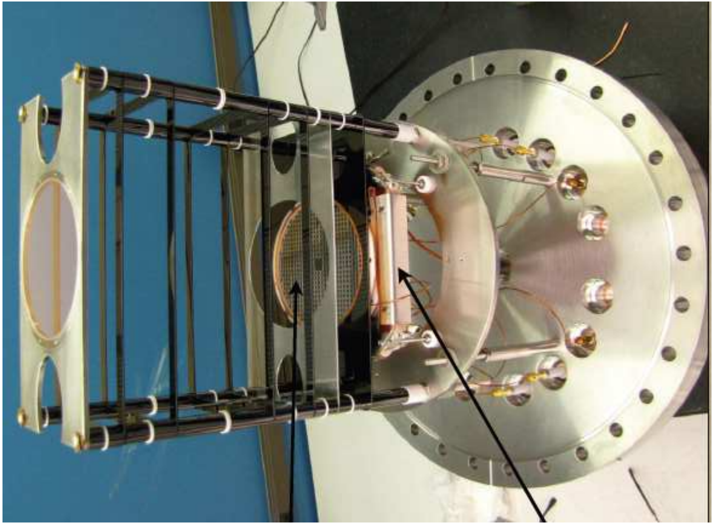
main TRIUMF cyclotron
'world's largest'
500 MeV H$^-$ (0.5 Tesla)



TRINAT lab: “tabletop experiment”



ion MCP assembly



14 inch CF flange

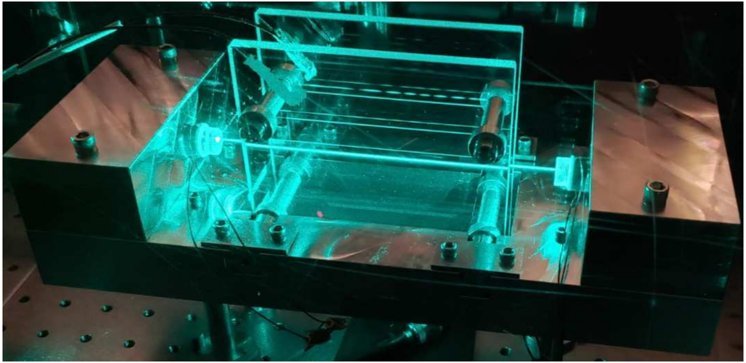
Electrostatic field

delay-line anode for position info

no stray wires

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

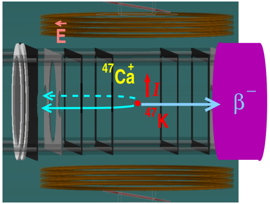
Optical PowerBuildupCavity



To drive the weak transition

- 316LN SS + titanium +PEEK (no magnetism)
- Q $\approx$ 4,000

- Laser frequency-locked to UltraLowExpansion cavity (drifts $\sim$ MHz/month)
- PBC length is locked by PZT stack to keep integral number of λ's in cavity

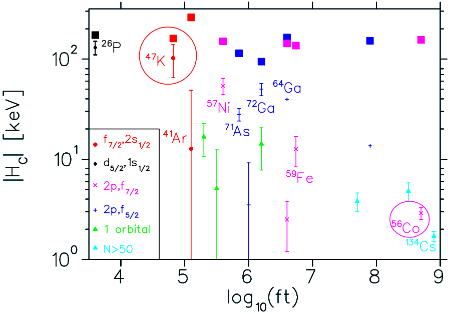


$\not{T}$ and analog-antianalog isospin mixing in ^{47}K β^- decay

Measuring ~~isospin~~ in $^{47}_{19}$K^{28} decay determines sensitivity to $\not{T}$ parity-even ~~isospin~~ N-N interactions via planned $D\vec{I}\cdot\vec{v_\beta}\times\vec{v_\nu}$

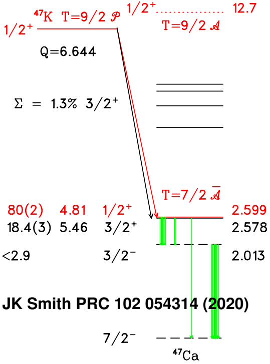
B. Kootte et al. Phys Rev C 109 L052501 2024

TOPE N-N naturally ~~isospin~~: Complementary to EDM's, NOPTREX



I=1/2$^+$ ^{47}K β^- decay has large:

- $H_C = \langle\bar{\mathcal{A}}|V_{\rm Coul}|\mathcal{A}\rangle$ = 101 ± 37 keV
- fraction of $\mathcal{A}-\bar{\mathcal{A}}$ mixing prediction Auerbach, Loc NPA 1027 122521 (2022)



JK Smith PRC 102 054314 (2020)

$^{47}_{20}$Ca^{27}'s single 1/2$^+$ state contains most of the $\bar{\mathcal{A}}$ config

$y = g_V M_F / g_A M_{GT}$ = 0.098±0.037

$D \propto y\frac{\langle f|TOPE|IAS\rangle}{\langle f|V_{ISB}|IAS\rangle} \rightarrow$ enhanced by $\sim$ 10 to 100 in isospin-suppressed β decay

Barroso and Blin-Stoyle PL45B 178 (1973)

^{47}Ca's 1/2$^+$ simple structure → calculating $\not{T}$ nuclear matrix elements of $\hat{r}\cdot\vec{p}$ practical?

Figure of merit:

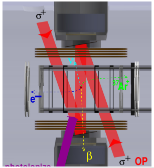
$\langle f|TOPE|IAS\rangle \propto M_{GT}\Delta E_{IAS-f} D_{\rm exp}$.

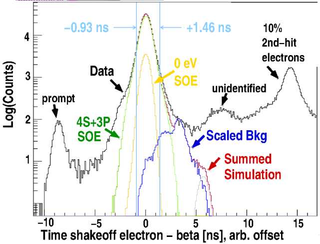
Although larger M_{GT} than ^{56}Co naively → poorer limit on TOPE for given σ_D, simplicity of f might increase $\langle f|TOPE|IAS\rangle$

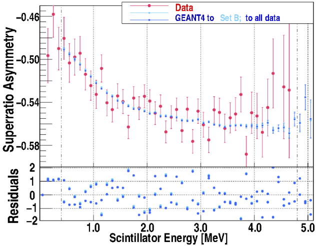
M. Anholm et al. PRC 113, L012201 (2026)

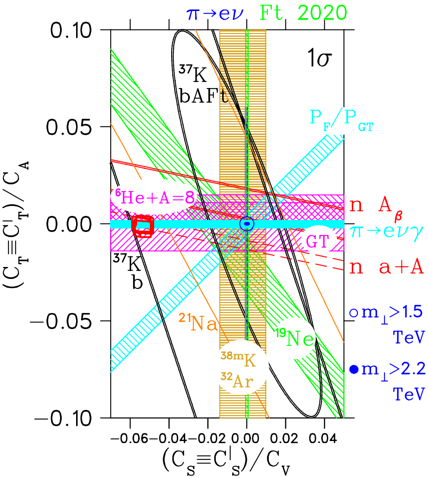
$A_\beta[E_\beta]$: New Physics with Opposite Helicity

TRINAT ^{37}K results don't rule out a new quantum number









- neutron $a_{\beta\nu}$ aSPECT 2025 3σ disagreement with SM at few ppt.
  - 2nd-class CVC-breaking e/A=-30 explains, evades: nuclear β decay (8 exps.)
    PSI $\pi \rightarrow e\nu\gamma$
    LHC $p + p \rightarrow e + M_T$
- e/A lepton-nucleon charged interaction induced by QCD has same signature as quark-lepton Lorentz scalar.

One model: a 2nd set of quarks with a new quantum number

Holstein Treiman 1976 Feynman called this "smell"

Improved measurement of ^{38m}K $\langle r^2_{ch} \rangle$ for V_{ud} corrections

J.A. Behr, P. Hembling, F. Klose, B. Ohayon, B.K. Sahoo

Isospin breaking of β decay

ψ_i and ψ_f can be related to triplets of isobaric charge radii Seng, Gorchtein Phys Lett B 2023

Only triplet with $\langle r^2_{charge} \rangle^{\frac{1}{2}}$ known is A=38:

^{38}Ca 3.467(1) fm,

^{38m}K 3.437(4) fm,

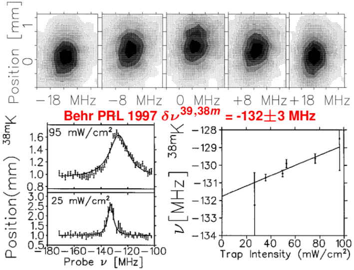
^{38}Ar 3.4028(19) fm

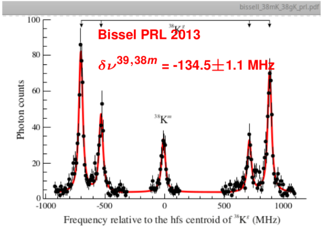
$\Rightarrow \Delta M_B^{(1)}$ = -0.03(54) fm^2;

models span 0.42 to 0.04 fm^2

Needs order of magnitude better $\langle r^2_{charge} \rangle^{\frac{1}{2}}$!

4S→4P$_{1/2}$ Γ=6 MHz





ISOLDE did much better

4S$_{1/2}$ → 5P$_{1/2}$: Γ = 1.1 MHz

for 0.1 MHz accuracy?

Katyal et al. PRA 2025 RCC K_{SMS}=-30.6±5.2