T-even symmetries:

- **Charged Weak current structure $\rightarrow$ A. Garcia**
- **Vud, b_{Fierz}, $\langle r^2 \rangle$ $\rightarrow$ C.-Y. Seng ||**
- **Neutral Weak current in Nuclei**
  - **np $\rightarrow$ d γ et al.**
  - **COHERENT nu scattering**
- **Atomic parity violation in Cs, Yb**

T-odd:

- **Electron EDM (semileptonic term)**
- **J=0 atomic/molecular EDM's**
  - **Octupole enhancement**
- **Neutron forward scattering p+s-wave**
- **β decay correlation P-odd and even**

Sterile ν

Nonlinear King plots and light bosons

$0\nu\beta\beta$ $\rightarrow$ Vandana Nanal 5/27

"Truth loves its limits, for there it meets the beautiful"

Rabindrinath Tagore, "Fireflies"

"Good people are key. Be nice."

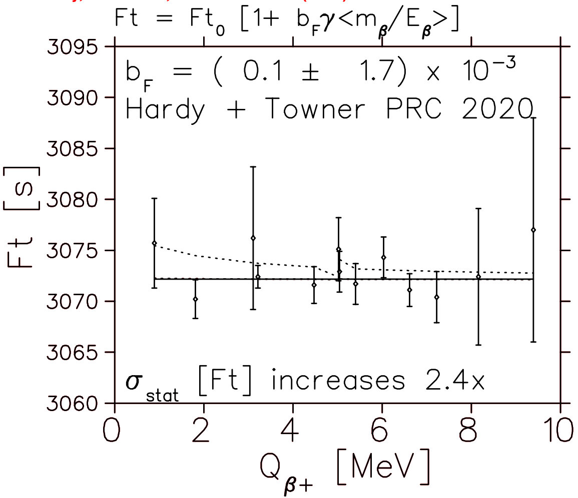
Jan Hall

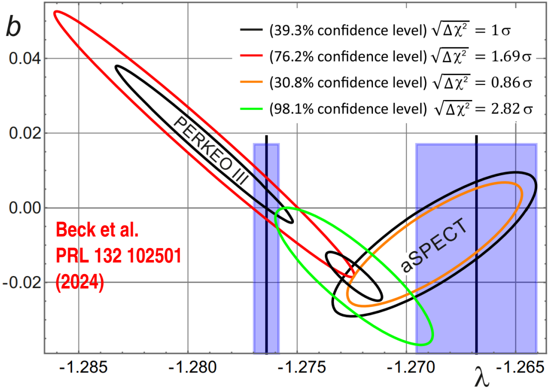
Nobel Prize talk DAMOP 2006

좋은 사람이 핵심이에요. 친절하게 대해주세요.

Floating b_{Fierz} increases Vud uncertainty 2.4 times

J.C. Hardy, I.S.Towner, PRC 102 044501 (2020)





Beck et al. shows finite Fierz term in neutron β decay

More accurate direct measurements of b_{Fierz} would help V_{ud} determination

Nab: 5/29 Fun sym Broussard 11:00, Alarcon 11:40 TRINAT ^{38m}K β-ν

Charge radii and Vud Isospin Breaking

- **Long-range Coulomb part of isospin breaking can be tested by comparing $\langle r^2_{ch} \rangle$ of isobaric analog states** Seng, Gorchtein PLB 2023**: operator and states are shared.**

QCD effects: Naito 5/27 11:00 Nucl St 2

- **Many-body atomic calculations needed to extract $\langle r^2_{ch} \rangle$ have improved by an order of magnitude**

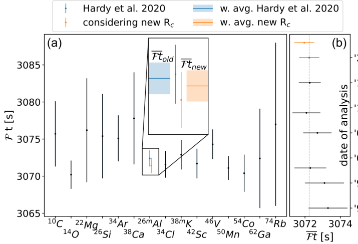
e.g. QED effects

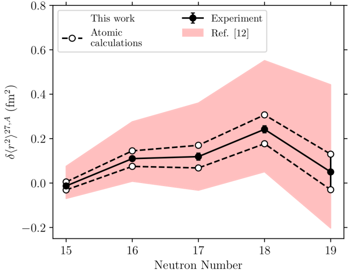
Skripnikov PRA 110 0128076 (2025)

reanalyzed ^{26m}Al $\rightarrow$

Relativistic Coupled Cluster to higher order Sahoo et al.

^{26m}Al $\langle r^2_{ch} \rangle$ Plattner PRL 131 222502 2023





isospin breaking for Vud Gorchtein 2502.17070

Seng, Gorchtein PLB 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 $\langle r^2_{ch} \rangle$ for ^{38m}K, being pursued 4S $\rightarrow$ 5P, 4S $\rightarrow$ 5S: narrower lines for greater precision; less dependence on atomic calculations: κ.

Katyal PRA 111 042813 (2025)

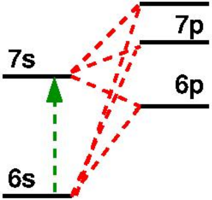
Muonic atom X-ray absolute charge radii in Cl and K 5/29 Heines 11:40 NucSt2

Weak Neutral Current

Existence of Z^0 boson, spin-1 partner of $W^{\pm}$ and the photon, was a S.M. prediction.

Searched for in :

- **ν scattering (winner: Gargamelle)**
- **Atomic $\not{P}$ by mixing atomic states of opposite parity (1st answers came in small, creating concern for the S.M. prediction; Cs APNC is the best low-energy measurement of e$^-$-q weak neutral coupling) $\propto Z^2 N$**



- **Parity violating N-N interaction, via γ asymmetries from decay of nuclear states.**

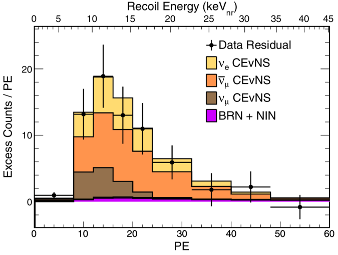
$\not{P}$ can also come from the known charged current (W^{+-}).
Isovector $\not{P}$ can only come from the neutral current, so that search was emphasized.
Isovector $\not{P}$ is suppressed compared to isoscalar and isotensor for reasons only understood more recently.
Otherwise Queens, Cal State L.A. ... would have measured weak neutral current in ^{18}F and shared Nobel with Gargamelle.

- **$\not{P}$ electron scattering on the proton at SLAC and QWeak JLAB; For n skin of ^{48}Ca, ^{208}Pb.**
- **COHERENT scattering of ν from CsI, Ar, GeCs agreeing so far with SM cross-section $\rightarrow$**

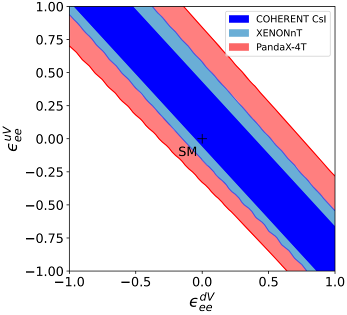
S' = S+ ϵP, Cs ϵ $\sim 10^{-8}$: constraining interactions $\sim 10^{-10}$ of E&M

COHERENT scattering of ν's from stopped π source

CsI agrees SM Akimov PRL 129 08101 (2022)

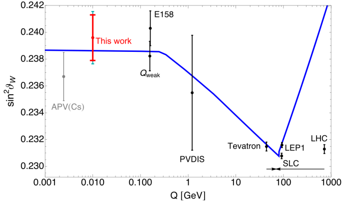


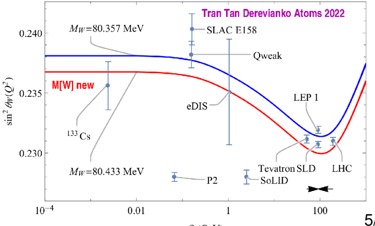
Constraints on new ν interactions compared to ^{8}B solar ν's in PandaX-4T and XENONnT Li PRD 111 035002 (2025)



Measurements also in Ar PRL 2021, **Ge** arXiv:2406.13806

Weak neutral current amplitude with 10% accuracy at Q=50 MeV. Average of COHERENT CsI and Atomic Parity violation in ^{133}Cs



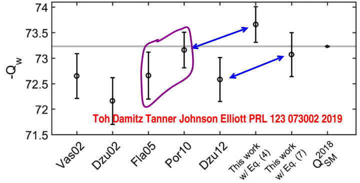


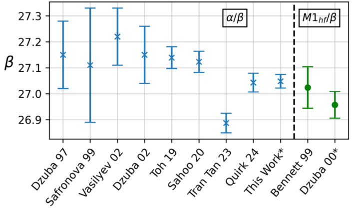
CONUS upper limit on reactor ν scattering arXiv:2401:07684
mild tension with reported discovery Collar PRD 103 122003 (2021)
Seo Hyn Lee Poster 571 reactor ν's NaI NEON

Improvements Cs APNC

- Extraction of weak coupling from APNC: 2 discrepant methods determining vector polarizability β Quirk PRA 109 062809 (2024)
- Many-body atomic theory Parity-mixed CC Tran Tan, Xiao, Derevianko PRA 105 022803 2022

Hyperfine for $\psi[0]$, QED Ginges Volotka PRA 2018; Roberts Ginges PRA 2021; Sanamyan R.,G., PRL 2023

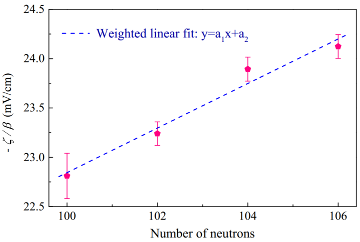


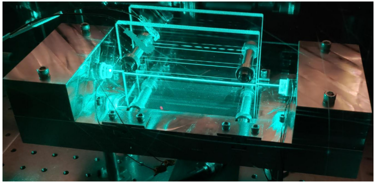


Yb result demonstrated dependence on N

Antypas Nat. Phys. 15 120 2019 Nanos 2411.11861

PHYSICAL REVIEW A **100**, 012503 (2019)





working systems:

Fr laser-cooled 7S $\rightarrow$ 8S M1 σ =10% Hucko thesis, submitted PhysRev $\rightarrow$

138BaF anapole sensitivity demo Altuntas PRL 120, 142501 (2018)

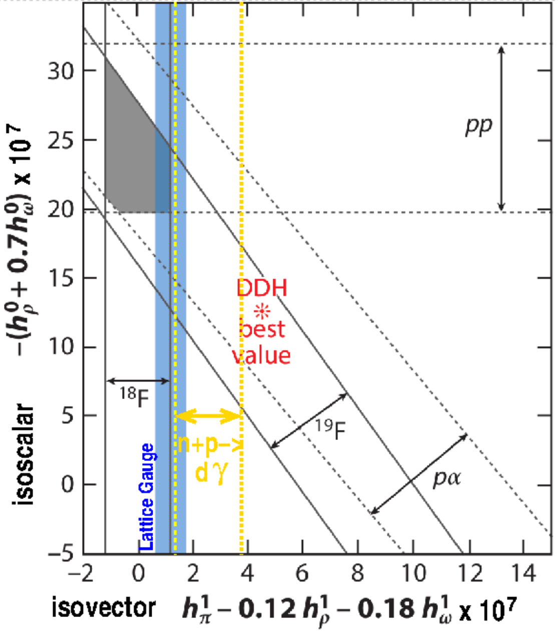
planned systems

BeNC nuclear spin-dependent Hao PRA 102, 052828 (2020)

TlF beam anapole Blanchard PRR 5 013191 (2023)

Penning trap nuclear spin-dependent Karthein PRL 133 033003 2024

Enantiomer shifts Baruch PRR 6 043115 (2024)



Gardner Haxton Holstein ARNPS 2017+ Blythe PRL 121 242002 (2018)

Weak interaction between nucleons, $\not{P}$

$W^{\pm}$, Z^0 (m=80.4, 91.2 GeV) are very short-ranged compared to mesons.

- **Parameterized by meson exchange (emitted weakly, absorbed strongly...)**

The isovector piece was long expected to be dominated by the weak neutral current, but the 1/Nc expansion suppresses isovector/isoscalar by $\sin^2(\theta_W)/N_C \approx 1/12$ (Phillips et al. PRL 114 062301 (2015).

- **A formal EFT produces similar results.**
- **Isovector and isoscalar parts now considered measured.**
- **$n + p \to d + \gamma$ isovector $\Rightarrow$ evidence for weak neutral current at 2σ**

An isotensor part is interesting and inspiring proposals like $\vec{\gamma} + d \to n + p$

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.**

The single known phase in the CKM matrix is consistent with $\not{CP}$ in $K\bar{K}$ and $B\bar{B}$ systems

T2K ν_μ oscillations different from $\bar{\nu_\mu}$ at 2 to 3 σ Nature 580 339 (2020)

But known $\not{CP}$ is too small by $\sim 10^{10}$ Caveats:

- **You could use $\not{CPT}$ though there are no complete models [Dolgov Phys Rep 222 (1992) 309]**
- **We need $\not{CP}$ in the early universe, not necessarily now**

Electric Dipole Moment in a fundamental particle breaks T: this is exact

Landau, Nucl Phys 127 3 (1957)

EDM $\vec{d} = \sum q_i \vec{r}_i$

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

$\vec{J} \overset{t \to -t}{\longrightarrow} -\vec{J} \qquad \vec{d} \overset{t \to -t}{\longrightarrow} +\vec{d}$

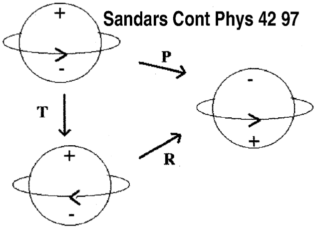
If the physics is invariant under T, this is a contradiction, $\Rightarrow a = 0$

Or there are 2 states, with opposite sign of d: T formally changes one state to the other. For most fundamental particles, we know there aren't 2 states

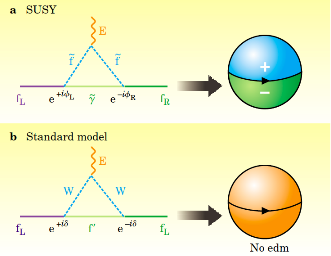
formal proofs: Engel arXiv:2501.02744

Budker Kimball DeMille Atomic Physics

Sandars Cont Phys 42 97



New physics with 2 phases $\to$ 1-loop EDM Fortson PT 2003



Schiff PR 132 2194 (1963)

atomic e^-'s rearrange; nonrelativistic e^-'s and point nucleus cancels $d_{\rm nuc}$

'Antiscreening' Sandars 1965

$d_{\rm atom} \overset{Z \gg 1}{\gg} d_{e-}$

The Schiff moment S involves $\sum q_i r_i^2 \hat{r}_i$ incompletely screened

$\langle S \rangle = \sum q_i (r_i^2 - \frac{5}{3}\langle R_{\rm ch}^2 \rangle) \approx R_{\rm nucleus}^2 d_{\rm nuc}$, so

$d_{\rm atom}/d_{\rm nuc} \sim R_{\rm nuc}^2/R_{\rm atom}^2 \sim 10^{-8}$

Combination of Large Z and relativistic wf's offset by $10\,Z^2 \approx 10^5$, with overall suppression of $d_{\rm atom} \sim 10^{-3} d_{\rm nuc}$

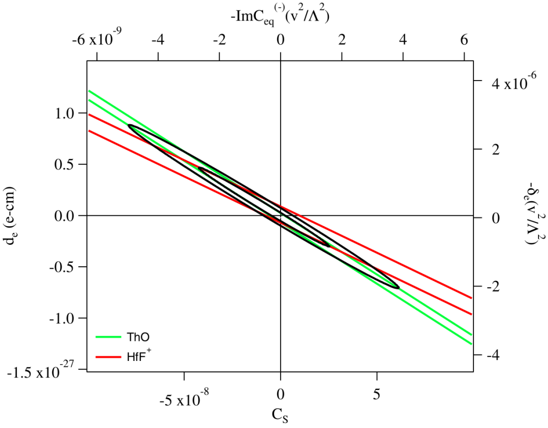
Nuclear magnetic quadrupole moment is $\not{T} \to$ unscreened $d_{\rm atom}$ Haxton+Henley PRL 51 1937 (1983)

J≠0 Atomic EDM can be from electron EDM or semileptonic term

$\sigma_d(\text{stat}) \propto \frac{1}{E\tau\sqrt{N}}$

Large internal E from molecules

Ω doublet cancels B field systematics



← Chupp... RMP 2019 ‘ **Lower Z like Cs would help**

N optimized by beam: ThO

$d_e = 4.3(3.1)(2.6) \times 10^{-30}$e-cm ACME Nat 2018

τ optimized by ion trap: HfF^+

$d_e = -1.3(2.0)(0.6) \times 10^{-30}$ Roussey Science 381 46 2023

planned:

BaF,RaF in frozen noble gas Vutha Horbatsch Hessels PRA 98 032513 2018, Li NJP 25 082001 2023, Ballof NIMB 541 224 2023

BaF demo method measuring E and Rabi frequency simultaneously Boeschoten PRA 2024

Traps of heaviest alkali Fr have similar discovery potential:

optical lattice (molecules possible) Aoki QSciTech 6 044008 2021

atomic fountain Cs → Fr Wundt PRX 041009 2012, Feinberg Gould AIP Advances 8 035303 2018

J=0 EDM progress

d(^{199}Hg)=-2.20(2.75)(1.48)$\times 10^{-30}$ e-cm Graner PRL 116 161601 (2016) **best measurement**

d(^{129}Xe) = 1.4(6.6)(2.0)$\times 10^{-28}$ e-cm Sachdeva PRL 123 143003 (2018) (Liu arXiv:2008.07975 reanalyzed 2x better syst)(!?)

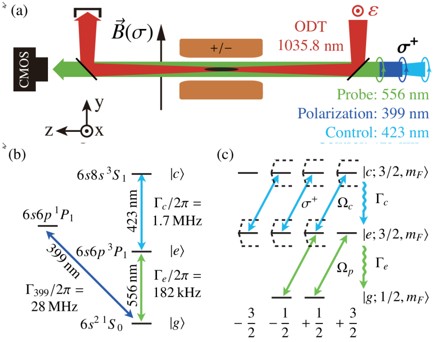
Atom Trap Progress ^{171}Yb

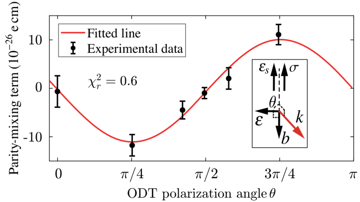
$|d| < 1.5 \times 10^{-26}$ Zheng PRL 129 083001 (2022)

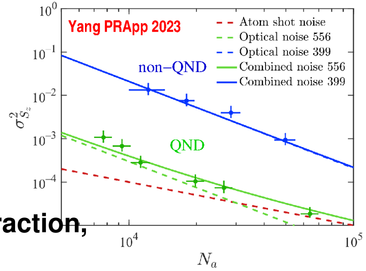
- **Key Systematic (Parity-mixing by static E)** Romalis Fortson 1999 **averaged over with 2 directions of ODT beam**
- **QND: used to create a cycling transition without disturbing populations**

Argonne ^{225}Ra will use

Martirosova DAMOP 2023 F01.00148

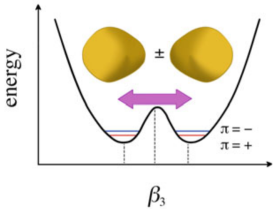






Global analyses (particle EDM's, isoscalar/vector/tensor NN interaction, θ_{QCD}): Konstantin Gaul Robert Berger J. High Energ. Phys. 2024 100 2024; Degenkolb arXiv 2403.02052 including nEDM... PSI Abel PRL 124 081803 2020 d_n=0.0(1.1)(0.2)$\times 10^{-26}$e-cm $\sim$ 4 groups plan 10^{-27}

Octupole enhancements of Schiff moments



Obertelli and Sagawa Fig. 7.33

Static octupole deformation: parity doublet of nearly identical states

J. Engel arXiv 2501.02744

$$S \approx \frac{\langle g|S_z|\bar{g}\rangle\langle\bar{g}|V_{PT}|g\rangle}{E_g - E_{\bar{g}}}$$

ΔE is determined by other interactions and can be very small.

$\langle S_z\rangle$ is close to the classical Schiff moment of the pair: DFT has this under control by relating to observables like E3 $0^+ \to 3^-$ in nearby even-even Dobaczewski PRL 121 232501 2018

Effective operators like $\sigma \cdot p$ need detailed ψ with tails and space-spin info

Spevak 1997, Sushkov 1984 use single-particle estimate; $\propto \beta_3$ uncontrolled approximation

Froese Navratil PRC 104 025502 2021 ^{19}F $1/2^+$ $1/2^-$ big effect no oct

Octupole vibrations can produce similar Schiff moments in nuclei near static octupoles Flambaum Zelevinsky 2003 but not farther away in N,Z in QRPA Auerbach PRC 2006 since these are small components of ψ

Schiff moment of ^{153}Eu is enhanced by 30 over spherical ^{207}Pb in a parity doublet known to not have static octupole deformation, by coupling octupole vibrations to Nilsson deformation Sushkov PRC 110 015501 (2024)

plans for molecules

RaF/RaOH Garcia Ruiz, Hutzler and Doyle, long coherence times CaOH arXiv:2505.09592

223FrAg Marc PRA 108 062815 (2023), DeMille DAMOP 2024 2A.00003

227ThF+ Kia Boon Ng (232ThF+ Boulder)

white paper 2022 Arrowsmith-Kron et al

Zülch arXiv 2203.10333 ^{229}PaF^{+3} ← Simpson 5/26 14:15 CeF^{2+}

^{229}Pa in diamond color centers Morris PhilTA 2025

Neutron Optical Parity and Time-Reversal Experiment

Most of this is from a Chinese Spallation Neutron Source Chinese NOPTREX 2023 workshop talk by T. Okudaira

Forward scattering amplitude term is T-odd P-odd

$\sigma_{\text{neutron}} \cdot (\hat{I}_{\text{nucleus}} \times \hat{k}_{\text{neutron}})$

Exciting p-wave resonances overlapping in compound nuclei with s-wave to enhance T-violating P-violating term

Negligible 'final-state effect' fake time reversal

Extensive characterization of ^{139}La PRC 109 044606 2024, ^{117}Sn PRC 109 014614 2024, ^{131}Xe PRC 107 054602 2003 resonances: ^{3}He spin filter, target polarization techniques, and neutron detector

also has a T-odd P-even observable

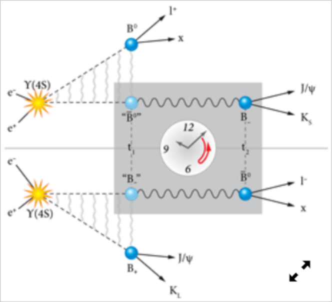
Statistical reaction theory in good shape to extract $\not{T}$ Gudkov et al.

Discovery potential rivals EDM measurements

Entanglement in decays

There exists microscopic true $\not{T}$ in nature! independent of assumptions about QFT, CPT theorem, unitarity...

- **BABAR PRL 2012: Entanglement of B meson pairs enables $\psi_{\text{initial}} \leftrightarrow \psi_{\text{final}}$ also seen in K's KLOE-2 PLB 2023**



APS/Alan Stonebraker

Figure 1: Electron-positron collisions at SLAC produce a $\Upsilon(4s)$ resonance that results in an entangled pair of B mesons. When one meson decays at time t_1 , the identity of the other is "tagged" but not measured specifically. In the top panel, the tagged meson is a "$\overline{B}^0$". This surviving meson decays later at t_2 , encapsulating a time-ordered event, which in this case corresponds to "$\overline{B}^0$" $\rightarrow B_-$. To study time reversal, the BaBar collaboration compared the rates of decay in one set of events to the rates in the time-reversed pair. In the present case, these would be the "B_-" $\rightarrow \overline{B}^0$ events, shown in the bottom panel.

M. Zeller Physics 2012

$\not{T}$ in β decay

Matter's Origin from RAdioactivity MORA

$D\hat{I} \cdot (\hat{v}_\beta \times \hat{v}_\nu)$

Goals $\sim$ 2 orders better than previous D n, ^{19}Ne, and testing final-state interactions by momentum dependence

Paul trap for alkali-like ^{39}Ca, ^{23}Mg
Spin-polarization by direct optical pumping

Symmetric highly segmented instrumentation

Proof of principle parallel talks
5/30 9:40 Motilla Martinez
and Delahaye 9:55

there are also T-even talks from MORA...

planned J. Murata Rikkyo U.
TRIUMF S2389
Test of Lorentz invariance in polarized Li-8 beta decay

Triumf Neutral Atom Trap TRINAT

Barroso Blin-Stoyle 1973

Comparing $\not{T}$ to small matrix element from isospin breaking

Measured ^{47}K isospin-hindered Fermi/G-T ratio Kootte PRC 109 L052501 2024
Simple final state in ^{47}Ca

Uncertainty budget projects to $\sigma_D \sim$ 0.001 would be 4x better than Freedman Calaprice et al in ^{56}Co in a calculable system

Upside is complementarity to EDM's for T-odd P-even Isospin-breaking N-N interactions

Behr 5/30 8:55

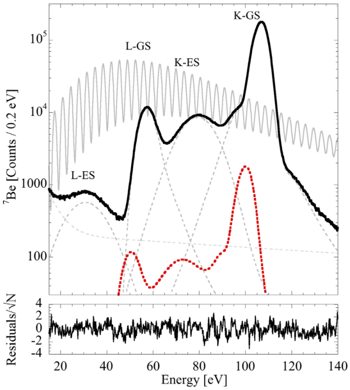
Sterile ν search from ^{7}Be EC

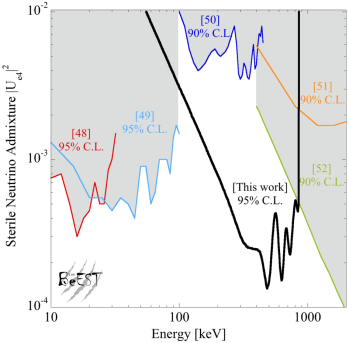
Friedrich et al. PRL 126 021803 (2021)

- **Progeny recoils measured in superconducting tunneling junctions would have lower energies if a massive ν were emitted**
- **Order-of-magnitude better limits on ν_{sterile} admixtures with ν_e over a wide range of masses**
- **Upgraded results parallel talk:** Kim 5/29 5:00 pm

plans for online STJ's
5/29 Fun Sym 11:55 Hayen ASGARD
5/27 Fun Sym Marino SALER
5/27 ν wavepacket Smolsky Lennarz

- Parallel talk "Connection between decay of ^{92}Rb, the reactor $\bar{\nu}$ Anomaly, and the Pygmy Dipole Resonance," Andreoiu 5/30 9:25





Optical isotope shift changes from long-range bosons

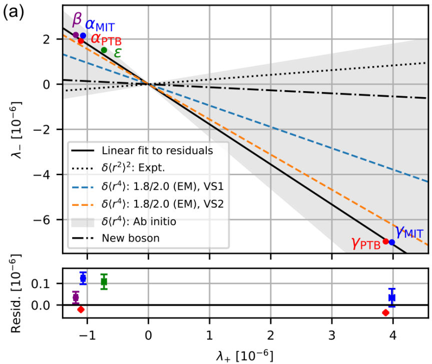
Non-relativistic "King plot": all isotopes corrected for com shifts fall on line

- **Nonlinear corrections from relativity, nuclear deformation...**

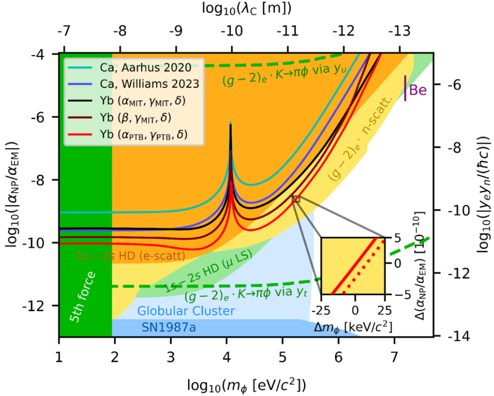
PHYSICAL REVIEW LETTERS **134,** 063002 (2025)

Probing New Bosons and Nuclear Structure with Ytterbium Isotope Shifts

Menno Door,[1,2,*,†] Chih-Han Yeh,[3,*,‡] Matthias Heinz,[4,5,1,§] Fiona Kirk,[3,6] Chunhai Lyu,[1] Takayuki Miyagi,[4,5,1] Julian C. Berengut,[7] Jacek Bieroń,[8] Klaus Blaum,[1] Laura S. Dreissen,[3,9] Sergey Eliseev,[1] Pavel Filianin,[1] Melina Filzinger,[3] Elina Fuchs,[3,6] Henning A. Fürst,[3,10] Gediminas Gaigalas,[11] Zoltán Harman,[1] Jost Herkenhoff,[1] Nils Huntemann,[3] Christoph H. Keitel,[1] Kathrin Kromer,[1] Daniel Lange,[1,2] Alexander Rischka,[1] Christoph Schweiger,[1] Achim Schwenk,[4,5,1] Noritaka Shimizu,[12] and Tanja E. Mehlstäubler[3,10,13]



- **More Yb atomic transitions**
- **Masses to 4x10^{-12}**
- **Many-body S.E. with known σ**



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- **Charged Weak current structure $\rightarrow$ A. Garcia**
- **Vud, b_{Fierz}, $\langle r^2 \rangle \rightarrow$ C.-Y. Seng ||**
- **Neutral Weak current in Nuclei**
  - **np $\rightarrow$ d γ et al.**
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- **Neutron forward scattering p+s-wave**
- **β decay correlation P-odd and even**

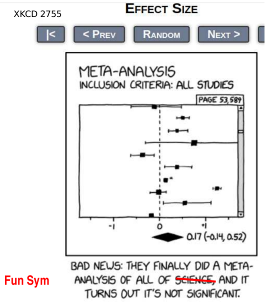
Sterile ν

Nonlinear King plots and light bosons

$0\nu\beta\beta \rightarrow$ Vandana Nanal 5/27

μ g-2 Kim 5/27 Fun Sym 12:25

^{229}Th Takatori poster 142 Okayama U.

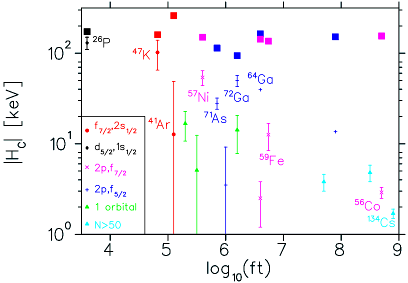


Fun Sym

Challenges for nuclear theory:

- **$0^+ \rightarrow 0^+$ Coulomb, strong isospin breaking**
- **$\sigma \cdot p$ NN $\not T$**

Kootte PRC 109 L052501 2024 TRIUMF

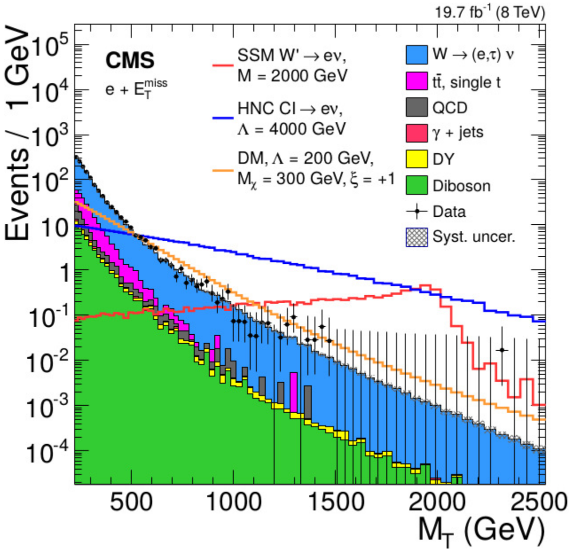


I=1/2$^+\rightarrow$1/2$^+$ ^{47}K β^- decay has large:

- **$H_C = \langle \bar{\mathcal{A}} | V_{\text{Coul}} | \mathcal{A} \rangle$ = 101 $\pm$ 37 keV**
- **fraction of $\mathcal{A} - \bar{\mathcal{A}}$ mixing prediction**

Auerbach, Loc NPA 1027 122521 (2022)

Constraints on β decay from LHC p+p $\rightarrow$ e + $E_{\text{missing}\perp}$



LHC8 $\sigma[p + p \rightarrow e + E_{\text{missing}\perp}]$

Gonzalez-Alonso and Naviliat-Cuncid Annalen der Physik 2013

2 events expected, 1 seen

(LHC13 had 2 events expected, 2 events seen)

Below a TeV or so, SM backgrounds become large, their precision limits the constraint

Comments on isospin breaking for Vud i.e. $\langle\psi_i|\psi_f\rangle < 1$

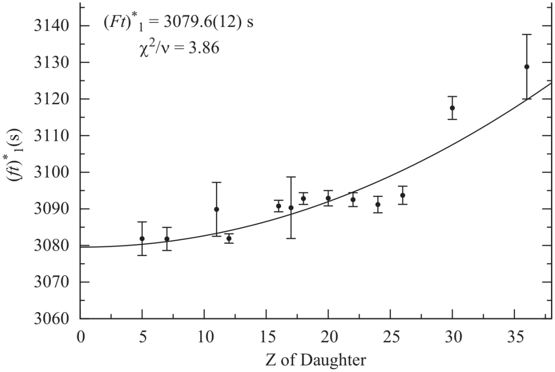


Fig. 2. Plot of the $(ft)^*_1$ data points that do not include theoretical corrections for isospin symmetry breaking and the resulting quadratic fit giving the global trend

• Similarly, letting the long-range Coulomb part of the isospin mixing float $\propto Z^2$ also would inflate the uncertainty on *Ft* by about a factor of 1.5-2

← Grinyer Svensson Brown NIMA 622 245 2010 after Wilkinson.

But floating short-range strong interaction isospin breaking $\propto$ Z would be problematic. Present local shell-model-based methodology (Towner and Hardy 2022) passes empirical tests, but these are not definitive at the 5% accuracy goal. This methodology fits Coulomb matrix elements to IMME and uses strong interaction ISB from Brown (Henley and Miller) fit to Nolen-Schiffer-Okamoto discrepancy in isobaric mirror masses.

DFT-based Konieczka Satula et al. with strong ISB fit to Nolen-Schiffer anomaly has several deviations from Towner Naito Tuesday calculates from QCD.