Analog-antianalog isospin mixing in ^{47}K β^- decay

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(Dated: February 16, 2024)

The decay widths of isobaric analog resonances are modelled well by analog-antianalog isospin mixing via the Coulomb interaction. However, the effects of isospin mixing of the antianalog on nuclear beta decay angular correlations are generally measured to be much smaller than predicted by analog-antianalog We have measured the isospin mixing of the I$^\pi$= 1/2$^+$ E$_x$=2.x MeV state in ^{47}Ca with the isobaric analog 1/2$^+$ state of ^{47}K. Using the TRIUMF atom trap for β decay, we have measured a nonzero asymmetry of the emitted ^{47}Ca with respect to the initial ^{47}K spin polarization, which supported by the beta asymmetry implies a nonzero ratio of Fermi to Gamow-Teller matrix elements y= -0.096±0.037. Interpreting as mixing between this state and the isobaric analog state implies a Coulomb matrix element magnitude 90 ± 35 keV. The latter is an order of magnitude larger than observed on β asymmetry measurements in similar decay systems, which we attribute to the simplicity of ^{47}K and ^{47}Ca states near doubly-closed shells, and thus a relatively unfragmented antianalog configuration. The result supports pursuing a search for time-reversal odd, parity-even, isovector interactions using a correlation in ^{47}K β decay.

I. INTRODUCTION

The neutron beta decays to its isobaric analog state, the proton, as does tritium. Many other isotopes undergo beta minus decay to states of same spin I and parity π, but because of the extra Coulomb energy at higher Z, decay to the isobaric analog state is energetically forbidden. So the Gamow-Teller operator dominates, while the Fermi operator linking isobaric analog states is only allowed if some low-lying final state of same I^π is mixed by an isospin-breaking interaction with the excited isobaric analog. We see such isospin breaking in an I^π=1/2$^+$ state in the ^{47}Ca nucleus 80% fed by the beta decay of ^{47}K. Interference between Gamow-Teller and isospin-suppressed Fermi amplitudes produces a small asymmetry of the progeny recoil direction with respect to the initial nuclear spin, which we measure with TRIUMF's Neutral Atom Trap for beta decay (TRINAT). Our result below from a weighted average of recoil and beta asymmetries is M$_F$/M$_{GT}$=-0.096±0.037, implying a Coulomb mixing matrix element 72±26 keV, an order of magnitude larger than measured in other beta asymmetry measurements in nearby nuclei.

Since ^{47}Ca and ^{47}K are near closed shells, that single known ^{47}Ca 1/2$^+$ state may contain much of the antianalog configuration and its predicted 190 keV mixing matrix element with the analog [1]. Sensitivity to time reversal-odd parity-even (TOPE) inherently isovector [2] N-N interactions through a β-ν-spin correlation is thought to be enhanced in these systems, as they are referenced to Coulomb rather than strong interactions [3], which motivates our measurement of isospin breaking in ^{47}K decay.

II. THEORY AND METHODS

A. Isospin-forbidden β decay

In the angular distribution for allowed I=1/2 β decay in terms of lepton momentum p and energy E [4]:

$$dW = F(E,Z)pEp_\nu E_\nu(1+a\frac{\vec{p_\beta}}{E_\beta}\cdot\frac{\vec{p_\nu}}{E_\nu}+\hat{I}\cdot(A_\beta\frac{\vec{p_\beta}}{E_\beta}+B_\nu\frac{\vec{p_\nu}}{E_\nu})), \quad (1)$$

isospin-suppressed Fermi decay alters the correlation coefficients from their Gamow-Teller values:

$$a=\frac{y^2-1/3}{y^2+1}; A_\beta = A_{\beta GT}+f(M_F); B_\nu = -A_{\beta GT}+f(M_F) \quad (2)$$

with $y = g_V M_f/g_A M_{GT}$ and $f(M_F) = 2\sqrt{\frac{J}{J+1}}y$. The recoil asymmetry is then proportional to A+B, which vanishes when M_F=0. (Analytic expressions for the proportion, possible if the Fermi function is set to unity, are given in Refs. [5, 6]: we compare here entirely to numerical simulations.)

B. Analog-antianalog mixing

The antianalog configuration has same spin and occupancy of spatial orbitals as the isobaric analog, but has

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$T = T_z$ with the antisymmetry of its wavefunction encoded differently between spin and isospin parts so that it is orthogonal to the analog state. Auerbach and Loc [1] using schematic harmonic oscillator wavefunctions write a closed-form expression for analog-antianalog Coulomb mixing for excess neutrons occupying two shells j_1 and j_2,

$$\langle \mathcal{A}|H_C|\bar{\mathcal{A}}\rangle = 0.35\frac{\sqrt{n_1 n_2}}{2T}\frac{Z}{A}(\langle j_1|r^2|j_1\rangle - \langle j_2|r^2|j_2 >) \quad (3)$$

$$= 0.35\frac{\sqrt{n_1 n_2}}{2T}\frac{Z}{A^{2/3}}\text{MeV}, \quad (4)$$

if n_1 and n_2 are the number of excess neutrons occupying shells differing by one $\hbar\omega$: the expression is much smaller otherwise. They back their calculation by RPA in demonstrative cases to accuracy ∼20%. In our case of ^{47}Ca, with $n1$=6 $f_{7/2}$ neutrons and $n2$=1 $2s_{1/2}$ neutron, the closed form expression gives 190 keV.

C. ^{47}K β^- decay to ^{47}Ca

The level scheme for ^{47}K is in Fig. 1. The ^{47}K I^π=1/2$^+$ ground-state has magnetic moment 1.933(9) μ_N [7], similar to the proton μ suggesting a large fractional component of single-particle $2s_{1/2}$. The 80% branch to the 1/2$^+$ 2560 keV state has log(ft)=4.82, which a literature shell-model calculation of the Gamow-Teller strength reproduces well, finding log(ft)$_{GT}$ = 4.39 [8]. This experimental $|M_{GT}|$=0.30 is considerably smaller than the single-particle $2s_{1/2}$ GT value of $\sqrt{3}$. We include in our simulations the 19% to the 2578 keV first excited 3/2$^+$ state, and another 1% known to decay to several other 3/2$^+$ states [9]: these can have no Fermi component and so simply dilute our measured $A_{\rm recoil}$.

For pure Gamow-Teller decay, the beta asymmetry $A_{\beta GT}$=-2/3 for the 1/2$^+$ → 1/2+ transition and +1/3 for all 1/2$^+$ → 3/2$^+$ transitions. The weighted average from the measured branches [9] is then $A_{\beta GT}$=-0.467 ± 0.020. We include this in our simulation of pseudoA_β below.

III. EXPERIMENT:

In this section we show experimental details of the atom trapping, the polarization techniques, the detectors (in-vacuum ion and shakeoff electron detection, and β^- ΔE-E telescopes), the data-taking, and backgrounds from untrapped atoms.

A. TRIUMF Neutral Atom Trap

In Fig. 2 we sketch (exported from a GEANT4 simulation, with laser beams superimposed) the detection

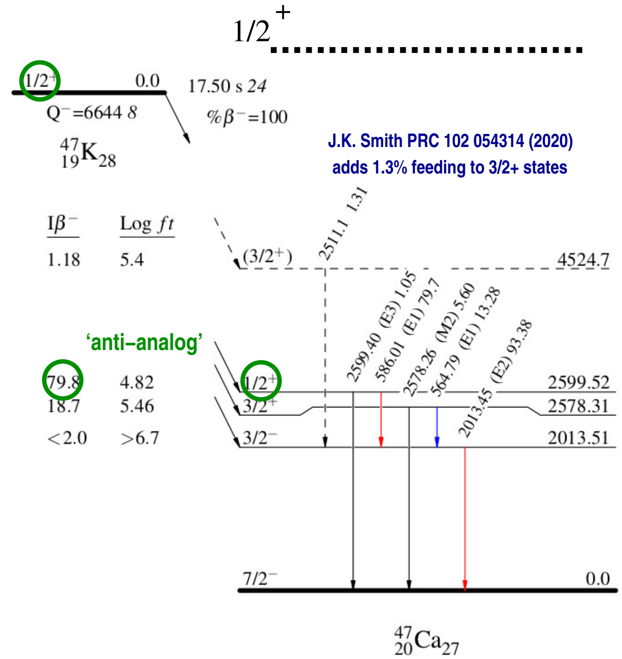

FIG. 1. ^{47}K decay, modified from ENSDF including info from Ref. [9]

apparatus of TRIUMF's Neutral Atom Trap for β decay (TRINAT). Not shown is the collection trap from a vapour cell cube nor the push beams [10].

We trapped 500-1,000 ^{47}K atoms over a 16 hr time period. We state here some foibles of our setup that did not compromise our measurement and that, once fixed, should allow us to trap more atoms in the future. We used 250 mW of light from a Ti:Sapph to trap atoms in the collection light, and similarly 200 mW to trap them in the detection trap. This light we found optimized the number of atoms trapped when tuned about 3 linewidths to the red of the $4S_{1/2}$ to $4P_{3/2}$ F=1 to F=2 transition, as measured with respect to the optical resonance measured by Ref. [7] (using offsets from acousto-optical modulators from a stable potassium saturation spectroscopy reference).

The repumping light on the F=0 to F=1 transition was about 50 mW from a tapered amplifier laser that was left on in the collection trap. In the detection trap, the repumping light was from the optical pumping beams only, which were left on all of the time. This meant no repumping light at all for the transverse cooling between traps.

B. Polarization by optical pumping

Details of optical pumping are very similar to our ^{37}K measurement [11]. Changes include much thinner pellicle mirrors along the optical pumping axis to reduce β straggling, made from 4 micron thick Kapton®–lined with 100 nm of gold. The optical pumping light quality is

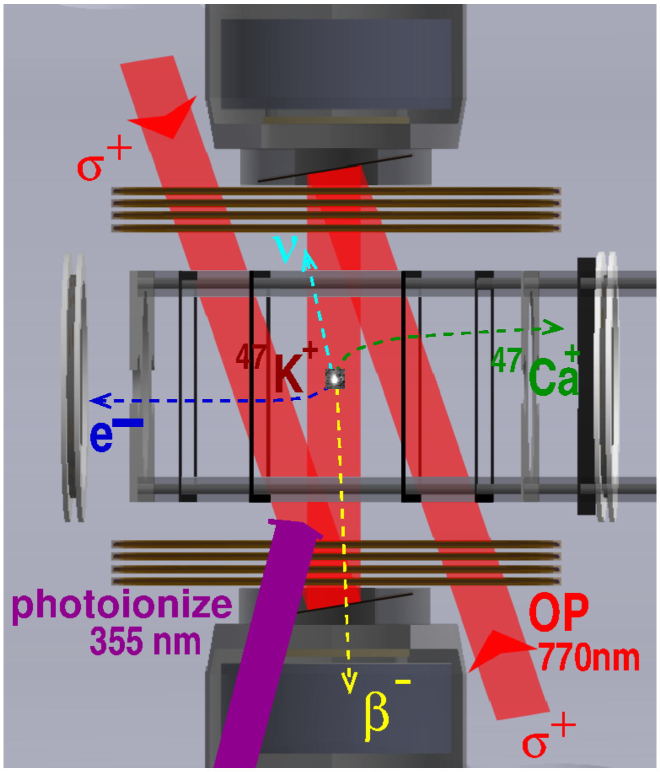

FIG. 2. TRINAT during the optical pumping time. Shown are β telescopes, mirrors for optical pumping light, magnetic field coils, electric field electrodes, and microchannel plates for electron and ion detection. A CMOS camera image of 1,000 trapped atoms is superimposed.

improved from 0.991 to closer to 0.996 Stokes parameter S_3.

We alternate 2.9 ms trapping with 1.1 ms optical pumping, during which we make the polarized beta decay measurements. It takes time to switch the magnetic field from the magneto-optical trap (MOT) quadrupole field to a uniform field by reducing currents and flipping one coil.

During the polarization time, we apply circularly polarized light along the quantization axis. Once we start the OP cycle, atoms increase spin to maximum, then stop absorbing in the $S_{1/2}$ to $P_{1/2}$ transition used. If light is linearly polarized, atoms keep absorbing, and the atoms and nuclei remain roughly polarized.

When excited, 0.5 nsec pulsed from a 355 nm width laser have enough energy/photon to photoionize (a small fraction) of them, detected in the same ion *microchannel plate detector* (MCP) used for the ^{47}Ca recoils from β decay. The photoions are distinguished by their time-of-Flight (TOF) and by their centre position. (We determine average trap cloud sizes and positions when the MOT light is on.) In Fig. 3 we show 11 photoions while linearly polarized (in about 1/4? the total time measured) and 1 photon circularly polarized.

For spin-1/2 all the sub-level transitions have equal probabilities, making the deduced nuclear polarization

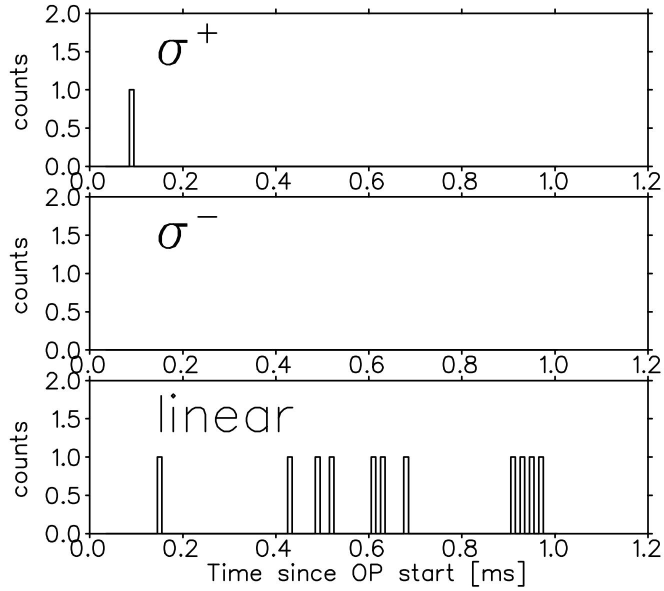

FIG. 3. Excited state population during the optical pumping time for circularly and linearly polarized light. See text for deduction of nuclear polarization.

simple to deduce independent of which nearly fully polarized states produce the remaining excited state population. We deduce a fraction of nuclear polarization achieved for the decaying ^{47}K atoms of $P = \langle Iz \rangle / I = 0.96 \pm 0.04$.

We note that the optical pumping light was degrading smoothly in power during the data-taking of both circular and linearly polarized light by a factor of about four, caused by degradation of lithium niobate 3.3 GHz electro-optic modulators from photorefraction at about 4 mW of input optical power. We find from rate equation optical pumping simulations that the ratio of circular to linearly polarized photoions is similar as a function of power, so the average polarization reported describes the degree of polarization throughout the experiment. This ratio is also similar as a function of detuning to well within the accuracy we quote, important because we did not determine the resonance location other than optimizing the number of trapped atoms in the MOT.

C. Geometry and Detectors

An electric field is formed by a combination of low-Z glassy carbon and titanium electrodes to minimize *beta* scattering. The field is calculated by standard finite element techniques to have average 650 V/cm, and taking this average as a uniform field is sufficiently accurate for our asymmetry simulations. The field collects ^{47}Ca ions produced in ^{47}K β^- decay to an MCP with 78 mm active diameter located 9.7 cm away. Decay by β^- naturally makes $^{47}Ca^{+1}$ ions. Additional low-energy atomic shakeoff electrons, which take an average of 6 ns to reach the opposite 40 mm diameter MCP, provide a starting trigger for the TOF of ^{47}Ca^{2} and higher.

Critical to β detection is discriminating β's from γ's, because their ratio in ^{47}K decay is about 1 to 2. We use the same 0.30 mm thick double-sided silicon strip detectors as Ref. [12], similarly requiring both X and Y strips above energy threshold and similar calibrated energy deposited. Our plastic 4x9cm scintillators for β^{+} detection now use Silicon Photomultiplier (SiPM) readouts and are characterized in Ref. [13].

IV. RESULTS

Here we show results of 12 hours of beamtime, using 6x10^{6}/s mass-separated ^{47}K delivered from the TRIUMF/ISAC ISOL-type facility.

A. e^{-}–Recoil Coincidences

Our main channel is coincidences between decay recoils on the ion MCP and shakeoff electrons on the e^{-} MCP (which correspond to ions with charge states 2+ and higher). The TOF spectrum in Fig. 4 has contributions from charge states +2 through +7. Their asymmetry wrt to polarization axis is shown to be nonzero in Fig. 5, directly implying a nonzero Fermi contribution to the $1/2^{+} \rightarrow 1/2^{+}$ transition.

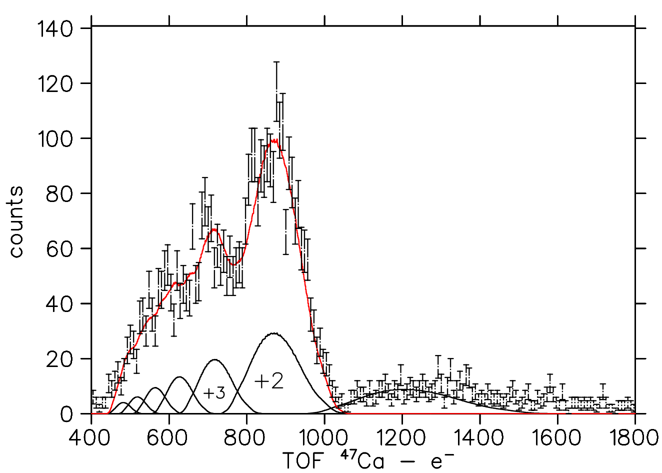

FIG. 4. Time-of-Flight (TOF) of ^{47}Ca ions triggered by shakeoff e^{-}.

We model this by a numerical integration of β and ν (Eqs. 1-2), with the resulting ^{47}Ca ions collected to the ion MCP by the 650 V/cm electric field. We find it adequate to include the momentum perturbation on the ^{47}Ca from a single 2 MeV γ subsequentially emitted isotropically — note the dominant γ must be isotropic. The result is y = -0.102 ± 0.041. Systematic uncertainties are listed in Table I.

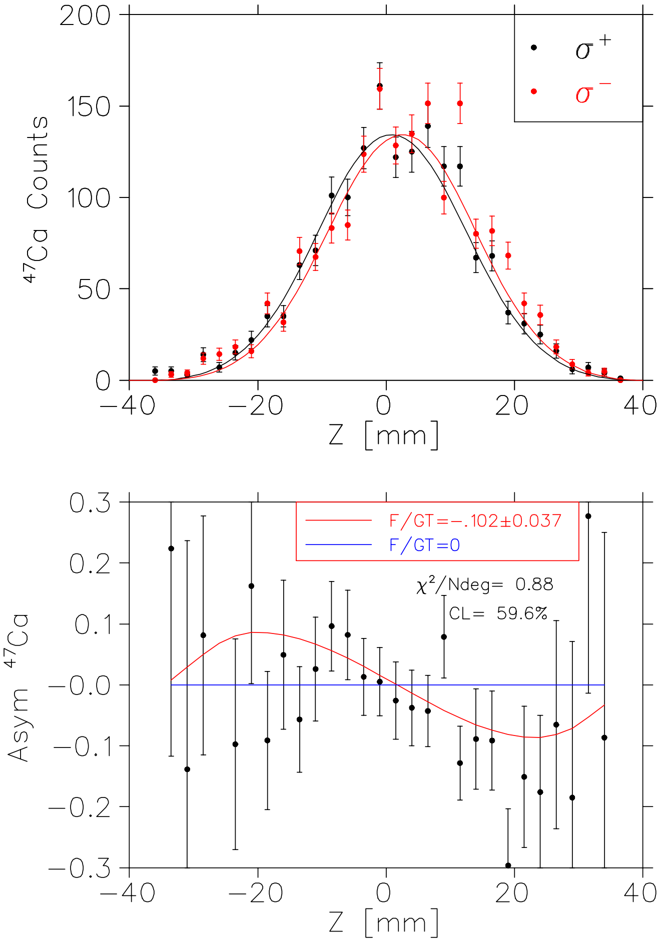

FIG. 5. Top: Distribution of shakeoff e^{-} coincidences with ^{47}Ca$^{+2...7}$ recoils along Z, the polarization axis, for the two polarizations. Bottom: The asymmetry of these distributions, i.e. the difference divided by the sum of the Top distributions. The nonzero asymmetry directly implies a nonzero Fermi contribution.

1. *Backgrounds from untrapped atoms and ^{47}Ca^{+1}*

Having $t_{1/2}$=19 sec and trap half-life of 10 sec for the trapped ^{47}K implies that more than half the atoms decay after leaving the trap. We have measured this background with 1 hour of data while deliberately ejecting

TABLE I. Systematic uncertainties for A_{recoil}

Source	Uncertainty
Fit range in Z ±20 to 34 mm	0.012
bkg 6±4%	0.014
Polarization 0.96±0.04	0.004
^{47}Ca^{+1} percent bkg	0.001
β^{+} Branching ratio	0.002
^{47}Ca^{+N} distribution from TOF	$<$ 0.0005
Fit Statistics	0.037
Total	0.041

atoms from the trap. We deduce a background of 6±4% of the events in the e^-–^{47}K channel roughly flat in TOF in the region we use of +2 through +7 charge states, and include that background in our simulation. This is consistent with a small fraction of the untrapped atoms sticking to the glassy carbon electrodes slightly farther away from the trap– shakeoff electrons from other surfaces are excluded from the electron MCP by the electric field. Our β collimation is sufficient that we see backgrounds consistent with zero for the β-recoil channel considered next.

As β^- decay makes a +1 ion without further electron emission, the late-coming ^{47}Ca^{+1} in Fig. 4 must be coincidences with other prompt products. Hypothesizing all β's would produce a ^{47}Ca^{+1} distribution dominated by the ν asymmetry [14], we find an effective B_ν about half the value expected, indicating some MCP triggers from γ's. So the ∼ percent contribution to our TOF-selected recoils would make an ∼0.001 correction, which we tabulate as an uncertainty.

B. β–Recoil Coincidences Using PseudoA_β

We also measure β's in coincidence with ^{47}Ca recoils. If we measured ^{47}Ca recoils over all directions and momenta, this would be a measurement of the beta asymmetry. However, some ^{47}Ca escape the MCP, perturbing the asymmetry of β's in coincidence by a well-defined combination of the β-ν correlation and the ν asymmetry.

This observable, which we name pseudoA_β, we also model by numerical integration, including the effects of a single 2 MeV γ. The results are in Fig. 6. Numerical simulations for three values of M_F/M_{GT} are shown to show sensitivity, along with the best fit. A single straight line for M_F=0 and hypothetical full collection of ^{47}Ca is shown, to indicate how the asymmetries are distorted from A_β from restrictions on the ^{47}Ca detection. The significantly smaller difference in asymmetry for positive vs. negative Z is due to an 0.5 mm displacement in the trap position along the Z-axis and subsequent change in ^{47}Ca collection, and is well-reproduced by the simulation.

We note that the sign of A_β is determined from this observable. We use this to determine the sign of our spin polarization, as we do not measure the absolute handedness of circularly polarized light.

To deduce a Fermi contribution from pseudoA_β requires more precision and accuracy than $A_{\rm recoil}$, because we must distinguish between the experimental value and the nonzero theoretical value for a pure Gamow-Teller transition. E.g., the average coefficient of A_β for ^{47}K for pure Gamow-Teller transitions is -0.467±0.NM, where the uncertainty is from the literature branching ratio 80±2.0% [9].

The uncertainties are summarized in Table II. The polarization uncertainty contributes. Based on our previous ^{37}K A_β measurement [12], we scale our experimental value by 1/1.023 to approximately account for backscatter, assigning here a more generous uncertainty here of 20% because we have not done full simulations of geometry changes.

The result from pseudoA_β, M_F/M_{GT}=-0.071±0.084, is consistent in sign with $A_{\rm recoil}$, but with larger uncertainty.

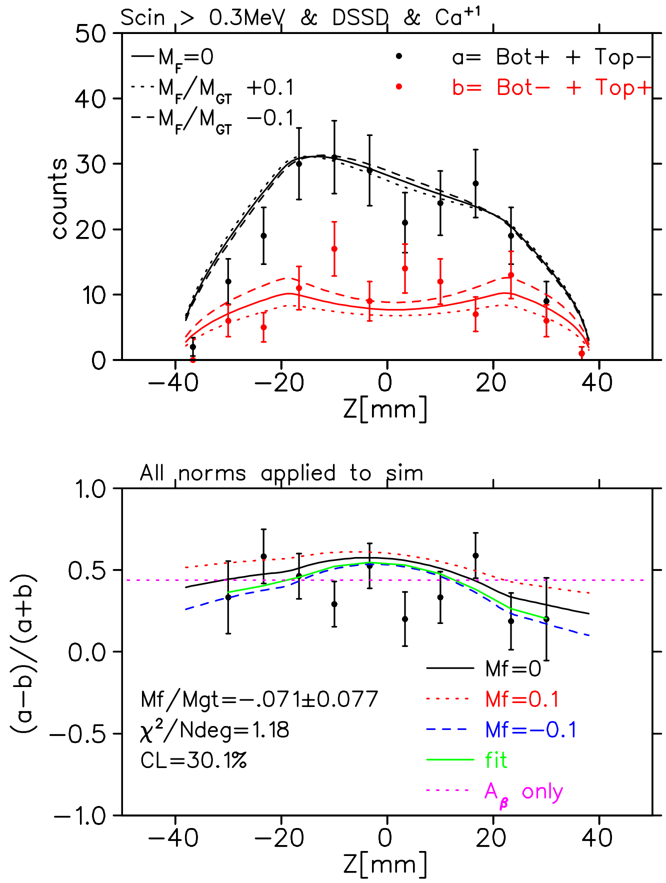

FIG. 6. Similar to Fig. 2, but for β-^{47}Ca$^{+1,2,3,4}$ coincidences.

TABLE II. Systematic uncertainties for β-recoil coincidences

Source	Uncertainty
Polarization	0.023
Backscatter correction -0.012±20%	0.0024
E field	0.025
β^- Branching ratio	0.022
Fit statistics	0.077
Weak Magnetism	0.005?
Total	0.084

1. *Recoil order corrections.*

These we can handle approximately for this non-precision measurement. Assuming the wavefunction of initial and final $1/2^+$ states is purely an $s_{1/2}$ nucleon, the weak magnetism has no orbital correction and becomes the nucleon value, and the first-class induced tensor vanishes. For the 20% branches to $3/2^+$ states, we further assume the final $3/2^+$ states are dominated by $d_{3/2}$, and use the single-particle expression for weak magnetism for Gamow-Teller transitions (see e.g. Ref. [15]). The result is a correction of less than 0.01 for A_β??,

C. Result and Isospin breaking

Our weighted average of results from $A_{\rm recoil}$ and pseudoA_β is then $y = g_V M_F / g_A M_{GT}$= -0.096±0.037 for the $1/2^+$ to $1/2^+$ transition.

Given the measured log(ft) of 4.82 (which implies $g_A M_{GT}$= 0.305), we deduce $|M_F|$= 0.029±0.011 (assuming we do not know the sign of M_{GT}). and the standard model value of $g_V = 1.00$). To compare to other nuclei thought to be dominated by analog-antianalog mixing, we use a first-order perturbation theory expression from the literature, including the standard ladder operator result for isospin [16, 17]: $M_F = \frac{\langle A|H_C|\bar{A}\rangle}{\Delta E}\sqrt{(T \mp T_z)(T \pm T_z + 1)}$ (upper vs. lower sign for β^- vs. β^+), along with the measured analog-antianalog splitting ΔE = 10.1 MeV [18], to deduce a Coulomb matrix element $|H_C|$= 90 ± 35 keV.

This Coulomb matrix element is nearly half of the prediction of analog-antianalog mixing. We attribute this to the simple structure of ^{47}Ca. That this is not the full prediction suggests the state is either more complex than the antianalog or there are contributions from other Coulomb mixing mechanisms. Since the antianalog has determined spin equal to the analog, it seems unlikely the antianalog configuration is contained in other states. Many of the experiments report values less than zero, though Ref. [1] does not calculate the sign.

Many β decays in such systems has much smaller Coulomb matrix elements and M_F. Fig. 7, a plot of literature measurements of y [16], suggests that M_F is roughly decreasing with M_{GT}, suggesting decrease of both with the complexity of nuclear states. At least two other cases with large M_F and H_C, ^{57}Ni and ^{71}Ga, are also near shell closures, consistent with Ref. [1] prediction of larger H_C if two major shells are occupied.

Ref. [3] advocates a time-reversal measurement in ^{134}Cs, which has a very large log(ft) (and a measurement was similarly pursued in ^{56}Co [19]), though if isovector TOPE nucleon-nucleon [20] matrix elements track Coulomb ones or have similar dependence on nuclear complexity, a faster Gamow-Teller decay like ^{47} would also be a favourable system for time-reversal decay.

V. CONCLUSION

For the ^{47}K β^- $1/2^+ \rightarrow 1/2^+$ transition, we have measured the ratio of Fermi to Gamow-Teller matrix elements y=-0.096±0.037, which implies a relatively large effective Coulomb mixing matrix element magnitude 90±35

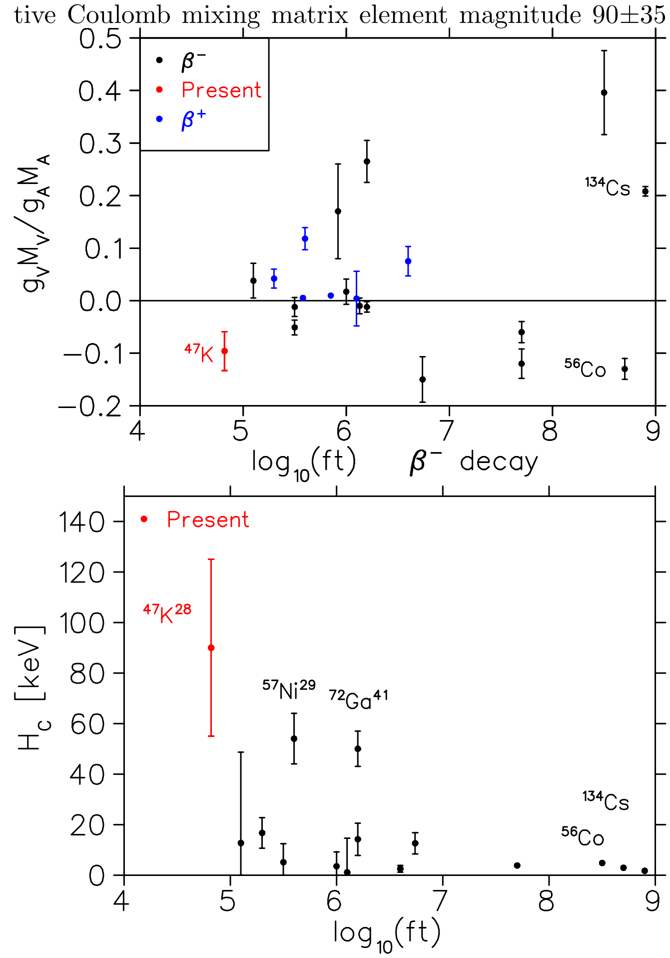

FIG. 7. Ratio of Fermi to Gamow-Teller matrix elements y as a function of log(ft) for isospin-suppressed transitions from Refs. [16, 21**?** –25]. The magnitude of the ratio can remain ∼0.1 even as M_{GT} falls two orders of magnitude. Bottom: Coulomb matrix elements from β decay. Large ones are near closed neutron shells, larger in Eq. 3

keV. This is about half the size predicted from analog-antianalog mixing [1] if the $1/2^+$ ^{47}Ca state were purely the antianalog configuration. We attribute this larger fraction than typical of analog-antianalog mixing to the existence of the single $1/2^+$ state in nearly doubly-closed ^{47}Ca, along with the general prediction that Coulomb mixing will be larger if neutrons occupy two major shells [1]

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