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Precision measurement of the β asymmetry in spin-polarized ^{37}K decay

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Using TRIUMF's neutral atom trap, TRINAT, for nuclear β decay, we have measured the β asymmetry with respect to the initial nuclear spin in ^{37}K to be $A_\beta = -0.5707(13)_{\text{stat}}(13)_{\text{syst}}(5)_{\text{pol}}$, a 0.3% measurement. This is the best relative accuracy of any β -asymmetry measurement in a nucleus or the neutron, and is in agreement with the standard model prediction $-0.5706(7)$. We compare constraints on physics beyond the standard model with other β -decay measurements, and improve the value of V_{ud} measured in this mirror nucleus by a factor of 4.

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Nuclear β -decay correlation experiments were instrumental in establishing the standard model (SM) charged weak interaction as a theory with spin-1 W^\pm bosons, coupling only to left-handed neutrinos through a vector minus axial-vector ($V-A$) current. Precision measurements continue to probe this structure [1]. Extensions to the SM propose that parity symmetry, which is maximally violated in the weak interaction, is restored at some higher energy scale by extending the $SU(2)_L \otimes U(1)_Y$ electroweak gauge group to include a right-handed $SU(2)_R$ sector. Manifest left-right symmetric models have an angle ζ which mixes the weak ($W_{L,R}$) eigenstates to form mass eigenstates with masses $M_{1,2}$, characterized by $\delta = (M_1/M_2)^2$ [2].

Atom and ion trapping techniques [3–6], and progress in neutron decay measurements [7, 8], have allowed correlation parameters in β -decay to be measured with improved precision recently, increasing their sensitivity as probes of non-SM physics. We present here an experiment combining a magneto-optical trap (MOT) with optical pumping (OP) to produce a set of nearly ideal conditions: an isomerically-selected source of highly-polarized [9] β -decaying atoms that are cold and localized within an exceptionally open geometry. We measure the correlation between the spin of a parent ^{37}K nucleus and the momentum of the outgoing β^+ , given by the decay rate [10]:

$$\frac{d^3\Gamma_{\text{angular}}}{dE_\beta d\Omega_\beta} \propto 1 + b \frac{m_e}{E_\beta} + \mathbf{P}_{\text{nucl}} \cdot \left(A_\beta \frac{\mathbf{p}_\beta}{E_\beta} \right), \quad (1)$$

where we have neglected terms that cancel in the asymmetry measurement of our geometry. In this expression, m_e , E_β , and \mathbf{p}_β are the mass, total energy, and momen-

tum of the positron, \mathbf{P}_{nucl} is the polarization of the parent nucleus, and b and A_β are correlation parameters whose values depend on the symmetries inherent in the weak interaction. We take the SM value $b = 0$ for this Letter, consistent with the E_β -dependence of our observed asymmetry as shown below. We will consider non-SM physics that depend on E_β in a future publication [11].

The β asymmetry has been measured previously in the neutron and ten different nuclei. The focus of this work is the mixed $I^\pi = 3/2^+ \rightarrow 3/2^+$ Fermi/Gamow-Teller β^+ decay of ^{37}K , which has a half-life of 1.236 51(94) s [12] and $Q_{\text{EC}} = 6.147 47(23)$ MeV [13]. The transition to the ground state of ^{37}Ar dominates with a branching ratio of 97.99(14)% [14]. The next most significant branch is to an excited $5/2^+$ state at 2.7961 MeV, which must be pure GT with a value of $A_\beta^{\text{GT}} = -0.6$. All other branches to excited states are below 0.03% [15].

The corrected comparative half-life for ^{37}K is $\mathcal{F}t = 4605.4 \pm 8.2$ s [12] based on the half-life, branching ratio and Q_{EC} values given above. The $\mathcal{F}t$ values for transitions between $T = 1/2$ isospin doublets in mirror nuclei is related to the $\mathcal{F}t$ value for $0^+ \rightarrow 0^+$ decays via:

$$\mathcal{F}t^{\text{mirror}} = \frac{2\mathcal{F}t^{0^+ \rightarrow 0^+}}{1 + \frac{f_A}{f_V} \rho^2}, \quad (2)$$

where $f_A/f_V = 1.0046(9)$ [14] is the ratio of statistical rate functions for axial/vector currents, and $\rho = \frac{C_A M_{\text{GT}}}{C_V M_F}$ is the ratio of Gamow-Teller and Fermi coupling constants (C_A/C_V) and matrix elements (M_{GT}/M_F). Eq. (2) with $\mathcal{F}t^{0^+ \rightarrow 0^+} = 3072.27(72)$ s [16] leads to $\rho = 0.5768(21)$.

For mixed transitions, the β asymmetry including the

possibility of right-handed currents is given by [10, 17]:

$$A_\beta = \frac{\frac{\rho^2(1-y^2)}{I+1} - 2\rho\sqrt{\frac{I}{I+1}}(1-xy)}{(1+x^2) + \rho^2(1+y^2)}, \quad (3)$$

where $x \approx (\delta - \zeta)/(1 - \zeta)$ and $y \approx (\delta + \zeta)/(1 + \zeta)$ are non-zero in left-right symmetric models. The SM prediction for ^{37}K is found by setting $x = y = 0$. With the above value of ρ derived from the measured $\mathcal{F}t$ value, the result is $A_\beta^{\text{SM}} = -0.5706(7)$. The value and sign of ρ is such that the sensitivity of A_β to its uncertainty is reduced compared to other observables, e.g. for the ν asymmetry it is nearly $2\times$ bigger, $B_\nu^{\text{SM}} = -0.7701(18)$. The value of ρ varies considerably among ^{37}K and the other well-studied mirror nuclei (^{19}Ne , ^{21}Na and ^{35}Ar) making each nucleus complementary to the others as each will have different dependencies on beyond the SM physics.

Recoil-order and radiative corrections to A_β [18] are included in our analysis. For isobaric analog decays, the induced 1st-order tensor form factor is very small (only present because of isospin symmetry breaking), and all but the very small induced pseudoscalar and q^2 -expansion of the Fermi and Gamow-Teller form factors [19] are given by the conserved vector current (CVC) hypothesis using measured electromagnetic moments [18]. These corrections combine to add $\approx -0.0028E_\beta/E_0$ to the expression for A_β .

The experiment described here was performed with the TRIUMF Neutral Atom Trap (TRINAT) [20, 21]. TRIUMF's radioactive ion beam facility, ISAC, delivered 8×10^7 ^{37}K ions/s, 0.1% of which were neutralized and trapped. Background from the decay of untrapped atoms in the collection MOT was avoided by pushing the trapped atoms every second by a pulsed laser beam to a second MOT [22] where the precision measurement took place, depicted in Fig. 1.

Once the atoms are collected in the second MOT, we apply a sub-Doppler cooling scheme unique to potassium [23]. Since the atoms can only be polarized while the MOT is off, we alternate between periods of trapping and polarizing the atoms. To optimize the shutoff time of the MOT's magnetic field, we employ an alternating-current MOT (AC-MOT) [24]. Once atoms are pushed from the first trap and cooled, a series of 100 cycles begins, where each cycle consists of 1.9 ms of polarizing the ^{37}K nuclei and collecting polarized decay data, followed by 3.0 ms of re-collecting the atoms with the AC-MOT. This cycle is repeated with the polarization direction (σ^\pm) flipped every 16 s.

While the MOT light and magnetic fields are off, we optically pump the atoms on the D_1 ($4s_{1/2} \rightarrow 4p_{1/2}$) transition with circularly polarized light. This technique directly polarizes the nucleus via the hyperfine coupling of the atomic and nuclear spins. It also lets us measure P_{nuc} non-destructively by probing the atoms with a pulsed 355 nm UV laser and detecting the resulting photo-ions

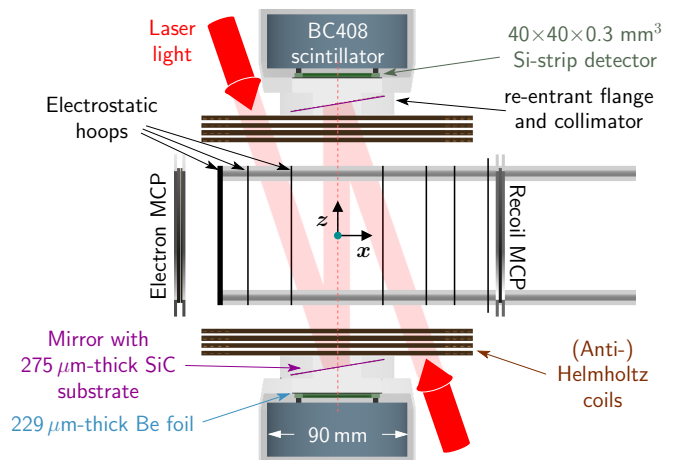


FIG. 1. The TRINAT detection chamber (color online). To polarize the atoms along the β -detection (\hat{z} -) axis, optical pumping light is brought in at a 19° angle with respect to the \hat{z} -axis and reflected off thin mirrors mounted within a β collimator on the front face of the re-entrant flanges. Thin Be foils behind the mirrors separate the Si-strip and scintillator β detectors from the 1×10^{-9} Torr vacuum of the chamber. Magnetic field coils provide the Helmholtz (optical pumping, 2 Gauss) and anti-Helmholtz (MOT) fields. Glassy carbon and titanium electrostatic hoops produce a uniform electric field of 150 to 535 V/cm in the \hat{x} direction to guide shakeoff electrons and ions towards microchannel plate detectors.

with the recoil MCP detector. The UV photons can only ionize atoms from the $4p$ excited state which fully polarized atoms cannot populate, so the rate of photo-ions is a sensitive probe of P_{nuc} . Since $1 - P_{\text{nuc}}$ is small, its determination to 10% precision is sufficient to achieve [9, 25]: $P_{\text{nuc}}^{\sigma^+} = 99.13(8)\%$ and $P_{\text{nuc}}^{\sigma^-} = -99.12(9)\%$.

The time-of-flight (TOF) between the photo-ions and the UV laser pulse images the trap along \hat{x} , while a delay-line anode readout of the MCP provides position sensitivity to image the other axes. Since the MOT's cycling transition produces a relatively large fraction of atoms in the $4p$ state, the position of the atoms is well known while the MOT is on. When the MOT light is off, very few atoms are available to be photo-ionized, and the trap position must be inferred from observations immediately before and after the polarized phase. From these measurements, we observed that the atom cloud moved 0.37(5) mm while expanding from a volume of 2.67(8) mm^3 to 16.9(3) mm^3 . The entire cloud was illuminated by the OP light of 20 mm diameter ($1/e^2$) throughout the optical-pumping cycle.

To identify decays that occurred within the region of optical pumping, we detect the low-energy shakeoff electrons (SOE) by sweeping them with an electric field towards an MCP and observing them in coincidence with the β^+ . At least one SOE is present for every β^+ decay [26, 27], because the Ar^- ion is unstable.

To detect the nuclear decay products, we employ a

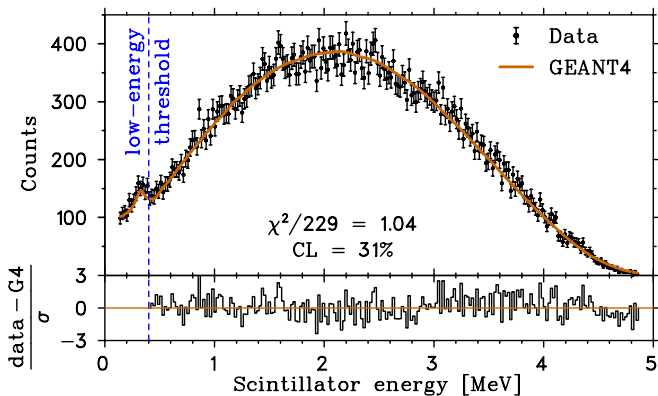


FIG. 2. (Color online) Scintillator spectrum in coincidence with its DSSSD and the electron MCP, showing a very clean selection of β -decay events originating from the trapping region. The GEANT4 comparison shows residuals consistent with statistics. The vertical dashed blue line shows the energy threshold used to exclude Compton-scattered annihilation radiation.

pair of β -telescopes along the vertical polarization axis (Fig. 1). Each consists of a thin double-sided Si-strip detector (DSSSD) backed by a 35-mm thick BC408 scintillator. The 300- μm thick DSSSDs are segmented into 1-mm strips on both sides providing position and ΔE information. Due to its low efficiency for detecting γ rays, it also suppresses the background from 511-keV annihilation radiation.

The plastic scintillators and DSSSDs were calibrated by comparing the observed spectra to a GEANT4 simulation. For the plastic scintillators, we assumed a linear calibration and a detector resolution with a $1/\sqrt{E}$ -dependence. The calibration was performed using the scintillator spectrum in coincidence with a SOE without adding the energy deposited in the DSSSD. The calibration spectrum included both β^+ events and the Compton edge of the 511-keV annihilation radiation. The resulting spectra including the DSSSD coincidence, shown in Fig. 2 for one detector, agree well with the simulation over the entire observed E_β range.

The asymmetry is calculated by comparing the observed rate of β particles in the two detectors. Since the experiment uses two symmetric detectors and reverses the sign of the polarization, we use the super-ratio technique which reduces many systematic uncertainties (see Refs. [28, 29] for details).

The data analysis was performed blind by temporarily culling an unknown fraction, up to 1%, of β -decay events from the analysis. All analysis cuts, corrections, and uncertainties were finalized on the biased data. The complete data set was then re-analyzed in this pre-defined way to obtain the final results presented here.

A detailed representation of the geometry of Fig. 1 was included in the GEANT4 simulation [30, 31]. The position of each decay was randomly sampled from the

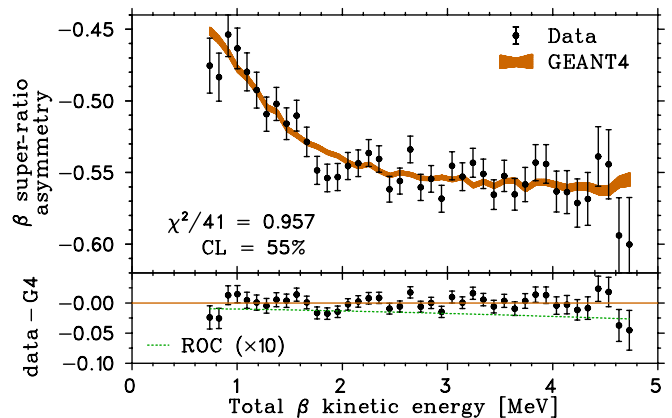


FIG. 3. (Color online) Top: The physics super-ratio of a subset of the data (points) fit to a GEANT4 simulation (filled band, with the width indicating its statistical uncertainty) where the only free parameter was the value of ρ . Bottom: Difference between the data and GEANT4, and the small size of the recoil-order+radiative corrections (ROC).

observed distribution, modeled as a Gaussian ellipsoid and including the effects of the cloud's expansion and drift. We used the `emstandard_opt3` variation of the standard physics lists as well as non-default values of $1\ \mu\text{m}$ for the cut-for-secondaries parameter and a range factor of $f_R = 0.002$ in order to simulate the low- E_β scattering of β^+ more accurately [32]. The multiple scattering (MSC) of e^\pm was simulated with the Urban MSC model of Ref. [33] to avoid the nonphysical behavior of the Goudsmit-Saunderson MSC model [34] observed in Ref. [32].

The simulation was tested by directly comparing the fraction of β^+ that backscattered out of the plastic scintillator. A large fraction of these events have the distinct signature of depositing energy in two different pixels of the DSSSD. The number of these backscattered events, normalized by the number of events leaving energy only in one pixel, was found to differ by only $(2.6 \pm 1.3)\%$ from the measured values [25].

Events are considered in the asymmetry analysis if they (i) occur during the portion of the duty cycle that the atoms are fully polarized, (ii) have a valid DSSSD hit as well as energy deposited in the scintillator, and (iii) are in coincidence with a SOE. The four spectra for upper/lower detector and spin up/down are compared at a number of energy bins using the super-ratio technique to calculate the observed asymmetry shown in Fig. 3. The energy dependence is dominated by the β 's finite helicity (p_β/E_β of Eq. (1)). The observed asymmetry is compared to the GEANT4 simulation in order to obtain the best-fit results for the input asymmetry.

Although our geometry is very open, β scattering off of volumes such as the opposite β telescope, electrostatic hoops, etc. (see Fig. 1), must be accounted for by GEANT4. Simulations indicate that 1.60% of accepted

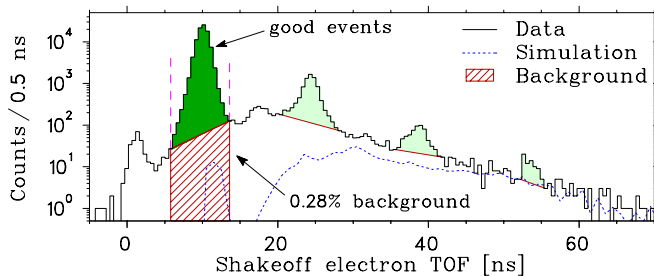


FIG. 4. (Color online) Shakeoff electron TOF spectrum with respect to the β^+ , showing all data at an electric field of 150 V/cm. This spectrum constrains the production of metastable Ar^- with $\tau = 260(25)$ ns [35] to be less than 4%, while the TOF cut eliminates any possible contribution. Overlaid is a simulation (dotted line) of the TOF from atoms that escaped the trap before decaying from an electrostatic hoop, where the only free parameter is the normalization fixed to times ≥ 43 ns. While this simulation reproduces the longer TOF very well, it does not explain all of the background (red hatched area) under the main peak of good events within our TOF cuts (dashed vertical lines).

events scattered by $\geq 24^\circ$ before being detected, leading to an effective $\langle \cos\theta \rangle = 0.9775$ [25, 31]. The GEANT4 simulations therefore apply a 2.30% correction due to β scattering. Using a combination of our data and some from the literature, we assign a systematic uncertainty which is 5.6% of the correction (see Table I), as explained in the Supplementary Material.

Accounting for our measured $\langle P \rangle = 99.13(9)\%$ [9], a simultaneous fit to all of our data yields a best-fit value $A_{\text{obs}} = -0.5699(13)$ with $\chi^2/123 = 0.82$.

The TOF spectrum of SOEs with respect to the β^+ (Fig. 4) has the expected large, narrow peak near $t = 10$ ns, the good events we use in our analysis. The peaks at 24, 39 and 53 ns come from electrons that do not fire the MCP, but produce a secondary e^- that is re-collected by the electric field which is registered by the MCP. We can simulate most of the broad TOF structure to be background from decays of atoms stuck to the SiC mirrors and electrostatic hoops. The same simulation suggests an unresolved peak at 12 ns from the electrode nearest the trapping region, but this does not account for the majority of the total background under the good peak: 0.28%. We conservatively assume that this unknown background is either fully polarized or unpolarized atoms and make a correction $A_\beta = A_{\text{obs}} \times 1.0014(14)$.

Although the super-ratio technique greatly reduces the systematic uncertainties (e.g. the cloud position, β detector differences, and β -scattering), this cancellation is not exact. Independently, we adjusted the trap position, size, temperature, drift velocity, and other parameters within the GEANT4 simulation, obtaining the systematic uncertainties shown in Table I.

TABLE I. Uncertainty budget for A_β . Each entry is given as the absolute uncertainty, and correction factors and the range varied are listed where applicable. Polarization uncertainties, detailed in Ref. [9], are statistically independent.

Source	Correction	Uncertainty
Systematics		
Background	1.0014	0.0008
β scattering [†]	1.0230	0.0007
Trap		
$(\sigma^+ \text{ vs } \sigma^-)$ {	position (typ. $\lesssim \pm 20 \mu\text{m}$)	0.0004
	sail velocity (typ. $\lesssim \pm 30 \mu\text{m/ms}$)	0.0005
	temperature (typ. $\lesssim \pm 0.2 \text{ mK}$)	0.0001
Si-strip		
{	radius [†] ($15.5^{+3.5}_{-5.5} \text{ mm}$)	0.0004
	energy agreement ($\pm 3\sigma \rightarrow \pm 5\sigma$)	0.0002
	threshold ($60 \rightarrow 40 \text{ keV}$)	0.0001
Shakeoff electron TOF region ($\pm 3.8 \rightarrow \pm 4.6 \text{ ns}$)		0.0003
Thick-nesses		
{	SiC mirror [†] ($\pm 6 \mu\text{m}$)	0.0001
	Be window [†] ($\pm 23 \mu\text{m}$)	0.00009
	Si-strip [†] ($\pm 5 \mu\text{m}$)	0.00001
Scintillator only vs. $E + \Delta E^\dagger$		0.0001
Scintillator threshold ($400 \rightarrow 1000 \text{ keV}$)		0.00003
Scintillator calibration ($\pm 0.4 \text{ ch/keV}$)		0.00001
Total systematics		0.0013
Statistics		0.0013
Polarization	1.0088	0.0005
Total	1.0338	0.0019

[†]Denotes sources that are related to β^+ -scattering.

The final result is

$$A_\beta = -0.5707(13)_{\text{sys}}(13)_{\text{stat}}(5)_{\text{pol}}, \quad (4)$$

where the third uncertainty combines the systematic and statistical uncertainties on the polarization measurement [9]. This result has the lowest relative uncertainty of any measurement of the β asymmetry in a nuclear system to date. Since the simulation includes the recoil-order and radiative corrections, this result may be directly compared to A_β^{SM} given earlier.

Figure 5 shows the allowed parameter space in the manifest left-right model. We vary ρ at each (ζ, δ) coordinate to minimize the χ^2 over all observables ($\mathcal{F}t$, A_β and B_ν). The ^{37}K limit includes our previous B_ν measurement [36], but is dominated by the present A_β result.

Assuming $\zeta = 0$ from other experiments (particularly Ref. [16]), our result implies $\delta = 0.004^{+45}_{-4}$ and a mass for a W_R coupling to right-handed ν^R greater than $340 \text{ GeV}/c^2$ at 90% confidence, a slight improvement over the P_β/A_β $310 \text{ GeV}/c^2$ limit [2, 38]. Much of the parameter space in left-right symmetric models has been excluded by other measurements. Constraints from polarized muon decay [46] are relaxed if the ν_μ^R is heavy (as e.g. in Ref. [47]). LHC searches directly exclude W_R with mass $< 3.7 \text{ TeV}/c^2$ if the right-handed gauge coupling $g_R = g_L$ [37], while our ^{37}K results imply $g_R < 8$ for

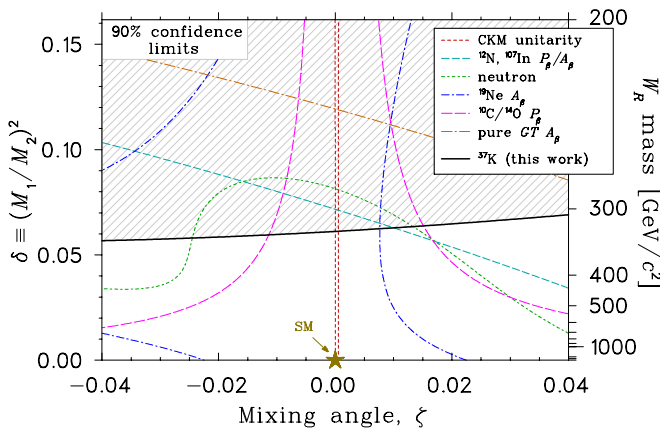


FIG. 5. (Color online) Constraints on manifest L-R symmetric models from nuclear and neutron [37] β decay: CKM unitarity [16]; the ratio of β^+ polarization to A_β of ^{12}N and ^{107}In [2, 38]; A_β of mixed GT/F ^{19}Ne [14, 39–41]; the β^+ polarization of ^{10}C compared to ^{14}O [42]; and the weighted average of A_β from three recent pure-GT cases [43–45].

a $4\text{ TeV}/c^2$ W_R . Manifest models with $M_{W'} < M_W$ and V_{ud}^R considerably less than unity are also constrained by β decay correlations [2].

If we make the assumption that the SM completely describes the β decay of ^{37}K , we can use the result to test the CVC hypothesis. Combining the present result for A_β with the previous measurement of B_ν [36], we find $\rho = 0.576(6)$. This, in combination with the $\mathcal{F}t$ value of Ref. [12], leads to $V_{ud} = 0.9744(26)$ for ^{37}K , a greater than $4\times$ improvement over the previous value [12]. Isospin-mixing calculations [14] contribute 0.0004 to this uncertainty, which only grows to 0.0005 if the span between the isospin-tuned shell model of Ref. [14] and the density functional of Ref. [48] is taken as the uncertainty. We compare this determination of V_{ud} to other nuclear β -decay measurements in Fig. 6. Our ^{37}K result has the same accuracy as ^{19}Ne [40] and improves a CVC test at $I > 1/2$ [49]. Combining the four values from the $T=1/2$ mirror transitions leads to a new average $\langle V_{ud} \rangle_{\text{mirror}} = 0.9727(14)$, only $6.7\times$ less precise than the $0^+ \rightarrow 0^+$ result [16] and slightly better than the neutron.

We have used a highly polarized, laser-cooled source of ^{37}K to measure the β asymmetry in its decay to be $A_\beta = -0.5707 \pm 0.0019$, placing limits on the mass of a hypothetical W_R coupling to right-handed ν 's as well as improving the value of V_{ud} from mirror transitions. The high precision of our nuclear polarization measurement on the atom cloud is enabling a further program of improved A_β , B_ν , and recoil asymmetry measurements.

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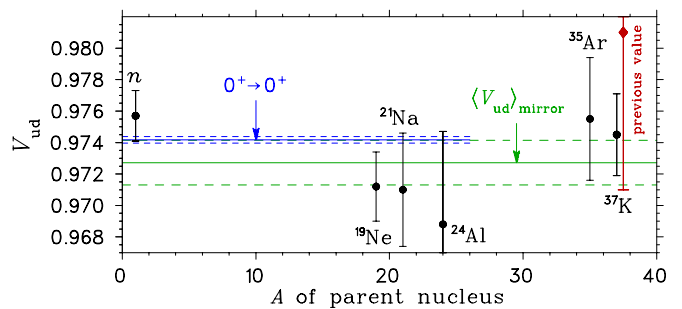


FIG. 6. (Color online) Measurements of V_{ud} comparing the values from the neutron [37], ^{24}Al [49], and the $T=1/2$ mirror nuclei: ^{19}Ne [40], ^{21}Na [50], ^{35}Ar [41], the previous value for ^{37}K [12], and the present work. The averages (uncertainties) in V_{ud} determined from $0^+ \rightarrow 0^+$ [16] and mirror transitions are shown as the solid (dashed) lines.

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- [1] B. R. Holstein, *J. Phys. G* **41**, 110301 (2014).
- [2] E. Thomas, R. Prieels, M. Allet, K. Bodek, J. Camps, J. Deutsch, F. Gimeno-Nogues, J. Govaerts, J. Lang, O. Naviliat-Cuncic, I. Pepe, P. Quin, N. Severijns, and J. Sromicki, *Nucl. Phys.* **A694**, 559 (2001).
- [3] J. A. Behr and A. Gorelov, *J. Phys. G* **41**, 114005 (2014).
- [4] M. G. Sternberg, R. Segel, N. D. Scielzo, G. Savard, J. A. Clark, P. F. Bertone, F. Buchinger, M. Burkey, S. Caldwell, A. Chaudhuri, J. E. Crawford, C. M. Deibel, J. Greene, S. Gulick, D. Lascar, A. F. Levand, G. Li, A. Pérez Galván, K. S. Sharma, J. Van Schelt, R. M. Yee, and B. J. Zabransky, *Phys. Rev. Lett.* **115**, 182501 (2015).
- [5] M. Mehlman, P. D. Shidling, R. Burch, E. Bennett, B. Fenker, and D. Melconian, *Hyperfine Interac.* **235**, 77 (2015).
- [6] G. Ban, D. Durand, X. Fléchar, E. Liénard, and O. Naviliat-Cuncic, *Ann. Phys.* **525**, 576 (2013).
- [7] D. Mund, B. Märkisch, M. Deissenroth, J. Krempel, M. Schumann, H. Abele, A. Petoukhov, and T. Soldner, *Phys. Rev. Lett.* **110**, 172502 (2013).
- [8] A. R. Young, S. Clayton, B. W. Filippone, P. Geltenbort, T. M. Ito, C.-Y. Liu, M. Makela, C. L. Morris, B. Plaster, A. Saunders, S. J. Seestrom, and R. B. Vogelaar, *J. Phys. G* **41**, 114007 (2014).
- [9] B. Fenker, J. Behr, D. Melconian, R. Anderson, M. Anholm, D. Ashery, R. Behling, I. Cohen, I. Craiciu, J. Donohue, C. Farfan, D. Friesen, A. Gorelov, J. McNeil, M. Mehlman, H. Norton, K. Olchanski, S. Smale, O. Thériault, A. Vantghem, and C. Warner, *New J. Phys.* **18**, 073028 (2016).
- [10] J. D. Jackson, S. B. Treiman, and H. W. Wyld, *Phys.*

- Rev. **106**, 517 (1957); J. Jackson, S. Treiman, and H. Wyld, Nucl. Phys. **4**, 206 (1957).
- [11] B. Fenker *et al.* (unpublished).
- [12] P. D. Shidling, D. Melconian, S. Behling, B. Fenker, J. C. Hardy, V. E. Iacob, E. McCleskey, M. McCleskey, M. Mehlman, H. I. Park, and B. T. Roeder, Phys. Rev. C **90**, 032501 (2014).
- [13] M. Wang, G. Audi, F. Kondev, W. Huang, S. Naimi, and X. Xu, Chinese Phys. C **41**, 030003 (2017).
- [14] N. Severijns, M. Tandecki, T. Phalet, and I. S. Towner, Phys. Rev. C **78**, 055501 (2008).
- [15] E. Hagberg, I. S. Towner, T. K. Alexander, G. C. Ball, J. S. Forster, J. C. Hardy, J. G. Hykawy, V. T. Koslowsky, J. R. Leslie, H.-B. Mak, I. Neeson, and G. Savard, Phys. Rev. C **56**, 135 (1997).
- [16] J. C. Hardy and I. S. Towner, Phys. Rev. C **91**, 025501 (2015).
- [17] P. Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (2001).
- [18] B. R. Holstein, Rev. Mod. Phys. **46**, 789 (1974); **48**, 673 (1974).
- [19] I. Towner (private communication).
- [20] J. A. Behr, A. Gorelov, K. P. Jackson, M. R. Pearson, M. Anholm, T. Kong, R. S. Behling, B. Fenker, D. Melconian, D. Ashery, and G. Gwinner, Hyperfine Interac. **225**, 115 (2014).
- [21] J. A. Behr and G. Gwinner, J. Phys. G: Nucl. Part. Phys. **36**, 033101 (2009).
- [22] T. B. Swanson, D. Asgeirsson, J. A. Behr, A. Gorelov, and D. Melconian, J. Opt. Soc. Am. B **15**, 2641 (1998).
- [23] M. Landini, S. Roy, L. Carcagní, D. Trypogeorgos, M. Fattori, M. Inguscio, and G. Modugno, Phys. Rev. A **84**, 043432 (2011).
- [24] M. Harvey and A. J. Murray, Phys. Rev. Lett. **101**, 173201 (2008).
- [25] See Supplemental Material at [\(APS link\)](#) for details, which includes Refs. [51, 52].
- [26] A. Gorelov, J. Behr, D. Melconian, M. Trinczek, P. Dubé, O. Häusser, U. Giesen, K. Jackson, T. Swanson, J. D'Auria, M. Dombisky, G. Ball, L. Buchmann, B. Jennings, J. Dilling, J. Schmid, D. Ashery, J. Deutsch, W. Alford, D. Asgeirsson, W. Wong, and B. Lee, Hyperfine Interac. **127**, 373 (2000).
- [27] A. Gorelov, D. Melconian, W. P. Alford, D. Ashery, G. Ball, J. A. Behr, P. G. Bricault, J. M. D'Auria, J. Deutsch, J. Dilling, M. Dombisky, P. Dubé, J. Fingler, U. Giesen, F. Glück, S. Gu, O. Häusser, K. P. Jackson, B. K. Jennings, M. R. Pearson, T. J. Stocki, T. B. Swanson, and M. Trinczek, Phys. Rev. Lett. **94**, 142501 (2005).
- [28] T. J. Gay and F. B. Dunning, Rev. Sci. Instrum. **63**, 1635 (1992).
- [29] B. Plaster, R. Rios, H. O. Back, T. J. Bowles, L. J. Broussard, R. Carr, S. Clayton, S. Currie, B. W. Filippone, A. García, P. Geltenbort, K. P. Hickerson, J. Hoagland, G. E. Hogan, B. Hona, A. T. Holley, T. M. Ito, C.-Y. Liu, J. Liu, M. Makela, R. R. Mammei, J. W. Martin, D. Melconian, M. P. Mendenhall, C. L. Morris, R. Mortensen, R. W. Pattie, A. Pérez Galván, M. L. Pitt, J. C. Ramsey, R. Russell, A. Saunders, R. Schmid, S. J. Seestrom, S. Sjue, W. E. Sondheim, E. Tatar, B. Tipton, R. B. Vogelaar, B. VornDick, C. Wrede, Y. P. Xu, H. Yan, A. R. Young, and J. Yuan (UCNA Collaboration), Phys. Rev. C **86**, 055501 (2012).
- [30] S. Agostinelli *et al.* (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res. **A506**, 250 (2003).
- [31] B. Fenker, Ph.D. Thesis, Texas A & M University (2016).
- [32] G. Soti, F. Wauters, M. Breitenfeldt, P. Finlay, I. Kraev, A. Knecht, T. Porobi, D. Zkouck, and N. Severijns, Nucl. Instrum. Methods Phys. Res. **A728**, 11 (2013).
- [33] H. W. Lewis, Phys. Rev. **78**, 526 (1950).
- [34] S. Goudsmit and J. L. Saunderson, Phys. Rev. **57**, 24 (1940).
- [35] I. Ben-Itzhak, O. Heber, I. Gertner, and B. Rosner, Phys. Rev. A **38**, 4870 (1988).
- [36] D. Melconian, J. Behr, D. Ashery, O. Aviv, P. Bricault, M. Dombisky, S. Fostner, A. Gorelov, S. Gu, V. Hanemaayer, K. Jackson, M. Pearson, and I. Vollrath, Phys. Lett. B **649**, 370 (2007).
- [37] C. Patrignani *et al.* (Particle Data Group), Chinese Phys. C **40**, 100001 (2016).
- [38] N. Severijns and O. Naviliat-Cuncic, Annu. Rev. Nucl. Part. Sci. **61**, 23 (2011).
- [39] F. P. Calaprice, S. J. Freedman, W. C. Mead, and H. C. Vantine, Phys. Rev. Lett. **35**, 1566 (1975).
- [40] L. J. Broussard, H. O. Back, M. S. Boswell, A. S. Crowell, P. Dendooven, G. S. Giri, C. R. Howell, M. F. Kidd, K. Jungmann, W. L. Kruihof, A. Mol, C. J. G. Onderwater, R. W. Pattie, P. D. Shidling, M. Sohani, D. J. van der Hoek, A. Rogachevskiy, E. Traykov, O. O. Versolato, L. Willmann, H. W. Wilschut, and A. R. Young, Phys. Rev. Lett. **112**, 212301 (2014).
- [41] O. Naviliat-Cuncic and N. Severijns, Phys. Rev. Lett. **102**, 142302 (2009).
- [42] A. S. Carnoy, J. Deutsch, T. A. Girard, and R. Prieels, Phys. Rev. Lett. **65**, 3249 (1990).
- [43] F. Wauters, V. DeLeebeeck, I. Kraev, M. Tandecki, E. Traykov, S. VanGorp, N. Severijns, and D. Zákoucký, Phys. Rev. C **80**, 062501 (2009).
- [44] F. Wauters, I. Kraev, D. Zákoucký, M. Beck, M. Breitenfeldt, V. De Leebeeck, V. V. Golovko, V. Y. Kozlov, T. Phalet, S. Roccia, G. Soti, M. Tandecki, I. S. Towner, E. Traykov, S. Van Gorp, and N. Severijns, Phys. Rev. C **82**, 055502 (2010).
- [45] G. Soti, F. Wauters, M. Breitenfeldt, P. Finlay, P. Herzog, A. Knecht, U. Köster, I. S. Kraev, T. Porobic, P. N. Prashanth, I. S. Towner, C. Tramm, D. Zákoucký, and N. Severijns, Phys. Rev. C **90**, 035502 (2014).
- [46] J. F. Bueno *et al.* (TWIST Collaboration), Phys. Rev. D **84**, 032005 (2011).
- [47] T. Asaka and M. Shaposhnikov, Phys. Lett. B **620**, 17 (2005).
- [48] M. Konieczka, P. Baczyk, and W. Satuła, Phys. Rev. C **93**, 042501 (2016).
- [49] E. G. Adelberger, P. B. Fernandez, C. A. Gossett, J. L. Osborne, and V. J. Zeps, Phys. Rev. Lett. **55**, 2129 (1985).
- [50] J. Grinyer, G. F. Grinyer, M. Babo, H. Bouzomita, P. Chauveau, P. Delahaye, M. Dubois, R. Frigot, P. Jardin, C. Leboucher, L. Maunoury, C. Seiffert, J. C. Thomas, and E. Traykov, Phys. Rev. C **91**, 032501 (2015).
- [51] J. A. Lonergan, C. P. Jupiter, and G. Merkel, J. App. Phys. **41**, 678 (1970).
- [52] D. H. Rester and J. H. Derrickson, J. App. Phys. **42**, 714 (1971).