Improved Limit on Tensor Currents in the Weak Interaction from $^6$Li $\beta$ Decay

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The electroweak interaction in the Standard Model (SM) is described by a pure vector-axial-vector current of the weak interaction. The coupling constants are the only Lorentz-invariant interactions [Scalar $(S)$, Axial-vector $(A)$, Tensor $(T)$, and Pseudoscalar $(P)$] that can arise in SM extensions. The coupling constants $C_i$ for “parity-even” interactions and $C'_i$ for “parity-odd” interactions are related by $C_i = C'_i$ in the SM. The $\beta$-decay correlation coefficient $a_{\beta\nu}$ correlates the directions of the emitted leptons in $\beta$ decay and is dependent on the coupling constants. For pure Gamow-Teller $(A)$ decays, $a_{\beta\nu}$ is expected to be $-1/3$ and $+1$, respectively. Non-SM interactions would lead to deviations from these values.

Measurements of angular correlations in nuclear $\beta$ decay are well suited and widely used to test the electroweak interaction Standard Model (SM) description while also serving as a broadband test for new physics. Though data presently favors only vector $(V)$ and axial-vector $(A)$ couplings in the electroweak Lagrangian, the other Lorentz-invariant interactions [Scalar $(S)$, Tensor $(T)$, and Pseudoscalar $(P)$] can arise in SM extensions, such as leptoquark exchanges and contact interactions. The coupling constants are defined as $C_i$ for “parity-even” interactions and $C'_i$ for “parity-odd” interactions (i.e., $S$, $V$, $T$, $A$, or $P$), with parity maximally violated ($C_i = C'_i$) in the SM. The $\beta$-decay correlation coefficient $a_{\beta\nu}$ correlates the directions of the emitted leptons in $\beta$ decay and is dependent on the coupling constants. For pure Gamow-Teller $(A)$ decays, $a_{\beta\nu}$ is expected to be $-1/3$ and $+1$, respectively. Non-SM interactions would lead to deviations from these values.

The highest precision nuclear $\beta$-decay correlation limits on $T$ currents were set from a corrected $^6$He $\beta$-decay measurement from 1963: $a_{\beta\nu} = -0.3308 \pm 0.0030$ [9] [10] and our previous $^6$Li work: $a_{\beta\nu} = -0.3342 \pm 0.0038$ [11], both of which involve Gamow-Teller decays. In 2019, a global analysis of available neutron and nuclear $\beta$-decay data estimated $0.003 < |C_T/C_A| < 0.078$ ($|C_T/C_A|^2 < 0.0061$) at 95.5% CL, with the assumption of right-handed couplings for tensor currents ($C_T = -C'_T$ and $b_{Fierz} = 0$). Here, for the purpose of discussion we use the same simplification. When lifted, the $a_{\beta\nu}$ result becomes $a_{\beta\nu}/(1 + b_{Fierz}m_e/E)$, where $E$ is the $\beta$ energy. The global analysis was updated in 2021 by Falkowski et al. [12] to include a 2020 aSPECT neutron decay measurement, which pushed the total right-handed tensor current...
strength from +1.8σ to +3.2σ away from the SM. High-energy measurements at the Large Hadron Collider provide tensor-current limits that are comparable or in the case of right-handed couplings, more stringent than those achieved from β decay, although substantially different energy scales and assumptions are required.

This Letter presents an improved limit on T contributions obtained from a high-precision study of ⁶Li β decay performed with the Beta-decay Paul Trap (BPT). The experimental setup and data analysis are built upon our earlier efforts to study ⁶Li.

The decay of ⁶Li is ideal for β-decay angular correlation measurements in an ion trap, due to its nearly-pure Gamow-Teller transition from the J⁺ = 2⁺, isospin T = 1 ground state to a broad J⁺ = 2⁺, T = 0 ⁸Be excited state that immediately breaks apart into two α particles (see Fig. 1[a]). Ab initio calculations indicate that the Fermi contribution to the 3-MeV-resonance matrix element is <10⁻³ and the nearest Fermi-decay strength is centered closely around the doublet transition between 16 and 17 MeV (“doublet,” hereafter). Both contributions are below our experimental sensitivity.

In the allowed approximation, the ⁶Li decay rate can be expressed as:

\[ d\Gamma \propto F(Z,E)p_e(E_0 - E)^2 \left[ g_1 + g_2 \frac{\tilde p_\alpha \cdot \tilde p_\nu}{E} \right] \]

where E₀ and (E, \tilde p_e) are the β endpoint energy and four-momentum, \tilde p_\alpha and \tilde p_\nu are the α and ν momentum unit vectors, respectively, and F(Z,E) is the Fermi function. The gᵢ terms are spectral functions dependent on the Cᵢ’s, and to a lesser degree, E, E₀, and several recoil-order form factors: the weak magnetism term b, the induced tensor term d \[ \rho \] , and the second-forbidden axial-vector terms j₂, j₃. These recoil-order corrections also give rise to additional correlations between the β, ν, and α particles that are ∼100× smaller than the terms shown in Eq. 1.

The triple-correlation term that arises from the delayed α emission can be exploited to increase sensitivity to αᵢ = g₂/g₁. When the β and an α particle are emitted in the same direction, the angular correlation factor of \( g_{12} \) becomes \( \frac{2}{3}(\tilde p_e \cdot \tilde p_\nu) \), resulting in \( a_{\beta\nu} = (g_2 + \frac{2}{3}g_{12})/g_1 \). In the ⁶Li decay spin sequence, \( g_1 = 1 \), \( g_2 = -1/3 \), and \( g_{12} = -1 \). Thus, by selecting approximately parallel α-β events, the measurement’s sensitivity to the β-ν angular correlation increases by up to 3x. Further, due to the large Q_β (16.00413(6) MeV) and small nuclear mass, the ⁸Be⁺ recoil energy is comparatively large, resulting in kinematic shifts that produce ∼400 keV α-particle energy differences ΔE_α in the lab frame. ΔE_α is straightforward to measure and is influenced by \( a_{\beta\nu} \).

The decay of ⁶Li populates a broad excitation energy spectrum, which leads to some complications. In Fig. 1 the ⁶Li level scheme is shown alongside R-matrix fits of the ⁸Be excitation energy Eₓ spectrum obtained from this data (similar to the fits in Refs. 20 21) with approximate individual state contributions to the spectrum 22. Though the doublet states are above Qₜ, their Gamow-Teller matrix elements are large and their resonance tails extend to significantly lower energies. The decay strength to the doublet increases with Eₓ, eventually dominating the transitions at Eₓ > 10 MeV. Furthermore, the 3-MeV and doublet transitions each have significantly different recoil-order form factors that must be considered. While the state-dependent recoil-order contributions are interesting in their own right 23 24, here we minimize these effects by focusing on transitions to Eₓ ~ 3 MeV (the shaded area in Fig. 1b-c).

In our previous work 11, the recoil-order form factors were taken from results in Sumikama et al. 25. Due to statistical constraints and the recoil effects’ small size, the measured form factors obtained from that work were averaged over the entire ⁸Be Eₓ spectrum and had comparatively large uncertainties. Utilizing ab initio symmetry-adapted no-core shell model (SA-NCSM) calculations 26 27 correlated to the measured ⁶Li ground-state quadrupole moment, more precise values of the form factors for each relevant ⁸Be transition have been determined 29 and were used here. With the exception of b, the values from Ref. 26 were approximately halfway between the 3-MeV and doublet transitions’ calculated form factors and all associated uncertainties of the 3-MeV transition values were constrained to within

![Figure 1](https://example.com/fig1.png)
In addition to reproducing the known $^8$Be states, the SA-NCSM calculations also predict a low-lying, $2^+$ $\alpha + \alpha$ state with a width of 10(3) MeV (calculated using a NNLO$_{opt}$ chiral potential) [29], which would be accessible to $^8$Li via allowed $\beta$ decay. There has been an ongoing debate about the existence of this so-called “intruder state,” though experimental evidence remains inconclusive [21, 23, 30–37]. This measurement was also unable to reach a conclusion on the intruder resonance’s existence based on R-matrix fitting. An R-matrix fit including a $2^+$ intruder state is shown in Fig. 1(c). Due to the interference between the lowest two broad states, the intruder state would contribute to the transition strength between $\sim$3-15 MeV, which introduces some minor systematic uncertainty in the $E_x$ range used in our angular-correlation analysis. More details on the intruder-state systematic will be discussed with the other uncertainties and our R-matrix fitting will be covered in a future publication.

A description of the experimental apparatus can be found in Refs. [11, 15]. Only key details and changes since the previous experiment [11] will be covered here. The ion production and transport at the Argonne Tandem-Linac Accelerator System (ATLAS) was modified to more efficiently produce $^7$Li$^+$, and the beam-line used to transport the ions after the $^7$Li$(d,p)^8$Li reaction was outfitted with a new gas catcher [38] and beamstop. These changes resulted in an order-of-magnitude increase in the rate of $^8$Li$^+$ ions delivered to the BPT compared to our previous experiment [11].

The BPT, shown schematically in Fig. 2, is a linear Paul trap with thin, segmented, planar electrodes that confine $^8$Li$^+$ ions within a small (∼1 mm$^3$) volume at the trap center. The BPT utilizes a combination of radio-frequency (RF) voltage (400 V$_{pp}$ at 1.3 MHz) and a static DC quadratic potential well with coefficient $\sim$3 V/cm$^2$ to provide radial and axial confinement, respectively. The ions are cooled through interaction with a high-purity helium buffer gas at a pressure of 10$^{-5}$ Torr. The trap frame is cooled to 100 K via liquid nitrogen to improve ion confinement and reduce leakage current in the detectors. Four 64×64×1 mm$^3$ double-sided silicon strip detectors (DSSDs) [39], each with 32 strips on the front and back sides, surround the trap. From the struck pixels, both $\alpha$ energies ($E_{\alpha 1}$ and $E_{\alpha 2}$), $\hat{p}_{\alpha 1}$, $\hat{p}_{\alpha 2}$, and $\hat{p}_e$ can be determined. The $\beta$-$\alpha$-$\alpha$ coincidence signature effectively eliminates all background events. The DSSDs are also bordered by stainless-steel shielding to minimize pickup from the RF voltage applied to the nearby trap electrodes and backed by plastic scintillator detectors [40] (6" × 6.2" $\varphi$) to collect the remaining $\beta$ energy.

Several upgrades to the BPT have been implemented since the experiment in Ref. [11]. Tunable notch filters for every DSSD front strip were added before the preamplifiers to remove remaining RF pickup. Of the 128 front strips, only signals from the eight edge strips and an additional five strips were consistently unusable. The in situ $^{148}$Gd and $^{244}$Cm calibration sources were upgraded to a set of spectroscopy-grade sources, which provide $\alpha$-particle lines at 3182.690(24) keV [11] and 5804.77(5) keV [42], with 20-keV full width at half-maximum [13].

Over the 14-day experiment, an average of $\sim$100 trapped $^8$Li ions were maintained in the BPT. Events were designated a “double” when two particles within the same 15-µs event window were detected on opposing DSSDs with deposited energies between 700 and 8000 keV (an $\alpha$-$\alpha$ coincidence), while “triple” events required an additional $\beta$ particle coincidence with deposited energy between 200 and 700 keV. The 700-keV threshold was chosen based on GEANT4 [41] simulations of the $\alpha$ and $\beta$ spectra compared to data.

The DSSD $\alpha$-energy response was calibrated following the method developed in Ref. [45], utilizing the $^{148}$Gd and $^{244}$Cm $\alpha$ lines alongside the DSSD minimum ionizing $\beta$ spectra from the $^8$Li decay, which served as a low-energy point. The $\beta$ minimum ionizing spectra was matched to GEANT4 simulations and cross-checked for consistency with cosmic muon data. Following Ref. [46], the calibrated energies were corrected for the detector dead layer, nonionizing energy losses (NIELs), and the silicon energy-response non-linearity [46, 47]. The data-collection system non-linearity was also accounted for [48].

After calibration, several cuts were applied. (i) Coincidences detected less than 30 ms after a new ion bunch is injected into the cloud were discarded, as opening the trap briefly disturbs the ion cloud’s thermal equilibrium. (ii) Both $E_{\alpha 1}$ and $E_{\alpha 2}$ must be greater than
850 keV to accommodate the aforementioned calibration corrections. (iii) $E_{a1} + E_{a2} < 3.75$ MeV (note: $E_{a} = E_{a1} + E_{a2} + 91.2$ keV − $E^\text{Be}_{\text{recoil}}$) to minimize uncertainty associated with the possible existence of an intruder resonance. (iv) The difference in recorded $\alpha$ energy between the front and back strips must be within 30 keV, which eliminates most $\alpha$ particle events that interact with the inter-strip gap between front strips, where charge is not fully collected.

This analysis focused on triple coincidences where the $\beta$ hit one of the detectors struck by an $\alpha$ particle, allowing for the increase in sensitivity to $a_\beta$. Taking into account all these constraints, the final number of triples used for analysis was $2.9 \times 10^5$, amounting to $\sim 1\%$ of all $^8\text{Li}$ decays in the BPT.

Our data were compared to a detailed simulation of the decay kinematics and experimental system [11, 48]. The decay is generated via Monte-Carlo sampling of the $\beta$-delayed $\alpha$ emission phase space [17, 49, 52]. The $^8\text{Be}^*$ final-state distribution is obtained from an R-matrix fit to the calibrated $^8\text{Li}$ data. Radiative corrections based on Glick’s methodology are included [53]. The $\beta$ particles’ deposited energies are determined with a detailed GEANT4 simulation using the “option3” standard electromagnetic physics list [44, 54, 55]. The geometry of the trap and detector array were imported into GEANT using a GDML-adapted [56] BPT design developed in Autodesk Inventor [57].

The simulation propagates the $\alpha$ particles to their projected detector hit locations, and the simulated $E_\alpha$ values are passed through an algorithm that applies a randomized shift to account for the energy-dependent DSSD response or “lineshape.” The lineshape distribution was constructed using calibration-source and beam measurements alongside the detector manufacturer’s specifications for the inactive dead layer and the charge-collecting aluminum strips mounted on deep silicon implants framing each strip. Refs. [45, 58] contain the lineshape convolution methodology.

For events where the $\beta$ and $\alpha$ strike the same detector, $T$ interactions result in larger average recoil energies than $A$ interactions due to the alignment of the lepton momenta. The recoil energy is observed through the kinematic shifts resulting in $\Delta E_\alpha$; consequently we are able to sensitively extract $|C_T/C_A|^2$ from the $\Delta E_\alpha$ spectrum. Spectra for a pure $A$ and a pure $T$ interaction are generated with our simulation. The data are then fit to a linear combination of the two spectra, with the relative amplitudes of couplings, $|C_T/C_A|^2$, and the normalization as the only fitting parameters [11]. The experimental results and the best fit to the data are shown in Fig. 3.

Table 1 summarizes the dominant systematic uncertainties at 1$\sigma$ for $|C_T/C_A|^2$. The total is calculated by summing the components in quadrature, with the exception of the intruder state, which is added in linearly at the end. The entries of Table 1 are briefly explained below.

**Intruder state**—If the $2^+$ intruder resonance is present, we estimate from our R-matrix fits that $\sim 6\%$ of events decay via that transition below the $E_{a1} + E_{a2} < 3.75$ MeV cutoff. Due to differences in the recoil-order terms, the intruder events would increase $|C_T/C_A|^2$ by $+0.0010$. To account for this, we shift our measured $|C_T/C_A|^2$ by half of the intruder state increase and take an uncertainty of $\Delta |C_T/C_A|^2 = 0.0005$, which spans either case.

**Recoil & Radiative Terms**—The uncertainties associated with all the SA-NCSM-calculated form factors in Ref. [29] yielded a total uncertainty on $|C_T/C_A|^2$ of 0.0013, with $d$ being the dominant contributor. This represents a $\sim 60\%$ improvement from the systematic uncertainty obtained by using the Sumikama et al. results [26]. The uncertainty associated with Z-independent radiative corrections was 0.0008. Summed in quadrature, the two yield a combined uncertainty $\Delta |C_T/C_A|^2 = 0.0015$.

**$\alpha$-energy calibration**—The largest contributions arise from several energy corrections during the calibration process: energy lost through the 100-nm-thick DSSD dead layer, fitted distributions of the NIEL generated in TRIM [59], and the measured silicon energy-response non-linearity parameters (uncertainties taken from Refs. 17, 60). The combined systematic uncertainty of $|C_T/C_A|^2$ for the $\alpha$-energy calibration is 0.0007.

**Detector lineshape**—Uncertainties in the lineshape model resulted in a $\Delta |C_T/C_A|^2 = 0.0009$, of which the largest contribution arose from uncertainty associated with charge sharing across the back strips.

**Data cuts**—All of the data cuts were adjusted within reasonable ranges and the resulting uncertainties were added in quadrature; this yielded $\Delta |C_T/C_A|^2 = 0.0009$, with the dominant contributor being the 700-keV threshold used to discriminate between $\alpha$ and $\beta$ particles.


| Source                      | Correction   | Uncertainty |
|-----------------------------|--------------|-------------|
| Intruder State (added linearly) | +0.0005      | 0.0005      |
| Recoil & Radiative Terms    | +0.0015      |             |
| α-Energy Calibration        | 0.0007       |             |
| Detector Lineshape          | 0.0009       |             |
| Data Cuts                   | 0.0009       |             |
| β Scattering                | 0.0010       |             |
| Total                       | +0.0005      | 0.0028      |

β scattering—Scattering within the trap increases the number of β particles striking the DSSDs and distorts the angular correlation for those extra triple events. Both the triple events/double events ratio (T3/D2) and the backscattered triple events/triple events ratio were consistent between simulation and data, even with much smaller statistical uncertainty, while the plastic detectors assisted with distinguishing between origins of scattering within the trap. The β-scattering uncertainty was determined by extracting $|C_T/C_A|^2$ using two sets of simulations—one set with some scattered triple events added and another with some scattered events discarded—to yield simulated T3/D2 ratios ±2σ from the measured ratio. The average magnitude of $Δ|C_T/C_A|^2$ was 0.0010.

Increasing the time reserved for measuring untrapped $^8$Li by 7× compared to the 2015 experiment [11] reduced the background systematic uncertainty to below our sensitivity. The systematic uncertainties associated with the simulated $^8$Be$^+$ final-state distribution, and the ion-cloud characteristics were also negligible.

The result of fitting the $ΔE_n$ spectrum and then applying the systematic correction was: $|C_T/C_A|^2 = 0.0012 ± 0.0019_{\text{stat}} ± 0.0028_{\text{syst}}$ with uncertainties reported at 1σ, which represents a 41% improvement on our previous work’s uncertainties and is the single most precise measurement of intrinsic tensor-current contributions to the weak interaction in the low-energy regime. Under the constraint that $C_T = −C_T' \left(b_{\text{Fierz}} \equiv 0\right)$, $|C_T/C_A|^2$ corresponds to:

$$a_{\text{gg}} = −0.3325 ± 0.0013_{\text{stat}} ± 0.0019_{\text{syst}}$$

and exceeds the precision of all previous measurements in Gamow-Teller decays. This result can also be interpreted as $|C_T/C_A|^2 < 0.0076$ or $|C_T/C_A| < 0.087$ at the 95.5% CL via a Bayesian analysis with a uniform prior for $|C_T/C_A|^2 > 0$. If the $C_T = −C_T'$ constraint is lifted, the 1σ region of possible $|C_T/C_A|$ and $|C_T'/C_A|$ combinations is bounded by the equation: $(|C_T/C_A| + 0.044)^2 + (|C_T'/C_A| + 0.044)^2 = 0.115^2$, with $(mc/eE) = 0.0878$. Our findings are in agreement with the SM, in contrast with the global nuclear limits presented in Falwokski et al. [12].

Analysis of a similarly-sized data set on the mirror nucleus $^8$B decay is underway, which will assist with examining the $E_x$-dependency behavior of the decay rate and probing for other non-SM physics, such as deviations from the CVC hypothesis via the weak magnetism term ($b$). However, an experimental confirmation of the existence of the $2^+$ intruder resonance would be highly beneficial to any further investigations in the $A = 8$ system.

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