Tests of the weak interaction with ^{8}Li and ^{8}B with the Beta-decay Paul Trap

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Over the last decade, the Beta-decay Paul Trap has made substantial improvements to limits on the tensor contribution to the electroweak interaction through the ^{8}Li and ^{8}B systems. Recent advances in detector characterization and a new trap design should enable the experiment to reach an uncertainty of $\Delta|C_T/C_A|^2 \leq 1 \times 10^{-3}$. In the next decade, the current experiment aims towards a statistical uncertainty on the Fierz interference term of $\Delta b \leq 3 \times 10^{-3}$ with 10^8 events with systematic uncertainties that are largely well understood. Reaching this precision level requires an improved theoretical understanding of the nuclear structure, radiative corrections, and recoil-order terms involved in the decays.

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Precision measurements of the weak interaction play an important role in constraining beyond-Standard Model (BSM) physics. Low-energy tests of the fundamental symmetries of the SM provide a complementary approach to high-energy colliders and can place competitive limits on new physics, as noted by the 2014 Fundamental Symmetries, Neutrinos, Neutrons and Astrophysics Town Hall [2]. Searches for BSM effects in the weak interaction with nuclei are a broadband, model-independent test of BSM physics. The Beta-decay Paul Trap (BPT) at Argonne National Laboratory (ANL) is used to search for a tensor current contribution to the weak interaction by studying the Gamow-Teller decays of ^{8}Li and ^{8}B using a linear Paul trap [3]. Ion traps offer several advantages over other techniques: any element can be trapped in the same instrument, and the trapping efficiency can be close to 100%, provided that the half-life of the ion of interest is sufficiently long for cooling, transport, and trapping, typically $\gtrsim 10$ ms. Decays of ions in free space have no energy losses from e.g. a foil, and the energy and momentum of both the decay products and the recoil can be detected. In addition to searches for BSM physics, the BPT studies the neutrino energy spectrum of ^{8}B which is relevant for solar neutrino astrophysics. The first measurement of this spectrum with an ion trap has been submitted for publication [4].

Both ^{8}Li and ^{8}B, which are mirror nuclei, decay through nearly-pure Gamow-Teller transitions to a broad 3 MeV resonance in ^{8}Be that subsequently breaks up into two alphas [5]. The high Q_β of the decays (16.00413(6) MeV and 16.9579(10), respectively [6]) means that the momentum of the decay products is essentially undisturbed by the trapping potential, allowing for a kinematically-complete reconstruction of the decay. The high Q_β value also means that the α particles, in the lab frame, can have energy differences of up to ~ 400 keV and may have momenta offset from anti-parallel by several degrees. The triple-coincidence of two alphas and the beta from the initial decay provide a clear experimental signature that eliminates essentially all backgrounds. By detecting the emitted beta and alpha particles in coincidence, the BPT is able to reconstruct the complete kinematics of the decay, including $a_{\beta\nu}$, the beta-neutrino angular correlation coefficient, or the tensor contribution relative to the axial-vector contribution $|C_T/C_A|^2$. Any deviation from zero in this fraction would indicate new physics.

The BPT uses the α-energy difference spectra to perform the measurement. In particular, the BPT uses only events where the β hits the same detector as an α (“parallel β” events), which means that one α will have its energy “shifted” with respect to the other due to energy and momentum conservation. This triple-coincidence from the

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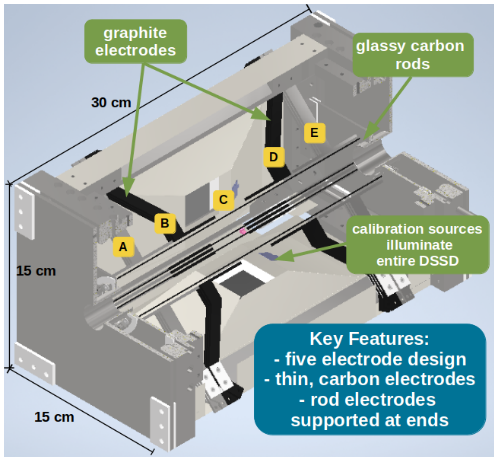
	Systematic Uncertainty	$\Delta\|C_T/C_A\|^2$
Theory	Intruder State *(added linearly)*	0.0005
	Recoil-Order Terms	0.0013
	Bremsstrahlung/Radiative Corrections	0.0008
Experiment	α-Energy Calibration	0.0007
	Detector Lineshape	0.0009
	Data Cuts	0.0009
	β Scattering	0.0010
Total		0.0028

TABLE I. Summary of dominant systematic uncertainties, listed at 1σ, from the latest BPT ^{8}Li result [9].



Key Features:
- five electrode design
- thin, carbon electrodes
- rod electrodes supported at ends

FIG. 1. The BPT Mk IV, recently built and commissioned at ANL [14], reduces β scattering by a factor of 4, the largest experimental uncertainty in the last ^{8}Li measurement [9].

delayed-α decay enhances the sensitivity of the experiment by a factor of 3 compared to prompt decays, due to the angular correlations present in the decay [7, 8]. The latest BPT result using ^{8}Li with ~300,000 events was recently published and obtained $|C_T/C_A|^2 = 0.0012 \pm 0.0019_{\text{stat}} \pm 0.0028_{\text{syst}}$, a result consistent with the SM and the most precise low-energy determination of a tensor contribution to date [9]. This measurement relied on improved theoretical uncertainties on the recoil-order terms in this decay, also recently published [10]. In addition, the first result using ^{8}B with 25,000 events has been submitted for publication [11]. Both of these results assume only right-handed neutrino coupling ($C_T = -C'_T$, $b_{\text{F}} \equiv 0$). Using the typical (although not exact for differential spectra like those of the BPT [12, 13]) $\tilde{a}$ treatment, it is possible to lift the $b_{\text{F}} \equiv 0$ restriction and set a limit in the $(C_T/C_A,\, C'_T/C_A)$ space. For the latest ^{8}Li result, this corresponds to a total uncertainty $\Delta b_{\text{F}} = 0.077$.

The systematic uncertainty table for the ^{8}Li result is provided in Table 1, showing that theory corrections in the recoil-order terms and radiative corrections are still the dominant systematic uncertainty. To address the experimental systematic uncertainty associated with β scattering, the BPT Mk IV (shown in Fig. 1) has been built and commissioned using glassy carbon and graphite electrodes to reduce scattering [14]. An on-going study of the detector response of the double-sided silicon strip detectors in use will reduce the detector-related systematic uncertainties further as well, by an estimated factor of 2. The measurement goal of this current generation of BPT experiments is to reach a precision of $\Delta|C_T/C_A|^2 \leq 1 \times 10^{-3}$ or $\Delta a_{\beta\nu} \leq 7 \times 10^{-4}$. With further improvements to the recoil-order terms, including the possibility of measuring these directly with the BPT Mk IV, the BPT project is close to achieving this goal in the next several years. Furthermore, noting that since ^{8}Li and ^{8}B are respectively β^- and β^+ decays, the b_{F} [15] and other, recoil-order terms contain opposite signs in the expanded equation describing the decay [7]. This allows for a joint limit using both ^{8}Li and ^{8}B to be set on $(C_T/C_A,\, C'_T/C_A)$, which greatly improves the limit. As an example, Fig. 2 shows the joint limit assuming the $\Delta|C_T/C_A|^2 \leq 1 \times 10^{-3}$ measurement goal of the current generation of BPT experiments, using the $\tilde{a}$ prescription.

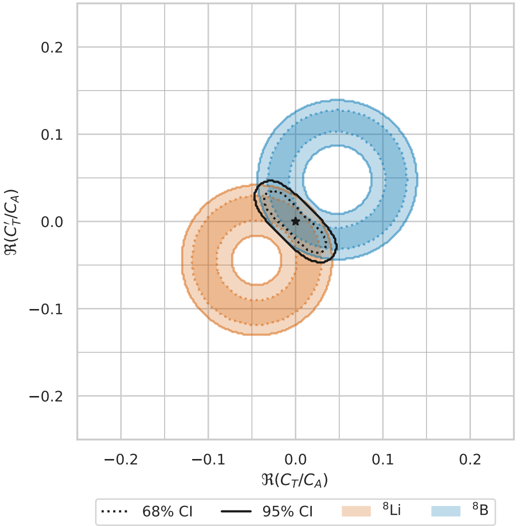


FIG. 2. Joint confidence limit of a $\Delta|C_T/C_A|^2 \leq 1 \times 10^{-3}$ precision measurement in both ^{8}Li and ^{8}B projected for the current experiment, using the $\tilde{a}$ prescription.

Looking forward to the next decade, measurements of ^{8}Li and ^{8}B with the BPT should remain competitive with other efforts to reach the $\Delta b_{\text{F}} \lesssim 1 \times 10^{-3}$ level of precision. It is possible to obtain dramatically higher statistics approaching 10^8 events at e.g. TRIUMF for ^{8}Li in a few days of running time. Despite the reduced sensitivity to b_{F} from the large β-endpoint values, the sensitivity remains competitive due to the delayed-α enhancement, wherein the triple correlation of αs and β provides a factor 3 increase in sensitivity. Note that delayed-particle enhancement in general is overlooked in a recent paper describing the kinematic sensitivity of differential spectra to $b_{\rm F}$ [12]. Using a Monte Carlo of a simplified recoil momentum spectrum integrated over the other kinematic variables, the projected statistical sensitivity of $\Delta b_{\rm F}$ for 10^8 events as a function of β-endpoint energy is provided. For a decay with a β-endpoint of 13 MeV, the statistical sensitivity is estimated to be 7.7×10^{-3} using the $\tilde{a}$ treatment (from Fig. 4 in [12]). However, performing our own Monte Carlo using a realistic ^{8}Li spectrum (including some broadening of the spectrum from ion cloud size and detector response), we obtain a much more sensitive result: using only the parallel β events, which is the experiment that is performed, the projected statistical sensitivity is 2.6×10^{-3} for 10^8 events, approximately a factor of 3 better as expected from the triple correlation enhancement. Note that using only the perpendicular β events, which essentially removes the triple correlation enhancement, gives a statistical sensitivity of 9.9×10^{-3}, slightly larger than Ref. [12].

In addition, at this level of sensitivity, a proper fitting treatment of $b_{\rm F}$ is likely essential, as [12] shows an additional improvement in sensitivity of about 30% at this β-endpoint energy. This treatment is not perfectly performed at the moment for ^{8}Li, as the full expression describing the delayed-α decay was derived under a SM assumption and therefore does not include a Fierz interference term [7]. It is expected that this term should be small and perhaps could be treated by including an approximation, but a more complete derivation would provide higher confidence in the ultimate result. To achieve this level of sensitivity additional theory work on the structure of ^{8}Be is required, particularly on the state population in these decays, as well as in predicting the state-dependent recoil-order terms with robust uncertainty quantification, similar to the work of Ref. [10]. In addition, a proper treatment of the radiative corrections to the triple correlation will be needed. Experimentally, the systematic uncertainties are largely understood, though additional improvements will still be required. These theory and experimental improvements are within reach and sustained effort on the mass-8 system will allow for testing the SM with nuclei at a level that remains competitive with the expected improvements from high-energy physics experiments.

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[1] Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) Town Meeting, Chapel Hill, NC, 2022, , `https://indico.phy.ornl.gov/event/209/`.
[2] A. Aprahamian *et al.*, p. 81 (2014).
[3] N. Scielzo *et al.*, Nucl. Instrum. Meth. A **681**, 94–100 (2012).
[4] B. Longfellow *et al.*, submitted.
[5] R. B. Wiringa, S. Pastore, S. C. Pieper, and G. A. Miller, Physical Review C **88**, 044333 (2013).
[6] M. Wang *et al.*, Chinese Physics C **41**, 030003 (2017).
[7] B. R. Holstein, Reviews of Modern Physics **46**, 789–814 (1974).
[8] M. Sternberg *et al.*, Physical Review Letters **115**, 182501 (2015).
[9] M. Burkey *et al.*, Physical Review Letters **128**, 202502 (2022).
[10] G. Sargsyan *et al.*, Physical Review Letters **128**, 202503 (2022).
[11] A. T. Gallant *et al.*, submitted.
[12] M. González-Alonso and O. Naviliat-Cuncic, Physical Review C **94**, 035503 (2016).
[13] H. Paul, Nuclear Physics A **154**, 160–176 (1970).
[14] L. Varriano *et al.*, in prep.
[15] J. D. Jackson, S. B. Treiman, and H. W. Wyld, Physical Review **106**, 517–521 (1957).