Determining $g_A/g_V$ with High Resolution Spectral Measurements Using an LiInSe$_2$ Bolometer

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Neutrinoless Double-Beta decay ($0\nu\beta\beta$) processes sample a wide range of intermediate forbidden nuclear transitions, which may be impacted by quenching of the axial vector coupling constant ($g_A/g_V$), the uncertainty of which plays a pivotal role in determining the sensitivity reach of $0\nu\beta\beta$ experiments. In this Letter, we present measurements performed on a high-resolution LiInSe$_2$ bolometer in a “source=detector” configuration to measure the spectral shape of the 4-fold forbidden $\beta$-decay of $^{115}$In. The value of $g_A/g_V$ is determined by comparing the spectral shape of theoretical predictions to the experimental $\beta$ spectrum taking into account various simulated background components as well as a variety of detector effects. We find evidence of quenching of $g_A/g_V$ at $>5\sigma$ with a model-dependent quenching factor of 0.655 $\pm$ 0.002 as compared to the free-nucleon value for the Interacting Shell Model. We also measured the $^{115}$In half-life to be $[5.18 \pm 0.06\text{(stat.)}^{+0.005}_{-0.015}\text{(sys.)}] \times 10^{14}$ yr within the Interacting Shell Model framework. This work demonstrates the power of the bolometric technique to perform precision nuclear physics single-$\beta$ decay measurements, which can help reduce the uncertainties in the calculation of $0\nu\beta\beta$ nuclear matrix elements.

INTRODUCTION

From the first observation of single $\beta$-decay [1] that led W. Pauli to propose the neutrino [2] and the subsequent efforts to develop a theory of $\beta$-decay by E. Fermi [3] to C.S. Wu’s ground-breaking work to determine the vector and axial vector form of the weak interaction [4], the study of $\beta$-decay has been used to elucidate the hidden world of nuclear and particle physics. Modern efforts continue this legacy, using nuclear $\beta$-decay to investigate the properties of neutrino mass including its absolute scale through endpoint measurements [5–7], and possible Majorana origin through searches for Neutrinoless Double-Beta decay ($0\nu\beta\beta$) [8–16].

In recent years, cryogenic bolometers have established themselves as a powerful technology in rare event searches for $0\nu\beta\beta$ [9, 11–16], direct Dark Matter detection [17–19], and more [20–24]. Such detectors operate at milli-kelvin temperatures and measure energy deposition events by converting phonons into a temperature increase within a sensitive thermometer. Bolometers benefit from excellent energy resolution, high electron containment efficiencies, low energy trigger thresholds, and strong particle-ID capabilities when equipped with a dual heat/light or heat/ionization readout [15, 23, 25]. Additionally, the ability to operate nearly any crystalline material as a bolometer provides practical means to study a very wide range of long-lived nuclear processes for which sufficient quantities of isotope may be procured and grown into crystalline form.

As pointed out by [26], theoretical calculations of the nuclear physics contributions to the $0\nu\beta\beta$ half-life have often assumed an axial-to-vector coupling ratio equal to that of the free neutron, $g_A/g_V = 1.276$ [27, 28], though it is common to use a quenched value to obtain agreement with observed single-$\beta$ transition rates [29–32]. The exact impact on $0\nu\beta\beta$ will depend on the underlying physics of axial quenching [33]; recently Ref. [34] provided evidence that the inclusion of two-nucleon currents and additional correlations may provide an explanation within light ($A \leq 14$) nuclei and certain super-allowed heavy nuclei $\beta$-decay transitions. Axial quenching creates a significant uncertainty in the interpretation of any $0\nu\beta\beta$ search when converting isotope-specific half-lives back to the underlying physics of interest [35], on top of the existing spread in the value of calculated Nuclear Matrix Elements (NMEs) for $0\nu\beta\beta$ isotopes [36].

As was proposed in [37], the shape of highly-forbidden $\beta$-decay spectra can be very sensitive to $g_A/g_V$, and studying such decays of nuclei with mass around $A \sim 100$ could shed light on axial quenching in a similar nuclear environment as those found in $0\nu\beta\beta$ decays. This anal-
FIG. 1. (Left) Photo of the LiInSe₂ bolometer with an NTD thermistor attached to the crystal. (Right) The combined detector setup in a tower configuration with two pairs of bolometers stacked in two stages. The light detector is placed above each "stage" of the tower for maximum photon absorption.

Analysis technique could also have applications in explaining reactor flux anomalies through examination of lst-order forbidden β-decay transitions [38]. This spectral shape technique was used for the first time in [39], where the experimental data from a CdWO₄ scintillation detector [40] were compared to theoretical spectra in order to extract a value for g₂ in the range of 0.90–0.93. More recently, COBRA has applied this spectral shape approach to their data of CdZnTe detectors in order to obtain a range for g₂ between 0.92 and 0.96 depending on the theoretical models used [41]. In this Letter, we make a precision β-decay spectral shape measurement using a high-resolution “source=detector” bolometer. In particular, we study the 4-fold forbidden β-decay of \(^{115}\text{In} \rightarrow ^{115}\text{Sn}\) with \(Q_β = 497.489\text{ keV}\) [42] with the most recent previously measured half-life of \(4.41±0.25\times10^{14}\text{ years}\) [43]. This decay occurs in a mass range relevant to \(0νββ\) isotopes of interest and provides a benchmark to test whether many-body nuclear calculations are capable of simultaneously explaining the β-decay spectral shape and rate. Recently, interest has been growing to measure this particular \(^{115}\text{In}\) decay mode by examining an \(\text{In}_2\text{O}_3\) bolometer in order to provide a measurement of \(g_2/\gamma\) [44]. Here we use a LiInSe₂ crystal with a natural abundance of \(^{115}\text{In}\) (95.72 % [45]), to evaluate \(g_2/\gamma\) for leading nuclear models, and make the most precise measurement of the \(^{115}\text{In}\) half-life to date.

**METHODS**

The LiInSe₂ crystal was grown by RMD Inc. [46] using the vertical Bridgman process [47, 48]. The crystal was enriched in \(^6\text{Li}\) to 95% for potential use as a neutron detector [49, 50], however, that analysis is beyond the scope of this work and does not affect the β-decay analysis. The LiInSe₂ crystal was instrumented with a Neutron Transmutation Doped (NTD) thermistor [51], and installed inside a cryostat at JIIClab (ex. CSNSM) in Orsay, France [52], see Fig. 1. The LiInSe₂ scintillation signal was monitored by a separate Neganov-Trofimov-Luke Ge light detector (LD) [53], which allowed us to perform particle identification and pile-up rejection. 42.2 g-days of data was collected over two weeks, with the pertinent measured/derived experimental parameters summarized in Table I.

The data was processed using the APOLO/DIANA software developed by the CUORE [54]/CUPID-0 [55]/CUORICINO [56] collaborations. Events are triggered with the Optimum Trigger (OT) [57] and processed following a procedure similar to [12, 54]. The trigger threshold was determined by injecting a series of low energy pulses through the attached Joule heater [58], achieving \(~\sim 100\%\) trigger efficiency above 20 keV. The LiInSe₂ detector is calibrated with a set of dedicated runs with a \(^{133}\text{Ba}\) source using the four most prominent γ peaks in the energy range 250–400 keV.

The internal \(^{115}\text{In}\) decay on its own results in an expected event rate of \(\approx 1.2\text{ Hz}\) in the 10.3 gram LiInSe₂ detector, which means that internal event pile-up is expected to be a significant background. The recovery time after an event is \(\sim 200\text{ ms}\), and the event window around each event includes 100 ms before the trigger and 500 ms after. Together, these lead to a significant paralyzable deadtime. The faster response time of the LD allows us to efficiently tag and remove these pile-up events that might otherwise slip through the LiInSe₂ data quality cuts (see Fig. 2), along with tagging α events through particle-identification via event-by-event light-yield cuts.

In order to filter out spurious events from \(^{115}\text{In}\) β⁻ events, a series of loose pulse shape cuts were employed to filter out electrical glitch and badly reconstructed events. Then a rise time pulse quality cut (see Fig. 2) was defined by a 3σ cut band determined by fitting the resulting

**TABLE I. Experimental parameters of the LiInSe₂ crystal during the October-November 2017 data runs.**

| Detector Parameter | LiInSe₂ Crystal |
|--------------------|-----------------|
| Crystal Dimensions | 1.3 x 1.6 x 0.7 cm |
| Total Crystal Mass | 10.3 grams |
| Effective \(^{115}\text{In}\) Mass | 4.1 grams |
| Noise Level | 1.1 keV (1σ) |
| Avg. Energy Resolution | 2.4 keV (1σ) |
| 100 % Trigger Threshold | 20.0 keV |
| Analysis Threshold | 160 keV |
| Containment Eff. | 96.6% @ 497 keV |
| Data Selection Cut Eff. | 47.6(2)% (160 – 500 keV) |
| Livetime Fraction | 52.54(8)% |
| Total Exposure | 39.7 g·days |
pulse shape variable profiles across each energy bin. We also employ a coincidence cut that enforces a single-event criterion. We require that an event is included in the final also employ a coincidence cut that enforces a single-event pulse shape variable profiles cuts as a function of energy. Outside of the 20–450 keV energy range, the cut values were kept constant due to large uncertainties in the profile fit parameters as a result of non-Gaussian parameter distributions or low statistics at the low/high energy ranges respectively.

To extract $g_{A}/g_{V}$ from the measured $^{115}$In spectrum, we follow a procedure similar to [59–62] and decompose it into various components: a model-dependent signal component from the $\beta$-decay of $^{115}$In which will depend on $g_{A}/g_{V}$, an untagged pile-up component, and other radioactive background contributions. The fit is implemented using the Bayesian Analysis Toolkit package [63], which implements a Markov Chain Monte-Carlo (MCMC) to sample the full joint posterior. We perform this decomposition on the spectrum in Fig. 3, which has a binning of 5/30 keV below/above 530 keV respectively up until the analysis cut-off at 1520 keV. This binning scheme allows for the fitting of as many broad spectral/peak features as possible present in the experimental data while maintaining the highest possible statistics per bin in the region beyond 530 keV. Despite the low trigger threshold of the LiInSe$_{2}$ crystal, we implement an analysis threshold of 160 keV to avoid low-energy pile-up events which are difficult to separate in time and can distort the spectrum.

To implement the MCMC, we define our binned likelihood as:

$$\mathcal{L} = \prod_{i} \text{Pois} \left( k_{i}; \sum_{j} a_{j} \lambda_{ij} \right),$$

(1)

enumerating bins by $i$ and fitted components by $j$. Here, $k_{i}$ is the number of observed counts within a given bin, $\lambda_{ij}$ is the normalized density of the $j^{th}$ component within the $i^{th}$ bin, and $a_{j}$ are the fitted normalizations for the different components. The densities $\lambda$ corresponding to $^{115}$In are $g_{A}/g_{V}$-dependent.

A numerical calculations for the structure of $^{115}$In are performed using ISM [64–66], IBM [67] and MQPM [68]. The resulting $\beta$-decay spectrum is generated as a function of energy for each of these structural models taking $g_{A}/g_{V}$ as an input. We generate a library of 200 discrete $\beta$-decay spectra for $g_{A}/g_{V}$ uniformly spaced across the range $0.6 < g_{A}/g_{V} < 1.3$ and then perform an interpolation for the spectral shape for $g_{A}/g_{V}$ values not in our library. Each $^{115}$In spectrum is then convolved with an
energy-dependent detector response function to account for energy losses as well as shifts in the spectral shape from β-particles that escape the absorber. This is calculated through a Geant4 simulation [69] that only simulates the LiInSe2 crystal and the copper plate it rests on. These simulations find that 96.66% of electrons at the β-decay endpoint will be fully contained within the detector, which represents the minimum containment efficiency over the 115In spectrum. Background component spectra are obtained by simulating in Geant4 various possible radiogenic contaminations including from daughter nuclei on various detector/cryostat components, for example the copper cryostat cold plates and lead shielding surrounding the detector. In total, we simulated the γ/β spectra stemming from 235U/232Th decay chains as well as 60Co, and 40K decays present uniformly throughout the LiInSe2 detector, to simulate possible contamination of the various cryostat components particularly the copper plate near the detector, and from external environmental sources. In addition, we simulated a separate background contribution coming solely from possible surface contaminations of the LiInSe2 crystal. All these input spectra components were then convolved with the detectors’ measured energy resolution and binned into the same binning scheme as the data before their use as a potential component of the MCMC fit. The inclusion of a pile-up component (the autoconvolution of the 115In β-spectrum) was designed to account for the inability to separate events which occur too closely in time and could then be mis-reconstructed as a single higher energy event.

The final MCMC fit only included the four most-dominant background components: 1/2) internal crystal contamination stemming from the 238U decay chains and 60Co decays, 3) 232Th decay chain events on the copper plate underneath the LiInSe2 crystal, and 4) 232Th decay chain events from external sources mostly in the form of γs. Contamination from α surface backgrounds can be ignored, thanks to the strong pulse shape and coincidence cuts that were applied to the collected data, resulting in predominantly bulk γ backgrounds. All other simulated background components were found to have only a negligible effect on the final fit parameters. This results in a satisfactory description of background features in the collected spectrum without introducing degeneracies in the fit from additional components which may not be differentiated with available data. We perform a separate fit for each nuclear model tested, and apply uniform priors to the normalizations of each fitted component within the regions of $g_A/g_V$ discussed below.

**DISCUSSION**

For all three nuclear models examined, the likelihood function within the fit is bi-modal with respect to $g_A/g_V$, exhibiting a local minimum both at low-$g_A/g_V$ values below 0.95, and at high-$g_A/g_V$ values above 1.05. Fits arising from the high-$g_A/g_V$ minimum result in a poor match to the observed spectral shape, with decreases in log-likelihood as compared to the low-$g_A/g_V$ minimum of at least 65 (IBM), 90 (MQPM) and 118 (ISM). Despite resulting in an overall worse fit, the high-$g_A/g_V$ fit minima are still sufficiently favored that without a restricted prior, the MCMC chain will take an unreasonably long time to achieve convergence. In order to ensure a good convergence of the MCMC chain about the global minimum while avoiding numerical instabilities, we restrict ourselves to a uniform prior on $g_A/g_V \in [0.6, 1.0]$.

We extract the best-fit values from the maximum a posteriori point (which we will refer to as the “best-fit” values), along with Bayesian Credibility Regions (BCRs) for parameters of interest pertaining to the 115In decay rate and value of $g_A/g_V$. We marginalize over all background component normalizations as nuisance parameters; all three fits result in compatible contributions from each of the included background components. The best-fit values for $g_A/g_V$ along with the central 1σ BCRs arising from the fits are summarized in Table II. Unsurprisingly, the various nuclear calculations prefer different values of $g_A/g_V$, however all models strongly reject the free-nucleon value of $g_A/g_V = 1.276$ at > 5σ as determined by the $\Delta \log \mathcal{L}$ between the best-fit values and the free-nucleon value, assuming Wilk’s theorem [70].

**TABLE II.** Fit results for each of the three nuclear models considered. For the parameters of interest of $g_A/g_V$ and $T_{1/2}$ for 115In, we quote the best fit value with uncertainty given by the width of the central 68% Bayesian credibility interval, along with the reduced-$\chi^2$ value for the best-fit reconstruction.

| Model    | $g_A/g_V$   | $T_{1/2}$ (10$^{17}$ yr) | Reduced $\chi^2$ |
|----------|-------------|--------------------------|------------------|
| ISM      | 0.830 ± 0.002 | 5.177 ± 0.060           | 1.58             |
| IBM      | 0.845 ± 0.006 | 5.031 ± 0.065           | 1.50             |
| MQPM     | 0.936 ± 0.003 | 5.222 ± 0.061           | 1.60             |
| Pfeiffer et al. [43] | 4.41 ± 0.25 |                       |                  |
| Watt and Glover [71]   | 5.1 ± 0.4   |                       |                  |
| Beard and Kelly [72]   | 6.9 ± 1.5   |                       |                  |

Additionally, using the normalization of the 115In component, we can extract the value of the half-life $T_{1/2}^{(115\text{In})} = [5.18 \pm 0.06 \text{(stat.)} \pm 0.015 \text{(sys.)}] \times 10^{14}$ years. Here we quote the best-fit value arising from the ISM model fit, with statistical uncertainty determined by the width of the 1σ central BCR with negligible contributions from uncertainties in the cut and live-time efficiencies which are propagated on top of the fitted 115In normalization. We choose to quote the spread in half-life with respect to the IBM and MQPM best-fit values (shown in Table II) as a systematic uncertainty. This is slower by 3σ with respect to the measurement within [43], but falls within 2σ of the older, less precise measurements [71, 72]. Figure 4b) displays the joint 2-dimensional
Bayesian credibility regions for $g_A/g_V$ and $T_{1/2}$ for each fitted nuclear model, along with the best-fit points. Each of the nuclear models calculations discussed in this letter are able to simultaneously calculate the $T_{1/2}$ as a function of $g_A/g_V$ values [73] as shown by the dash-dotted lines in Figure 4. In our analysis, our best fit values for the half-life given by each model overestimates the half-lives by factors of 1.2 (IBM), 2.2 (MQPM), and 2.0 (ISM) compared to [43], and simultaneously does not fall upon one of the theory curves. This suggests that quenching-dependent calculations that we used are not yet able to simultaneously match the spectral shape and decay rate in $^{115}$In. It is worth noting that the half-life in [43] is similarly incapable of simultaneously matching the spectral shape and decay rate.

Previous work with COBRA $^{113}$Cd data has shown that the tension between the independently measured half-life and the quenched $g_A/g_V$ values extracted from the spectral shape analysis can be relaxed via the introduction of a small relativistic nuclear matrix element correction that affects the spectral shape due to the enforcement of the conserved vector current assumption [74]. Additionally due to the closeness of our results with the measurements presented in [71, 72], we do not present any conclusion regarding the accuracy of any single nuclear model presented here. This letter seeks to showcase the ability of this technique to simultaneously provide two additional experimental cross checks to any nuclear calculation model, namely spectral shape and half-life, on any provided nuclear model able to address highly forbidden nuclear $\beta$-decays.

**CONCLUSION**

From these data, it is clear that the value of $g_A/g_V$ that governs this highly forbidden decay process is quenched by approximately 0.65–0.75 compared to the decay of the free neutron. Interestingly, for each of the three nuclear models examined there is strong disagreement between the measured half-life from [43] and the predicted half-life value for the favored value of $g_A/g_V$ calculated from spectral shape analysis. This tension could point to possible issues with regards to the many-body approaches and Hamiltonians used in the various calculation frameworks. At the same time, our better agreement with the older measurements of [71, 72] may point to additional systematics effects that could play a vital role in the determination of any half-life measurement/calculation.

This measurement shows the utility of cryogenic bolometers for precision studies across multiple energy bins to test various spectral shapes that stem from rare/forbidden nuclear processes. Further developments in cryogenic detectors which exhibit faster timing resolution, such as those using TESs for heat and/or light readout, would provide better separation of low-energy pile-up events and could offer even better energy resolutions than the NTDs used in this experiment [25, 76]. Coupled with further improvements in the theory calculations of the nuclear matrix elements [77, 78], this would allow for future studies of $^{115}$In and other candidate isotopes for such as $^{113}$Cd [74] (for an expanded list see [79]) further increasing the sensitivity to $g_A/g_V$ and opening the door to reducing this source of uncertainty on the nuclear matrix elements utilized by $0\nu\beta\beta$ experiments in their current and projected sensitivity limits.

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