PHYSICAL REVIEW C **87**, 031303(R) (2013)

Electron capture on ^{116}In and implications for nuclear structure related to double-β decay

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(Received 27 November 2012; published 7 March 2013)

The electron capture decay branch of ^{116}In has been measured to be $[2.46 \pm 0.44(\text{stat.}) \pm 0.39(\text{syst.})] \times 10^{-4}$ using Penning trap-assisted decay spectroscopy. The corresponding Gamow-Teller transition strength is shown to be compatible with the most recent value extracted from the (p, n) charge-exchange reaction, providing a resolution to longstanding discrepancies. This transition can now be used as a reliable benchmark for nuclear-structure calculations of the matrix element for the neutrinoless double-β decay of ^{116}Cd and other nuclides.

DOI: 10.1103/PhysRevC.87.031303 PACS number(s): 23.40.Hc, 27.60.+j, 14.60.Pq

If neutrinoless double-β ($0\nu\beta\beta$) decay were observed then the neutrino would be identified with its antiparticle [1,2]. The rate of this rare process could then be used to extract the effective neutrino mass or other new physics if the corresponding nuclear matrix element were known. Matrix elements for the candidate $0\nu\beta\beta$ decays are calculated using a variety of theoretical nuclear-structure methods that yield results with considerable spread [3]. In order to improve these calculations and converge on reliable values for the $0\nu\beta\beta$ matrix elements, it is important to provide experimental benchmarks.

The $\beta\beta$ decay process, with neutrinos or without, can be thought of as proceeding via two-step virtual transitions through states in the intermediate nucleus. The $0\nu\beta\beta$ decay would proceed via intermediate states of all spins and parities, whereas the $2\nu\beta\beta$ decay is restricted to Gamow-Teller (GT) transitions through intermediate states with $J^\pi = 1^+$ due to the relatively low momentum transfer. The double-β^- ($2\nu\beta\beta$) decay rates have been measured for many cases and can be used to benchmark the corresponding portion of $0\nu\beta\beta$-decay calculations, but there is more than one way to achieve a sum that equals the $2\nu\beta\beta$ matrix element. Therefore, detailed constraints on the addends are necessary and they can be derived by measuring the strengths of the transitions that connect the 0^+ $\beta\beta$ decay parent and daughter to each intermediate 1^+ state. For example, charge-exchange (CE) reactions may be used to to measure these strengths for both ground and excited intermediate states, albeit indirectly. In cases where the ground state of the intermediate nucleus has a spin and parity of $J^\pi = 1^+$, its electron capture (EC) and β-decay rates to the $J^\pi = 0^+$ parent and daughter, respectively, are both experimentally accessible, potentially providing direct benchmarks [4–6]. In the cases of ^{100}Mo and ^{116}Cd, for which the intermediate ground states have $J^\pi = 1^+$, the $2\nu\beta\beta$ decay matrix elements estimated using only the ground-state virtual transitions roughly reproduce the measured $2\nu\beta\beta$ decay rates [7–10], qualitatively consistent with the single-state dominance (SSD) hypothesis [11–14]. Unfortunately, it is currently impossible to draw quantitative conclusions about the $A = 116$ system because there are inconsistencies in the Gamow-Teller strength $B(\text{GT})$[1] of the transition connecting the ground states of ^{116}Cd and ^{116}In.

CE values for $B(\text{GT})$ are precise but scattered, varying by as much as a factor of 2. Orihara *et al.* measured the $^{116}\text{In}(p, n)^{116}\text{Cd}$ reaction to deduce $B(\text{GT}) = 0.16 \pm 0.02$ [15], but the beam energy of 35 MeV may have been too low for a reliable extraction [8]. Akimune *et al.* then measured the $^{116}\text{In}(^3\text{He},t)^{116}\text{Cd}$ reaction at 450 MeV and reported a value of $B(\text{GT}) = 0.032 \pm 0.005$ [16] that was later revised to be 0.14 ± 0.03 due to problems with the target [17]. A recent (p, n) measurement at 300 MeV by Sasano *et al.* yielded $B(\text{GT}) = 0.28 \pm 0.03$ [8,18].

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[1]Throughout the present paper, we define $B(\text{GT}) \equiv B(\text{GT})[0^+ \rightarrow 1^+]$ in units where the free neutron decay has $B(\text{GT}) = 3$, as in Ref. [18].

There is only one measurement of $B(\mathrm{GT}) = 0.47 \pm 0.13$ from EC on ^{116}In [7]. This value was derived from the average of a pair of experiments by Bhattacharya *et al.* that yielded $(1.94 \pm 1.04) \times 10^{-4}$ and $(2.46 \pm 0.80) \times 10^{-4}$ for the EC branch on ^{116}In, neither of which were statistically definitive (5σ) detections. These values for the EC branch were determined by normalizing to the 1294-keV ^{116}In β-delayed γ-ray intensity from Ref. [19] rather than the one from Ref. [20]. Using the latter would increase $B(\mathrm{GT})$ by a factor of 2.24, and this makes the $B(\mathrm{GT})$ value from Ref. [7] questionable [21].

Evidently, issues with the $B(\mathrm{GT})$ value for the ^{116}Cd to ^{116}In transition preclude its use as a meaningful benchmark for models that are used to calculate $0\nu\beta\beta$ matrix elements. We present here a more precise measurement of the EC branch of ^{116}In that takes advantage of state-of-the-art Penning-trap purification techniques to deliver exclusively ^{116}In states and employs a complementary normalization technique using β particles.

We measured the ^{116}In EC branch at the Ion Guide Isotope Separator On-Line (IGISOL) Facility of the University of Jyväskylä in Jyväskylä, Finland. ^{116}In ($t_{1/2} = 14.10 \pm 0.03$ s [22]) was produced by the ^{115}In(d, p) reaction using a primary deuteron beam of 7.6 MeV and 10 μA provided by the K130 cyclotron that impinged on a 1 mg/cm^2 natural In target evaporated on a 2 mg/cm^2 Ni backing. The reaction products were slowed down and thermalized with helium gas. Ions were extracted from the gas cell and transported through an rf sextupole guide, while the He gas was differentially pumped away. The ions were then accelerated using an electrostatic potential of ≈30 kV. After coarse isobaric separation using magnetic analysis, the ions were bunched in a linear segmented rf quadrupole trap [23] and injected into the JYFLTRAP Penning trap [24,25], which provided a mass resolving power of 25,000. This combination of instrumentation was used to select ^{116}In in a highly efficient manner while eliminating the coproduced radioactivities in the beam.

^{116}In ions were extracted from JYFLTRAP and delivered as a 30-keV ion beam to a counting station (Fig. 1) consisting of a planar, high-purity Ge detector of γ and x rays and a 4π scintillator block that was optically coupled to photomultipliers on opposite faces to discriminate β decay events [9,26]. Samples of ^{116}In were implanted into a thin Al foil located at the end of a cylindrical void inside the scintillator. 3 mm

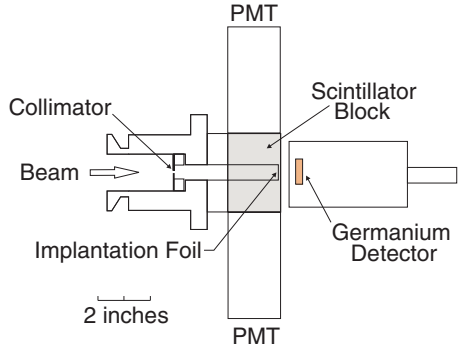

FIG. 1. (Color online) Schematic of detection apparatus.

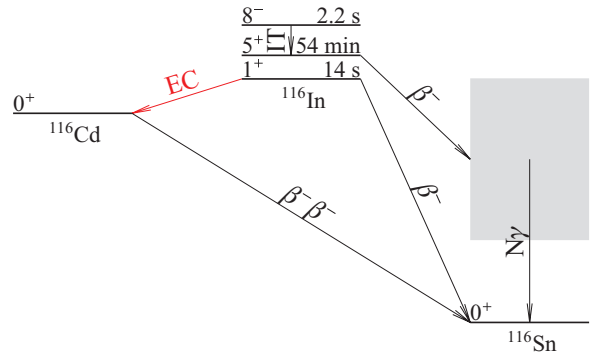

FIG. 2. (Color online) Simplified decay scheme of the $A = 116$ double-β decay system focusing on branches most relevant to the present work. The energy scale for ^{116}In is magnified.

of active scintillator separated the foil from the Ge detector's casing, which abutted the scintillator.

Measurements were carried out in 60-s cycles that comprised runs of 1–2 h. During each cycle, ^{116}In and its 2.2-s and 54-min isomers (Fig. 2) were delivered to the counting station for 30 s and then blocked upstream for the next 30 s while counting was performed. In addition, measurements were taken using extended counting times to investigate the 54-min isomer. Room background was measured off line.

The EC branch $BR(\mathrm{EC})$ of ^{116}In can be determined using Cd atomic K-shell x rays via

$$BR(\mathrm{EC}) = \frac{N_{\mathrm{x}}^{\mathrm{Cd}} \epsilon_{\beta}^{g}}{P_{\mathrm{x}}^{\mathrm{Cd}} \epsilon_{\mathrm{x}}^{\mathrm{Cd}} N_{\beta}^{g}}, \tag{1}$$

where $P_{\mathrm{x}}^{\mathrm{Cd}}$ is the probability of producing a Cd $K\alpha$ x ray per EC decay of the ^{116}In ground state (g.s.). $N_{\mathrm{x}}^{\mathrm{Cd}}$ is the number of those Cd $K\alpha$ x rays detected in the Ge detector (over the time interval $9 \leqslant t \leqslant 30$ s, where t is the time after the beginning of the relevant 30-s decay period), and $\epsilon_{\mathrm{x}}^{\mathrm{Cd}}$ is the corresponding detection efficiency. N_{β}^{g} is the number of β decays of the ^{116}In g.s. to ^{116}Sn detected in the scintillator over the same time interval and ϵ_{β}^{g} is the corresponding detection efficiency. The β decay of the 54-min isomer can be described using similar notation,

$$\frac{N_{\mathrm{x}}^{\mathrm{Sn}}}{P_{\mathrm{x}}^{\mathrm{Sn}} \epsilon_{\mathrm{x}}^{\mathrm{Sn}}} = \frac{N_{\beta}^{m}}{\epsilon_{\beta}^{m}}. \tag{2}$$

We used Eq. (2) in combination with Eq. (1) to obtain a ratio with minimal sensitivity to systematic uncertainties:

$$BR(\mathrm{EC}) = \frac{P_{\mathrm{x}}^{\mathrm{Sn}}}{P_{\mathrm{x}}^{\mathrm{Cd}}} \frac{N_{\mathrm{x}}^{\mathrm{Cd}}}{N_{\mathrm{x}}^{\mathrm{Sn}}} \frac{\epsilon_{\mathrm{x}}^{\mathrm{Sn}}}{\epsilon_{\mathrm{x}}^{\mathrm{Cd}}} \frac{N_{\beta}^{m}}{N_{\beta}^{g}} \frac{\epsilon_{\beta}^{g}}{\epsilon_{\beta}^{m}}. \tag{3}$$

Fitting of the x-ray spectra was complicated by the presence of a low-energy shoulder to each full-energy peak produced by the scattering of x rays prior to their interaction with the active volume of the Ge detector. In order to understand the x-ray spectra in sufficient detail to search for the weak Cd x-ray peak, we deconvoluted the effective response of the detection system. The x-ray spectrum measured in coincidence with scintillator signals, or "calibration spectrum," (Fig. 3, top

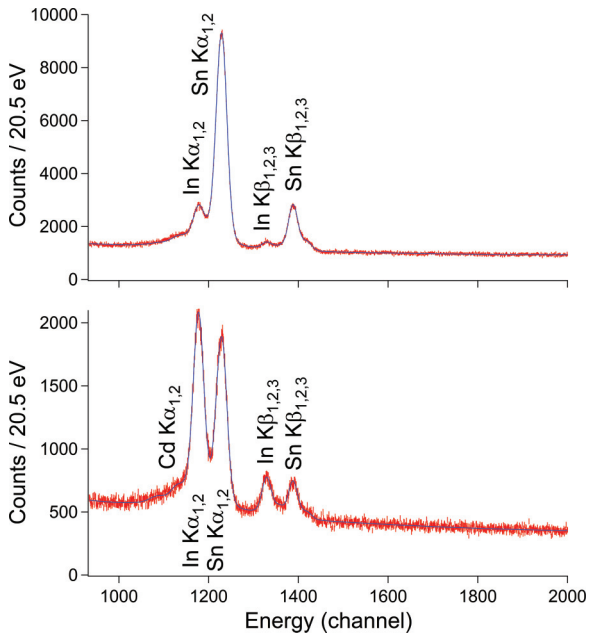

FIG. 3. (Color online) X-ray energy spectra recorded by the Ge detector over the time interval $9 \leqslant t \leqslant 30$ s. The top panel shows the spectrum in coincidence with scintillator events referred to in the text as the "calibration spectrum." The solid line is the best fit obtained by convoluting a simulated Monte Carlo spectrum with a response function consisting of the sum of two exponentially modified Gaussian functions. The bottom panel shows the spectrum vetoed by scintillator events. The solid line is the best fit obtained by convoluting a simulated Monte Carlo spectrum with the empirical response function extracted from the calibration spectrum.

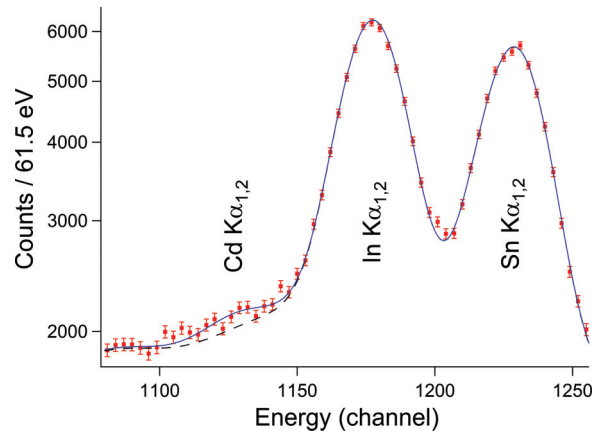

FIG. 4. (Color online) Log-scale magnification of the spectrum in the bottom panel of Fig. 3 compressed to three channels per bin showing the $K\alpha$ x-ray region. The solid line is the fit from Fig. 3 that includes the Cd x-ray peak and the dashed line is the same fit with the Cd component subtracted.

panel) was used for this purpose. The calibration spectrum includes high statistics data on In and Sn x rays from the IT decay of the ^{116}In 2.2-s isomer and β decay of the ^{116}In 54-min isomer, respectively, and it was filtered by the time window $9 \leqslant t \leqslant 30$ s. To provide a physical basis for fitting this spectrum, perfect-resolution spectra representing all of the K-shell x rays of ^{116}In and ^{116}Sn were produced using a Monte Carlo simulation [9,26] that incorporated the experimental geometry. The calibration spectrum was fit with the sum of the simulated In and Sn spectra convoluted with an effective response function whose shape was iterated until a satisfactory fit was converged upon. It was found that the effective response could be described by the sum of two exponentially modified Gaussian functions that account for a low-energy tail.

In order to determine the number of Cd x rays detected, another Ge-detector spectrum filtered by the time window $9 \leqslant t \leqslant 30$ s was produced. This spectrum was vetoed by coincident scintillator events to reduce Sn x-ray backgrounds produced by β decays. To fit this spectrum, the effective response was fixed to the one derived from the calibration spectrum and convoluted with a simulated spectrum consisting of the sum of Cd, In, and Sn contributions. The positions and relative amplitudes of the K-shell peaks for each element were also fixed based on the fit of the calibration spectrum. The six free parameters in the fit consisted of one amplitude for each of the three elements and a quadratic background, yielding $\chi^2/\nu = 1071/1061$. The spectrum and the corresponding fit are shown in Figs. 3 (bottom panel) and 4. Integrating the Cd $K\alpha_{1,2}$ full-energy peaks and taking into account a $(-10.1 \pm 10.1)\%$ correction due to slight inconsistencies between the modeled and observed shapes of the x-ray shoulders in the calibration spectrum yielded $N_{\mathrm{x}}^{\mathrm{Cd}} = 1061 \pm 191(\mathrm{stat.}) \pm 119(\mathrm{syst.})$. The number of Sn $K\alpha$ x rays detected over the same time window was determined to be 310 289 by integrating the full-energy peaks from the calibration spectrum and the scintillator-vetoed spectrum. Uncertainties associated with this value are negligible in comparison to those associated with the Cd peak. Combining the x-ray values yields $\frac{N_{\mathrm{x}}^{\mathrm{Cd}}}{N_{\mathrm{x}}^{\mathrm{Sn}}} = 0.003\,42 \pm 0.000\,62(\mathrm{stat.}) \pm 0.000\,37(\mathrm{syst.})$.

The K-shell x-ray detection efficiency of the Ge detector was on the order of 10%. We used the Monte Carlo simulation to determine a central value for the ratio of efficiencies. We used the relative intensities of K-shell x-ray peaks in the calibration spectrum to verify the accuracy of the Monte Carlo simulation and estimate the uncertainty, yielding $\frac{\epsilon_{\mathrm{x}}^{\mathrm{Sn}}}{\epsilon_{\mathrm{x}}^{\mathrm{Cd}}} = 1.100 \pm 0.033$.

β particles from the decays of the ^{116}In g.s. and 54-min isomer could not be distinguished on an event-by-event basis in the scintillator. Instead, we plotted the decay curve for events in the scintillator with respect to the start of the relevant decay cycle to distinguish these two decays in a bulk fashion using their distinct half-lives. A fit was performed in the $9 \leqslant t \leqslant 30$ s time window consisting of the sum of three exponential functions corresponding to the three ^{116}In states and a relatively weak constant background whose rate was fixed based on off-line measurements. Due to the low rate associated with the 2.2-s isomer and the nearly constant rate of 54-min isomer decays within this time window, the fit was not sensitive to their half-lives, which were consequently fixed to their literature values [22] and only their intensities were used as free parameters in the fit. For the third exponential, the half-life and the intensity were both allowed to vary. The half-life of this third component was found to be 14.9 ± 0.8 s, consistent with the known ^{116}In half-life. Integrating the 54-min and 14.9-s

exponentials over the time interval of interest and including a $(-9 \pm 3)\%$ correction for the sensitivity of the scintillator to γ rays yielded a value of $\frac{N_\beta^m}{N_\beta^g} = 3.506 \pm 0.213$.

The β-particle detection efficiency of the scintillator was measured using data from the well-known [22,27] β decay of the 54-min isomer of ^{116}In. In a low-gain Ge-detector spectrum, four β-delayed γ rays were selected that correspond to known β-decay endpoint energies in the range of 0.3–1.1 MeV. By gating on each of these γ-ray peaks and counting the percentage of events with a coincident event in the scintillator (with appropriate corrections for its sensitivity to γ rays) the efficiency of the scintillator for detecting β decays with the corresponding endpoint energy was determined. Monte Carlo simulations [9] were run for the endpoints of interest, yielding simulated efficiencies that were found to be consistently higher than the measured values by an average of 10%. We used the measured values to determine $\epsilon_\beta^m = (71.5 \pm 4.5)\%$, where the uncertainty is based on the spread of the difference between the measurements and the simulations. The value of ϵ_β^g was estimated because its β endpoint energy of 3.3 MeV was far higher than the measured range. We assigned a value of $\epsilon_\beta^g = (93 \pm 5)\%$, between the simulated value of 98% and the value of 88% obtained by assuming that the true efficiency is 10% lower than the simulated value. The adopted ratio of β-particle detection efficiencies is $\frac{\epsilon_\beta^g}{\epsilon_\beta^m} = 1.30 \pm 0.11$.

Lastly, we employed literature values of $P_x^{\mathrm{Cd}} = 0.589 \pm 0.006$ [28] and $P_x^{\mathrm{Sn}} = 0.008\,47 \pm 0.000\,25$ [22], yielding $\frac{P_x^{\mathrm{Sn}}}{P_x^{\mathrm{Cd}}} = 0.014\,38 \pm 0.000\,45$.

Substituting the ratios discussed into Eq. (3) yields $BR(\mathrm{EC}) = [2.46 \pm 0.44(\mathrm{stat.}) \pm 0.39(\mathrm{syst.})] \times 10^{-4}$. This value represents the first measurement of EC on ^{116}In with a statistical significance over five standard deviations and it is in good agreement with both previous measurements [7], which produced a weighted average of $(2.27 \pm 0.63) \times 10^{-4}$.

Using our EC branch and the half-life of ^{116}In yields a partial half-life of $[5.72 \pm 1.03(\mathrm{stat.}) \pm 0.91(\mathrm{syst.})] \times 10^4$ s for EC on ^{116}In. Combining this value with the phase-space factor $f = 0.496$ calculated using the Q value of 462.71 ± 0.27 keV [29,30] and the tables of Ref. [31] yields $ft = [2.84 \pm 0.51(\mathrm{stat.}) \pm 0.45(\mathrm{syst.})] \times 10^4$ s. We use this value and the equation

$$B(\mathrm{GT}) = 3\frac{K}{g_A^2 G_V^2 \left(1 + \Delta_R^V\right) ft} \tag{4}$$

to determine $B(\mathrm{GT}) = 0.402 \pm 0.072(\mathrm{stat.}) \pm 0.064(\mathrm{syst.})$, where we adopt $\frac{K}{G_V^2(1+\Delta_R^V)} = 6143.62 \pm 1.66$ s from superallowed $0^+ \to 0^+$ nuclear β decays [32] and $g_A = -1.270\,1 \pm 0.002\,5$ for the axial-vector coupling constant from the β decay of the free neutron [33].

Revising the previous EC result [7] using the same value of f yields $B(\mathrm{GT}) = 0.37 \pm 0.10$, consistent with our value, suggesting that the $\beta\gamma$ branches in Ref. [19] are more accurate than those in Ref. [20]. Our value is also compatible with the most recent (p, n) value [18] (at slightly beyond the 1σ level if the uncertainties are added in quadrature). The $B(\mathrm{GT})$ values from the older CE experiments [15–17] remain more than a factor of 2 lower.

Combining our matrix element with the ^{116}In β^- decay one [22], we find that the $2\nu\beta\beta$-decay matrix element for the virtual transition through the ground state of ^{116}In is $0.168 \pm 0.015(\mathrm{stat.}) \pm 0.13(\mathrm{syst.})\ \mathrm{MeV}^{-1}$, which is larger than the total value of $0.129 \pm 0.005\ \mathrm{MeV}^{-1}$ derived[2] using the measured $2\nu\beta\beta$ decay rate of ^{116}Cd [34–38] and the SSD phase-space factor from Ref. [39]. This shows that the intermediate ground state makes a large contribution to the ^{116}Cd $2\nu\beta\beta$ decay (as it does for ^{100}Mo [9,10]) and provides a hint that contributions of the opposite sign from virtual transitions through ^{116}In excited states may provide some cancellation.

In conclusion, we have measured the EC decay of ^{116}In to ^{116}Cd with 5σ statistical significance for the first time, confirming previous evidence [7] for this decay. Our branch leads to a value of $B(\mathrm{GT})$ that agrees with the existing EC value [7] and is compatible with the most recent CE value [18], providing a consistent set of values for the matrix element corresponding to this transition. The complete trio of matrix elements corresponding to the transitions connecting the ground states of ^{116}Cd, ^{116}In, and ^{116}Sn through EC, β decay, and $2\nu\beta\beta$ decay can now be used together as necessary (but not sufficient) benchmarks for $0\nu\beta\beta$-decay matrix element calculations.

We gratefully acknowledge the staffs of CENPA and IGISOL and also D. L. Fang and R. Zegers for comments on the manuscript. This work was supported by the US DOE under Contracts No. DE-FG02-97ER41020 (CENPA) and No. DE-AC02-06CH11357 (ANL), the US NSF under Contract No. RC100609 (NSCL), and the Academy of Finland under the Finnish Centre of Excellence Programme 2006–2011, Project No. 213503 (JYFL).

[2]It is possible that g_A assumes a lower effective value in nuclei than it does in neutron decay. For the calculation of both $2\nu2\beta$ decay matrix elements we have consistently used the value of $g_A = -1.27$ from the decay of the free neutron, which enters at the same power in both cases. Therefore, changing g_A would affect both values by the same amount.

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