Low-lying GT$^+$ strength in ^{116}In from a $(d,^2$He) reaction experiment and its implications for ^{116}Cd double β decay

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We have used the $(d,^2$He) reaction to obtain the GT$^+$ strength distribution for ^{116}Sn → ^{116}In transitions. Here, ^{116}In is the intermediate nucleus in the second-order perturbative description of ^{116}Cd double beta ($\beta\beta$) decay. In this paper we will review what is known about the nuclear matrix elements for the ^{116}Cd $2\nu\beta\beta$ decay, discuss the single-state dominance hypothesis and combine our new data with other existing data from charge-exchange reactions to obtain a $2\nu\beta\beta$-decay half-life. The deduced value $T_{1/2} = (4 \pm 1) \times 10^{19}$y compares well with the one known from direct counting experiments.

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I. INTRODUCTION

The $(d,^2$He) charge-exchange reaction at intermediate energies ($E \approx 100$ MeV/nucleon) has become an established tool to study spin-isovector excitations in the $\Delta T_z = +1$ direction [1–9]. In particular, one can exploit the fact that at low momentum transfer $\Delta q \sim 0$ there is an enhanced sensitivity to Gamow-Teller transitions, which are characterized by $\Delta L = 0$, $\Delta S = 1$, and $\Delta T = 1$. Further, compared to (n, p) or $(t,^3$He) reactions, the $(d,^2$He) reaction has a number of important advantages:

i. No secondary beams are required like in the (n, p) case [10–12], where as a consequence of this, experimental resolution is usually limited. Triton beams, on the other hand, are also either of secondary type [13] or severely intensity limited [14].
ii. Primary high intensity beams in $(d,^2$He) experiments make the use of thin isotopically enriched targets affordable, and moreover, energy resolutions on the order of 100 keV can routinely be achieved.
iii. The coincident detection of the protons from the decaying ^{2}He largely eliminates instrumental background. This is especially important for the spectroscopy of the continuum region of the nuclear response.

However, the coincident detection of the two protons requires enhanced detection techniques, as the major background originates from deuteron breakup (d, pn) reactions in the Coulomb field of the target nucleus. These single protons have momenta similar to those from the $(d,^2$He) reaction. Break-up cross sections depend almost quadratically on the target charge Z and are up to 10^6 times larger than those of the $(d,^2$He) reaction [15].

At intermediate energies and in the case of vanishing momentum transfer, the $(d,^2$He) reaction is mediated predominantly by the $\boldsymbol{\sigma\tau}$ part of the effective interaction. The measured cross section is then directly proportional to the B(GT) strength, which in the (n, p) or (p, n) case is [16,17]:

$$\frac{d\sigma(q=0)}{d\Omega} = \left(\frac{\mu}{\pi\hbar^2}\right)^2 \frac{k_f}{k_i} N_D J_{\sigma\tau}^2 B(GT^+). \tag{1}$$

$J_{\sigma\tau}$ is the volume integral of the spin-dependent isovector central part of the effective nucleon-nucleon interaction at $q = 0$ and can be obtained from Refs. [18,19]. The distortion factor N_D is usually estimated in Born approximation by calculating the ratio of the distorted-wave (DW) and plane-wave (PW) cross sections. The cross section $d\sigma(q = 0)/d\Omega$ is obtained by extrapolating the measured cross section to $q = 0$ using a DWBA (distorted-wave Born approximation) model calculation. This is a reliable procedure if measurements are being performed near 0°.

The proportional relationship of Eq. (1) for the $(d,^2$He) reaction has been verified in a number of recent publications even in cases where the transitions are weak [1,5]. However, angular distributions are an important additional information to confirm the character and the multipolarity of the respective transitions.

The present interest in studying the ^{116}Sn$(d,^2$He)^{116}In reaction is motivated by the fact that ^{116}Sn is the final nucleus in ^{116}Cd $\beta\beta$ decay. The $2\nu\beta\beta$ decay mainly proceeds through low-lying GT$^+$ and GT$^-$ single-particle transitions, which provide the main nuclear structure ingredient for the determination of the $\beta\beta$-decay half-life (see Fig. 1). Complete knowledge of both GT components, which can be determined through (n, p) and (p, n) type charge-exchange reactions on the daughter and parent nuclei, respectively, will allow the determination of the $\beta\beta$-decay half-life and could help to guide

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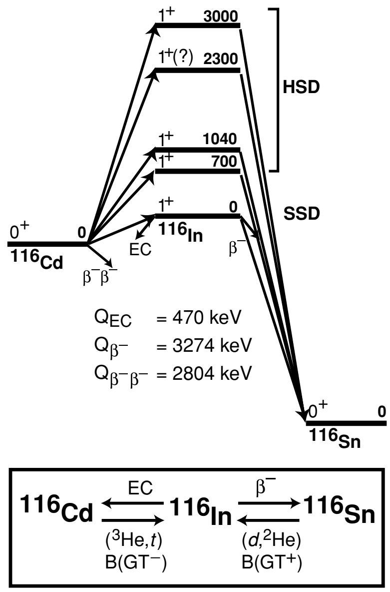

FIG. 1. Level scheme of the $A = 116$ isobar members involved in the ^{116}Cd $\beta\beta$ decay together with the notation of the transition directions. The single-state dominance (SSD) hypothesis assumes that the $2\nu\beta\beta$ decay proceeds predominantly through the allowed ground-state transitions, whereas higher lying states could equally well play a role. This is referred to as higher order state dominance (HSD) in Refs. [20,21]. The quoted excited states J^π assignments are based on the present analysis.

present and future counting experiments, which are usually time consuming and rather involved.

II. THE ^{116}CD DOUBLE BETA DECAY

The nuclear $\beta\beta$ decay proceeds as a second-order weak transition. Two reaction modes are at the center of attention, the neutrinoless ($0\nu\beta\beta$) and the two-neutrino ($2\nu\beta\beta$) decay. The neutrinoless mode is kinematically favored, but violates lepton-number conservation and is therefore forbidden in the Standard Model. The two-neutrino decay mode, in contrast, is kinematically suppressed as four leptons have to share energy and momentum, thus reducing the overall phase space, but it is allowed by all selection rules and has even directly been observed in a few cases [22].

The $\beta\beta$ decay represents a test of our knowledge of nuclear wave functions. The decay mechanism in the perturbative description is seen as a combination of two sequential virtual decays: from a parent nucleus to the adjacent intermediate nucleus, to which ordinary β decay is either energetically forbidden or suppressed by angular momentum, followed by the transition to the daughter nucleus, which then lies energetically below the parent [23,24].

The $2\nu\beta\beta$ half-life is connected with the double-Gamow-Teller (DGT) matrix element by

$$\left[T_{1/2}^{(2\nu)}\right]^{-1} = G^{(2\nu)}|M^{(2\nu)}(\mathrm{DGT})|^2, \tag{2}$$

where $G^{(2\nu)}$ combines the weak-coupling constant and the phase-space factor. If the initial and final states both have $J^\pi = 0^+$, the double-Gamow-Teller matrix element is given by

$$\begin{aligned} M^{(2\nu)}&(\mathrm{DGT}) \\ &= \sum_m \frac{\langle 0^{(f)}_{\mathrm{g.s.}} \| \sum_k \sigma_k \tau_k^- \| 1^+_m \rangle \langle 1^+_m \| \sum_k \sigma_k \tau_k^- \| 0^{(i)}_{\mathrm{g.s.}} \rangle}{{}^1\!/_2\, Q_{\beta\beta}\left(0^{(f)}_{g.s.}\right) + E_x(1^+_m) - E_0} \\ &= \sum_m \frac{M_m(\mathrm{GT}^+) \cdot M_m(\mathrm{GT}^-)}{E_d^m} \\ &= \sum_m M_m(\mathrm{DGT}). \end{aligned} \tag{3}$$

$E_x(1^+_m) - E_0$ is the energy difference between the mth intermediate 1^+ state and the initial ground state, and the sum $\sum_k$ runs over all the neutrons of the decaying nucleus. Contributions from Fermi-type virtual transitions are negligible [23], because initial and final states belong to different isospin multiplets. In fact, the transition matrix is essentially a product of two ordinary β-decay Gamow-Teller matrix elements between the initial and intermediate state, and between the intermediate and the final ground state, respectively.

Units are often a source of confusion. In this paper, B(GT) values are given in units in which the neutron decay has $B(\mathrm{GT}) = 3$. Further,

$$B(\mathrm{GT}) = \frac{1}{2J_i + 1}|M(\mathrm{GT})|^2. \tag{4}$$

Spin factors have been taken into account, but the presently quoted B(GT) values always refer to the $0^+ \longrightarrow 1^+$ transitions among the involved isobars. The energy denominators E_d^m in Eq. (3) are in units of the electron rest mass m_e. The connection between the *ft* value and B(GT) is [25,26]:

$$ft = \frac{(6146 \pm 6)\ \mathrm{s}}{g_A^2 B(\mathrm{GT})}, \tag{5}$$

where $g_A = 1.257$. The phase space factor for the ^{116}Cd $2\nu\beta\beta$ decay is $G^{(2\nu)} = 7.4 \times 10^{-18}\ \mathrm{y}^{-1}$ taken from Ref. [24], where several important phase-space integrals $G^{(2\nu)}$ are summarized.

Isobars in which the intermediate nucleus has a $J^\pi = 1^+$ ground state (g.s.) are of particular interest, as it has been conjectured [20] that the matrix element $M^{(2\nu)}$(DGT) may be dominated by the virtual ground-state transitions only. This hypothesis is known as single-state dominance (SSD). Its validity has been studied theoretically and experimentally [21,27,28]. The two most important cases are the $\beta\beta$-decay nuclei ^{100}Mo and ^{116}Cd, as here the $2\nu\beta\beta$-decay half-lives are known with good precision [29].

In the present work, we will focus on the ^{116}Cd case. Several classes of data are available. These include experimental *ft* values from the ^{116}In(g.s.) $\longrightarrow$ ^{116}Sn(g.s.) β^- decay [30], as well as from the ^{116}In(g.s.) $\longrightarrow$ ^{116}Cd(g.s.) EC transition [31]. A charge-exchange reaction of the type ^{116}Cd(^{3}He,*t*)^{116}In has been performed by Akimune *et al.* [32], in which the ground-state transition connects to the above EC process. The (d,^{2}He) data presented here refer to the path ^{116}Sn(g.s.) $\longrightarrow$ ^{116}In. Of course, the hadronic reactions can connect to all the excited

TABLE I. Collection of $2\nu\beta\beta$-decay half-lives for ^{116}Cd. Row 1 gives the half-life from counting experiments [29,34–36], row 2 combines the (^{3}He,t) data and the ^{116}In(β^-) ft value, and row 3 is based on the recent ^{116}In EC measurement [31] and the β^- decay. In row 4 we quote one of the most recent theoretical calculations [37]. In all these three cases the SSD hypothesis is assumed. The situation deduced from the present paper is quoted for comparison in row 5, where the values correspond to the summed B(GT).

Case	$B(\mathrm{GT}^-)$	$B(\mathrm{GT}^+)$	M(DGT)	$T_{1/2}^{(2\nu)}$ [10^{19} y]
direct	–	–	0.064	3.3
(^{3}He,t)/β^-	0.032	0.256	0.025	22.0
EC/β^-	0.47	0.256	0.095	1.5
theory	1.165	0.065	0.075	2.4
(^{3}He, t)/(d,^{2}He)	0.061*	1.09*	0.058	4.0

*Note: these values denote summed B(GT) values and should not be confused with the individual quantities used to evaluate M(DGT).

states in the intermediate nucleus ^{116}In and are therefore not limited to the ground-state transitions only.

Table I summarizes the rather unsatisfactory situation of the ^{116}Sn $\beta\beta$ decay when evaluating the single-state-dominance approach as there are conflicting individual ground-state B(GT) values. The table also quotes an example of a recent theoretical calculation. Note that we use a notation where the isospin direction always refers to the respective charge-exchange reaction starting from the stable initial and the stable final nucleus, so that the β^- or EC transition of the unstable intermediate ground state is always connected to the opposite isospin direction, i.e., ^{116}In(β^-) to $B(\mathrm{GT}^+)$ and ^{116}In(EC) to $B(\mathrm{GT}^-)$. The ^{116}In β^-decay [31] to the ground state has a branching ratio of 99.97%, and the ground-state transition strength $B(\mathrm{GT}^+) = 0.256$ is known with an error of only 0.4%. On the other hand, the ^{116}In EC transition to ^{116}Cd has an evanescently small branching ratio of less than 0.03%, which was measured at the Notre Dame Tandem Accelerator Laboratory [31]. Based on the extracted ft value ($\log ft = 4.39\,^{+0.10}_{-0.15}$), the Gamow-Teller transition strength is deduced to be $B(\mathrm{GT}^-) = 0.47 \pm 0.13$. The strength from the (^{3}He, t) experiment for the same transition measured by Akimune *et al.* [32] has been determined to be $B(\mathrm{GT}^-) = 0.032 \pm 0.005$. There is an obvious discrepancy of a factor of 15, which is difficult to comprehend. One could argue that the proportionality between B(GT) and (^{3}He, t) charge-exchange cross section [Eq. (1)] is not safely established [31,33], but such a large factor would be rather exceptional, especially since the EC rate indicates a rather low degree of forbiddeness, which ought to translate into a rather strong charge-exchange transition. Further measurements are clearly warranted to resolve this issue.

The results from a quasiparticle random-phase approximation (QRPA) calculation [37] also deserve a comment. Although the $2\nu\beta\beta$ half-life [29] is predicted with an acceptable precision, neither the $B(\mathrm{GT}^+)$ nor the $B(\mathrm{GT}^-)$ values of the single β decays are reasonably well reproduced. The $B(\mathrm{GT}^-)$ is larger than any of the experimental values and would translate into a $\log ft = 4.0$, which is not too common in this mass region. Conversely, the $B(\mathrm{GT}^+)$ is too small by a factor of 4. This demonstrates the importance of experimental input for the tuning of the models, as has been stated in recent articles by Suhonen and Civitarese [24] and by Elliott and Vogel [22]. This may be even more important as $2\nu\beta\beta$ decay calculations are commonly used to adjust the correlation parameter g_{pp}, which is input to $0\nu\beta\beta$ decay QRPA calculations [38].

III. EXPERIMENTAL TECHNIQUE

The experiment was performed at the AGOR superconducting cyclotron located at the KVI facility, Groningen. We used the EuroSuperNova (ESN) detector, which consists of a focal-plane detection system (FPDS) with two vertical drift chambers (VDCs) and another tracking detector further downstream, which comprises a set of four multiwire proportional chambers (MWPCs) [39,40]. The detector is placed at the focal plane of the Big-Bite Spectrometer (BBS) [41]. The tracking information from the MWPCs is processed in real-time by a dedicated computer system, which checks the coincidence condition [42]. Read-out rates are typically around 50,000 s^{-1}, while "real" ^{2}He rates from a target with $Z = 50$ are about one per minute.

A beam of 183 MeV deuterons was delivered by the AGOR cyclotron. The spectrometer and the beam line were set up in dispersion-matched mode to ensure good momentum resolution.

The target was a self-supporting metallic foil enriched to 91.4% with a thickness of 5.0 mg/cm^2. The reaction Q value is -4.71 MeV. Hydrogen is an ever-present contaminant, especially in a metallic target. Its peak from the ^{1}H(d,^{2}He)n reaction is visible at a "negative" excitation energy in the final spectrum. At a scattering angle of $\Theta \geqslant 4^\circ$, the hydrogen peak moves into the ^{116}In spectrum, and thus the spectrometer angle settings have been chosen to be 0°, 1.5°, and 3°.

Each data set was divided into two angle bins of equal size. In one case the counting statistics required a reassembling of the data back to one large bin.

Beam currents were measured by a Faraday cup. Typical intensities were 100 to 500 pA, depending on the spectrometer angle. The detector efficiency for two-track events including the tracking efficiency of the data analysis software has been evaluated to be (86 ± 2)%. The calibration of the energy scale and also the checks of the detection efficiency were accomplished by changing to a ^{12}C target after certain time intervals. The ^{12}B final spectrum exhibits a prominent ground-state peak at a Q value of -14.87 MeV, which translates to 10.16 MeV in the ^{116}In excitation spectrum (at 0°). Even in the ^{116}In spectrum, a small reaction peak from a ^{12}C contamination is visible. The peak from the unavoidable hydrogen contamination present in both targets further aids the energy calibration. Its kinematic tilt at finite angles further helps to verify the scattering angle calibration.

Figure 2 shows the excitation energy spectrum of the ^{116}Sn(d,^{2}He) reaction at $\Theta_{\mathrm{BBS}} = 0^\circ$. The data reduction procedure described in Ref. [40] has been applied. The spectra are largely free of any instrumental background or background

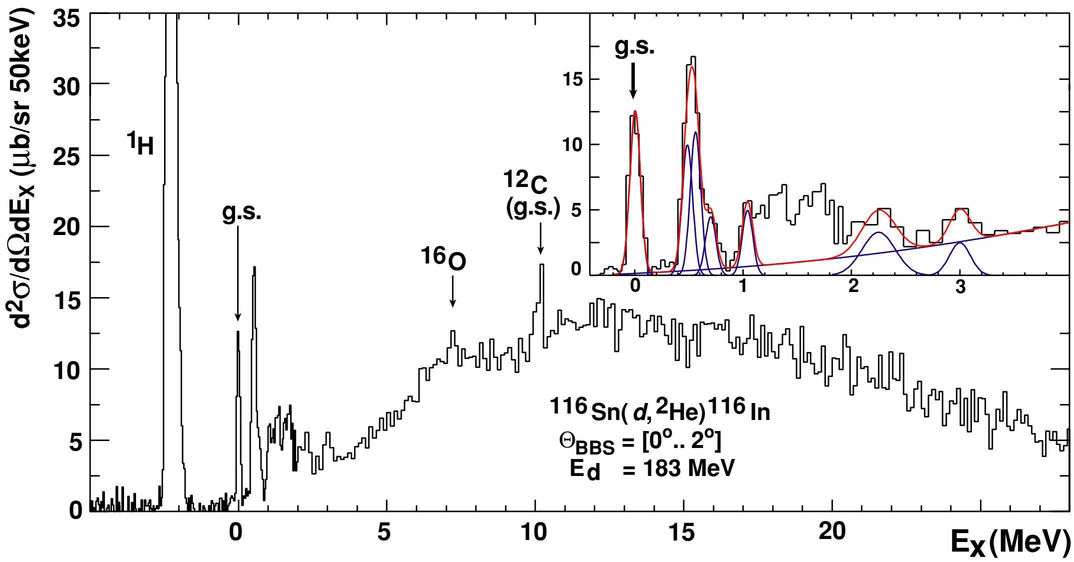

FIG. 2. (Color online) Excitation energy spectrum of the ^{116}Sn(d,^{2}He)^{116}In reaction. The spectrum has been binned into 50 keV bins up to 2 MeV, whereas for the continuum above a bin-size of 150 keV has been used. The energy resolution is 110 keV. The peaks from the ever-present hydrogen contamination and those from ^{16}O and ^{12}C are indicated in the spectrum. The inset shows the magnified low-energy part of the spectrum together with the respective peak fits. The fits include the low-energy tail of the continuum. For details see text.

from random correlations. The energy resolution was between 110 keV and 120 keV (FWHM) depending on the spectrometer angle. As the final odd-odd nucleus has a rather high level density, identification of discrete states was only possible up to about 1 MeV excitation energy. Between 1.5 and 3 MeV, some broad structures are observed, whereas the spectrum above 3 MeV is largely featureless.

The triple-differential (d,^{2}He) cross sections $d^3\sigma/d\Omega\, dE_x d\varepsilon$ have been integrated over the ^{2}He internal energy distribution $F(\varepsilon)$ from 0 to 1 MeV as described in Ref. [1]. Therefore, the process of the acceptance correction introduces a small model-dependent scale into the determination of absolute cross sections. For the extraction of low-lying GT transitions we apply Eq. (1) and use the well-known log ft value from the ^{116}In(β^-) ground-state decay as a calibration standard.

Peak integration and peak fitting was performed with the computer program FIT [43] in manual fitting mode. The peak from the transition to the ground state was well described by a Gaussian shape with a full width at half maximum (FWHM) of 115 ± 5 keV. The errors quoted in the following reflect the counting statistics (including contributions from random coincidences) and systematic errors, which arise from the uncertainties in the acceptance correction among different angular settings [5], target thickness, detection efficiency, current integration, etc., and are estimated conservatively to add up to 20%. A third contribution originating from the multipole decomposition techniques has been evaluated separately and will be mentioned when needed.

IV. DATA ANALYSIS AND INTERPRETATION

The inset of Fig. 2 and the lower panel of Fig. 4 show the low excitation energy part of the (d,^{2}He) spectrum at a c.m. angle interval of $[0^\circ \cdots 2^\circ]$. The level density in the odd-odd final nucleus increases rapidly with excitation energy. Fits of single peaks could be performed only up to about 1 MeV. Even here, the peak structure next to the ground state turned out to be a superposition of three peaks at 0.48, 0.56, and 0.70 MeV, the latter being visible as a shoulder on the 0.48/0.56 MeV peak. The peak at 1.04 MeV is a member of a conglomerate of excitations roughly between 1 and 2 MeV. It is the only part of the structure that can be fitted by a Gaussian shape, and it can be further distinguished from the higher energy part by its clearly forward-peaked angular distribution (see below). Two further peak-like structures are located at 2.3 and 3.0 MeV on the low-energy tail of the rather featureless continuum. In the following, we will refer to the structures "A," "B," and "C" indicated in the spectrum of Fig. 4, of which "A" is the region of 1.2 − 2.0 MeV, "B" is the peak structure at 2.3 MeV, and "C" the structure at 3.0 MeV. Above 3 MeV, the spectrum is smooth and nearly featureless.

We note that contributions from the other Sn isotopes in the target, mostly ^{118,120}Sn, are truly negligible. The parts from the ^{118,120}Sn $\rightarrow$ ^{118,120}In g.s. transitions would be of order or less than 4%, which is less than the statistical error of the spectrum.

As the total GT strength and consequently the GT cross sections in the β^+ direction in this mass region are small owing to neutron blocking, excitations of higher multipoles could be comparable in size even at forward angles. This necessitates an analysis of the angular distributions in order to extract possible underlying multipole components. Such an analysis is performed by a comparison with DWBA model calculations.

For the DWBA calculations we used the code ACCBA, which is specialized for the (d,^{2}He) reaction and describes the outgoing channel in the adiabatic approximation [44]. We employed deuteron optical model parameters from (d, d) measurements, which were performed for this purpose [45] at the same time. Proton optical model parameters for the

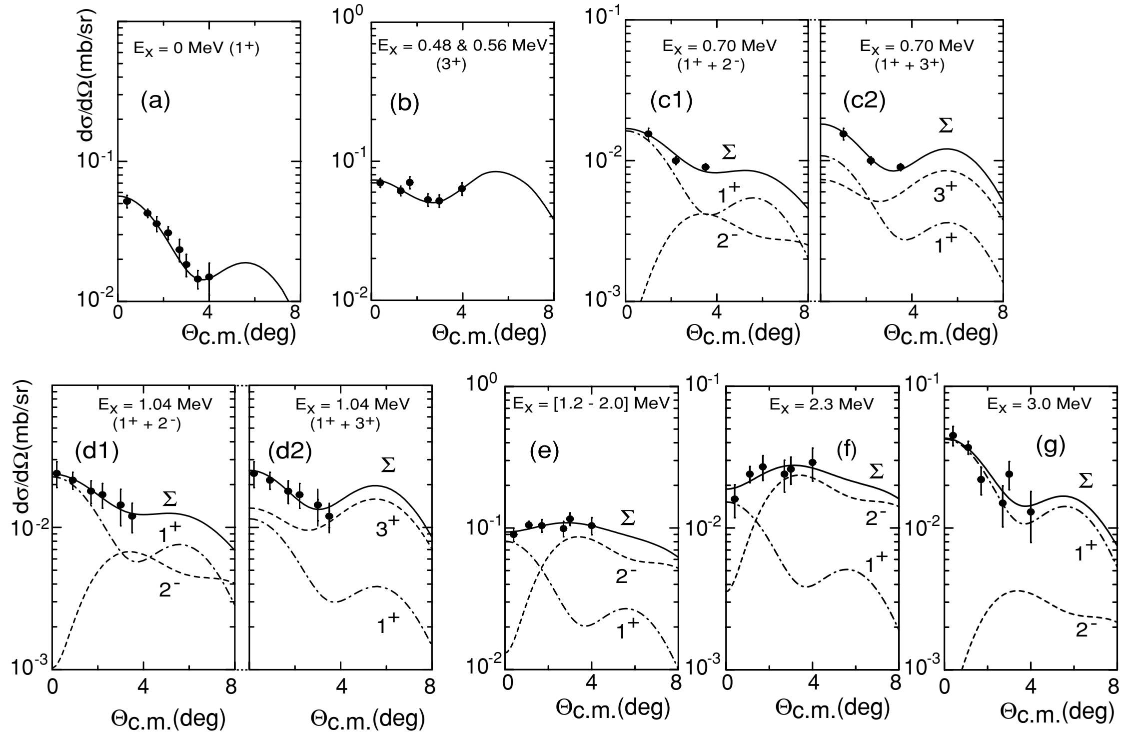

FIG. 3. Cross section angular distributions for the low-lying transitions. The error bars reflect the statistical errors only. Panels (a) and (b) show the ground-state transition described by a 1^+ transition, and the excitation of the doublet at 0.48 and 0.56 MeV by a 3^+ transition. The excitations at 0.70 and 1.04 MeV are forward peaked and were described by an incoherent sum of a 1^+ and a 2^- transition [(c1) and (d1)] or a 1^+ and a 3^+ transition [(c2) and (d2)]. The angular distributions for the broad structures, which are referred to as "A," "B," and "C" in Fig. 4, are shown in panels (e)–(g) together with $1^+/2^-$ model calculations.

outgoing channel were taken from Ref. [46], and the T-matrix nucleon-nucleon interaction by Franey and Love [18,19] for projectile energies of 100 MeV was applied. Transition amplitudes have been generated using normal modes [47,48] with occupation numbers from Ref. [49].

In order to evaluate higher multipole contributions to the excitation spectrum, generic calculations of 1^+, 2^-, and 3^+ excitations were performed. From unpolarized data, a distinction between different spin couplings to a particular ΔL transfer is not possible. For instance, dipole excitations of 1^- and 2^- states have largely similar angular distributions, while the 0^- excitations are significantly flatter. As the total spin-dipole strengths of $(0, 1, 2)^-$ excitations are expected to have a ratio of $1 : 3 : 5$, a 2^- calculation has been taken as a prototype for the dipole analysis. The situation is similar for quadrupole excitations, though the form factor varies barely among the $(1, 2, 3)^+$ calculations. We chose the 3^+ calculation as a generic form factor.

The 5% admixture of a D wave to the deuteron ground state introduces additional admixtures of higher multipoles, whose effects are, however, small and only of the order of 1–3%. A further non-GT type contribution can arise from the comparatively poorly known magnitude of the tensor force in the effective interaction, as was already discussed in Refs. [1,5]. This effect is, however, more of a concern at momentum transfers higher than those of the data presented here. All calculations were done with the full tensor force according to Ref. [19].

The data for the two prominent peaks, the ground state and the doublet at 0.48 and 0.56 MeV, are displayed in panels (a) and (b) of Fig. 3. The good description of the ground-state transition indicates that the $(d,{}^2\mathrm{He})$ cross section exhibits the expected typical behavior of a 1^+ transition even in a heavy nucleus such as ^{116}Sn and even for a relatively weak transition. The excitation of the doublet at 0.48 and 0.56 MeV excitation energy is well reproduced by a 3^+ calculation, which is shown in the graph. No significant GT transition strength can be extracted here.

Two structures, which show clearly forward-peaked behavior are located at 0.70 and 1.04 MeV. As a 1^+ calculation alone does not describe the data, higher multipoles from superimposed excitations needed to be taken into account. With the limited angular range of the data it is not possible to distinguish between the different contributing multipolarities. Panels (c) and (d) of Fig. 3 show for each peak a combination of $1^+/2^-$ [(c1)/(d1)] and $1^+/3^+$ [(c2)/(d2)] calculations. For this case, the systematic error for the GT strength is estimated by assuming that the $1^+/2^-$ fit gives the highest and the $1^+/3^+$ fit gives the lowest GT strength. The systematic errors derived in this way are 20% for the 0.70 MeV state and 35% for the 1.04 MeV state.

Panels (e)–(f) of Fig. 3 show the data of the broad structures "A"–"C." The structure "A" exhibits a rather flat angular distribution. In order to obtain an upper limit for the contained GT strength, a combination of 1^+ and 2^-

TABLE II. Excitations in ^{116}In. For areas A and B, the B(GT) extraction is ambiguous and only an upper limit is given.

E_x (MeV)	$d\sigma/d\Omega(\Theta_{\rm min})$ (μb/sr)	$d\sigma/d\Omega(\Delta L = 0, q = 0)$ (μb/sr)	B(GT$^+$)
0	58 ± 12	62 ± 12	0.256 ± 0.001*
$0.48 + 0.56$	72 ± 14	–	0
0.70	15.5 ± 3.1	16.9 ± 3.4	0.07 ± 0.03
1.04	24.0 ± 4.8	26.4 ± 5.3	0.11 ± 0.06
$1.20 - 2.00$	90 ± 18	90 ± 18	<0.37
2.30	16.0 ± 3.2	17.3 ± 3.4	<0.07
3.00	45 ± 9	50 ± 10	0.21 ± 0.04
		$\sum B$(GT$^+$) :	$1.09\,^{+0.13}_{-0.57}$

*Reference value from ^{116}In(β^-) decay [30].

calculations was performed, which always gives the highest GT strength among all possible multipole combinations. The more peaklike structures "B" and "C" ride on the tail of the continuum, which contains mostly spin-dipole excitations. The angular distribution of "B" is clearly backward peaked, yet the 2^- calculation does not alone account for all of the small angle cross section. An upper GT strength limit was obtained similar to the procedure described for the region "A." The area indicated by "C" has a more forward peaked distribution and can be reasonably well described by a pure 1^+ transition. Adding a 2^- component only marginally improves the description of the data with few consequences, however, for the extracted GT strength.

Table II summarizes the results of the analysis of the (d,^{2}He) reaction leading to low-lying 1^+ excitations. The conversion of cross sections into B(GT) values was performed according to Eq. (1) using the well-known β^--decay ft value as a calibration standard. Before proceeding to the discussion of the data in terms of double beta decay, it may be interesting to comment on the summed strength. By summing all B(GT$^+$) strength up to 3.2 MeV one obtains $S(\mathrm{GT}^+) = 1.09^{+0.13}_{-0.57}$. The large error arises from the fact that only upper limits were obtained for the structures "A" and "B." Of course, some additional GT strength may still reside in the continuum region of the spectrum; however, by taking realistic occupation numbers from Ref. [49] the normal modes calculation yields $S(\mathrm{GT}^+) = 2.51$. This means that in the experiment the low-lying ($E_x < 3.2$ MeV) 1^+ excitations exhaust 43% of the normal modes sum rule. Considering the usual quenching factor of 60%, about 2/3 of the GT strength seems therefore to be located in this energy region.

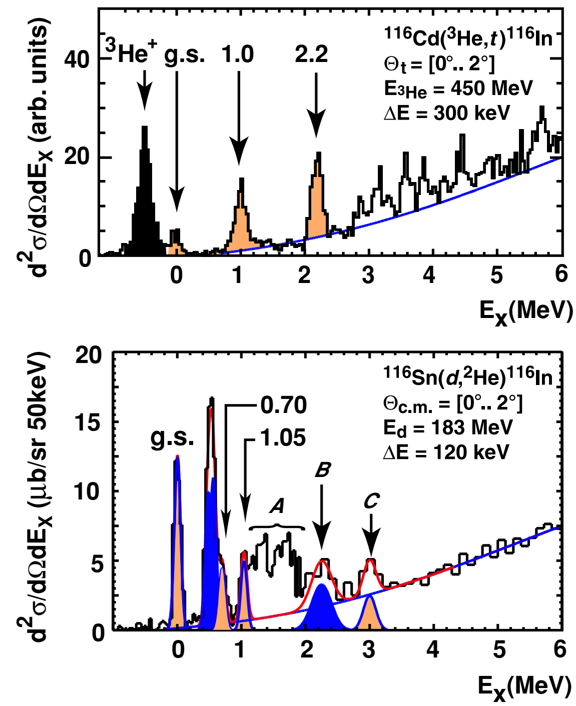

FIG. 4. (Color online) Spectra of (^{3}He, t) and (d,^{2}He) charge-exchange reactions performed at forward angles. Both reactions populate states in the intermediate nucleus ^{116}In. In the (^{3}He, t) spectrum, the peak labelled as ^{3}He$^+$ is the singly-charged ^{3}He beam component produced through an ion charge exchange of the incident ^{3}He^{++} beam upon traversing the target.

V. IMPLICATIONS FOR $\beta\beta$ DECAY

Table III shows the results of the present (d,^{2}He) data together with the results from the (^{3}He, t) experiment by Akimune *et al.* [32]. Figure 4 shows the spectra of both charge-exchange reactions for the same excitation energy range in the same final nucleus. The ground state of ^{116}In is only weakly excited in (^{3}He, t) but the transition is comparatively

TABLE III. Summation over DGT matrix elements obtained from (^{3}He, t) and (d,^{2}He) charge-exchange reactions populating intermediate 1^+ states in ^{116}In. B(GT$^-$) values are from Ref. [32]. B(GT$^+$) values are from the present work, but evaluated with reference to the ground-state ft value [30].

^{116}Cd $\longrightarrow$ ^{116}In		^{116}Sn $\longrightarrow$ ^{116}In			
E_x (MeV)	B(GT$^-$)	E_x (MeV)	B(GT$^+$)	$\lvert M_m^{\rm DGT}\rvert$	$\sum_m \lvert M_m^{\rm DGT}\rvert$
0	0.032 ± 0.005	0	0.256 ± 0.001	0.025 ± 0.004	0.025 ± 0.004
–	–	0.70	0.07 ± 0.03	0	
1.00	0.12 ± 0.02	1.04	0.11 ± 0.06	0.020 ± 0.006	0.045 ± 0.005
2.20	0.17 ± 0.03	2.30	<0.07	0.013 ± 0.013*	0.058 ± 0.008
–	–	3.00	0.21 ± 0.04	0	0.058 ± 0.008
		from counting experiment half-life:		$\lvert M^{(2\nu)}(\mathrm{DGT})\rvert = 0.064 \pm 0.007$	

*As only an upper limit of B(GT) was obtained, we assume a 100% error.

strong in $(d,^2\text{He})$. The state seen in the $(d,^2\text{He})$ reaction at 0.70 MeV has no partner in the $(^3\text{He},t)$ reaction. At about 1 MeV both reactions seem to populate the same 1^+ state with about equal strength. At about 2.3 MeV, the situation is again reversed. Both charge-exchange reactions spectra show a state in ^{116}In, which is reported as a strong GT$^-$ transition in $(^3\text{He},t)$, however, the angular distribution of the $(d,^2\text{He})$ data indicates that only little strength in the GT$^+$ direction is present. Finally, the state at 3 MeV excited through the $(d,^2\text{He})$ reaction has, if anything, only a weak partner in $(^3\text{He},t)$.

The present situation is reminiscent of the ^{48}Ca case investigated in Ref. [3], where one also observes that the relevant pairs of GT$^\pm$ transitions have a pattern of opposite relative strength. We note that this microstructure mismatch should not be confused with neutron blocking; it is intrinsic to the nuclear wave functions involved.

In Table III we also added a column for the running sum of the various $\beta\beta$-decay matrix elements according to Eq. (3). The sum has been calculated assuming that the matrix elements $M_m(\text{DGT})$ add constructively. Its value is $\sum_m |M_m(\text{DGT})| = 0.058 \pm 0.08$, which translates into a half-life of $T_{1/2} = (4.0 \pm 1.1) \times 10^{19}$ y. The central values compare well with the values from the counting experiment, i.e., $M(\text{DGT}) = 0.064 \pm 0.007$ and $T_{1/2} = (3.3 \pm 0.7) \times 10^{19}$ y. It is also instructive to see that the single-state-dominance approach may in general be too simple for reliable calculations of $\beta\beta$-decay half-lives.

VI. SUMMARY

We have presented data for the $(d,^2\text{He})$ charge-exchange reaction on ^{116}Sn measured at an intermediate energy of 183 MeV, which complement earlier $(^3\text{He},t)$ data of Akimune *et al.* [32] on ^{116}Cd at an intermediate energy of 450 MeV. Both charge-exchange reactions mediate GT transitions to the ground and excited states of the intermediate nucleus ^{116}In, and are therefore suited to extract the nuclear matrix elements relevant for the ^{116}Cd $2\nu\beta\beta$ decay in a perturbative description. Although the extracted GT ground-state transition strength for $^{116}\text{Cd}(^3\text{He},t)^{116}\text{In}$ was reported to be at variance with recent ^{116}In EC-decay data by at least a factor of 15 [31], the two combined charge-exchange data sets do, in fact, give a value for the $2\nu\beta\beta$-decay half-life, which is in almost perfect agreement with the value from counting experiments. This also forces one to conclude that the single-state-dominance hypothesis for evaluating the $2\nu\beta\beta$-decay half-life is in general a too simple approach. Of course, some reservation is always in order, as the charge-exchange reactions do not give any information about possible phase cancellations when summing individual GT-strength values.

Recent QRPA calculations for mass $A = 116$ have been able to reproduce the experimental $2\nu\beta\beta$-decay half-life even with the assumption of a single state dominance, but they fail badly in the prediction of individual GT$^\pm$ transition strengths. The agreement must therefore be regarded as fortuitous. The issue is discussed in a recent paper of Suhonen [50], who concludes that theoretical model calculations should also be confronted with experimentally obtained single β-decay rates.

Charge-exchange reactions in the (n,p) and (p,n) directions are a powerful means to evaluate $\beta\beta$-decay half-lives. Of course, they cannot fully replace direct measurements, but they could act as a guide for present and future counting experiments. This is also true for the 0ν variant of the $\beta\beta$ decay, although in this case, a complete set of even higher order multipole transitions would have to be combined for the relevant matrix element. That, however, constitutes a significant experimental challenge. A key issue is the high energy resolution needed for such experiments. The presently achieved $(d,^2\text{He})$ final state resolution of $\sim$100 keV is a significant step in this direction, which is further complemented by the unprecedented $\sim$40 keV resolution available at the Research Center for Nuclear Physics (RCNP) in Osaka for $(^3\text{He},t)$ experiments [51].

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