Nuclear matrix elements for the ^{48}Ca two-neutrino double-β decay from high-resolution charge-exchange reactions

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The two-neutrino double-β ($2\nu\beta\beta$) decay represents a test case for our knowledge about the nuclear structure of the involved isobars. The decay of ^{48}Ca is an especially interesting case because it holds an anomaly of a uniquely high $Q_{\beta\beta}$ value and a comparatively long half-life, which points to a peculiar nuclear structure situation. The nuclear matrix element relevant for $\beta\beta$ decay can be calculated, if the complete set of Gamow-Teller (GT) matrix elements for the two virtual transitions in the perturbative description are known. Using the high-resolution $(d,{}^{2}\mathrm{He})$ probe, we have measured the GT^{+} strength distribution in ^{48}Sc, which is the intermediate nucleus in the ^{48}Ca $\beta\beta$ decay. By combining our measured GT distribution with data from a $^{48}\mathrm{Ca}(p,n)$ experiment and taking into account relative phases between individual matrix elements, which can be gained from theoretical models, one can compute the double-GT matrix element and deduce the half-life of the ^{48}Ca $2\nu\beta\beta$ decay.

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The nuclear double-β ($\beta\beta$) decay continues to be a subject of fascination, both in the experimental and the theoretical sense. It proceeds as a second-order transition of the weak interaction. 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, thus, forbidden in the standard model. The two-neutrino decay mode, in contrast, is kinematically suppressed but allowed by all selection rules and has even directly been observed in a few cases [1].

The double-β decay not only represents a stringent test of our knowledge about the nuclear wave functions, but, even more, it is a test of our fundamental understanding of quantum mechanics. The decay mechanism is believed to be 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 considerations, followed by the transition to the daughter nucleus, which then lies energetically below the parent.

Decay rates for the allowed second-order $2\nu\beta\beta$ mode can be deduced assuming that [2]

(i) the leptons are in an s-wave state,
(ii) the leptons share the phase space equally, and
(iii) a complete set of virtual excitations of the intermediate odd-odd nucleus is included in the second-order perturbative matrix element. Approximations over average energy denominators should be avoided [2].

One obtains for the $2\nu\beta\beta$ decay half-life

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

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

$$M_{DGT}^{(2\nu)} = \sum_m \frac{\langle 0_{g.s.}^{(f)} \| \sum_k \sigma_k \tau_k^- \| 1_m^+ \rangle \langle 1_m^+ \| \sum_k \sigma_k \tau_k^- \| 0_{g.s.}^{(i)} \rangle}{\frac{1}{2} Q_{\beta\beta}(0_{g.s.}^{(f)}) + E_x(1_m^+) - E_0}$$
$$= \sum_m \frac{M_m^{GT^+} M_m^{GT^-}}{\frac{1}{2} Q_{\beta\beta}(0_{g.s.}^{(f)}) + E_x(1_m^+) - E_0}. \tag{2}$$

$E_x(1_m^+) - E_0$ is the energy difference between the mth intermediate 1^+ state and the initial ground state, and the sum Σ_k runs over all the neutrons of the decaying nucleus.

Contributions from Fermi-type virtual transitions are negligible [3], 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.

The ^{48}Ca nucleus is an especially interesting test case, as it has the highest decay energy $Q_{\beta\beta} = 4.27$ MeV of all $\beta\beta$-decaying nuclei. This means that the half-life ought to be accordingly short, as $T_{1/2} \propto (Q_{\beta\beta})^{-11}$. Surprisingly however, the measured half-life is about the same as, e.g., the one of

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^{116}Cd [1], for which $Q_{\beta\beta}$=2.80 MeV. Clearly, this anomaly can only originate from the different nuclear structure involved.

An elegant way to determine the matrix elements of Eq. (2) experimentally, and thereby the half-life of the nucleus, is offered by hadronic charge-exchange reactions. At intermediate energies ($E \gtrsim 100$ MeV), charge-exchange reactions proceed mainly through the isovector spin-flip component of the effective interaction, and at low momentum transfer, i.e., at forward scattering angles, these transitions are governed by the above mentioned Gamow-Teller transition operator. Charge-exchange reactions like (p,n) or (n,p) are well-established tools for the extraction of GT strength distributions in a nucleus [4–7]. Though the measurements presented here have been performed using a bombarding energy of only 90 MeV per nucleon, the dominance of the central $\sigma\tau$ interaction and thus the proportionality between B(GT) and the cross section is still given, as has been shown in previous publications [8–10].

Experimentally, the first virtual transition of the $\beta\beta$ decay can be accessed by (p,n)-type reactions on the parent nucleus, whereas the matrix elements of the second virtual transition can be obtained from (n,p)-type reactions on the $\beta\beta$ decay daughter nucleus. A ^{48}Ca(p,n) experiment at incident energies of 134 and 160 MeV was carried out by Anderson *et al.* [11], which yielded a GT$^-$ strength distribution with a resolution of about 400 keV (full width at half maximum). It was observed that almost all GT$^-$ strength in the low excitation energy regime (i.e., $0 < E_x < 6$ MeV) was concentrated in one $J^\pi = 1^+$ state at 2.52 MeV. As shown in Fig. 1, several other low-lying 1^+ states above the 2.52 MeV state exist, but these are only weakly excited and can only barely be resolved from the (p,n) data alone.

Alford *et al.* have performed the complementary (n,p) measurement [13] and combined their $B(\mathrm{GT}^+)$ values with the (p,n) data. However, energy resolution was poor ($\Delta E \approx 1.3$ MeV) and, further, the use of an oxide target led to ^{16}O contamination in the spectrum at energies above 5 MeV. Thus, a fitting procedure was necessary to relate the GT strength to the states in the intermediate ^{48}Sc nucleus. In the fitting, the positions of the possible 1^+ states were taken from low-energy spectroscopic ^{46}Ca$(^3\mathrm{He},p)$ [14] or ^{48}Ti$(t,^3\mathrm{He})$ [15] information.

From the combined (p,n) and (n,p) cross sections the ^{48}Ca$(\beta\beta)$ decay half-life was evaluated to 0.75×10^{19} yr. As this result is at variance with the most recent experimental values published in Refs. [16,17], $T_{1/2}^{(2\nu)} = 4.3^{+2.4+1.4}_{-1.1-1.4} \times 10^{19}$ yr and $T_{1/2}^{(2\nu)} = 4.3^{+3.3}_{-1.3} \times 10^{19}$ yr, respectively, the question why ^{48}Ca is so stable against double-β decay still remains unresolved.

Theoretical shell-model calculations for both virtual β decays may give guidance to the understanding of this puzzle. Model calculations have been carried out, e.g., by Caurier *et al.* [18] in a full $0\hbar\omega$ model space, and by Zhao *et al.* [19] in a slightly truncated $0\hbar\omega$ model space. In both calculations one observes that the centroids of the GT strength distributions for the ^{48}Ti(β^+) and ^{48}Ca(β^-) directions are displaced by about 4–5 MeV, and neither the regions nor any two strong excitations for the two directions would overlap. The

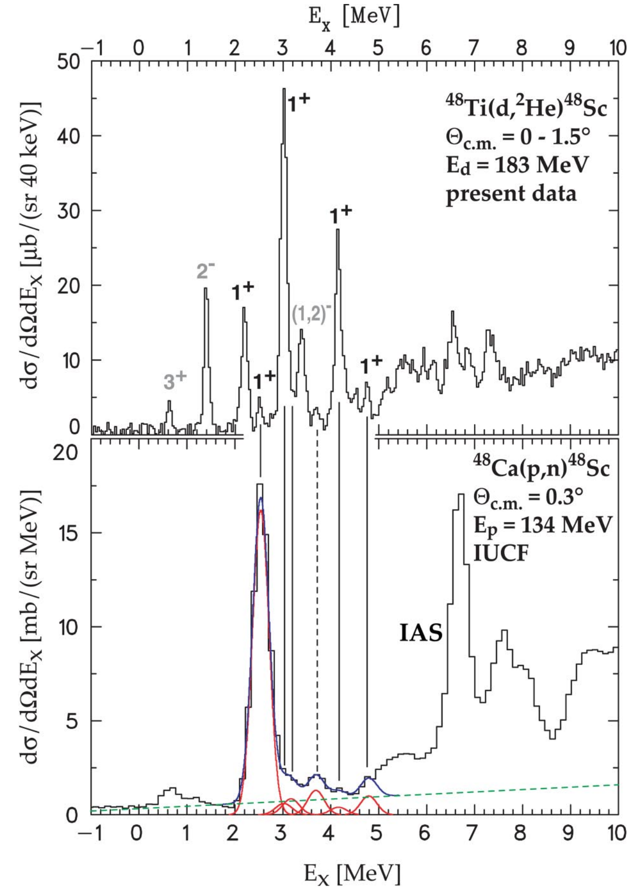

FIG. 1. (Color online) Excitation energy spectra for ^{48}Ti$(d,^2\mathrm{He})^{48}$Sc (upper panel) and ^{48}Ca$(p,n)^{48}$Sc (lower panel, from Ref. [11]). The $(d,^2\mathrm{He})$ spectrum was taken at a spectrometer setting of 0° covering a center-of-mass angular range between 0° and 1.5°. The excitation energies of 1^+ levels obtained from the $(d,^2\mathrm{He})$ measurement, together with spectroscopic information from Ref. [12], were used to fit the (p,n) spectrum. Levels visibly excited by both reactions are connected by the vertical lines. The dashed line connects a level excited by a higher multipole transition.

calculations give half-lives of $T_{1/2}^{(2\nu)} = 3.7 \times 10^{19}$ yr and $T_{1/2}^{(2\nu)} = 1.9 \times 10^{19}$ yr, respectively, which both seem to be in the right range. Reference [20] gives a comparative study of calculations for the ^{48}Ca $\beta\beta$ decay, employing shell model and quasiparticle random phase approximation (QRPA) methods. In recent overview articles, Elliott and Vogel deplore a lack of detailed nuclear spectroscopy predictions [1], and Suhonen and Civitarese [2] point out that for all double-β nuclei experimental data is highly demanded for tuning theoretical models, even though experimental data may be restricted to excited states below the continuum (in this case $E_x < 5$ MeV).

Meanwhile, the shortcomings of the limited resolution of the (n,p) experiments have been overcome by using $(d,^2\mathrm{He})$ reactions [8,21]. With such reactions, energy resolutions in the order of 100 keV are now routinely achieved [9]. As in the (n,p) or (p,n) cases, zero-degree cross sections scale linearly with the GT strength [4,5], and the extraction of $B(\mathrm{GT}^+)$ values is relatively straightforward, as shown in Ref.

[8]. The only difference with the (n,p) case is the appearance of an additional scaling factor that connects $B(\mathrm{GT}^+)$ values with the measured $(d,{}^2\mathrm{He})$ cross section. In the case of light- and medium-mass nuclei, this scaling factor is found to be largely mass independent [21,10].

In this paper we present a $^{48}\mathrm{Ti}(d,{}^2\mathrm{He})$ measurement, which allows a high-precision determination of the GT$^+$ transition strength distribution connecting the intermediate and the final nucleus in the ^{48}Ca double-β decay. We used a 183 MeV deuteron beam from the AGOR cyclotron at KVI, Groningen. A metallic, self-supporting ^{48}Ti target with 4.9 mg/cm^2 thickness and an enrichment of 99% was used. Diprotons from the ^{2}He ejectiles were detected in coincidence using the Big-Bite Spectrometer (BBS) [22] and the EuroSuperNova (ESN) detector [23]. A full account of how $(d,{}^2\mathrm{He})$ experiments are carried out and analyzed can be found in Ref. [8]. The achieved resolution was about 120 keV. Together with the measured angular distributions, a reliable selection of the $J^\pi=1^+$ states excited by GT$^+$ transitions was possible.

To confirm the purity of the ^{48}Ti target, we performed a separate $^{48}\mathrm{Ti}(d,p)^{49}\mathrm{Ti}$ measurement at $\Theta=8°$. The experimental setup is flexible enough to accommodate this by simply changing the data-acquisition software from two-proton to single-proton detection, and by using a different magnetic field in the spectrometer. In the final ^{49}Ti spectrum, all the low-lying ^{49}Ti levels were present and no significant contamination was observed.

A $(d,{}^2\mathrm{He})$ spectrum at a center of mass angle interval $\Theta_{\mathrm{c.m.}}=[0°\ldots1.5°]$ is shown in Fig. 1 (upper part). The energy scale was calibrated using the peak position of $^1\mathrm{H}(d,{}^2\mathrm{He})$ and some known 1^+ levels in ^{48}Sc [12]. Hydrogen is an ever-present contaminant and the $^1\mathrm{H}(d,{}^2\mathrm{He})n$ ($Q=-2.224$ MeV) signal appears in the spectrum at an equivalent negative excitation energy of -3.20 MeV. Excitation energies are accurate to ≈20 keV. The fitting of structures in the spectra was done manually, aided by spectroscopic information from Ref. [12]. A Gaussian peak shape of constant width turned out to be suitable for the entire energy range considered. The 1^+ assignments of the states were made on the basis of their distinct angular distributions.

As predicted by the shell-model calculations [18,19], the overall GT$^+$ strength is small and concentrated at low excitation energies ($E_x<5$ MeV). The cross section above 5 MeV is dominated by higher multipole excitations. Because of the small GT$^+$ strength, higher-multipole excitations yield cross sections of comparable size even at $\Theta=0°$, notably clear in the spectrum for the 2^- level at 1.40 MeV.

Figure 1 also shows the comparison with the (p,n) spectrum at $E_p=134$ MeV [11]. The most striking feature is the fact that the strongest GT transition (at 2.52 MeV) in the direction of (p,n) is correlated with the weakest transition in the direction of (n,p), respectively, $(d,{}^2\mathrm{He})$, and similarly, the strongest transitions appearing in the $(d,{}^2\mathrm{He})$ data (here the structures at ≈3 MeV and 4.14 MeV) are barely visible in the (p,n) data. In a medium-energy resolution experiment one would likely not recognize that these states are only weakly connected and consequently arrive at too low a half-life, as seemed to be the case in the (n,p) experiment by Alford *et al.* [13].

In order to perform an accurate estimate of the double-β decay half-life, we converted the (p,n) and $(d,{}^2\mathrm{He})$ cross sections into the respective $B(\mathrm{GT}^\pm)$ values. The $B(\mathrm{GT}^-)$ values were extracted by assuming that all Fermi strength $B(F)=N-Z=8$ is concentrated in the isobaric analog state (IAS) at 6.67 MeV, whose cross section is published in Ref. [27], and by applying the common relation between Fermi and GT unit cross sections, $\hat{\sigma}_{GT}/\hat{\sigma}_F=(E_p/E_0)^2$ [5] with $E_0=(55\pm1.7)$ MeV. For the $(d,{}^2\mathrm{He})$ case, a unit cross section was determined using the prescription from Refs. [21,10] and a distortion factor $N_D=0.073$ from a distorted wave Born approximation (DWBA) calculation [24] with appropriate proton and deuteron optical-model parameters [25,26]. The systematic errors are 20% for the $(d,{}^2\mathrm{He})$ case and 12% for the (p,n) case [27]. For the latter, we have added a further 25% error for the weakly excited states (i.e., all states besides the strong 2.52 MeV level) in order to account for fitting errors and uncertainties in the $B(\mathrm{GT}^-)$ extraction, which is less safe for weak excitations. Table I shows the detailed comparison.

The summed GT$^+$ strength for excitation energies $E_x\leqslant5$ MeV is $S(\mathrm{GT}^+)=0.427\pm0.108$. This is in agreement with the (n,p) result, which yielded $S(\mathrm{GT}^+)=0.54\pm0.09$, and with the result from the shell-model calculation presented in Ref. [19], which gives $S(\mathrm{GT}^+)=0.53$. The shell-model calculation in Ref. [18] yields a slightly higher summed GT strength $S(\mathrm{GT}^+)=0.69$. Both model calculations use effective operators $\widetilde{\sigma\tau}=0.77\sigma\tau$.

Of course, the correlation of levels suffers from the 400 keV resolution in the (p,n) spectrum. As an example, the known doublet at 2.98 and 3.05 MeV can barely be resolved in the $(d,{}^2\mathrm{He})$ spectrum, and not at all in the (p,n) case. We tried different possible combinations other than those listed in Table I, but the resulting $M_{DGT}^{(2\nu)}$ varied by less than 10%.

The summation over the combined matrix elements is performed under the naive assumption that all matrix elements add constructively. This assumption may be too simple. However, the shell-model calculations of Refs. [18,19] suggest that, except for one level, all matrix elements below 5 MeV indeed contribute constructively, whereas levels above 5 MeV, which are not resolved in any of the charge-exchange reactions, would generally contribute destructively [19] and thereby lower the overall $M_{DGT}^{(2\nu)}$ by about 24%. The only low-lying and destructively contributing level would be located at $E_x=2.76$ MeV [19] or $E_x=3.0$ MeV [18], depending on the underlying model. Experimentally, around 3 MeV there is an unresolved cluster of three levels existent. However, any further information about possible negative interference effects would at least require a much higher resolution of (p,n)-type data, which could be possible by using the alternative $(^3\mathrm{He},t)$ reaction [28] on ^{48}Ca.

Combining our measurement with the results from the (p,n) experiment yields for the $\beta\beta$ matrix element $M_{DGT}^{(2\nu)}=0.0740\pm0.0150$. Adopting the phase space factor from Ref. [29], $G^{(2\nu)}=1.1\times10^{-17}\ \mathrm{yr}^{-1}(\mathrm{MeV})^2$, was also used in Refs. [13,18,19], we deduce a half-life of

TABLE I. Experimental nuclear structure results for the ^{48}Ca double-β decay. Cross sections $d\sigma/d\Omega$ have been extrapolated to $q=0$ for the $(d,{}^2\mathrm{He})$ case, and to $q=0.077$ fm^{-1} for the (p,n) case to match the momentum transfer of the isobaric analog state. Errors given in the table are statistical for $(d,{}^2\mathrm{He})$ cross sections and total errors for $B(\mathrm{GT}^{\pm})$ and $M_{DGT}^{(2\nu)}$. The cross sections at 2.98 and 3.05 MeV have been combined into one B(GT) value, in order to avoid errors from the deconvolution of the doublet.

GT$^+$ transition $(d,{}^2\mathrm{He})$			GT$^-$ transition (p,n)			
E_x (MeV)	$d\sigma/d\Omega$ (μb/sr)	$B(\mathrm{GT}^+)$	E_x (MeV)	$d\sigma/d\Omega$ (mb/sr)	$B(\mathrm{GT}^-)$	$M_{DGT}^{(2\nu)}(\beta\beta)$ (MeV^{-1})
2.20	63.7±3.3	0.047±0.012	-			
2.52	19.1±2.3	0.014±0.005	2.54	6.80	1.328±0.159	0.0313±0.0054
2.98	97.4±2.3	0.192±0.046	3.02	0.25	0.049±0.018	0.0199±0.0043
3.05	161.0±6.6					
3.15	23.1±2.6	0.017±0.005	3.17	0.36	0.070±0.026	0.0069±0.0017
3.70[a]	29.2±4.6[a]		3.69[a]	0.58[a]		
4.00	20.8±2.4	0.016±0.005	-			
4.14	120.7±5.5	0.090±0.022	4.14	0.17	0.032±0.012	0.0090±0.0020
4.28	33.5±3.4	0.025±0.008	-			
4.76	34.3±3.2	0.026±0.008	4.79	0.42	0.082±0.030	0.0069±0.0016
Σ		0.427±0.108			1.561±0.246	0.0740±0.0150

[a]Angular distributions suggest that levels do not have $J^{\pi}=1^{+}$.

$$T_{1/2}^{(2\nu)} = (1.66 \pm 0.67) \times 10^{19}\ \mathrm{yr}.$$

The central value is lower than the most recent result from counting experiments [16,17], $T_{1/2}^{(2\nu)}=4.3^{+2.4+1.4}_{-1.1-1.4}\times 10^{19}$ yr. However, all matrix elements are summed constructively, and contributions from levels with $E_x>5$ MeV are not accounted for. If one applies the reduction of the $\beta\beta$ matrix element $M_{DGT}^{(2\nu)}$ by the aforementioned 24% originating from destructive contributions of higher (and unresolved) levels, as the shell-model calculation [19] suggests, one would deduce

$$T_{1/2}^{(2\nu)} = (2.87 \pm 0.51) \times 10^{19}\ \mathrm{yr}.$$

In summary, we have carried out a $^{48}\mathrm{Ti}(d,{}^2\mathrm{He})^{48}\mathrm{Sc}$ experiment at $\Theta=0°$ with an excitation energy resolution of $\Delta E=120$ keV. $B(\mathrm{GT}^+)$ values were extracted and compared to $B(\mathrm{GT}^-)$ values from a complementary $^{48}\mathrm{Ca}(p,n)$ reaction, which excites the same levels in ^{48}Sc. Owing to the high resolution of the $(d,{}^2\mathrm{He})$ probe, it was possible to combine the matrix elements of the excited states and deduce the double-GT matrix element for the ^{48}Ca two-neutrino double-β decay. The half-life resulting from a pure constructive summation is about a factor of 2 shorter than the one observed in counting experiments, yet still within the given confidence limits. A shell-model calculation suggests a reduction of the matrix element by about 24% arising from destructive contributions from high-lying, unresolved levels. The application of the reduction raises the half-life closer to the central value obtained by counting experiments. The GT$^+$ distribution from our high-resolution experimental data is in good agreement with theoretical findings. Further measurements, e.g., for the $A=76$ isobar will follow. We stress that experimental data should be exploited in fine tuning the parameters of nuclear models.

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