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The ^{71}Ga(^{3}He, t) reaction and the low-energy neutrino response

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ABSTRACT

A ^{71}Ga(^{3}He, t)^{71}Ge charge-exchange experiment was performed to extract with high precision the Gamow–Teller (GT) transition strengths to the three lowest-lying states in ^{71}Ge, i.e., the ground state ($1/2^-$), the 175 keV ($5/2^-$) and the 500 keV ($3/2^-$) excited states. These are the relevant states, which are populated via a charged-current reaction induced by neutrinos from reactor-produced ^{51}Cr and ^{37}Ar sources. A precise measurement of the GT transition strengths is an important input into the calibration of the SAGE and GALLEX solar neutrino detectors and addresses a long-standing discrepancy between the measured and evaluated capture rates from the ^{51}Cr and ^{37}Ar neutrino calibration sources, which has recently spawned new ideas about unconventional neutrino properties.

1. Introduction

After the discovery of the missing solar neutrinos in the Homestake chlorine-based neutrino detector [1], GALLEX and SAGE [2–5] were launched in the late 1980s. These two new initiatives had the objective to measure the flux of the low-energy part of the solar neutrino spectrum, which the chlorine detector was insensitive to. This low-energy part was the least contentious in the Standard Solar Model (SSM), as it is the major component originating from the best understood initial *pp* process. These two experiments have since then significantly advanced our knowledge about neutrinos, as they gave decisive proof for low energy neutrino oscillations and neutrino–matter effects in the sun.

In the SAGE and GALLEX experiments the ^{71}Ga(ν_e, e^-)^{71}Ge charged-current (CC) reaction was the tool for the detection of the low-energy neutrinos. This was motivated by the low reaction threshold of 232 keV. In fact, this low threshold makes the reaction sensitive to a significant fraction of the *pp*-neutrino spectrum, which itself extends to $E_{max} = 423.4$ keV [6]. The expected CC reaction rate on ^{71}Ga from the full solar neutrino spectrum (with no oscillation) was about 132 SNU [7]. Both detectors, GALLEX and SAGE, confirmed the missing solar neutrino flux even for the low-energy *pp* neutrinos. The most recent values of the solar neutrino rate reported by the two collaborations are $67.6 \pm 4.0(\text{stat.}) \pm 3.2(\text{sys.})$ SNU (GALLEX combined with its successor experiment GNO) and $65.4^{+3.1}_{-3.0}$ SNU (SAGE) [3,5].

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Table 1
The ratio of the number of ^{71}Ge atoms produced during the neutrino activation to the number calculated using neutrino cross sections. The SAGE experiment has used two different neutrino sources, ^{37}Ar and ^{51}Cr.

Experiment	Source	Ratio	Reference
GALLEX	^{51}Cr-1	0.95 ± 0.11	[3]
GALLEX	^{51}Cr-2	0.81 ± 0.11	[3]
SAGE	^{51}Cr	0.95 ± 0.12	[4]
SAGE	^{37}Ar	0.79 ± 0.10	[8]
Average	^{37}Ar, ^{51}Cr	0.87 ± 0.05	[5,9]

Table 2
Neutrino energies and branching ratios from the electron capture of ^{51}Cr [6].

E_ν	Transition	Branching ratio
747.3 keV	K-EC to ^{51}V g.s.	81.6 %
752.1 keV	L-EC to ^{51}V g.s.	8.5 %
427.2 keV	K-EC to ^{51}V*(320.1)	8.95 %
432.0 keV	L-EC to ^{51}V*(320.1)	0.9%

As an additional proof and to exclude unknown systematic errors, the detectors were calibrated separately by using two strong reactor-produced neutrino sources with precisely known fluxes. The two sources used were ^{51}Cr and ^{37}Ar, which were placed directly into the detectors during these calibration runs. Both nuclei decay exclusively by electron capture with a total decay energy of $Q_{EC} = 753$ keV (^{51}Cr) and $Q_{EC} = 814$ keV (^{37}Ar). In the $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ CC reaction the largest part of these neutrinos is captured into the ^{71}Ge ground state (g.s.) ($J^\pi = 1/2^-$) owing to the larger phase space and the larger B(GT) strength. The transition is a ($J^\pi = 3/2^- \to J^\pi = 1/2^-$) GT transition, whose B(GT) strength is well known from the $\log ft$ of the ^{71}Ge decay. The 175 keV ($J^\pi = 5/2^-$) state and the 500 keV ($J^\pi = 3/2^-$) state can also be reached by the CC GT transitions from both neutrino sources. The contribution from these two excited states to the activation of ^{71}Ge is, however, not well enough known and has always been a matter of debate.

Table 1 shows the measured number of ^{71}Ge atoms normalized to the number of expected atoms, which were evaluated from the best values [6] of capture cross sections. The various independent measurements give numbers consistently smaller than unity with the weighted average being about 2.5σ away. The chances of this being a statistical fluctuation are about 5% according to a detailed analysis given in Ref. [5]. There are other possible scenarios, which may be entertained for this discrepancy [9]:

1. An overestimation of the ν-capture cross section; however, the major contribution is from the g.s. transition, which is known from the experimental ft-value, and since the contribution from the excited states in ^{71}Ge has so far been assumed to be of order 5%, even a zero-value cannot fully account for the observed 10–13% effect (see Table 1);
2. The possibility of a new ν-oscillation phenomenon, which is something that has been discussed in terms of a ν_e oscillation to a sterile neutrino at short distances [9–11].

For the present discussion it is sufficient to focus on the neutrino response from the ^{51}Cr source, as most of the calculations have been performed for this nucleus. Table 2 shows the relevant neutrino energies emitted from this source together with the relevant branching ratios [6]. The additional internal bremsstrahlung component, which gives rise to a continuous ν-spectrum is typically less than 10^{-4} per captured electron [12–14] and shall not be considered in the present context.

Hata and Haxton [15] have calculated the neutrino cross sections for the spectrum of the ^{51}Cr neutrinos (see Table 2) and derive a simple formula for the contributions from the excited states in ^{71}Ge:

$$\sigma\left(^{51}\mathrm{Cr}\right) = \sigma_0\left(^{51}\mathrm{Cr}\right)\left[1 + 0.67\frac{B_1(\mathrm{GT})}{B_0(\mathrm{GT})} + 0.22\frac{B_2(\mathrm{GT})}{B_0(\mathrm{GT})}\right] \quad (1)$$

where $\sigma_0(^{51}\mathrm{Cr})$ is the g.s. cross section, and the ratios in the bracket are the GT transition strengths for the excited states at 175 and 500 keV in units of the g.s. B_0(GT) value. The coefficients are the relative phase-space factors. The "best-estimate" g.s. ν-cross section for ^{71}Ga was given by Bahcall [6] to be $\sigma_0(^{51}\mathrm{Cr}) = 5.81 \cdot 10^{-45}$ cm^2. For this value, Bahcall uses an ft-value based on the ^{71}Ge half-life measured by Hampel and Remsberg [16] and an electron capture decay Q-value $Q_{EC} = 232.69 \pm 0.15$ keV [6,17]. The NNDC $\log ft$-calculator [18] gives $\log ft = 4.3500(13)$, from which one deduces the g.s. GT transition strength $B_0(\mathrm{GT}) = 0.0852(3)$ using an axial vector coupling constant $g_A = -1.2694(28)$ [19].

The various GT strength values of the excited states were taken from a $^{71}\mathrm{Ga}(p,n)$ charge-exchange experiment [20]. Charge-exchange reactions are sensitive to the GT transition due to the strong $\vec{\sigma}\vec{\tau}$ effective nucleon–nucleon interaction at zero momentum transfer and at typical intermediate energies. However, (p,n) reactions usually suffer from poor energy resolution, typically of order 200–300 keV, and limited statistics. In the above quoted experiment the 175 keV ($5/2^-$) state was not resolved and the 500 keV ($3/2^-$) state was only vaguely observed in the forward-angle spectrum. From this experiment, Bahcall [6] used the ratios $B_1(\mathrm{GT})/B_0(\mathrm{GT}) = 0.028$ and $B_2(\mathrm{GT})/B_0(\mathrm{GT}) = 0.146$, which were taken from the thesis work of Krofcheck [21] published in 1987 and are therefore slightly different from the ones quoted in Ref. [20]. For the purpose of being definitive, Bahcall took for the first value simply 50% of the measured upper limit $B_1(\mathrm{GT})/B_0(\mathrm{GT}) < 0.056$. Taking those numbers, the contribution from the excited states amounted to 5.1% of the g.s. ν-capture cross section with no uncertainties attached.

In Refs. [22–24] a $(^3\mathrm{He},t)$ experiment on ^{71}Ga was reported. The experiment was performed at an incident energy of 450 MeV at the Research Center of Nuclear Physics (RCNP), Osaka, using the Ring-Cyclotron and the Grand Raiden spectrometer for the triton momentum measurement. The resolution was again limited to 140–160 keV. However, the objective was to extract the full response of ^{71}Ga to solar neutrinos up to the particle threshold energy of about 8.4 MeV excitation in ^{71}Ge. The value came out to be in remarkably good agreement (i.e. 132 ± 17 SNU) with the predictions by Bahcall and Pinsonnault [7]. The GT transition strengths to the 175 keV and 500 keV states, which are the relevant ones for the ^{51}Cr neutrinos, were quoted as $B_1(\mathrm{GT}) = 0.0049(18)$ and $B_2(\mathrm{GT}) = 0.0208(21)$ based on the forward-angle cross section. This gives a 9 ± 3% contribution to the ^{51}Cr neutrino capture rate according to Eq. (1), which would amplify the discrepancy seen in the SAGE and GALLEX calibration data.

2. Experiment

The RCNP cyclotron and its beam line to the Grand Raiden spectrometer have since been significantly improved to enable high-resolution experiments [25–28]. The present experiment was performed with a 420 MeV $^3\mathrm{He}^{2+}$-beam at an intensity of ≈ 10 nA (electrical), which is slightly lower than the energy used in Ref. [22] and avoids a Grand Raiden magnetic-field setting close to saturation. The beam transport system and the Grand Raiden spectrometer were operated in dispersion-matched mode for best energy and angle resolution. The scattering angle calibration was performed using a sieve-slit placed at a given distance behind the target in front of the entrance of the spectrometer. The final angle resolutions of the dispersive and non-dispersive planes were $\Delta\theta \approx 5$ mrad and $\Delta\phi \approx 8$ mrad. A 3.64 mg/cm^2 thick ^{71}Ga target with an isotopic enrichment of 99.5% was used. The target preparation is described in Ref. [29]. During the experiment, additional spectra from an enriched ^{69}Ga target (99.7%) and from a target with a natural composition of gallium were accumulated for later consistency checks in the analysis. The energy calibration was performed with a separate ^{nat}Mg target, which features a number of well-known transitions. Further, the ^{69}Ga target contained a minuscule amount of carbon, which was sufficient to identify the ^{12}C(^{3}He, t)^{12}N$_{\mathrm{g.s.}}$ reaction with the reaction Q-value of $Q_R = -17.357$ MeV and use it for a precise energy calibration extending to energies close to the entire momentum acceptance. The isotopic purity of the ^{71}Ga and ^{69}Ga targets was verified by the observation of a single spectral line from the respective isobaric analog state, which for ^{71}Ge is located at 8.913 MeV.

The determination of the target areal thicknesses by weighing turned out to be insufficiently accurate because of the difficulty of determining the total area. Cutting the targets after their preparation into a well defined area would have caused the gallium to liquefy near the cutting line (melting point at 29.8 °C). Therefore, the area, which was finally subjected to the primary beam, was scanned by performing energy-loss measurements of α-particles traversing the target foils in a specially designed setup. In the present case the α-source contained the three radioisotopes ^{239}Pu, ^{241}Am and ^{244}Cm, which feature three strong decay branches at 5.154 MeV (^{239}Pu), 5.486 MeV (^{241}Am) and 5.805 MeV (^{244}Cm). The calculation of the thickness from these energy-loss measurements was done using the computer code SRIM [30].

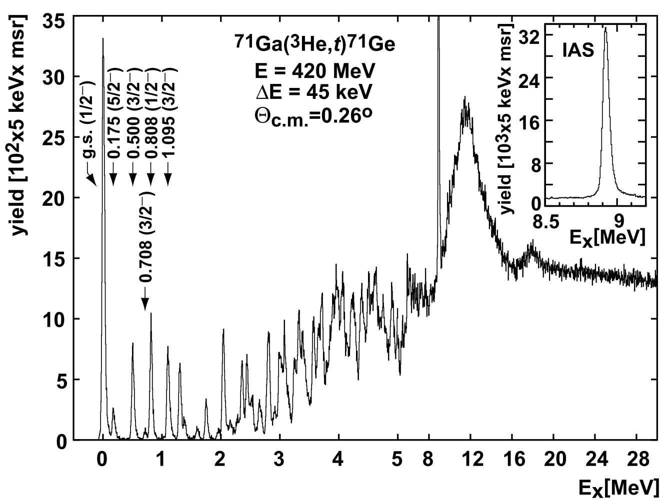

Fig. 1. Excitation-energy spectrum of the ^{71}Ga(^{3}He, t)^{71}Ge reaction at 420 MeV. The inset shows the isobaric analog resonance at 8.913 MeV. Note the change of energy scale above 5 MeV excitation.

Fig. 1 shows the excitation-energy spectrum from the ^{71}Ga(^{3}He, t)^{71}Ge reaction near zero degree. With an energy resolution of 45 keV (FWHM), which is mainly given by the target thickness, the low-lying states up to about 3 MeV are well resolved. At 8.913 MeV one observes the strong isobaric analog resonance as a single line. The state lies on the low-energy tail of the Gamow–Teller giant resonance (GTGR), which peaks at about 11.75 MeV. The structure at 18.0 MeV features an angular distribution, which is indicative of a GT transition and which also appears in the reaction on ^{69}Ga. We may interpret this as the $T_>$ component of the GTGR [31]. A full analysis of these states will be the subject of a forthcoming paper. The experiment was performed at four spectrometer-angle settings, i.e. 0°, 2.5°, 4.0° and 6.0°. Appropriate solid angle cuts allowed generating angular distributions ranging from 0° to about 8°.

In Fig. 2 we show the angular distributions of the three states in question, i.e. the ground state, the 175 keV and the 500 keV state. All three angular distributions feature an initial fall-off of the cross section with increasing scattering angle, however, with rather different slopes and on rather different scales. Whereas the steep fall-off of the g.s. angular distribution indicates the presence of a rather strong GT component, the one at 175 keV already indicates a comparatively small fraction of a GT cross section.

3. Analysis

An attempt was made to describe the angular distributions by a reaction calculation in a distorted-wave formalism. Because the initial target nucleus has a g.s. spin of $J^\pi = 3/2^-$, several combinations of target/projectile angular momentum transfers will add

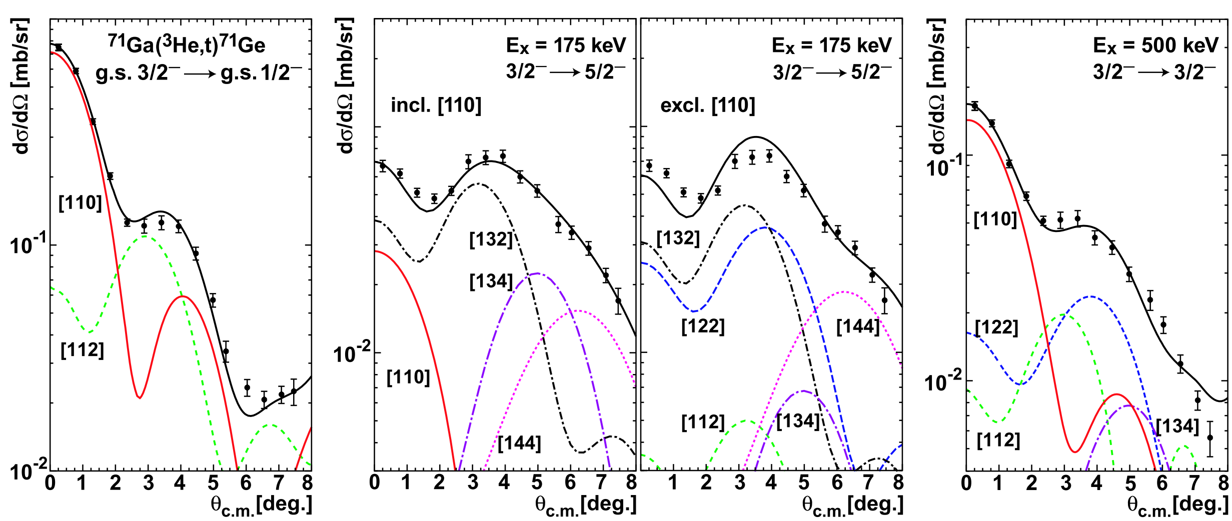

Fig. 2. Angular distributions for the ^{71}Ga(^{3}He, t)^{71}Ge reaction. The three transitions to the ground state, the 175 keV and the 500 keV states in ^{71}Ge are the relevant ones, which can be populated by neutrinos from ^{51}Cr decay. The various curves denote the incoherent contributions from the different projectile/target angular-momentum transfer combinations [$J_{pro} J_{tar} J_{rel}$]. The [110] contribution near zero degree reflects the strength of the GT transition. For the transition to the 175 keV state an attempt was made to describe the data without the [110] amplitude.

incoherently to the cross section. These components will be denoted as $[J_{pro} J_{tar} J_{rel}]$, where the indices stand for *projectile, target* and *relative*. Of course, a GT transition, which is mediated by the $\vec{\sigma}\vec{\tau}$ part of the effective NN-interaction, requires the combination [110]. However, one may also note that this correspondence is not unique, as tensor contributions mediated by the $\mathbf{T}\vec{\tau}$ effective interaction may contribute as well [32]. Those components add coherently to the cross section and are a concern for relatively weak transitions.

Angular distributions for performing a Multipole Decomposition Analysis (MDA) were calculated with the code FOLD [33]. The form factors were extracted by double folding the effective nucleon–nucleon interaction of Love and Franey [34,35] at 140 MeV/A over the transition densities of the target/residue and projectile/ejectile systems. One-body transition densities (OBTDs) were calculated in the shell-model code NuShellX [36] using the GXPF1a [37,38] interaction in the full fp-model space. Single-particle radial wave functions for ^{71}Ga and ^{71}Ge were generated in Woods–Saxon potentials, for which the depths were adjusted such that the binding energies matched those calculated with the Skx Skyrme interaction [39] in the code OXBASH. For the t and ^{3}He particles, radial densities obtained from Variational Monte-Carlo calculations [40] were used. Form factors were produced for every combination of $\vec{J}_{pro}$, $\vec{J}_{tar}$ and $\vec{J}_{rel}$ $(= \vec{J}_{pro} + \vec{J}_{tar})$, which could contribute to a transition from the ground state of ^{71}Ga ($J_i = 3/2^-$) to a final state J_f in ^{71}Ge. For (^{3}He, t) reactions, $\vec{J}_{rel} = \vec{L}_{tar}$, the orbital angular momentum transfer in the target system, and the shape of the angular distributions is, therefore, similar for transitions with equal J_{rel}. In this scheme, the $[J_{pro} J_{tar} J_{rel}]$ contributions to the parity conserving $3/2^- \to 1/2^-$, $3/2^-$, $5/2^-$ transitions are limited to even values of J_{rel}.

These form factors then served as input to calculations in a distorted-wave Born approximation (DWBA). Since no ^{3}He elastic scattering data on ^{71}Ga are available, optical model potential parameters were taken from ^{3}He elastic scattering data on ^{58}Ni [41]. We note that these parameters are close to those obtained from elastic scattering on ^{90}Zr [41] and are therefore likely to provide a reasonable input for DWBA calculations for the intermediate ^{71}Ga as well. Following Ref. [42], well-depths of the real and imaginary potentials for the outgoing triton channel were set to 85% of the well-depths for the incoming ^{3}He channel.

The differential cross sections calculated in DWBA were taken to fit the experimental angular distributions of each transition, whereby the different $[J_{pro} J_{tar} J_{rel}]$ components were varied independently to match the data. Contributions with $J_{rel} \leqslant 4$ turned out to be sufficient for a good description of the data (see Fig. 2). Since the dataset extends to rather large angles, the procedure allows to isolate the [110] part of the cross section rather clearly and the contribution gets increasingly well-determined as one approaches zero degree.

The angular distribution for the rather weak transition to the 175 keV $5/2^-$ state may deserve some extra consideration. As indicated in Fig. 2 (middle left), the [110] contribution to the cross section at zero degree amounts to only about 40%, and it may be worthwhile to address the level of significance. Therefore, an attempt was made to describe the angular distribution without the [110] contribution, yet adding several additional form factors to account for this missing part. The result (Fig. 2 (middle right)) shows that without the [110] contribution the level of agreement with the data is indeed reduced.

The isobaric analog state has been analyzed to ensure consistency among the various datasets. The angular distribution of the IAS transition is shown in Fig. 3. It is described, as expected, by a dominant [000] contribution and only at larger angles there seems to be a need to add extra components. We also note that

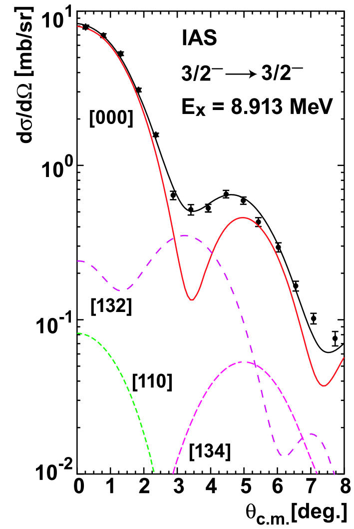

Fig. 3. Angular distribution for the transition to the IAS at 8.913 MeV. A slightly improved fit to the data was achieved by adding a 1% [110] contribution to the IAS excitation.

Table 3
Various low-energy cross sections and B(GT) values for the ^{71}Ga(^{3}He, t)^{71}Ge reaction. The values for the Fermi transition to the IAS have been included. The errors are statistical errors only, whereby we conservatively added 50% of the non-GT, resp. non-F component of the calculated $q = 0$ cross section into the error calculations for the B(GT), resp. B(F) values. The g.s. B(GT) value and the B(F) value are, however, reference values, whose error numbers (given in curly brackets) enter into the evaluation of the effective interaction volume integrals (see text).

^{71}Ge E_x [keV]	J^π of level	Data point $\theta = 0.26°$ [mb/sr]	$d\sigma/d\Omega$ ($\theta = 0°$) [mb/sr]	$d\sigma/d\Omega$ ($q = 0$) [mb/sr]	% GT	B(GT) ($\times 10^{-2}$)
g.s.	$1/2^-$	0.746(23)	0.777(9)	0.786(9)	92%	8.52{40}
175	$5/2^-$	0.067(5)	0.070(4)	0.071(4)	40%	0.34(26)
500	$3/2^-$	0.165(9)	0.169(4)	0.171(4)	87%	1.76(14)
					% F	B(F)
8913 $\Gamma \approx 50$	IAS	7.89(40)	8.35(11)	9.04(12)	96%	9.00{22}

a $3/2^- \to 3/2^-$ transition may contain possible GT components. By adding a 1% [110] contribution to the IAS angular distribution, a slightly improved fit to the data was achieved. However, the significance of this number is certainly no better than a factor of 3.

4. GT strength extraction

Following Refs. [43,44], the GT strength relates to the GT part of the cross section at zero momentum transfer ($q = 0$) in the following way:

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

with $N_D^{\sigma\tau}$ the distortion factor and $|J_{\sigma\tau}|$ the volume integral of the effective nucleon–nucleon interaction of Love and Franey [34,35]. A similar relation holds for the Fermi strength, which is contained in the IAS peak. In extracting the GT strength value, we assume approximate equality between $\frac{d\sigma^{GT}}{d\Omega}(q=0)$ and $\frac{d\sigma^{[110]}}{d\Omega}(q=0)$, which is a fair assumption for B(GT) values larger than 0.01 [32].

Since the products of the distortion factor and the square of the volume integral of the effective interaction lack the precision needed for the present study, we have used the known isobaric analog strength and the known g.s. B(GT) value instead, to extract these quantities. Taking the distortion factors from the eikonal approximation given in [45], $N_D^{\sigma\tau} = \exp(1 - 0.895A^{1/3})$ and $N_D^{\tau} = \exp(2.3 - 1.225A^{1/3})$ we derive for the volume integrals at an energy of 140 MeV/A the values $J_{\sigma\tau} = 161.5 \pm 3.5\ \text{MeV fm}^3$ and $J_\tau = 56.7 \pm 0.9\ \text{MeV fm}^3$. The quantities are consistent with those given in Refs. [24,44] for 150 and 120 MeV/A. Further, the ratio $R^2 = \frac{k_f(\text{g.s.})}{k_f(\text{IAS})} \frac{N_D^{\sigma\tau}}{N_D^{\tau}} (\frac{J_{\sigma\tau}}{J_\tau})^2 = 8.76 \pm 0.46$ is in close agreement with the global trend given in Ref. [46]. The final strength values extracted in this way appear in Table 3.

Eq. (1) does not necessarily require knowledge of the absolute $B(\text{GT})$ values, however, it is re-assuring that the measurements provide a high level of consistency. In order to evaluate the contribution to the $^{71}\text{Ga}(\nu_e, e^-)$ reaction from the excited states in ^{71}Ge, one may therefore proceed with Eq. (1) taking for the g.s. $B(\text{GT})$ strength the number, which is extracted from the ft-value, $B(\text{GT}) = 0.0852(3)$. The contribution from the excited states to the $^{71}\text{Ga}(\nu_e, e^-)$ cross section is then evaluated to be $7.2 \pm 2.0\%$ (i.e., $2.7 \pm 2.0\%$ from the first and $4.5 \pm 0.35\%$ from the second excited state).

5. Conclusion

In the present Letter we have presented a high-statistics and high-resolution measurement of the $(^3\text{He}, t)$ charge-exchange reaction on ^{71}Ga over a wide angular range and with a full analysis of the angular distributions. Gamow–Teller strength values have been extracted for the low-lying states in ^{71}Ge, which may contribute to the neutrino induced CC reactions on ^{71}Ga from the ^{51}Cr or ^{37}Ar neutrino sources. A rather precise value of $7.2 \pm 2.0\%$ for this contribution has been evaluated, which exceeds the 5.1% value previously used by Bahcall. Thus, the discrepancy observed in the SAGE and GALLEX calibration data is further confirmed and possibly even slightly amplified.

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