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(^{6}Li,^{6}He) measurements as an alternative calibration for solar neutrino detectors

E. Aschenauer,* H. Dennert, W. Eyrich, A. Lehmann,† M. Moosburger, and H. Wirth‡
Physikalisches Institut der Universität Erlangen-Nürnberg, D-8520 Erlangen, Federal Republic of Germany

H. J. Gils, H. Rebel, and S. Zagromski
Kernforschungszentrum Karlsruhe, Institut für Kernphysik III, D-7500 Karlsruhe, Federal Republic of Germany

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The (^{6}Li,^{6}He) reaction was studied on the nuclei ^{37}Cl and ^{71}Ga at $E_{^6\mathrm{Li}} = 156$ MeV at extreme forward angles including zero degree. Gamow-Teller strength and the corresponding B(GT) values were extracted. It is shown that these measurements provide an alternative method to calibrate solar neutrino detectors.

A serious problem in astrophysics is the discrepancy that the solar neutrino capture rate observed in the ^{37}Cl experiment [1,2], which used the $^{37}\mathrm{Cl}(\nu,e^-)^{37}\mathrm{Ar}$ inverse β decay, is only about one-third of that predicted by the standard solar model (SSM). The ^{37}Cl detector used has a threshold of 0.814 MeV, therefore it is not sensitive to neutrinos from the basic reaction of the p-p chain $p+p \rightarrow {}^2\mathrm{H}+e^+ +\nu$, which has an end point of 0.420 MeV. The neutrinos detected by the ^{37}Cl detector stem primarily from the decay of ^{8}B. The production of ^{8}B in the Sun, however, is highly temperature and therefore model dependent. In order to remove the sensitivity to parameters of the solar model a detector responding directly to the pp neutrinos is needed, because their flux is nearly independent of the applied solar model. Two realized experiments use ^{71}Ga as target material [3,4]. The solar neutrinos are detected especially via the transition $^{71}\mathrm{Ga}(\mathrm{g.s.},\frac{3}{2}^-) \rightarrow {}^{71}\mathrm{Ge}(\mathrm{g.s.},\frac{1}{2}^-)$ with a threshold of only 0.236 MeV, which give response to pp neutrinos. Excited-state transitions with higher thresholds in comparison to the ground-state transition may also contribute and considerably increase the sensitivity of the ^{71}Ga detector to neutrinos from the decay of ^{8}B and also ^{7}Be [5,6]. So it is possible to verify the results of the ^{37}Cl experiment too. The gallium experiments are also able to test nonstandard effects like neutrino oscillations [7,8]. In this context, it is an essential requirement to know the detector efficiency precisely.

There are three standard methods to calibrate solar neutrino detectors (SNDs). The first is to use natural neutrino sources, especially ^{51}Cr. This method has the disadvantage that the emitted neutrinos have no energy distribution; therefore, it is only possible to calibrate the detectors at one discrete energy [9]. A second method is the determination of the B(GT) values for the transitions $^{37}\mathrm{Cl}(\nu,e^-)^{37}\mathrm{Ar}$ and $^{71}\mathrm{Ga}(\nu,e^-)^{71}\mathrm{Ge}$ by means of the derivation of the matrix elements from electron capture (E.C.) or from β decays of other nuclei in the corresponding mass region. By this means exact values for the ground-state transitions are determined using the corresponding logft values [10,11]. But the only method to measure the Gamow-Teller (GT) strength in the total interesting energy range is the use of related charge-transfer reactions. Up to now the (p,n) reaction was mostly used for this purpose [12]. It is the aim of this paper to present the (^{6}Li,^{6}He) reaction as an alternative method. The most important difference between these two charge-exchange reactions are the selection rules based on the quantum numbers of the involved particles. In the case of the relevant monopole transitions the selection rules $\Delta S=1$ and $\Delta T=1$ of the (^{6}Li,^{6}He) reaction are responsible for the sensitivity to pure Gamow-Teller transitions. In the (p,n) reaction Gamow-Teller and also Fermi transitions are possible. Although at higher proton energies spin-isospin transfer predominates the (p,n) reaction, contributions of $\Delta S=0$ are less suppressed than in the (^{6}Li,^{6}He) reaction, for which the dominance of one-step processes and the high selectivity towards $\Delta S=\Delta T=1$ transition was shown in Refs. [13–15]. For the (^{6}Li,^{6}He) reaction as well as for the (p,n) reaction the Gamow-Teller mode as monopole strength peaks at a reaction angle of 0°.

In this paper we report on (^{6}Li,^{6}He) measurements on the nuclei ^{37}Cl and ^{71}Ga at extreme forward angles including 0°. The measurements were performed at the Karlsruhe Isochronous Cyclotron with a 156-MeV $^6\mathrm{Li}^{3+}$ beam, using the magnetic spectrograph "Little John" [16–18]. Figure 1 shows a scheme of the experimental setup. For the 0° measurements a movable Faraday cup is used to stop the $^6\mathrm{Li}^{3+}$ beam in the interior of the dipole. This is possible, because the $^6\mathrm{Li}^{3+}$-beam particles are more bent than the $^6\mathrm{He}^{2+}$ ejectiles. Many $^6\mathrm{Li}^{2+}$ ions, which originate in the target by rechargement processes, reach the focal plane on the high-energy side separated from the $^6\mathrm{He}^{2+}$ spectrum due to the negative Q value of the (^{6}Li,^{6}He) reaction; they are faded out by a lead shielding. This setup makes it possible to suppress disturbing particles and to get spectra also at 0° without any experimental background. This fact is the main experimental advantage of the (^{6}Li,^{6}He) reaction using a magnetic spectrograph for the spectroscopy of charged ejectiles.

For the $^{37}\mathrm{Cl}(^6\mathrm{Li},^6\mathrm{He})^{37}\mathrm{Ar}$ measurements we used a ^{39}KCl target of natural chlorine. The effective thickness of ^{37}Cl was 1.10 mg/cm^2. Figure 2 shows a

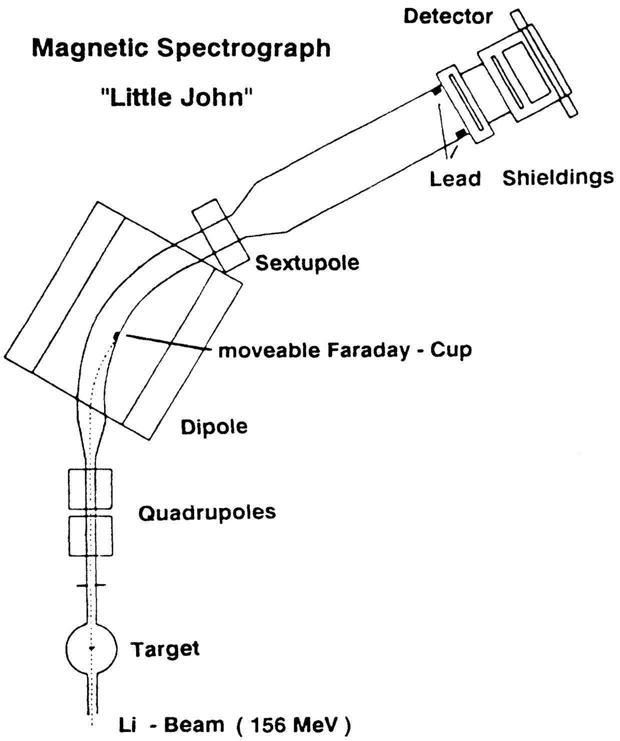

FIG. 1. Cross section of the magnetic spectrometer "Little John" at the Karlsruhe Isochronous Cyclotron.

^{37}Cl(^{6}Li,^{6}He)^{37}Ar spectrum at zero degree, where the states up to an excitation energy of 5 MeV represent pure contributions of ^{37}Cl. The Gamow-Teller transition to the ground state of ^{37}Ar is well separated from the next excited states (a superposition of a $\frac{1}{2}^{+}$ and a $\frac{7}{2}^{-}$ state at 1.41 and 1.61 MeV, respectively). An additional peak, which is composed of transitions of various multipolarities, is visible between 2 and 5 MeV. At excitation energies higher than 5.0 MeV states of ^{35}Ar and ^{39}Ca overlay the ^{37}Ar spectrum. Due to an achieved energy resolution of about 400 keV in our ^{37}Ar spectra, the quantitative separation of the ground state from the first excited state at 1.41 MeV is possible. Therefore the cross section of the g.s. transition can be extracted directly without any problem of background of higher multipolarities. The (^{6}Li,^{6}He) reaction on ^{37}Cl was measured over an angular region ranging from 0° to 4°. The angular distribution of the g.s. cross section is shown in Fig. 3(a). The experimental data points are drawn together with their corresponding statistical errors. The solid line represents a distorted-wave Born-approximation (DWBA) calculation, which was performed with the computer code DWUCK5 [20] using a collective form factor and with inclusion of a tensor term. The curve is adjusted to the measured value of the zero-degree data point. A comparison with the result of a calculation assuming a pure $L=0$ excitation (dashed line) shows that at extreme forward angles (0°–1°) the contribution of the $L=2$-like tensor term is small. The result, that the calculation without tensor force gives a much steeper slope than the experimental values, was also found on various nuclei [13,15].

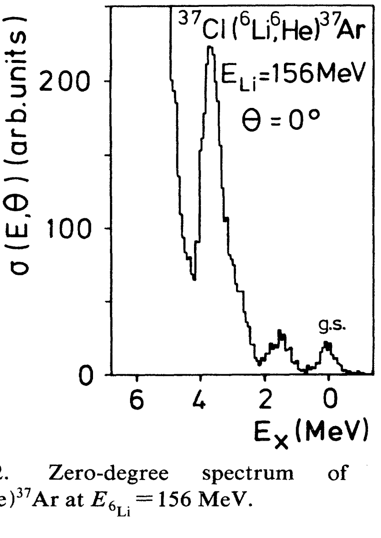

FIG. 2. Zero-degree spectrum of the reaction ^{37}Cl(^{6}Li,^{6}He)^{37}Ar at $E_{^{6}\mathrm{Li}}=156$ MeV.

Let us now describe our results obtained at the system ^{71}Ga$\rightarrow$^{71}Ge, which should give information for the current solar neutrino experiments using ^{71}Ga detectors. We studied the reaction ^{71}Ga(^{6}Li,^{6}He)^{71}Ge up to an excitation energy of about 20 MeV. For these measurements a ^{71}Ga$_2$O$_3$ target with a thickness of 5.23 mg/cm^2 of en-

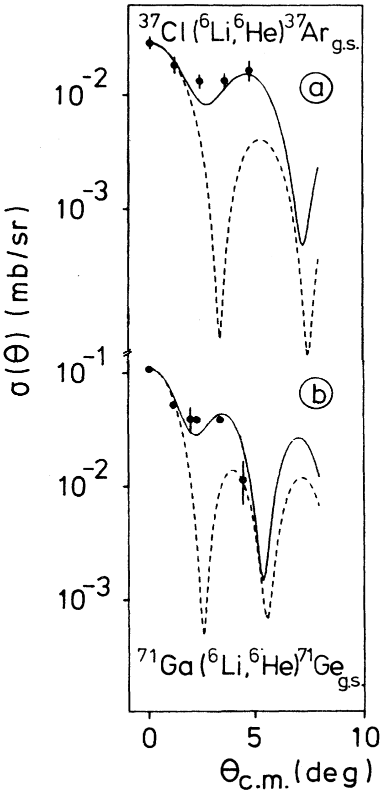

FIG. 3. Experimental angular distribution of the (^{6}Li,^{6}He) reaction together with DWBA calculations. (a) ^{37}Cl$\rightarrow$^{37}Ar; (b) ^{71}Ga$\rightarrow$^{71}Ge.

riched ^{71}Ga on a melinex foil was used. In Fig. 4(a) a 0° spectrum is shown, where the GT strength is in its maximum, together with a 1° spectrum, where it already clearly decreased. To extract the GT strength we applied the maximum-minimum method. This means that one subtracts a spectrum, in which the Gamow-Teller strength is in a minimum or has strongly decreased, from a spectrum, in which the Gamow-Teller strength is in its maximum. If additionally the cross section of higher multipolarities is nearly constant over the interesting angular region, in the subtraction spectrum only GT states will contribute significantly. In Ref. [13] we could show for the representative systems ^{48}Ca$\rightarrow$^{48}Sc and ^{90}Zr$\rightarrow$^{90}Nb that the maximum-minimum method is applicable, even in cases where the GT strength is situated on a strong physical continuum consisting of various multipolarities. From these results on both nuclei we conclude that the method can be also applied to the present Ga spectra of 0° and 1°. Using this subtraction technique we got the spectrum of Fig. 4(b), representing the GT-strength distribution of the observed ^{71}Ga system with a high precision. All strengths with higher multipolarities should have vanished. Since also $L=0$ contributions may be subtracted, the resulting spectrum has to be normalized to the GT strength in the ground-state peak. The uncertainty of the renormalization must be included into the quantitative evaluation of the cross sections; the relative strength distribution in the difference spectrum, however, remains unaffected. For comparison in Fig. 4(c) a zero-degree (p,n) spectrum is shown taken at a beam energy of 120 MeV [21], which is dominated at this incident energy by $L=0$—especially GT transitions. It is evident that the general shape of the spectra is the same. The only striking difference is the missing of the isobaric analog state (IAS) in the (^{6}Li,^{6}He) data showing the high selectivity towards the excitation of GT transitions and the good suppression of $\Delta S=0$ background.

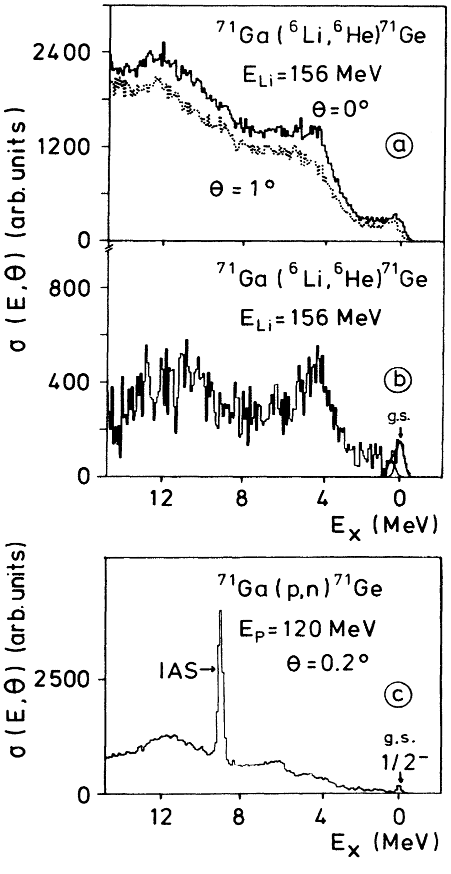

FIG. 4. (a) Spectra of the reaction ^{71}Ga(^{6}Li,^{6}He)^{71}Ge at $\theta=0°$ and 1°. (b) Difference spectrum with fits for the Gamow-Teller states at low energies. (c) A 0.2° spectrum of the reaction ^{71}Ga(p,n)^{71}Ge at $E_p=120$ MeV (see Ref. [21]).

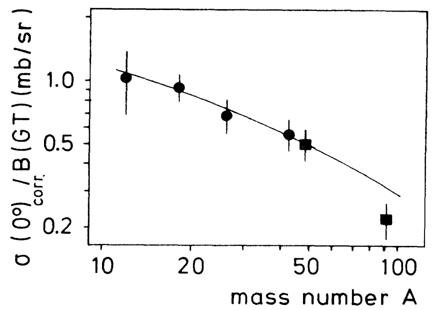

FIG. 5. Mass dependence of $\sigma_{\rm corr}(0°)/B(\rm GT)$. $\sigma_{\rm corr}(0°)$ extracted from (^{6}Li,^{6}He) measurements. B(GT) values from β decay (●) and (p,n) measurement (■).

A (p,n) measurement [22] at $E_p=35$ MeV reported an additional Gamow-Teller strength for the transition ^{71}Ga(g.s.,$\frac{3}{2}^-$)$\rightarrow$^{71}Ge(0.175 MeV, $\frac{5}{2}^-$). This result was not confirmed by theoretical works and the 120 MeV (p,n) measurement of Ref. [21], which found no $L=0$ contribution to this transition. This problem is also avoided in our case, where strength with higher multipolarities is removed automatically using the maximum-minimum method.

The whole energy region, which is interesting for the solar neutrinos from the hydrogen burning, is covered by Fig. 4(b). The low-lying Gamow-Teller states are reproduced by Gaussian curves. The first one is the ground state; the second one belongs to a $\frac{3}{2}^-$ state at 0.499 MeV. In Fig. 3(b) the angular distribution of the ground-state cross section can be seen together with a DWBA calculation performed in the same way as for ^{37}Ar. Again the general trend was found that the calculation without ten-

TABLE I. A comparison of the B(GT) values deduced from (^{6}Li,^{6}He), (p,n) measurements and E.C. for the transitions to the ground states of ^{37}Ar and ^{71}Ge.

g.s.	^{37}Ar	^{71}Ge
B(GT)(^{6}Li,^{6}He)	0.033±0.007	0.11±0.03
B(GT)(p,n)	0.034±0.007[a]	0.085±0.015[b]
B(GT)(E.C.)	0.0316±0.0008[c]	0.091±0.0002[c]

[a] Reference [19].
[b] Reference [21].
[c] logft values from Refs. [10,11].

TABLE II. B(GT) values for the whole energy range of solar neutrino interaction in the system $^{71}\mathrm{Ga}\rightarrow{}^{71}\mathrm{Ge}$.

E_x(MeV)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	Σ
B(GT)	0.17 ±0.03	0.14 ±0.03	0.13 ±0.03	0.35 ±0.06	0.71 ±0.14	0.61 ±0.15	0.55 ±0.14	0.55 ±0.14	3.2 ±0.4

sor terms gives a much steeper slope than the experimental data show, but dominates the angular region used for the maximum-minimum method strongly.

A more detailed evaluation results in the quantitative determination of GT transition strength for the investigated nuclei ^{37}Cl and ^{71}Ga. In one of our previous works [23] it has been shown that in order to extract the GT strength from the results of the zero-degree (^{6}Li,^{6}He) measurements, the cross sections have to be corrected due to the different Q values of the investigated reaction. Regarding the 0° cross sections of DWBA calculations as a function of the Q value, one gets a smooth curve for all investigated nuclei, similar to (p,n) [24]. This function can be used for the correction of the measured 0° cross sections to a momentum transfer of $q=0$. The results of our analysis on various nuclei [13,23] are shown in Fig. 5, where the ratios $\sigma_{\mathrm{corr}}(0^\circ)/B(\mathrm{GT})=F(A)$ are plotted versus the mass number A. The cross sections are evaluated from the (^{6}Li,^{6}He) measurements. The B(GT) values are known from β-decay investigations (closed circle) and from (p,n) experiments (closed square). A fit to the data points according to the formula $F(A)=C\exp(-xA^{1/3})$ is included. This functional behavior of $F(A)$, taken from the (p,n) work [25], represents the expected mass dependence very well. Corresponding to this characteristic behavior the B(GT) values related to the measured cross sections in the interesting energy region of solar neutrinos were calculated with the help of the following equation:

$$B(\mathrm{GT})=\frac{[\sigma_{\mathrm{DWBA}}(Q=0)/\sigma_{\mathrm{DWBA}}(Q)]\sigma_{\mathrm{exp}}(0^\circ)}{F(A)}\;.$$

As mentioned before the factor $\sigma_{\mathrm{DWBA}}(Q=0)/\sigma_{\mathrm{DWBA}}(Q)$ is necessary to correct the momentum transfer at 0°, caused by the Q values of the (^{6}Li,^{6}He) reaction. For the ground-state region of ^{37}Cl and ^{71}Ga this factor is 1.0 and can be neglected, but at higher excitation energies it increases to about 1.5 and must be taken into consideration. The mass factors $F(A=37)=0.61$ and $F(A=71)=0.38$ are taken from the fit shown in Fig. 5. This yields a B(GT) value of 0.033 ± 0.007 and of 0.11 ± 0.03 for the g.s. transitions to ^{37}Ar and ^{71}Ge, respectively. Our results for the ground states are compared with (p,n) and β-decay data in Table I. The values of all methods show a rather good agreement within the error bars; a fact, which shows again the suitability of the applied analysis of the (^{6}Li,^{6}He) measurements to extract Gamow-Teller transition strengths. An evaluation of the GT-strength distribution of Fig. 4(b) is presented in Table II where a quantitative summary of the extracted B(GT) values in the system $^{71}\mathrm{Ga}\rightarrow{}^{71}\mathrm{Ge}$ is given in steps of 1 MeV up to an excitation energy of 8 MeV, which is just the interesting region for solar neutrino detectors. The errors of the values include assumed systematic uncertainties of the applied extraction methods. The summed strength up to 8 MeV of 3.2 ± 0.4 has to be compared with the tentative higher value of 4.3 ± 0.7 from the (p,n) work [21].

This work has shown that the distribution of the GT strength can be extracted and evaluated quantitatively for the decisive transitions of a solar neutrino interaction with satisfying precision. In summary, we can conclude that the (^{6}Li,^{6}He) reaction is an appropriate alternative to calibrate solar neutrino detectors. Moreover, we suggest to extend the method to higher beam energies, leading to an increase of Gamow-Teller cross sections in comparison to higher multipolarities, which should improve the precision of the extracted data additionally.

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*Present address: Paul Scherrer Institut, CH-5232 Villigen, Switzerland.

†Present address: Institut für Physik an der Universität Basel, CH-4056 Basel, Switzerland.

‡Present address: CERN, Division PPE, CH-1211 Genève 23, Switzerland.

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