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GAMOW–TELLER STRENGTH IN THE BETA–DECAY OF ^{37}CA AND ITS IMPLICATIONS FOR THE DETECTION OF THE SOLAR NEUTRINO FLUX

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Abstract: We have studied the β-decay of ^{37}Ca at the projectile fragment separator FRS at GSI Darmstadt. The resulting Gamow-Teller strength function B(GT) which is important for determining the detection efficiency of the Homestake mine ^{37}Cl detector is significantly changed by the inclusion of previously unobserved β-delayed γ-rays. With the new results former discrepancies between the B(GT) values measured in the ^{37}Ca β-decay and those extracted from ^{37}Cl(p,n)^{37}Ar reactions are drastically reduced. Additionally, our data yield evidence for an isospin-forbidden Fermi transition in the β-decay of ^{37}Ca.

1. Introduction

In order to calibrate solar neutrino flux measurements performed by means of the Homestake mine ^{37}Cl detector[1] the Gamow-Teller strength function B(GT) of the ^{37}Cl$(\nu_e, e^-)^{37}$Ar reaction is required[2]. Since data from the ^{37}Ar(EC)^{37}Cl decay yield only the B(GT) value for the ground-state transition, one needs a method to determine the B(GT) strength for transitions into excited states of ^{37}Ar. In principle, this information can be deduced from data on the zero-momentum ^{37}Cl(p,n)^{37}Ar charge-exchange reaction[3]. However, as pointed out by Bahcall and Barnes[4], B(GT) values for the solar neutrino capture cross-section can also be determined, under the assumption of isospin symmetry, by measuring the ^{37}Ca β-decay branches. The ^{37}Ca β-decay energy release (Q_{EC}=11639(22) keV, ref. 5) is large enough to cover the whole range of excitation energies in ^{37}K important for the ^{37}Cl detector, since in the isospin analogue ^{37}Ar α-emission starts to compete successfully with γ-deexcitation at excitation energies of about 8.4 MeV[6].

Recently, a high resolution study of the β-delayed proton emission from ^{37}Ca was performed by Garcia *et al.*[6] at ISOLDE. In this work, the total widths Γ of all proton-unbound states in ^{37}K fed by β-decay of ^{37}Ca were assumed to be equal to their proton widths Γ_p. Furthermore, the observed β-decay branching ratio into the isobaric analog state (IAS) was normalized by using the model-independent value[7] $B_{IAS}(F)=3$ and the shell-model result[8] $B_{IAS}(GT)=0.10$. Assuming isospin symmetry,

Garcia *et al.* determined the decay branching ratio into the ^{37}K ground-state from the B(GT) value of the ^{37}Ar(EC)^{37}Cl mirror transition. Since all decay branchings must sum to unity, these assumptions, together with the half-life of 0.175(3) s of ^{37}Ca (ref. 9), yield the branching ratio for the decay into the proton-bound state at E_x=1370.9 keV in ^{37}K.
It is clear that an accurate measurement of ^{37}Ca β-decay branching ratios would allow one to verify the assumptions made by Garcia *et al.*. This is important as discrepancies exist between these β-decay data and the ^{37}Cl(p,n)^{37}Ar reaction results measured by Rapaport *et al.*[10] for excitation energies near and below the IAS. These discrepancies led Adelberger *et al.*[11] to question whether (p,n) charge-exchange experiments are a reliable tool to obtain accurate B(GT) strengths.
Meanwhile, the ^{37}Cl(p,n)^{37}Ar reaction has been reinvestigated with enhanced resolution and reduced background by Wells *et al.*[12]. This experiment successfully disentangled the B(GT) strength from the dominating B(F) contribution near the IAS by measuring spin transfer cross-sections. The resulting B(GT) strength near the IAS is qualitatively consistent with the β-decay results. However, the new experiment confirmed the large discrepancies present at low excitation energies in comparison to the β-decay data. As pointed out by Goodman *et al.*[13], the claimed discrepancy below the IAS could be an artifact due to a dominant γ-decay ($\Gamma \approx \Gamma_\gamma$) of the proton-unbound level at E_x=3239.3 keV in ^{37}K, which was confirmed qualitatively by Magnus *et al.*[14]. An estimate of $\Gamma_\gamma/\Gamma_p \approx 40$ for this level extracted from ^{36}Ar(p,γ)^{37}K reactions has been given by Iliadis *et al.*[15], but more accurate data are clearly needed.
In this contribution we report on a detailed study of the β-delayed proton (βp) and the β-delayed γ ($\beta\gamma$) decay of ^{37}Ca. In comparison to a preliminary analysis[16], the data presented here result from a more precise determination of the βp- and $\beta\gamma$-decay branching ratios and of the half-life of ^{37}Ca. In addition, we performed a similar study of the β-decay of ^{36}Ca which will be presented elsewhere.

2. Experimental Technique

The experiment was performed at the projectile fragment separator FRS at GSI Darmstadt[17]. A ^{37}Ca secondary beam, produced by means of reactions of a 300 Mev/u ^{40}Ca beam impinging on a 1g/cm^2 ^{9}Be target, was identified and separated using a $B\rho$–energy-loss–time-of-flight method[18]. About 30 atoms/s were implanted into a 30mm×30mm×0.5mm silicon counter (implantation detector) at the final focus of the FRS. This detector was positioned between two similar silicon counters for the detection of β-rays (β-detectors). Two large-volume germanium detectors for the detection of γ-rays were mounted close to the silicon detector array (figure 1).
Since we used the monoenergetic mode of the FRS, the implantation profile of ^{37}Ca had a very small width of approximately 100μm (FWHM) in beam direction. Correspondingly, we were able to trigger the detection of the γ-rays emitted from the implanted activity with 100% efficiency via the energy-loss of the accompanying β-rays in the implantation detector. Therefore, only γ-rays originating from nuclei decaying

inside the implantation detector were detected and the room background was suppressed efficiently. A drawback of the monoenergetic FRS mode is that the isotonic contaminants ^{36}K and ^{35}Ar were also implanted at a ratio N(^{37}Ca)/N(^{36}K)/N(^{35}Ar) of 0.8232/0.1639/0.0129. However, since ^{35}Ar does not decay by emission of delayed charged particles and ^{36}K only with negligibly small branching ratios[19], the βp-spectrum observed in the implantation detector was almost entirely originating from the decay of ^{37}Ca.

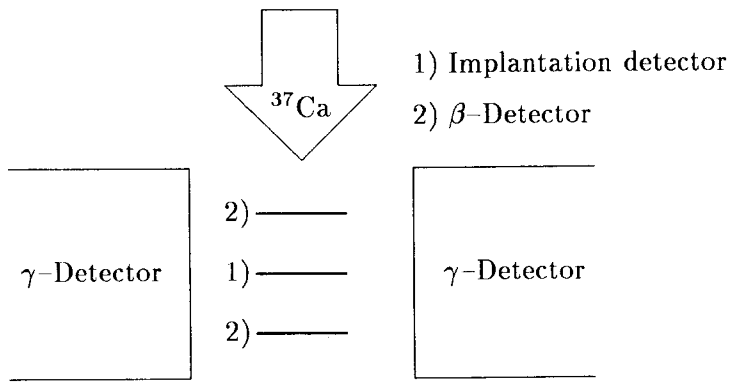

Figure 1: Detection setup.

For the absolute normalization of decay branching ratios the number N(^{37}Ca) of ^{37}Ca atoms, that were stopped in the implantation detector, had to be determined. This was achieved by two different methods:

a) N(^{37}Ca) was obtained from the total number of identified atoms coincident with a high-energy event in the implantation detector. This number had to be corrected for the losses due to secondary reactions in the stopping process following the energy-loss–time-of-flight identification. In determining this correction factor the energy distribution along the stopping path of the ^{37}Ca atoms in the different layers of matter was calculated by means of the code ATIMA[20] and the total nuclear cross-section was taken from an empirical parametrization[21].

b) N(^{37}Ca) was extracted from the total number of all decay events observed in the implantation detector. This procedure includes the β-rays emitted from the implanted contaminants by using the known ratio N(^{37}Ca)/N(^{36}K)/N(^{35}Ar). A calculation of the secondary losses of ^{36}K and ^{35}Ar atoms in the stopping process similar to the one mentioned in a) showed that they were almost the same as for ^{37}Ca. The determination of the ^{37}Ca contribution to the measured decay activity took into account the above-mentioned implanted contaminants as well as ^{37}K decays originating from those ^{37}Ca decays which do not lead to proton emission. Since all contributing β-transitions are characterized by high energy-release, the electron-capture contributions of these decays were negligible[19,22].

Furthermore, the decay of the ^{37}K-daugther ^{37}Ar was disregarded because it does not produce any β-rays (Q_{EC}=813.5(3) keV, ref. 5).

The energy resolution of the βp-spectrum measured in the implantation detector was very poor because of the summing between the proton signal and the continuously distributed energy-loss of the coincident β-ray. Therefore, the absolute normalization of all βp decay branching ratios was achieved by comparing the proton spectrum measured in this work with the high resolution data obtained by Garcia *et al.*[6].
For the determination of the $\beta\gamma$-decay rates, a precise calibration of the γ-efficiency was performed by using a calibrated ^{56}Co source. The spatial distribution of this source corresponded to the implantation profile measured for ^{37}Ca during the experiment. Since almost every γ-ray emitted from ^{56}Co is part of a γ-cascade[23], a correction for cascade summing effects, which was found to be important for our high-efficiency detection setup, was performed[24]. The detection geometry also required a correction for losses in the photopeaks of β-delayed γ-lines due to summation with β-rays or 511 keV annilihation radiation. It was found that these effects diminished the intensity of the γ-lines by 10–20%, depending on the corresponding β-endpoint energy[24].
For the determination of the ^{37}Ca half-life, we used the proton spectrum accumulated in a pulsed beam-mode (0.5s beam on, 2.5s beam off), with the time of each decay event being recorded by means of a high-precision clock. In order to assure, that the measured time spectrum is free of β-ray energy-loss signals originating from the decay of ^{36}K, ^{35}Ar or ^{37}K, a coincidence with one of the β-detectors was required resulting in a reduction of the β-ray energy-loss[25]. Through this coincidence condition, the protons with energies above 3 MeV, which originate mainly from the superallowed β-decay, were clearly separated from decay events with a smaller energy signal. In the accumulation of the time spectrum only these high-energy protons were taken into account. A time-dependent correction for dead-time effects, extracted from a randomly distributed pulser, was included in the half-life analysis.

3. Results and Discussion

3.1 Beta-delayed γ-rays from the ^{37}Ca decay

A total number of 2.6×10^{6} ^{37}Ca atoms was implanted during the experiment, the N(^{37}Ca) results obtained from method a) and b) agreeing within less than 0.7%. Figure 2 shows the γ-ray spectrum observed in our measurement. The γ-deexcitation of the first three excited states of ^{37}K fed by allowed β-decay of ^{37}Ca with excitation energies of 1370.9(2), 2750.4(2) and 3239.3(2) keV and $\beta\gamma$ branching ratios of 2.1(1), 2.8(1) and 4.8(2)%, respectively, has been observed for the first time. The ^{36}Ar γ-rays[9] originate mainly from the β-decay of the implanted contaminant ^{36}K, but also from the βp-decay of ^{37}Ca into excited states of ^{36}Ar (ref. 6). Since we observed a total β-decay branching ratio of 5.1(2)% into the state at 3239.3 keV indicating an allowed transition, we have umambigously identified this state as the mirror state of the $J^{\pi}=\frac{5}{2}^{+}$ state at 3171.3 keV in ^{37}Ar (ref. 9).

3.2 Lifetimes and decay widths of excited states in ^{37}K

Combining the $\beta\gamma$ and βp intensities measured in this work with the known[26] γ-deexcitation pattern of the 2750.4 keV state, we obtain Γ_γ/Γ_p=0.54(3) for the state at 2750.4 keV and Γ_γ/Γ_p=22(2) for the 3239.3 keV state. The latter value is surprisingly high, since for proton-unbound states γ-deexcitation is expected to only compete significantly · ith proton-emission for excitation energies near the particle threshold[27] ($S_p(^{37}K)$= ı857.77(09) keV, ref. 5).
However, nuclear structure calculations based on Wildenthals universal sd-shell interaction[28,29] (USD) explained this effect at least qualitatively, namely by assuming to better describe the $J^\pi=\frac{5}{2}^+$ states at 2750.4 and 3239.3 keV as mixtures of the two original USD states[30,31].

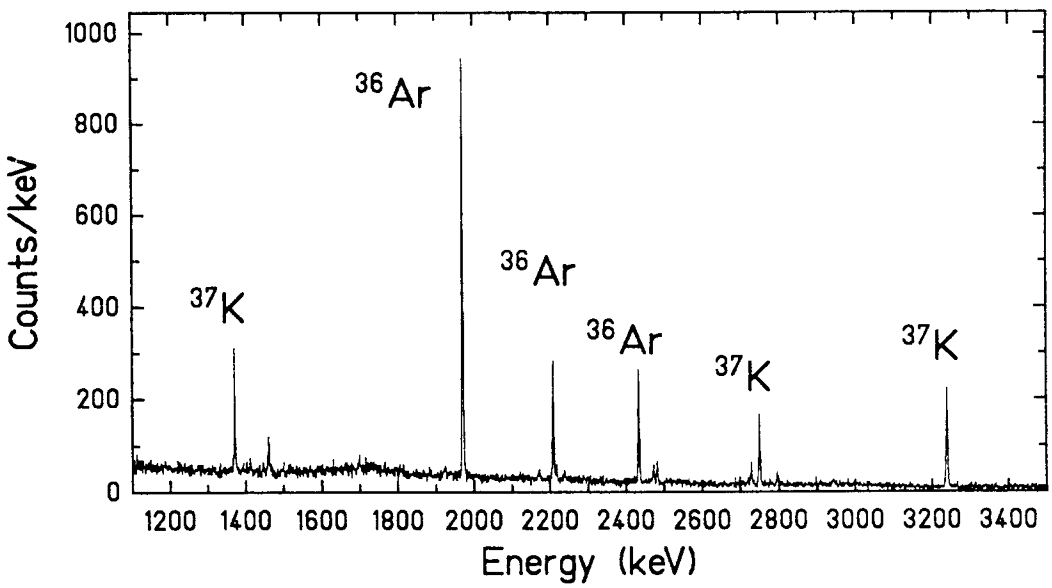

Figure 2: γ-spectrum from the decay of ^{37}Ca, measured in coincidence with β-rays. The assignment for the dominant lines is given by indicating the nuclides in which the transitions occur. The lines of lower intensity are due to weaker transitions in ^{36}Ar or to single or double escape effects.

With the known resonance strengths $\omega\gamma$ of the ^{36}Ar(p,γ)^{37}K reaction of 0.208(30) eV (ref. 32) and 0.60(15) meV (ref. 15) for the states at 2750.4 keV and 3239.3 keV, respectively, and the new Γ_γ/Γ_p values, we can deduce the partial widths and the corresponding mean lifetimes τ (see table 1) using[15]

$$\omega\gamma = \frac{(2J+1)}{(2j_p+1)(2j_t+1)} \frac{\Gamma_p \Gamma_\gamma}{(\Gamma_p+\Gamma_\gamma)}.$$

Here, J, j_p and j_t represent the spin of the resonance (i.e. the excited state in ^{37}K), of the projectile and of the target nucleus, respectively. Our value of τ=2.2(2) fs for the 2750.4 keV state is consistent with the previously found[26] upper limit τ <3 fs, whereas our partial γ-decay widths Γ_γ are considerably different from the known[9] widths of the mirror states in ^{37}Ar (these states are proton-bound and are thus characterized by $\Gamma=\Gamma_\gamma$).

Table 1: Lifetimes and decay widths of excited states in ^{37}K.

E/keV	Γ_p/eV	Γ_γ/eV	Γ/eV	τ/fs	$\Gamma(^{37}\mathrm{Ar})/\mathrm{eV}^a$
2750.4	0.20(3)	0.11(2)	0.30(4)	2.2(2)	0.033(10)
3239.3	2.1(6)$\times10^{-4}$	4.6(1.2)$\times10^{-3}$	4.8(1.2)$\times10^{-3}$	140(40)	8(1)$\times10^{-3}$

^{a} taken from ref. 9

3.3 The transition strength of the ^{37}Ca β-decay

From the pulsed-beam data, the ^{37}Ca half-life was determined to be $T_{1/2}$=0.181(1) s, which is two standard-deviations larger than the previously accepted result[9]. By using the new half-life the transition strength in the β-decay of ^{37}Ca was determined on the basis of the relation

$$(\mathrm{B(F)} + \mathrm{B(GT)})_i = \frac{K}{f(E_i)t_i}$$

were B(F) is the Fermi strength, K=6170(4) s (ref. 8), and E_i, t_i and $f(E_i)$ are the β-endpoint energy, the partial half-life and the phase-space factor[33], respectively, of a β-transition to a level i in ^{37}K.

For the transition into the IAS at 5050.6 keV (ref. 6), we get (B(F)+B(GT))=3.00(7) whereas for the transition into the $J^\pi=(\frac{3}{2},\frac{5}{2})^+$ level at 5016.1 keV (ref. 6), i.e. only 34.5 keV below the IAS, we obtain $(\mathrm{B(F)+B(GT)})_{5016}$=0.124(4). It is thus possible that the 5016 keV state contains some Fermi strength. This conclusion takes into account that (i) γ-deexcitation of the IAS has been found to be negligible[6], (ii) USD calculations[8] yield $\mathrm{B(GT)}_{\mathrm{IAS}}$=0.10, and (iii) $\mathrm{B(F)}_{\mathrm{total}}$=3 follows from angular momentum theory[7]. The shell model value for $\mathrm{B(GT)}_{\mathrm{IAS}}$ is apparently quite accurate, because the effective USD interaction, which yields agreement with measured M1 transitions and magnetic moments in sd-shell nuclei[8,29,33], predicts for the ground state of ^{37}Cl a magnetic moment which agrees with the experimental value within 4% (ref. 35). Since the Gamow-Teller operator represents the isovector contribution to

the magnetic moment and the IAS in ^{37}K and the ground states of ^{37}Ca and ^{37}Cl are identical in the exact isospin limit, we assume that the USD value for $B(GT)_{IAS}$ is as accurate as indicated by the agreement in the case of the ^{37}Cl magnetic moment. Accordingly, we conclude that there is evidence for an isospin-forbidden Fermi transition within the the β-decay of ^{37}Ca. The isospin-mixing matrix element V_{IM} (ref. 36) between the IAS and the 5016 keV state amounts to $|V_{IM}| = 6.3^{+0.7}_{-2.8}$keV.
Our result is in excellent agreement with the value of 5.5 keV for an isospin-mixing matrix element of a $J^{\pi}=\frac{3}{2}^{+}$ state near the IAS, obtained in the shell-model calculations of isospin-forbidden Fermi transitions recently presented by Nakamura *et al.*[37]. It is important to note that these calculations reproduce the seven experimentally known isospin-mixing matrix elements in the sd-shell fairly well.
The integrated B(GT) strength resulting from our experiment is 2.97(9). With a value of 2.32(6) our experiment confirms the previously observed[6] large amount of B(GT) strength into states above the IAS in ^{37}K. This observation has recently led to a discussion whether the axial-vector coupling constant g_A is to be renormalized in the nuclear medium[11,38].

Table 2: B(GT) values for low excitation energies. The values of the (p,n)-data[10] have been multiplied by $(g_A/g_V)^2 = (1.26)^2$, because of a different definition of B(GT).

$E_x(^{37}K)$/MeV	β-decay (this work)	β-decay (Ref. 6)	(p,n) (Ref. 10)	(p,n)[a] (Ref. 12,30)
0.0	0.048(2)[b]	0.0483(14)[c]	0.054(11)	
1.3709	0.0127(6)	0.074(10)[d]	< 0.014	0.014(4)
2.7504	0.102(3)	0.067(4)		0.077(10)
3.2393	0.087(4)	0.0039(9)		0.136(15)
3.6222	0.074(2)	0.075(4)		
3.8402	0.093(3)	0.094(5)		
2-4	0.357(6)	0.240(8)	0.37(6)	

[a] preliminary values (see text)
[b] deduced from intensity balance (see text)
[c] inferred from the ^{37}Ar(EC)^{37}Cl decay
[d] deduced from intensity balance under assumption c (see text)

The low-energy part of the B(GT) function from this work is shown in table 2 in comparison to the previous β-decay results[6], to the (p,n)-data of Rapaport *et al.*[10] and to the preliminary results of the new (p,n)-data of Wells *et al.*[12], discussed in ref. 30. Our B(GT) value for the ground-state transition has been obtained from $I_{GS} = 1 - \sum_i I^i_\beta$, I_{GS} and I^i_β being the decay branching ratios to the ground state and the level i in ^{37}K, respectively. This B(GT) value agrees very well with that of the ^{37}Ar(EC)^{37}Cl mirror transition[8]. On the basis of the Γ_γ/Γ_p results obtained in this work, the B(GT) values for the transitions into the first three excited states of ^{37}K are drastically changed compared to the previous β-decay data but agree well with the data of ref. 10. In comparison with preliminary results of the new (p,n) data, whose normalization is based on the assumption that the strength of the ^{37}Cl(p,n)^{37}Ar ground-state transition is equal to that of the ^{37}Ar(EC)^{37}Cl electron capture rate[30], we find good agreement of the B(GT) values for the transitions into the first excited state whereas significant differences occur for the ^{37}K states at 2750.4 keV and 3239.3 keV.

On the one side, the discrepancy between our data and those obtained by Wells *et al.* is surprising, since a recent high-resolution study of the B(GT) function in the β-decay of ^{38}Ca reveals an excellent agreement with the results extracted from the ^{38}Ar(p,n)^{38}K mirror transition[39]. On the other hand, one cannot expect exactly the same accuracy for the A=37 case, since in the A=38 comparison the final states in ^{38}K are identical. Furthermore, as has recently been pointed out[38], the ratio $B(GT)_{pn}/B(GT)_{\beta}$ seems to be different for spin-flip transitions ($d_{3/2} \rightarrow d_{5/2}$) and non-spin-flip transitions (for example $p_{1/2} \rightarrow p_{1/2}$ or $d_{3/2} \rightarrow d_{3/2}$). Therefore, a calibration of the $B(GT)_{pn}$ function to non-spin-flip transitions might not be adequate for spin-flip transitions and vice versa. Hence, we cannot conclusively decide whether the remaining discrepancies between the ^{37}Ca β-decay data and the ^{37}Cl(p,n)^{37}Ar results are inherent to the (p,n) reaction mechanism or whether they originate from "real" isospin asymmetries.

3.4 ^{37}Cl neutrino capture cross-section

We used the B(GT)+B(F) values from this work to determine the neutrino capture cross-section $\sigma(^{37}\mathrm{Cl})$. In this context, it might be argued that phase-space limitations hinder the accurate extraction of the B(GT) function at high excitation energies. However, the B(GT) for the strong transition seen at E_x=7.65 MeV in the (p,n) experiment[10] is quantitatively reproduced by the sum of the β-decay B(GT) values in this region. The neighbouring peak in the (p,n) data at 9.65 MeV is well beyond the above-mentioned threshhold $E_x \approx 8.4$ MeV were ^{37}Ar becomes effectively unbound against α-emission (i.e. $\Gamma \approx \Gamma_\alpha$). Additionally, if B(GT) strength in this energy region remained unobserved in the β-decay experiment the corresponding influence on $\sigma(^{37}\mathrm{Cl})$ is very small[6].

In our calculations for $\sigma(^{37}\mathrm{Cl})$, we took the ^{37}Ar excitation energies in case of known isobaric correspondences[9] and the excitation energies in ^{37}K for the remaining states. In the latter case, we assumed the mean deviation between the mirror states as the uncertainty of the excitation energies. For the neutrino capture into the ground state of ^{37}Ar the B(GT) value of the ^{37}Ar(EC)^{37}Cl decay was used.

The dominant part of the predicted solar-neutrino capture rate for the ^{37}Cl detector is ascribed to those neutrinos originating in the ^{8}B decay. The corresponding neutrino spectrum has been calculated by Bahcall and Holstein[40] who included forbidden corrections to the weak interaction. The capture cross-section for ^{8}B was calculated by folding this spectrum with the energy-dependent cross-section. Correspondingly, we obtained $\sigma(^{37}\mathrm{Cl})$ for the detection of the neutrinos originating in the ^{3}He(p,e$^+\nu$)^{4}He

reaction by using the neutrino spectrum given in ref. 2.
For the ^{8}B cross-section, our result agrees with that obtained previously[6] (see table 3). This is due to the fact that our experiment reveals more transition strength for the states at low excitation energies and less at higher excitation energies. Moreover, the $\sigma(^{37}Cl)$ result obtained in this work agrees very well with the standard value given by Bahcall and Holstein[40]. Thus the origin of the discrepancies between the solar neutrino flux predicted by standard model calculations[2] and the value measured with the ^{37}Cl detector remains still open.

Table 3: Solar neutrino cross-sections σ for the ^{37}Cl detector. Depicted are only the values for those neutrino sources whose detection is affected by transitions into excited states of ^{37}Ar. All values are given in units of $10^{-42}cm^2$.

neutrino source	$\sigma_{\beta-\text{decay}}$ (this work)	$\sigma_{\beta-\text{decay}}$ (Ref. 6)	σ_{standard} (Ref. 2,40)
$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$	1.09(3)	1.09(3)	1.06(10)
$^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$	4.23(10)	4.26(15)	3.9

4. Summary and Outlook

The results obtained in this work have drastically reduced the previous discrepancies between the ^{37}Ca β-decay data and the $^{37}Cl(p,n)^{37}Ar$ results. However, more data for β-decay/(p,n) comparisons are necessary to clarify the origin of the remaining inconsistencies. A $^{36}S(p,n)^{36}Cl$ experiment would be useful in this context since the extracted B(GT) function could be be compared to the forthcoming ^{36}Ca β-decay data.
In the ^{37}Ca β-decay, a contribution of isospin forbidden Fermi decay seems to dominate the transition into the 5016 keV state. It should be possible to unambigously clarify this effect in a high-resolution study of the ^{37}Ca βp-decay. Such an experiment would make use of β-ν angular correlations which cause significantly different line shapes for Fermi and Gamow-Teller transitions in βp-spectra[41]. As has recently been shown at ISOLDE[42], a necessary requirement for this measurement, namely the availability of high-purity ^{37}Ca sources, can bet met by using a fluorination technique. However, it is not clear whether the high source strengths needed for precision line-shape experiments can be reached.
The $\sigma(^{37}Cl)$ values found in this work confirm the values used in standard solar model calculations[2] and thus give no hints for a solution of the solar neutrino problem.
In conclusion, we have shown that the combination of high-precision decay studies of one and the the same nucleus at an ISOL mass separator and the FRS represents a powerful tool to study very proton-rich nuclei and to get thereby a deeper insight into questions of nuclear structure and/or astrophysical relevance.

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