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(This work is part of the Ph.D. thesis of W. Trinder)

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β-Decay of ^{37}Ca *

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Abstract: The β-decay of ^{37}Ca has been studied. The half-life was remeasured with improved precision to be 181(1) ms, and β-delayed γ-rays were observed for the first time. The surprisingly high Γ_γ/Γ_p values for proton-unbound states in ^{37}K drastically reduce former discrepancies between the Gamow-Teller strength values B(GT) measured in the ^{37}Ca β-decay and those deduced from the ^{37}Cl(p,n)^{37}Ar mirror reaction.

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The β-decay of ^{37}Ca has recently attracted much interest due to a twofold motivation. Firstly, the deduced Gamow-Teller strength B(GT) can be used to calibrate solar neutrino flux measurements performed by means of the Homestake mine ^{37}Cl detector [1, 2]. Secondly, the large energy release (Q_{EC} = 11639(22)keV [3]) allows a detailed comparison with the B(GT) values extracted from ^{37}Cl(p,n)^{37}Ar charge-exchange reactions. Under the assumption of isospin symmetry the two B(GT) functions should be identical. A high resolution study of the β-delayed proton emission from ^{37}Ca was performed by Garcia *et al.* [4]. In this work, the B(GT) function was determined assuming $\Gamma = \Gamma_p$ for all proton-unbound states and using the model-independent value B(F) = 3 [5] and the shell-model result B(GT) = 0.10 [6] for the transition into the isobaric analog state (IAS). The ground-state transition strength was taken from the ^{37}Ar(EC)^{37}Cl mirror decay. Since all decay branchings must sum to unity, the transition rate into the proton-bound state in ^{37}K at E_x = 1370.9 keV was then extracted on the basis of the measured half-life of 0.175(3) s [7]. The ^{37}Cl(p,n)^{37}Ar reaction has been studied by Rapaport *et al.* [8] and, with enhanced resolution, by Wells *et al.* [9]. Large discrepancies between the β-decay and (p,n) B(GT) functions led Adelberger *et al.* [10] to question whether (p,n) experiments are a reliable tool for B(GT) determinations. However, an estimate of $\Gamma_\gamma/\Gamma_p \approx 40$ for the level at E_x = 3239.3 keV in ^{37}K extracted from ^{36}Ar(p,γ)^{37}K reactions [11] indicated that the discrepancies might originate from a wrong normalization of the ^{37}Ca β-decay scheme.

In this letter we report on a detailed study of the β-delayed proton (βp) and the β-delayed γ ($\beta\gamma$) decay of ^{37}Ca. By using the projectile fragment separator FRS at GSI Darmstadt [12] a ^{37}Ca secondary beam of about 30 atoms/s, produced by means of reactions of a 300 MeV/u ^{40}Ca beam impinging on a 1g/cm^2 ^{9}Be target, was implanted into a 30 mm × 30 mm × 0.5 mm silicon counter (implantation detector) at the final focus of the FRS. This detector was positioned between two silicon counters of similar dimensions, which served for β-ray counting (β-detectors). Two large-volume germanium γ-detectors were mounted close to the silicon detector array. The monoenergetic mode of the FRS assured a very narrow ^{37}Ca implantation profile in beam direction (FWHM $\approx$ 100 μm). Hence, 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 coincident β-rays in the implantation detector. Therefore, only γ-rays originating from nuclei decaying inside the implantation detector were measured whereas the room background was suppressed efficiently.

In the determination of the number of implanted ^{37}Ca atoms, necessary for the absolute normalization of the decay rates, the values resulting from two independent methods, namely i) the number of identified ^{37}Ca atoms corrected for losses due to secondary reactions in the stopping process and ii) the total number of decay events corrected for contributions of implanted contaminants and daughter decays, agreed within 0.7%. Since the energy resolution of the βp-spectrum measured in the implantation detector was very poor due to β-ray summing effects, the βp decay rates were determined by comparing the βp-spectrum from this work with the high resolution data obtained by Garcia *et al.* [4]. 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 whose size corresponded to the measured implantation profile. Additionally, the accurate determination of the γ-decay rates required corrections for cascade-summing in the ^{56}Co source measurements and for losses in the photopeak intensity due to summation between γ-rays and β-rays or 511 keV annilihation radiation [13]. The ^{37}Ca half-life was determined by using the βp-spectrum accumulated in a pulsed beam-mode were the time of protons with an energy above 3 MeV, mainly originating from the transition into the IAS was recorded. A time-dependent dead-time correction was included.

A total number of 2.6×10^6 ^{37}Ca atoms was implanted during the experiment. Figure 1 shows the observed γ-ray spectrum. 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 originate mainly from the β-decay of the implanted contaminant ^{36}K [7], but also from the βp-decay of ^{37}Ca into excited states of ^{36}Ar [4]. Since we observed a log*ft* value of 4.85(2) for the transition into the state at 3239.3 keV indicating an allowed transition, we have unambigously identified this level as the analog of the

$J^\pi = \frac{5}{2}^+$ state at 3171.3 keV in ^{37}Ar [7].

Combining the $\beta\gamma$ and βp intensities measured in this work with the known [7] γ-deexcitation pattern of the 2750.4 keV state, we obtain $\Gamma_\gamma/\Gamma_p = 0.54(3)$ for the level at 2750.4 keV and $\Gamma_\gamma/\Gamma_p = 22(2)$ 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 with proton-emission for excitation energies near the particle threshold [14] ($\mathrm{S_p}(^{37}\mathrm{K}) = 1857.77(09)$ keV [3]). Calculations based on the universal sd-shell interaction [6] (USD) can account for this effect at least qualitatively, namely by describing the $J^\pi = \frac{5}{2}^+$ states at 2750.4 and 3239.3 keV as mixtures of the two original USD states [15]. It is possible to explain this mixing by a small adjustment within the uncertainty of the applied residual interaction [16].

With the known resonance strengths $\omega\gamma$ of the ^{36}Ar(p,γ)^{37}K reaction of 0.208(30) eV [7] and 0.60(15) meV [11] 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). Our value of $\tau = 2.2(2)$ fs for the 2750.4 keV state is consistent with the previously found upper limit $\tau < 3$ fs [7], whereas our partial γ-decay widths Γ_γ are considerably different from the known widths of the particle-bound (i.e. $\Gamma = \Gamma_\gamma$) mirror states in ^{37}Ar [7].

With the ^{37}Ca half-life of $\mathrm{T}_{1/2} = 0.181(1)$ s, two standard-deviations larger than the previously accepted result (see above), the transition strength in the β-decay of ^{37}Ca was determined by using

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

where B(F) is the Fermi strength, $\mathrm{K} = 6127(9)$ s [17], and E_i, t_i and $f(E_i)$ are the β-endpoint energy, the partial half-life and the phase-space factor [18], respectively, of a β-transition to a state i in ^{37}K. For the transition into the IAS at 5050.6 keV [4], we get $\mathrm{B(F)} + \mathrm{B(GT)} = 2.98(7)$ whereas for the transition into the $J^\pi = (\frac{3}{2}, \frac{5}{2})^+$ level at 5016.1 keV [4], i.e. only 34.5 keV below the IAS, we obtain $\mathrm{B(F)} + \mathrm{B(GT)} = 0.123(4)$. It is thus possible that the 5016 keV state contains some Fermi strength. This conclusion takes into account the USD value $\mathrm{B(GT)_{IAS}} = 0.10$ [6] and $\mathrm{B(F)_{total}} = 3$ (see above). The shell-model value for $B(GT)_{IAS}$ is apparently quite accurate, because the USD interaction, which yields general agreement with measured M1 transitions and magnetic moments in sd-shell nuclei, reproduces in particular the measured magnetic moment of the ^{37}Cl ground state within 4% [19]. 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. Hence, we conclude that there is evidence, on a level of 1.7 standard deviations, for an isospin-forbidden Fermi transition in the β-decay of ^{37}Ca. The isospin-mixing matrix element V_{IM} [5] between the IAS and the 5016 keV state amounts to $|V_{IM}| = 6.9^{+0.1}_{-2.5}$ 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 recently presented by Nakamura *et al.* [20]. It is important to note that these calculations reproduce the seven experimentally known isospin-mixing matrix elements in the sd-shell fairly well.

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 and to the two (p,n) data sets. 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 [6]. 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 significantly changed from the previous β-decay values so that they are no longer inconsistent with the low-resolution (p,n) data [8]. In comparison with preliminary results of the new (p,n) data [9, 15], 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 decay rate, 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.

These discrepancies seem to be surprising, since the B(GT) functions of the ^{38}Ca β-decay and the ^{38}Ar(p,n)^{38}K mirror transition were recently shown to agree fairly well [21]. However, one cannot expect exactly the same accuracy for the $A = 37$

case because in the $A = 38$ comparison the final states in ^{38}K are identical. Furthermore, it has been pointed out [22] that the ratio $B(GT)_{pn}/B(GT)_{\beta}$ might be different for spin-flip transitions ($d_{3/2} \to d_{5/2}$) and core-polarisation terms (for example $p_{1/2} \to p_{1/2}$ or $d_{3/2} \to d_{3/2}$). 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.

We used the $B(GT) + B(F)$ values from this work and the calculated ^{8}B neutrino spectrum [23] to determine the neutrino capture cross-section $\sigma(^{37}\mathrm{Cl})$ for solar neutrinos produced in the ^{8}B decay to be $1.09(3) \times 10^{-4}\mathrm{cm}^{-2}$. Our result is consistent with the value $1.06(10) \times 10^{-4}\mathrm{cm}^{-2}$ used in the standard solar model calculations [2, 23]. Thus the origin of the discrepancies between the solar neutrino flux predicted by standard model and the value measured with the ^{37}Cl detector remains still open.

In summary, we have shown in this work that high-precision β-decay data can be gained by using relativistic heavy-ion beams, a magnetic spectrometer and a β-proton-γ detector array. Our results, together with those available from high-resolution βp-decay studies, have allowed us to deduce improved B(GT) and B(F) values, to show evidence for an isospin-forbidden Fermi transition, to reduce the discrepancy between β-decay and (p,n) work, and to redetermine the ^{37}Cl solar-neutrino capture cross-section.

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References

[1] R. Davis *et al.*, Phys. Rev. Lett. 20 (1968) 1205.

[2] J.N. Bahcall, *Neutrino Astrophysics* (Cambridge University Press, Cambridge, 1989) p. 198.

[3] G. Audi and A.H. Wapstra, Nucl. Phys. A565 (1993) 1.

[4] A. Garcia *et al.*, Phys. Rev. Lett. 67 (1992) 3654,
A. Garcia, Ph.D. thesis, University of Washington, 1991.

[5] S. Raman *et al.*, At. Data Nucl. Data Tables 16 (1975) 451.

[6] B.A. Brown and B.H. Wildenthal, At. Data Nucl. Data Tables 33 (1985) 347.

[7] P.M. Endt, Nucl. Phys. A521 (1990) 1.

[8] J. Rapaport *et al.*, Phys. Rev. Lett. 47 (1980) 1518.

[9] D.P. Wells *et al.*, Bull. Am. Phys. Soc. 37(1992) 1296.

[10] E.G. Adelberger *et al.*, Phys. Rev. Lett. 67 (1992) 3658.

[11] C. Iliadis *et al.*, Phys. Rev. C48 (1992) R1479.

[12] H. Geissel *et al.*, Nucl. Instr. Meth. B70 (1992) 286.

[13] W. Trinder, Ph.D. thesis, Universität Frankfurt a.M., in preparation.

[14] C.E. Rolfs and W.S. Rodney, *Cauldrons in the Cosmos* (The University of Chicago Press, Chicago, 1988) p. 169.

[15] M.B. Aufderheide *et al.*, Phys. Rev. C49 (1994) 678.

[16] B.A. Brown, private communication.

[17] D.H. Wilkinson, Nucl. Instr. Meth. A335 (1993) 172, 201.

[18] D.H. Wilkinson and B.E.F. Macefield, Nucl. Phys. A232 (1974) 58.

[19] M.B. Aufderheide *et al.*, Phys. Rev. C46 (1992) 2251.

[20] S. Nakamura *et al.*, Nucl. Phys. A575 (1994) 1.

[21] P. Baumann *et al.*, private communication.

[22] B.A. Brown, Phys. Rev. Lett. 69 (1992) 1034.

[23] J.N. Bahcall and B.R. Holstein, Phys. Rev. C33 (1986) 2121.

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

E/keV	Γ_p/eV	Γ_γ/eV	τ/fs	$\Gamma(^{37}\mathrm{Ar})$/eV [7]
2750.4	0.20(3)	0.11(2)	2.2(2)	0.033(10)
3239.3	$2.1(6)\times10^{-4}$	$4.6(1.2)\times10^{-3}$	140(40)	$8(1)\times10^{-3}$

Table 2: B(GT) values for low excitation energies in ^{37}K. The values of the (p,n)-data [8] have been multiplied by $(g_A/g_V)^2 = (1.26)^2$ because of a different definition of B(GT).

$E_x(^{37}\mathrm{K})$/MeV	β-decay (this work)	β-decay [4]	(p,n) [8]	(p,n)[a] [9, 15]
0.0	0.048(2)[b]	0.0483(14)[c]	0.054(11)	
1.3709	0.0126(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	0.073(2)	0.075(4)		
3.8402	0.093(3)	0.094(5)		
2–4	0.354(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)

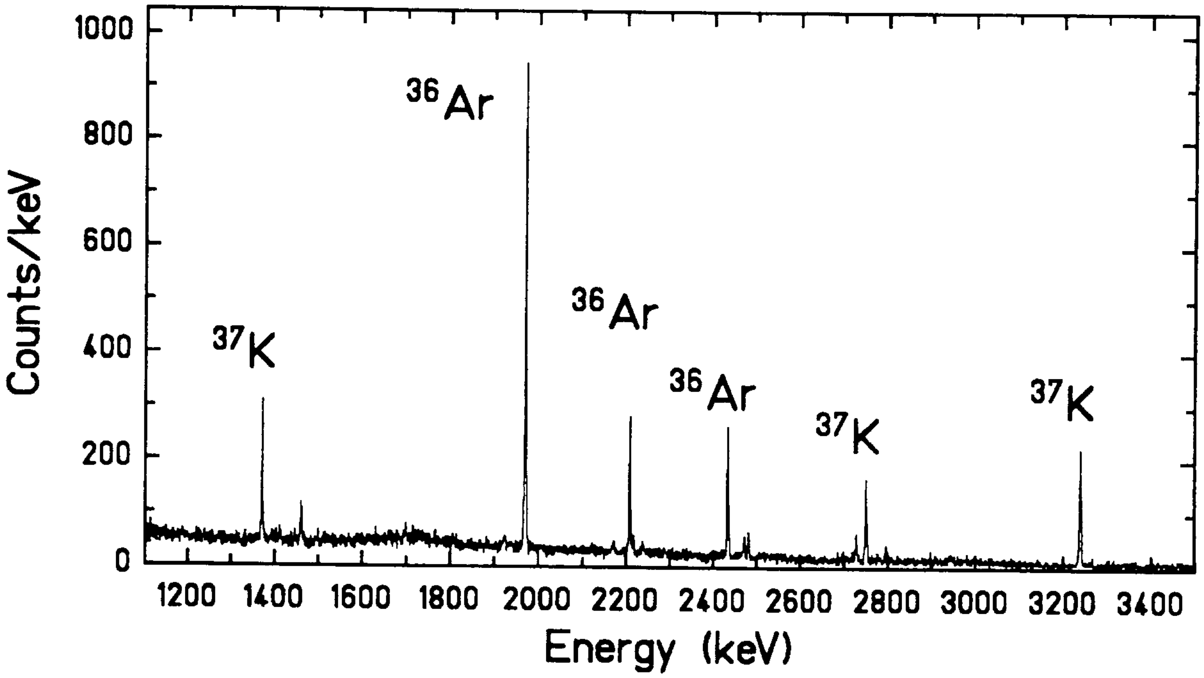

Figure 1: γ-spectrum from the decay of ^{37}Ca, measured in coincidence with β-rays. The assignment for the dominant lines is given by indicating the nuclides in which the transitions occur. The lines of lower intensity are due to weaker transitions in ^{36}Ar or to single or double escape effects.