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Gamow–Teller strength in the β-decay of ^{36}Ca [★]

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Abstract

The β-decay of ^{36}Ca has been studied at the projectile fragment separator at GSI Darmstadt. The measured Gamow–Teller strength function $B(\mathrm{GT})$, deduced from the observed β-delayed proton- and γ-emission and from the measured half-life of 102(2) ms, is compared to results obtained from large-scale sd-shell model calculations. A systematic underestimation of the measured strength by the theory is found.

The Gamow–Teller strength, $B(\mathrm{GT})$, observed in nuclear β decay is generally significantly suppressed compared to shell-model predictions. For example, $(2s1d)^n$ shell-model wavefunctions predict $B(\mathrm{GT})$'s that are in much better agreement with the data if the "free-nucleon" Gamow–Teller operator is scaled by a factor of approximately 0.7 ("effective" operator). This "quenching" is commonly ascribed to two rather different mechanisms: higher-order configuration mixing neglected in the model calculations, and a "renormalization" process involving subnucleonic degrees of freedom [3]. However, to make a decisive test of the quenching mechanism, one needs to find where the "missing strength" is located.

During the last few years improvements in experimental techniques have permitted detailed studies of the β-decays of very proton-rich nuclei [4]. These decays have high energy releases and allow one to investigate Gamow–Teller transitions to a large range of excitation energies in the daughter nucleus. A recent study of the high energy release β-decay of ^{37}Ca [5,6] ($Q_{\mathrm{EC}} = 11639(22)$ keV [7]) revealed that the good agreement between experiment and the quenching theory did not extend to high excitation energies where much more strength was observed than predicted by the quenching theory. In fact, the total $B(\mathrm{GT})$ strength observed in this experiment agreed better with the free-nucleon theory. A similar effect was found in the high energy release β-decay of ^{33}Ar [8].

In this letter we report a detailed study of the β-delayed proton (βp) and γ-ray ($\beta\gamma$) emission of ^{36}Ca ($Q_{\mathrm{EC}} = 10990(40)$ keV [7]). The single previous study of ^{36}Ca decay [9] yielded only the excitation energy of the isobaric analog state (IAS) in ^{36}K,

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4258(24) keV, and a 100 ms estimate for the ^{36}Ca half-life.

The FRS projectile fragment separator at GSI Darmstadt [10] was used to implant a ^{36}Ca secondary beam of about 1 atom/4 s, produced by a 300 MeV/u ^{40}Ca beam impinging on a 1 g/cm^2 ^{9}Be target, into a 30 mm × 30 mm × 500 μm silicon counter (implantation detector). This detector was positioned between two silicon counters of similar dimensions that detected β-rays, while two large-volume germanium detectors mounted nearby registered γ-rays from the implanted activity. The monoenergetic mode of the FRS assured a very narrow ^{36}Ca implantation profile in beam direction (FWHM $\approx$ 100 μm) which was centered around an implantation depth of 250 μm. This shape of the profile assured that up to medium proton energies ($\approx$4 MeV) all protons were fully stopped in the implantation detector, whereas the deposited energy of high-energy protons was sufficient to separate them as lines in the βp-spectrum. Furthermore, the narrow profile enabled us 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 and the room background was suppressed efficiently.

We determined the number of implanted ^{36}Ca atoms $N(^{36}\mathrm{Ca})$, needed for normalizing the decay rates, using two independent methods – i) $N(^{36}\mathrm{Ca})$ was obtained from the number of identified ^{36}Ca atoms corrected for losses due to secondary reactions in the stopping process (= 11(2)% [11]), and ii), since the decay into the ^{36}K ground-state is a second-forbidden transition, $N(^{36}\mathrm{Ca})$ was given by the total number of βp and $\beta\gamma$ decays of ^{36}Ca. The two values for $N(^{36}\mathrm{Ca})$ agreed within the experimental uncertainty. The βp energy calibration was based on α-calibration sources and the known [5] βp energies of a preceding study of the ^{37}Ca decay with the same detection system [6]. Since for ^{36}Ca and ^{37}Ca the β-decay energy releases (see above) and proton separation energies ($S_p(^{36}\mathrm{K})$ = 1666(8) keV, $S_p(^{37}\mathrm{K})$ = 1857.77(09) keV [7]) are similar, the line shifts due to the summation of the β-ray energy loss to each proton signal [11] were almost equal. Furthermore, the *difference* of the line shifts due to pulse-height defects of the recoil atoms (^{35}Ar, ^{36}Ar) in ^{36}Ca and ^{37}Ca decay was negligible [12]. The absolute $\beta\gamma$-decay rates were obtained using a precise calibration of the γ-efficiency obtained with a calibrated ^{56}Co source whose size corresponded to the measured implantation profile. The γ-decay rates were corrected for cascade-summing in the ^{56}Co source measurements and for losses in the photopeak intensity from summing of γ-rays with β-rays or 511 keV annihilation radiation [11]. The ^{36}Ca half-life was determined using βp events accumulated after each 0.2 s beam pulse had ended. During the 2.5 s beam-off period the time distribution of events in the βp-spectrum with an energy above 2.5 MeV was recorded. This part of the βp-spectrum, mainly originating from the transition into the IAS, is free of background arising from β-ray energy loss signals.

A total number of 2.8×10^4 ^{36}Ca atoms was implanted during the experiment. Fig. 1 shows the observed $\beta\gamma$ and βp spectra and the decay time characteristics, whereas the deduced ^{36}Ca decay scheme is shown in Fig. 2 together with the absolute decay branching ratios I_β. We observed two strong $\beta\gamma$ transitions to proton-bound states in ^{36}K at 1112.8(4) and 1619.0(2) keV; six transitions to proton-unbound levels at 3370(29), 4266(21), 4457(33), 4687(37), 5947(47) and 6798(71) keV were identified in the βp spectrum as shown in Table 1. The energies for the 3370(29) keV state and the IAS at 4266(21) keV are weighted means of our values of 3390(41) and 4287(39) keV and the literature data of 3350(40) and 4258(24) keV [14,9]. The ^{36}Ca half-life was measured to be 102(2) ms.

The log ft values (see Table 1), extracted from the decay branching ratios and the half-life along with the phase-space factor f [13], indicate that all the observed Gamow–Teller transitions are allowed and thus require a spin-parity assignment of $J^\pi = 1^+$ for the final states. We identify the ^{36}K states at 1112.8(4) and 1619.0(2) keV as the mirrors of the 1164.9 and 1601.1 keV levels in ^{36}Cl [14], respectively, while clear correspondences cannot be drawn for the 1^+ states at higher excitation energies in ^{36}K. Additionally, we conclude that the first excited state in ^{36}K at 800(15) keV seen in ^{36}Ar(^{3}He,t)^{36}K charge-exchange reactions [14] is the analog of the 788.4 keV level ($J^\pi = 3^+$) in ^{36}Cl [14]. Because the third excited 1^+ state in ^{36}Cl occurs at 2676.4 keV [14] we can exclude a 1^+ assignment for the ^{36}K states at 1670(20) and

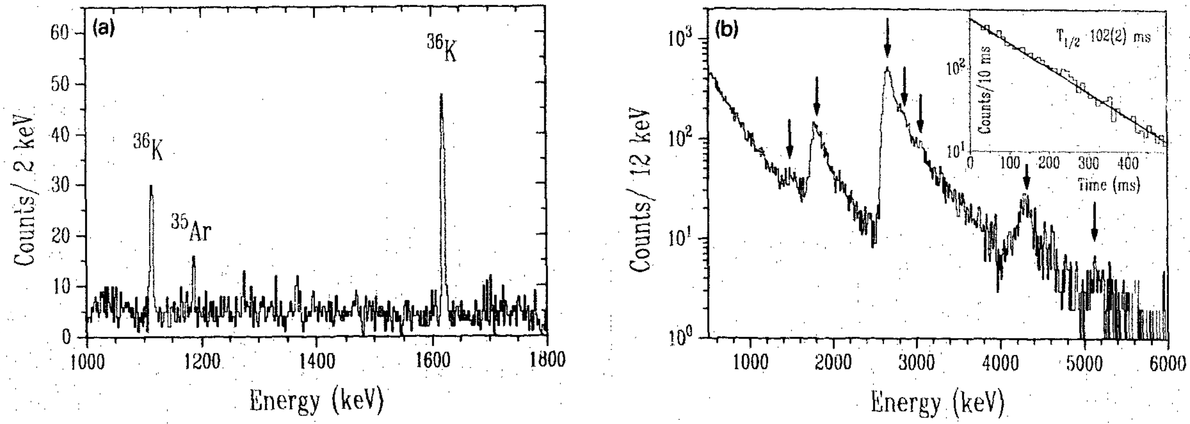

Fig. 1. γ-spectrum in coincidence with β-rays (left-hand side) and proton-spectrum (right-hand side) from the decay of ^{36}Ca. The assignment for the γ lines is given by indicating the nuclides in which the transitions occur. The weak ^{35}Ar line originates from the β-decay of the implanted contaminant ^{35}K and from the proton decay of the IAS in ^{36}K to the first excited state in ^{35}Ar (see text). In the proton-spectrum the arrows indicate the different lines. The time characteristics of the ^{36}Ca decay is inserted in the proton-spectrum.

1890(20) keV [14]. These states lie near the proton-threshhold and thus could be important resonances in the ^{35}Ar(p, γ) reaction in stellar medium [15].

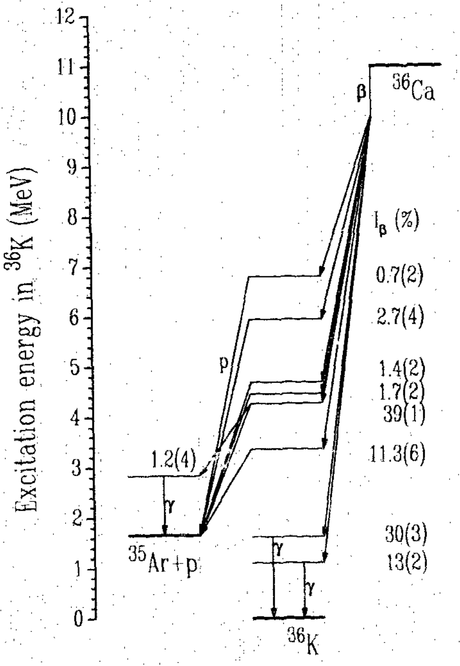

Fig. 2. ^{36}Ca decay scheme, deduced from the observed γ- and proton-spectrum, together with the observed decay branching ratios I_β. For ^{36}K only the ground-state and the states seen in our experiment are depicted.

The ^{36}Ca β-decay transition strength for a transition to level i in ^{36}K was computed using [16]

$$\left(B(\mathrm{F}) + \left(\frac{g_A}{g_V}\right)^2 B(\mathrm{GT})\right)_i = \frac{6127(9)\ s}{ft_i}$$

where $B(\mathrm{F})$ is the Fermi strength and $g_A/g_V = -1.262$. For the transition to the IAS we obtain $B(\mathrm{F}) = 4.0(2)$ which is consistent with the model-independent value $B(\mathrm{F}) = (Z - N) = 4$ [1]. The ^{36}K IAS decays mainly by proton emission to the ^{35}Ar ground state (p_0) and with a weak branch to the first excited state of ^{35}Ar (p_1). From the line intensities in the βp-spectrum a value of $\Gamma_{p_1}/\Gamma_{p_0} = 0.03(1)$ was extracted.

The strengths of the Gamow–Teller transitions are given in Table 1 along with the shell-model calculations based on the universal *sd*-shell interaction (USD) [1] and the effective Gamow–Teller operator. We see very good agreement for the transitions to the first, second, and fourth excited state in ^{36}K. The retarded transition predicted by the theory to a state at 2381 keV ($\approx$ 0.7% branch) could not be confirmed because the large β-ray energy loss background in this energy region prevented us from observing a very weak βp line at $E_p \approx 700$ keV. The integrated $B(\mathrm{GT})$ strength in ^{36}Ca (see Fig. 3) reveals a behavior similar to that seen in ^{37}Ca decay. At low excitation energies the integrated experimental strength agrees well with the predictions of the quenching theory,

Table 1
Excitation energy, log ft and $B(\mathrm{GT})$ values for ^{36}Ca β-decay measured in this work (exp) and calculated using the USD interaction and the effective GT operator (th). The E_{exp}/keV data were deduced from measured γ or proton energies (see text). The theoretical values are shown only up to excitation energies of 8 MeV in ^{36}K; phase-space limitations prevented us from seeing the weak transitions at higher energies predicted by the USD calculations.

E_{exp}/keV	$\log ft_{\mathrm{exp}}$	$B(\mathrm{GT})_{\mathrm{exp}}$	E_{th}/keV	$B(\mathrm{GT})_{\mathrm{th}}$
1112.8(4)	4.56(6)	0.11(2)	1120	0.149
1619.0(2)	4.08(5)	0.32(4)	1453	0.260
			2381	0.012
3370(29)	4.02(3)	0.36(2)	3531	0.437
4266(21)	3.18(2)		4242	
4457(33)	4.49(5)	0.13(2)	5540	0.005
4687(37)	4.47(5)	0.13(2)	5984	0.390
5947(47)	3.65(8)	0.9(2)	6783	0.032
6798(71)	3.8(1)	0.6(2)	6939	0.037
			7899	0.238

which, on the other side, predicts too little strength at higher energies where the *total* observed $B(\mathrm{GT})$ strength is better described using the free-nucleon GT operator. Note, however, that the total strength seen in our experiment, $B(\mathrm{GT})_{\mathrm{exp}} = 2.6(3)$, is only 22% of the sum-rule value $3(Z-N) = 12$ [18].

The failure of the theory to account for the GT strengths in ^{36}Ca and ^{37}Ca decay could arise from deficiencies in the $(2s1d)$ shell-model interaction and its associated effective GT operators, and/or from neglect of higher-order configurations in the model space. It has been shown that the Chung–Wildenthal Hamiltonian (CWH) [19] yields better agreement with experiment for ^{37}Ca and ^{38}Ca decays than the USD interaction [18,20]. However, the CWH interaction fails to reproduce our ^{36}Ca $B(\mathrm{GT})$ data in a state-by-state comparison for transitions to low-lying levels and in particular predicts much more strength near 6.5 MeV than seen in the experiment.

The *number* of ^{37}K states fed in ^{37}Ca decay, which greatly exceeds those predicted by the $(2s1d)^n$ model, reveals the contribution of $1f2p$ intruder configurations at high excitation energies. However, this $1f2p$ contribution affects the integrated GT *strength* only in second order. The limited energy resolution of this experiment prevents us from making a similar statement about the number of levels fed in ^{36}Ca decay. Accordingly, there is at present no compelling explanation for the patterns of GT strength observed in the high energy release β decays of the light Ar and Ca isotopes.

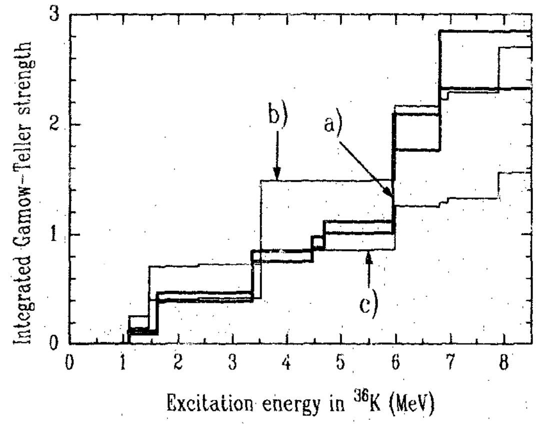

Fig. 3. Comparison of the measured summed $B(\mathrm{GT})$ strength [labelled a)] with the results of USD calculations obtained by using the free-nucleon [$g_A/g_V = -1.262$, labelled b)] and effective [$g_A/g_V = -0.95$, labelled c)] GT operators. For the experimental result the $\pm 1\sigma$ uncertainty band is displayed.

In summary, we have measured a complete $B(\mathrm{GT})$ distribution of ^{36}Ca which is the heaviest $T_z = -2$ nucleus where such information is available. The term "complete" refers to the fact that both β-delayed protons and γ-rays were observed, that the normalization of the branching ratios was achieved by counting decays and decaying atoms, that high precision has been obtained for the half-life, and that a reasonably sensitive upper limit has been placed on unobserved $B(\mathrm{GT})$ strength up to 6.8 MeV. The results of this work, together with those previously obtained for the decays of ^{37}Ca and the light argon isotopes [8], show conclusively that current shell-model calculations do not reproduce $B(\mathrm{GT})$ strength over a wide range of excitation energies.

It is worth noting that the $B(\mathrm{GT})$ distributions measured in the β-decays of neutron-deficient calcium isotopes can be compared to the strength functions extracted from (p, n) [21] or (^{3}He, t) [22] charge-exchange reactions on the stable $N = 20$ mirror nuclei. Under the assumption of isospin symmetry, the corresponding $B(\mathrm{GT})$ functions should be identical, allowing one to test the accuracy of $B(\mathrm{GT})$ values inferred from charge-exchange data. Recent studies have shown good agreement for $A = 38$ [20], but not for $A = 37$ [17]. In order to shed more light on this intriguing problem, and to clarify the discrepancies between experiment and shell-model predictions discussed in this letter, it will be useful to compare the ^{36}Ca β-decay results from this work to those from future $^{36}S(p,n)^{36}$Cl or ^{36}S(^{3}He, t)^{36}Cl experiments. Furthermore, ^{36}S(n,p) or ^{36}S(t,^{3}He) data could provide information on the importance of higher-order shell model configurations because the GT strength in these reactions vanishes in the $(2s1d)^n$ approximation. In addition it would be very interesting to have high-resolution, high-sensitivity delayed proton data on ^{36}Ca decay which would probably uncover still more GT strength at high excitation energies.

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