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

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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 Gamow-Teller strength function B(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.

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The Gamow-Teller strength, B(GT), observed in nuclear β decay is generally significantly suppressed compared to shell-model predictions. For example, $(2s1d)^n$ shell-model wavefunctions predict B(GT)'s that are in much better agreement with the data if the "free-nucleon" GT operators are scaled by a factor of approximately 0.7. 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_{EC} = 11639(22) keV [7]) revealed that the good agreement between experiment and the quenched theory did not extend to high excitaton energies where much more strength was observed than predicted by the quenched theory. In fact, the total B(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_{EC} = 10990(40) keV [7]). The single previous study of ^{36}Ca decay [9] yielded only the the excitation energy of the isobaric analog state (IAS) in ^{36}K, 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/4s, produced by a 300 MeV/u ^{40}Ca beam impinging on a 1g/cm^2 ^{9}Be target, into a 30 mm × 30 mm × 0.5 mm 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 ≈ 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 and the room background was suppressed efficiently.

We determined the number of implanted ^{36}Ca atoms, needed for normalizing the decay rates, from two independent sources from the number of identified ^{36}Ca atoms corrected for losses due to secondary reactions in the stopping process [11], and from the total number of βp and $\beta\gamma$ decays of ^{36}Ca (note that it was not necessary to account for the decay into the ^{36}K ground-state because it is a second-forbidden transition). These agreed within the experimental uncertainty. The βp energy calibration was based on α-calibration sources and the known [5] βp energies of a preceeding 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 ($S_p(^{36}K) = 1666(8)$ keV, $S_p(^{37}K) = 1857.77(09)$ keV [7]) are similar, the line shifts due to positron summing effects [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 $\beta\gamma$-decay rates were normalized 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 lifetime 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 proton events with energies above 2.5 MeV, mainly originating from the transition into the IAS, was recorded (see Figure 1). The resulting half-life was 102(2) ms.

A total number of 2.8×10^4 ^{36}Ca atoms was implanted during the experiment. Figure 2 shows the observed $\beta\gamma$ and βp spectra. 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 log*ft* values (see Table 1), extracted from our decay branching ratios and ^{36}Ca half-life along with the phase-space factor f [13], indicate that all the observed transitons are allowed and require spin-parity assignments of $J^\pi = 1^+$ for all the states except the IAS. 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; 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 1890(20) keV [14] that could be important resonances in the ^{35}Ar(p, γ) reaction in stellar medium [15] as they lie near the proton-threshhold.

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

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

where B(F) is the Fermi strength and $g_A/g_V = -1.262$. For the transition to the IAS we obtain B(F) = 4.0(2) which is consistent with the model-independent value B(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 ($\Gamma_{\mathrm{p}_1}/\Gamma_{\mathrm{p}_0} = 0.03(1)$) to the first excited state of ^{35}Ar (p$_1$). 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]. We see very good agreement for the transitions to the first, second, and fourth excited state in ^{36}K. The retarded transition predicted to the 2381 keV state ($\approx 0.7\%$ 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(GT) strength in ^{36}Ca (see Figure 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 quenched theory, but the theory predicts too little strength at higher energies so that the *total* observed B(GT) strength is better described using the free-nucleon GT operators.

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(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. Although the *number* of ^{37}K states fed in ^{37}Ca decay, which greatly exceeds those predicted by the $(2s1d)^n$ model, shows that $1f2p$ intruder configurations play a role, these affect 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.) So, at present, there is no compelling explanation for the patterns of GT strength observed in the high energy-release β decays of the light Ar and Ca isotopes.

In summary, we have measured a complete B(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(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(GT) strength over a wide range of excitation energies.

It is worth noting that the B(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(GT) functions should be identical, allowing one to test the accuracy of B(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 $^{36}\mathrm{S}(\mathrm{p,n})^{36}\mathrm{Cl}$ or $^{36}\mathrm{S}(^3\mathrm{He,t})^{36}\mathrm{Cl}$ 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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Table 1: Excitation energy, branching ratio br, log*ft* and B(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	br_{exp}/%	$\log ft_{exp}$	$B(GT)_{exp}$	E_{th}/keV	$B(GT)_{th}$
1112.8(4)	13(2)	4.56(6)	0.11(2)	1120	0.149
1619.0(2)	30(3)	4.08(5)	0.32(4)	1453	0.260
				2381	0.012
3370(29)	11.3(6)	4.02(3)	0.36(2)	3531	0.437
4266(21)	39(1)	3.18(2)		4242	
4457(33)	1.7(2)	4.49(5)	0.13(2)	5540	0.005
4687(37)	1.4(2)	4.47(5)	0.13(2)	5984	0.390
5947(47)	2.7(4)	3.65(8)	0.9(2)	6783	0.032
6798(71)	0.7(2)	3.8(1)	0.6(2)	6939	0.037
				7899	0.238

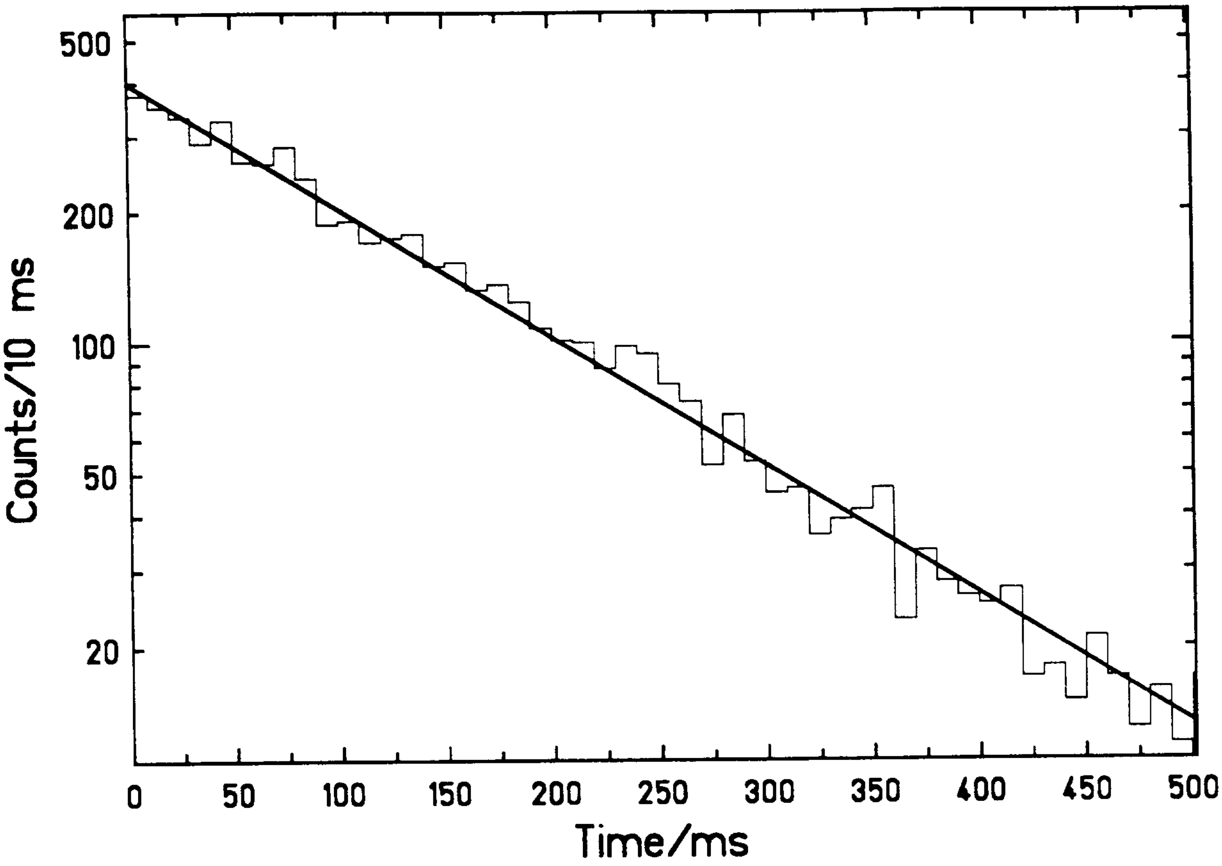

Figure 1: Decay spectrum of β-delayed protons with energies above 2.5 MeV. The solid line shows the best fit half-life of 102(2) ms.

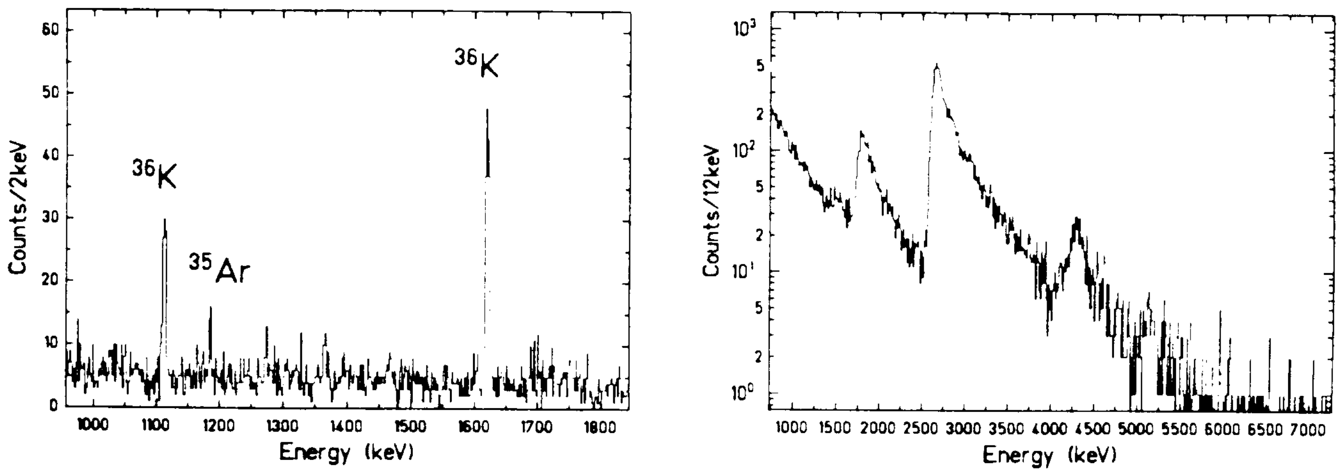

Figure 2: γ-spectrum in coincidence with β-rays (left side) and proton-spectrum (right side) from the decay of ^{36}Ca. The assignment for the γ lines is given by indicating the nuclides in which the transitions occur. The weak ^{35}Ar line originates from the β-decay of the implanted contaminant ^{35}K and from the proton decay of the IAS in ^{36}K to the first excited state in ^{35}Ar (see text).

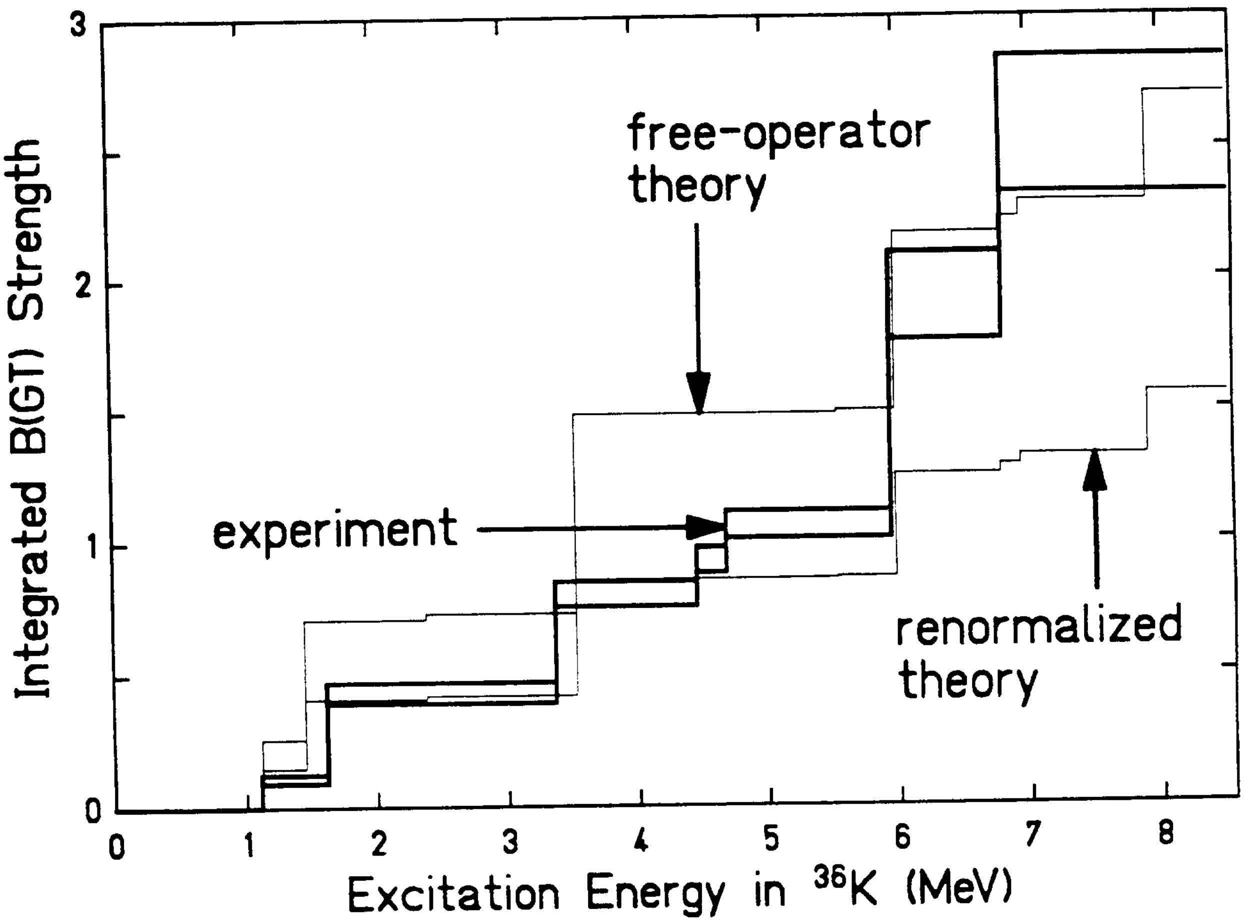

Figure 3: Comparison of the measured summed B(GT) strength with the results of USD calculations obtained by using the free-nucleon ($g_A/g_V = -1.262$) and effective ($g_A/g_V = -0.95$) GT operators. For the experimental result the $\pm 1\sigma$ uncertainty band is displayed.