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Abstract: The β-decay of the $T_z = -\frac{5}{2}$ nucleus ^{35}Ca was studied at the LISE3 spectrometer at GANIL. The ^{35}Ca decay scheme was deduced from its β-delayed proton emission into the ground and excited states of ^{34}Ar and from its β-delayed two-proton emission. The ^{35}Ca half-life was determined to be 25.7±0.2 ms. The measured transition strength function B(GT) is compared to results obtained from large-scale *sd*-shell model calculations.

PACS: 23.40.–s, 29.30.Ep, 29.30.Kv, 29.40.Wk, 21.60.Cs

Keywords: RADIOACTIVITY ^{35}Ca from ^{nat}Ni(^{40}Ca,X), E = 95 A×MeV; Measured E_p, I_p, $\beta p\gamma$; $T_{1/2}$; Si, Ge and NaI detectors; *sd*-shell model

The study of Gamow-Teller transition strength functions B(GT) in nuclear β-decays provides an excellent tool for testing nuclear model calculations because the corresponding operator is known and quite simple. Hence, differences found between experiment and theory allow one to deduce improvements in the applied model wave functions. During the last years, new developments in experimental techniques have permitted detailed studies of β-decays of very proton-rich nuclei [1]. These decays are characterized by high energy-releases and allow one to investigate Gamow-Teller transitions to a large range of excitation energies in the daughter nucleus. Recent studies of the high energy-release β-decays of ^{37}Ca [2, 3, 4, 5] ($Q_{EC} = 11638(22)$ keV [6]) and ^{36}Ca [7, 5] ($Q_{EC} = 10985(41)$ keV [6]) revealed that the good agreement between experiment and the shell-model calculations [8, 9] did not extend to high excitation energies where much more strength was observed than calculated. A similar deviation was found in the high energy-release β-decay of ^{33}Ar [10]. It was stressed, however, that (the size of) this effect seems to depend strongly on the interaction applied in the theory [11, 5].

This letter reports a detailed study of the β-decay of ^{35}Ca whose very high decay-energy window ($Q_{EC} = 15607(73)$ keV [6]) allows one to extend the knowledge of the B(GT) strength in regions of high excitation energies. In addition, the β-decay of ^{35}Ca can be compared to the decay of its mirror nucleus ^{35}P. The single previous study of the ^{35}Ca decay [12] was devoted only to β-delayed two-proton ($\beta 2p$) decay branches. In this study the excitation energy of the isobaric analog state (IAS) in ^{35}K was deduced to be 9053(45) keV and the ^{35}Ca half-life was estimated to 50(30) ms.

The experiment was performed at the SISSI-Alpha and LISE3 spectrometers at GANIL [13]-[15]. A ^{35}Ca secondary beam was produced by fragmentation reactions of a 95 A×MeV ^{40}Ca^{20+} beam at an average intensity of about 400 enA impinging on a rotating 500 μm ^{nat}Ni target. The secondary beam purity was enhanced by a 550 μm ^{9}Be wedge shape degrader at the intermediate focal point and by using the Wien velocity filter at the exit of the LISE3 spectrometer. The 98%

pure secondary ^{35}Ca beam ($\approx$ 0.3 pps) was implanted into a 500 μm thick silicon implantation detector; the main contaminant stopped in this detector was ^{33}Ar ($\approx$ 5$\times$10^{-3} pps). The implantation detector was positioned between two silicon counters of the same thickness for detecting β-rays (β-detectors). Two additional silicon counters, one of which being 500 μm thick and the other 150 μm thick and position sensitive, were mounted upstream. These detectors provided the energy-loss (ΔE) and time-of-flight signals for identifying the isotopes transmitted to the final focus of the LISE3 spectrometer. Three large-volume (70%) germanium and two NaI detectors for registering γ-rays were mounted close to the implantation detector.

A total statistics of 6$\times$10^4 ^{35}Ca atoms was collected in two different implantation modes. In the first setting (3.5$\times$10^4 atoms), the ^{35}Ca implantation profile (FWHM $\approx$ 70 μm) was positioned at a depth of about 300 μm. In a second setting (2.5$\times$10^4 atoms), the profile was shifted to 450 μm, thus nearer to the downstream β-counter, by removing the 150 μm ΔE detector. In the following, these two implantation modes are referred to as setting 1 and 2, respectively. βp-events arising from the decay of ^{33}Ar and β-events from daughter decays were suppressed in the spectrum of ^{35}Ca by: *(i)* selecting only those ^{35}Ca atoms for the analysis that were separated in time by more than five ^{33}Ar half-lives from the implantation of the preceeding ^{33}Ar atom and whose decay events occurred *before* the arrival of the next ^{33}Ar atom, and *(ii)* restricting the decay analysis window for the analysis of the βp-spectra to 100 ms, which is about four ^{35}Ca half-lives.

The βp-energy scale was calibrated by implanting the well-known βp-emitter ^{37}Ca [2] under similar conditions in an additional LISE3 setting. Corrections were made for slightly different implantation depths of ^{35}Ca and ^{37}Ca atoms ($\Delta \approx$ 10 μm) and for the non-linear recoil effect [16]. For the known 2p-decay of the IAS in ^{35}K [12], a small ($\approx$ 7 keV) difference in the recoil effect between the 1p and 2p decay modes was taken into account in determining the corresponding value for the excitation energy. The full-energy detection efficiency for high-energy βp-events and the part of each peak area arising from energy-loss events of higher-energy protons were obtained from a Monte Carlo simulation based on the measured range profiles of the two implantation modes. Positron and 511 keV summation effects were included in the γ-efficiency calibration as described in [17]. The number of identified and implanted ^{35}Ca atoms was corrected for losses due to secondary reactions in the stopping process [18, 17]. Absolute β-decay branching ratios were determined directly by dividing the number of observed decay events for a given transition by the number of decaying ^{35}Ca atoms.

Figure 1a shows the raw βp-spectrum of setting 1 while Figures 1b and 1c show the βp-spectra of setting 1 and 2, respectively, under the condition of a small energy-loss of the coincident β-rays in the downstream β-detector ($\Delta E_\beta \leq 300$ keV). The resolution in the raw spectrum is poor because a continuously distributed β-energy loss is added to each proton signal. Spectra 1b and 1c have much better resolution because their condition selects βp-events where the β-ray leaves little energy in the implantation detector (for more details about this technique see [19, 17]).

Nineteen βp-transitions, listed in Table 1, were extracted from the spectra shown in Figure 1. Several of these transitions could be identified only in the β-coincident spectra 1b and 1c. The "lines" 2, 4, 16 and 18 represent unresolved regions in the βp-spectrum. The number of lines was determined from the conservative point of view that only those structures were assigned as single transitions that showed consistency between the two β-coincident spectra 1b and 1c. The signals of the germanium and NaI detectors were used to identify proton decays of ^{35}K states into the excited ^{34}Ar states at 2090.9, 3287.5, and 3871.0 keV [20, 21], referred to as p_1, p_2, and p_3 decays, respectively (4th column of Table 1, the proton decay to the ^{34}Ar ground state being denoted as p_0). The βp-lines 3, 7 and 17 could be clearly identified as p_1 decays. The 2090.9 keV γ rate coincident with the unresolved region 2 is consistent with a 100% $p\gamma$ decay mode of this part of the βp-spectrum. This is not surprising, because assuming a p_0 contribution in region 2 would require the existence of additional $J^\pi = (\frac{1}{2}, \frac{3}{2})^+$ states at low excitation energies in ^{35}K (a $J^\pi = \frac{1}{2}^+$ assignment for the ^{35}Ca ground state was adopted from the ground state spin of the mirror nucleus ^{35}P). However, the well-known region at low excitation energies in ^{35}S shows only one $J^\pi = \frac{1}{2}^+$ state (and no $\frac{3}{2}^+$ state below 2.9 MeV) [20], corresponding to the ^{35}K mirror state de-excited by the 1427 keV proton decay. In addition, from the 1196.6 and 1780.1 keV γ rates it can be deduced that 12.1(4.9)% and 23.9(7.9)% of the unresolved group 2 represent p_2 and p_3 decays, respectively, leaving 64.0(9.3)% for pure p_1 decays. The 2090.9 keV γ rate coincident with the unresolved region 4 in the βp-spectrum is consistent with a 100% $p\gamma$ decay. The group 4 was fully assigned to p_1 decays, since no significant p_2 or p_3 contributions could be identified. Furthermore, the lines 3 and 10 were identified as the p_1 and p_0 decay of a ^{35}K state at 4976(24) keV.

In addition to the known [12] $2p_0$ decay of the IAS in ^{35}K into the ^{33}Cl ground state (line 8), two additional decay modes, the p_0 (line 17) and p_1 (line 19) decays to ^{34}Ar were identified in the present work. From the corresponding values for the excitation energy, 9181(32) keV ($2p_0$), 9139(91) keV (p_0) and 9152(30) keV (p_1), a weighted mean of 9163(26) keV was deduced, which is 2.4σ larger than the previous value 9053(45) keV. Contrary to the work [12] no sign for the $2p$ decay of the ^{35}K IAS into the first excited state of ^{33}Cl ($2p_1$) was found. The line 5, which is closest in energy to support this assumption, is still 90 keV (2.4σ) too high in energy. Furthermore, no signature for a coincident 810.52 keV ^{33}Cl γ-deexcitation [20] was found for the line 5 while, using the measured γ-ray efficiency curve, 31(4) counts would be expected for a $2p_1$ decay in the spectrum of the germanium detectors. The measured $2p/1p$ ratio 0.98(9) for the decay of the IAS agrees well with the theoretical estimate 1 [22].

No pure β-delayed γ decays ($\beta\gamma$) of ^{35}Ca could be identified in the spectra of the germanium and NaI detectors. From the total of all βp-decays, 100.5±1.4% (Table 1), an upper limit of 0.9% (1σ) for the *sum* of all $\beta\gamma$-decay branchings and the β-decay to the ^{35}K ground state could be deduced.

The ^{35}Ca half-life was extracted from the time differences between the implanted atoms and their subsequent decay events. A background of β-rays or fast charged particles penetrating all three detectors was excluded by a two-dimensional condition on βp-energy versus the β-detector signals. Corrections were made for a small background in the time spectrum arising from ^{35}Ca or ^{33}Ar βp-decay events where the arrival of the corresponding atom was missed for dead-time reasons, and for events where the arrival of a second atom closed the correlation gate *before* the first atom had decayed. The resulting value for the ^{35}Ca half-life 25.7±0.2 ms, is in agreement with the previous, estimated value 50±30 ms [12]. From a part of the experimental data with a significantly higher ^{33}Ar contamination (6×10^{-2} pps, total ^{33}Ar statistics 1.8×10^{3}), a half-life of 171±15 ms was extracted for the ^{33}Ar β-decay which agrees well with the more precise literature value 173±2 ms [10].

The ^{35}Ca decay information is summarized in Table 2. The experimental β-decay transition strength in column 3 for a transition to level i in ^{35}K was calculated using [23, 24]

$$\left[\mathrm{B(F)} + \mathrm{B(GT)}\right]_i = \frac{6127(9)\,\mathrm{s}}{ft_i}$$

where B(F) is the Fermi strength. The B(GT) for the transition into the first excited state at 1547 keV in ^{35}K, 0.387(15), can be compared with the mirror β-decay of ^{35}P ($\mathrm{B(GT)} = 0.462(7)$ [25]), resulting in $\delta = ft^{+}/ft^{-} - 1 = 0.19(5)$, which is within the range of known isospin symmetries [26].

Figure 2 compares the integrated experimental B(GT) strength with shell-model values. The model calculations were performed with the OXBASH code [27] including all single-particle states of the *sd*-shell without any restriction on their occupancies and using Wildenthal's highly successful USD interaction [28]. The calculations were performed in the isospin formalism and also in the proton-neutron formalism. In the latter approach an isospin-nonconserving (INC) part was added to the Hamiltonian [29] for calculating isospin-forbidden proton emission, which is especially important for the decay of the isobaric analog state in ^{35}K. The known low-lying energy spectrum of ^{35}K was well produced in the calculation. The transition strength

B(GT) was calculated as described in [30]. The INC interaction gave Gamow-Teller strengths that follow closely the results obtained with the bare USD interaction. For example, the GT strength to the IAS reduces by only 3%. The calculated B(GT) value for the IAS is 0.312 with the USD interaction. Taking into account Gamow-Teller "quenching" factor 0.78 established below we get $\mathrm{B(GT)}_{\mathrm{IAS}} = 0.24$. Thus the experimental result 4.3(4) implies that B(F) = 4.1(4), which, in comparison with the model-independent value B(F) = (Z − N) = 5 [9], suggests exceptionally strong isospin mixing ($a^2 \approx 18\%$ [30]). This value is not supported by the shell-model calculation using the above mentioned INC interaction, which resulted in the isospin impurity of only about 0.5%. The missing Fermi strength 5-4.1(4) = 0.9(4), corresponding to a missing decay intensity of 1.5(6)%, could be explained by the fact that the experiment was not sensitive enough to the observation of high-energy γ transitions from the IAS. The shell-model calculation gives a total γ-decay branching of the IAS of the order of 5% ($\approx$ 0.4% in total decay intensity) with a dominant M1 transition to the first excited $J^{\pi} = \frac{1}{2}^{+}$ state in ^{35}K (subsequent emission of a 1427 keV proton) and could explain most of the missing Fermi strength.

The overall Gamow-Teller strength was measured up to about 8 MeV excitation. Within this energy window the ratio of the experimental to theoretical strength was 0.78(4) indicating a weaker quenching than average in the *sd*-shell. The β-decay half-life, also a measure of the total strength, was calculated to be 15.8 ms when using the calculated Q_{EC}-value of 15.353 MeV. This, when taking into account the above mentioned quenching factor of the *sd*-shell, results in a half-life of about 28 ms, which is in good agreement with the experiment.

In summary, this work represents the first detailed study devoted to the β-decay of the $\mathrm{T}_z = -\frac{5}{2}$ nucleus ^{35}Ca including *i)* the identification of its β-delayed proton emission into the ground and excited states of ^{34}Ar, *ii)* the normalization of the decay branching ratios by counting decays and decaying atoms, *iii)* a precise measurement of the β-decay half-life, and *iv)* the mapping of the B(GT) function up to $\mathrm{E}_x \approx 8$ MeV. In comparison with previous data, significant differences concerning the excitation energy and the decay pattern of the IAS in ^{35}K were found. In order to solve the problem of the missing Fermi strength and to measure the B(GT) function in regions of higher ^{35}K excitation energies, additional data with higher statistics and higher γ-ray detection efficiency is needed. Furthermore, details on the nature of the $2p$ decay of the ^{35}K IAS (sequential decay or ^{2}He emission) as well as a higher resolution in the βp-spectrum can be obtained by using a more advanced high-granularity detection system such as the one used in a recent experiment on the multi-proton decay of ^{31}Ar [31].

This work was supported by the *Training and Mobility of Researchers* programme of the Commission of the European Communities, under Contract N° ERBFMBICT950394.

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Table 1: Absolute ^{35}Ca βp-intensities x_i. For the decay modes see text.

Line	E_p (keV)	x_i(%)	decay mode
1	1427(5)	48.5(1.3)	p_0
(2)	1909-2647 1)	8.4(6)	p_1,p_2,p_3
3	2727(13)	6.0(5)	p_1
(4)	2947-3500 1)	2.2(3)	p_1
5	3592(25)	3.0(3)	p_0
6	3822(36)	3.8(3)	p_0
7	4041(71)	2.9(3)	p_1
8	4305(26) 2)	4.2(3)	$2p_0$
9	4570(48)	2.9(3)	p_0
10	4754(38)	4.2(4)	p_0
11	5018(71)	3.9(3)	p_0
12	5294(48)	0.72(18)	p_0
13	5466(48)	0.61(15)	p_0
14	5616(37)	1.43(17)	p_0
15	5834(60)	1.40(19)	p_0
(16)	5983-6649 1)	1.09(17)	p_0
17	6783(22)	3.8(2)	p_1
(18)	7131-7887 1)	1.1(2)	p_0
19	8802(89)	0.41(6)	p_0
total		100.5(1.4)	

1) Not resolved into indvidual transitions.

2) *Summed* two-proton energy.

Table 2: Absolute ^{35}Ca decay branchings x_i and transition strengths.

E_x (keV)	x_i(%)	B(F)+B(GT)	decay mode
1547(21)	48.5(1.3)	0.388(15)	p_0
3776(38)	3.0(3)	0.060(6)	p_0
4013(41)	3.8(3)	0.084(8)	p_0
4514(381)1)	5.4(9)	0.15(4)	p_1
4782(52)	2.9(3)	0.092(9)	p_0
4976(24)	10.2(7)	0.35(3)	p_0,p_1
5244(74)	3.9(3)	0.155(16)	p_0
5487(285)1)	2.2(3)	0.10(2)	p_1
5528(52)	0.72(18)	0.033(8)	p_0
5705(52)	0.61(15)	0.031(8)	p_0
5711(381)1)	1.0(4)	0.05(2)	p_2
5859(42)	1.43(17)	0.078(10)	p_0
6084(63)	1.40(19)	0.086(13)	p_0
6294(381)1)	2.0(7)	0.14(6)	p_3
6329(74)	2.9(3)	0.20(2)	p_1
6529(292)1)	1.09(17)	0.09(2)	p_0
7808(390)1)	1.1(2)	0.21(7)	p_0
9163(26)	8.4(4)	4.3(4)	p_0,p_1,2p_0
total		2.29(11)2)	

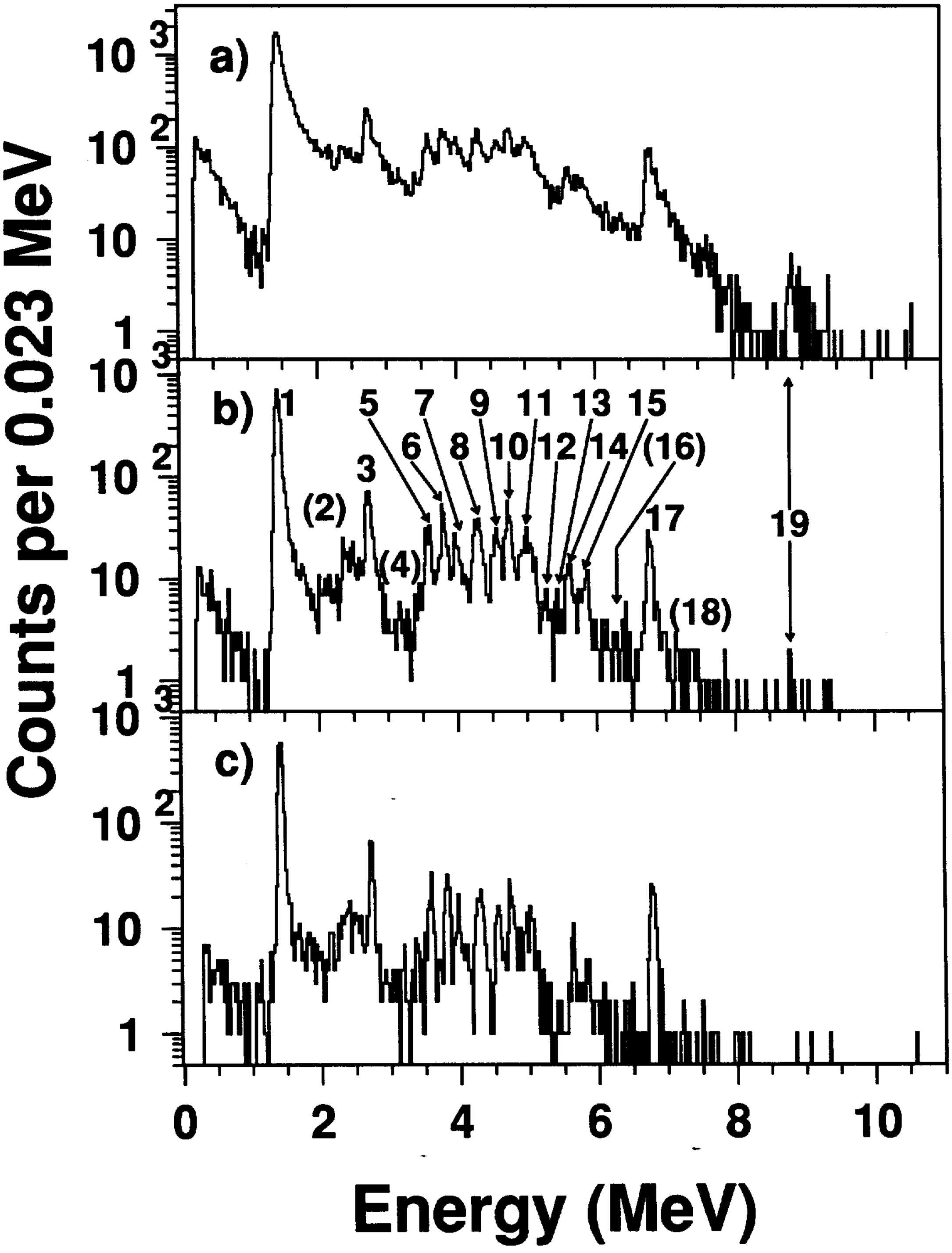
1) Not resolved into indvidual states.

2) Summed B(GT) strength for $E_x \leq 8$ MeV.

Figure 1: Delayed proton spectra from the ^{35}Ca β-decay: Raw spectrum of setting 1 (a), β-coincident spectra of setting 1 (b) and setting 2 (c) (see text).

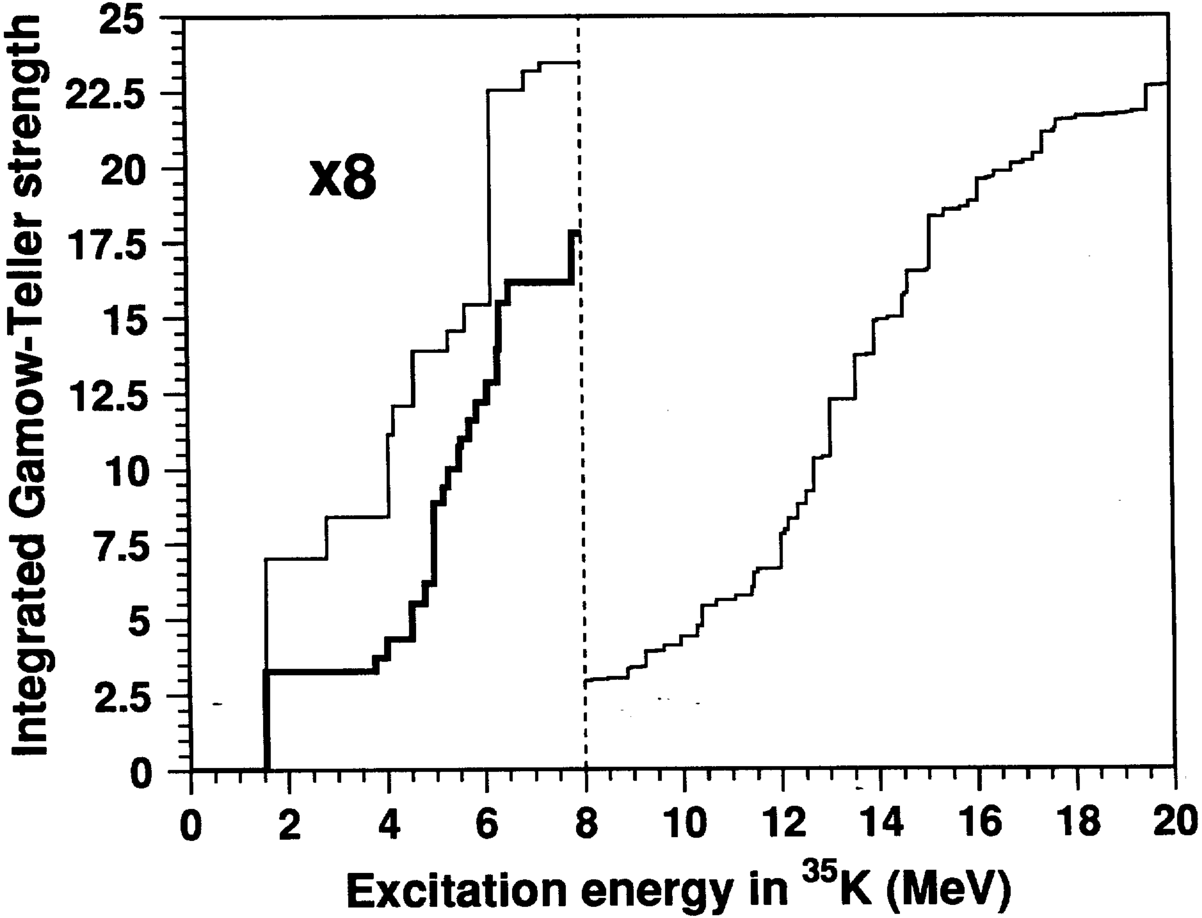
Figure 2: Comparison of the measured summed B(GT) strength in the ^{35}Ca β-decay with theoretical data. The integrated B(GT) strength is shown as a function of the excitation energy in ^{35}K for the experimental data (thick line) and for the *sd*-shell model calculations using the USD interaction (thin line). Below $E_x \leq 8$ MeV the B(GT) values are scaled by a factor of 8.

Figure 1



a)
b)
c)
1
(2)
3
(4)
5
6
7
8
9
10
11
12
13
14
15
(16)
17
(18)
19
10^3
10^2
10
1
0
2
4
6
8
10
Counts per 0.023 MeV
Energy (MeV)

Figure 2


Integrated Gamow-Teller strength
25
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
x8
0
2
4
6
8
10
12
14
16
18
20
Excitation energy in 35K (MeV)