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Short note

New transitions in the β-decay of ^{36}Ca

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Abstract. The β-decay of the $T_z = -2$ nucleus ^{36}Ca was studied at the LISE3 magnetic spectrometer at GANIL. Two new proton-emitting states have been detected and the other nine known βp and $\beta\gamma$ transitions have been remeasured with improved resolution. A simulation with the GEANT code has been applied to this experimental setup. A comparison with shell model calculations is given.

PACS. 27.30.+t 20< A <38 – 21.10.Pc Single-particle levels and strength functions – 23.50.+z Decay by proton emission – 25.70.Mn Projectile and target fragmentation

During the past few years, improvements in experimental techniques have enabled the study of β-decay properties of very proton-rich nuclei [1]. Characterized by high energy release, these decays allow one to extract the Gamow-Teller (GT) strength for transitions to a large range of excitations energies in the daughter nucleus and thus to test the quality of model calculations.

Previous studies of high energy release β-decays of ^{37}Ca [2–5] ($Q_{\mathrm{EC}} = 11638(22)$ keV [6]) and ^{36}Ca [5,7] (Q_{EC} = 10985(40) keV [6]) revealed that the good agreement between experiment and shell-model calculations [8,9] did not extend to high excitation energies where much more strength was observed than calculated. It was stressed, however, that the size of this effect seems to depend strongly on the interaction applied in the theory [5,10].

This note reports on a new detailed study of the β-decay of ^{36}Ca produced at the GANIL facility. The experiment was performed using the SISSI-ALPHA and LISE3 spectrometers [11–13]. A ^{36}Ca secondary beam was produced by fragmentation reactions of a 95 AMeV ^{40}Ca^{20+} beam at an average intensity of ∼400 enA impinging on a rotating 560 μm thick $^{\mathrm{nat}}$Ni target. The secondary beam purity was enhanced by a 550 μm thick wedge-shaped ^{9}Be degrader at the intermediate focal point and by using the velocity filter at the exit of the LISE3 spectrometer. The 96% pure secondary ^{36}Ca beam (12 atoms per s) was implanted into a 500 μm thick silicon detector; the main contaminant stopped in this detector was ^{35}K (0.5 atoms per s). The implantation detector was positioned between two silicon counters of the same thickness for detecting β-rays (β-detectors). Two additional silicon counters, the first one with a thickness of 500 μm and the second one, position sensitive, with a thickness of 150 μm, 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 detectors with a total efficiency of 0.02 at 1.1 MeV for registering γ-rays were mounted close to the implantation detector.

The energy calibration has been performed by implanting the well-known β-delayed proton (βp) emitter ^{37}Ca under similar conditions in an additional LISE3 setting, the proton separation energies of ^{37}Ca and ^{36}Ca being similar (S_{p} = 1857.77 (9) and S_{p} = 1666(8) keV [14], respectively). Corrections were made for different

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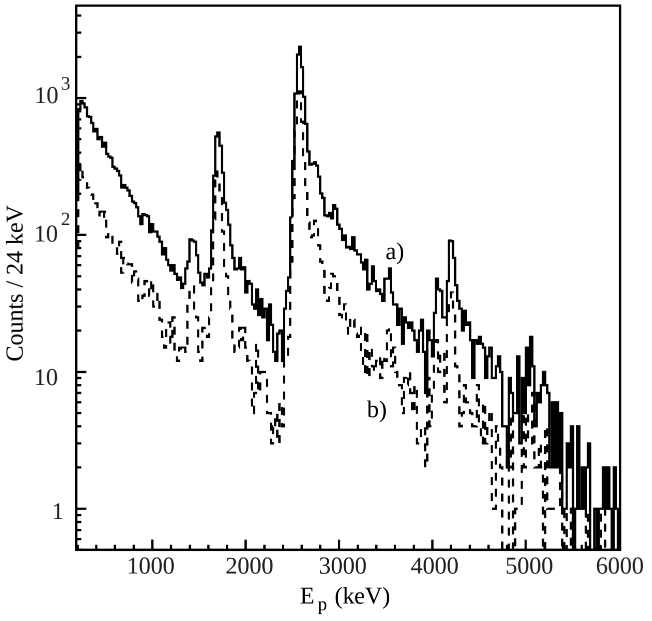

Fig. 1. ^{36}Ca βp decay spectrum: a) β conditioned spectrum. b) spectrum conditioned with ΔE_β less than 300 keV.

implantation depths of ^{36}Ca and ^{37}Ca atoms ($\Delta \approx 100$ μm) by means of the well-known proton transition from the Isobaric Analogue State (IAS) [15]. The *difference* of the line shifts due to pulse-height defects of the recoil atoms (^{35}Ar,^{36}Ar) in the decay of ^{36}Ca and ^{37}Ca is negligible.

In the first setting (48516 atoms), the ^{36}Ca implantation profile (FWHM $\sim$ 68 μm) was positioned at a depth of about 142 μm. In a second setting (53891 atoms), the profile was shifted to 292 μm, *i.e.*, nearer to the downstream β-counter, by removing the 150 μm thick ΔE detector. Figure 1 shows the measured ^{36}Ca βp energy spectra: a) proton spectrum in coincidence with β particles and b) under the condition of a small energy-loss of the coincident β-rays in the downstream β-detector ($\Delta E_\beta \leq 300$ keV).

Nine βp transitions were extracted from the spectra shown in fig. 1. These lines have been assigned to single proton transitions between levels in ^{36}K and ^{35}Ar.

The relative intensities are deduced by integrating the full-energy peaks and applying a correction factor to account for protons for which the energy is only partially collected in the implantation detector. We have used GEANT [16] simulations to obtain the correction factor. The implantation depth profile deduced from the ^{36}Ca energy-loss spectrum in the implantation detector has been taken into account. The number of identified and implanted ^{36}Ca atoms was corrected for losses due to secondary reactions in the stopping process [17,18]. This correction factor was 1%. Absolute proton intensities are obtained by dividing the corrected number of protons by the number of ^{36}Ca ions collected in the implantation detector.

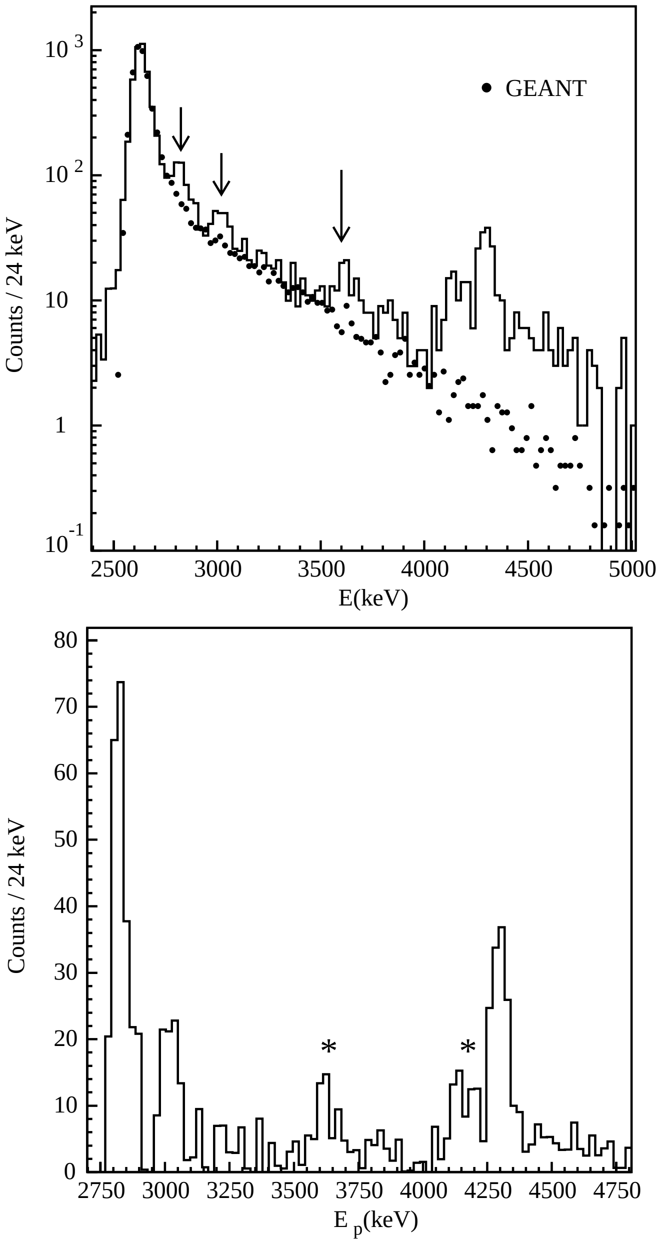

Fig. 2. On the top, we show the proton spectrum in the ^{36}K IAS region and the simulated βp IAS decay spectrum (dots). The arrows indicate very weak transitions. On the bottom, the background-subtracted spectrum is plotted. The two marked peaks correspond to the new βp transitions observed in this experiment. The other peaks were already identified in Trinder's work [5].

Figure 2 (top) shows the experimental IAS region of the ^{36}K proton spectrum and the simulated βp IAS decay spectrum (dots). The GEANT simulations give results which are in good agreement with experimental data for the decay of the IAS. The simulated spectrum has been used as a background spectrum to determine the intensities of the small peaks in the tail of the IAS peak. Figure 2 (bottom) shows the background-subtracted spectrum. We can observe two new weak βp transitions in the ^{36}Ca decay (marked by a star).

Table 1. Summary of excitation energies, branching ratios, log ft values and B(GT) strengths of the daugther levels in the ^{36}Ca β-decay from the present work. Data from the last column correspond to reference [5].

E_x(keV)	x_i(%)abs	$\log ft$	B(GT)	B(GT) [5]
1111.9(4)	14.4(6)	4.54	0.111(6)	0.11(2)
1617.2(4)	31.3(1.7)	4.05	0.34(2)	0.32(4)
3358(23)	9.3(8)^a	4.11	0.30(3)	0.36(2)
	$< 13.4^b$	> 3.95	< 0.43	
4290(23)	37(1)	3.2		
4457(23)	3.5(5)	4.16	0.27(4)	0.13(2)
4644(46)	1.0(3)	4.6	0.10(3)	0.13(2)
5250(23)	0.6(2)	4.6	0.10(3)	*
5761(69)	0.9(2)	4.2	0.24(7)	*
5919(46)	1.7(3)	3.86	0.5(1)	0.9(2)
6791(69)	0.3(1)	3.53	1.1(4)	0.6(2)

a: from proton decay only
b: from proton decay and upper limit of γ-decay

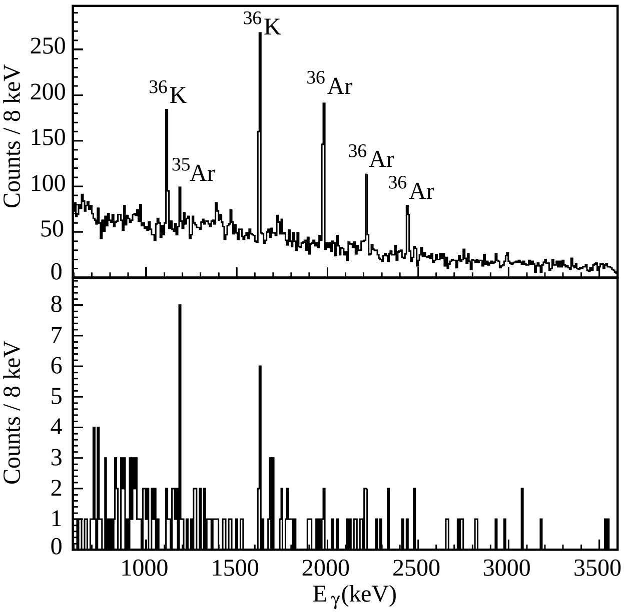

Fig. 3. Upper part: γ-ray spectrum from the ^{36}Ca β-decay in coincidence with β particles. Lower part: γ spectrum coincident with the proton from the decay of the ^{36}K IAS to the first excited state of ^{35}Ar.

Figure 3 (top) shows the γ-ray spectrum obtained. Two β-delayed γ ($\beta\gamma$) decays in ^{36}K were identified. Also, three γ-rays are observed from the β-decay of the ^{36}K into excited states of ^{36}Ar. A weak ^{35}Ar γ line at 1185(1) keV has been observed. This γ-ray is emitted after the proton decay ($\sim$ 1.4 MeV) of the IAS in ^{36}K to the first excited state of ^{35}Ar as identified in [5]. This is confirmed by the γ spectrum coincident with this decay proton as shown in fig. 3 (bottom). Corrections were made for losses in the photopeaks of $\beta\gamma$ lines due to summation with β-rays. The $\sim$10% losses have been estimated in our γ detection setup for the detected ^{36}K γ transitions.

Table 2. Comparison of the measured B(GT) values in the ^{36}Ca β-decay with theoretical data [25]. For the *sd*-shell model calculations the USD interaction has been used. Level energies are also compared.

J^π	E_x^{exp}	$B(\mathrm{GT})^{\mathrm{exp}}$	E_x^{USD}	$B(\mathrm{GT})^{\mathrm{USD}}$
1^+	1111.9(4)	0.111(6)	1221	0.159
1^+	1617.2(4)	0.34(2)	1603	0.319
1^+			2502	0.0075
1^+	3358(23)	0.30(3)	3659	0.45

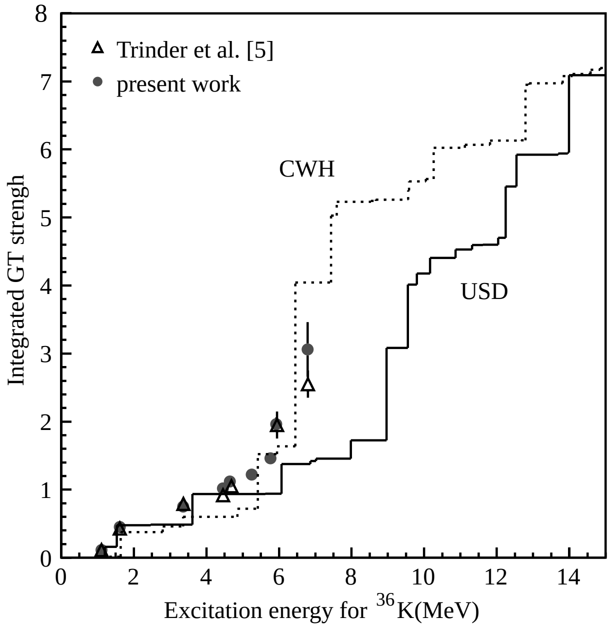

Fig. 4. Integrated Gamow-Teller strength for the decay of ^{36}Ca as a function of the excitation energy in ^{36}K. Experimental data are compared to the shell model calculations [25] with the USD interaction (solid line) and the CWH interaction (dashed line). Triangles correspond to data of reference [5] and filled circles correspond to the data of this work.

In the decay of ^{37}Ca, a competition between γ decay and proton emission has been observed for the levels at E^* = 3239 keV and E^* = 2750 keV in ^{37}K [5,19,20]. The large $\frac{\Gamma_\gamma}{\Gamma_\mathrm{p}}$ values are of astrophysical relevance for the explosive hydrogen burning which may lead to a rapid depletion of ^{36}Ar in stellar environments. As similarly large $\frac{\Gamma_\gamma}{\Gamma_\mathrm{p}}$ value might be present also in the decay of the 3358 keV state in ^{36}K. Therefore, we searched for γ-rays de-exciting the level at 3358 keV. This level can γ-decay either by a γ cascade via the level at 1617.2 keV or directly to the ground state. In our spectrum in fig. 3, we have weak evidence for such a decay. We determined an upper limit for this γ transition of 3.3%, where 2.4% is the upper limit from the cascade transition and 0.9% from the decay to the ground state. This branching ratio limit corresponds to an upper limit for $\frac{\Gamma_\gamma}{\Gamma_\mathrm{p}}$ of 0.39. All extracted energies and intensities of the excited states in ^{36}K are listed in table 1.

The experimental β-decay transition strength for a transition to level i in ^{36}K was calculated using [21–23]:

$$\left[B(\mathrm{F})+\left(\frac{g_A}{g_V}\right)^2 B(\mathrm{GT})\right]_i=\frac{kx_i}{f(E_i)\tau_{1/2}}\,,$$

$$k=6127(9)\ \mathrm{s}\,,\quad \tau_{1/2}=102(2)\ \mathrm{ms}\,,\quad \frac{g_A}{g_V}=-1.262\,,$$

where $B(\mathrm{F})$ is the Fermi strength, E_i is the β-endpoint energy, $f(E_i)$ the phase-space factor, x_i the branching ratio of a β-transition to the i-th daughter level.

In table 1, we compare our measured $B(\mathrm{GT})$ strengths with the values from previous work [5]. For the pure Fermi decay of ^{36}Ca into the IAS in ^{36}K we obtain $B(\mathrm{F}) = 3.87(20)$ in agreement with the previous value $B(\mathrm{F}) = 4.05(13)$ [5]. The GT strength calculated with the USD [9] and CWH [24] interactions is compared to the experimental data for ^{36}K in table 2 and in fig. 4. The shell model calculations were performed with the ANTOINE code [25]. The calculation includes quenching by the recommended value $(0.77)^2$ for the *sd* shell. For the low-lying states up to 4 MeV, the agreement of experimental data with the USD interaction is better. At higher excitation energy, the CWH Hamiltonian calculations agree better with experimental data, as in the case of other nuclei such as ^{37}Ca [5], ^{31}Ar [26], etc.

In summary, by improving the energy resolution of the charged particles detection compared to previous experimental studies, two new weak transitions have been detected for the ^{36}Ca decay and the other nine known βp and $\beta\gamma$ transitions have been remeasured with improved resolution. GEANT simulations accurately reproduce the experimental data. Experimental data have been compared with shell model calculations. A good agreement is found between the theoretical $B(\mathrm{GT})$ values obtained with the CWH interaction and the experimental values for the new states. Contrary to the study of ^{37}Ca, we did not find clear evidence for a competition between γ-decay and proton emission for the level at 3358 keV.

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