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Beta decay of exotic T_Z = -1, -2 nuclei: the interesting case of ^{56}Zn

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Abstract. The β decay properties of the T_z = -2, ^{56}Zn isotope and other proton-rich nuclei in the *fp*-shell have been investigated in an experiment performed at GANIL. The ions were produced in fragmentation reactions and implanted in a double-sided silicon strip detector surrounded by Ge EXOGAM clovers. Preliminary results for ^{56}Zn are presented. The ^{56}Zn decay proceeds mainly by β delayed proton emission, but β delayed gamma rays were also detected. Moreover, the exotic β delayed gamma-proton decay was observed for the first time. The ^{56}Zn half-life and the energy levels populated in the ^{56}Cu daughter have been determined. Knowledge of the gamma de-excitation of the mirror states in ^{56}Co and the comparison with the results of the mirror charge exchange process, the ^{56}Fe(^{3}He,*t*) reaction (where ^{56}Fe has T_z = +2), were important in the interpretation of the ^{56}Zn decay data. The absolute Fermi and Gamow-Teller strengths have been deduced.

1 Introduction

Beta (β) decay is a powerful tool to investigate the structure of nuclei far from the line of β stability, giving direct access to the absolute value of the Fermi (F) and Gamow-Teller (GT) transition strengths, B(F) and B(GT), respectively. However the finite Q_β value only allows access to states at low excitation energy. On the other hand, Charge Exchange (CE) studies, at intermediate beam energies and zero momentum transfer, allow the determination of relative B(GT) values up to high

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excitation energy [1, 2]. Thus β decay and CE reactions complement each other. Under the assumption of isospin symmetry, the β decay of proton-rich nuclei and CE reactions carried out on the mirror, stable nuclei can be combined to determine the absolute B(GT) strength up to high excitation energies. Absolute B(GT) values can be obtained even for GT transitions starting from extremely unstable nuclei if the β decay half-life $T_{1/2}$ and the Q_β value are precisely known. This "merged analysis" [1, 3] method has been successfully employed to study T_z = -1, proton-rich nuclei in the *fp*-shell [1, 3, 4].

2 The experiment

T_z = -1 and -2 nuclei in the *fp*-shell were produced in an experiment performed at the LISE3 facility of GANIL [5] in 2010. The experiment was focused on the study of ^{56}Zn. A ^{58}Ni^{26+} primary beam with average intensity of 3.7 eμA was accelerated to 74.5 MeV/u and fragmented on a 200 μm thick, natural Ni target. The fragments were selected by the LISE3 separator, and implanted into a Double-Sided Silicon Strip Detector (DSSSD) surrounded by four Ge EXOGAM clovers for gamma (γ) detection. The DSSSD was 300 μm thick and had 16 X and 16 Y strips with a pitch of 3 mm, defining 256 pixels. The DSSSD was used to detect both the implanted ions and the subsequent β decays, using two parallel electronic chains with different gains. The implanted nuclei were identified on an event-by-event basis using the energy loss signal, measured in a silicon ΔE detector located before the DSSSD, and the Time-of-Flight, measured between the cyclotron radio-frequency and the ΔE signal. Any implantation event triggering the ΔE detector was acquired. Decay events were characterized by a signal above threshold (typically 50-90 keV) in the DSSSD with no coincident signal in ΔE.

3 Beta decay of the exotic ^{56}Zn isotope

The ^{56}Zn half-life was determined from the time correlation between each decay event happening in a given pixel of the DSSSD and all the ^{56}Zn implants occurring before and after it in the same pixel. The time difference between these two types of event defines the correlation time. From the correlations of ^{56}Zn implants with the protons (above 800 keV, see below), the half-life was obtained by fitting the correlation time spectrum with a function including the β decay of ^{56}Zn and a constant background from the random correlations. A half-life $T_{1/2}$ = 32.9 ± 0.8 ms was obtained for ^{56}Zn.

The decays of the T_z = -2 nuclei are more complex than the T_z = -1 cases (where only β delayed γ emission is observed) because both β delayed γ rays and β delayed proton (p) emission can occur because of the extremely low proton separation energy S_p. In the $T_z = -2 \rightarrow -1$, β decay the ^{56}Zn nucleus decays to ^{56}Cu ($Q_\beta^{\#}$ = 12870 ± 300 keV [6], where # means from systematic). In the ^{56}Cu nucleus, $S_p^{\#}$ = 560 ± 140 keV [6] only. Thus it is expected that the energy levels populated in ^{56}Cu above S_p will decay via p-emission to the ^{55}Ni ground state (gs).

Fig. 1a shows the charged-particle spectrum for the decay events correlated with ^{56}Zn implants, after subtraction of the random background. Most of the strength in the spectrum can be attributed to β delayed proton decays to the ^{55}Ni$_{gs}$: four intense and two weaker proton peaks are identified above 800 keV (labeled according to the corresponding excitation energies in ^{56}Cu), while the bump below 800 keV could be attributed to β decays which are not in coincidence with protons. The thinner DSSSD detector used in the present experiment, as compared to a previous experiment by Dossat et al. [7], produced a better energy resolution for the protons, 70 keV FWHM. The 0^+ Isobaric Analogue State (IAS) populated in the Fermi transition is clearly identified as the strong peak at 3508 keV (as in [7]). Most of the other levels correspond to the excitation of 1^+ states in ^{56}Cu via GT transitions. Fig. 1b shows the spectrum obtained from the mirror $T_z = +2 \rightarrow +1$, ^{56}Fe(^{3}He,t)^{56}Co CE reaction measured at RCNP Osaka [8]. A good correspondence is observed between the states in the two mirror nuclei, ^{56}Cu and ^{56}Co, with the energies differing by less than 100 keV. Here ref. [6] was used for the estimation of S_p and Q_β. Using ref. [9] the same comparison gives energy differences of ~ 400 keV.

It is worth noting that the proton decay of the T = 2, ^{56}Cu IAS state at 3508 keV (Fig. 1a) to the T = 1/2, ^{55}Ni$_{gs}$ is isospin forbidden, which makes the competing γ de-excitation possible. Indeed the γ

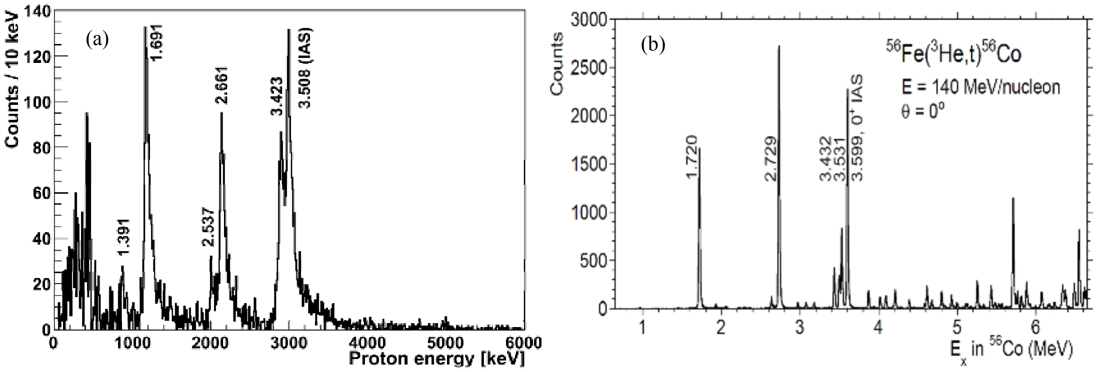

Figure 1. a) Charged-particle spectrum measured in the DSSSD for decay events correlated with ^{56}Zn implants. The peaks are labeled according to the corresponding excitation energies in ^{56}Cu (in MeV). b) The ^{56}Fe(^{3}He,t)^{56}Co reaction spectrum [8]. The peaks are labeled by the excitation energies in ^{56}Co.

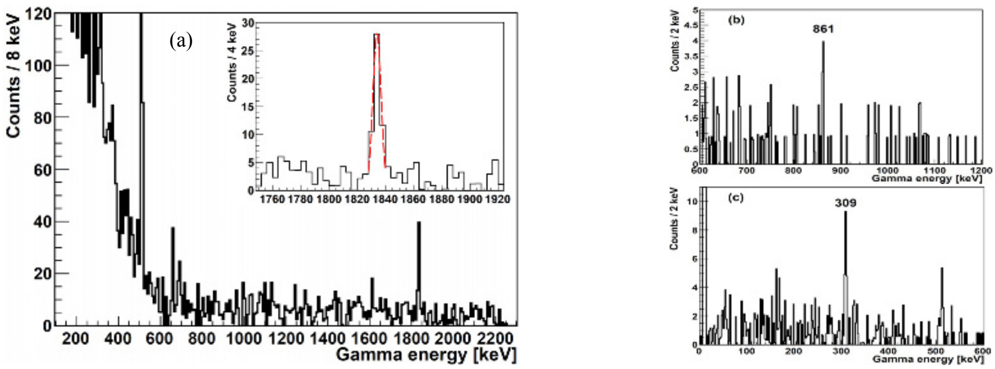

Figure 2. a) Gamma-ray spectrum measured in coincidence with the charged-particle-decays correlated with ^{56}Zn implants. b) γ rays coincident with the p-peak at 2661 keV. c) γ rays coincident with the p-peak at 1391 keV.

spectrum measured in coincidence with the decays correlated with ^{56}Zn (Fig. 2a) exhibits a line at 1834.5 ± 1.0 keV. This energy agrees with the difference between the 3508 and 1691 keV states, namely 1817 ± 15 keV, therefore this γ line is attributed to the electromagnetic transition connecting these levels. Further confirmation arises from the fact that the 1835 keV line is in coincidence with the p-decay from the 1691 keV level. Moreover, the half-life of the 1835 keV peak is $T_{1/2}$ = 27 ± 8 ms, in good agreement with the ^{56}Zn value. Since the 1691 keV level is also p-unbound (estimated $\Gamma \sim 10^{-8}$ MeV), we have observed an exotic decay, namely a β delayed gamma-proton decay, for the first time.

Imposing coincidence conditions on the various proton peaks in Fig. 1a, two additional γ rays are observed (Fig. 2b, 2c). The first one is at 861 keV and corresponds to the de-excitation from the 3508 keV IAS to the 2661 keV state. The second lies at 309 keV and is related to the electromagnetic transition connecting the 1691 and 1391 keV states. Thus, the level at 1391 keV could correspond to the 0^+ anti-analogue state [10] at 1451 keV in the mirror ^{56}Co and could be indirectly populated by the γ decay from the 1691 keV state, as occurs in the mirror ^{56}Co nucleus.

The ^{56}Zn decay scheme summarizing all of the observations from the present experiment is shown in Fig. 3. The ^{56}Cu level energies have an accuracy of ~ 10 keV from the determination of the proton peak centroids; the larger error indicated in Fig. 3 is due to the uncertainty in S_p [6]. Solid lines indicate experimental observations, while dashed lines indicate transitions observed in the mirror ^{56}Co nucleus. Three cases of β delayed γ-proton emission are seen experimentally, involving the levels at 2661, 1691 and 1391 keV and the γ rays at 861, 1835 and 309 keV.

The β feeding to each level populated in ^{56}Cu is estimated from the area of the proton peaks, corrected for the amount of indirect feeding produced by the γ de-excitation. The latter comes from the intensity of the observed γ lines and the de-excitation pattern in the mirror ^{56}Co nucleus [10].

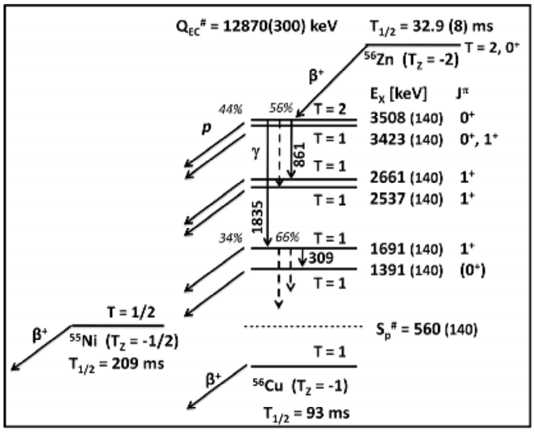

Figure 3. Decay scheme of ^{56}Zn as deduced from the present experiment. Observed proton or gamma decays are indicated by solid lines. Transitions observed in the mirror ^{56}Co nucleus are shown by dashed lines. The level energies are deduced from our data, where the intrinsic uncertainty is estimated to be ~ 10 keV. The larger error is due to the uncertainty in the proton separation energy.

Assuming 100% DSSSD efficiency for both implants and protons [7], a total proton branching ratio of 88.5 ± 0.9 % is deduced by comparing the total number of ^{56}Zn implants with the number of protons observed above 800 keV (Fig. 1a). The missing 11.5 ± 0.9 % is attributed to the γ decay of the 1691 keV level, where the estimated partial proton half-life is $t_{1/2}$ ~ 10^{-14} s, thus the γ de-excitation can compete with the p-emission (being γ the 56% and 66% of total decays from IAS and 1691 keV state).

The β feedings, $T_{1/2}$, Q_β [6] and total proton branching ratio were used to determine the B(F) and B(GT) values. The ^{56}Cu IAS at 3508 keV has a preliminary B(F) = 2.7 ± 0.5 units instead of the expected value of $|N - Z| = 4$. Besides the IAS, three other states at ~ 3.5 MeV are observed in the mirror ^{56}Co nucleus (Fig. 1b); one of them is also fed by the Fermi transition (like the IAS), the others by GT transitions. Fragmentation of the IAS has been observed in this mass region and in the case of ^{56}Co it is due to $T = 2$ and $T = 1$ isospin mixing [8, 11]. For ^{56}Cu (Fig. 1a) the proton peak at 3423 keV is wider than the others thus it probably contains three peaks, or at least two, corresponding to these three ^{56}Co states. In particular, one of these levels probably is populated by the Fermi transition, as occurs in ^{56}Co. All this indicates that the ^{56}Cu IAS is also fragmented and thus the missing Fermi strength goes to the lower state close to the observed 3423 keV energy.

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