BETA DECAY OF THE EXOTIC $T_z = -2$, ^{56}Zn NUCLEUS AND HALF-LIFE OF VARIOUS PROTON-RICH $T_z = -1$ NUCLEI*

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Preliminary results of an experimental study of the β-decay of the exotic $T_z = -2$, ^{56}Zn nucleus and other proton-rich $T_z = -1$ nuclei are presented. The ions were produced at GANIL using fragmentation reactions, separated by the LISE3 spectrometer and implanted in a double-sided silicon strip detector surrounded by Ge detectors. The half-lives of ^{56}Zn and four $T_z = -1$ nuclei in the fp-shell have been measured. While the decay of the $T_z = -1$ nuclei proceeds essentially by β-delayed gamma emission, in the case of ^{56}Zn β-delayed proton emission is also observed. Moreover, the exotic β-delayed gamma-proton decay is seen for the first time. The information from the decay study has been used to determine the absolute Fermi and Gamow–Teller transition strengths. The results for ^{56}Zn have been compared with the mirror Charge Exchange process, the (^{3}He,t) reaction on the $T_z = +2$, ^{56}Fe target nucleus. This comparison is important for understanding the ^{56}Zn decay data.

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1. Introduction

The beta decay is a weak interaction process, where the well-known τ and $\sigma\tau$ operators govern the Fermi (F) and Gamow–Teller (GT) transitions, respectively. The GT transitions are the most common weak interaction processes of $\sigma\tau$ type in atomic nuclei. Due to their simple ($\Delta L = 0$, $\Delta S = 1$) nature, they are an important tool for the investigation of nuclear structure, especially for unstable nuclei. Charge-Exchange (CE) reactions are a strong interaction process, however, under some experimental conditions, they also proceed by F and GT transitions [1, 2]. Under the assumption of isospin symmetry, the β-decay of proton-rich nuclei and CE reactions on the mirror stable target nuclei complement each other. Therefore, the combined analysis of these mirror processes [1, 3] allows the determination of the absolute GT strengths up to high excitation energies.

Based on these ideas, a series of β-decay experiments and CE reactions starting from mirror nuclei were carried out. The β^+ decays of the $T_z = -1$ ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni nuclei were studied at GSI [3–5]. The results motivated further investigations on more exotic $T_z = -1$, fp-shell nuclei and the $T_z = -2$, ^{56}Zn nucleus, which have been studied at GANIL. The β^--type mirror CE reaction on the $T_z = +2$, ^{56}Fe target nucleus was carried out at RCNP Osaka [6] using the (^{3}He,t) reaction at 140 MeV/u and $\theta = 0°$.

2. The experiment

The experiment was mainly focused on ^{56}Zn. Data were also taken for the $T_z = -1$, ^{58}Zn nucleus, of astrophysics interest since it constitutes a waiting point in the rp-process. The experiment was performed in 2010 at the LISE3 facility of GANIL [7]. A 74.5 MeV/u ^{58}Ni^{26+} primary beam with average intensity of 3.7 $e\,\mu$A was fragmented on a 200 μm $^{\mathrm{nat}}$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 300 μm thick DSSSD, with 16×16 strips and a pitch of 3 mm, was used both as an implantation detector and to detect the subsequent decays, using two parallel electronic chains with different gains. The implanted nuclei were identified on an event-by-event basis thanks to the measurement of the energy loss ΔE in a silicon detector before the DSSSD, and the Time-of-Flight (TOF) measured between the cyclotron RF and the ΔE detector. Implantation events were those triggering the ΔE detector. Decay events were triggered by a signal above threshold (typically 50–90 keV) in the DSSSD, with no coincident signal in the first ΔE detector.

3. The half-life analysis

The identification of the implanted nuclei on an event-by-event basis using the two dimensional ΔE–TOF matrix makes possible the selection of the ion of interest by applying off-line gates on such a matrix. The implantation signals were recorded in the X and Y strips of the DSSSD, which define the implantation pixel for each event. A low gain amplification was used for the implanted ions, while high gain amplification was used for the decay signals. The correlation time was defined as the time difference between a decay event in a given pixel of the DSSSD and all the implantation events that occurred before and after it in the same pixel that satisfied the appropriate conditions to select the nuclear species. This procedure ensured that true correlations were taken into account. However, many random correlations were also included and, as expected, they produced a large constant background that had to be accounted for when performing the half-life analysis. Finally, the half-life value of the nucleus of interest was obtained by fitting the correlation-time spectrum with a function which included the radioactive decay of the nucleus of interest, the growth and decay activity of the daughter nucleus, and a constant background.

3.1. Half-life results for the $T_z = -1$ nuclei

The half-lives obtained with the above procedure for the $T_z = -1$ nuclei, produced with magnetic settings optimized for ^{58}Zn, are shown in Table I. In these nuclei, the β-delayed proton (p) emission is not important and, essentially, only β-delayed γ decay is observed. Usually, the β decay of the daughter leads to a stable or long-lived nucleus. The half-lives measured for the $T_z = -1$ nuclei are in agreement with the results of a previous GANIL experiment [8] and the literature values.

TABLE I

Experimental $T_{1/2}$ values of various $T_z = -1$ proton-rich nuclei produced in the ^{58}Zn setting.

Nucleus	$T_{1/2}$[ms]	Number of implantations
^{58}Zn	88 ± 5	82138
^{56}Cu	82 ± 2	554374
^{54}Ni	115 ± 4	263497
^{52}Co	124 ± 23	19483

3.2. Half-life of the $T_z = -2$, ^{56}Zn nucleus

The decay of the $T_z = -2$, ^{56}Zn nucleus is more complex than the $T_z = -1$ cases discussed above, because both β-delayed γ rays and β-delayed p-emission are present (see the discussion in Section 4). The ^{56}Zn half-life was determined by correlating the ^{56}Zn implantations with the protons (DSSSD energy above 800 keV, see the next section). The half-life was then obtained by fitting the correlation-time spectrum with a function including the β decay of ^{56}Zn and a constant background to account for the random correlations. A half-life $T_{1/2} = 32.9 \pm 0.8$ ms was obtained for ^{56}Zn.

4. The exotic decay of ^{56}Zn

Preliminary results of the study of the $T_z = -2 \to -1, \beta^+$ decay of ^{56}Zn to ^{56}Cu are summarized in Fig. 4. How we reach this stage will be presented step-by-step. The decay will populate two kinds of state in the daughter ^{56}Cu nucleus: the 0^+ Isobaric Analogue State (IAS) and 1^+ excited states, populated by the Fermi and GT transitions, respectively. Since all of these states are expected to lie well above 1 MeV [9] and the proton separation energy is $S_p = 560 \pm 140$ keV in ^{56}Cu (from systematics [10]), it is expected that these levels will decay via p-emission. The ^{56}Zn β decay was already explored in Ref. [9], where the β-delayed protons were observed and no γ-ray de-excitation was observed. In the present experiment, a thinner DSSSD detector was used than in the previous measurement and a better energy resolution for the protons, 70 keV FWHM, was achieved.

The charged-particle spectrum for decay events correlated with the ^{56}Zn implantations, after subtraction of the random background, is shown in Fig. 1. Most of the strength can be attributed to β-delayed proton decay to the ^{55}Ni ground state (g.s.), in accord with the very low S_p value. The bump observed in the spectrum below 800 keV could be attributed to β particles which are not in coincidence with protons. Four intense and two weaker proton peaks are identified above 800 keV, which are labeled in Fig. 1 according to the corresponding excitation energies in ^{56}Cu (in MeV). The 0^+ IAS is clearly identified as the strong peak at 3508 keV (in agreement with Ref. [9]). Most of the other levels correspond to the excitation of 1^+ states in ^{56}Cu via GT transitions.

The mirror $T_z = +2 \to +1$ Fermi and GT transitions can be studied in the β^--type CE reaction on the stable ^{56}Fe target. Figure 2 shows the spectrum obtained from the high resolution ^{56}Fe(^{3}He,t)^{56}Co reaction, performed at RCNP Osaka [6], where the peaks are labeled by the excitation energies in the final ^{56}Co nucleus. A good correspondence is observed between the states in the two mirror nuclei, ^{56}Cu and ^{56}Co, with the energies differing by less

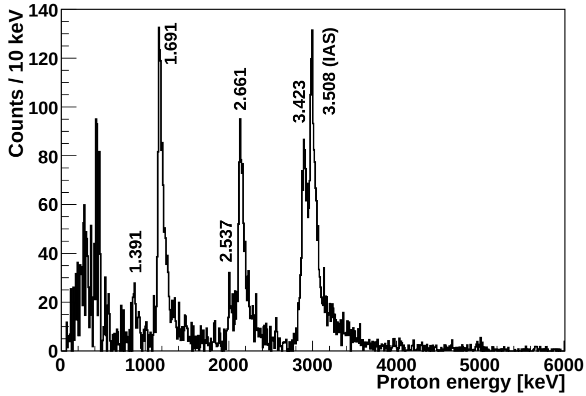

Fig. 1. Charged-particle spectrum measured in the DSSSD for decay events correlated with the ^{56}Zn implants. The peaks are labeled according to the corresponding excitation energies in ^{56}Cu (in MeV).

than 100 keV. Here, Ref. [10] was used for the estimation of Q_β and S_p, and not the latest values given in Ref. [11]. Using the latter values [11], the same comparison gives energy differences of ~ 400 keV.

From the ^{56}Cu spectrum in Fig. 1, one can notice that the proton peak labeled as 3423 keV is wider than the others. The comparison with the mirror ^{56}Co spectrum in Fig. 2 suggests that the 3423 keV peak in ^{56}Cu probably contains three (or at least two) proton peaks corresponding to the three levels observed in the mirror ^{56}Co spectrum. Moreover, one of these levels probably corresponds to the 0^+ level observed in ^{56}Co at 3531 keV and is also fed by the Fermi transition, like the IAS. The fragmentation of the IAS has been observed in this mass region and in the case of ^{56}Co it is attributed to the isospin mixing of the $T = 2$ and $T = 1$ states [6, 12].

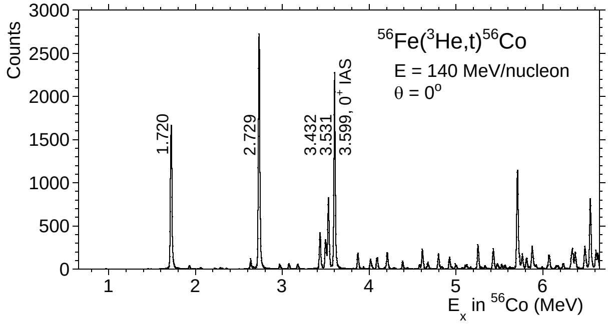

Fig. 2. ^{56}Fe(^{3}He,t)^{56}Co reaction spectrum [6]. Peaks are labeled by the excitation energies in ^{56}Co.

The proton decay of the 3508 keV, $T = 2$ IAS in ^{56}Cu to the $T = 1/2$, ^{55}Ni$_{\rm gs}$ is isospin forbidden, making the competing γ de-excitation possible. Indeed, a γ line of 1834.5 ± 1.0 keV was observed (see Fig. 3) in coincidence with the charged-particle decays correlated with the ^{56}Zn implantations. 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 level at 1691 keV. Moreover, the half-life of the 1835 keV peak is $T_{1/2} = 27 \pm 8$ ms, in good agreement with the ^{56}Zn half-life. Since the 1691 keV level is also particle-unbound (with an estimated width $\Gamma \sim 10^{-8}$ MeV), we have observed a rare and exotic decay process, namely a beta-delayed gamma-proton decay for the first time.

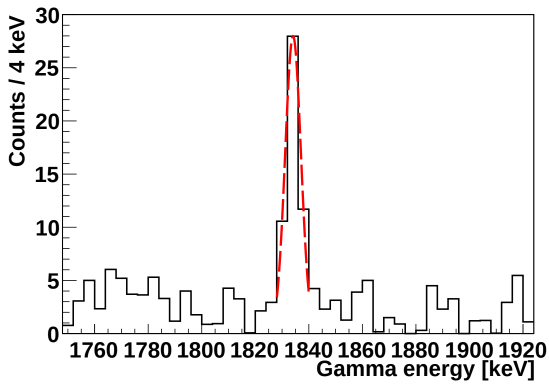

Fig. 3. γ-ray observed at 1835 keV in coincidence with the charged-particle decays correlated with the ^{56}Zn implants.

Imposing coincidence conditions on the various proton peaks in Fig. 1, two additional γ rays are observed. The first one is seen 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 [13] at 1451 keV in the mirror ^{56}Co nucleus and could be indirectly populated by the γ decay from the 1691 keV state, as occurs in ^{56}Co. Finally, the small proton peak seen at 2537 keV in ^{56}Cu (Fig. 1) could correspond to the 2635 keV, 1^+ level in the mirror (Fig. 2). Since the latter is only weakly populated by CE at $0°$, it is expected that the ^{56}Cu, 2537 keV level receives indirect γ feeding from the IAS at 3508 keV and only a small amount of direct β feeding.

The ^{56}Zn decay scheme summarizing all of the observations from the present experiment is shown in Fig. 4. 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. 4 is due to the uncertainty in S_p [10]. Solid and dashed lines represent experimental observations and transitions observed in the mirror ^{56}Co nucleus, respectively. 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.

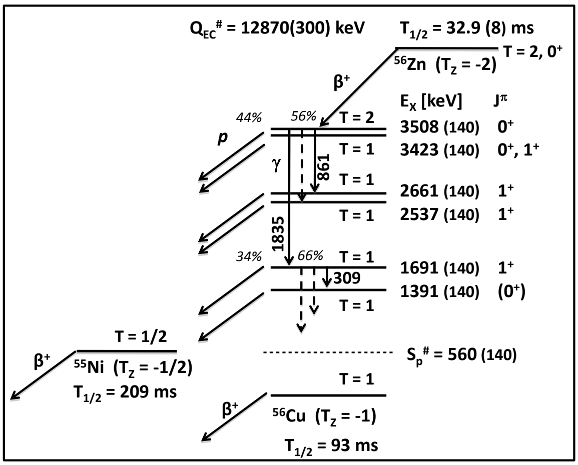

Fig. 4. The ^{56}Zn decay scheme deduced from the present experiment. Solid lines correspond to observed proton or γ decays. Dashed lines indicate transitions observed in the mirror ^{56}Co nucleus. The level energies are deduced from our data, having an intrinsic uncertainty of ~ 10 keV. The larger error comes from the uncertainty in the proton separation energy.

Assuming 100% DSSSD efficiency for both implants and protons [9], a total proton branching ratio of $88.5 \pm 0.9\%$ is obtained by comparing the total number of ^{56}Zn implantations with the number of protons observed above 800 keV (Fig. 1), where the uncertainty originates from reasonable assumptions in determining the integration limits for the protons. The missing $11.5 \pm 0.9\%$ is attributed to the β-delayed γ emission from the 1691 keV level, where the estimated partial proton half-life is $t_{1/2} \sim 10^{-14}$ s, thus the γ de-excitation can compete with the p-emission. A preliminary estimate for such competition indicates that the γ decays are 56% and 66% of the total decays from the IAS and 1691 keV state, respectively. The β feeding to each level populated in ^{56}Cu is estimated from the area of the proton peaks and γ peaks, corrected for the amount of indirect feeding produced by the γ de-excitation, which comes from the intensity of the observed γ lines and estimations using the de-excitation pattern in the mirror ^{56}Co nucleus [13].

A preliminary value for the Fermi strength of the 3508 keV IAS state is $B(\mathrm{F}) = 2.7 \pm 0.5$ units, instead of the expected value of 4. This is an additional confirmation that the ^{56}Cu IAS is fragmented and thus the missing Fermi strength goes to the lower state close to the observed 3423 keV peak (value to be compared with 3527 keV in the mirror nucleus [13]).

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