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Competition of β-delayed protons and β-delayed γ rays in ^{56}Zn and the exotic β-delayed γ-proton decay

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Abstract

Remarkable results have been published recently on the β decay of ^{56}Zn. In particular, the rare and exotic β-delayed γ-proton emission has been detected for the first time in the fp shell. Here we focus the

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discussion on this exotic decay mode and on the observed competition between β-delayed protons and β-delayed γ rays from the Isobaric Analogue State.

1 Introduction

Decay spectroscopy is a powerful tool for exploring the structure of nuclei at the drip-lines. β-decay studies, in particular, provide direct access to the absolute values of the Fermi and Gamow-Teller transition strengths, B(F) and B(GT), respectively.

The proton-rich ^{56}Zn nucleus was observed for the first time at GANIL in 1999 [1]. ^{56}Zn is a weakly-bound nucleus lying very close to the proton drip-line. It has a quite small proton separation energy, S_p = 560(140) keV [2], and third component of the isospin quantum number T_z = -2.

The first study of the β decay of ^{56}Zn was reported in $ref.$ [3]. More recently, some interesting results on ^{56}Zn decay have been reported in $ref.$ [4]. Among them the discovery of a rare and exotic decay mode, β-delayed γ-proton decay, which has been seen for the first time in the fp shell. The consequences of this rare decay sequence for the determination of the Gamow-Teller (GT) strength have also been analyzed.

2 The experiment

The experimental study of ^{56}Zn decay was performed at GANIL in 2010. The experiment used a primary beam of ^{58}Ni^{26+} to produce ^{56}Zn. The ^{58}Ni beam, of 3.7 eμA and accelerated to 74.5 MeV/nucleon, was fragmented on a natural Ni target, 200 μm thick. The fragments were selected by the LISE3 separator and implanted into a Double-Sided Silicon Strip Detector (DSSSD). The detection set-up comprised the aforementioned DSSSD detector, 300 μm thick, a silicon ΔE detector located 28 cm upstream, and four EXOGAM Ge clovers surrounding the DSSSD.

The EXOGAM clovers were used to detect β-delayed γ rays. The purpose of the DSSSD was the detection of both the implanted fragments and the subsequent charged-particle decays, *i.e.*, β particles and β-delayed protons. An implantation event was defined by simultaneous signals in both the ΔE and DSSSD detectors. A decay event was defined by a signal above threshold (50-90 keV) in the DSSSD and no coincident signal in the ΔE.

The implanted ions were identified and selected by putting a gate in a two-dimensional identification matrix, obtained by combining the energy loss signal from the ΔE detector and the Time-of-Flight. The latter was defined as the time difference between the cyclotron radio-frequency and ΔE signal.

3 Results on the β decay of ^{56}Zn

The results on the β decay of ^{56}Zn [4] are summarized in the decay scheme in $fig.$ 1 and in table 1, and discussed below.

A half-life of $T_{1/2} = 32.9(8)$ ms was obtained for ^{56}Zn, in agreement with $ref.$ [3]. To determine $T_{1/2}$, a decay-time spectrum has been constructed from the time correlations between a decay event in a given pixel of the DSSSD (with a total of 256 pixels) and any implantation signal that occurred before and after it in the same pixel, satisfying the identification condition required to select ^{56}Zn.

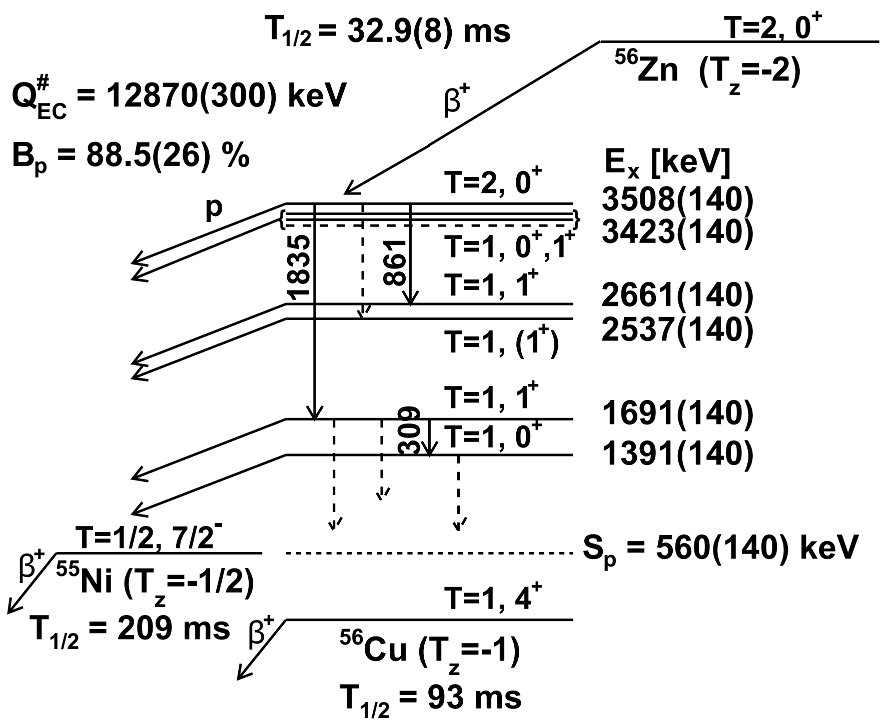

Figure 1: Scheme of the β decay of ^{56}Zn. The solid lines indicate observed proton or γ transitions, while the dashed lines correspond to transitions observed in the mirror ^{56}Co nucleus.

The analysis of the charged-particle spectrum measured in the DSSSD has provided new spectroscopic information on the energy levels populated in the ^{56}Cu nucleus, the β-daughter of ^{56}Zn. These levels are shown in $fig.$ 1. The comparison of this level spectrum with that of the mirror ^{56}Co, obtained by the ^{56}Fe(^{3}He,t) charge exchange reaction [5], has been very fruitful.

The analysis of the γ spectrum measured in the EXOGAM clovers and γ-proton coincidences have identified three γ rays at 309, 861 and 1835 keV.

Absolute B(F) and B(GT) strengths have been determined (table 1).

Table 1: β feedings, Fermi and Gamow Teller transition strengths to the ^{56}Cu levels populated in the β^+ decay of ^{56}Zn.

E_X(keV)	I_β(%)	B(F)	B(GT)
3508(140)*	43(5)	2.7(5)	
3423(140)	21(1)	1.3(5)	≤0.32
2661(140)	14(1)		0.34(6)
2537(140)	0		0
1691(140)	22(6)		0.30(9)
1391(140)	0		0

*Main component of the IAS.

3.1 Competition of β-delayed protons and β-delayed γ rays

In the first study of the ^{56}Zn β decay [3], the emission of β-delayed protons was observed but no β-delayed γ rays were seen. This was not a surprise because, in general, in proton-rich nuclei the proton decay is expected to dominate for states well above (>1 MeV) the proton separation energy S_p. The consequence is that normally the β feeding is directly inferred from the measured intensities of the proton peaks. However, cases where there is a competition between β-delayed proton emission and β-delayed γ de-excitation have also been observed, *e.g.*, in $refs.$ [3, 6].

In the $T_z = -2 \rightarrow -1, \beta^+$ decay of ^{56}Zn to ^{56}Cu, the ^{56}Zn ground state decays with a Fermi transition to its Isobaric Analogue State (IAS) in ^{56}Cu. It should be noted that the de-excitation of this $T = 2$, $J^\pi = 0^+$ IAS via proton decay to the ground state of ^{55}Ni ($T = 1/2$, $J^\pi = 7/2^-$) is isospin forbidden. Therefore the proton emission that we observe can only happen through a $T = 1$ isospin impurity present in the IAS. Moreover in general, when the proton emission is isospin forbidden, the competitive emission of de-exciting γ rays from the IAS also becomes possible and can be observed even from IAS lying at an excitation energy well above S_p [3, 6].

The competition between β-delayed protons and γ rays has indeed been observed in ^{56}Zn. The γ decays represent 56(6)% of the total decays from the 3508 keV IAS. Thus one has to take into account the intensities of both the proton and γ peaks to determine the Fermi strength correctly.

We have also found evidence for the fragmentation of B(F) due to a strong isospin mixing with a 0^+ state at 3423 keV [4], which is important in terms of the mass evaluation [7]. The isospin impurity in the ^{56}Cu IAS, $\alpha^2 = 33(10)\%$ (defined as in *ref.* [5]), and the off-diagonal matrix element of the charge-dependent part of the Hamiltonian, $\langle H_c \rangle = 40(23)$ keV, which is responsible for the isospin mixing of the 3508 keV IAS ($T = 2$, $J^\pi = 0^+$) and the 0^+ part of the 3423 keV level ($T = 1$), are similar to the values obtained in the mirror ^{56}Co nucleus [5].

Thus, the proton decay of the IAS proceeds thanks to the $T = 1$ component. However, considering the quite large isospin mixing in ^{56}Cu, the much faster proton decay ($t_{1/2} \sim 10^{-18}$ s) should dominate on the γ de-excitation ($t_{1/2} \sim 10^{-14}$ s in the mirror). This is not the case since we are still observing the γ decay of the IAS in competition with it.

The knowledge on the nuclear structure of the three nuclei involved in the decay, *i.e.*, ^{56}Zn, ^{56}Cu and ^{55}Ni, can provide us with a possible explanation for the hindrance of the proton decay. Shell model calculations are in progress to clarify this point.

3.2 The β-delayed γ-proton decay

Besides the competition between β-delayed proton emission and γ decay, the exotic sequence of β-delayed γ-proton decay has been detected. Indeed ^{56}Zn does β decay to its IAS in ^{56}Cu and from there we observe the emission of two γ rays of 861 and 1835 keV, populating the ^{56}Cu levels at 2661 and 1691 keV, respectively. Due to the low S_p, these levels are still proton-unbound and thereafter they decay by proton emission. Consequently the rare and exotic β-delayed γ-proton decay has been observed. In addition to these two branches, there is a third case. The 1691 keV level emits a γ ray of 309 keV, going to the level at 1391 keV that is again proton-unbound and then it de-excites by proton emission.

The β-delayed γ-proton decay has been observed here for the first time in the fp shell. This rare decay mode was seen only once before, in the *sd* shell in ^{32}Ar [6], but the consequences for the determination of B(GT) were not addressed in *ref* [6].

The observation of this special decay mode is very important because it does affect the conventional way to determine B(GT) near the proton drip-line. For a proper determination of $B(\mathrm{GT})$, indeed, it is crucial to correct the intensity of the proton transitions for the amount of indirect feeding coming from the γ de-excitation. This finding indicates that it is important to employ γ detectors in such studies. This decay mode is expected to be significant in heavier proton-rich nuclei with $T_z \leq -3/2$ under study at RIKEN.

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