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S.E.A. Orrigo, B. Rubio, Y. Fujita, Bertram Blank, W. Gelletly, et al.. Competition of  $\beta$ -delayed protons and  $\beta$ -delayed  $\gamma$  rays in  ${}^{56}$ Zn and the exotic  $\beta$ -delayed  $\gamma$ -proton decay. 12th International Conference on Nucleus - Nucleus Collisions, Jun 2015, Catania, Italy. pp.06019, 10.1051/epj-conf/201611706019. in2p3-01316683

# HAL Id: in2p3-01316683 https://hal.in2p3.fr/in2p3-01316683

Submitted on 4 Jul 2016

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# Competition of $\beta$ -delayed protons and $\beta$ -delayed $\gamma$ rays in <sup>56</sup>Zn and the exotic $\beta$ -delayed $\gamma$ -proton decay

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#### Abstract

Remarkable results have been published recently on the  $\beta$  decay of <sup>56</sup>Zn. In particular, the rare and exotic  $\beta$ -delayed  $\gamma$ -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  $\beta$ -delayed protons and  $\beta$ -delayed  $\gamma$  rays from the Isobaric Analogue State.

### 1 Introduction

Decay spectroscopy is a powerful tool for exploring the structure of nuclei at the drip-lines.  $\beta$ -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 <sup>56</sup>Zn nucleus was observed for the first time at GANIL in 1999 [1]. <sup>56</sup>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  $\beta$  decay of <sup>56</sup>Zn was reported in ref. [3]. More recently, some interesting results on <sup>56</sup>Zn decay have been reported in ref. [4]. Among them the discovery of a rare and exotic decay mode,  $\beta$ -delayed  $\gamma$ -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 <sup>56</sup>Zn decay was performed at GANIL in 2010. The experiment used a primary beam of <sup>58</sup>Ni<sup>26+</sup> to produce <sup>56</sup>Zn. The <sup>58</sup>Ni beam, of 3.7 e $\mu$ A and accelerated to 74.5 MeV/nucleon, was fragmented on a natural Ni target, 200  $\mu$ m 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  $\mu$ m thick, a silicon  $\Delta E$  detector located 28 cm upstream, and four EXOGAM Ge clovers surrounding the DSSSD.

The EXOGAM clovers were used to detect  $\beta$ -delayed  $\gamma$  rays. The purpose of the DSSSD was the detection of both the implanted fragments and the subsequent charged-particle decays, *i.e.*,  $\beta$  particles and  $\beta$ -delayed protons. An implantation event was defined by simultaneous signals in both the  $\Delta E$  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  $\Delta E$ .

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  $\Delta E$  detector and the Time-of-Flight. The latter was defined as the time difference between the cyclotron radio-frequency and  $\Delta E$  signal.

## 3 Results on the $\beta$ decay of <sup>56</sup>Zn

The results on the  $\beta$  decay of <sup>56</sup>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 <sup>56</sup>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 <sup>56</sup>Zn.



Figure 1: Scheme of the  $\beta$  decay of <sup>56</sup>Zn. The solid lines indicate observed proton or  $\gamma$  transitions, while the dashed lines correspond to transitions observed in the mirror <sup>56</sup>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 <sup>56</sup>Cu nucleus, the  $\beta$ -daughter of <sup>56</sup>Zn. These levels are shown in *fig.* 1. The comparison of this level spectrum with that of the mirror <sup>56</sup>Co, obtained by the <sup>56</sup>Fe(<sup>3</sup>He,t) charge exchange reaction [5], has been very fruitful.

The analysis of the  $\gamma$  spectrum measured in the EXOGAM clovers and  $\gamma$ -proton coincidences have identified three  $\gamma$  rays at 309, 861 and 1835 keV. Absolute B(F) and B(GT) strengths have been determined (table 1).

Absolute  $D(\mathbf{F})$  and  $D(\mathbf{G1})$  strengths have been determined (table 1).

Table 1:  $\beta$  feedings, Fermi and Gamow Teller transition strengths to the <sup>56</sup>Cu levels populated in the  $\beta^+$  decay of <sup>56</sup>Zn.

$E_X(\text{keV})$	$I_{\beta}(\%)$	$B(\mathbf{F})$	B(GT)
3508(140)*	43(5)	2.7(5)	
3423(140)	21(1)	1.3(5)	$\leq 0.32$
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 $\beta$ -delayed protons and $\beta$ -delayed $\gamma$ rays

In the first study of the <sup>56</sup>Zn  $\beta$  decay [3], the emission of  $\beta$ -delayed protons was observed but no  $\beta$ -delayed  $\gamma$  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  $\beta$  feeding is directly inferred from the measured intensities of the proton peaks. However, cases where there is a competition between  $\beta$ -delayed proton emission and  $\beta$ -delayed  $\gamma$  deexcitation have also been observed, *e.g.*, in *refs*. [3,6].

In the  $T_z = -2 \rightarrow -1$ ,  $\beta^+$  decay of <sup>56</sup>Zn to <sup>56</sup>Cu, the <sup>56</sup>Zn ground state decays with a Fermi transition to its Isobaric Analogue State (IAS) in <sup>56</sup>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 <sup>55</sup>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  $\gamma$  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  $\beta$ -delayed protons and  $\gamma$  rays has indeed been observed in <sup>56</sup>Zn. The  $\gamma$  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  $\gamma$  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<sup>+</sup> state at 3423 keV [4], which is important in terms of the mass evaluation [7]. The isospin impurity in the <sup>56</sup>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<sup>+</sup> part of the 3423 keV level (T = 1), are similar to the values obtained in the mirror <sup>56</sup>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 <sup>56</sup>Cu, the much faster proton decay  $(t_{1/2} \sim 10^{-18} \text{ s})$  should dominate on the  $\gamma$  deexcitation  $(t_{1/2} \sim 10^{-14} \text{ s in the mirror})$ . This is not the case since we are still observing the  $\gamma$  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 $\beta$ -delayed $\gamma$ -proton decay

Besides the competition between  $\beta$ -delayed proton emission and  $\gamma$  decay, the exotic sequence of  $\beta$ -delayed  $\gamma$ -proton decay has been detected. Indeed <sup>56</sup>Zn does  $\beta$  decay to its IAS in <sup>56</sup>Cu and from there we observe the emission of two  $\gamma$  rays of 861 and 1835 keV, populating the <sup>56</sup>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  $\beta$ -delayed  $\gamma$ -proton decay has been observed. In addition to these two branches, there is a third case. The 1691 keV level emits a  $\gamma$  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  $\beta$ -delayed  $\gamma$ -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 sdshell in <sup>32</sup>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(GT), indeed, it is crucial to correct the intensity of the proton transitions for the amount of indirect feeding coming from the  $\gamma$  de-excitation. This finding indicates that it is important to employ  $\gamma$  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.

# Acknowledgements

This work was supported by the Spanish MICINN grants FPA2008-06419-C02-01, FPA2011-24553; Centro de Excelencia Severo Ochoa del IFIC SEV-2014-0398; CPAN Consolider-Ingenio 2010 Programme CSD2007-00042; *Junta para la Ampliación de Estudios* Programme (CSIC JAE-Doc contract) co-financed by FSE; MEXT, Japan 18540270 and 22540310; Japan-Spain coll. program of JSPS and CSIC; Istanbul University Scientific Research Projects, Num. 5808; UK Science and Technology Facilities Council (STFC) Grant No. ST/F012012/1; Region of Aquitaine. R.B.C. acknowledges support by the Alexander von Humboldt foundation and the Max-Planck-Partner Group. We acknowledge the EXOGAM collaboration for the use of their clover detectors.

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