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# Competition of $\beta$-delayed protons and $\beta$-delayed $\gamma$ rays in $^{56}$Zn and the exotic $\beta$-delayed $\gamma$-proton decay

S. E. A. Orrigo[1*], B. Rubio[1], Y. Fujita[2], B. Blank[3], W. Gelletly[4], J. Agramunt[1], A. Algora[1,5], P. Ascher[3], B. Bilgier[6], L. Cáceres[7], R. B. Cakirli[6], H. Fujita[8], E. Ganioğlu[6], M. Gerbaux[3], J. Giovinazzo[3], S. Grévy[3], O. Kamalou[7], H. C. Kozer[6], L. Kucuk[6], T. Kurtukian-Nieto[3], F. Molina[1,9], L. Popescu[10], A. M. Rogers[11], G. Susoy[6], C. Stodel[7], T. Suzuki[8], A. Tamii[8] and J. C. Thomas[7]

[1]Instituto de Física Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain
[2]Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[3]Centre d'Etudes Nucléaires de Bordeaux Gradignan, CNRS/IN2P3 - Université Bordeaux 1, 33175 Gradignan Cedex, France
[4]Department of Physics, University of Surrey, Guildford GU2 7XH, Surrey, UK
[5]Inst. of Nuclear Research of the Hung. Acad. of Sciences, Debrecen, H-4026, Hungary
[6]Department of Physics, Istanbul University, Istanbul, 34134, Turkey
[7]Grand Accélérateur National d'Ions Lourds, BP 55027, F-14076 Caen, France
[8]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[9]Comisión Chilena de Energía Nuclear, Casilla 188-D, Santiago, Chile
[10]SCK.CEN, Boeretang 200, 2400 Mol, Belgium
[11]Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

**Abstract**

Remarkable results have been published recently on the $\beta$ decay of $^{56}$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

*e-mail: sonja.orrigo@ific.uv.es

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 $^{56}$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 $\beta$ 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, $\beta$-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 $^{56}$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 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 $^{56}$Zn

The results on the $\beta$ 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.

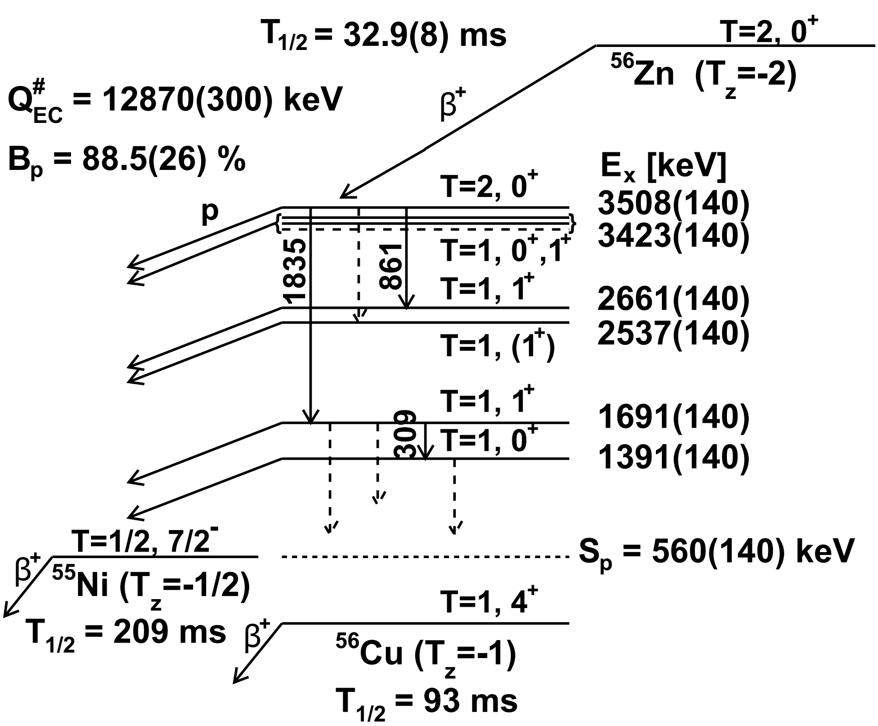


Figure 1: Scheme of the $\beta$ decay of $^{56}$Zn. The solid lines indicate observed proton or $\gamma$ transitions, while the dashed lines correspond to transitions observed in the mirror $^{56}$Co nucleus.

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 $\beta$-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 $\gamma$ 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).

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

| $E_X$(keV) | $I_\beta$(%) | $B$(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 $^{56}$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 $\gamma$ 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 $\gamma$ 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 $^{56}$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 $0^+$ 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 $\gamma$ de-excitation ($t_{1/2} \sim 10^{-14}$ 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 $^{56}$Zn does $\beta$ decay to its IAS in $^{56}$Cu and from there we observe the emission of two $\gamma$ 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 $\beta$-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 $sd$ 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 $\gamma$ 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.

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