**β-DELAYED γ-PROTON DECAY IN $^{56}$Zn: ANALYSIS OF THE CHARGED-PARTICLE SPECTRUM**

S.E.A. Orrigo$^a$, B. Rubio$^a$, Y. Fujita$^b$, B. Blank$^c$, W. Gelletly$^d$
J. Agramunt$^a$, A. Algora$^{a,e}$, P. Ascher$^c$, B. Bilgier$^f$
L. Cáceres$^g$, R.B. Cakirli$^f$, H. Fujita$^h$, E. Ganioğlu$^f$
M. Gerbaux$^c$, J. Giovinazzo$^c$, S. Grévy$^c$, O. Kamalou$^g$
H.C. Kozer$^f$, L. Kucuk$^f$, T. Kurtukian-Nieto$^c$, F. Molina$^{a,j}$
L. Popescu$^j$, A.M. Rogers$^k$, G. Susoy$^f$, C. Stodel$^g$, T. Suzuki$^h$
A. Tamii$^h$, J.C. Thomas$^g$

$^a$Instituto de Física Corpuscular, CSIC-Universidad de Valencia
46071 Valencia, Spain

$^b$Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

$^c$Centre d’Études Nucléaires de Bordeaux Gradignan, CNRS/IN2P3 —
Université Bordeaux 1, 33175 Gradignan Cedex, France

$^d$Department of Physics, University of Surrey, Guildford GU2 7XH, Surrey, UK

$^e$Institute of Nuclear Research of the Hungarian Academy of Sciences
Debrecen, 4026, Hungary

$^f$Department of Physics, Istanbul University, Istanbul 34134, Turkey

$^g$Grand Accélérateur National d’Ions Lourds, BP 55027, 1407 Caen, France

$^h$Research Center for Nuclear Physics, Osaka University, Ibaraki
Osaka 567-0047, Japan

$^i$Comisión Chilena de Energía Nuclear, Casilla 188-D, Santiago, Chile

$^j$SCK.CEN, Boeretang 200, 2400 Mol, Belgium

$^k$Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

(Received January 12, 2015)

A study of the β decay of the proton-rich $T_z = -2$ nucleus $^{56}$Zn has been reported in a recent publication. A rare and exotic decay mode, β-delayed γ-proton decay, has been observed there for the first time in the fp shell. Here, we expand on some of the details of the data analysis, focusing on the charged particle spectrum.

DOI:10.5506/APhysPolB.46.709
PACS numbers: 23.40.–s, 23.50.+z, 21.10.–k, 27.40.+z

* Presented at the Zakopane Conference on Nuclear Physics “Extremes of the Nuclear Landscape”, Zakopane, Poland, August 31–September 7, 2014.
1. Introduction

The $\beta$ decay of the $T_z = -2$ nucleus $^{56}\text{Zn}$ has been studied recently [1]. Among the interesting results, a rare and exotic decay mode has been observed for the first time in the $fp$ shell, the $\beta$-delayed $\gamma$-proton emission. Here, we provide more detail of the data analysis, not discussed in Ref. [1], that is important for the proper determination of the $\beta$-decay strengths. We focus on the determination and subsequent analysis of the charged-particle spectrum measured by the Double-Sided Silicon Strip Detector (DSSSD).

2. The experiment

The $\beta$-decay experiment was performed at GANIL using a $^{58}\text{Ni}^{26+}$ primary beam of 3.7 $\text{e}\mu\text{A}$, accelerated to 74.5 MeV/nucleon and fragmented on a 200 $\mu$m thick $\text{natNi}$ target. The fragments were selected by the LISE3 separator and implanted into a DSSSD (300 $\mu$m thick), surrounded by four EXOGAM Ge clovers for $\gamma$ detection. The DSSSD had 16 X and 16 Y strips, defining 256 pixels. The DSSSD was used to detect both the implanted fragments and subsequent charged-particle decays, by employing two parallel electronic chains of different gain. An implantation event was defined by simultaneous signals in both a silicon $\Delta E$ detector located upstream and the DSSSD. The implanted ions were identified by combining the energy loss signal in the $\Delta E$ detector and the Time-of-Flight (ToF) defined as the time difference between the cyclotron radio-frequency and the $\Delta E$ signal (see Fig. 1). Decay events were defined as giving a signal above threshold (50–90 keV) in the DSSSD and no coincident $\Delta E$ signal.

![Fig. 1. $\Delta E$ versus ToF identification plot showing the position of the $^{56}\text{Zn}$ implants.](image)

3. The DSSSD charged-particle spectrum

The correlation time is defined as the time difference between a decay event in a given pixel of the DSSSD and any implantation signal that occurred before and after it in the same pixel and also satisfied the conditions required to identify the nuclear species. This procedure ensured that all the
true correlations were taken into account. However, many random correlations were also included producing, as expected, a large constant background. The correlation-time spectrum for $^{56}\text{Zn}$ including all the decays ($\beta$s and protons) is shown in Fig. 2 (a).
where the number of counts is low. Moreover, the choice of an interval on
the left of the time peak ensures that only randoms are included in the bg
spectrum.

The DSSSD spectrum was calibrated using an $\alpha$-particle source and the
peaks of known energy from the decay of $^{53}$Ni [2]. Most of the strength
in Fig. 2 (b) is interpreted as $\beta$-delayed proton emission. The resolution
is limited by the summing with the coincident $\beta$ particles, which also affects
the lineshape of the peak. Monte Carlo simulations were performed for a
Silicon DSSSD strip, using the 4.9.6 Geant4 code. The radioactive sources
were located in an extended area in the middle of the detector, with an
implantation profile obtained from LISE calculations. Protons of a given
energy $E_p$ were emitted at the same time as $\beta$ particles following a distri-
bution determined by the Fermi function ($\beta$-decay event generator), with
end-point energy corresponding to $Q_\beta - E_p - S_p$ (where $S_p$ is the proton
separation energy in the daughter nucleus). At the event generation level,
a widening of 70 keV FWHM was imposed, corresponding to the DSSSD
experimental resolution. As an example, the result of the simulations for a
single level at $E_X = 1.7$ MeV ($E_p = 1.1$ MeV) is shown in Fig. 2 (c). To a
good approximation the lineshape is given by a Gaussian plus an exponential
high-energy tail. This result is an additional confirmation of the procedure
widely used in Ref. [2]. The lineshape obtained from the simulations, which
was also checked with the well isolated $^{57}$Zn peak at $E_p = 4.6$ MeV, was
then used to fit the experimental spectrum (Fig. 2 (b)). The shape was kept
fixed (i.e., the Gaussian-exponential joining and the slope of the exponen-
tial), while the parameters of the Gaussian (height, mean, sigma) were fitted
to the experimental proton peaks. This procedure allows one to determine
the intensities of the proton peaks properly and hence obtain the $\beta$-decay
strengths.

This work was supported by the Spanish MICINN grants FPA2008-
06419-C02-01, FPA2011-24553; CPAN Consolider-Ingenio 2010 Programme
CSD2007-00042; MEXT, Japan 18540270 and 22540310; Japan–Spain col-
aboration program of JSPS and CSIC; Istanbul University Scientific Re-
search Projects, No. 5808; UK Science and Technology Facilities Council
(STFC) Grant No. ST/F012012/1; Region of Aquitaine. R.B.C. acknowl-
dges support from the Alexander von Humboldt foundation and the Max-
Planck-Partner Group. We acknowledge the EXOGAM collaboration for
the use of their clover detectors.

REFERENCES