First observation of $\beta$-delayed $\gamma$-proton decay in the $T_z = -2$, $^{56}$Zn nucleus

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We report on the first experimental observation of a very exotic decay mode at the proton drip-line, the $\beta$-delayed $\gamma$-proton decay, clearly seen in the $\beta$ decay of the $T_z = -2$, $^{56}$Zn nucleus. The $^{56}$Zn half-life and decay scheme have been determined. The decay proceeds by $\beta$-delayed proton emission and $\beta$-delayed $\gamma$ de-excitation. The exotic $\beta$-delayed $\gamma$-proton emission was also detected in three cases. It affects the usual determination of the Gamow-Teller (GT) strength. Absolute Fermi and GT strengths have been deduced. Evidence for fragmentation of the Fermi strength due to isospin mixing is found.

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The study of the properties of nuclei far from the valley of nuclear stability lies at one of the main frontiers of modern nuclear physics. Measurements of nuclear masses, radii, and studies of decay modes of exotic nuclei are the vital input and guidance needed to sustain and support major advances in theories of nuclear structure [1]. Our descriptions of nuclear properties are moving away from the empiricism of the past towards a comprehensive, quantitative framework that is able to predict nuclear properties even in the Terra Incognita at the drip-lines. Instead of the familiar $\alpha$, $\beta$, and $\gamma$-decay, a marked change is the appearance of new decay modes as the nuclei become more weakly bound. In an extreme case such as $^{11}$Li many decay channels are open [2]. For heavier nuclei we find on the neutron-rich side of stability $\beta$-delayed fission [3,4], and close to the proton drip-line proton ($p$) [5] and 2$p$-radioactivity [7,8].

Among many possible observables, the $\beta$ decay strengths provide important testing grounds for the nuclear structure theories far from stability. The mechanism of $\beta$ decay is well understood and dominated by allowed Fermi (F) and Gamow-Teller (GT) transitions, where the strengths are expressed in terms of $B(F)$ and $B(GT)$, respectively. The Fermi transition feds the Isobaric Analogue State (IAS), which forms an isospin multiplet with the ground state (gs) of the mother nucleus. Isospin is a good quantum number in nuclei, thus the isospin selection rule has to be satisfied also in the decay.

In this Letter we present the first observation of a new decay mode that can strongly affect the conventional way of analyzing the $\beta$-decay data to deduce absolute $B(F)$ and $B(GT)$ values. These quantities are estimated, for each state populated in the decay, from the $\beta$ feeding to that state, together with the half-life $T_{1/2}$ and decay energy. The $\beta$ feeding is obtained by measuring the intensities of $\beta$-delayed particles or $\gamma$ rays de-excitating the state. From medium to heavy nuclei, close to the stability, the de-excitation proceeds via $\beta$-delayed $\gamma$ decay. As the nuclei become more exotic, the particle separation energy decreases, thus the strong interaction sets in and the de-excitation proceeds via $\beta$-delayed particle emission. For example, in proton rich nuclei the proton decay mode dominates for states well above the proton separation energy $S_p (>1$ MeV above $S_p$). However, when the de-excitation of the IAS via proton decay is isospin forbidden [9, 10], competition between $\beta$-delayed proton emission and $\beta$-delayed $\gamma$ de-excitation becomes possible, as observed in the decay of the $^{52}$Co IAS [9], situated 1.3 MeV above $S_p$. In such a case, one has to take into account the intensity of the proton emission and $\gamma$ transition to estimate $B(F)$.

We report here the results of a study of the $T_z = -2 \rightarrow -1, \beta^+ \gamma$ decay of $^{56}$Zn to $^{56}$Cu [$T_z = (N - Z)/2$], where we observe competition between $\beta$-delayed proton and $\gamma$ emission in states well above $S_p$. Moreover we observe for the first time $\beta$-delayed $\gamma$ rays that populate levels in
the daughter nucleus that are proton unbound and decay by proton emission. This observation is very important not only because a new exotic decay mode has been discovered, but also because it does affect the conventional determination of \( B(GT) \). Usually \( B(GT) \) is simply deduced from the intensity of the proton decay but here, in order to properly determine \( B(GT) \), the intensity of the proton transition has to be corrected for the amount of indirect feeding coming from the \( \gamma \) de-excitation. The physics information can be extracted only if the charged particle detectors are combined with \( \gamma \) detectors of adequate efficiency. This decay mode will occur also in heavier systems with \( T_z \leq -3/2 \), whose study is planned at present and future radioactive beam facilities.

Prior to the present work little was known about \( ^{56}\text{Zn} \) and the excited states of its daughter \( ^{56}\text{Cu} \). \( \beta \)-delayed protons were observed \cite{9}, but not \( \beta \)-delayed \( \gamma \) rays. The present experiment is of interest also in terms of the comparison with the mirror charge exchange (CE) reaction on the \( T_z = +2 \) nucleus \( ^{56}\text{Fe} \) \cite{14}. Indeed \( \beta \) decay and CE studies are complementary tools and, under the assumption of isospin symmetry, they can be combined to determine the absolute \( B(GT) \) up to high excitation energies \cite{12,14}.

The \( \beta \)-decay experiment was performed at the LISE3 facility of GANIL \cite{14} in 2010, using a \( ^{58}\text{Ni}^{26+} \) primary beam with an average intensity of 3.7 e\( \mu \)A. This beam, accelerated to 74.5 MeV/nucleon, was fragmented on a 200 \( \mu \)m thick natural Ni target. The fragments were selected by the LISE3 separator and implanted into a Double-Sided Silicon Strip Detector (DSSSD), surrounded by four EXOGAM Ge clovers for \( \gamma \) detection. The DSSSD was 300 \( \mu \)m thick and had 16 X and 16 Y strips with a pitch of 3 mm, defining 256 pixels. They were used to detect both the implanted fragments and subsequent charged-particle (\( \beta \)s and protons) decays. For this purpose, two parallel electronic chains were used having different gains: low and high gain amplification for this purpose, two parallel electronic chains were used having different gains: low and high gain amplification for the energy loss signal in the first \( \Delta E \) detector located upstream and the DSSSD. The implanted ions were identified by combining the energy loss signal in the first \( \Delta E \) detector (300 \( \mu \)m thick) and the Time-of-Flight (ToF) defined as the time difference between the cyclotron radio-frequency and the \( \Delta E \) signal. Decay events were defined as giving a signal above threshold (typically 50-90 keV) in the DSSSD and no coincident signal in the \( \Delta E \) detector.

The \( ^{56}\text{Zn} \) ions were selected by setting gates off-line on the \( \Delta E \)-ToF matrix. The total number of implanted \( ^{56}\text{Zn} \) nuclei was 8.9x10\(^{-3} \). 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 that satisfied the conditions required to identify the nuclear species. The proton decays were selected by setting an energy threshold above 800 keV (removing the daughter \( \beta \) decays, see the discussion about the DSSSD spectrum) and looking for correlated \( ^{56}\text{Zn} \) implants happening within ± 50 s. 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 \( ^{56}\text{Zn} \) is shown in Fig. 1. The data were fitted with a function including the \( \beta \) decay of \( ^{56}\text{Zn} \) and a constant background. A half-life \( (T_{1/2}) \) of 32.9(8) ms was obtained for \( ^{56}\text{Zn} \), in agreement with \cite{9}.

The charged-particle spectrum measured in the DSSSD for decays associated with \( ^{56}\text{Zn} \) implants is shown in Fig. 2(a). It was formed as in \cite{9} and calibrated using an \( \alpha \)-particle source and the \( ^{53}\text{Ni} \) peaks of known energy.

Two kinds of state are expected to be populated in the \( \beta \) decay of \( ^{56}\text{Zn} \) to \( ^{56}\text{Cu} \): the \( T = 2 \), \( 0^+ \) IAS, and a number of \( T = 1 \), \( 1^+ \) states. From the comparison with the mirror nucleus \( ^{56}\text{Co} \), all of these states will lie above \( S^p \) = 560(140) keV \cite{16} (\( S^p \) means from systematics), thus they will decay by proton emission. Indeed most of the strength in Fig. 2(a) is interpreted as \( \beta \)-delayed proton emission to \( ^{55}\text{Ni}^{9+} \). We attribute the broad bump below 800 keV to \( \beta \) particles that are not in coincidence with protons. The proton peaks seen above 800 keV are labeled with the level excitation energies in \( ^{56}\text{Cu} \). The large uncertainty in the estimated \( S^p \) leads to the error of ±140 keV in the \( ^{56}\text{Cu} \) level energies. The energy resolution for protons is 70 keV FWHM, however the achievable resolution is limited by the summing with the \( \beta \) particles. The proton decay of the IAS is identified as the peak at 3508 keV, as in \cite{9}.

Figure 2(b) shows the corresponding states in \( ^{56}\text{Co} \), populated in the mirror \( T_z = +2 \rightarrow +1 \), \( \beta^- \)-type CE reaction on the stable \( T_z = +2 \) target \( ^{56}\text{Fe} \). The spectrum was obtained with high resolution in the \( ^{56}\text{Fe}(^3\text{He},t)^{56}\text{Co} \) reaction at RCNP Osaka \cite{14}. Figs. 2(a) and 2(b) have been aligned so that the peaks labeled by excitation energy in \( ^{56}\text{Co} \) lie below the \( \beta^- \)-delayed proton peaks marked by the excitation energies of the levels in \( ^{56}\text{Cu} \). There is
It should be noted that the energies of the corresponding levels in $^{56}\text{Cu}$ and $^{56}\text{Co}$ differ by less than 100 keV if we take the value of $S_p$ from [16]. If we use the latest value from [19] we find that the energies differ by $\sim 400$ keV. Accordingly we have adopted $Q_{EC} = 12870(300)$ keV, the value given in [16].

The proton decay of the 3508 keV, $T = 2$ IAS in $^{56}\text{Cu}$ to the $T = 1/2$, $^{55}\text{Ni}_{gs}$ is isospin forbidden [9, 10], which makes the competing $\gamma$ de-excitation possible. The $\gamma$-ray spectrum measured in coincidence with the decays correlated with $^{56}\text{Zn}$ implants is shown in Fig. 2(a), after removal of the background of random correlations as in the DSSSD spectrum. A $\gamma$ line was observed at 1834.5(10) keV, in agreement with the energy difference between the 3508 and 1691 keV $^{56}\text{Cu}$ states (1817(15) keV), therefore this $\gamma$ 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 proton decay from the level at 1691 keV (Fig. 3(b)). Moreover, the half-life associated with the 1835 keV peak, $T_{1/2} = 27(8)$ ms, is in good agreement with the $^{56}\text{Zn}$ half-life.

Other cases of $\gamma$ decay from an IAS above $S_p$ have been observed in this mass region [9]. The particular circumstance here is that the 1691 keV level is also proton-unbound (with an estimated width $\Gamma \sim 10^{-8}$ MeV) and consequently a rare and exotic decay process has been observed for the first time, which is a $\beta$-delayed gamma-proton decay. This observation cannot be interpreted as a $\beta$-delayed proton-decay to an excited state of $^{55}\text{Ni}$, followed by a $\gamma$ decay to the $^{55}\text{Ni}_{gs}$, because the state populated would have an energy of 1835 keV, while the first excited state in $^{55}\text{Ni}$ lies at 2089 keV.

Imposing coincidence conditions on the various proton peaks in Fig. 2(a), two additional $\gamma$ rays were observed. The first one is seen at 861 keV (Fig. 3(c)) and corresponds to the de-excitation from the 3508 keV IAS to the 2661 keV state. The second lies at 309 keV (Fig. 3(d)) and is interpreted as the electromagnetic transition con-
necting the 1691 and 1391 keV states.

All of our observations are summarized in the $^{56}$Zn decay scheme shown in Fig. 4. Solid lines indicate experimentally observed proton and $\gamma$ decays, while dashed lines represent transitions seen in the mirror $^{56}$Co nucleus. Three cases of $\beta$-delayed $\gamma$-proton emission have been established experimentally, involving the $\gamma$ rays at 1835, 861 and 309 keV and the levels at 1691, 2661 and 1391 keV, respectively.

For a proper determination of $B(F)$ and $B(GT)$, the $\beta$ feeding to each $^{56}$Cu level was estimated from the areas of the $\gamma$ and proton peaks, corrected for the amount of indirect feeding produced by the $\gamma$ de-excitation. The latter comes from the intensities of the observed $\gamma$ lines and estimates based on the $\gamma$ de-excitation pattern in the mirror $^{56}$Co nucleus [13]. Assuming 100% DSSSD efficiency for both implants and protons [9], a total proton branching ratio $B_p = 88.5(26)\%$ is obtained by comparing the total number of $^{56}$Zn implants with the number of observed protons above 800 keV (Fig. 2(a)), where the uncertainty takes account of the systematics due to the choice of the integration limits for the protons. The missing 11.5(26)\% is attributed to the $\beta$-delayed $\gamma$ emission from the 1691 keV level (in analogy with $^{56}$Co), where the estimated partial proton half-life is $t_{1/2} \sim 10^{-14}$ s, an order-of-magnitude where the $\gamma$ de-excitation can compete with the proton emission. In particular, it is estimated that the $\gamma$ decays represent $56(6)\%$ and $66(22)\%$ of the total decays from the 3508 keV IAS and 1691 keV state, respectively.

The measured $t_{1/2}$, $\beta$ feedings and $B_p$ were used, together with the $Q_{EC}^g$ from [10], to determine the $B(F)$ and $B(GT)$ values, which are shown in Table I.

The total Fermi transition strength has to be $|N - Z| = 4$. The $^{56}$Cu IAS at 3508 keV gets a Fermi strength $B(F) = 2.7(5)$. The missing strength, 1.3(5), has to be hidden in the broad peak at 3423 keV. This is a confirmation that the $^{56}$Cu IAS is fragmented and thus part of the feeding of the 3423 keV level (in analogy with $^{56}$Co), where the estimated partial proton half-life is $t_{1/2} \sim 10^{-14}$ s, an order-of-magnitude where the $\gamma$ de-excitation can compete with the proton emission.

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

| $^{56}$Cu level (keV) | $\beta$ feeding (%) | $B(F)$ | $B(GT)$ |
|-----------------------|----------------------|--------|---------|
| 3508(140) (IAS)       | 43(5)                | 2.7(5) | $\leq 0.32$ |
| 3423(140)             | 21(1)                | 1.3(5) | 0        |
| 2661(140)             | 14(1)                | 0.34(6)| 0        |
| 2537(140)             | 0                    | 0      | 0        |
| 1691(140)             | 22(6)                | 0.30(9)| 0        |
| 1391(140)             | 0                    | 0      | 0        |

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