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Study on the isomeric decay of neutron-rich isotope ^{67}Fe

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Abstract: Gamma-delayed spectroscopy measurements of ^{67}Fe have been performed at RIKEN, Japan. The spectra from (p, 2p) and (p, pn) channels show a sharp peak at 367 keV. While the total isomer-yield spectrum presents clearly 2 peaks at 367 and 387 keV. The ratio of these two gammas' intensity was determined to be equal to 0.126(3), in agreement with previous experiments. The origin of these two gammas could be from different isomers of ^{67}Fe. The half-life ($T_{1/2}$) of the isomer which decays to the 367 keV level was determined to be equal to 150(10) □s, more than twice as long as from previous experiments.

Keywords: *SEASTAR, BigRIPS, ZeroDegree, EURICA, ^{67}Fe, isomer.*

I. INTRODUCTION

With the availability of high-intensity Radioactive Isotope Beams (RIBs), many experiments have been carried out to study the structure of (very) neutron-rich nuclei. Besides prompt gamma spectroscopy [1-3], cross sections [4] and momentum distribution [5-6] measurements, the isomers of neutron-rich nuclei have also been studied [7-11]. The study on the isomeric states provides unique structural information of the nucleus under consideration, for example particle-hole configurations leading to the nuclear deformation [12] or intruder states [9].

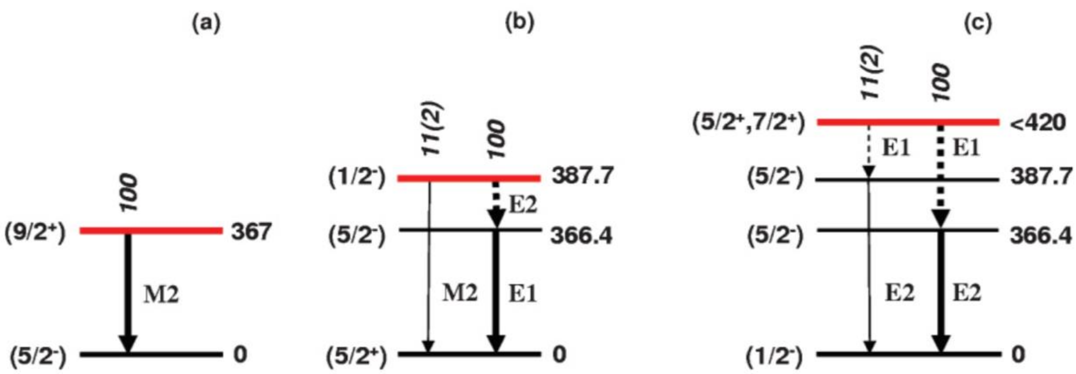

Fig. 1. Level scheme of ^{67}Fe. Panels a), b), and c) are proposed in Refs. [9], [10] and [11], respectively. The red lines are isomeric levels. This figure is taken from Ref. [11].

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In particular, for ^{67}Fe, isomeric states were studied via 367 and 387 keV transitions [9-11]. However, the origins of the isomeric states are still controversial. The first study observed the 367 keV transition [9]. This level was thought to be isomeric state $9/2^+$ decaying to the ground state $5/2^-$ via a M2 transition, see Figure 1.a. Afterwards, M. Sawicka *et al.* reported that beside 367 keV they also observed 387 keV transition from ^{67}Fe isomer [10]. The 387 keV level was concluded isomeric and the 367 keV was in the cascade of this isomer when it decays to the ground state. The branching ratio ($I_{\square}$) of these two transitions was Iγ(387)/Iγ(367)=0.11(2) [10]. The summary of the study in Ref. [10] is presented in Figure 1.b. Recently, an important conclusion was reported by J.M. Daugas *et al.* in Ref. [11]. Where, the 367 and 387 keV prompt transitions of ^{67}Fe were observed in the β-decay of ^{67}Mn. It meant that the 387 keV level is not isomeric. Moreover, the ratio of these transitions were determined to be Iγ(387)/Iγ(367)=0.77(26), different from the above value of 0.11(2) obtained in Ref. [10]. This led to the conclusion that the initial isomers of the 367 and 387 keV transitions may be different. No information concerning the direct feeding of the isomeric states was extracted by the ^{67}Mn β-decay experiment in Ref. [11]. Together with the studies in Refs. [9-10], the isomeric levels were proposed to be above 387 keV, which decays via highly converted transition or γ transition of too low energy to be observed. Therefore, the isomeric levels were proposed to be less than 420 keV. The explanation for the measurement in Ref. [11] is shown in Figure 1.c. According to the calculation [11], the 2 possibly isomeric states are $5/2^+$ and $7/2^+$. The ground state is $1/2^-$ obtained from Ref. [13]. In addition to the gamma spectrum, the half-life of the isomeric state which decays to the 367 keV level was determined with large discrepancy, 43(30) μs in Ref. [9] and 75(21) μs in Ref. [10].

In this paper, a study of the above mentioned isomers of ^{67}Fe is reported. First, we discuss the delayed-gamma-ray energy spectrum. Afterwards, we discuss the half-life of the isomeric state based on the time-dependence of the observed events. The experiment was performed within the framework of the "*Shell Evolution And Search for Two-plus energies At RIBF*" (RIBF-Radioactive Isotope Beam Factory) project [14], in short SEASTAR.

II. EXPERIMENTAL METHOD

A ^{238}U primary beam with the mean intensity of 12 pnA was accelerated up to 345 MeV/*u* energy by the Superconducting Ring Cyclotron (SRC). Afterwards, it bombarded a ^{9}Be primary target at the F0 focal plane of the BigRIPS [15] separator to produce the secondarily cocktail beam. The secondary beam was transported to the user location at the F8 focal plane and interacted with MINOS [16] LH_2 active target. Prompt gamma de-excitation from residues was detected by the DALI2 [17] NaI crystals surrounding the MINOS target. Measuring prompt gamma-ray energies was the main purpose of the SEASTAR experiments. The experimental setup for this purpose is shown in Figure 2, and described in details in Refs. [18-19].

For the delayed-gamma study, an additional detector setup, EURICA (Euroball-RIKEN Cluster Array) [20], was located at the end of the experimental setup described in Figure 2, at the F11 focal point. This gamma-ray detector array consists of 84 high-purity germanium crystals (HPGe) subdivided into 12 7-crystal clusters distributed in three different rings at 51^o (five clusters), 90^o (two clusters), and 129° (five clusters) relative to the beam axis at a nominal distance of 22 cm from the center. The energy resolution of the HPGe crystal detector was better than 3 keV at E_γ=1.3 MeV with a photo-peak efficiency of about 15% for E_γ= 662 keV [20]. The beam was stopped in a thick-aluminium plate centered in the arrays. A picture of the stopper surrounded by the EURICA clusters is shown in Figure 3.

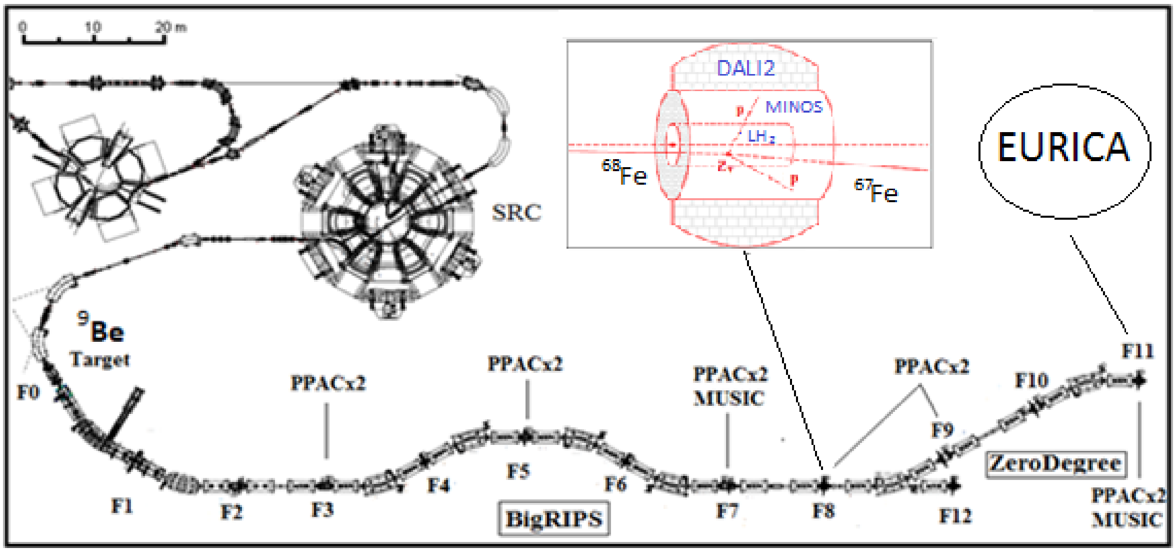

Fig. 2. Experimental setup for prompt-gamma detection in SEASTAR experiments. The label Fn indicates the position of foci. BigRIPS is from F1-F8. ZeroDegree is from F9-F11. PPACs and MUSICs were used for tracking and identifying purpose. The inset is a sketch of the main detectors MINOS and DALI2 with an illustration for ^{68}Fe(p, pn)^{67}Fe. Z_v is the vertex point. EURICA was located at F11 for the decay study.

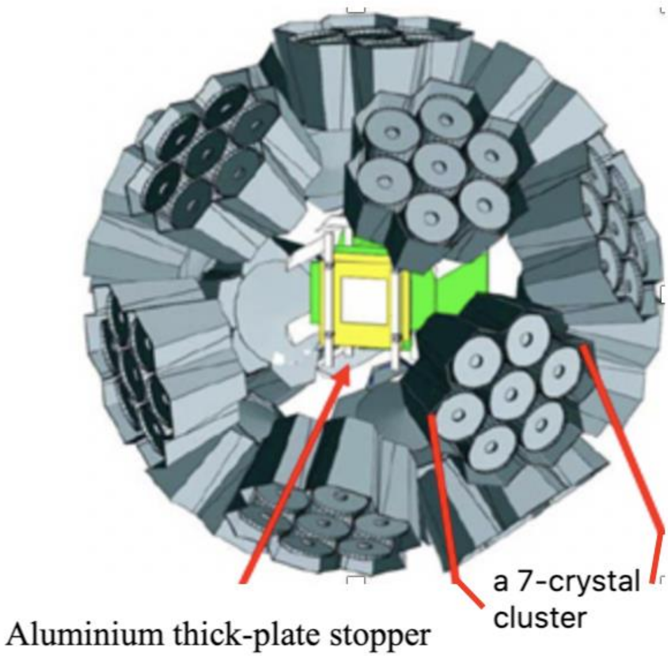

Fig. 3. Illustration of EURICA detector with a thick-aluminium-plate stopper at the center.

III. DATA ANALYSIS AND RESULTS

For the present isomeric study, the identification for the implanted ^{67}Fe ions in the aluminium stopper was considered. This required the particle identification (PID) from the ZeroDegree spectrometer [15], in other words the PID for outgoing particles from the MINOS target. EURICA detected the gammas emitted from implanted ions. The independent ZeroDegree and EURICA data was merged according to their time stamp with an additional in-beam trigger from DALI2 for separation of the data into different reaction channels, or analyzed independently for high-statistics total isomer-yield.

Due to the inclusion of BigRIPS data via the DALI2 data stream, it was possible to identify the relative ratio of ^{67}Fe isomeric-decay intensity from the different channels [21]. The channel PID has been discussed in details in Ref. [18-19]. As an example, the ^{68}Fe(p, pn)^{67}Fe identification is shown in Figure 4.

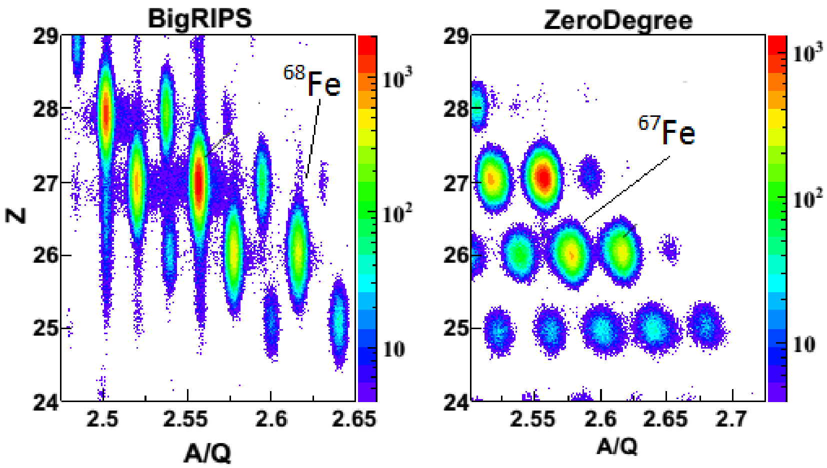

Fig. 4. Particle identification via atomic charge (Z) versus mass-to-charge ratio (A/Q). The marked crowns are identified for ^{68,67}Fe at BigRIPS and ZeroDegree, respectively, for ^{68}Fe(p,pn)^{67}Fe channel.

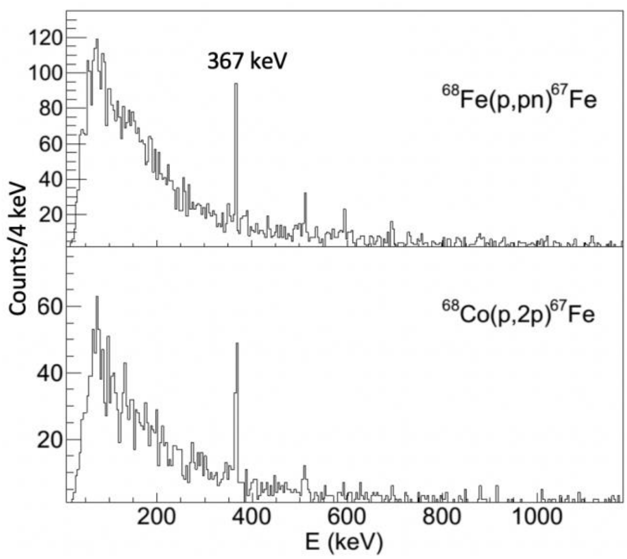

Fig. 5. Delayed gamma energy spectra of ^{67}Fe from (p,2p) and (p,pn) channels detected by EURICA.

The delayed gamma energy spectra of ^{67}Fe from (p,2p) and (p,pn) channels are presented in Figure 5. In both cases, the gamma of 367 keV are clearly observed.

For higher statistics, the trigger without DALI2 gamma detection was used. In this case, only the ZeroDegree trigger was consider to identify implanted ^{67}Fe ions into aluminium thick-plate stopper, see Figure 3. The total isomeric spectrum is presented in Figure 6. Two lines are observed at 367 and 387 keV. The relative ratio Iγ(387)/Iγ(367) is determined to be equal to 0.126(3) in agreement with the value 0.11(2) reported in Ref. [10]. This might be from the fact that the implanted ^{67}Fe ions in the present study and Ref. [10] were produced by knockout reactions of an approximately 250 MeV/u cocktail beam on a proton target and by fragmentation of the 60 MeV/u ^{86}Kr beam on ^{nat}Ni target, respectively. As the result, the ^{67}Fe isomers were fed by these similar mechanisms that was not the case of the ^{67}Mn β-decay experiment in Ref. [11].

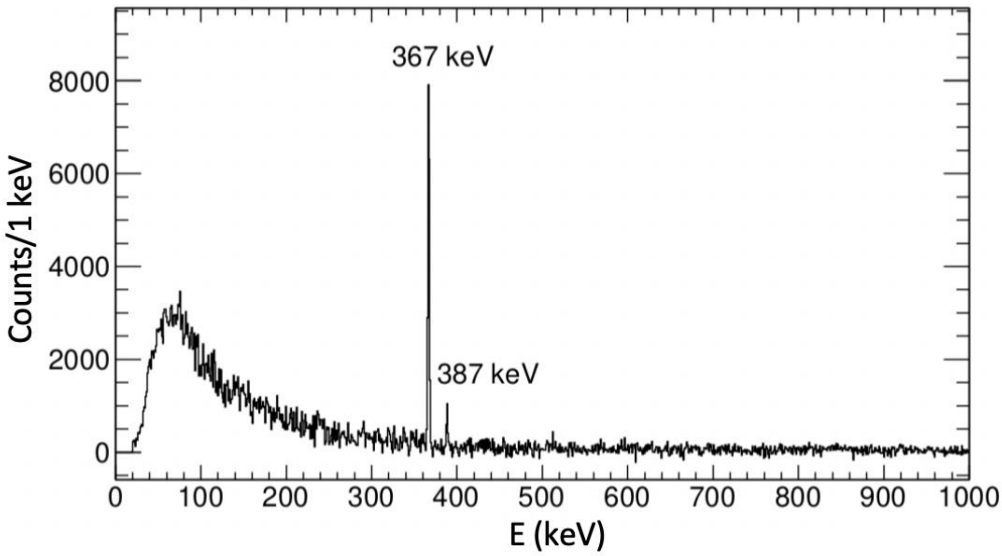

Fig. 6. The total isomer-yield gamma energy spectrum of ^{67}Fe detected by EURICA.

From Figure 5 and 6, it is seen that the 387 keV line is visible only in the total isomer-yield gamma spectrum. This is explained that either the particular (p, 2p) and (p, pn) reactions do not feed the isomer which decays to the 387 level or the statistic is not enough.

The decay curve was built by gating on 367 keV in the EURICA HPGe array and plotting the time-difference between the HPGe and the final BigRIPS scintillator, see Figure 7. This curve was fitted with an exponential function to get the half-life of the decay. From this we obtained a half-life of $T_{1/2}$=150(10) µs. Compared to the previous result, the current value is about twice the most recently reported value of 75(21) µs [10]. This discrepancy could be related to the time range in the current experiment, up to 100 µs, while the range was only 45 µs in Ref. [10]. For a long half-life, this leads to a bias of the fitting results for too short time-ranges. Moreover, our statistics are much higher than previous work [10] which also influences the fitting results.

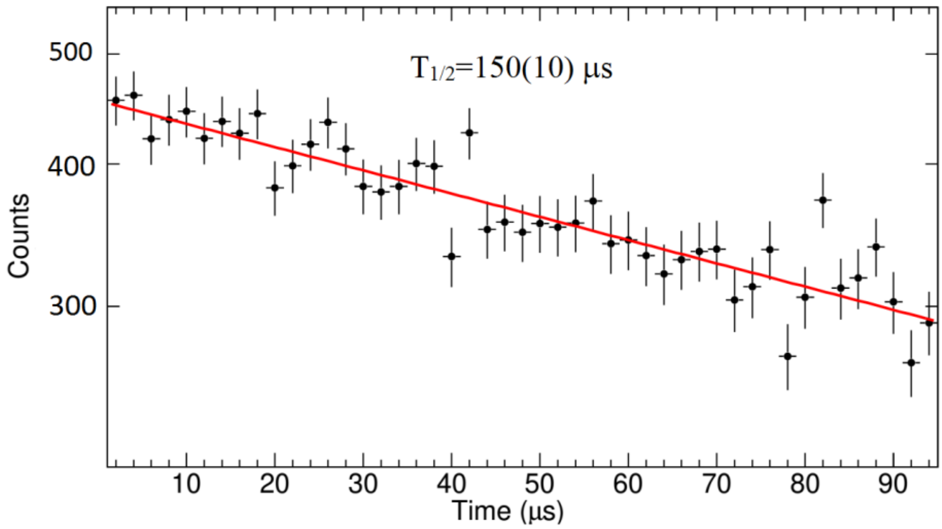

Fig. 7. Decay curve of the isomer via 367 keV state in ^{67}Fe. The points with error bar are experimental data. The solid line is the fitting exponential curve.

IV. CONCLUSIONS

In this paper, the study on the isomeric decay of neutron-rich isotope ^{67}Fe is reported. The gamma-delayed energy spectra of this isotope were recorded from ^{68}Co(p, 2p)^{67}Fe and ^{68}Fe(p, pn)^{67}Fe channels as well as ^{238}U fission. The spectra obtained from these first 2 channels clearly show the peak at 367 keV. While the total isomer-yield spectrum clearly presents 2 lines at 367 and 378 keV. The invisibility of 378 keV line was explained either the (p, 2p) and (p, pn) channels did not feed these isomer which decays to ground state via 387 keV gamma emission or the statistics is not enough. The half-life time of the isomer which decays to the 367 keV level was measured to be equal to 150(10) μs, significantly longer than previously measurements.

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