Letter

β-delayed two-proton decay of ^{27}S at the proton-drip line

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(Received 3 March 2021; accepted 21 May 2021; published 15 June 2021)

The β-delayed two-proton ($\beta 2p$) decay of ^{27}S was studied using a state-of-the-art silicon array and Clover-type HPGe detectors. An energy peak at 6372(15) keV with a branching ratio of 2.4(5)% in the decay-energy spectrum was identified as a two-proton transition via the isobaric-analog state in ^{27}P to the ground state of ^{25}Al in the β decay of ^{27}S. Two-proton angular correlations were measured by the silicon array to study the mechanism of two-proton emission. Based on experimental results and Monte Carlo simulations, it was found that the main mechanism for the emission of $\beta 2p$ by ^{27}S is of sequential nature.

DOI: 10.1103/PhysRevC.103.L061301

Nuclei far from the β-stability line exhibit various decay modes [1–3]. Of particular interest are the β-delayed one- or multiparticle emissions, which become more dominant near the neutron or proton drip lines and provide access to the nuclear structure properties. One of the interesting decay modes is the β-delayed two-proton ($\beta 2p$) emission, which is a rare decay process for nuclei in the proton-rich region with the

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window of $Q_{\beta^+} - S_{2p} > 0$. The exotic phenomenon of $\beta 2p$ decay was first predicted and discussed by Goldanskii [4]. It was followed almost immediately by the first experiment performed by Cable *et al.* [5], in which two $2p$ transitions to the first-excited and ground state of ^{20}Ne were observed in the β decay of ^{22}Al. A number of $\beta 2p$ emitters have been identified since then [1–3]. Recently, a $\beta 2p$ emission through the isobaric-analog state (IAS) of ^{22}Al was observed in the decay of ^{22}Si, the lightest nucleus with $T_z = -3$ in the nuclide chart [6].

In the β2p emission, energy and momentum conservation [7] are not sufficient to fully explain the momenta and energy distribution between emitted protons. In general, the two-proton emission can be classified as follows: (1) direct emission, where two protons escaping simultaneously show strong correlations, and (2) sequential emission, where two protons emitted through an intermediate state can be treated as two independent protons. Based on branching ratios and decay widths calculated by shell model, it was predicted that only a small percentage of direct emission happened in $\beta 2p$ [8]. Indeed, all experiments performed thus far have indicated that the predominant mechanism of the emission is sequential. Two individual experiments on the β decay of ^{22}Al were performed by Cable *et al.* [5] and Wang *et al.* [9], which reported an upper limit of 15% and 29(13)% for the direct emission, respectively. However, both experiments did not have sufficient statistics to draw a conclusion. On the other hand, it has been shown that the detailed analysis of the $\beta 2p$ mechanism of ^{31}Ar provides precise data for studying nuclear structure [10,11].

The first decay spectroscopy of ^{27}S was performed by implanting the ions into silicon detectors [12]. $\beta 2p$ from the IAS at 12 MeV of ^{27}P to the ground state of ^{25}Al was observed, but no other decay channel was reported due to the low statistics and high contamination. Canchel *et al.* repeated the experiment by using the similar method and observed several high-energy β-delayed proton branches [13]. The successful determination of absolute branching ratios of two low-energy proton transitions were achieved via a time-projection chamber technique [14]. Recently, the emissions of β-delayed one proton and γ by ^{27}S were measured by Sun *et al.* [15]. The precise decay data of ^{27}S gave an experimental constraint on the ^{26}Si$(p,\gamma)^{27}$S reaction rate, confirming that the dominant contribution of the galactic ^{26}Al synthesis is from the β^+ decay of ^{26}Si [16]. In this Letter, we report on the results of the two-proton emission from the IAS of ^{27}P to the ground state of ^{25}Al in the β decay of ^{27}S and discuss its mechanism based on measured angular correlations.

The β-decay experiment of ^{27}S was performed at the National Laboratory of Heavy Ion Research Facility of Lanzhou (HIRFL) [17]. The nuclei of interest were produced via the projectile fragmentation of a 80.6 MeV/nucleon ^{32}S^{16+} primary beam impinging upon a 1581-μm-thick ^{9}Be target. The projectile fragments were separated and purified using the Radioactive Ion Beam Line in Lanzhou (RIBLL1) [18]. The ions in the secondary beam were identified by using the energy loss (ΔE) and time-of-flight (ToF) information obtained with two quadrant silicon detectors (QSDs) and two plastic scintillators, respectively. During the 95.3-hour measurement, the average intensity and purity of ^{27}S delivered to the detection array (shown in Fig. 1) were 0.14 pps and 0.024%, respectively. Under a continuous-beam mode, the isotopes of interest were implanted into three W1-type double-sided silicon strip detectors (DSSDs) with thicknesses of 142 μm (DSSD1), 40 μm (DSSD2), and 304 μm (DSSD3) in a certain proportion. Each DSSD was segmented into 16 horizontal and 16 vertical strips with an active area of 5×5 cm^2, providing a pixel resolution of 3.1×3.1 mm^2 for the position measurement for charged particles. The thinnest DSSD2 installed between DSSD1 and DSSD3 was mainly used to detect low-energy protons to reduce the peak shifts from the β-summing effect [19,20]. The thicker ones, DSSD1 and DSSD3, were employed for the measurement of high-energy protons and β particles. A total of 3×256 pixels were used to encode the position and energy information of charged particles. All charged signals processed by the DSSDs were split and fed to high-gain and low-gain preamplifiers for decay charged-particles (β and protons) and implanted heavy-ions, respectively. The energy calibrations for all DSSDs were done by using β-delayed proton peaks from ^{25}Si decay with known energies, which is the same as Ref. [15]. The efficiency for two-proton emission in the β decay of ^{27}S was deduced from the efficiency curve fixed by the known β-delayed two-proton peaks of ^{22}Al [21] and ^{26}P [22], assuming a uniform efficiency of the DSSDs for two-proton emission from ^{22}Al, ^{26}P, and ^{27}S decays [15]. A 1546-μm-thick quadrant silicon detector (QSD1) was placed behind DSSD3 for β particle measurements. In addition, another two quadrant silicon detectors (QSD2, QSD3) with a similar thickness of 300 μm were installed at the end of the silicon array to serve as veto detectors to reduce light-particle contamination in the secondary beam. γ rays were detected by five Clover-type high-purity Germa-

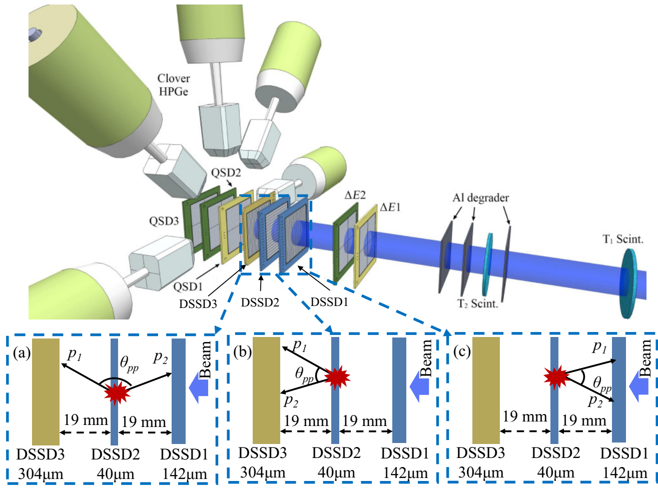

FIG. 1. Schematic layout of the detection system locating at Terminal 2 of the RIBLL1. The zoom-in figures for silicon array marked with (a), (b). and (c) demonstrate the methods for the proton-proton coincidence. The ^{27}S ions were stopped by DSSD2 and the escaping two protons after β decay, p_1 and p_2, were (a) separately measured by DSSD3 and DSSD1, both measured by (b) DSSD3, and (c) DSSD1. θ_{pp} is the opening angle between p_1 and p_2 in which three pixels were fired simultaneously.

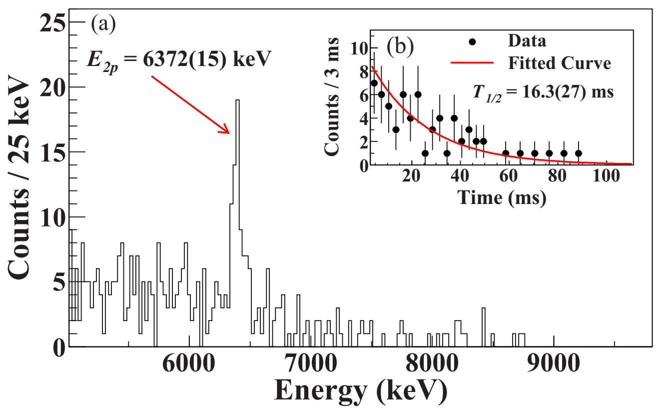

FIG. 2. (a) Energy spectrum of β-delayed proton from the decay of ^{27}S measured by DSSD3 above 5000 keV. (b) The decay time spectrum gated on the 6372-keV peak.

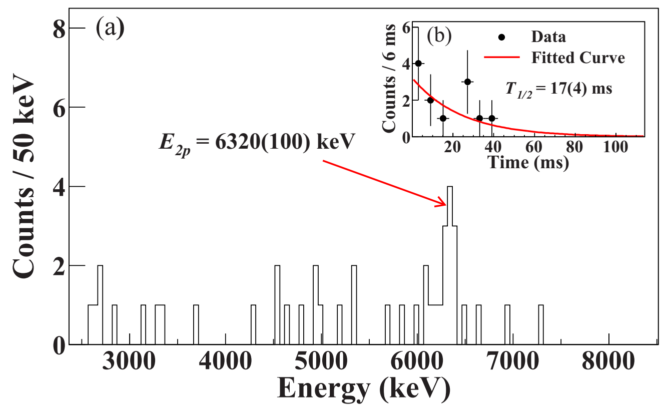

FIG. 3. (a) Summed energy spectrum of the events in which three pixels were fired using proton-proton coincident method. (b) Decay time spectrum gated on the summed energy at 6320 keV ranging from 6200 to 6500 keV.

nium (HPGe) detectors surrounding the silicon array. Details on the detection array and implantation-decay correlations are described in Refs. [15,23]. Al degraders with a total thickness of 320 μm sufficient to stop most of the ^{27}S ions in the DSSD array, 40.7% in DSSD2, and 58.7% in DSSD3, respectively, were placed upstream [15].

Figure 2(a) shows the β-delayed proton spectrum measured by DSSD3 within a time window of ten half-lives of ^{27}S after implantation. To improve the energy resolution, the β-summing effect on DSSD3 was suppressed by considering the anticoincidence with β-like particle signals in QSD1. The proton peaks with energies lower than 5 MeV have been analyzed and discussed in Ref. [15]. The 6372-keV peak corresponding to the transition from the IAS of ^{27}P to the ground state of ^{25}Al [12,13] was identified as a two-proton emission according to the relationship among the energy losses, positions, and path lengths of the escaping particles in different DSSDs [6]. Its half-life was obtained by fitting the time-profile illustrated in Fig. 2(b) using an exponential function plus a flat background. The fitted result of 16.3(27)ms is consistent with the β-decay half-life of ^{27}S 16.3(2) ms [15], implying that the 6372-keV peak is from the β decay of ^{27}S. Considering the two-proton detection efficiency, the branching ratio of 2.4(5)% for the 6372-keV peak was obtained, which is consistent with Borrel's measurement [12]. However, the other two-proton transition at 5315 keV [13] was not observed in this experiment. In addition, we did not observe the 945-keV peak reported earlier [15] in our γ spectrum, indicating that no transition feeds the first $3/2^+$ state of ^{25}Al.

High statistics of ^{27}S enabled detection of sufficient amount of proton-proton coincidences which can be attributed to the two-proton emission. The proton-proton coincidence was deduced based on the setup of the silicon array in which the DSSD2 served as a heavy ion stopper, while DSSD1 and DSSD3 were used to measure the two escaping protons. Because of its thickness of only 40 μm, β-delayed protons could easily escape from DSSD2. When the escaping two protons (p_1 and p_2 in Fig. 1) were detected by the adjacent DSSD1 and/or DSSD3, threes pixel would be fired simultaneously and the corresponding energies and positions would be recorded.

The total decay energy of the two-proton emission should be the sum of the valid energy signals from the three fired pixels. To reduce the misidentification between the β particles and low-energy protons, an energy threshold of 300 keV was set for DSSD1 and DSSD3 since the energy loss for β particles is usually smaller than 300 keV. As a result, a total of 42 proton-proton coincident events were identified. The energy peak at 6320(100) keV shown in Fig. 3 with 12 valid events ranging from 6200 to 6500 keV, which is consistent with the 6372-keV two-proton peak, corresponds to the two-proton transition from the IAS of ^{27}P to the ground state of ^{25}Al. This result was confirmed by its determined half-life of 17(4) ms, as shown in Fig. 3(b). Energy-energy correlations of individual protons from $\beta 2p$ of ^{27}S were reconstructed based on path lengths, energy losses, and positions in DSSDs [15], as illustrated in Fig. 4. The red circles stand for the identified 6320-keV $2p$ events in this experiment. The distribution of

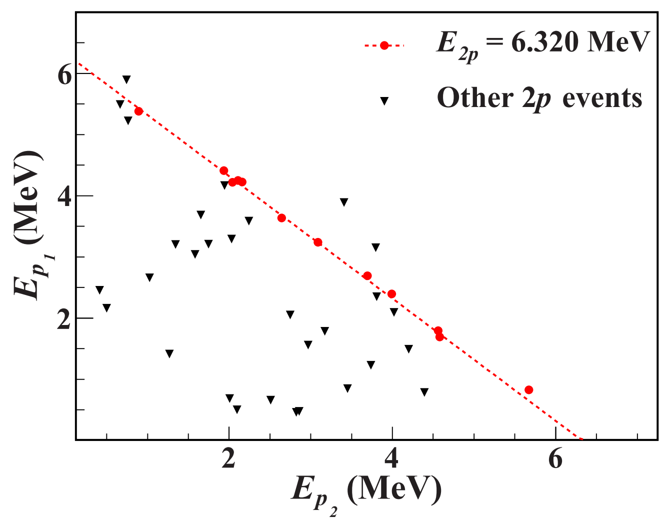

FIG. 4. Energy-energy correlations of individual protons of $\beta 2p$ of ^{27}S. The red circles and the black triangles represent the 6.320-MeV $2p$ events and other $2p$ events, respectively.

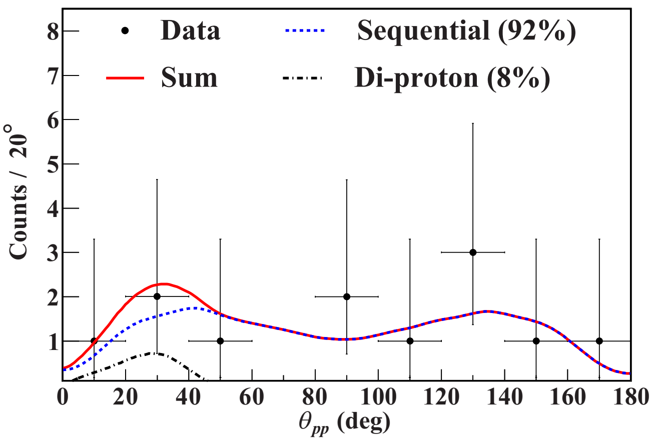

FIG. 5. Distribution of the opening angle of two protons with total energies ranging from 6200 to 6500 keV in Fig. 3. The colored lines are Monte Carlo simulation results and the black dots are the experimental results in present work.

these events seems to be uniform along the dotted line. The remaining coincident events shown with black triangles were considered other two-proton emission branches that cannot be deduced owing to low statistics.

Proton-proton angular correlations were extracted from the positions of the escaping two protons based on the proton-proton coincidence measurement method. To balance the angular resolution and angular coverage of the DSSD array, the distance between the DSSDs was set to 19 mm, resulting in a solid angle coverage of about 4.5 sr as shown in Fig. 1. The simulated angular resolution of about 10° was obtained based on the present DSSD array geometry. Gating on the summed energy spectrum at 6320(100) keV in Fig. 3, the measured proton-proton angular distribution is presented with black dots in Fig. 5. The spectrum shows a nearly isotropic distribution for the θ_{pp}.

The theoretical models of the two-proton emission were well discussed in detail by Grigorenko *et al.* [24–28] and successfully applied to $2p$ decays of many nuclear systems, such the ground state of ^{45}Fe [29]. In this work, we performed Monte Carlo simulations based on a schematic model [30–33], considering two extreme cases: the diproton emission and the sequential emission, to better understand experimental angular correlations, and to investigate the mechanisms of the $\beta 2p$ of ^{27}S. The diproton emission assumes that a preformed ^{2}He resonance with the quasi-bound $^1S_0$ configuration in the parent nucleus penetrates the Coulomb barrier and breaks up into two protons outside the barrier [30], whereas the sequential emission is a two-stage procedure, in which two protons are sequentially emitted with an intermediate state involved. The DSSD array geometry, energy resolution, energy detection threshold, and experimental heavy ion implantation distributions were taken into account in the simulations. The simulations indicated that the diproton and sequential emissions show different trends. The angular distribution of the diproton emission tends to have a marked peak at around 30° due to a quasibound s-singlet configuration as shown by the black dot-dashed line in Fig. 5. On the other hand, the simulated angular distribution of the sequential emission is approximately isotropic. The observed "double hump" is caused by geometrical effects due to detector arrangements. Since the three DSSDs were placed parallel to each other, the detection efficiency of two protons with an opening angle around 90° was relatively small, resulting in a much reduced effective angular distribution shown by the blue dashed line in Fig. 5. By fitting the experimental data with the Monte Carlo simulation results using the maximum-likelihood method, sequential emission with branching ratio of $92^{+8}_{-16}\%$ was observed as shown in Fig. 5. This result indicates that the dominant mechanism for the $2p$ emission from the IAS of ^{27}P to the ground state of ^{25}Al is of sequential nature.

In summary, the $\beta 2p$ of ^{27}S was studied. The experiment was carried out with a silicon array consisted of three DSSDs with different thicknesses using RIBLL1 at HIRFL, Lanzhou. A two-proton emission from the IAS of ^{27}P to the ground state of ^{25}Al was observed at 6372(15) keV with a branching ratio of 2.4(5)% in the β decay of ^{27}S. The angular distribution for this two-proton branch was also measured to study the two-proton emission mechanism. Comparing with the simulation results, it was found that the dominant component for the two-proton emission in the ^{27}S β decay is the sequential emission. A small contribution of diproton component cannot be considered the evidence for strong angular correlations due to insufficient statistics. Further experiments with higher statistics and detailed theoretical discussion are needed.

We wish to acknowledge the support of the HIRFL operations staff for providing high-quality beams. This work is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences, Grant No. XDB34010300, the Ministry of Science and Technology of China under National Key R&D Programs No. 2018YFA0404404 and No. 2016YFA0400503 and National Natural Science Foundation of China under Grants No. U1932206, No. U1632136, No. 11635015, No. 11805120, No. 11705244, No. U1432246, No. 11775316, No. 11775277, No. U1732145, No. 11705285, No. U1867212, No. 11805280, No. 11825504, No. 11675229, and No. 11490562, and by the Continuous Basic Scientific Research Project No. WDJC-2019-13.

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