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Measurement of the Radiative-Decay Probability of the Hoyle State

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Abstract. The radiative-decay probability of the Hoyle state is actually controversial because new data which contradicts the currently adopted value has been recently reported. In this work, we performed the new reliable measurement of the radiative-decay probability of the Hoyle state. We successfully obtained 40 triple-coincidence events of scattered α particles, recoil ^{12}C, and emitted γ rays for the first time. Further analysis will determine the radiative-decay probability, and puzzle over the radiative-decay probability.

1 Introduction

The triple alpha (3α) reaction is one of the most important reactions in the nucleosynthesis, because it is the doorway reaction that bypasses the A = 5 and 8 bottlenecks and allows the production of heavier nuclei. In the 3α reaction, an α particle is captured by a 2α resonant state in ^{8}Be, and a 3α resonant state in ^{12}C is formed. Most of the 3α states decay back to 3α, however, they undergo radiative decay to the ground state by emitting γ rays or a e^+e^- pair with a slight probability. At normal stellar temperatures around $T \sim 10^8$ K, the 3α reaction via the 0_2^+ state at E_x = 7.65 MeV, called Hoyle state, is dominant. Therefore, The radiative-decay probability of the Hoyle state is a very important parameter to determine the 3α reaction rate in the nucleosynthesis.

The radiative-decay probability was extensively measured in the 1960s and 1970s [1–8]. The previous experimental data of the radiative-decay probability of the Hoyle state are plotted by solid and open circles in Fig. 1. Most of the results except Ref. [2] are consistent within their uncertainties, and $\Gamma_{\rm rad}/\Gamma = 4.16(11) \times 10^{-4}$ is recommended by the experimental compilation [9]. Recently, the radiative-decay probability was re-measured by Kibédi *et al.* by detecting the two γ rays from the cascade decay of the Hoyle state populated by the ^{12}C (p, p') reaction [10]. The new value of $\Gamma_{\rm rad}/\Gamma = 6.2(6) \times 10^{-4}$ is 50% higher than the recommended value in Ref. [9]. After this striking result, we reported the coincidence measurement of the scattered proton and the surviving ^{12}C after the radiative decay of the Hoyle state in the ^{12}C (p, p') reaction. The radiative-decay probability of the Hoyle state was found to be $\Gamma_{\rm rad}/\Gamma = 4.3(8) \times 10^{-4}$, which is consistent with the previous recommended value [11].

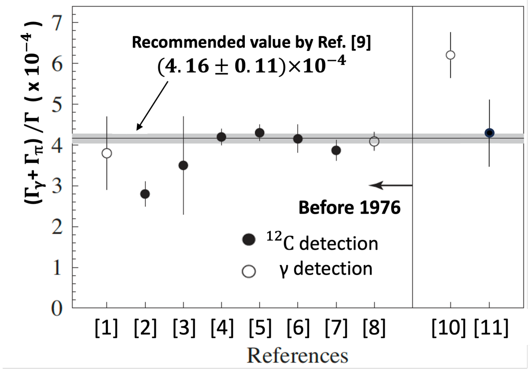

Figure 1. Previous experimental data of the radiative-decay probability of the Hoyle state. The solid circles are taken by measuring the surviving ^{12}C while the open circles are by measuring the decay γ rays. The horizontal solid line and gray band present the adopted value of the radiative-decay probability and its uncertainty [9].

This inconsistent results between Ref. [10] and Ref. [11] might be due to the different measurement methods. Most of the previous data [2–7] plotted by the solid circles in Fig. 1 were taken by measuring ^{12}C nuclei surviving af-

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ter they were excited to the Hoyle state. The authors of Ref. [10] suggested that the measurement of the surviving ^{12}C nuclei might not be appropriate to determine the radiative-decay probability because the coincidence measurement at high counting rates above 10 kHz was very challenging due to accidental coincidences. It should be noted that the two old data plotted by the open circles, which were obtained by measuring the decay γ rays from the Hoyle state, are consistent with the adopted value. However, the experimental data from Ref. [9] is clean and appears to be quite reliable. Therefore, a new measurement is strongly desired to solve this inconsistent situation.

2 Experiment

In this work, we performed a triple-coincidence measurement of the scattered α particles, recoil ^{12}C, and emitted γ rays to determine the radiative-decay probability of the Hoyle state. The experiment was conducted at Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering. A ^{4}He^{2+} beam at 25.0 MeV provided by the tandem accelerator was transported to the scattering chamber. Figure 2 shows the experimental setup around the scattering chamber. The beam impinged on the $^{\mathrm{nat}}$C target with a thickness of 50 μg/cm^2 to produce the Hoyle state. A ^{13}C target with a thickness of 30 μg/cm^2 was also used to subtract background events originated from ^{13}C contained in the $^{\mathrm{nat.}}$C target. The scattered α particles and recoil ^{12}C were measured with a ring-shaped double sided Si strip detector (DSSD) Design S1 by Micron Semiconductor Ltd. The inner and outer radii of the sensitive area are 24 mm and 48 mm, respectively, while the thickness is 500 μm. The junction side of the detector is divided into 4 sector-shape segments with a central angle of 90°, and each segment is divided into 16 arc-shaped strips with a pitch of 1.5 mm. On the other hand, the ohmic side is separated into 16 radial sectors. The DSSD was placed at 40-mm downstream of the target to cover θ_{lab} = 31.0°–50.2°. Signals from the DSSD were processed with Mesytec MPR-16 or MPR-32 preamplifiers, and their pulse shapes were acquired with CAEN V1730SB 500 MS/s flash digitizers. The pulse-shape analysis (PSA) was employed for particle identification (PID). The output signals from the preamplifiers were also input to Mesytec MSCF-16 modules to generate trigger signals for data acquisition. Two γ rays from the cascade decay of the Hoyle state were detected with the ROSPHERE γ-ray spectroscopy array consisting of large 24 LaBr$_3$ scintillators. Each LaBr$_3$ was coupled to a BGO scintillator as the Compton suppressor but the data of the Compton suppressor were not used in the following analysis due to technical issues during the experiment. Detailed configuration of ROSPHERE can be found in Ref. [12].

3 Analysis

3.1 Pulse-Shape Analysis (PSA)

In Si semiconductor detectors, radiation energy is measured by collecting pairs of electrons and holes excited by radiation incident on the depletion layer at the junction surface between P-type and N-type semiconductors. Since electrons intrude from near the PN junction surface to the P-type side, a non-uniform electric field is formed in the depth direction inside the detector. As a result, the risetime of the readout signal varies with the nuclide and their energies.

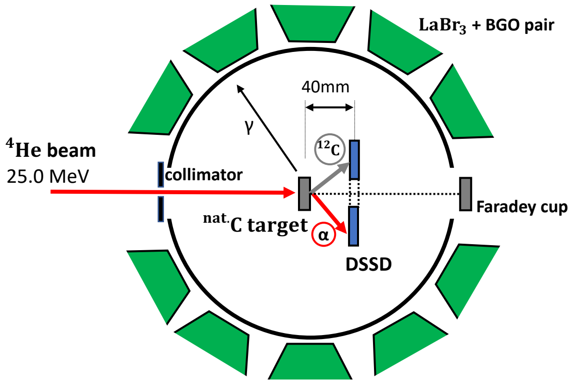

Figure 2. Experimental setup around the scattering chamber.

We performed PID for decay particles using the PSA. The amplitude of the differential waveform of the output signal from the preamplifier (A_{max}) is a useful PID parameter [13]. Figure 3 shows the correlation between A_{max} and kinetic energies of detected particles. We successfully separated α particle from proton, deuteron, and ^{12}C using PSA. The dashed line shows the trigger threshold for the data acquisition. Since the trigger signal was generated with the timing filter amplifier in the MSCF-16 module, the threshold level varied depending on the risetime of the readout signal from the Si detector. The low-energy α particles below the trigger threshold were decay α particles emitted from excited states in ^{12}C, which were detected in coincidence with the inelastically scattered α particles. The continuous locus lying above the discrete loci due to the scattered α particles emitted from the target is background events due to beam particles scattered by upstream collimators. Although these background particles were α particles, their A_{max} values showed the different trend from the α particles emitted from the target. Because the background α particles had smaller incident angles to the Si detector than the α particles from the target, the risetime of the signals was different. Only scattering α particles exciting the Hoyle state were selected in the analysis.

3.2 α-^{12}C-γ coincidence

First, we picked up the coincidence events in which the scattered α particle and the recoil ^{12}C were detected within a a time window of 30 ns. To eliminate the background events originated from the 3α decay of the Hoyle state, a coplanarity condition was applied for the event selection. This condition required that only one particle was detected in the segment on the opposite side of the segment where the scattered α particle hit. The excitation energy of the recoil ^{12}C was determined from the energy and scattered an-

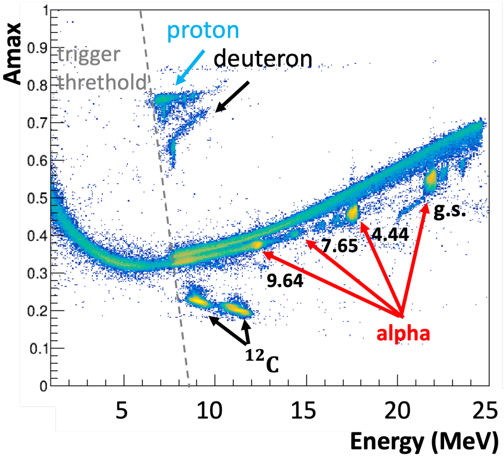

Figure 3. Correlation between $A_{\max}$ and kinetic energies of detected particles. The dashed line presents the trigger threshold for the data acquisition.

gle of the α particle. Figure 4 shows the excitation-energy spectrum of ^{12}C in the coincidence events of the scattered α particle and recoil ^{12}C. The black and blue lines represent the spectra taken by the $^{\text{nat.}}$C and ^{13}C target, respectively. The ^{13}C spectrum was scaled by the target thickness, the ^{13}C abundances in the ^{13}C and $^{\text{nat.}}$C targets, and the integrated beam charges for quantitative comparison with the $^{\text{nat.}}$C spectrum. By fitting the continuous spectrum beneath the Hoyle state with an exponential function, the yield of the coincidence events of the scattered α particle and surviving ^{12}C from the Hoyle state was determined to be 481.

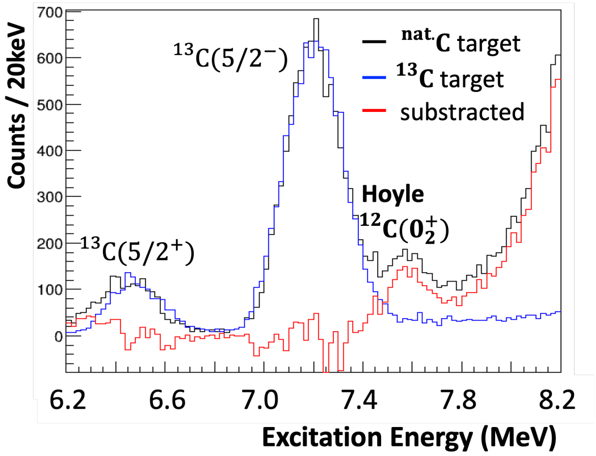

Figure 4. Excitation-energy spectrum of ^{12}C when the scattered α and recoil ^{12}C were detected in coincidence. The black and blue lines represent the spectra obtained by the $^{\text{nat.}}$C and ^{13}C targets, respectively.

Next, we sought for the triple-coincidence events between the scattered α particle, the recoil ^{12}C, and the γ ray. True coincidence window between the α particle and γ ray was set within 10 ns. Figure 5 shows the energy spectrum of γ rays measured by ROSPHERE in the coincidence events between the scattered α particle and the recoil ^{12}C surviving from the Hoyle state. The black and red lines represent the true and accidental coincidence events, respectively. The total absorption peaks of the two γ rays at E_γ = 4.44 and 3.21 MeV emitted from the cascade decay of the Hoyle state were observed with a high S/N ratio. Finally, we successfully obtained 40 events in the total absorption peak at E_γ = 4.44 MeV for α-^{12}C-γ coincidence events. In the future, detection efficiencies of α-^{12}C-γ coincidence events with the Si detector ROSPHERE will be estimated to determine the radiative-decay probability of the Hoyle state.

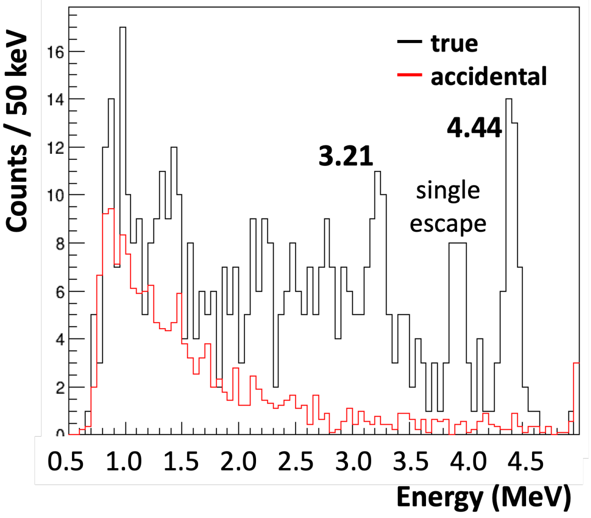

Figure 5. Energy spectrum of γ rays for the coincidence events with the scattered α particle and the recoil ^{12}C surviving from the Hoyle state. The black and red lines represent the true and accidental coincidence events, respectively.

4 Summary

We measured the radiative-decay probability of the Hoyle state with a new method taking triple coincidence between the scattered α particle, recoil ^{12}C, and γ rays. The measurement successfully demonstrated a high S/N ratio, and we acquired the 40 α-^{12}C-γ coincidence events. In the future work, we will estimate the detection efficiencies of α-^{12}C coincidence events with the Si detector and γ rays by the ROSPHERE array to determine the radiative-decay probability of the Hoyle state. The new experimental result will likely solve the puzzle regarding the radiative-decay probability of the Hoyle state, which arouse from the inconsistency among the previous measurements.

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