I. 2. Test Experiment of the 0° Measurement of Decay α Particles in the $^{12}C(^{12}C,3\alpha)$ Reaction

Ando S.[1], Itoh M.[1], Aoki T.[1], Arikawa H.[1], Ezure S.[1], Harada K.[1], Hayamizu T.[1], Inoue T.[1,2], Ishikawa T.[1], Kato K.[1], Kawamura H.[1,2], Uchiyama A.[1], and Sakemi Y.[1]

[1]Cycrotoron and Radioisotope Center, Tohoku University
[2]Frontier Research Institute for Interdisciplinary Sciences (FRIS), Tohoku University

The 0_2^+ state at E_x = 7.65 MeV in ^{12}C is called Hoyle state, which plays an important role in the creation of the ^{12}C nucleus in stellar nucleosynthesis. Moreover, in nuclear structure studies, the Hoyle state is considered to have a dilute gaslike structure in which the α clusters are loosely coupled to each other[1,2)]. Because of these astrophysical importance and specificity in nuclear structure, it has been studied from both theory and experiment for a long time. However, clear evidence for the dilute α gaslike structure has not been obtained, yet. About a decade ago, Tohsaki et al. proposed that this dilute α gaslike structure was similar to the Bose-Einstein condensation of α clusters in the nucleus[3)]. Recently, the 2_2^+ state at 10 MeV has been found[4-6)]. It is considered to be the 2^+ excitation of the Hoyle state. However, since there is not enough experimental evidence for the structure of the Hoyle state, it is still controversial.

To study the structure of the Hoyle state, we performed the measurement of the decay 3α particles via the $^{12}C(^{12}C\ ,^{12}C^*(0_2^+)[3\alpha])^{12}C$ reaction at the 41 course at CYRIC. By measuring the momenta and scattering angles of decay three α particles from the Hoyle state, the relative momentum distribution was obtained. This relative momentum distribution is considered as reflecting the α structure of the Hoyle state. Figure 1 shows a picture of the inside of the scattering chamber. The $^{12}C^{4++}$ beam was accelerated up to 110 MeV by the K110 AVF cyclotron and bombarded on a self-supporting natural carbon foil target with a thickness of 200 μg /cm^2 (or 100 μg /cm^2) installed in the scattering chamber. The incident ^{12}C was inelastically excited to the Hoyle state and the breakup three α particles were detected in a double-sided Si strip detector (DSSD) with a size of 50 × 50 mm and a thickness of 1,500 μm. The DSSD consists of 16 × 16 strips oriented vertically in the front side and horizontally in the rear side with a size of 3 × 50 mm. The positions of three α particles at the DSSD which was located at 290 mm from the target, were determined by comparing the energies obtained from the strips in the front and the rear sides. For monitoring the beam position, the recoiling ^{12}C of elastic scattering was caught in the silicon detectors at -79.35° (SSD1) and 79.35° (SSD2). The latest experimental result for the upper limit of the direct decay branching ratio from the Hoyle state is less than 5 × 10^{-3}. To determine the structure of the Hoyle state better than the previous result, more than 20,000 events of the decay three α particles from the Hoyle state is needed.

The purpose of this test experiment was to find an efficient setup for detecting the three α particles from the Hoyle state. In the previous experiment, we measured decay three α particles at the DSSD angle of 7.5° to the ^{12}C beam axis. The event rate of the Hoyle state in that experiment was 130 events per hour. In this experiment, in order to increase the detection efficiency of the three α, we measured by condition that DSSD was located at 0°. There are two reasons for this condition of DSSD. The first reason is that cross section of the ^{12}C(^{12}C, ^{12}C*(0_2^+))^{12}C reaction is maximum at 0°. The second reason is that the relative energy of the decay three α particles is small enough to detect by a DSSD. However, in this condition, the background would become much larger than the measurement at 7.5° because the ^{12}C beam enters on the DSSD directly. Thus, we installed a beam-stopper together with an Al plate in 4.7 mm front of the DSSD. The thickness of the Al plate was 200 μm, and the size of beam-stopper was 6 mm ϕ , which is enough to stop the ^{12}C beam. The protons and deuterons events generated by the reaction were rejected by the VETO signal from a plastic scintillator located just behind the DSSD. To reduce the trigger rate from the background, we studied the trigger condition by changing multiplicity of DSSD signals from 1 to 3. In order to optimize the measurement, we varied the combination of the following conditions.

1. Trigger multiplicity of discriminator module : 1, 2, 3
2. VETO signal by plastic scintillator : ON or OFF
3. Beam Stopper : IN or OUT
4. Thickness of the ^{12}C target : 100 μg/cm^2 or 200 μg/cm^2

The sum of kinetic energies of detected three α particles and recoiling ^{12}C is equal to the beam energy being reduced by separation energy of threeα particles from ^{12}C . The energy of recoiling ^{12}C at 0° is much small. Thus, in the spectrum of that, the peak of the Hoyle state is located about 103 MeV. Figures 2(a) and, 2(b) show the spectra of the summed kinetic energies of three detected particles respectively. Figure 2(a) shows the spectrum in condition (a) that trigger multiplicity sets 2, VETO is ON, beam-stopper is OUT, and thickness of ^{12}C is 200 μg/cm^2. On the other hand, Fig. 2(b) shows the spectrum in condition (b) where existence of beam-stopper is only difference from the condition (a). The entries in Figs. 2(a) and 2(b) correspond to the measurement time. By comparing these two spectra, the background in Fig. 2(b) was less than in Fig. 2(a), and it is possible to find the definitive peak of the Hoyle state in Fig. 2(b). Consequently, the setup in condition (b) found to be the best for detecting the three α particles decayed from the Hoyle state. The event rate was 700 events per hour. However, the setup in condition (b) is not suitable for detecting the α particles via the direct decay from the Hoyle state. Figure 3 shows the symmetric Dalitz-plot of the α particles from the Hoyle state in the condition (b). The X- and Y- axis labels, x and y, of the Daltz-plot are defined in Refs. 7-9. The x and y are calculated by the α particles energies in the ^{12}C* rest frame normalized to the total kinetic energies of the decay 3α particles. Different decay mechanisms result in different Dalitz-plot distributions[8-9)]. In Fig. 3, we found that the α particles detected in the condition (b) were all α particles via sequential decay[8-9)]. The cause of this problem is the small direct decay branch of the Hoyle state, the upper limit is 0.2%[8-9)]. In Fig. 2(b), there are events which have the energy higher than 103 MeV. The summed energy of the decay three α particles cannot be higher than 103 MeV, because the separation energy of three α particles is 7.27 MeV. Thus, the background are contained in the peak of the Hoyle state in condition (b). We considered a reason for background is accidental coincidence. Since we cannot remove these background, this setup is not suitable for the precise measurement of the small branch reaction of the direct decay from the Hoyle state. Further development for clean measurement is in progress.

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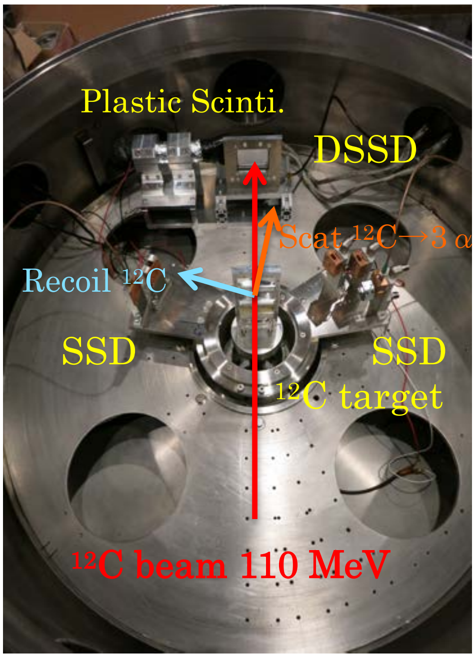

Figure 1. Detectors setup in the large Scattering chamber.

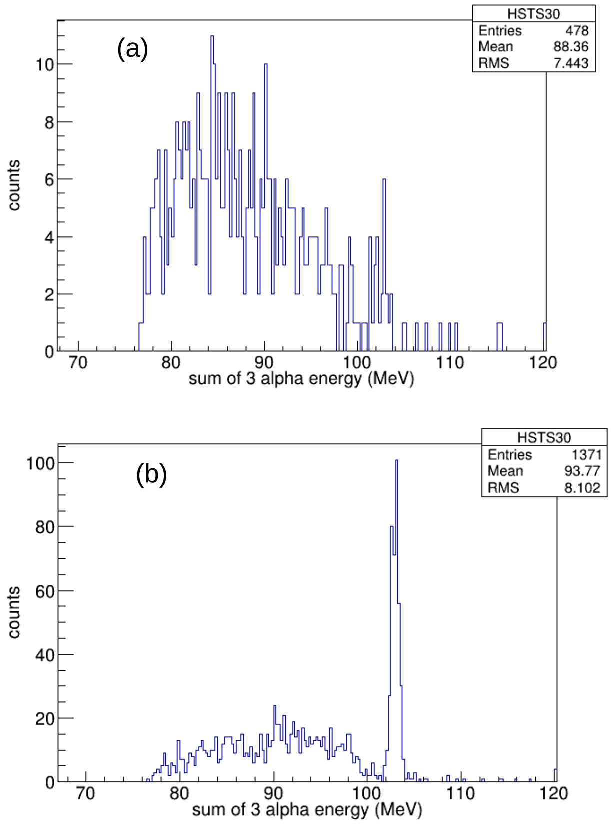

Figure 2. The spectra of the summed kinetic energies of three detected particles. (a): The spectrum in condition that trigger multiplicity sets 2, VETO is ON, beam-stopper is OUT, and thickness of ^{12}C is 200 μg/cm^2. (b): The spectrum in same condition as condition (a), except for beam-stopper.

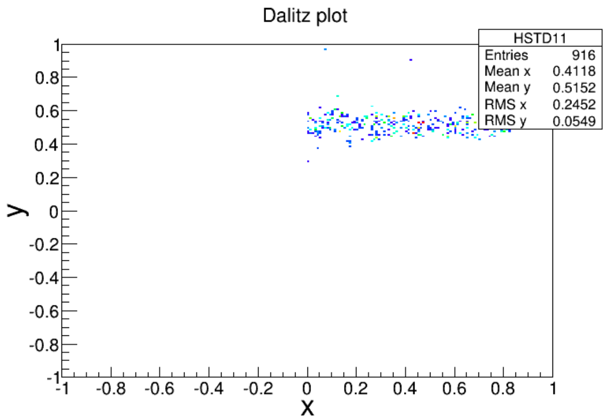

Figure 3. Symmetric Dalitz plots of the α particles from the Hoyle state in the condition (b) are shown. The X and Y labels, x and y, are defined in Ref. 8.