I. 1. Further Improvement of the Upper Limit on the Direct 3α Decay from the Hoyle State

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The 0_2^+ state at E_x = 7.65 MeV in ^{12}C plays an important role in the creation of the ^{12}C nucleus in stellar nucleosynthesis. The ^{12}C nucleus is produced by the triple-α reaction: two α particles form the resonance state of ^{8}Be at first, and the short-lived ^{8}Be captures a third particle before decaying back to two α particles. Fred Hoyle claimed that the capture of a third α particle proceeds through a resonant state in ^{12}C near the α + ^{8}Be threshold, thus, enhancing the triple-α reaction rate[1)]. This resonant state, 0_2^+, in ^{12}C was discovered soon after his prediction[2)]. For that reason, the 0_2^+ state in ^{12}C is called the Hoyle state.

The structure of the Hoyle state is highly related to the triple-α reaction rate, since it is considered to have a typical 3α cluster structure. According to the microscopic α cluster models, the Hoyle state has been considered to have a dilute gaslike structure in which the α clusters are loosely coupled to each other[3,4)]. 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[5)]. Recently, a lattice calculation with the chiral effective field theory, which is one of the *ab initio* calculations, succeeded in reproducing the excitation energy of the Hoyle state in ^{12}C. It indicated that the Hoyle state was considered to have a “bent-arm” or obtuse triangular configuration[6)]. Therefore, its configuration of 3α clusters is still controversial.

It is difficult to determine the structure of the nuclear excited state, especially the unbound states, experimentally. One possible way is the decay particle measurement. Recently, Rana *et al.* reported the nonzero value of the direct 3α decay branch from the Hoyle state[7)]. Although it could be evidence for the 3α cluster structure of the Hoyle state, it was incompatible with the previous experimental result as the upper limit of 0.5% on the direct 3α decay branch[8)].

In order to investigate the structure of the Hoyle state, experimentally, we have performed a measurement of decay α particles from the Hoyle state via the $^{12}C(^{12}C,^{12}C^{*}[3\alpha])^{12}C$ reaction using the large scattering chamber in Target Room 4. The $^{12}C^{4+}$ beam was accelerated up to 110 MeV by AVF cyclotron, and bombarded to the self-supported carbon foil with a thickness of 50 μg/cm^2. The decay 3α particles were detected by the double-sided silicon strip detector (DSSD) with a size of 50 × 50 mm^2 and with a thickness of 1500 μm which has 16 × 16 strips oriented vertically in the front side and horizontally in the rear side. The recoiling ^{12}C particles were caught by a silicon detector with a thickness of 150 μm at 67°. This angle corresponds to that of the third maximum of the angular distribution for the $^{12}C(^{12}C,^{12}C^{*}[0_2^{+}])^{12}C$ reaction. The silicon detectors were kept cooling around 0 ℃ during the experiment. Figure 1 shows the kinematics of the $^{12}C(^{12}C,^{12}C^{*}[3\alpha])^{12}C$ reaction and the energy spectrum of the recoiling ^{12}C particles. The thick solid line in Fig. 1(b) shows that in coincidence with the decay 3α particles. It indicates only the Hoyle state can be coincident with the decay 3α particles.

To visualize the energy correlation of the decay 3α particles, the symmetric Dalitz plot is adopted. Figure 2 shows the symmetric Dalitz plot in the present experiment. We compared it with the Monte Carlo simulation of the experiment. Three decay mechanisms were compared to the result of the experiment. The first is the sequential decay (SD) through the ^{8}Be. The second is the direct decay with an equal energy of three α particles (DDE). The third is the direct decay to the phase space uniformly (DDΦ). In order to obtain the branching ratio for each decay mechanism, we fitted the normalized energy distribution for the highest energy among the decay 3α particles with those obtained in the simulation. The normalized energy, ε_x, is defined as $\varepsilon_x = E_x/(E_i+E_j+E_k)$, x=$i,j,k$. $E_{i,j,k}$ are kinetic energies of the decay 3α particles, and defined as $E_i>E_j>E_k$. Figure 3 shows the result of the fit. The decay branch of the SD mechanism was almost 100%. After the statistical treatment, the upper limit of 0.2% on the DDE and DDΦ mechanisms was obtained. In Fig. 3, results obtained by Rana et al. were also shown. It seems to reproduce the shoulders in Fig. 3. However, from the result of the simulation, we found they were originated from the misassignment of the position of decay α particles due to the finite energy resolution of the DSSD.

This result has been already published in Ref. 9.

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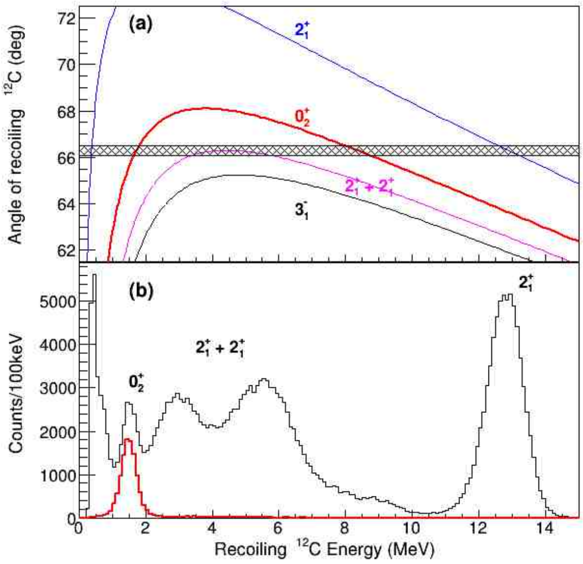

Figure 1. (a) The kinematics of the $^{12}C(^{12}C,^{12}C^{*}[3\alpha])^{12}C$ reaction. The of the 4.44 MeV 2_1^+, the 7.65 MeV 0_2^+, and the 9.64 MeV 3^- states are drawn by the blue, the red, and the black lines. The mutual 2_1^+ excitations for the beam and the target ^{12}C is indicated by the magenta line. (b) Energy spectra of the recoiling ^{12}C at 67° are shown. The black and red lines show that of the singles trigger and the coincidence energy spectrum.

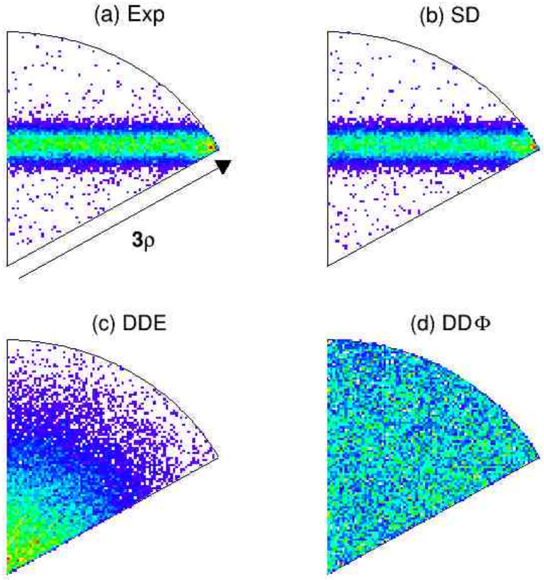

Figure 2. Symmetric Dalitz plots for (a) the experiment, (b) the sequential decay (SD), (c) the direct decay with an equal energy of three α particles (DDE) and (d) the direct decay to the phase space uniformly (DDΦ) are shown. The Dalitz plots for the SD, DDE and DDΦ are obtained by the Monte Carlo simulation.

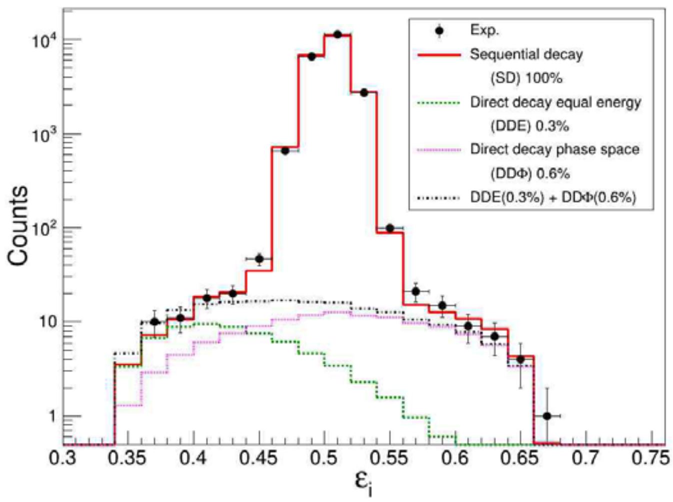

Figure 3. The normalized energy distribution for the highest energy of the decay 3α particles. The experimental result was reproduced completely by the Monte Carlo simulation of the SD mechanism.