Direct 3α decay from the Hoyle state in ^{12}C

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Introduction

The second 0^+ 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 ^{8}Be + α 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 be a typical 3α cluster structure. In the simple shell model, the 0^+ state does not appear at such a low excitation energy as 7.65 MeV in ^{12}C. According to the microscopic α cluster models, the Hoyle state has been considered to have a dilute gas-like structure in which the α-cluster is loosely coupled to each other [3, 4]. About a decade ago, Tohsaki *et al.* proposed this dilute α gas-like structure was similar to the Bose-Einstein condensation of α clusters in the nucleus by the model wave function for the α condensation [5]. Recently, some *ab initio* calculations have been tried to explain properties of the Hoyle state including the ground state band in ^{12}C [6–8]. Among them, a lattice approach with chiral effective field theory succeeded in reproducing the excitation energy of the Hoyle state [7, 9]. In their result, the Hoyle state is considered to have a "bent-arm" or obtuse triangular configuration. Therefore, its configuration of 3α clusters is still controversial.

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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 [10]. 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 [11].

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*[3α])^{12}C reaction. In this contribution, we report further improvement of an upper limit on the direct 3α decay from the Hoyle state ^{12}C [12].

Experiment

The experiment was preformed at the Cyclotron and Radioisotope Center (CYRIC), Tohoku University. 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 $\times$ 50 mm^2 and with a thickness of 1500 μm which has 16 $\times$ 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°. The silicon detectors were kept cooling around 0°C during the experiment. From a complete kinematics method, in which all particles participated in the reaction were measured, we reconstructed the excitation energy of ^{12}C and the decay channel.

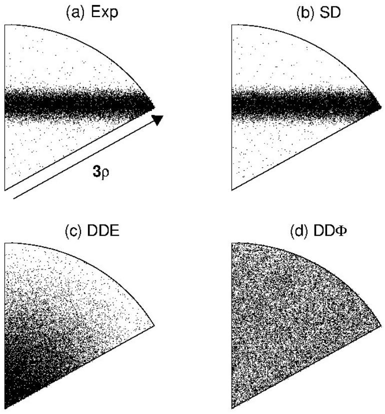

FIG. 1: Symmetric Dalitz plots for (a) experimental data, (b) the sequential decay (SD), (c) the direct decay with an equal energy of three α particles (DDE), and (d) the direct decay to the phase space uniformly (DDΦ) are shown. The Dalitz plots for the SD, DDE, and DDΦ are obtained by the Monte Carlo simulation.

Symmetric Dalitz plot

To visualize the energy correlation of the decay 3α particles, the symmetric Dalitz plot is adopted. Figure 1 shows the symmetric Dalitz plots obtained in the present measurement and the Monte Carlo simulation. The number of events in each plot in Fig. 1 was same as that of the experimental plot. Three decay mechanisms were compared to the result of the experiment. The first is the sequential decay (SD) mechanism through the ground state of ^{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). The experimental plot seems to be almost same as that of the SD mechanism.

In order to obtain the branching ratio for each decay mechanism, we fitted the energy distribution for the highest energy among the decay 3α particles with those obtained in the simulation. The decay branch of the SD mechanism was almost 100%. After statistical treatment, the upper limit of 0.2% on the direct decay mechanisms was obtained. From the result of the simulation, we found small fractions at a place except the locus of the ^{8}Be + α decay were originated from the misassignment of the position of decay α particles due to the finite energy resolution of the DSSD.

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