Feasibility study to search for the rare $\gamma$-decay mode in $^{12}$C

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Abstract. Excited states in $^{12}$C nuclei play a very important role in the nucleosynthesis in the universe. $^{12}$C nuclei are synthesized by the triple $\alpha$ reaction in the universe. Since heavier elements are synthesized via $^{12}$C, the triple $\alpha$ reaction plays a crucial role in the nucleosynthesis in the universe.

In the triple $\alpha$ reaction, an $\alpha$ particle collides with a 2$\alpha$ resonant state, and consequently, excited states of $^{12}$C are produced as 3$\alpha$ resonant states as shown in Fig. 1. After that, most of these excited $^{12}$C nuclei decay back into 3$\alpha$, but a tiny fraction of these excited $^{12}$C nuclei decays into the ground state of $^{12}$C by emitting $\gamma$-rays. Therefore, $\gamma$-decay probabilities are the key parameters in the $^{12}$C synthesis. For example, the $\gamma$-decay probability of the Hoyle state (the 0$^+_2$ state at $E_x = 7.65$ MeV in $^{12}$C) is known as $(4 \pm 1) \times 10^{-4}$ and the triple $\alpha$ process proceeds via this state at the normal stellar temperature. However, at high temperature $T > 10^9$ K, a contribution of the highly excited 3$\alpha$ resonant states such as the 3$^+_1$ state at $E_x = 9.64$ MeV and the 2$^+_2$ state at $E_x = 9.84$ MeV play a part of the triple $\alpha$ reaction. Unfortunately, the $\gamma$-decay probability of the 3$^+_1$ state has not been determined, therefore we planned to determine the $\gamma$-decay probability using the inverse kinematic reaction $^3$He($^{12}$C, $^{12}$Cp) without measuring $\gamma$-rays. The test experiment was carried out at the cyclotron facility in RCNP. The results of the test experiment are reported in the present paper.

1. Introduction

1.1. $^{12}$C synthesis in the universe

$^{12}$C nuclei are synthesized by the triple $\alpha$ reaction in the universe. Since heavier elements are synthesized via $^{12}$C, the triple $\alpha$ reaction plays a crucial role in the nucleosynthesis in the universe.

In the triple $\alpha$ reaction, an $\alpha$ particle collides with a 2$\alpha$ resonant state, and consequently, excited states of $^{12}$C are produced as 3$\alpha$ resonant states as shown in Fig. 1. After that, most of these excited $^{12}$C nuclei decay back into 3$\alpha$, but a tiny fraction of these excited $^{12}$C nuclei decays into the ground state of $^{12}$C by emitting $\gamma$-rays. Therefore, $\gamma$-decay probabilities are the key parameters in the $^{12}$C synthesis. For example, the $\gamma$-decay probability of the Hoyle state (the 0$^+_2$ state at $E_x = 7.65$ MeV) is known as $4.4(1) \times 10^{-4}$ and the triple $\alpha$ process proceeds via this state at the normal stellar temperature. However, at high temperature $T > 10^9$ K, a contribution of the highly excited 3$\alpha$ resonant states such as the 3$^+_1$ state at $E_x = 9.64$ MeV and the 2$^+_2$ state at $E_x = 9.84$ MeV becomes important.

Unfortunately, the $\gamma$-decay probabilities of these states are still unknown, and it causes uncertainty to calculate the triple $\alpha$ reaction rate. Thus we have planned to determine the...
\( \gamma \)-decay probability of the \( 3_{1}^{-} \) state.

1.2. \( \gamma \)-decay probability of the \( 3_{1}^{-} \) state

It is difficult to measure the \( \gamma \)-decay probability of the \( 3_{1}^{-} \) state because it is very small. The present knowledge about the total decay width, \( \Gamma \), \( \gamma \)-decay width \( \Gamma_{\gamma} \) and \( \gamma \)-decay probability \( \Gamma_{\gamma}/\Gamma \) of the \( 3_{1}^{-} \) state is summarized in Table 1 [3].

The \( \gamma \)-decay width to the ground state \( (\Gamma_{0}) \) was obtained from the inelastic electron scattering. Since \( \Gamma_{\gamma} \) must be larger than \( \Gamma_{0} \), the lower limit of \( \Gamma_{\gamma} \) of the \( 3_{1}^{-} \) state is \( \Gamma_{0} = 0.31(4) \text{ meV} \). The upper limit was reported in the measurement of the \( ^{12}\text{C} (\alpha, \alpha' 12\text{C}) \) reaction [4]. In this previous measurement, only the upper limit of \( \Gamma_{\gamma} \) was determined because the \( 13\text{C} \) contaminants in the isotopically enriched \( 12\text{C} \) target caused serious background. Therefore, we decided to use the inverse kinematic reaction \( ^{1}\text{H} (12\text{C}, \alpha_{p}) \), because no \( 13\text{C} \) contaminants are included in \( 12\text{C} \) beam.

### Table 1. Total decay width \( \Gamma \), \( \gamma \)-decay width \( \Gamma_{\gamma} \) and \( \gamma \)-decay probability \( \Gamma_{\gamma}/\Gamma \) of the \( 3_{1}^{-} \) state [3].

| \( \Gamma \) | \( \Gamma_{\gamma} \) | \( \Gamma_{\gamma}/\Gamma \) |
|------------|----------------|-------------------|
| 34(5) keV  | > 0.31(4) meV | > 9.1 \times 10^{-9} |
| \( < 14 \text{ meV}(1\sigma \text{ C.L.}) \) | \( < 4.1 \times 10^{-7} \) |

**Figure 1.** Level diagram related to the triple \( \alpha \) reaction.

**Figure 2.** (a) \( \alpha \)-decay events and (b) \( \gamma \)-decay events in the \( ^{1}\text{H} (12\text{C}, 12\text{C}p) \) reaction.

2. Experimental consideration

2.1. Experimental procedure

A hydrogen target is bombarded with a \( ^{12}\text{C} \) beam as shown in Fig. 2. The excitation energy of the inelastically scattered \( ^{12}\text{C} \) is determined from the energy and angle of the recoiled proton. Most of the \( ^{12}\text{C} \) nuclei excited to the \( 3_{1}^{-} \) state decay into \( 3\alpha \) as shown in Fig. 2(a), but a tiny fraction of them decays into the ground states by emitting \( \gamma \)-rays as shown in Fig. 2(b). Therefore, if the scattered \( ^{12}\text{C} \) is detected in coincidence with the recoiled proton, the \( \gamma \)-decay event is identified without the \( \gamma \)-ray detection and the \( \gamma \)-decay probability \( \Gamma_{\gamma}/\Gamma \) is obtained from the ratio of the number of all the inelastic events to the number of the \( \gamma \)-decay events.

Before the physics run, we carried out a test experiment for eight hours using the \( \text{CH}_{2} \) target in order to study the feasibility of this plan.
2.2. Experimental setup

The experiment will be performed at the cyclotron facility in Research Center for Nuclear Physics, Osaka University. A solid hydrogen target \([5]\) with a thickness of 0.5 mm is bombarded with a 250-MeV \(^{12}\text{C}\) beam as shown in Fig. 3.

The recoiled proton is detected and particle-identified by the Si+CsI telescope in the scattering chamber. The front and rear sides of the Si detector are segmented into the 32 vertical and 16 horizontal strips, respectively. The recoiled angle of the proton is obtained from the double-sided Si strip detector. The excitation energy of the scattered \(^{12}\text{C}\) is determined by the energy and angle of the recoiled proton.

The scattered \(^{12}\text{C}\) is analyzed by the Grand Raiden spectrometer and detected by the two multi-wires drift chambers (VDC1 and VDC2) and two plastic scintillators at the focal plane of the spectrometer. The thicknesses of the plastic scintillators are 1 mm at the upstream and 10 mm at the downstream. The scattered \(^{12}\text{C}\) cannot penetrate the 1-mm scintillator, while \(\alpha\) particles can penetrate and stop at the 10-mm scintillator. Therefore, the trigger signal for the \(^{12}\text{C}\) detection was generated using the anti-coincidence technique between the two scintillators.

2.3. Improvement of the signal to noise ratio

Accidental coincidence events are expected to cause serious backgrounds. A true-coincidence event [Fig. 4(a)] is an event in which a recoiled proton and a scattered \(^{12}\text{C}\) derived from the same reaction are detected in coincidence, while an accidental coincidence event [Fig. 4(b)] is an event in which a recoiled proton and a scattered \(^{12}\text{C}\) derived from the different reactions are accidentally detected at the same time. The number of the accidental coincidence events can be estimated by making random coincidence between different beam bunches, but a special treatment to remove the accidental coincidence events is needed because the true coincidence events are extremely rare. In addition, contaminations the target also cause serious background.

A detailed Monte Carlo simulation was performed to estimate the signal to noise (S/N) ratio and it was found that the S/N ratio was less than 1/250 if no special treatment to remove backgrounds was done. Therefore we planned to introduce some tricks to improve the S/N ratio, for example, a thin solid hydrogen target for impurities reduction, an event-tagging Si+CsI telescope for removal of accidental coincidence events, and so on.

3. Results of the test experiment

The test experiment was carried out at RCNP using the \(\text{CH}_2\) target instead of the solid hydrogen target. Figure 5(a) shows the excitation energy spectrum including all the inelastic events. The solid line indicates the spectrum with the \(\text{CH}_2\) target, and the hatched histogram presents the...
spectrum with the natural carbon target. The prominent peaks of the ground state, the $2^+_1$ state at $E_x = 4.44$ MeV, the $0^+_2$ state at $E_x = 7.65$ MeV, and the $3^+_1$ state at $E_x = 9.64$ MeV are clearly observed in Fig. 5(a). The excitation energy resolution about the $3^+_1$ state is 220 keV in the standard deviation $\sigma$, and the observed number of the inelastic events exciting the $3^+_1$ state is $5.90(4) \times 10^6$ within the $\pm 2\sigma$ width shown by the vertical dashed lines in Fig. 5.

Figure 5(b) shows the excitation energy spectrum of the $\gamma$-decay events. The peaks of the $2^+_1$ state at $E_x = 4.44$ MeV and the $1^+_1$ state at $E_x = 12.71$ MeV are clearly observed. Figure 6 is the same spectrum as Fig. 5(b) but expanded around $E_x = 9.64$ MeV. In Fig. 6, no peaks of the $3^+_1$ state is observed but the continuous background is observed. At present, this continuous background limits the sensitivity to the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ in the test experiment. The number of the observed $\gamma$-decay events within $\pm 2\sigma$ around the $3^+_1$ state is 48(12), therefore the sensitivity of the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ is $2.0(5) \times 10^{-5}$ in the test experiment. The sensitivity was estimated by considering the statistical error and the geometrical acceptance of the detectors. On the other hand, the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ of the $1^+_1$ state at $E_x = 12.71$ MeV is found to be $2.07(14) \times 10^{-2}$. This result is quite close to the known value $2.21(7) \times 10^{-2}$ [3] and it endorses that the present method using inverse kinematic reactions is useful to determine $\gamma$-decay probabilities above particle-decay thresholds.

4. Summary

We planned to determine the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ of the $3^+_1$ state in $^{12}$C using the inverse kinematic reaction $^1$H($^{12}$C, $^{12}$Cp) for the precise determination of the triple $\alpha$ reaction rate, and performed the test experiment. As a result, the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ for the $1^+_1$ state in $^{12}$C was successfully determined without measuring $\gamma$-rays. However, the sensitivity to the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ in the present measurement is $2.0(5) \times 10^{-5}$, and it is not good enough to determine the $\gamma$-decay probability $\Gamma_{\gamma}/\Gamma$ of the $3^+_1$ state. The origin of the continuous background must be examined.

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