I. 1. $^{13}\text{C}(\alpha, n)^{16}\text{O} \text{ Reaction at } E_\alpha = 50 \text{ MeV}$


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Much attention is concentrated on the experimental studies for nuclear structure of $^{16}\text{O}$. Among them, single- and multi-nucleon transfer reactions have been extensively investigated in order to make clear one particle one hole 1p-1h, 2p-2h, 3p-3h and cluster structures of this closed shell nucleus. The recent interest on the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction is related to the topics of nucleo synthesis in the universe. The $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction is one of the main source reaction for the slow-process. Because of very low energy property of this story, the reaction might be influenced by the sub-threshold state at 6.356 MeV, which is only 2-keV below the $\alpha-$threshold in $^{17}\text{O}$. Since the resonance strength is proportional to the $\alpha$-width of the sub-threshold state, the spectroscopic factor of $\alpha$–transfer reaction e.g. $^{13}\text{C}(^{6}\text{Li}, d)^{17}\text{O} (6.356 \text{ MeV})$ has been studied1).

In this report, experimental results of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction carried out at $E_\alpha = 50 \text{ MeV}$ by utilizing the fast neutron time of flight method. Measured q-dependency of differential cross sections is compared with finite-range DWBA predictions, where neutron knock-out process is dominant for transitions leading to low-lying state in $^{16}\text{O}$, while $^{3}\text{He}$ pick-up process dominates for those to high-lying states in $E_x\sim20\text{MeV}$. By comparing the present $^{13}\text{C}(\alpha, n)^{16}\text{O}$ spectrum with those for $^{15}\text{N}(d, n)^{16}\text{O}$[Ref. 2], $^{14}\text{N}((\alpha, d)^{16}\text{O}$[Ref. 3], $^{12}\text{C}(^{6}\text{Li}, d)^{16}\text{O}$1), $^{13}\text{C}(^{6}\text{Li}, t)^{16}\text{O}$) reactions, many-particle many-hole characters of the individual state are discussed.

The experiments were performed using a 50-MeV $\alpha$-beam from the K=50 MeV AVF cyclotron at Cyclotron and Radioisotope Center (CYRIC), Tohoku University. Neutron energies were measured by the time of flight technique. Twelve neutron detectors containing totally 23 litter of liquid-scintillator NE213 were set at a flight path of 44 m from
the target, where the effective neutron detection solid angle was 0.23 msr. Angular distributions of neutrons were measured using a beam-swinger system. Detector efficiency for the most energetic neutrons was 3%, which was determined by the $^7\text{Li}(p, n)^7\text{Be}$ reaction through activation analysis. Details of the CYRIC TOF facility have been described elsewhere\(^5,6\). Metallic carbon enriched to 99% in $^{13}\text{C}$ with the thickness of 2.42 mg/cm\(^2\) was used as the target. Overall energy resolution was 200 keV (FWHM) for the most energetic neutrons leading to the low-lying states in the residual nuclei. The target was prepared by the thermo-clacking of enriched acetylene gas on the tantrum plate heated to 1800°C in a 2.612x10\(^3\) Pa atmosphere. The amount of the tantrum impurity was tested by the PIXE-method to be less than 0.08 $\mu$g/cm\(^2\). Gamma-ray events have been rejected by pulse-shape-discrimination technique. Errors in the absolute magnitudes of cross section are estimated to be less than 12%, the dominant part of which is due to the uncertainty of the detector efficiency.

Figure 1 shows a neutron excitation energy spectrum taken at a laboratory angle of 40 degree for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. Due to angular momentum mismatching between entrance-alpha and exit-neutron channels, ground state transition is highly inhibited. A spectrum for the $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ reaction\(^1\), which may exhibit typical $\alpha$-transfer nature with $\Delta T=0$, are also shown in Fig. 2 for comparison. Alpha transfer leading to the $0^+$(0.0), $2^+$(6.1 MeV), $4^+$(10.35 MeV), and $6^+$(14.8 MeV) rotational states is clear in both reactions, though their intensities are less systematic for the case of the present $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. The other peculiar feature of the ($^6\text{Li}, d$) spectrum is it’s structure less aspect in the higher excitation energy region beyond ~16MeV as seen in Fig. 2, while many prominent peaks are observed in the ($\alpha, n$) spectrum. The latter may be due to excitation of $T=1$, many-particle many-hole states including high-spin states.

Measured angular distributions of emitted neutrons are shown in Figs. 3 through 11 along with theoretical predictions. Theoretical cross sections have been calculated by the code TWOFNR\(^7\), by which we are able to obtain finite-range form factors and multi-step reaction cross sections. Optical potential parameters for the entrance $\alpha$-channel have been determined by the elastic scattering measurement on $^{13}\text{C}$ at 50 MeV by Watson et al\(^8\). Those for neutron are parameter set by Carlson et al\(^9\). Two kinds of reaction mechanism have been assumed. The first one is knock-on reaction, where the incident $\alpha$-particle knock-out the target neutron forming 4p-4h states in the residual nucleus. The other one is stripping reaction, where three nucleons in the $\alpha$-particle is stripped to form 3p-3h states.
An experimental differential cross section is compared with theoretical one with the code TWOFNR by:

\[
\frac{d\sigma}{d\Omega}_{\text{exp}} = \varepsilon C^2 s \left( \frac{d\sigma}{d\Omega} \right)_{\text{TWOFNR}}, \quad C = (T_i T_z \Delta T_i \Delta T_z | T_f T_z),
\]

where \( C \) is Clebsh-Gordan coefficient for isospin not included in TWOFNR. In the present case, \( C = 1/2 \) for \( T=0 \) and \( T=1 \) of final state isospin. The factor \( s \) in the formula is the light particle spectroscopic factor and is 2 for the (a, n) reaction, while \( \varepsilon \) is the normalization factor introduced to fit theoretical cross sections to the data.

Comparing the present (\( \alpha \), n) data with those by (\( ^6\text{Li} \), d) reaction, we have identified the rotational band. Figures 3, 5 and 6 show q-dependency of differential cross sections exciting the 4p-4h states forming a rotational band consisting of the 0+, 2+, and 4+ states at their excitation energy \( E_x \) equal to 0.0, 6.92 and 10.4 MeV, respectively. Curves are theoretical calculations obtained by the \( (p_{1/2})^4(sd)^4 \) configuration. Theoretical cross sections are normalized to experimental results. An exception of these discussion is excitation of the second excited 3- state at \( E_x = 6.13 \) MeV, which has been observed, for example, by the \(^{15}\text{N}(d, n)^{16}\text{O} \) reaction as a prominent transition. Note that this state has been observed in the \((^6\text{Li}, d) \) reaction as seen in Fig. 2. As such, pick-up process should be also taken into accounts in analysis for this transition as illustrated in Fig. 4. The prominent transition, q-dependency for which is illustrated in Fig. 7, has been predicted theoretically by Zuker et al\textsuperscript{10} to be a pure 2p-2h state.

A number of prominent peaks have been observed in higher excitation energy region \( E_x \sim 20 \text{MeV} \), in contrast to the monotonous aspect of the \((^6\text{Li}, d) \) spectrum in this region. Angular distributions of the differential cross section for these typical transitions to the 20.6- and 24.7-MeV states are illustrated in Figs. 10-11. In Fig. 10 for the 20.6-MeV transition, two possibilities of 5+ with \( \Delta L=5 \), \( (p_{1/2})^2(d_{5/2})^2 \) configuration and 7+ with \( \Delta L=6 \) \( (p_{1/2})^3(d_{5/2})^3 \) configuration are shown for spin-parity assignment. In Fig. 11 for the 24.7-MeV transition, a possibility of 7+ with \( \Delta L=6 \), \( (p_{1/2})^3(d_{5/2})^3 \) configuration is shown for spin-parity assignment by the analog relation to the 11.78-MeV (7+) state in \(^{16}\text{N} \). For these transitions, the normalization factors \( \varepsilon \) lay in the same order of magnitude.

In a summary, experimental study of the \(^{13}\text{C}(\alpha, n)^{16}\text{O} \) reaction was carried out at \( E_\alpha = 50 \) MeV by utilizing the fast neutron time of flight method. Measured q-dependency of differential cross sections have been compared with finite range DWBA predictions,
where neutron knock-out process is dominant for transitions leading to low-lying state in $^{16}$O, while $^3$He pick-up process dominates for those to high-lying states in $E_x \sim 20$ MeV. By comparing the present $^{13}$C($\alpha$, n)$^{16}$O spectrum with those for $^{15}$N(d, n)$^{16}$O, $^{14}$N($\alpha$, d)$^{16}$O, $^{12}$C($^6$Li, d)$^{16}$O, $^{13}$C($^6$Li, t)$^{16}$O reactions, many-particle many-hole characters of the individual state were discussed. In particular, a number of 2p-2h and 3p-3h like high-spin states were located at higher excitation energy region.

References
7) Igarashi M., computer code TOWFN, unpublished.

Figure 1. Energy spectrum of the $^{13}$C($\alpha$, n)$^{16}$O reaction at $\theta_{lab} = 40^o$ with a flight path of 44.3 m. Energy per channel is 50 keV.

Figure 2. Energy spectrum of the $^{12}$C($^6$Li, d)$^{16}$O reaction at $\theta_{lab} = 5^o$ by Becchetti et al. Known levels are indicated by $E_x$ (MeV) and $J^+$ values while other groups are indicated by $E_x$ only. Due to limited resolution, the spectrum in a composite of several overlapping spectra.
Figure 3. Differential cross sections for neutrons leading to the 0⁺ ground state. The curves are theoretical predictions described in the text.

Figure 4. Same as Fig. 3 but for neutrons leading to the 3⁻, 6.1-MeV state.

Figure 5. Same as Fig. 3 but for neutrons leading to the 1⁻ and 2⁺ states at 7.0 MeV.

Figure 6. Same as Fig. 3 but for neutrons leading to the 4⁺, 10.4-MeV state.

Figure 7. Same as Fig. 3 but for neutrons leading to the 5⁺, 14.4-MeV state.

Figure 8. Same as Fig. 3 but for neutrons leading to the 6⁺, 14.9-MeV state.
Figure 9. Same as Fig. 3 but for neutrons leading to the 5+, 18.6-MeV state.

Figure 10. Same as Fig. 3 but for neutrons leading to the 7(5+), 20.6-MeV state.

Figure 11. Same as Fig. 3 but for neutrons leading to the 7-, 24.7-MeV state.