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# I. 1 Study of $^{12}C(^{3}He,n)^{14}O$ Reaction at 45 MeV

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A two-proton stripping reaction is of particular interest for the study of two-proton excitations, since it provides a unique spectroscopic information about the $T_z=T_z$(target)-1 member of isospin triplet states formed with a core nucleus plus excited two-protons, proton and neutron pair, and two-neutrons. In the frame work of the direct reaction theory the two-proton stripping reaction is assumed to be the transfer of a singlet di-proton to the target nucleus. When the target nucleus has a zero-spin, the reaction leads to the natural-parity states with the same total angular momentum transfer $\Delta J$ as the orbital angular momentum transfer $\Delta L$. Thus, this fact enables us to make the unique spin-parity assignment of the observed level from the experimental angular distribution characterized by the $\Delta L$ value. Of course, unnatural-parity states can be also excited through more complex processes such as a sequential transfer process, but they are considered to have reduced yields at a higher incident energy. Thus an experiment of the two-proton stripping with relatively high incident energy has an advantage of enhancing the direct reaction process up to the highly excited two-particle states.

The study of a $^{12}C(^{3}He,n)^{14}O$ reaction is one of the useful probe to get the information of the two-proton excitations in the $^{14}O$ nucleus. The spectroscopic information about T=1 states which consist of two protons in the $1p_{1/2}$ orbit and in the 1d-2s shell plus core can be obtained. Though investigations of excited levels in $^{14}O$ are found in previous works by the reaction of $^{16}O(p,t)^{14}O$ 1), $^{14}N(p,n)^{14}O$ 2), $^{14}N(^{3}He,t)^{14}O$ 3), and by using heavy ion reactions such as $^{10,11}B$, $^{12}C$ and $^{14}N$ incident on the $^{12}C$ target4,5), the nuclear structure informations of this nucleus are still not well known, especially on highly excited levels. The studies of $^{12}C(^{3}He,n)^{14}O$ reactions have been appeared in several references.6,7) However excited states higher than 10 MeV have not been studied, because the low bombarding energies so far used.

Measurements were carried out by using the $^{3}He$ beam at 45 MeV provided from the AVF cyclotron and by employing the time-of-flight (TOF) facilities8) at the Cyclotron and Radioisotope Center, Tohoku University. The incident $^{3}He$ beam has an energy spread of less than 50 keV and a micro-burst time resolution of approximately 0.9 nsec. In order to obtain an appropriate dynamic range in the time spectrum, the beam repetition period was reduced to 372.6 nsec by use of an external beam chopper. The neutrons following the $^{12}C(^3He,n)^{14}O$ reaction were detected by four detectors containing a total of 7.5 litters of NE213 liquid scintillator. Energies of neutrons were analyzed by a TOF method employing a flight pass of 24.6 m. On-line data were taken by a CAMAC data acquisition system controlled by a PDP11/44 computer. A natural carbon foil of 6.75 mg/cm$^2$ in thickness was used for the target.

A typical neutron spectrum at $\theta_{Lab.}=3°$ with respect to the beam axis is shown in fig. 1. The abscissa corresponds to the excitation energy of the residual $^{14}O$ nucleus translated from the TOF spectrum with a bin width of 50 keV. The energy resolution for 42 MeV neutrons corresponding to the ground state transition was 400 keV (FWHM). In this spectrum, previously assigned levels of 0.0 MeV $0^+$, 5.17 MeV $1^-$ and 7.77 MeV $2^+$ were seen. But in the present resolution 5.92 MeV $0^+$, 6.27 MeV $3^-$ and 6.59 MeV $2^+$ states, and 9.72 MeV ($2^+$) and 9.92 MeV $4^+$ states were not able to be separated. In the higher excitation energy region above 10 MeV, two prominent peaks at 12.6 MeV and 14.3 MeV, and a broad bump around 15.8 MeV, which have been observed in $^{14}N(^3He,t)^{14}O$ reaction$^{3)}$, but for which the $J^\pi$ values have not been assigned, were seen to be excited. A doublet peak at 12.6 MeV where the energy resolution was 350 keV (FWHM) was analyzed by using a peak fitting program. The level of 15.8 MeV has not been observed in the previous observations of $^{14}O$ nucleus.

Angular distributions of emitted neutrons leading to observed levels in $^{14}O$ are shown in figs. 2a, 2b and 2c. The curves drawn on the experimental points are the predictions of the zero-range DWBA calculation which will be described in the next section. Error bars attached to the experimental points stand for the uncertainties of the statistics, the peak separation and the subtraction of backgrounds. The errors of the absolute magnitudes of the differential cross sections were estimated to be within 20%, which come from uncertainties in the determination of the detector efficiency and the target thickness.

Calculations of differential cross sections for the $^{12}C(^3He,n)^{14}O$ reaction were carried out by using the zero-range DWBA code DWUCK4.$^{9)}$ The optical model parameters for the entrance channel of the $^3He+^{12}C$ system were obtained from ref. 14. Those for the exit channels of the $n+^{14}O$ system were obtained from the systematics derived by Carlson et al.$^{10)}$ These parameters used here are listed in table 1. In the present calculation, the zero-range normalization factor $D_0^2 = 22\times10^4$ MeV$^2$fm$^3$ was employed. The form factors were calculated by the method of Bayman and Kallio.$^{11)}$ Transferred protons were bound in the residual nucleus in a Wood-Saxon well with parameters $r_0 = 1.25$ fm, $a_0 = 0.65$ fm, $r_{s.o.} = 1.01$ fm, $a_{s.o.} = 0.65$ fm and $r_c = 1.25$ fm. The form factor of the two-proton bound states of 0.0 MeV, 5.17 MeV and 6.3 MeV were calculated for protons bound with the energy of a one-half of the two proton separation energy. Usually, it has been found that the calculated differential cross section are strongly dependent on the used form factor, but the binding energy effect was shown to be little.$^{12)}$ The calculation for the unbound region were performed by assuming the levels to be bound. This method gives an agreement with more rigorous calculation in the order of 15%. While the relative magnitudes of the cross sections are sensitive to the sets of wave functions, two-proton wave functions presented by True$^{13)}$, which was based on the closed $^{12}$C core with $p_{1/2}$, $s_{1/2}$, $d_{5/2}$ and $d_{3/2}$ orbits, for the T=1 levels in $^{14}$N were used in the present DWBA calculation.

As discussed in previous works$^{9)}$, the cross section obtained from DWBA for ($^3$He,n) reaction is expressed by the formula

$$\frac{d\sigma_{exp}}{d\Omega} = D_0^2 \cdot N \frac{2J_f+1}{2J_i+1} \cdot \frac{\sigma_{DWBA}}{2\Delta L+1} \tag{1}$$

where N is a normalization factor thought to reflect the effect of finite radius of the transferred two-proton and the nature of the target nucleus. The normalization factors for each transition are tabulated in table 2. The comparison with the experimental results re shown in figs. 2a, 2b and 2c, where the solid lines for the 0.0 MeV and 5.17 MeV present the normalized curve, and that for the 6.3 MeV state presents the summed values of the contribution from $0^+$, $2^+$ and $3^-$ components. Curves for the higher excited levels are calculated as bound states.

Most of the low-lying structure of the $^{14}$O nucleus assumed to be couplings of two-protons in various orbits with a $^{12}$C core. The ground-states (GS) should be mainly two $1p_{1/2}$ protons plus the $^{12}$C core, as described in the True's wave function. The DWBA calculation provides a good fit for the GS transition with the angular momentum transfer L=0. The shapes of calculated angular distributions were characteristic of a particular angular momentum transfer, but insensitive to the choice of form factor. The GS is an analog state of the 2.31 MeV state in the $^{14}$N and also a mirror state of the $^{14}$C GS. The absolute magnitude as seen in table 2 is 40% larger than the theoretical prediction. The angular distribution of the 5.17 MeV level, which was previously assigned as $1^-$, was well reproduced by L=1 transfer with the main configuration of $(1p_{1/2})(2s_{1/2})$ protons coupled to a $^{12}$C core. This state is also identified as a 8.06 MeV analog state in $^{14}$N and a 6.09 MeV mirror state in $^{14}$C. The observed cross section for the first $1^-$ state is smaller than the prediction. This may come from the assumption of the closure of $^{12}$C core. The prominent peak around 6.42 MeV can not be described by a single component. In the previous assignment, there are two or three levels of 5.90 MeV $0^+$, which may be weakly excited, 6.30 MeV $3^-$ and 6.59 MeV $2^+$. The angular distribution of 7.77 MeV level previously assigned as a $2^+$ state is characterized by a L=2 component. As for the excited states higher than this state a transferred di-proton is unbound, the DWBA analysis were not attempted for these states, but we can assume the level assignment by the shapes of the angular distribution characteristic of the angular momentum transfer and an analog and a mirror structures in $^{14}N$ and $^{14}C$ nuclei. The angular distribution of the 7.7 MeV state indicates the L=2 transfer pattern. The analog and mirror state correspond to this state can be found at 10.43 MeV $2^+$ in $^{14}N$ and 8.32 MeV $2^+$ in $^{14}C$. The 9.9 MeV state is also assumed to be a mixture of 9.71 MeV $2^+$ and 9.915 MeV $4^+$.

Above 10 MeV, the spin parity assignments are not clear in the previous works. The 10.89 MeV level which was suggested as a $2^-$ state is not populated in the neutron spectrum (see fig. 1), in agreement with the present one-step DWBA analysis. Though the angular distributions of the levels located at 12.6, 14.3 and 15.8 MeV show ΔL=2 or ΔL=3 pattern, it is difficult to give transfer ΔL assignments from the present analysis.

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Table 1. Optical model parameter sets used in the analysis

| Channel | $V_{vol}$ | $r_{OR}$ | $a_R$ | $W_{vol}$ | $r_{OI}$ | $a_I$ | $4W_s$ | $r_{OI}$ | $a_I$ | $V_{LS}$ | $r_{LS}$ | $a_{LS}$ | $r_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $^3He+^{12}C$ | -144.3 | 1.20 | 0.72 | -26.0 | 1.40 | 0.88 | | | | | | | 1.30 |
| $n+^{14}O$ | | | | | | | | | | | | | |
| (43.8 MeV) | -45.7 | 1.17 | 0.75 | -8.1 | 1.26 | 0.58 | 15.2 | 1.26 | 0.58 | -24.8 | 1.01 | 0.75 | 1.25 |
| (38.6 MeV) | -47.4 | 1.17 | 0.75 | -6.9 | 1.26 | 0.58 | 20.1 | 1.26 | 0.58 | -24.8 | 1.01 | 0.75 | 1.25 |

Well depth in MeV, radii and diffuseness in fm.
a) Ref. 10.
b) Ref. 14.

Table 2. States populated in the $^{12}C(^3He,n)^{14}O$ reaction

| Excitation Configuration Energy (MeV) | Transfer L | Normalization Factor | Previous J Assignment |
|---|---|---|---|
| 0.0 | 0 | 1.4 | $0^+$ |
| 5.17 | 1 | 0.7 | $1^-$ |
| 7.7 | 2 | 0.4 | $2^+$ |

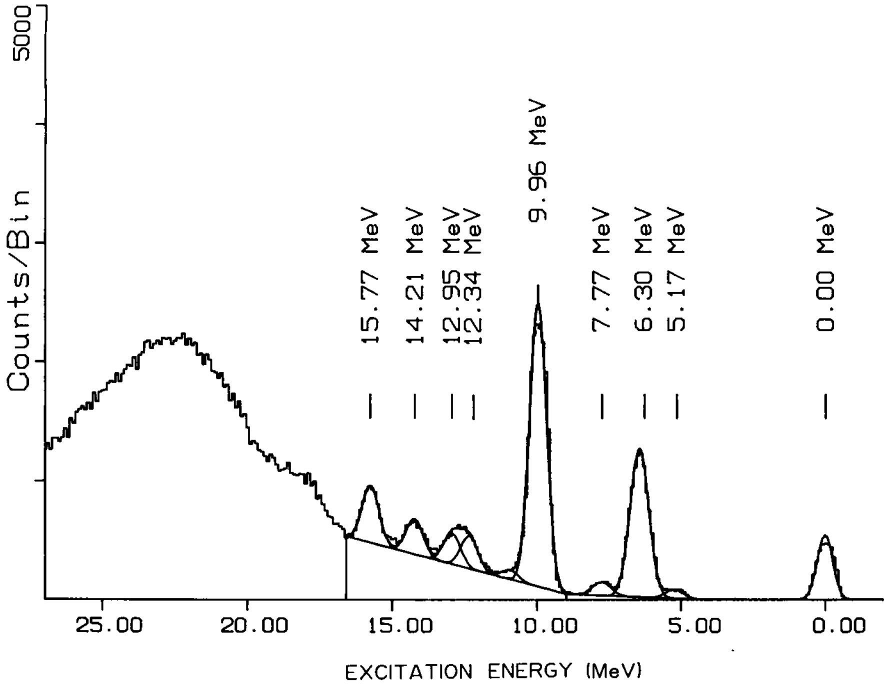

Fig. 1. Neutron energy spectrum from $^{12}C(^3He,n)^{14}O$ reaction at 3 deg. (Lab.) with respect to the beam axis.

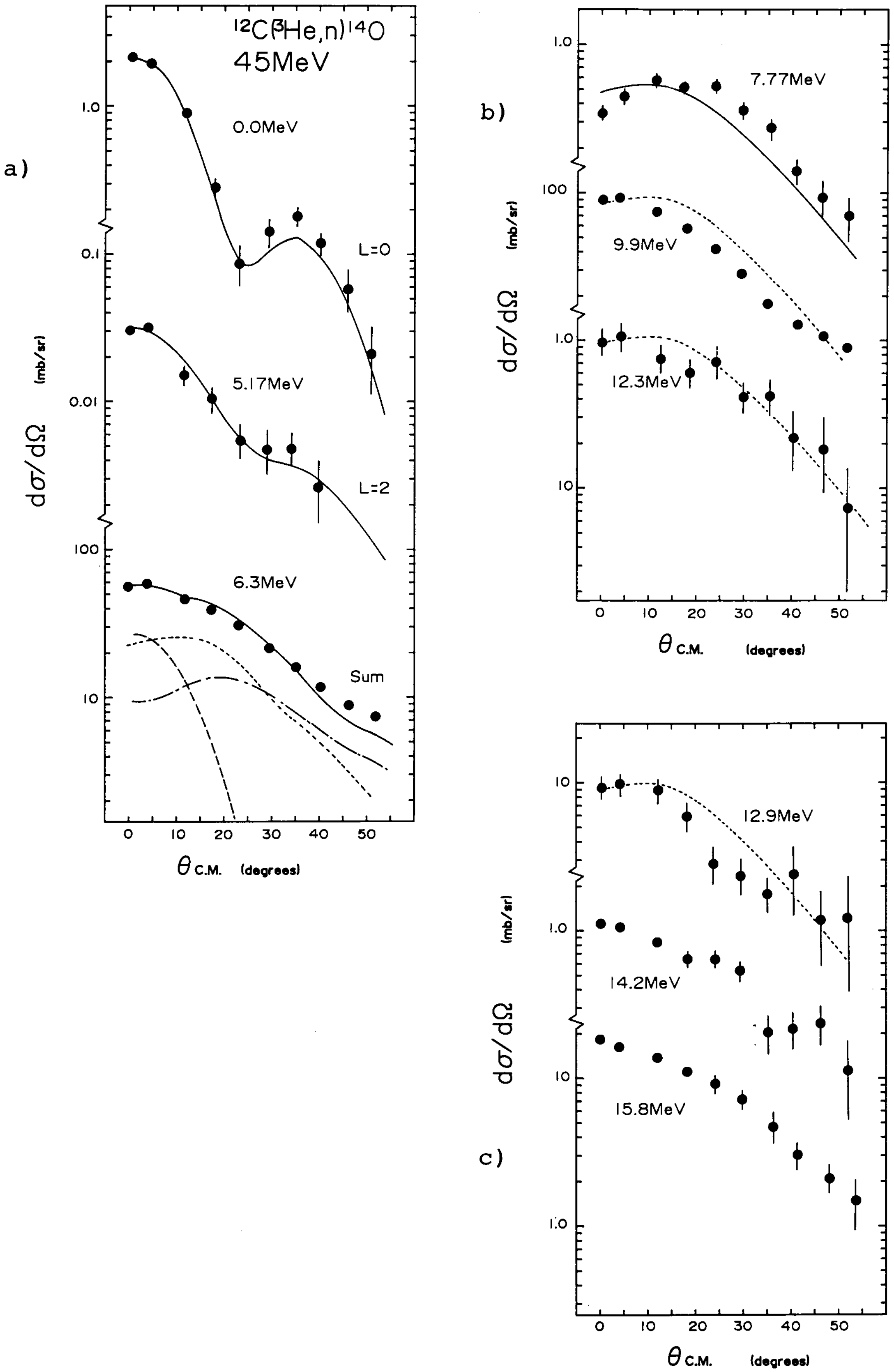

Fig. 2(a, b, c). Neutron angular distributions from $^{12}C(^3He,n)^{14}O$ reaction. Curves are DWBA predictions.