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THE REACTION $^{12}\text{C}(^{16}\text{O},^{12}\text{C})^{16}\text{O}$

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April 1971

Abstract:

The transfer reaction $^{12}\text{C}(^{16}\text{O},^{12}\text{C})^{16}\text{O}$ and the scattering reaction $^{12}\text{C}(^{16}\text{O},^{16}\text{O})^{12}\text{C}$ were studied simultaneously at $E(^{16}\text{O}) = 69.45$ MeV (lab). The levels of $^{16}\text{O}$ and $^{12}\text{C}$ which were excited suggest that at forward angles of $^{12}\text{C}$ the reaction is a four-nucleon transfer, while at backward $^{12}\text{C}$ angles inelastic scattering of $^{16}\text{O}$ predominates. The $Q=0$-MeV angular distribution is in qualitative agreement with these conclusions.

The $(^{16}\text{O},^{12}\text{C})$ reaction has recently been used to excite four-particle (quartet) states in a variety of nuclei between $^{40}\text{Ti}$ and $^{68}\text{Zn}$. Since four-particle levels resembling those postulated in this work are well-known in $^{16}\text{O}$ (supposed to be the members of the rotational band based on the $6.05$-MeV $0^+$ level), we studied the reactions $^{12}\text{C}(^{16}\text{O},^{16}\text{O})^{12}\text{C}$ and $^{12}\text{C}(^{16}\text{O},^{12}\text{C})^{16}\text{O}$ (elastic and inelastic scattering of $^{16}\text{O}$ by $^{12}\text{C}$, and four-nucleon transfer respectively). The reactions have been studied previously but there is little published information about precisely which levels of $^{16}\text{O}$ are excited by the two reactions.

The experiment was done with $69.45$-MeV $^{16}\text{O}$ $(3^+)$ ions accelerated in the third harmonic mode by the Berkeley 88-inch cyclotron. Reaction products were
detected in a $\Delta E(11\mu) - E(250\mu)$ counter telescope at a resolution of about 400 keV. They were identified by computing for each event the function $\Delta E(E + E_0 + K\Delta E)$, where $E_0$ and $K$ are adjustable constants. With so thin a $\Delta E$ counter, separation of adjacent masses of a given $Z$ was not possible, but adjacent elements were completely resolved. Isotopes of C and Ne were much more abundant than N or F.

Examination of the C and O spectra as a function of angle showed that no peaks could be attributed to $^{11}\text{C}$, $^{13}\text{C}$, $^{14}\text{C}$, $^{14}\text{O}$, $^{15}\text{O}$, or $^{17}\text{O}$ or to any excited states of these nuclei.

In the $^{12}\text{C}$ spectra, peaks corresponding to levels of $^{16}\text{O}$ and the ground state of $^{12}\text{C}$ are narrow. Decay in flight causes the peak corresponding to excitation of $^{12}\text{C}$ to the 4.439-MeV level to be broadened to a width of about 1 MeV. Since all other $T = 0$ excited states of $^{12}\text{C}$ decay predominantly by particle emission, the 4.439-MeV level is the only $^{12}\text{C}$ excited state that should be observed in the $^{12}\text{C}$ spectra. This is confirmed experimentally.

In the $^{16}\text{O}$ spectra, on the other hand, peaks due solely to excitation of $^{12}\text{C}$ cannot be broadened by decay in flight, while peaks corresponding to $\gamma$-decaying levels of $^{16}\text{O}$ should be broad. Particle-decaying levels of $^{16}\text{O}$ should be absent. Again these expectations are confirmed by the experiment.

Figure 1 shows a spectrum of $^{12}\text{C}$. A preliminary energy scale was constructed by least-squares fitting the peak centroids for the $Q = 0$ and $Q = -4.439$-MeV levels and the corresponding calculated particle energies at all measured angles. This scale permitted assignment of $Q = -6.917$ and $-10.34$ MeV to two additional peaks. A second least squares fit including these levels was then made to 51 pairs of centroid-energy values. The fit included a small second order term. The standard deviation was 0.18%. The accuracy was
insufficient to determine whether the peak at \( Q \approx -6 \, \text{MeV} \) is due to the 6.052-MeV 0+ level of \( {}^{16}O \) or to the 6.131-MeV 3- level. The experimental value was \( Q = -6.08 \pm 0.04 \, \text{MeV} \). However, the 6.917-MeV 2+ member of the \( {}^{16}O \) band is strongly excited. The peak at \( Q = -10.34 \pm 0.04 \, \text{MeV} \) could be either the 10.342-MeV 4+ member of the rotational band or the 10.351-MeV \( {}^{16}O \) level.\(^9\) From its observed energy and small width, it cannot be due to the double excitation \( {}^{12}C(4.439 \, \text{MeV}) + {}^{16}O(6.052 \, \text{MeV}), \, Q = -10.491 \, \text{MeV} \).

At just a few angles, peaks appeared in the \( {}^{12}C \) spectrum corresponding to \( Q = -10.95 \pm 0.09 \) and \(-14.7 \, \text{MeV} \). The former is visible only in the neighborhood of 30° (lab). At other angles it is replaced by a broad structure which is probably due to the double excitations \( {}^{12}C(4.439 \, \text{MeV}) + {}^{16}O(6.052, 6.131 \, \text{MeV}) \). The only \( {}^{16}O \) levels near the observed energy are the 10.952-MeV 0- and 11.080-MeV 3+, neither of which can be excited in first order by \( \alpha \)-transfer or inelastic scattering of \( {}^{16}O \). The double excitation could be responsible for the sharp peak in the vicinity of 30° if there were a sufficiently strong correlation between the motion of the \( {}^{12}C \) excited nucleus and its decay \( \gamma \)-ray to suppress the broadening.

The peak at about \( Q = -14.7 \, \text{MeV} \) could be either the 14.82-MeV 6+ or the 14.80-MeV 0+, 1- levels of \( {}^{16}O \). At most angles it is replaced by a broad structure that is probably due to the double excitation \( {}^{12}C(4.439 \, \text{MeV}) + {}^{16}O(10.34 \, \text{MeV}) \). A strong peak at \( \sim 14.8 \, \text{MeV} \) has been previously observed in the \( {}^{14}N(\alpha,d){}^{16}O \) (Ref. 10), \( {}^{12}C(Li^7,t) \) (Ref. 11), \( {}^{12}O({}^{16}O,{}^{12}C){}^{16}O \) (Ref. 7) and \( {}^{12}C(\alpha,\alpha){}^{12}C \) (Ref. 6) reactions. The level, if the same in all cases, must have considerable 2p-2h and 4p-4h strength.

The 6+ member of the \( {}^{16}O \) band, at 16.2 MeV, was not observed at any angle, probably because the energy of the outgoing \( {}^{12}C \) ion would be substantially
below the $^{12}\text{C} + ^{16}\text{O}$ coulomb barrier. However, it is not strong even at an oxygen bombarding energy of 97 MeV (lab).\(^7\)

The $^{16}\text{O}$ levels observed in the $^{12}\text{C}$ spectra appear to be excited by the $\alpha$-transfer mechanism rather than by inelastic scattering. The $^{16}\text{O}$ levels most strongly excited by ($\alpha,\alpha'$) are (in decreasing order of cross section) the $6.131 \text{ MeV } 3^-$, $6.917 \text{ MeV } 2^+$ and the $7.119 \text{ MeV } 1^-$.\(^{12}\) In the present experiment the energy scale based on the $Q=0$ and $-4.439 \text{ MeV}$ peaks gave $Q = -6.902 \pm 0.018 \text{ MeV}$ for the peaks in this region. Furthermore, the peak was always symmetric and as narrow as the peak at $Q = -6.1 \text{ MeV}$. Thus the $7.119$-MeV level must be very weak, whereas in ($\alpha,\alpha'$) its cross section is about half that of the $6.92$-MeV level.

In ($\alpha,\alpha'$), the level at $10.34 \text{ MeV}$ is excited only about one tenth as strongly as the $6.92 \text{ MeV}$ level, whereas in the $^{12}\text{C}$ spectra it is at least as strong and usually much stronger. The $14.7\text{-MeV}$ level observed in the $^{12}\text{C}$ spectra is weak or absent in ($\alpha,\alpha'$) spectra. The elastic angular distribution shown in Fig. 2 shows a rise towards forward $^{12}\text{C}$ angles which may be indicative of a transfer mechanism at small $^{12}\text{C}$ angles. There is a typical elastic scattering diffraction pattern at large $^{12}\text{C}$ angles (small $^{16}\text{O}$ angles).

The $^{16}\text{O}$ spectra are less useful since most of the peaks are broadened by decay in flight. An energy scale was constructed by least square fit to the $Q=0$ and $Q = -4.439 \text{ MeV}$ peaks. The standard deviation was $0.15\%$. Apart from the $Q=0$ and $Q = -4.439 \text{ MeV}$ peaks, there was a broad intense peak at $Q = -6.36 \pm 0.04 \text{ MeV}$ corresponding to excitation of the unresolved $^{16}\text{O}$ levels between $6.05$ and $7.12 \text{ MeV}$. The $^{12}\text{C} 3^-$ level at $9.64 \text{ MeV}$ was observed: it is strongly excited by $^{12}\text{C}(\alpha,\alpha')^{12}\text{C}$.\(^{12}\) A strong broad peak at $Q = -10.72 \pm 0.13 \text{ MeV}$
can only correspond to $^{12}\text{C}(4.439 \text{ MeV}) + ^{16}\text{O}(6.05 + 6.13 + 6.92 + 7.12 \text{ MeV})$. The $14.7$-MeV $^{16}\text{O}$ level was not visible in the $^{16}\text{O}$ spectra at any angle; it is presumably particle-unstable, as are the $10.34$- and $10.35$-MeV $^{16}\text{O}$ levels.

The cross sections for the $Q=0$- and $Q = -4.439$-MeV levels in the $^{12}\text{C}$ spectra are about equal. However, excitation of the $^{12}\text{C} 4.439$-MeV level was not observed in any ($^{16}\text{O}$,$^{12}\text{C}$) reactions with medium weight targets. This could be due to the presence of a continuum of $^{12}\text{C}$ ions (arising perhaps from three-body break-up of $^{16}\text{O}$ and from the high level density), and the broadening and lowering of the $^{12}\text{C}$ excited state peaks by $\gamma$-decay. Furthermore, the weakness of the sum peaks in Fig. 1 shows that while the residual system $^{12}\text{C}(4.439 \text{ MeV}) + ^{16}\text{O}(0 \text{ MeV})$ is more probable than $^{12}\text{C}(0 \text{ MeV}) + ^{16}\text{O}(0 \text{ MeV})$, residual systems containing $^{12}\text{C}(4.439 \text{ MeV}) + ^{16}\text{O}(\text{excited})$ are less visible than $^{12}\text{C}(0 \text{ MeV}) + ^{16}\text{O}(\text{excited})$. 
FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Energy spectrum of $^{12}\text{C}$ ions at 30° (lab).

Fig. 2. Angular distributions of $^{12}\text{C}$ particles for $Q = 0$– and $Q = -4.439$-MeV.

Cross sections forward of 85° (c.m.) were obtained from $^{12}\text{C}$ spectra, those backward of 85° (c.m.) from $^{16}\text{O}$ spectra.
Fig. 1

Counts / channel

Channel number

000 600 050 400 300 200 100 0

Channel number

12C gs. + 16O gs
12C 4.439 MeV
16O 0.6052 + 6.131 MeV
16O 10.34 MeV 4+
16O 10.95 MeV 2+
16O 14.7 MeV

ΔE counter (+)
cut-off

300° LAB
160° (8+)

XRL-713-3015
Fig. 2

- Elastic scattering
- Q = 4439 MeV x 10
- Transfer
- Q = 0 MeV
- Elastic scattering

\( \frac{d\sigma}{d\Omega} \) (mb/sr)

\( \theta_{\text{c.m.}} \) (deg) of \(^{12}\text{C}\)
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