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LAWRENCE RADIATION LABORATORY
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THE REACTION $^{12}C(^{16}O,^{12}C)^{16}O$*

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Abstract:

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

The $(^{16}O,^{12}C)$ reaction has recently been used to excite four-particle (quartet) states in a variety of nuclei between ^{44}Ti and ^{68}Zn.[1-4] Since four-particle levels resembling those postulated in this work are well-known in ^{16}O[5] (supposed to be the members of the rotational band based on the 6.05-MeV 0+ level),[6] we studied the reactions $^{12}C(^{16}O,^{16}O)^{12}C$ and $^{12}C(^{16}O,^{12}C)^{16}O$ (elastic and inelastic scattering of ^{16}O by ^{12}C, and four-nucleon transfer respectively). The reactions have been studied previously[7,8] but there is little published information about precisely which levels of ^{16}O are excited by the two reactions.

The experiment was done with 69.45-MeV ^{16}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 ΔE 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}C, ^{13}C, ^{14}C, ^{14}O, ^{15}O, or ^{17}O or to any excited states of these nuclei.

In the ^{12}C spectra, peaks corresponding to levels of ^{16}O and the ground state of ^{12}C are narrow. Decay in flight causes the peak corresponding to excitation of ^{12}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}C decay predominantly by particle emission, the 4.439-MeV level is the only ^{12}C excited state that should be observed in the ^{12}C spectra. This is confirmed experimentally.

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

Figure 1 shows a spectrum of ^{12}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 $Q \approx -6$ 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 $Q = -6.08 \pm 0.04$ MeV. However, the 6.917-MeV 2+ member of the ^{16}O band is strongly excited. The peak at $Q = -10.34 \pm 0.04$ MeV could be either the 10.342-MeV 4+ member of the rotational band or the 10.354-MeV ^{16}O level.[9] From its observed energy and small width, it cannot be due to the double excitation ^{12}C(4.439 MeV) + ^{16}O(6.052 MeV), $Q = -10.491$ MeV.

At just a few angles, peaks appeared in the ^{12}C spectrum corresponding to $Q = -10.95 \pm 0.09$ and -14.7 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 MeV) + ^{16}O(6.052, 6.131 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 α-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 γ-ray to suppress the broadening.

The peak at about $Q = -14.7$ 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 MeV) + ^{16}O(10.34 MeV). A strong peak at ∿ 14.8 MeV has been previously observed in the $^{14}N(\alpha,d)^{16}O$ (Ref. 10), $^{12}C(Li^7,t)$ (Ref. 11), $^{12}C(^{16}O,^{12}C)^{16}O$ (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 $^{12}C + ^{16}O$ coulomb barrier. However, it is not strong even at an oxygen bombarding energy of 97 MeV (lab).[7]

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

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

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

The cross sections for the Q=0- and Q = -4.439-MeV levels in the ^{12}C spectra are about equal. However, excitation of the ^{12}C 4.439-MeV level was not observed in any (^{16}O,^{12}C) reactions with medium weight targets.[1-4] This could be due to the presence of a continuum of ^{12}C ions (arising perhaps from three-body break-up of ^{16}O and from the high level density), and the broadening and lowering of the ^{12}C excited state peaks by γ-decay. Furthermore, the weakness of the sum peaks in Fig. 1 shows that while the residual system ^{12}C(4.439 MeV) + ^{16}O(0 MeV) is more probable than ^{12}C(0 MeV) + ^{16}O (0 MeV), residual systems containing ^{12}C(4.439 MeV) + ^{16}O(excited) are less visible than ^{12}C(0 MeV) + ^{16}O(excited).

FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

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

Fig. 2. Angular distributions of ^{12}C particles for Q = 0- and Q = -4.439-MeV. Cross sections forward of 85° (c.m.) were obtained from ^{12}C spectra, those backward of 85° (c.m.) from ^{16}O spectra.

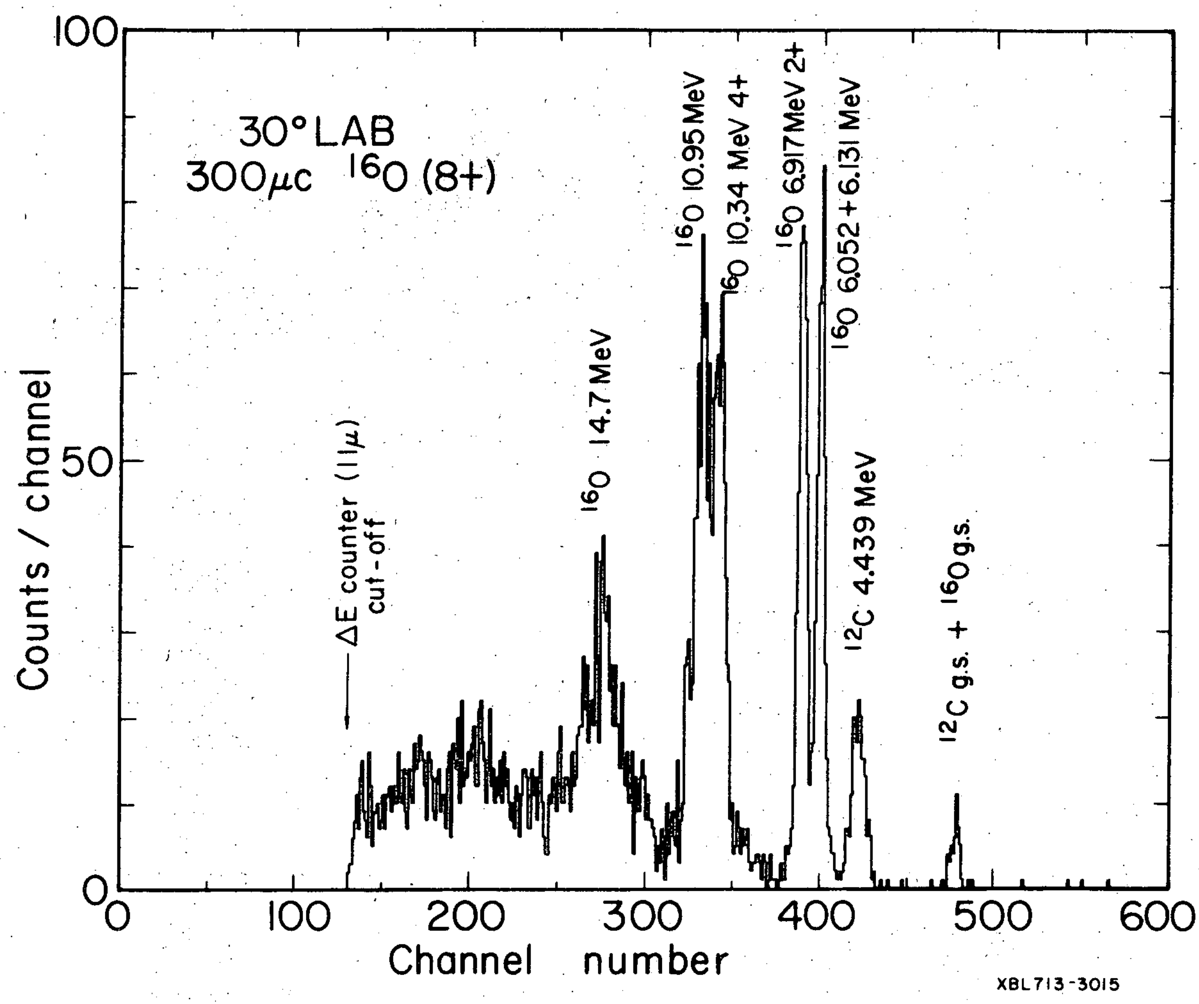
30° LAB
300μc 16O (8+)
Counts / channel
Channel number
0
50
100
0
100
200
300
400
500
600
ΔE counter (11μ) cut-off
16O 14.7 MeV
16O 10.95 MeV
16O 10.34 MeV 4+
16O 6.917 MeV 2+
16O 6.052 + 6.131 MeV
12C 4.439 MeV
12C g.s. + 16O g.s.
XBL 713-3015

Fig. 1

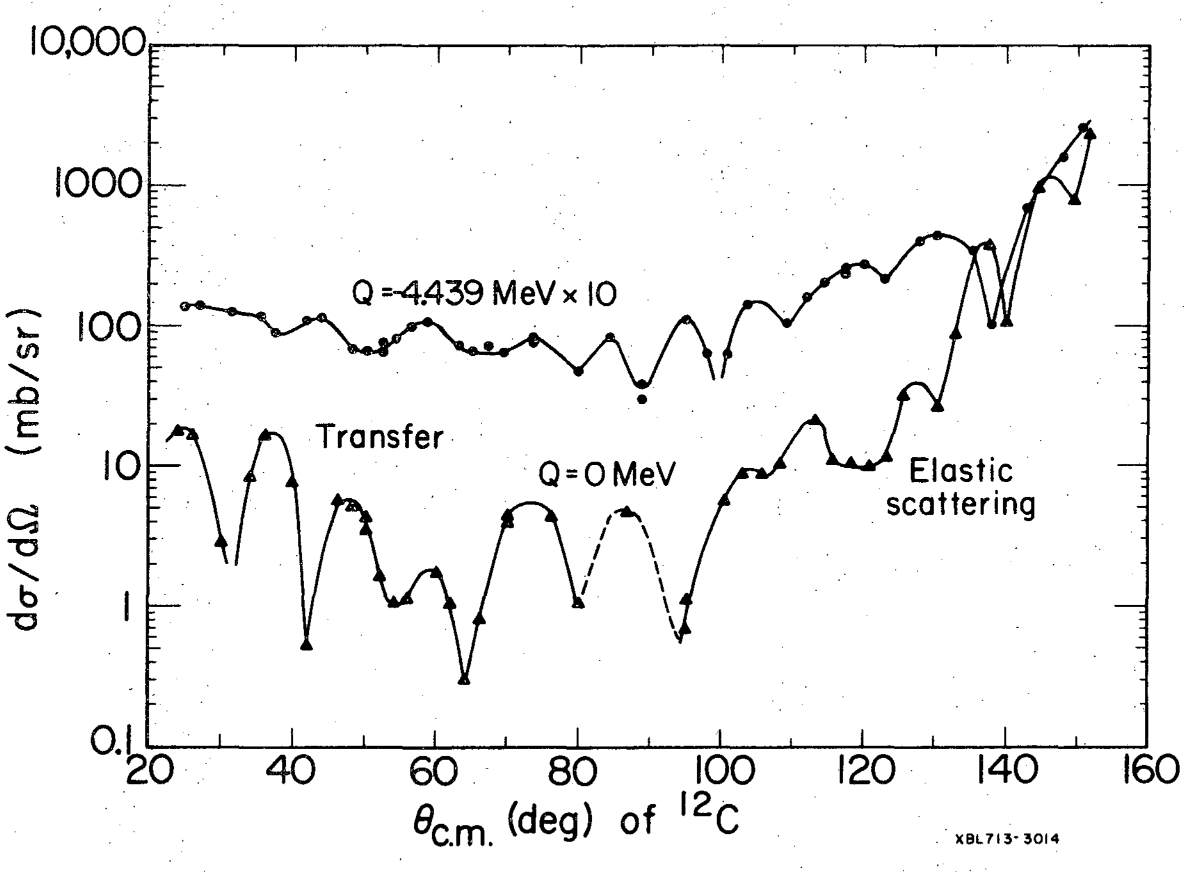
10,000
1000
100
10
1
0.1
20
40
60
80
100
120
140
160
dσ/dΩ (mb/sr)
θc.m. (deg) of 12C
Q=-4.439 MeV × 10
Transfer
Q=0 MeV
Elastic scattering
XBL713-3014

Fig. 2

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