PHYSICAL REVIEW C VOLUME 23, NUMBER 3 MARCH 1981

Structure in the $^{14}C+^{16}O$ reaction cross sections

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(Received 10 November 1980)

The yields of several nuclides produced in the $^{14}C + ^{16}O$ reaction have been measured over the range $E_{c.m.} = 16$–34 MeV. The excitation function for the production of ^{22}Ne displays a regular sequence of narrow fine-structure resonances similar to those previously observed in the $^{12}C + ^{16}O$ reaction. This is the first time that such structure has been observed for systems of non-α-particle nuclei. Intermediate-width resonances are observed in the yield of ^{18}O at $E_{c.m.} = 19.5$, 23.5, 27.5, and 31 MeV. Correlated structure appears in the inelastic scattering cross section to the 3^- state of ^{14}C at all these energies, except possibly $E_{c.m.} = 19.5$ MeV. The resemblance of the 23.5-MeV structure to anomalies previously observed in the $^{16}O + ^{16}O$ and $^{12}C + ^{16}O$ reactions is noted, and some properties of the compound system are deduced.

[NUCLEAR REACTIONS $^{14}C(^{16}O,x)$; $E_{c.m.} = 16$–34 MeV; σ total; correlated fine-structure and intermediate resonances discussed; properties of ^{30}Si deduced.]

The $^{16}O+^{14}C$ system, though it is relatively poorly investigated because of the difficulty of producing ^{14}C targets or beams, nevertheless has been shown to display some interesting phenomena. One of the early experiments was the study of two-nucleon transfer by the Marburg group,[1] who noted the rather strongly oscillatory angular distributions accompanied by anomalously large and strongly energy-dependent back-angle cross sections. These features are reminiscent of more recent results[2] on systems such as $^{16}O+^{28}Si$, which are usually interpreted in the context of surface-transparent optical model potentials. However, the Marburg group at the time emphasized that their experimental angular distributions could be reproduced with "normal" strongly absorbing potentials. They noted that, for this rather unique system, two-nucleon and α-particle transfer are physically indistinguishable processes which must be treated coherently. The resulting calculations, involving interference between the two transfer amplitudes, require rather large and energy-dependent spectroscopic factors for α-transfer but otherwise are quite reasonable. One might, however, question the interpretation of this experiment if the $^{16}O+^{14}C$ reaction cross sections were shown to display strong resonant structure in the 10-25 MeV (c.m.) region.

In this regard the more recent elastic scattering experiment of Bernhardt *et al.*[3] is interesting because of correlated structures at 19.5, 23, and 27.5 MeV (c.m.) which persist over many angles. The peak-to-valley ratios of these "resonances" are about one order of magnitude, the largest yet observed in heavy-ion exit channels. In addition, it was noted that the two-nucleon transfer channel also showed some evidence of resonant structure, although data were only obtained at a single angle. Heenen and Baye[4] interpreted this last observation as due to the particularly favorable coupling between the $^{16}O+^{14}C$ and $^{18}O+^{12}C$ channels. This coupling has previously been investigated by Webb *et al.*,[5] who showed that ^{14}C was a major reaction product from the $^{18}O+^{12}C$ system. In this paper we report a measurement of reaction-product yields from the $^{16}O+^{14}C$ system.

The experiment was performed using the γ-ray technique, which has been discussed in some detail in Ref. 6. The target consisted of 105 $\mu g/cm^2$ of C deposited onto a thick Au backing. Its ^{14}C content was measured to be 75 ± 15 $\mu g/cm^2$, the remainder being natural C. Because of this 25–30% isotopic impurity, we were unable to extract a total fusion cross section for $^{14}C + ^{16}O$. In fact, accurate yields could only be determined for those reaction products which are not strongly produced in the $^{12}C + ^{16}O$ reaction. Among these is the ^{22}Ne 2α-evaporation channel, and the excitation function for the production of this nuclide is shown in Fig. 1. It is instructive to compare these data with the corresponding excitation function for the yield of ^{20}Ne from the $^{12}C + ^{16}O$ reaction.[6] First of all, we note that the peak yield of ^{22}Ne is only 140 mb, as opposed to 540 mb for ^{20}Ne. If the 2α-evaporation process proceeded in the same way in both reactions the estimated maximum fusion cross section of $^{14}C + ^{16}O$ would be 275 mb, i.e., far smaller than the 1 b predicted from systematics[7]

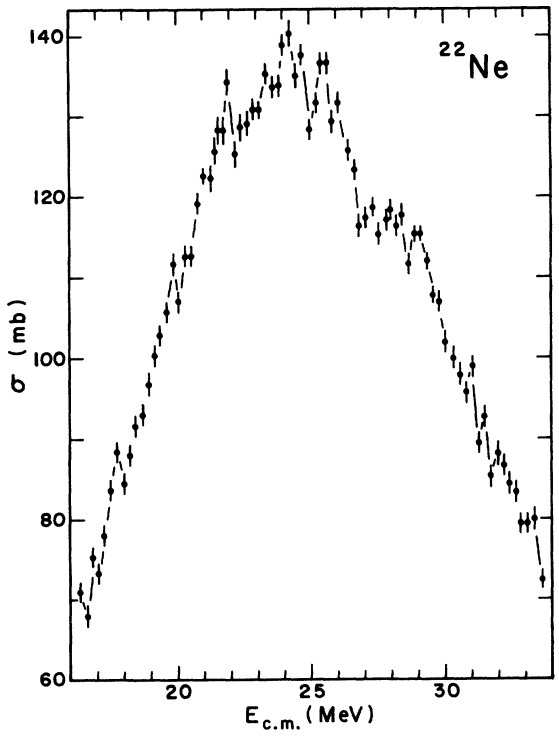

FIG. 1. Excitation function for the production of ^{22}Ne from the $^{14}C(^{16}O,x)$ reaction. The error bars reflect relative errors only. In addition, the absolute cross section scale is uncertain to ± 25% due primarily to the uncertainty in target thickness. Note the narrow, regular fluctuations, superimposed on a long-term behavior which is essentially that expected from evaporation-model calculations.

in this mass region. Actually, the extra two neutrons must considerably modify the evaporation process in the case of $^{14}C + ^{16}O$, as suggested by both Hauser-Feshbach calculations and observations on a number of C + C systems by Heusch *et al.*[8] In fact, the measured yield of ^{22}Ne (Fig. 1) is considerably *more* than might be expected from straightforward extrapolation of the results of Ref. 8. We therefore conclude that our data are not inconsistent with a maximum fusion cross section for $^{14}C + ^{16}O$ in the neighborhood of 1 b.

It is also of interest to note the remarkable resemblance between the fine structure evident in Fig. 1 and that previously observed for $^{12}C + ^{16}O$. In the latter case, narrow, regular oscillations in the yield of ^{20}Ne (and in the total fusion cross section), with an average width of 125–200 keV and a periodicity of about 725 keV, were conclusively shown *not* to be Ericson fluctuations.[6] However, a contribution of direct α-transfer to the ^{20}Ne production cross section could not be ruled out. In the present case, and equally striking series of fine-structure resonances is apparent (Fig. 1) but the simplest direct-transfer process that can contribute is $^{14}C(^{16}O, ^{8}Be)$. The nature of these very narrow structures, which must originate in the initial formation of the compound nucleus, is an important puzzle which still remains to be solved. It is particularly intriguing that the extra two neutrons in the $^{14}C + ^{16}O$ system have not caused these resonances to be damped away.

Turning now to the question of the broader resonances observed by Bernhardt *et al.*[3] at $E_{c.m.}$ = 19.5, 23, and 27.5 MeV, it can be seen that there is no evidence for these structures in Fig. 1. On the other hand, they all appear quite strongly in the yield of ^{18}O (Fig. 2) which, as we have previously mentioned, can come from α-transfer, from two-neutron transfer, or from 3α evaporation from the compound system. Systematics[6] suggests that the 3α-evaporation process should not become important until somewhat higher c.m. energies than those measured here, and we conclude that the nonstatistical intermediate structure observed in the elastic scattering data of Ref. 3 is correlated with the direct α-transfer (or possibly two-neutron-transfer) channel. An additional resonance is vis-

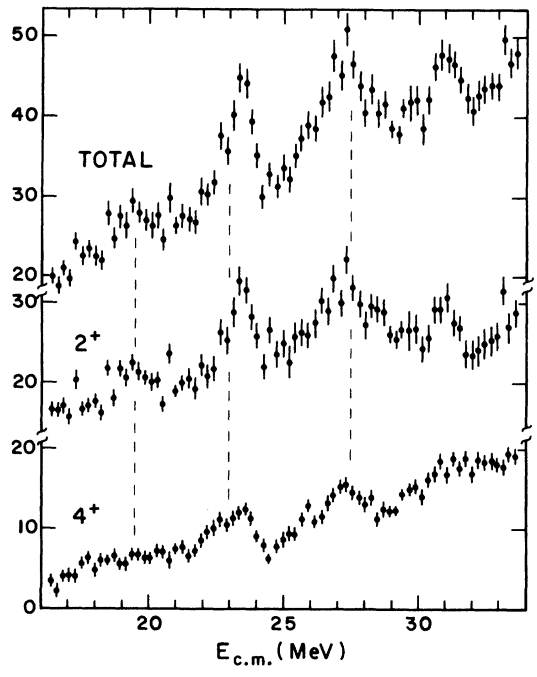

FIG. 2. Excitation functions for the production of ^{18}O from the $^{14}C(^{16}O,x)$ reaction. The upper data set gives the total ^{18}O production cross section, which is divided into individual yields to the first 2^+ and 4^+ states in ^{18}O in the lower two curves. Note the presence of intermediate-width structures at $E_{c.m.}$ =19.5, 23.5, 27.5, and 31 MeV. The dashed lines show the location of resonances reported in Ref. 3.

ible in Fig. 2 at 31 MeV (c.m.), i.e., just above the maximum energy investigated by Bernhardt *et al.*,[3] and there is evidence that these broad structures are actually multiplets. Finally, we have also been able to measure excitation functions for some inelastic scattering and single-nucleon transfer channels, and find that resonant structure appears in the scattering cross section to the 3^- state of ^{14}C, but not in the one-proton or one-neutron transfer yields (Fig. 3).

The intermediate-width resonances discussed above, and especially the 23.5-MeV structure, bear a striking resemblance to similar anomalies in the $^{16}O+^{16}O$ and $^{16}O+^{12}C$ reaction cross sections. In particular, we refer to the 26.5-MeV resonance[9,10] in the production of ^{20}Ne from $^{16}O+^{16}O$, and the 20.5-MeV anomaly[6] (also in the ^{20}Ne yield) in $^{16}O+^{12}C$. The similarity extends even to the characteristic shape of the resonance, which typically rises slowly with increasing c.m. energy, and then falls rather rapidly. In each case, the resonance occurs in the α-transfer channel, and is correlated with a weaker structure in one of the inelastic scattering channels. The present data represent

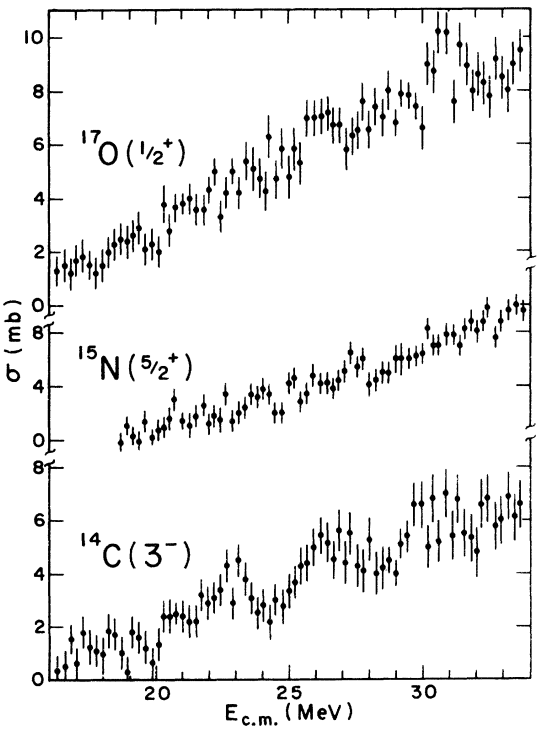

FIG. 3. Excitation functions for some inelastic scattering and single-nucleon-transfer reactions from $^{14}C(^{16}O,x)$. Note the structure in the $^{14}C(3^-)$ yield, which is correlated with that shown in Fig. 2. The single-nucleon-transfer yields, on the other hand, are relatively smooth.

the second observation of this resonance in a system which does not consist entirely of α-particle nuclei. In a recent article,[11] it has been shown that an anomaly of this kind constitutes a characteristic signature which occurs when the limits to fusion in a system are reached. On the basis of the band-crossing model presented there one can deduce, for example, that the 23.5-MeV resonance in the $^{16}O+^{14}C$ reaction should have $J^\pi = 16^+$, an "assignment" which is in good agreement with the elastic scattering angular distribution measured by Bernhardt *et al.*[3] We also predict that the total fusion cross section for $^{16}O+^{14}C$ will saturate at approximately 1100 mb, and at an excitation energy of 46 MeV in the compound system. This prediction should be tested by further experiments, perhaps using a ^{14}C beam to eliminate the target contamination problem. Finally, we can compute the moment of inertia $\mathcal{I}$ of the crossing band and compare it with that observed for other systems (Table I). It can be seen that, although $\mathcal{I}$ increases smoothly with the mass of the compound system, the ratio to the moment of inertia of a rigid sphere actually *decreases* as one goes from ^{24}Mg to ^{32}S.

The ^{30}Si compound system presents yet another opportunity to test the model of Ref. 11, since measurements of the reaction cross sections for $^{18}O+^{12}C$ are available,[5,7,12,13] This system is well matched to $^{16}O+^{14}C$. For example, at an excitation energy of 45 MeV in ^{30}Si the corresponding c.m. energies and grazing angular momenta differ by 1 MeV and less than one unit, respectively. A "characteristic" resonance is observed[12,13] in the inelastic scattering to the first excited state of ^{18}O at $E_{c.m.} = 20.0$ MeV, in excellent agreement with the energy at which the complete fusion yield saturates.[7] If we assume that this structure has $J^\pi = 16^+$, as deduced for the 23.5 MeV $^{16}O+^{14}C$ resonance discussed above, then the predicted maximum fusion yield is greater than 1300 mb, which exceeds both the measured value[7] (1195 mb) and the optical-model total reaction cross section (1160 mb). On the other hand, the assignment $J^\pi = 15^-$ results in a prediction of 1170 mb, in good agreement with both theory and experiment. There is, unfortunately, no direct evidence on the spin

TABLE I. Moment of inertia of the crossing band.

Compound system	$\mathcal{I}/\hbar^2$ (MeV^{-1})	$\mathcal{I}/\mathcal{I}_{rig}$ [a]
^{24}Mg	2.63	0.75
^{28}Si	2.79	0.62
^{30}Si	2.96	0.59
^{32}S	3.16	0.56

[a] $\mathcal{I}_{rig}$ is the rigid-body moment of inertia for a sphere of radius $1.35A^{1/3}$ fm.

of this resonance, although $J^\pi = 15^-$ has been determined[5] for a resonance at $E_{c.m.} = 19.0$ MeV. If we assume $J^\pi = 15^-$, the calculated moment of inertia for the crossing band is 7% smaller than that given in Table I. However, as discussed in Ref. 10, one might expect somewhat different moments of inertia for the even- and odd-parity bands. Note that the predicted $J^\pi = 16^+$ resonance is at $E_{c.m.} =$ 22.5 MeV, which is just at the limit of the data presented in Ref. 12. A structure at about 22 MeV observed by Freeman and Haas[12] was reproduced in the later work of Chan *et al.*,[13] but the c.m. energy interval in this experiment was too large to permit definitive conclusions, and no spin assignment has yet been made. This suggests that further studies of the $^{12}C + ^{18}O$ system to somewhat higher c.m. energies would be desirable.

In conclusion, we have shown that the non-α-particle $^{16}O + ^{14}C$ system displays a remarkable sequence of narrow, regular oscillations in its fusion-evaporation excitation function, which is quite similar to that previously observed[6] for the $^{16}O + ^{12}C$ system. Although the exact nature of these structures is not known, it would appear that they will require a more surface-transparent optical-model potential than that used by the Marburg group.[1] Strong intermediate-width resonances are observed in the ^{18}O production cross section at 19.5, 23.5, 27.5, and 31 MeV (c.m.). Correlated structure appears at most of these energies in the inelastic scattering to the 3^- state in ^{14}C. The similarity of these resonances (and particularly the one at 23.5 MeV) to those observed in other systems suggests that they represent a general phenomenon of the interaction of "light" heavy ions.

This work was partially supported by the IN2P3 (France) and the U. S. National Science Foundation. The ^{14}C target was obtained from the University of Munich.

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