Possible Nuclear Molecule at 36.5 MeV in Si^{28}†

R. Stokstad, D. Shapira, L. Chua, P. Parker, M. W. Sachs, R. Wieland, and D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520

(Received 7 March 1972)

A number of unusual phenomena occur in $O^{16}+C^{12}$ induced reactions at $E_{c.m.}=19.7$ MeV. We suggest an interpretation of these effects in terms of a molecular resonance.

The interaction of O^{16} with C^{12} has recently received intensive study.[1-7] The most important two-body channels, $Mg^{24}+\alpha$, $Al^{27}+p$, elastic and inelastic scattering, have been scanned as functions of energy in the O^{16}-C^{12} entrance channel and three-body final states have been investigated at two bombarding energies.[1,7] This unusual approach, a comprehensive study of one specific interaction, has been extremely instructive; several characteristic processes and important structures have been established.

The O^{16}-C^{12} interaction is known to proceed, to a large extent, through a resonant scattering mechanism. At low bombarding energies, the ingoing flux is strongly attracted toward the compound nucleus. At energies near and below the Coulomb barrier, well-developed quasimolecular resonances have been observed,[8] and C^{12}-C^{12} and O^{16}-C^{12} remain the only systems displaying such a striking behavior.[9] At energies above the Coulomb barrier, the observed resonant scattering has been shown to be consistent with the formation of a statistical compound nucleus.[3] Such a mechanism is expected to a lesser extent at high bombarding energies where a large amount of angular momentum is introduced by the grazing partial waves; the centrifugal barrier inhibits the formation of a compound nucleus, the density of levels in the compound nuclear at a given excitation decreases rapidly with increasing spin, and very few of the energetically allowed exit channels are capable of carrying away the angular momentum present in the entrance channel.

A somewhat similar situation has been recognized in the O^{16}-O^{16} interaction, and the data for the elastic scattering channel have been reproduced through introduction of an l-dependent imaginary potential.[10] Similar angular-momentum–based explanations have been applied[11] to the observed O^{16}-C^{12} elastic scattering cross sections in order to explain the rise in cross section at backward angles. The interaction between O^{16} and C^{12}, however, need not be as simple as that between two O^{16} nuclei because of the possibility of four-nucleon transfer in the former, and it is expected that elastic transfer makes a significant contribution to the backward scattering.[12]

In this Letter, we wish to draw attention to several interesting phenomena which occur in the various exit channels for the $O^{16}+C^{12}$ reaction at a bombarding energy of 19.7 MeV (c.m.), and to suggest a possible interpretation for these phenomena.

The elastic scattering of O^{16} by C^{12} has been measured by Siemssen[5] in the energy range 9 to 26 MeV c.m. and for center-of-mass angles between 40° and 160°. He noted an "anomaly" in the elastic scattering excitation functions at $E_{c.m.} \sim 19.7$ MeV and measured complete angular distributions at and near this energy. Excitation functions spanning the region of $E_{c.m.}=19.7$ MeV for the reaction $C^{12}(O^{16},\alpha)Mg^{24}$ at $\theta_{c.m.}=3°$ and 177° have been reported by Bromley *et al.*[1] In each case, the target and projectile species were interchanged and the emergent α particles were detected at $\theta_\alpha \sim 2°$ (lab). Although the data obtained with the O^{16} beam (3°, c.m.) did not exhibit any very unusual behavior, those obtained with the C^{12} beam (177°, c.m.) did. A number of the cross sections for selectively populated, highly excited states in Mg^{24} displayed a pronounced, correlated minimum at $E_{c.m.} \sim 19.7$ MeV. Excitation functions for the $Al^{27}+p$ exit channel has been reported by Cosman *et al.*; the yield for states selectively populated in this reaction also shows a corresponding minimum.[6]

Figure 1 presents excitation functions measured for elastic scattering of O^{16} from 20-μg/cm^2 C^{12} at angles of 90° and 178° c.m. A new experimental system, described in Ref. 1, has been developed in order to measure cross sections at center-of-mass angles close to 180°. The 90° data are in agreement with those of Ref. 5, while the 178° data demonstrate that the "anomaly" is especially enhanced for the extreme backward angles. Excitation functions for inelastic scattering (Fig. 1) to the excited states of O^{16} show a correlated maximum for states at 6.05 and/or 6.13 MeV; groups of these states could

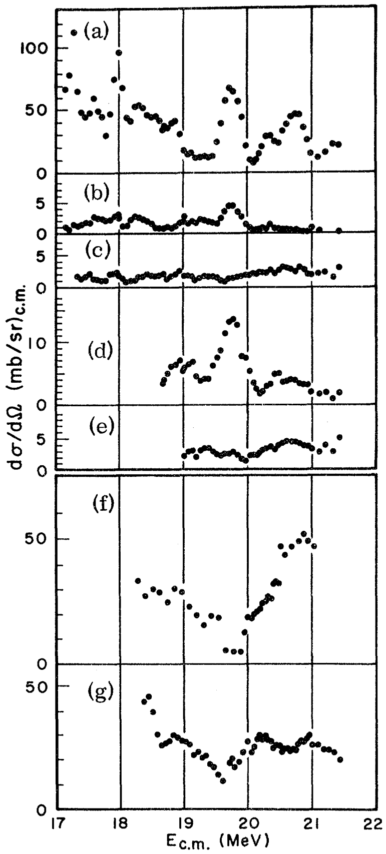

FIG. 1. Comparison of excitation functions for the $O^{16}+C^{12}$ interaction. (a), (b) O^{16}-C^{12} scattering at $\theta_{c.m.}=176°$ and 90°; (c), (d), (e) inelastic scattering leading to O^{16}(g.s.) + C^{12*}(4.44 MeV), to C^{12}(g.s.) + O^{16*}(6.05 + 6.13), and to C^{12}(g.s.) + O^{16*}(6.92 + 7.12); and (f), (g) excitation functions for scattering angles of $\theta_{c.m.}=177°$ and 3° for the reactions $C^{12}(O^{16},\alpha)Mg^{24}$ summed over twelve separate transitions to states in Mg^{24} at $E_x=6.01$, 7.35, 7.56, 8.11, 9.29, 9.52, 13.45, 13.86, 14.14, 15.15, 16.29, and 16.56 MeV. These latter states have been selected only on the basis of a clear identification over the full energy range and specifically not on the basis that they necessarily show the minimum under discussion.

not be resolved. Neither the states at (6.92, 7.12) MeV in O^{16} nor the state at 4.43 MeV in C^{12} indicates a correlation. In Figs. 1(f) and 1(g), excitation functions[1] for twelve final states in the reaction $C^{12}(O^{16}, \alpha)Mg^{24*}(E_x=6.01-16.56)$ have been added to display this correlated minimum in the cross sections. This is particularly evident at $\theta_{c.m.}=177°$ and to a much lesser extent at 3°. Finally, we note here that maxima and minima of the angular distributions for elastic scattering[5] at angles > 75° c.m. exhibit a rather precise $[P_{14}(\cos\theta)]^2$ dependence at $E_{c.m.}=19.7$ MeV, but not at the adjacent energies.

The phenomena described above are inconsistent with the usual statistical picture of nuclear reactions, although they may not be inconsistent with the statistical theory of Moldauer,[13] which allows for occasional, very large fluctuations in widths when strongly absorbed channels are involved. The latter, however, does not exclude the possibility of a particularly large "fluctuation" arising from a special type of nuclear structure.

Many of the "anomalous" experimental observations which we have presented and summarized here might well be explained in terms of a molecular-type structure at $E_x = \sim 36.5$ MeV in the Si^{28} compound system. The gross structure (~3 MeV width) observed in heavy-ion reactions has been interpreted in terms of broad, orbiting resonances which reflect the average nuclear potential.[14] The observation of narrow correlated resonances, not associated with the usual statistical fluctuations, indicates the presence of additional forces. If we consider the entrance channel as two C^{12} cores plus four nucleons in the $p_{1/2}$ shell, the existing symmetry then allows these four nucleons to be attracted by each of the two cores and a strong molecular binding can arise from their exchange. This could then give rise to a narrow resonance of the type presented here. The total angular momentum of 14 units implied by the angular distributions for elastic scattering[5] is the same as that of the grazing partial wave in the entrance channel. Thus the resonance is associated with the partial wave which also would most favor nucleon exchange between the C^{12} cores. Furthermore, the resonance is observed to be expecially strong at the extreme backward scattering angles (Fig. 1) for which, again, nucleon exchange is favored. Statistical-model calculations indicate that the states selectively populated in the $Mg^{24}+\alpha$ and $Al^{27}+p$ exit channels are also fed primarily through the fourteenth partial wave. Thus, the associated minima in the $Mg^{24}+\alpha$ and $Al^{27}+p$ exit channels may result from the depletion of flux in the fourteenth partial wave by the $O^{16}+C^{12}$ exit channels, i.e., the molecular resonance has a small overlap with the former exit channels and a large overlap with the latter.

An interesting aspect of this resonance is the lower limit of 2×10^{-21} sec on its lifetime, corresponding to the experimentally observed width of 350 keV. This relatively long lifetime would allow the molecule to perform at least a full rotation and may be related to the exchange time of the four nucleons (equivalent to the familiar resonant scattering[15] in atomic physics). The importance of four-nucleon exchange in the reaction mechanism populating the resonance may also be investigated by a comparison of the (Li^7, t) and (O^{16}, C^{12}) reactions on C^{12} at the appropriate center-of-mass energies and angles. At higher bombarding energies of 24 and 29 MeV, respectively, we observe a striking similarity between the reaction[16] $C^{12}(Li^7, t)O^{16*}$ and reactions $C^{12}(O^{16}, C^{12})O^{16*}$ leading to the 4p-4h (four-particle, four-hole) states in O^{16}.

Several interesting questions are raised by these phenomena and this interpretation, which point towards additional experiments. Important information on the detailed structure of the resonance will be provided (a) by knowledge of the extent to which particular states in O^{16} (6.05 0^+ or 6.13 3^-, 6.92 2^+ or 7.12 1^-) are populated on resonance, since these states have quite different structure, and (b) by a phase-shift analysis of complete angular distributions measured in fine energy steps across the resonance. Such measurements are in progress in this laboratory. The generality of this interpretation could be investigated by a search for similar phenomena at other excitation energies and in other systems, such as $O^{16}+Ne^{20}$.

The authors wish to acknowledge several informative discussions with J. Ginocchio and R. Ascuitto. P. Maurenzig participated in the data analysis and E. Fehr, C. Gingell, and K. Sato contributed vital technical assistance.

---

†Work supported by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-3074.

[1] D. A. Bromley, L. Chua, A. Gobbi, P. R. Maurenzig, P. D. Parker, M. W. Sachs, D. Shapira, R. G. Stokstad, and R. Wieland, in Proceedings of the Symposium on Heavy Ion Reactions and Many Particle Excitations, Saclay, France, September, 1971 (to be published); D. Shapira, L. Chua, A. Gobbi, P. Maurenzig, and D. A. Bromley, Bull. Amer. Phys. Soc. 17, 77 (1972).

[2] R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Rev. Lett. 24, 1436 (1970).

[3] M. L. Halbert, F. E. Durham, and A. Van der Woude, Phys. Rev. 162, 899 (1967); M. L. Halbert, F. E. Durham, C. D. Moak, and A. Zucker, Phys. Rev. 162, 919 (1967).

[4] J. Gastebois, in Proceedings on the Symposium on Heavy Ion Reactions and Many Particle Excitations, Saclay, France, September 1971 (to be published).

[5] R. H. Siemssen, in *Proceedings of the Symposium on Heavy Ion Scattering, Argonne National Laboratory, 1971*, edited by R. H. Siemssen (Argonne National Laboratory, Argonne, Ill., 1971).

[6] E. R. Cosman, Bull. Amer. Phys. Soc. 16, 1421 (1971); E. R. Cosman, A. Sperduto, W. H. Moore, T. N. Chin, and T. M. Cormier, Phys. Rev. Lett. 27, 1074 (1971).

[7] M. J. LeVine and D. Schwalm, Bull. Amer. Phys. Soc. 17, 77 (1972).

[8] J. R. Patterson, B. N. Nagorcka, G. D. Symons, and N. M. Zuck, Nucl. Phys. A165, 545 (1971).

[9] D. A. Bromley, J. A. Kuehner, and E. Almqvist, Phys. Rev. Lett. 4, 365 (1960), and Phys. Rev. 123, 878 (1961).

[10] R. A. Chatwin, J. S. Eck, D. Robson, and A. Richter, Phys. Rev. C 1, 795 (1970).

[11] D. Robson, in *Proceedings of the Symposium on Heavy Ion Scattering, Argonne National Laboratory,* see Ref. 5.

[12] U. C. Voos, W. von Oertzen, and R. Bock, Nucl. Phys. A135, 207 (1969).

[13] P. Moldauer, Phys. Rev. Lett. 18, 249 (1967).

[14] A. Gobbi, in *Proceedings of the Symposium on Heavy Ion Scattering, Argonne National Laboratory,* see Ref. 5.

[15] G. J. Lockwood and E. Everhart, Phys. Rev. 125, 567 (1962).

[16] P. Parker and M. Cobern, private communication.