Structure in the reaction channels of $^{14}C + ^{14}C$

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The reaction channels of $^{14}C + ^{14}C$ have been studied from $E_{c.m.} = 12.5$ to 32.5 MeV by γ-ray techniques. Correlated oscillatory structure has been observed in inelastic, transfer, and fusion-evaporation channels. These features are comparable to the behavior of $^{16}O + ^{16}O$ where similar dynamical conditions prevail.

[NUCLEAR REACTIONS $^{14}C + ^{14}C$, $E_{c.m.} = 12.5$–32.5 MeV, measured I_γ. Deduced resonant structure in reaction channels. Enriched target.]

In this Communication we would like to report on the striking resemblance that exists between the structure we have found in the heavy-ion reaction $^{14}C + ^{14}C$ and that in $^{16}O + ^{16}O$. Up to an energy several times the Coulomb barrier the gross features of the $^{16}O + ^{16}O$ reaction are rather simple: A series of broad resonantlike structures has been observed in the elastic scattering,[1] and in many of the reaction channels[2–7] the same periodic pattern appears, out of phase with the 90° elastic scattering data. The dynamical mechanism responsible for the observed structures in the reaction channels is still undetermined. However, in all the proposed explanations, whether they rely on "resonant"[4,8–11] or "nonresonant"[12] models, each structure is associated with a single even incoming grazing partial wave which feels a selective absorption.

It has been pointed out[13] that structure in heavy-ion reactions should not be restricted only to purely α-cluster nuclei but may also be observed in systems involving ^{14}C. Indeed, in two recent experiments[14,15] the elastic scattering of ^{14}C on ^{14}C has been studied and the similarity with $^{16}O + ^{16}O$ has been apparent. In one of these experiments[14] the inelastic channel was also observed but no obvious correlation with the elastic data could be established. The purpose of the present experiment was to determine how widespread is the occurrence of structure among the *reaction* channels. We have therefore used the γ-ray technique which allows angle-integrated excitation functions for a variety of reaction channels to be studied simultaneously in an inherently high energy-resolution experiment.

The experiment was undertaken at the Munich MP tandem accelerator where facilities exist both for a ^{14}C beam and for the fabrication of ^{14}C targets. The ^{14}C target, approximately 60 $\mu g/cm^2$ thick, was made by thermal cracking of $^{14}CH_3$-I onto a Ta backing. The appreciable ^{12}C contamination of the ^{14}C isotope necessitated a concurrent study of the $^{12}C + ^{14}C$ reaction. Measurements were made at all energy points with a similar target of natural carbon to enable the ^{12}C contribution to be subtracted out. The $^{12}C + ^{14}C$ results will be reported elsewhere. Between ^{14}C bombarding energies of 40 to 57 MeV they reproduced our previous results,[16] but outside these limits and especially at lower energies there are new and interesting data. At the beginning of the experiment the natural carbon and ^{14}C target were bombarded with ^{12}C and ^{14}C beams. From these measurements the relative thickness of both targets was determined and the 20% ^{12}C contamination quoted by the suppliers of the ^{14}C isotope was verified. A measurement at the end of the experiment proved that the ^{12}C buildup on the ^{14}C target was negligible. The absolute cross sections were obtained by normalization to our previous $^{12}C + ^{14}C$ results and are subject to a 25% error.

As in earlier experiments of this nature[4,16] the γ rays were detected in two large volume Ge(Li) detectors placed at 55° and 90° to the beam direction. A typical γ-ray spectrum, recorded for one of the points of the excitation function, is shown in Fig. 1.

The $^{14}C + ^{14}C$ reaction was studied from bombarding energies $E_{lab} = 25$ to 35 MeV in steps of 0.5 MeV and thereafter in 1.0 MeV steps to 65 MeV. The measurements were not extended to lower energies as it was expected that the nuclear absorption would become too strong near the Coulomb barrier (~15 MeV) to observe resonant effects. The experiment

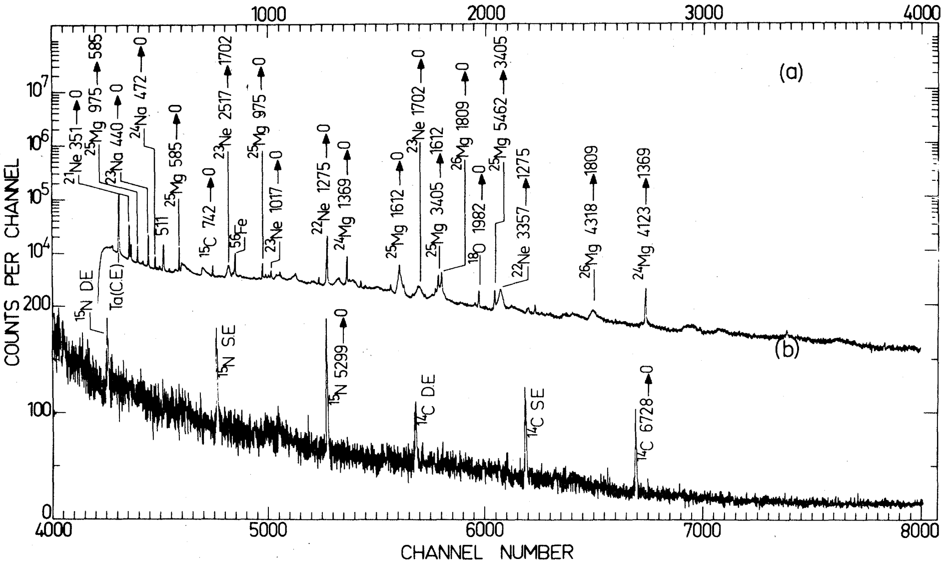

FIG. 1. γ-ray spectrum recorded during the $^{14}C + ^{14}C$ experiment in the 90° Ge(Li) detector for a bombarding energy of 40 MeV. Channels 0–4000 and 4000–8000 are shown in parts (a) and (b), respectively. Prominent transitions from the ^{14}C target and ^{12}C contamination are identified by the residual nucleus and by the initial- and final-level energies given in keV. Transitions in ^{15}N, ^{23}Na, and ^{24}Mg are due to the β decay of ^{15}C, ^{23}Ne, and ^{24}Na. The strength of the 815-keV transition suggests a yrast assignment for the 2517-keV level of ^{23}Ne.

was terminated at $E_{lab} = 65$ MeV where the spectra were beginning to be flooded with γ rays from reactions of ^{14}C in the Ta backing.

As can be seen from Fig. 2 which summarizes the main results for the excitation functions, the strongest channels are fusion-evaporation processes to the Ne isotopes (αxn). The summed cross section to the Ne isotopes is shown in Fig. 2(c) along with the individual contribution for ^{22}Ne in Fig. 2(d) (more correctly the cross section for all paths cascading through the first excited 2^+ state of ^{22}Ne). At lower energies ^{23}Ne (deduced from the β^- decay to the first excited $\frac{5}{2}^+$ state of ^{23}Na) is the dominant channel and at higher energies the ^{21}Ne cross section increases rapidly. An oscillation is clearly visible in these results which resembles remarkably the structure which appears in the fusion channels of the $^{16}O + ^{16}O$ reaction. By extracting the smooth contribution in the Ne curve the maxima of the six structures were observed to be located close to the following energies: $E_{c.m.} \sim 13$, 16.1, 19.2, 23.0, 27.0, and 31.5 MeV. In the case of the $^{16}O + ^{16}O$ reaction the maxima corresponded to minima in the 90° elastic scattering data. Some of the maxima of the $^{14}C + ^{14}C$ results agree roughly with minima in the elastic scattering[14,15] but no simple relationship is evident throughout the whole of the energy region studied.

The rest of the fusion cross section could be almost entirely accounted for in the (xn) channels to Mg isotopes. Evidence for other evaporation chains was meager. The ^{25}Mg results have enabled us to compare the excitation functions for the formation of two states whose spins differ by 6 $\hbar$ and excitation energies by less than 5 MeV. The yield curves for the first excited state ($J^\pi = \frac{1}{2}^+$, $E_x = 0.585$ MeV) and a high spin yrast state ($J^\pi = \frac{13}{2}^+$, $E_x = 5.462$ MeV) are shown in Figs. 2(e) and 2(f). Traces of the oscillation which appears in the Ne results are only seen for the high spin state. This is an additional indication that the structure originates in the higher angular momentum partial waves. There was also evidence for the oscillation in the results for the 1.612-MeV state ($7/2^+$) of ^{25}Mg but the γ-ray peak is broad and its analysis liable to greater uncertainties. Other Mg channels proved even more difficult to extract from the raw data and for this reason only partial results have been obtained. In most other systems where structure has been observed for the fusion channels it has been found associated with α-particle emission. The structure which has been observed for $^{14}C + ^{14}C$ in channels where only neutrons are emitted is rather uncommon.

The results for two direct channels which could be extracted from the γ-ray spectra are shown in Figs. 2(a) and 2(b). These are the inelastic scattering to the 6.73-MeV level (3^-) of ^{14}C and the production of ^{15}C [deduced from the 2.5-s β^- decay to the 5.30-MeV level ($\frac{1}{2}^+$) of ^{15}N] formed by one-neutron transfer. There are only two bound states in ^{15}C, the ground ($\frac{1}{2}^+$) state and the first excited ($\frac{5}{2}^+$) state. From the intensity of the transition between the two it was deduced that the transfer process feeds

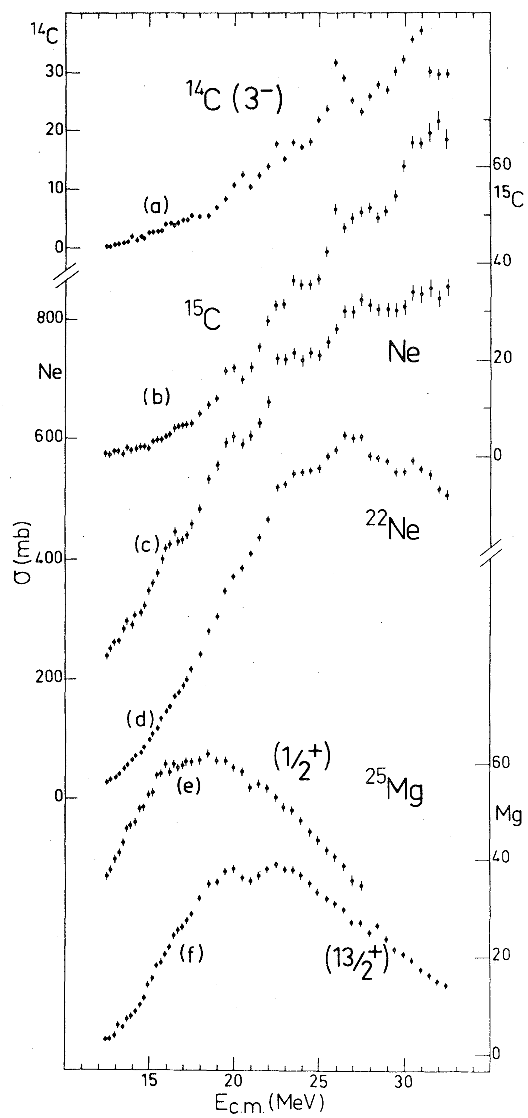

FIG. 2. Excitation functions for the $^{14}C+^{14}C$ reaction deduced from the γ-ray data. (a) Excitation of the 6728-keV level of ^{14}C. (b) Production of ^{15}C. (c) Production of Ne isotopes ($^{21}Ne+^{22}Ne+^{23}Ne$). (d) Yield for the 1275-keV transition of ^{22}Ne. (e) Yield for the 585-keV transition of ^{25}Mg. (f) Yield for the 2056-keV transition from the 5462-keV level of ^{25}Mg.

predominantly the first excited state. The energy dependence of the cross section for the direct processes differs from the typical bell-shaped forms observed for fusion. The yields rise steadily above $E_{c.m.}=15$ MeV in the region where the total fusion cross section should begin to saturate. Some structure appears on these curves which is roughly correlated with the oscillation of the Ne results. It may be that some intermediate structure is also present. In particular, the peak at $E_{c.m.}=26$ MeV is close in energy to a strong sharp anomaly in the elastic scattering.

The oscillatory behavior which appears in many of the reaction channels of $^{14}C+^{14}C$ closely resembles the situation in $^{16}O+^{16}O$. There are, of course, considerable differences between the two reactions in the way in which the outgoing flux is partitioned into various channels. In the neutron-rich system the neutron largely replaces the role of the α particle in transfer and evaporation processes. But aside from this observation the oscillatory structure is similar in both reactions. It is observed in fusion channels, especially those in which there is an α particle in the evaporation chain, and at the higher energies it is observed in direct reactions like transfer and inelastic scattering.

The similarities between the $^{14}C+^{14}C$ and $^{16}O+^{16}O$ systems demand a common origin for the gross structure of both reactions. In the framework of the models[4,8–12] which have been proposed to describe $^{16}O+^{16}O$ collisions, the observation of pronounced and regular gross structure in the 90° elastic scattering and reaction cross sections requires that the three following conditions be satisfied: (1) The system should be composed of identical bosons; (2) there should be no direct reactions strongly coupled to the incoming channel; and (3) the reaction should be surface transparent.

The first of these conditions is obviously fulfilled, with its sequel that the reaction is described by the even partial waves only. In principle gross structure may also exist for other systems but with double the number of oscillations and with diminished amplitude.

The second condition is also relatively easy to justify. ^{14}C and ^{16}O are the only nuclei (with $A>4$) where the gap between the ground state and the first excited state is greater than 6 MeV. There are no low lying collective states in these "spherical" nuclei which can couple strongly to the entrance channel. As soon as one of the ions is replaced by the deformed nucleus ^{12}C stronger and more complex structures appear. It is suspected that the resonant behavior of the $^{12}C+^{14}C$ and $^{12}C+^{16}O$ reactions stems largely from the strong coupling of the entrance channel to the first 2^+ collective state of ^{12}C.

The third condition, surface transparency, is more open to debate because although a phenomenological surface transparency seems to be required to describe "light" heavy-ion collision[17] it is difficult to estimate quantitatively. Systems where there are a very large number of open channels available for the outgoing flux are generally regarded as strongly absorbing. However, most of the exit channels involve the emission of light particles, i.e., nucleons and α particles, which are less capable of carrying away the increasing angular momentum of the compound system with increasing energy. The centrifugal barrier severely limits the number of channels which are effectively open for the grazing partial waves. If, in addition, the system is composed of α-cluster nuclei, notably ^{12}C and

^{16}O, the stability of these nuclei imply lower Q values in the exit channels and an even greater limitation on the number of paths open for the outgoing flux. It is a combination of these two effects which has been evoked[18] to justify the surface transparency of reactions like $^{16}O + ^{16}O$. A similar situation should apply for ^{14}C as the two additional neutrons to ^{12}C close the p shell and form a particularly stable configuration of nucleons. In this respect it is interesting to note that in the recent calculations by Haas and Abe[19] the number of open channels for $^{16}O + ^{16}O$ and $^{14}C + ^{14}C$ are comparable.

In this Communication we have presented results for the $^{14}C + ^{14}C$ reaction and have shown that the excitation functions for reaction channels are characterized by a sequence of regular structures like those observed in the elastic scattering. Several models have been proposed to explain similar behavior in the more widely studied $^{16}O + ^{16}O$ reaction. The parallel behavior, which is observed in $^{14}C + ^{14}C$ reflects the prevalence of similar dynamical conditions.

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[1]J. V. Maher *et al.*, Phys. Rev. 188, 1665 (1969).
[2]P. P. Singh *et al.*, Phys. Rev. Lett. 28, 1714 (1972).
[3]H. H. Rossner, G. Hinderer, A. Weidinger, and K. A. Eberhard, Nucl. Phys. A218, 606 (1974).
[4]J. J. Kolata *et al.*, Phys. Rev. C 16, 891 (1977); *ibid.* 19, 2237 (1979).
[5]I. Tserruya *et al.*, Phys. Rev. C 18, 1688 (1978).
[6]B. Fernandez *et al.*, Nucl. Phys. A306, 259 (1978).
[7]V. K. C. Cheng *et al.*, Nucl. Phys. A322, 168 (1979).
[8]W. A. Friedman, K. W. McVoy, and M. C. Nemes, Phys. Lett. 87B, 179 (1979).
[9]Y. Kondo, D. A. Bromley, and Y. Abe, Phys. Rev. C 22, 1068 (1980).
[10]O. Tanimura and T. Tazawa, Phys. Rep. 61, 253 (1980).
[11]R. Vandenbosch and A. J. Lazzarini, Phys. Rev. C 23, 1074 (1981).
[12]R. L. Phillips, K. A. Erb, D. A. Bromley, and J. Weneser, Phys. Rev. Lett. 42, 566 (1979).
[13]D. Baye, P.-H. Heenen, and M. Libert-Heinemann, Nucl. Phys. A308, 229 (1978).
[14]D. Konnerth *et al.*, Phys. Rev. Lett. 45, 1154 (1980).
[15]D. M. Drake *et al.*, Phys. Lett. 98B, 36 (1981).
[16]R. M. Freeman, F. Haas, and G. Korschinek, Phys. Lett. 90B, 229 (1980).
[17]R. H. Siemssen, in *Nuclear Molecular Phenomena*, edited by N. Cindro (North-Holland, Amsterdam, 1978), p. 79.
[18]R. W. Shaw, R. Vandenbosch, and M. K. Melta, Phys. Rev. Lett. 25, 457 (1970).
[19]F. Haas and Y. Abe, Phys. Rev. Lett. 46, 1667 (1981).