80/29, 1980 (unpublished); W. Bartel *et al.* (JADE Collaboration), DESY Report No. 80/123 (unpublished); Ch. Berger *et al.* (PLUTO Collaboration), DESY Report No. 80/116, 1980 (unpublished).

[16]A. Wagner, in Proceedings of the XVIth Rencontre de Moriond, Moriond, France, 1981 (to be published).

Surface Transparency and Resonant Behavior in Some Lighter–Heavy-Ion Reactions

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Resonance phenomena observed experimentally in some lighter–heavy-ion collisions at energies well above the Coulomb barrier are discussed in terms of the number of open channels available to direct reactions for the even-even C + C, C + O, and O + O systems. The calculated number of open channels shows a characteristic energy dependence which reflects the surface transparent absorption needed to observe resonant structure. The weak absorption is particularly pronounced in reactions involving ^{12}C, ^{14}C, and ^{16}O nuclei.

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Resonance phenomena are one of the most outstanding features of some lighter–heavy-ion collisons. They have now been observed in the excitation functions of various exit channels for a number of systems and for bombarding energies from the Coulomb barrier to several times the barrier heights.[1] The resonant structure was first discovered and confined to the ^{12}C + ^{12}C and ^{12}C + ^{16}O reactions[2] at energies close to the Coulomb barrier. The specificity of these two systems has been explained as a consequence of the small spreading width of the entrance-channel resonances which is due to the exceptional low level density of the corresponding compound nucleus.[3] As the experimental studies were extended to higher bombarding energies, one might have expected from a naive point of view a stronger absorption of the interaction potential resulting in smooth and gradual changes in cross sections as a function of energy. However, striking surprises emerged and recent experimental data[1] show clear evidence not only of the nonstatistical resonant behavior in many lighter–heavy-ion interactions at energies well above the Coulomb barrier but also of the key role played in the resonant process by inelastic and other direct reaction channels.

The aim of the present Letter is not to discuss the dynamics responsible for the observed structure, which is still an open question, but rather to evaluate in a quantitative way the favorable conditions for resonant phenomena not to be obscured by strong absorption at higher energies. This is because we think that the problem of the resonance width is as important as is the formation mechanism itself. Guided by the experimental observations,[1] we wanted in particular to explore the idea that at high incident energies, the observation of resonant structure might arise from weak absorption due to the small number of open direct reaction channels. If this were the case, it would be strongly correlated with a "surface transparent" interaction and not with the formation of a compound nucleus as already indicated by elastic scattering[4-6] and fusion–cross-section[7-10] experimental data and their interpretation. In particular, it has been shown recently[8-10] that the saturation of the fusion cross sections at high incident energies can be explained in terms of phase-space limitation for compound-nucleus formation. The obvious consequence is a vanishing contribution to the fusion process from the more peripheric partial waves with angular momenta between L_c, the corresponding limiting angular momentum for compound-nucleus formation, and L_g, the grazing angular momentum.

To get a systematic and quantitative understanding of resonant structure occurrence at bombarding energies above the Coulomb barrier, we have calculated for the experimentally well-studied even-even C + C, C + O, and O + O systems the number of open channels (NOC) which are, as a function of bombarding energy, available to carry away the angular momentum brought in by each incident partial wave. For each system NOC has been obtained by a triple summation over all possible two-body mass partitions in the exit channels, over all possible angular-momenta couplings, and, finally, over all possible energy distributions between the fragments. The contributions to NOC of the different fragments have been evaluated explicitly with use of the discrete energy levels reported in recent compilations[11] while for the high-excitation-energy region we have adopted a shifted and angular-momentum-dependent level density expression with parameters proposed by Gadioli and Zetta.[12] In the NOC calculations, the transmission coefficients were obtained by a semiclassical method[13] with use of an inverted parabolic approximation to the potential shape in the region of the outer barrier. The details of these calculations and their sensitivity to level densities and transmission coefficients will be discussed extensively in a forthcoming paper.[14] As already mentioned, the present discussion is focused on resonant behavior at bombarding energies well above the Coulomb barrier. In this energy range, there is a strong correlation between resonant behavior and the peripheral incident partial waves which is well established from measurements of elastic-scattering[4] and reaction cross sections, in particular for the $^{12}C + ^{12}C$ (Ref. 15), $^{12}C + ^{16}O$ (Ref. 16), and $^{16}O + ^{16}O$ (Ref. 17) reactions where most pronounced structure has been observed in the direct reaction channels. These arguments justify the representation of the present calculations adopted in Fig. 1, where the number of open channels available to carry away the incident flux of the grazing partial wave is shown versus the corresponding grazing angular momentum (L_g) calculated from a semiclassical formula with interaction parameters proposed by Wilczyński.[18]

The remarkable feature of *all* the calculated NOC vs L_g curves shown in Fig. 1 is the existence of a minimum at energies well above the Coulomb barrier. The occurrence of such a dip can be explained by considering the individual binary-channel contributions to NOC which is illustrated in Fig. 2 for the $^{12}C + ^{12}C$ and $^{14}C + ^{14}C$ reactions. At low energies (small L_g), nucleon and α fusion-evaporation channels dominate the reaction process. Their influence decreases with increasing angular momentum in the entrance channel and the corresponding drop in NOC is due to the increasing difficulty the compound nucleus has to dissipate angular momentum by the evaporation of light particles. At high energies, inelastic and transfer channels become open effec-

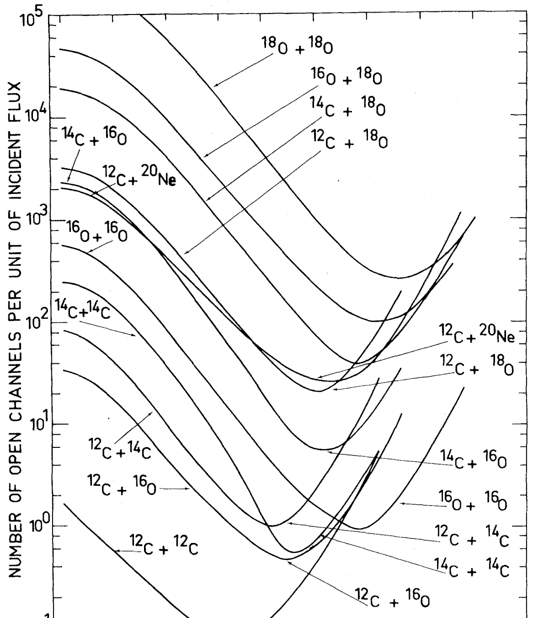

FIG. 1. Calculated number of open channels (for all even-even C + C, C + O, and O + O collisions and for the $^{12}C + ^{20}Ne$ reaction) available for carrying away the incident flux of the grazing partial wave with angular momentum corresponding to a large range of bombarding energies above the Coulomb barrier. The number of open channels has been normalized to 1 mb of the grazing-partial-wave flux.

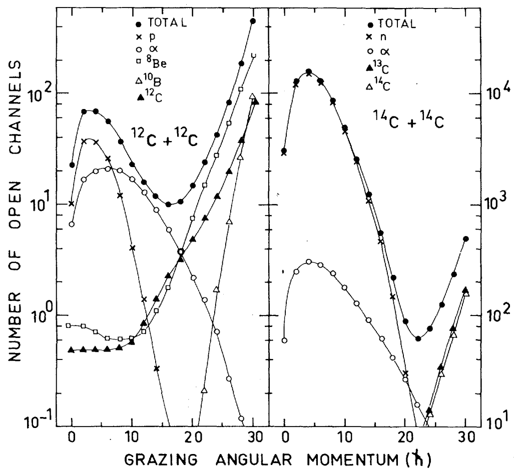

FIG. 2. Calculated number of open channels as a function of the grazing angular momentum for the $^{12}C + ^{12}C$ and $^{14}C + ^{14}C$ reactions. The different curves show, in addition to the total number of open channels, the individual contributions of the $p + ^{23}Na$, $\alpha + ^{20}Ne$, $^{8}Be + ^{16}O$, $^{10}B + ^{14}N$, and $^{12}C + ^{12}C$ binary channels in the case of the $^{12}C + ^{12}C$ reaction and of the $n + ^{27}Mg$, $\alpha + ^{24}Ne$, $^{13}C + ^{15}C$, and $^{14}C + ^{14}C$ binary channels in the case of the $^{14}C + ^{14}C$ reaction.

tively and a subsequent rise occurs in NOC due to an increasing number of these direct reaction channels which are able to carry away large angular momenta. Such a variation of NOC can be considered to be a general feature of the lighter-heavy-ion collisions which is most pronounced for reactions with incident channels composed of stable heavy ions with symmetric or nearly symmetric mass combinations. In contrast, it can be shown[14,19] that NOC calculated as a function of the limiting angular momentum L_c for compound-nucleus formation does not present such a minimum and, in this case, the α and even the nucleon fusion-evaporation channels continue to contribute appreciably to NOC at higher energies.

To permit comparison between NOC vs L_g (Fig. 1) and experimental data, in Fig. 3, we have represented angle-integrated direct-reaction cross sections (vs L_g) reported for several C + C, C + O, and O + O systems where resonant structure has been observed.

Although all curves shown in Fig. 1 present minima, the amplitudes of these minima depend strongly on the systems and reflect the varying degree of absorption of the surface partial waves. At the Coulomb barrier ($L_g = 0$), the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ reactions have the smallest number of open channels, and experimentally[2] it is only in these two reactions that resonant structure has been observed at energies close to the Coulomb barrier. This is a consequence of the low level density[3] of the compound nucleus, i.e., the small spreading widths of the entrance-channel resonances. With increasing energy, the absorption of the most peripheral partial waves into the direct reaction channels becomes more and more important compared with compound-nucleus formation. From the comparison of NOC (Fig. 1) for the different systems, we would like to stress the following points:

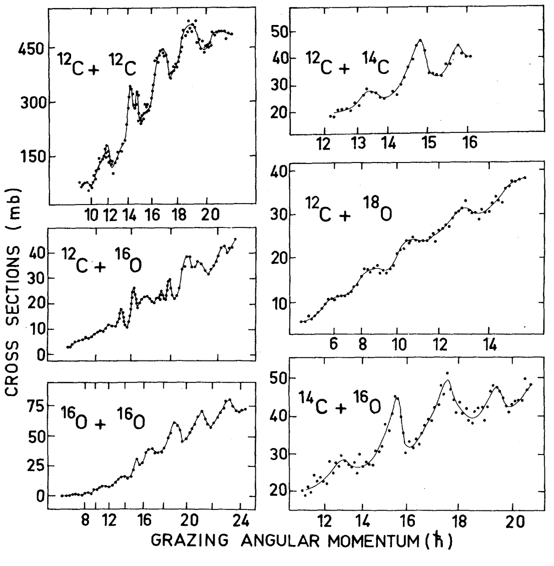

FIG. 3. Experimental evidence of resonant structure in direct reaction channels of several C + C, C + O, and O + O reactions. The represented cross sections correspond to the integrated γ-ray yields of the following transitions and reactions: The $^{12}C(2^+ \rightarrow 0^+)$ transition observed in the $^{12}C + ^{12}C$ reaction (Ref. 20), $^{16}O(3^- \rightarrow 0^+)$ in $^{12}C + ^{16}O$ (Ref. 16), $^{16}O(3^- \rightarrow 0^+)$ in $^{16}O + ^{16}O$ (Ref. 17), $^{13}C(\frac{5}{2}^+ \rightarrow \frac{1}{2}^-$ and $\frac{5}{2}^+ \rightarrow \frac{5}{2}^-)$ in $^{12}C + ^{14}C$ (Ref. 21), $^{18}O(2^+ \rightarrow 0^+)$ in $^{12}C + ^{18}O$ (Ref. 22), and $^{18}O(2^+ \rightarrow 0^+)$ in $^{14}C + ^{16}O$ (Ref. 23). The values of the grazing angular momenta have been obtained as indicated in the text and correspond to those reported in Fig. 1.

(1) The $^{12}C + ^{12}C$ system is, as is well established, an extreme case because NOC is small over a wide range of L_g. At high energies the observation of resonant structure expected on the basis of the present calculations (Fig. 2) in inelastic scattering and in the binary $^8Be + ^{16}O$ and $^{10}B + ^{14}N$ channels has been reported experimentally (Fig. 3 and Ref. 24).

(2) The $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$ systems, composed of tightly bound α-like nuclei, have small NOC minima values, i.e., weak absorption, consistent with recent observation of prominent resonant structure (Fig. 3). It should also be noted from Fig. 1 that the ratio in NOC between $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ is reduced by a factor of 100 in going from $L_g = 0$ to L_g at the minima of NOC.

(3) The present calculations predict strikingly small NOC minima values for the $^{14}C + ^{14}C$, $^{12}C + ^{14}C$, and even $^{14}C + ^{16}O$ reactions. Although ^{14}C is a non-α-like nucleus, it has a closed neutron shell and a closed proton subshell, displays a large separation ($E > 6$ MeV) between ground state and first excited state, and thus resembles the closed-shell nucleus ^{16}O. We have reported recently the observation in this laboratory of very strong resonant structure in direct reaction channels of the $^{12}C + ^{14}C$ (Ref. 21) and $^{14}C + ^{16}O$ (Ref. 23) reactions (see Fig. 3). More recently, Konnerth *et al.*[25] studied the $^{14}C + ^{14}C$ elastic scattering and found, at $\theta_{c.m.} = 90°$, a pronounced and regular gross structure similar to the elastic scattering[4] of the surface transparent $^{16}O + ^{16}O$ interaction. Such an observation is in perfect agreement with the present calculations. Moreover, it is expected, from Fig. 2, that at higher energies ($E_{c.m.} \geq 20$ MeV, $L_g \geq 14$) resonant structure should also be observed for the $^{14}C + ^{14}C$ reaction in inelastic

scattering and in the $^{13}C+^{15}C$ transfer channel.

(4) The $^{14}C+^{16}O$ and $^{12}C+^{18}O$ reactions lead to the same compound nucleus; the differences in NOC explain the differences in the amplitude of resonant structure observed experimentally (Fig. 3), although dynamical arguments will have to be considered in order to explain the pronounced structure and large cross sections in the $^{14}C+^{16}O$ reaction. For the $^{12}C+^{18}O$ reaction, the available data[22] is restricted to an energy region where NOC is still quite high and this fact leads us to a general remark: In all the systems mentioned here (except $^{12}C+^{12}C$), the observation of structure in the direct (or binary) reaction channels is limited to bombarding energies corresponding to L_g a little smaller than the minima in Fig. 1. There is thus an urgent need to extend the data to higher energies and to explore the entire region of small NOC values, i.e., the surface transparent region.

(5) The present NOC calculations for the $^{16}O+^{16}O$, $^{12}C+^{20}Ne$, and $^{18}O+^{18}O$ reactions show large differences in absorption for the three reactions due to very different degrees of direct-reaction-channel coupling. Such a conclusion is in agreement with the interpretation proposed by Shaw, Vandenbosch, and co-workers[6] to explain the differences observed in the elastic scattering data for these three systems.

For the lighter-heavy-ion systems considered in the present paper, the calculated number of open channels for the incident peripheral partials shows a characteristic energy dependence which provides a quantitative understanding of the concept of surface transparency in heavy-ion scattering. In addition, the present calculations offer a coherent explanation of selective resonance phenomena observation in various systems at energies well above the Coulomb barrier in terms of the number of open *direct* reaction channels. Surface transparency is closely related to the imaginary part of the optical potential and the present calculations should be considered as a first step towards deriving quantitatively the energy and angular momentum dependence of the imaginary potential from the correlation between resonant behavior and the number of open reaction channels.

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[1] Readers are referred to the most recent review articles in the proceedings of the following topical conferences on the subject: *Nuclear Molecular Phenomena*, edited by N. Cindro (North-Holland, Amsterdam, 1978); Proceedings of the International Conference on the Resonant Behavior of Heavy Ion Systems, Aegean Sea, Greece, 1980 (to be published).

[2] E. Almqvist *et al.*, Phys. Rev. Lett. 4, 515 (1960); J. R. Patterson *et al.*, Nucl. Phys. A165, 545 (1971).

[3] D. L. Hanson *et al.*, Phys. Rev. C 9, 1760 (1974).

[4] J. V. Maher *et al.*, Phys. Rev. 188, 1665 (1969).

[5] R. A. Chatwin *et al.*, Phys. Rev. C 1, 795 (1970).

[6] R. W. Shaw *et al.*, Phys. Rev. Lett. 25, 457 (1970); R. Vandenbosch *et al.*, Phys. Rev. Lett. 33, 842 (1974), and Nucl. Phys. A230, 59 (1974).

[7] D. G. Kovar *et al.*, Phys. Rev. C 20, 1305 (1979).

[8] R. Vandenbosch, Phys. Lett. 87B, 183 (1979); R. Vandenbosch and A. J. Lazzarini, Phys. Rev. C 23, 1074 (1981).

[9] S. M. Lee *et al.*, Phys. Rev. Lett. 45, 165 (1980).

[10] J. P. Wieleczko *et al.*, Phys. Lett. 93B, 35 (1980).

[11] F. Ajzenberg-Selove, Nucl. Phys. A320, 1 (1979), and references therein.

[12] E. Gadioli and L. Zetta, Phys. Rev. 167, 1016 (1968).

[13] K. W. Ford *et al.*, Ann. Phys. (N.Y.) 7, 239 (1979).

[14] F. Haas and Y. Abe, to be published.

[15] J. J. Kolata *et al.*, Phys. Rev. C 21, 579 (1980).

[16] J. J. Kolata *et al.*, Phys. Rev. C 19, 408 (1979).

[17] J. J. Kolata *et al.*, Phys. Rev. C 19, 2237 (1979).

[18] J. Wilczyński, Nucl. Phys. A216, 386 (1973).

[19] Y. Abe, in Proceedings of the International Conference on the Resonant Behavior of Heavy Ion Systems, Aegean Sea, Greece, 1980 (to be published).

[20] T. M. Cormier *et al.*, Phys. Rev. Lett. 38, 940 (1977).

[21] R. M. Freeman *et al.*, Phys. Lett. 90B, 229 (1980).

[22] R. M. Freeman and F. Haas, Phys. Rev. Lett. 40, 927 (1978).

[23] F. Haas, in Proceedings of Deuxième Colloque Franco-Japonais de Physique Nucléaire avec des Ions Lourds, Gif-sur-Yvette, France, 1979 (unpublished); J. J. Kolata *et al.*, Phys. Rev. C 23, 1056 (1981).

[24] B. R. Fulton *et al.*, Phys. Rev. C 21, 198 (1980); M. R. Clover *et al.*, Phys. Rev. Lett. 43, 256 (1979).

[25] D. Konnerth *et al.*, Phys. Rev. Lett. 45, 1154 (1980).