Intermediate structure in $^{12}C + ^{12}C$ elastic scattering

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A band crossing model with a smooth-cutoff representation of absorption effects is applied to the intermediate structure observed in elastic scattering of the $^{12}C + ^{12}C$ system. The model is found to reproduce the experiment extremely well, which suggests strongly that the intermediate structure is a reflection of the existence of molecular resonances. The values of parameters in a smooth-cutoff representation of absorption effects are extracted by an analysis of the oscillatory fusion cross section.

[NUCLEAR REACTIONS $^{12}C(^{12}C, ^{12}C)^{12}C$, $6 \leq E_{c.m.} \leq 30$ MeV; $\theta_{c.m.} = 90°$; calculated $\sigma(E)$. Resonance mechanism for Heavy Ion Reactions, absorption effects extracted from fusion data.]

INTRODUCTION

Since the first observation of resonances[1] in the $^{12}C + ^{12}C$ system below the Coulomb barrier, the intermediate structure[2] observed in the elastic and inelastic scattering and in the various channels has posed an interesting problem concerning the interactions between heavy ions. Similar structure has been found recently in heavier nuclear systems[3] as well as in other light systems such as $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$.[4] Currently resonance phenomena can be considered to be one of the general aspects of interactions between heavy ions, not confined to special systems and/or to special reactions. As yet, however, no satisfactory explanation of the phenomena has been available, although several moderately successful attempts[5,6] at such an understanding have been reported. This is true even for the intermediate structure observed in the elastic excitation function of the $^{12}C + ^{12}C$ system[7]—the most thoroughly studied of all heavy ion systems and the one in which resonant phenomena are most prominent.

A detailed study of the available data in the $^{12}C + ^{12}C$ system has been reported by Shapira *et al.*[8]; they conclude that it is *possible* to encompass all the observed structure in the elastic and reaction excitation functions within the framework of a purely statistical model. But they emphasize that they do *not* imply or require that the observed data have *necessarily* a statistical origin; rather, they emphasize that in order to claim molecular origin for structure in such excitation functions it is necessary to evolve more detailed signatures for it or to correlate specific structural details of the data with detailed predictions of a molecular model.

A band crossing model[9] (BCM) has been proposed within the framework of the general nuclear molecular picture developed by the present authors for resonant mechanisms in heavy ion reactions.

Briefly, we have extended the Nogami-Imanishi model[5] by including all the available degrees of freedom involved when one or both of the interacting nuclei is excited during the interaction. This excitation reduces the relative kinetic energy temporarily and results in quasimolecular binding. In the simplest application of such a model wherein *only* the 2_1^+ state of ^{12}C at 4.44 MeV is allowed to be excited in *one* of the interacting nuclei, we obtain, in addition to the elastic molecular band (first proposed by Arima *et al.*[10] and independently by Fink *et al.*[6] on the basis of the Reilly potential[11]) *three* inelastic bands with spins J equal to $L-2$, L, $L+2$, where L stands for the relative angular momentum between two nuclei.

The BCM is based on the observation that one of these inelastic bands with an *aligned* configuration of its intrinsic spin and orbital angular momentum (the aligned band, in our notation) crosses the elastic molecular band, and that in the energy region around the crossing point a strong mixing of wave functions occurs among the original resonance states in the elastic and the inelastic bands;

this would be expected to be reflected in correlated intermediate structure in relevant channels.

Essential physics requires emphasis here. The elastic molecular band comprises two unexcited, ground state nuclei bound in a molecular configuration in their mutual potential; as such, it is immediately accessible to the experimental entrance channel. The aligned band has an excited molecular configuration in which one (or both) of the nuclei is an excited state. The mixing of the band wave functions in the crossing region then provides a direct mechanism for coupling entrance channel flux into the particular excited molecular configuration involved; indeed, this is the reason why, in the BCM, we ignore all *but* the aligned inelastic bands inasmuch as the others do *not* cross or mix with the elastic molecular band.

The BCM was first applied to elastic and inelastic scattering in the $^{12}C + ^{16}O$ system[9] and was found to explain characteristic features of the resonances systematically over a wide energy range well above the Coulomb barrier; specifically, the model successfully reproduces the fact that resonances involving particular structural excitations are dominant in some energy ranges, do not appear at lower energies, and fade away above these ranges.

The BCM has also been applied[12] to the structure recently observed in the angle-integrated inelastic cross sections for the $^{12}C + ^{12}C$ system at higher energies. It has been found to reproduce the experiment extremely well; the correlated resonances (with spins 12–14 at about 20–25 MeV) which have been observed in both the single excitation (of the 2_1^+ collective excited state of ^{12}C) and the mutual excitation channels appear naturally. This success is readily understood from inspection of the schematic diagram of the aligned rotational bands shown in Fig. 1.

The purpose of the present paper is to examine the extent to which the BCM, with appropriate additions, is adequate to reproduce characteristic structure[7] observed in the *elastic* scattering of ^{12}C on ^{12}C.

It is immediately clear that the BCM predicts that the strength of the broad potential resonances in the elastic channel should be fragmented by coupling to inelastic excitations—by crossing of the elastic molecular and the aligned rotational bands as indicated in Fig. 1. We further have recognized from the outset that in addition to interfering Coulomb scattering amplitudes, absorption effects normally represented by the imaginary part of an optical potential can have dramatic effects upon the behavior of the elastic differential cross section. Our problem then is one of incorporating these absorption effects adequately within a BCM treatment of the scattering problem.

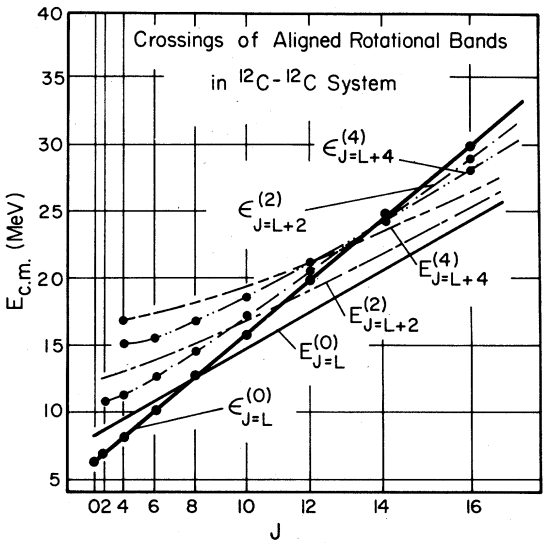

FIG. 1. Schematic diagram of band crossings for the single and the mutual excitations of ^{12}C in the $^{12}C + ^{12}C$ system. $\epsilon_J^{(0)}$, $\epsilon_J^{(2)}$, and $\epsilon_J^{(4)}$ represent resonance energies of elastic, aligned single 2_1^+, and aligned mutual 2_1^+ excitation channels, respectively. $E_J^{(0)}$, $E_J^{(2)}$, and $E_J^{(4)}$ represent barrier heights of these channels, respectively.

Fortunately, we have found it possible to separate the scattering problem into two parts, one reflecting the imaginary and one reflecting the real part of the equivalent optical model. Specifically, we shall use the previously described BCM to reflect the effects of the real potential in determining the resonance position and fragmentation, and a semiclassical smooth-cutoff strong absorption model of the fusion process to provide details of the imaginary potential or absorption effects.

As we shall show, an analysis of the experimental fusion cross section[13] makes possible the unique identification of the angular momentum of the partial wave responsible for each maximum in the fusion cross section together with a description of the way in which the absorption of the particular partial wave in question depends upon energy in the region of maximum absorption. In short, we have found it possible to extract, quantitatively, from the measured fusion cross section, the reflection coefficients. We subsequently combine these coefficients, carrying information on absorption effects, with the S-matrix elements obtained from the BCM, reflecting real potential scattering effects, to obtain a complete description of the elastic scattering process and a predicted excitation function which can be compared directly with the experimental results.

The reproduction of the experimental data has been gratifyingly detailed; this lends substantial

support to the BCM, to this method of incorporating absorption effects, and to the physical reality of the underlying nuclear molecular concepts.

In Sec. II a smooth-cutoff model is applied to the experimental fusion cross section for the $^{12}C+^{12}C$ system and reflection coefficients are extracted from the analysis. The results are compared with transmission coefficients estimated by a semiclassical barrier penetration with an inverted parabolic approximation to the potential barrier in the outer region. Results and discussion of an analysis of $^{12}C+^{12}C$ elastic excitation function by the BCM with the smooth-cutoff representation of absorption effects are presented in Sec. III. The conclusion is summarized in Sec. IV.

II. FUSION CROSS SECTION AND SMOOTH-CUTOFF MODEL

The experimental fusion cross section[13] for the $^{12}C+^{12}C$ system is now known to show a characteristic oscillatory structure. Phenomenologically, we can describe it easily using a smooth-cutoff model. We parametrize the reflection coefficients in the usual notation as follows:

$$\eta_L(E)=\frac{1}{1+\exp[(E-E_L)/\Delta E_L]}\,. \tag{1}$$

This parametrization implies that a partial wave with an angular momentum L will suffer strong absorption at energies higher than E_L with ΔE_L providing a smoothing of the transition region. The absorption cross section is then given, as usual, by

$$\sigma_{\rm abs}(E)=\frac{2\pi}{k^2}\sum_{L}^{\rm even}(2L+1)\cdot(1-\eta_L{}^2), \tag{2}$$

where k is the wave number. The calculated cross section is shown in Fig. 2 as the solid line, together with the experimental data.[13] Values of the parameters E_L are taken to be close to the barrier heights of the corresponding total potential, i.e., approximately equal to the height of the outer potential maximum in the total interaction potential adopted in the BCM calculation that includes nuclear, Coulomb, and centrifugal terms and, in view of the latter, is different for each partial wave; these values of E_L are indicated in the figure by vertical arrows. ΔE_L is taken to be 0.5 MeV for all partial waves.

In Fig. 2, it is clear that the oscillatory features of the data are reproduced extremely well by the model in addition to the absolute value of the fusion cross section. It is interesting to note here that each maximum in the fusion cross section reflects the contribution of a single partial wave $\sigma_L=2\pi/k^2\cdot(2L+1)(1-\eta_L{}^2)$, several of which isolated contributions are also shown in Fig. 2. Thus, it can be considered that the maxima are signatures for strong absorption suffered by partial waves entering a critical energy region one after another, as the incident energy increases. It is, however, not yet certain whether the structure reflects only barrier penetration or whether it reflects contributions from some other important mechanism, e.g., molecular resonances, since the observation of these structures has generally been considered as evidence for them.

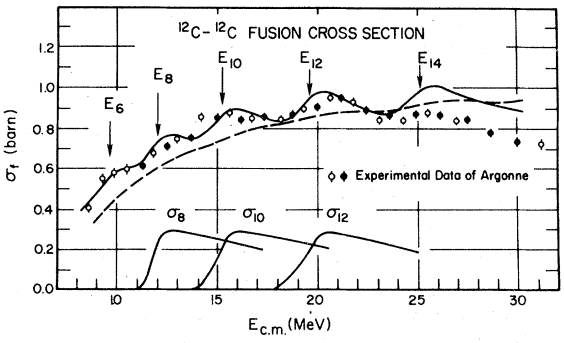

FIG. 2. Analysis of the fusion cross section in the $^{12}C+^{12}C$ system. Solid lines show the results calculated in a smooth-cutoff model. Vertical arrows show the values of E_L. Several partial wave contributions are also shown. The dashed line shows a fusion cross section estimated by the semiclassical treatment of the barrier penetration.

A crucial experimental question in this context is whether or not the broad maxima shown in Fig. 2 fragment when observed under conditions of higher energy resolution. There is preliminary evidence from the work of Taras *et al.*[14] at Montreal and Kolata *et al.*[15] at Strasbourg that this is indeed the case. Under these conditions, the strong absorption would be associated with the shape or molecular resonance, whereas the fragmentation would reflect coupling—via temporary inelastic excitation to quasibound states in the potential.

To estimate the effects of barrier penetration on the fusion cross section, transmission coefficients are calculated in a semiclassical approximation using an inverted parabolic approximation to the potential shape in the region of the outer barrier. The result[16] is

$$T_L=\frac{1}{1+\exp[2\pi(E_L-E)/\hbar\omega_L]}\,, \tag{3}$$

where

$$\hbar\omega_L=\hbar\left(\frac{1}{\mu}\left|\frac{d^2V}{dR^2}\right|_{R=R_0}\right)^{1/2}. \tag{4}$$

In these expressions V is the total potential adopt-

ed in the BCM calculation (see Sec. III), μ is the reduced mass of the system, and R_0 is the radius corresponding to the top of the outer potential maximum. Under the assumption of a strong absorption of wave functions at the inside of the potential barrier, transmission coefficients given in Eq. (3) can be related to the reflection coefficients as follows:

$$T_L = 1 - \eta_L^2 . \tag{5}$$

The calculated fusion cross section thus obtained is shown in Fig. 2 as the dashed line. In this calculation, $\hbar\omega_L$ plays much the same role as does ΔE_L in the smooth-cutoff model in that both determine the width of the structure. ΔE_L is obtained empirically from fitting the measured fusion cross section, whereas $\hbar\omega_L$ is implicit in the model. In both cases there is a trade-off in the sense that increasing the maximum height of a peak reduces its width, i.e., to first order the area remains constant. Figure 2 shows that effects of the barrier penetration produce some structure, but the amplitude of this structure is much too small to reproduce the experimental maxima which reflect smaller values of $\hbar\omega_L$. It is suggestive, however, that the weak structure does match the experiment in terms of the energy regions in which the cross section is enhanced. What we require, therefore, is a mechanism to increase the magnitude of the structure to more nearly correspond with the data.

This mechanism may simply enhance the tendency toward barrier penetration, although there still remains a possibility that some nuclear potential could give small enough values of $\hbar\omega_L$ to correspond to more pronounced structure. It is not clear, as yet, what the character of these additional contributions might be. But they will have the same spin as that in the semiclassical model, i.e., that of a grazing partial wave, since within our model we find that partial waves of lower angular momentum are totally absorbed, while higher partial waves, because of the correspondingly greater centrifugal potential terms, are barred from participation in the interaction at a given energy. This is simply a restatement of the original discovery by Gobbi *et al.*[17] that in these light nuclear systems—and in particular those involving identical particles—only a single partial wave is active over substantial energy ranges in their interactions.

An important point in our phenomenological analysis in terms of a smooth-cutoff model is that the angular momentum corresponding to each of the maxima in the fusion cross sections can be determined unambiguously. If we change the values of E_L artificially so as to associate a different partial wave from that in Fig. 2 with a particular maximum in the fusion cross section, e.g., a partial wave with an angular momentum larger or smaller by two units, then we obtain, as shown in Fig. 3, quite different predicted absolute values for the fusion cross sections larger or smaller, by about 300 mb, than the original values which matched the experimental ones. This simply corresponds to the observation that an absolute fusion cross section determines the maximum angular momentum participating in the fusion process—assuming always a simple geometrical model for it. It is important to emphasize that our suggested analysis of the structure in the fusion cross section in terms of a smooth-cutoff model thus provides precise information on the energy dependence of the absorption for each uniquely identified partial wave—information otherwise difficult to obtain. The reflection coefficients thus obtained will be utilized in Sec. III to obtain a complete description of the elastic scattering process.

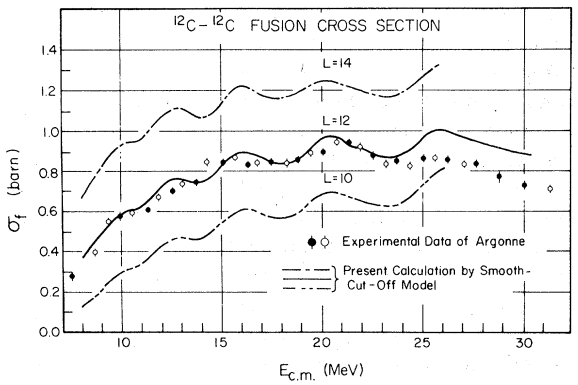

FIG. 3. Calculated fusion cross sections with different assignments for the grazing angular momentum of the peak at $E_{c.m.} = 20$ MeV. Assignments of $L = 14$ and $L = 10$ for the fusion peak produce cross sections larger and smaller by about 300 mb than the original one ($L = 12$), respectively.

III. BAND CROSSING MODEL WITH SMOOTH-CUTOFF PRESCRIPTION

In this section a prescription, results, and discussion of an analysis of the $^{12}C + ^{12}C$ elastic excitation function by the BCM with the smooth-cutoff representation of absorption effects is presented. Since a formulation of the usual BCM via coupled channel equations is described elsewhere,[9,18] we do not repeat it in this paper.

We can solve the coupled channel equations using a real interaction potential only, that is, without introducing any imaginary part, because we have already used the smooth-cutoff model as a representation of the absorption effects. The real

nuclear potential parameters are adjusted to yield an elastic potential resonance with $J^\pi = 12^+$ at about 20 MeV and a resonance with $J^\pi = 2^+$ at about 6 MeV. The former is suggested by detailed analysis of correlated resonances[19,20] as well as by our analysis of the fusion data just presented. The latter is fixed by a previous analysis[18] of the fragmented 2^+ resonances in the sub-Coulomb region reported by the present authors. We take a two range Woods-Saxon potential; one component is the short range repulsive core which represents the effects of the Pauli principle, while the other is the long range attractive component with specific L dependence included. These features are suggested by all microscopic studies on the interactions between composite nuclei.[21] The values of the parameters are the height $V_1 = 100.0$ MeV, the range $R_1 = 4.0$ fm, and the diffuseness $a_1 = 0.35$ fm for the core part and the depth $V_2 = -48.0 - L(L+1)/17.0$ MeV, the range $R_2 = 4.67$ fm, and the diffuseness $a_2 = 0.5$ fm for the attractive part. A coupling interaction among the elastic, the single excitation, and the mutual excitation channels, was obtained, as usual, by the expansion of the attractive potential in terms of the quadrupole deformation parameters for the carbon nuclei. The values of the deformation parameters β_2 are taken to be -0.2 in the first order and -0.7 in the second order terms in our expansion.[12] Inclusion of the second order term is essential to give the rather large inelastic cross section for mutual 2_1^+ excitation which is observed experimentally[22]; this reflects the fact that the second order term connects the elastic channel directly with the mutual excitation channel. The larger value of β in the latter term might be an artificial incorporation of the enhancement of mutual excitation of such rotational states through meshing of the surfaces in grazing collisions—a mechanism not naturally included via the expansion technique. For the coupling between elastic and 3_1^- excitation channels a phonon type one[9,12] is assumed, and the coupling strength γ is taken to be 0.2. The method for solving our coupled channel equation has been given in a previous paper.[9]

We define the physical S-matrix elements as products of our original $\bar{S}$ matrices and the reflection coefficients η_L which were obtained by the above smooth-cutoff analysis of the fusion cross section, yielding,

$$S_{00}^L = \eta_L(E) \cdot \bar{S}_{00}^L , \tag{6}$$

where $\bar{S}_{00}^L$ is the elastic S-matrix element obtained by the BCM including only the *real* potential. It is important to emphasize this factorization of the problem; the $\bar{S}_{00}^L$ matrix elements reflect only *real* potential effects while the reflection coefficients η_L reflect the *imaginary* potential effects. By using the physical S-matrix element S_{00}^L we calculate an elastic excitation function for the $^{12}C + ^{12}C$ system at $\theta_{c.m.} = 90°$ as an example of where prominent structure is observed experimentally. The results are shown in Fig. 4 together with the experimental data. We can see that the experimental intermediate structure is reproduced remarkably well by the BCM with the addition of a smooth-cutoff representation of absorption effects. Furthermore, we can recognize from the energy dependence of the elastic phase shifts, shown in the upper part of Fig. 4, that each calculated prominent peak corresponds approximately to a resonance obtained in the BCM with a real potential only. It is particularly striking that the characteristic doublet observed at $E_{c.m.} \simeq 20$ MeV is reproduced correctly by the present calculation as well as by another small peak at slightly lower energy. This is not by chance but a natural consequence of the BCM, because three bands, that

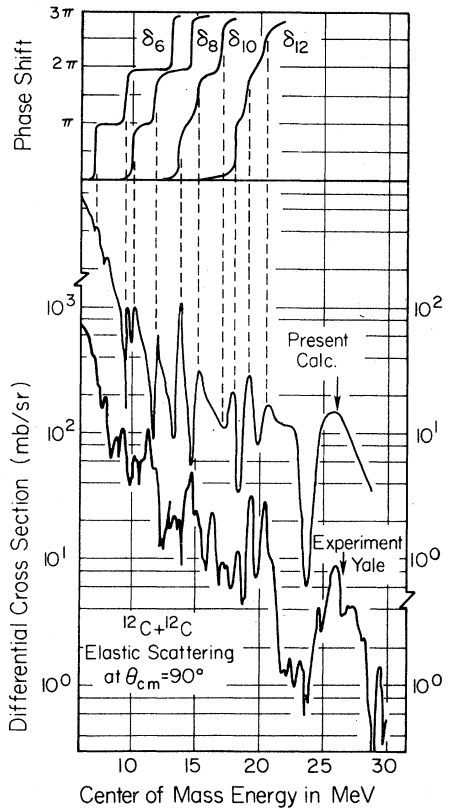

Fig. 4. Comparison of the calculated results with the measured elastic excitation function at $\theta_{c.m.} = 90°$ in the $^{12}C + ^{12}C$ system. Several phase shifts obtained in the BCM with the real potential only are also shown in the upper part. In this calculation we include the coupling of single and mutual 2_1^+ excitations and 3_1^- excitation of ^{12}C with the elastic channel.

is, the elastic potential resonance band and the aligned rotational bands with single and mutual 2_1^+ excitations, cross at about 20 MeV and $J^\pi = 12^+$, as illustrated in Fig. 1. In other words, these peaks may be considered as a reflection of the fragmentation of the 12^+ elastic potential resonance strength. Similar correspondence between calculated and experimental peaks can be recognized for the lower energy region. These facts strongly suggest that the observed structure in the elastic excitation function is a reflection of the existence of molecular resonances.

The fact that the calculated curve of Fig. 4 lacks structure corresponding to the experimental data at energies above $E_{c.m.} = 20$ MeV merely reflects the fact that in these calculations we have only included single and mutual excitation of the 2_1^+ state and 3_1^- excitation in ^{12}C. Data of Erb *et al.*[23] show clearly that at higher energies the 4_1^+ member of the ^{12}C ground state rotational band as well as the mutual $2_1^+ - 4_1^+$ excitation plays an important role. We believe that the inclusion of these higher excitations in our model can readily provide a reproduction of the higher energy data, but these calculations have not yet been completed.

IV. CONCLUSION

In this paper the structure in the $^{12}C + ^{12}C$ fusion cross section has bee shown to be well described by a smooth-cutoff model. This analysis has provided detailed information on the absorption for each partial wave. Each maximum in the fusion cross section can be attributed to the strong absorption of a particular grazing partial wave. The band crossing model with the addition of this smooth-cutoff representation of absorption effects has been successfully used to reproduce the experimental data for elastic scattering at $\theta_{c.m.} = 90°$ in the $^{12}C + ^{12}C$ system, and the excellent agreement obtained suggests strongly that the intermediate structure observed in the elastic scattering is a reflection of the existence of molecular resonances, not a consequence of some complicated nuclear dynamic effects. We also suggest that the separation of the real and imaginary potential effects proposed herein may have broader use in the study of heavy ion interactions.

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