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MOLECULAR RESONANCES, FUSION REACTIONS AND SURFACE TRANSPARENCY OF INTERACTION BETWEEN HEAVY IONS.

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Abstract :

A review of the Band Crossing Model is given, including recent results on the $^{16}O + ^{16}O$ system. Surface Transparency is discussed in the light of the recent developement in our understanding of the fusion reaction mechanisms and by calculating the number of open channels available to direct reactions.

The existence of the Molecular Resonance Region is suggested in several systems by the fact that Band Crossing Region overlaps with the Transparent Region. A systematic study predicts molecular resonances in the $^{14}C + ^{14}C$ and $^{12}C + ^{14}C$ systems as prominent as those observed in the $^{16}O + ^{16}O$ and $^{12}C + ^{16}O$ systems.

1. INTRODUCTION

Resonant phenomena in heavy ion reactions have a fairly long history since the discovery of the sub-Coulomb resonances in the $^{12}C + ^{12}C$ system in 1960[1]. Nowadays we have a lot of experimental data which show resonant behavior to varying extents, as already reported by several preceding speakers. We, however, have not yet clarified their resonance mechanisms and their nuclear structures, although many efforts are being devoted to the problem.

Just after the discovery of the resonances, people inferred that those resonances were signals of the existence of the simple di-nuclear molecule.

Subsequently Nogami[2] proposed a more sophisticated but still simple picture for the mechanism of long lived resonances : as we all know, incident heavy ions interact to excite collective levels of the ions, lose the relative kinetic energy, and form a quasi-stationary state. Imanishi[3] formulated the picture in the coupled channel framework and succeeded in reproducing the carbon partial widths of the triplet in good agreements with the experiment. Scheid,Greiner and Lemmer [4] applied it to the intermediate structure observed in ^{16}O-^{16}O scattering emphasizing the so called "double resonance mechanism".

The picture looked reasonable and promising, and was actually found to be fairly successful in reproducing resonant behaviors of several experimental data. Nevertheless it had not necessarily been accepted by most people. One of the reasons is that one could not make any simple qualitative prediction about the occurence of resonances based on this picture. Another reason is that in the calculation of resonances one has used artificially weak imaginary potentials, even no imaginary potential in inelastic channels. The present report is concerned with these two points. First a review is given of the Band Crossing Model (BCM) which gives us a simple overview of the onset and fading-away of resonances which have molecular configurations[5]. (§ 2). The results of dynamical calculations based on the BCM are also discussed for the $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ systems (§3). Secondly the surface transparency of interaction between heavy ions[6] is discussed, because a weak imaginary potential for surface partial wave is essential in the calculation of molecular resonances. The imaginary part of the optical potential is considered to come from fusion and direct reactions. Systematic studies of fusion reactions[7] show the existence of the bending in excitation functions in almost all the cases studied, which is simulated by a critical angular momentum for compound nucleus formation smaller than the grazing angular moment [8] (§ 4).

Thus absorption in surface partial wave at energies higher than the bending energy of the fusion should be due to direct reactions. The calculations[9] for the number of open channels available to direct reactions show a characteristic energy dependence corresponding to the surface transparency observed in several systems (§ 5). The existence and non-existence of the molecular resonance region will be discussed for all the combinations of even-even Carbon and Oxygen isotopes, including a prediction of molecular resonances in the $^{14}C + ^{14}C$ and $^{12}C + ^{14}C$ systems (§ 6).

Recently there have been a new wave of activity in experimental study of heavy ion resonance reactions. Not only resonances in inelastic channels but also those in rearrangement channels have been observed. Some of them have been found to fall in the strong absorption region [10]. In the present report we discuss mainly about the formers which fall in the surface transparent region.

2. REMINDER OF THE BCM.

Microscopic studies of interaction between complex nuclei have revealed several characteristic aspects, as reported by Baye [12]. One of them is that the relative motion between complex nuclei has a series of bound or quasi-bound states which are described well by the rotational energy expression with the total spin equal to the orbital angular momentum. An example of the result of such a calculation is shown in Fig.1 for the $^{16}O + ^{16}O$ system, which was obtained by Ando, Ikeda and Tohsaki-Suzuki[13]. It should be noticed here that there is no experimental data directly related to these individual states which are theoretically obtained. That is considered to be due to the fact that these states are located at fairly high excitation energies of the compound system, and thus they couple with many other degrees of freedom which are activated there (to some extent this will be found to be not always true in the latter part of the present paper). Experiments show rather gross structure with intermediate width structures upon it [14]. Thus it is most likely that such molecular states as those obtained in microscopic calculations couple to other degrees of freedom and strongly to some of them to give rise to the structures. The most strongly coupling modes of motion are, as is well known, collective excitations of the incident ions themselves.

In order to see the consequence of the coupling schematically, we assume the existence of the rotational band with the incident molecular configuration as suggested by microscopic calculations. Then an excited molecular configuration locates at an energy higher than the elastic molecular band by the intrinsic excitation energy of the ion. In the case where the excited state has non zero intrinsic spin I, (here we assume the ground state has spin zero) there are degenerate states with the same orbital angular

momentum L but with a different total spin J due to the angular momentum coupling between L and I, as shown in Fig.2. Hence we have several quasi-rotational bands with the excited molecular configuration. What is interesting here is that at least one of them crosses the elastic molecular band at a certain spin. We call this band the "aligned molecular band", simply because L and I couple parallelly to give the maximum total spin J = L + I. Around the crossing point two molecular configurations mix strongly with each other even if the coupling interaction is not extremely strong. New states resulting from the coupling have approximately half of the partial widths of the elastic and excited molecular configurations. Such mixed molecular configurations should be observed prominently in the elastic and inelastic scattering. It should be remarked here that the crossing point is nothing but the point where "double resonance condition" is fulfilled. The value of the crossing spin is easily estimated as follows.

The energy of a member of the elastic molecular band is assumed to be simply described by the rotational energy expression,

$$E_J^{(o)} = E_o^{(o)} + \frac{\hbar^2}{2\mathcal{J}} J(J+1) \qquad (2\text{-}1)$$

where $\mathcal{J} \simeq \mu R^2$, $R = r_o \cdot (A_1^{1/3} + A_2^{1/3})$ and μ is the reduced mass of the incident heavy ion system. The nuclear range parameter $r_o = 1.25$ fm gives a good estimation of $\mathcal{J}$ for light heavy ion systems.

The energy of a member of the aligned molecular band is given by :

$$E_{J=L+I}^{(1)} = \Delta E_1 + E_0^{(o)} + \frac{\hbar^2}{2\mathcal{J}} L(L+1)\Big|_{L=J-I} \qquad (2\text{-}2)$$

where ΔE_1 is the intrinsic excitation energy of the ion. By equating the two expressions, we obtain the crossing spin value :

$$J_{cross} = \frac{1}{2} \frac{\Delta E_1}{\frac{\hbar^2}{2\mathcal{J}} \cdot I} + \frac{1}{2} I - \frac{1}{2} \qquad (2\text{-}3)$$

In eq. (2-3), J_{cross} is given as a function of ΔE_1, I and $\mathcal{J}$. Thus we can simply predict with what spin values resonances occur carrying certain molecular configuration as a dominant component, although we still need an indicative experiment or a reliable microscopic calculation for the band head energy if we want to know resonance energies also, as well as their spins.

Furthermore according to Eq. (2-3), aligned molecular configurations with various collective excitations of the incident ions have in general different J_{cross}'s, depending on different intrinsic excitation energies and spins. Hence we expect that dominant components of prominent resonances change systematically among various aligned molecular configurations. This has been already confirmed in the $^{12}C + ^{12}C$ system by a recent experiment by B.R.Fulton, T.M.Cormier and B.J.Herman[15]. Another interesting aspect of this simple argument is that among all other angular momentum coupling the aligned configurations should be dominant in prominent resonances. This could be checked by polarization-type experiments.

3. EXAMPLES

Fig.3 shows an example of the Band Crossing Diagram for the $^{12}C + ^{12}C$ system. This is just what the author showed at the Resonance Confrence held at Hvar island in Yugoslavia [16] several years ago. At that moment only a qualitative argument was given for the correspondence between the crossing spins for the single and mutual 2^+ aligned molecular band and the observed resonances in the excitation functions for the single and mutual 2^+ inelastic scattering [17].

In order to see whether such a simple picture can really reproduce characteristic features of the resonances, i.e., the widths and yields as well as a sequence of resonances, we have solved dynamical coupling among these molecular configurations with a scattering boundary condition [18]. We assumed a phenomenological potential which permits us to set up an elastic molecular rotational band, and a macroscopic form factor for the coupling interaction. A crucial assumption is the surface transparent imaginary potential with the J-dependence proposed by Chatwin et al.[19]. This will be discussed in the latter part of this paper. Channel wave functions are those as usual, but a simplification is made on the space employed. As discussed in § 2, aligned configurations are most important in resonances, and in the extreme case we retain only these components. In the simplest case the equation that we have to solve is reduced to a simple two channel problem. Of course we can make finer calculations by including all the other sub-channels.

In Fig.4 results for the dynamical calculation of the resonance cross section are compared with measured excitation functions for the inelastic scattering in the $^{12}C + ^{12}C$ system. The panels (a), (b) and (c) show the angle-integrated 2^+ inelastic excitation function, the angle-

integrated 2^+ mutual excitation inelastic excitation function, and the 3^- inelastic excitation function at one angle, respectively. We can see that this simple calculation reproduces quite well the gross feature of a series of resonances as well as the yields and widths of resonances experimentally observed.

Another example is the $^{16}O + ^{16}O$ system, where the resonance structure has recently been observed in γ-ray measurements[20]. Fig.5 shows the Band Crossing Diagram for the system. The aligned molecular bands of the 3^- single (6.13 MeV) and mutual (12.26 MeV) excitations cross the elastic molecular band around spin $\sim$ 18. At slightly higher spins and hence higher energies, the 4^+ and $3^- \times 2^+$ mutual excitation configurations are expected to play a role. As a preliminary study, two channel problem has been solved including only the elastic and aligned sub-channel of the 3^- inelastic channels[21]. In Fig.6 calculated inelastic cross sections are compared with the 6.13 MeV γ-ray yields. Taking into account the inclusive character of the experimental data (the measured yields include contributions from other reaction cross sections producing the same γ-ray), resonance widths and yields are again reproduced quite well. It is very interesting to see the excitation functions for the 3^- and $3^- \times 3^-$ mutual excitation inelastic scattering separately, because Fig.5 tells us that the mutually excited configuration should appear as a dominant component of resonances almost in the same energy region as the singly excited configuration.

4. WHAT FUSION REACTION SYSTEMATICS TELL US.

In the above phenomenological analyses, the most ambiguous part is the imaginary potential adopted. In order to reduce the ambiguities, we have tried to reproduce the fusion and elastic excitation functions at the same time as the resonant inelastic excitation function. Fig.7 shows such an example for the $^{16}O + ^{16}O$ system [21]. The same calculation that has given the resonant 3^- inelastic cross section shown in Fig.6 reproduces the fusion and elastic excitation functions quite well. Several other groups have measured smaller experimental fusion cross sections[7] than the one adopted here[22]. This would be more favorable for the resonance calculation. As a phenomenological study of heavy ion resonant scattering, the above analysis is satisfactory. But at the same time it is still meaningful to ask further whether such a surface transparent potential we assumed is really justified or not, because the strength of the imaginary potential is crucial in preserving a resonance behavior. As is well-known, if we use a strong imaginary potential, all the resonance peaks are smeared out. The origins of the

imaginary part of the optical potential are fusion and direct reactions. Of course we can add the so called deep-inelastic process.

First a qualitative discussion is given for an important information obtained from the studies of the fusion reaction between light heavy ions. Nowadays we have systematic experimental data on the excitation functions of the fusion reaction[7]. A general characteristic phenomenon is the bending of the cross section at a certain energy, which shows up clearly in the plot of the cross section versus 1/E. This characteristic energy dependence of the fusion cross section has been successfully described by the phenomenological model proposed by Glas and Mosel[8]. They assumed the existence of a critical distance for fusion reactions between heavy ions. On the other hand the same type of description can be obtained also from the properties of the compound nucleus, i.e., from the energy and angular momentum dependence of the level density of the compound nucleus [23]. Recently Matsuse, Lee and Arima[24] have shown that compound nucleus properties can really explain the systematics of the maximum fusion cross sections measured. Though for the moment the physical origin of the bending is not yet completely clarified, the important point is that at high energies there exist a critical angular momentum for fusion reaction l_{cr} smaller than the grazing angular momentum l_g.

Fig.8 shows the situation schematically. At a certain energy fusion cross sections drop down below the total reaction cross section, which is interpreted as l_{cr} becoming smaller than l_g. Thus at energies higher than the bending energy, the incident partial waves between l_{cr} and l_g do not go into the fusion channel, although they reach the interaction region. What can happen to these partial waves ? The incident flux could be carried away by direct reaction and/or deep-inelastic scattering, or could return to the incident channel. Hence whether these partial waves feel a transparent potential or not depends totally on direct reaction and possibly on deep-inelastic scattering.

5. NUMBER OF OPEN CHANNELS

Absorption due to direct reactions between heavy ions has been discussed during the last ten years. Chatwin et al.[19] introduced the angular momentum dependence in the imaginary part of the optical potential as a reflection of the poor matching between the angular momenta in the elastic channel and those in the nonelastic channels. They introduced a smooth cutoff parametrization of the strength of the absorptive potential as a function of the total angular momentum of the heavy ion system, and succeeded in reproducing the gross structure observed in the elastic excitation function of the $^{16}O + ^{16}O$ system. Shaw et al.[25] made a comparison of configurations

directly coupled to the elastic channel between the $^{16}O + ^{16}O$ and $^{18}O + ^{18}O$ systems, and correctly pointed out that several direct reaction channels are responsible for the J-dependence of the imaginary part at high energies. The present author discussed effective barrier heights of various reaction channels in the $^{12}C + ^{12}C$ system, which is an equivalent but inverted method with respect to that used by Chatwin et al.[19] and Shaw et al.[25]. Fig.9 shows these for the $^{12}C + ^{12}C$ system, which was first shown at the Resonance Conference at Hvar island in Yugoslavia [16], mainly for the purpose of discussion about two body molecular configurations which are possibly related to the observed resonances.

It clearly shows that at high energies the effective barriers for nucleon and nucleon-transfer channels are higher than that for the incident channel. Therefore those channels cannot carry away the incident flux of the grazing partial waves. Only some of the α-channels, ^{8}Be-channels and of course inelastic channels can be active there. Hence we can expect that at high energies there exist a surface transparent region in the $^{12}C + ^{12}C$ system, just as schematically shown in Fig.8. Recently Baye et al.[26] argued in a similar way about the absorption in heavier systems such as $^{40}Ca + ^{40}Ca$ by assuming the dominance of inelastic channels over multi-nucleon transfer channels due to the coupling interaction.

What we would like to have is a general feature of direct reactions between heavy ions, which would be described by the imaginary part of the optical potential, and which would provide us with a systematic understanding for the existence and non-existence of surface transparency among various combinations of heavy ions. As a first step in this direction it is interesting to consider the energy and spin dependence of the Number of Open Channels available to direct reactions[9]. Here we will define the number of open channels as a simple summation of transmission coefficients,

$$N^J(E_{c.m.}) = \int T_\ell(\epsilon_{12}) \qquad (5\text{-}1)$$

The transmission coefficient which we employ is equal to 1 for completely open channels, is equal to 0 for completely closed channels, and between these two extremes is smoothly connected by a semi-classical model of inverted parabolic barrier penetration [27],

$$\begin{aligned} T_\ell(\epsilon) &= 1/\left\{1 + \exp\left[(\epsilon_\ell - \epsilon)/\Delta\epsilon_\ell\right]\right\} \\ \epsilon_\ell &= V_c(R_B) + \frac{\hbar^2}{2\mu R_B^2}\,\ell(\ell+1), \\ R_B &= r_{oB}(A_1^{1/3} + A_2^{1/3}) + \Delta R_B. \end{aligned} \qquad (5\text{-}2)$$

where r_{oB} = 1.35 fm and ΔR_B = 0.5 fm after Wilczynski[28]. $\Delta\varepsilon_\ell$ is related to the curvature of the outer barrier made by the total potential V_ℓ composed of the Coulomb, centrifugal and nuclear force,

$$\Delta\varepsilon_\ell = \frac{1}{2\pi}\sqrt{\frac{\hbar^2}{\mu}\left|\frac{\partial^2 V_\ell}{\partial R^2}\right|_{R_B}} \tag{5-3}$$

where R_B should be determined by the condition,

$$\frac{\partial V_\ell}{\partial R}\Big|_{R_B} = 0 \tag{5-4}$$

We, however, assume that R_B thus determined would be approximately equal to that given in Eq. (5-2), and use Eq. (5-4) for the purpose of eliminating the depth of the nuclear attractive potential of the Saxon-Woods form, where the range parameter is assumed to be the first term of the expression for R_B in Eq. (5-2) and the diffuseness parameter is assumed to be equal to the second term ΔR_B. The summation $\int$ is made over all the possible two-body mass partitions, over all the possible energy distributions among the fragments and relative motion, and over all the possible angular momentum couplings.

$$\begin{aligned} &E_1^* + E_2^* + \varepsilon_{\ell} + Q_{12} = E_{c.m.} + Q_{inc.}, \\ &\vec{I}_1 + \vec{I}_2 + \vec{\ell} = \vec{J} \le \vec{J}_g \end{aligned} \tag{5-5}$$

where E_1^* and E_2^* are the excitation energies of the fragments, and Q_{12} and $Q_{inc.}$ are the reaction Q-values of the outgoing and incident channels. I_1 and I_2 are spins of the fragments, and J_g is the grazing spin of the incident channel.

We have used known discrete excited levels of the outgoing fragments as far as available, and after that, we have employed the level density formula for the continuum region,

$$\rho(I,E) = \frac{\hbar^3(2I+1)}{12\sqrt{\mathcal{J}}}\, e^{-\frac{I(I+1)}{2\sigma^2}}\, \sqrt{a}\; \mathcal{J}^{-3/2}\; \frac{e^{2\sqrt{aU}}}{(U+t)^2} \tag{5-6}$$

$$U = at^2 - t \equiv E - \Delta + 70/A,$$

$$\sigma^2 = \frac{\mathcal{J}}{\hbar^2}\sqrt{\frac{U+t}{a}}\,, \quad \mathcal{J} = 0.7\,\mathcal{J}_{rigid},$$

$$\mathcal{J}_{rigid} = \frac{2}{5}\,A.M.R^2, \quad R = 1.5\,A^{1/3},$$

$$a = 0.127.A,$$

where the values of the parameters are taken from Gadioli and Zetta who made a systematic study of level densities in light nuclei $A < 70$ [29]. The gap energies are those by Gilbert and Cameron[30] and those calculated from the empirical formula $12/\sqrt{A}$ [31].

Fig.10 shows the calculated numbers of open channels as a function of the grazing angular momenta for the $^{12}C + ^{12}C$ and $^{14}C + ^{14}C$ incident channels, because we are interested in higher partial waves between l_{cr} and l_g. What is remarkable here is that there exist minima in the total numbers of open channels at spins 16 and 22 respectively, as expected from Fig.9. In the $^{12}C + ^{12}C$ system J_{bend}, where the fusion cross section bends, is observed at about $10 \sim 12$. Thus around the minimum point of the total number of open channels, incident fluxes of the grazing partial waves do not go into compound nucleus formation but are carried away by the very small number of open channels available. Some of these channels couple strongly to the elastic channel, i.e., the inelastic channels to the collective excitations. In this situation, each strongly coupled channel should display its own characteristic energy dependence, such as barrier penetration effect, or even potential resonances, without being smeared out by other reaction channels. This just corresponds to what is observed in $^{12}C + ^{12}C$ scattering.

Before proceeding to a systematic study, it is better to understand the reason why such a minimum exists in the number of open channels. Fig.10 shows also the contribution from each mass partition for several dominant ones, i.e., those from nucleon -, α-channels and so on. At low spins and hence low energies, nucleon-and α-channels dominate. As is well known, the compound nucleus decays through these channels. But they decrease as the spin increases, because they cannot carry away the high angular momenta brought in by the heavy ion incident channel. On the other hand, inelastic and nucleon-transfer channels (also α-transfer channel in the $^{12}C + ^{12}C$ system) become activated at somewhat higher energies due to their reaction Q-values. Thus before such reaction channels, which can carry away large angular momentum, are effectively open, there exists a minimum in the total number of open channels. This can be considered to be a general feature of the cases with incident channels of stable heavy ions with symmetric or quasi-symmetric mass combinations. For the sake of comparison an example of a normal situation is shown in Fig.11, together with the previous case. The number of open channels in the $^{12}C + ^{12}C$ system has been calculated as a function of J_{cr}, i.e., along the limit of strong absorption into compound nucleus formation. There does not exist any minimum in the total number of open channels. In this case the α-channel still continue to contribute dominantly at higher energies and even the nucleon-channel contributes appreciably.

We have made a systematic study of the total number of open channels in all the possible combinations of even-even Carbon and Oxygen isotopes. Fig.12 shows calculated results of the total number of open channels divided by the incident grazing flux (N/μ), i.e., the total number of open channels which on the average is available for the unit incident flux (1 mb). First it is very striking that all these systems have minima at high grazing spins, although minimum values are different from each other. This means that a surface transparency exists in these system at high energies. Next it is found that the $^{12}C + ^{12}C$ system is the extreme case, i.e., it has the smallest number of open channels over a wide range of grazing spins. The $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$ systems have also very small minimum values. This is consistent with the prominent resonant behavior recently observed in these systems [20,32]. In addition it is interesting to note that the $^{12}C + ^{14}C$ and $^{14}C + ^{14}C$ systems have strikingly small minimum values comparable to those for the $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$ systems, although these systems include non-α nuclei. These systems can be expected to have enough transparency to allow prominent resonances to show up at high grazing spins and hence at high energies. In order to see whether molecular type resonances are expected or not, the band crossing diagram is shown in Fig.13 for the $^{14}C + ^{14}C$ system as an example. The aligned bands of the 3^- single (6.73 MeV) and mutual (13.46 MeV) excitations etc. cross the elastic band successively. The bending spin value of the fusion cross section J_{bend} is estimated to be 14, indicated by an arrow, and the minimum spin value of the number of open channels has been calculated to be 22, indicated by another arrow in the Figure. It is seen that the band crossing region and the surface transparent region overlap with each other. Thus we can surely expect to observe molecular type resonances at high energies in the $^{14}C + ^{14}C$ system.

6. DISCUSSION AND CONCLUSIONS

As discussed in § 2 an important quantity for molecular resonances is the crossing spin J_{cross} where an inelastic aligned band crosses the elastic molecular band. Another important factor is a transparency in the interaction between heavy ions, whose existence can be discussed qualitatively by two spin values, i.e., bending spin J_{bend} and minimum spin J_{min} where the fusion cross section undergoes bending and the number of open channels is a minimum. In Fig.14 these three types of important spin values are shown for all the possible combinations of even-even Carbon and Oxygen isotopes. As for J_{cross}, the lowest excited states with spins 2^+, 3^-, 4^+ are taken into account for each heavy ion, most of which are known to be collective states and to be excited strongly in scattering process. Values of J_{bend} are those estimated by assuming the

"statistical yrast line" proposed by Lee et al.[23]. J_{min}'s are those given in Fig.12 in the previous section.

In the $^{12}C + ^{12}C$, $^{14}C + ^{14}C$, and $^{16}O + ^{16}O$ systems band crossing points fall into the transparent region, while in the $^{18}O + ^{18}O$ system they do not. In $^{12}C + ^{14}C$, $^{12}C + ^{16}O$, and $^{14}C + ^{16}O$ they also fall in the transparent region, but in $^{14}C + ^{18}O$ and $^{16}O + ^{18}O$ like the $^{18}O + ^{18}O$ system, most of them do not fall in the region. The $^{12}C + ^{18}O$ and $^{12}C + ^{20}Ne$ systems are intermediate between above two cases. This qualitative classification seems to correspond well to recent experiments on several combinations of Carbon and Oxygen isotopes, which were reported by Freeman [33]. Experimental data on the interesting system $^{14}C + ^{14}C$ is still missing. Measurements on excitation functions for the elastic and inelastic scattering are strongly desirable as well as those of the $^{12}C + ^{14}C$ and $^{14}C + ^{16}O$ system at high energies in order to check the present prediction.

We conclude that there exists a "molecular resonance region" at high energies with high spin in several combinations of light heavy ions. The molecular resonance region is fairly well defined by the overlapping between the band crossing and transparent regions, and there several molecular configurations couple with each other, without suffering strong absorption due to other degrees of freedom.

It is interesting to extend the present type of study to heavier systems and also interesting to derive quantiatively energy - and angular - momentum-dependence of the imaginary part of optical potential between heavy ions.

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Note added in proof at the Conference : The author was informed about an existence of experimental data on the $^{14}C + ^{14}C$ system recently measured at Munich and at Los Alamos. Eberhardt reported the excitation functions of the elastic and $3^- \times 3^-$ mutual excitation inelastic scattering, while Cindro did the elastic excitation function. Gross structure in the elastic excitation function and resonances in the inelastic cross section were observed similar to those in the $^{16}O + ^{16}O$ system though with certain differences. These observed phenomena seem to be in good agreement with the prediction made in this report.

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31. A.Bohr and B.Mottelson, "Nuclear Structure I" (North Holland, Amsterdam 1969), p. 169.
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33. R.M.Freeman, invited talk in the present Conference.

Figure Captions

Fig.1 Elastic molecular bands in the $^{16}O + ^{16}O$ system calculated microscopically by T.Ando et al.[13]

Fig.2 Schematic diagram of Band Crossing.

Fig.3 Band Crossing Diagram for the $^{12}C + ^{12}C$ system with 2^+ single and mutual excitations.

Fig.4 Comparison of calculated results with the experimental data on the inelastic scattering. The solid lines shows the calculated cross sections and the dotted line the experimental ones.

Fig.5 Band Crossing Diagram for the $^{16}O + ^{16}O$ system.

Fig.6 Comparison of calculated 3^- inelastic cross sections with the γ-ray yields measured by Kolata et al.[20]

Fig.7 Comparison of calculated fusion and elastic cross sections with the experimental ones.

Fig.8 Schematic diagram of fusion reaction and surface transparency. Relations are given between the formula of Glas-Mosel[8] and Lee et al.[24].

Fig.9 Several typical effective barriers are shown for the $^{12}C + ^{12}C$ system, together with observed resonances. Above spin 12, most effective barriers are higher than that for the $^{12}C + ^{12}C$ entrance channel.

Fig.10. Numbers of open channels are shown as functions of grazing angular momentum for the $^{12}C + ^{12}C$ and $^{14}C + ^{14}C$ systems.

Fig.11. Number of open channels as a function of the "statistical yrast line" is compared with that as a function of grazing angular momentum.

Fig.12. Numbers of open channels divided by the incident flux are shown for all the possible combinations of even-even Carbon and Oxygen isotopes, together with the $^{12}C + ^{20}Ne$ case.

Fig.13. Band Crossing Diagram for the $^{14}C + ^{14}C$ system. The band head energy is assumed to be 0.0 MeV. Thick solid line is the elastic molecular band.

Fig.14 Three types of important spins J_{cross}, J_{bend} and $J_{min.}$ are shown for all the combinations of even-even Carbon and Oxygen isotopes.

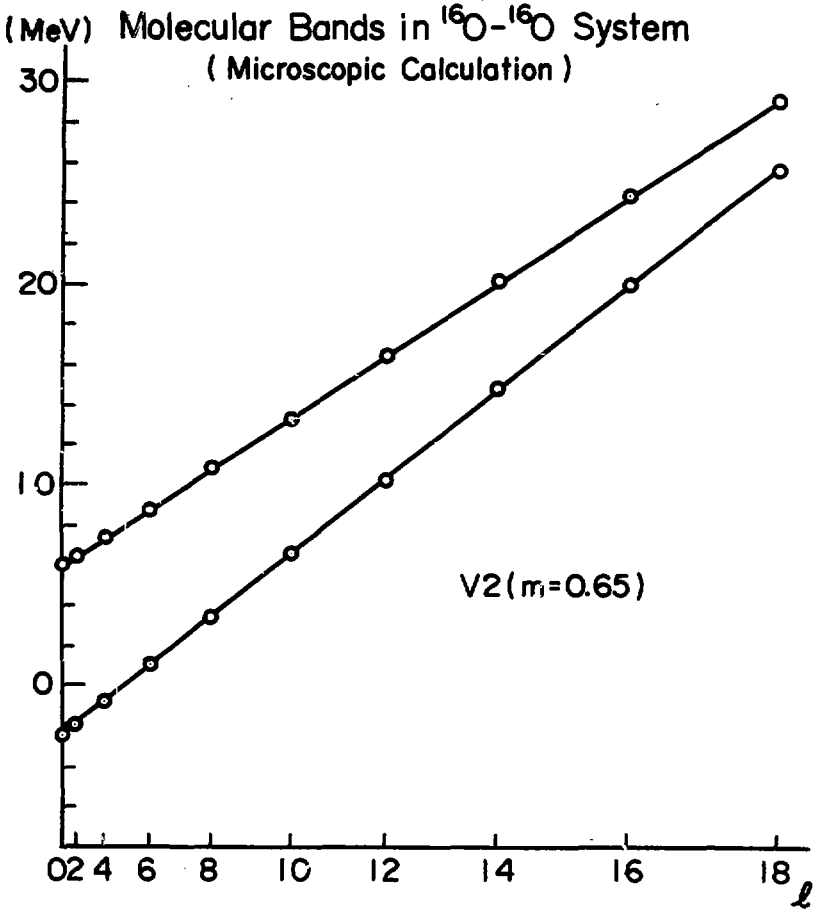
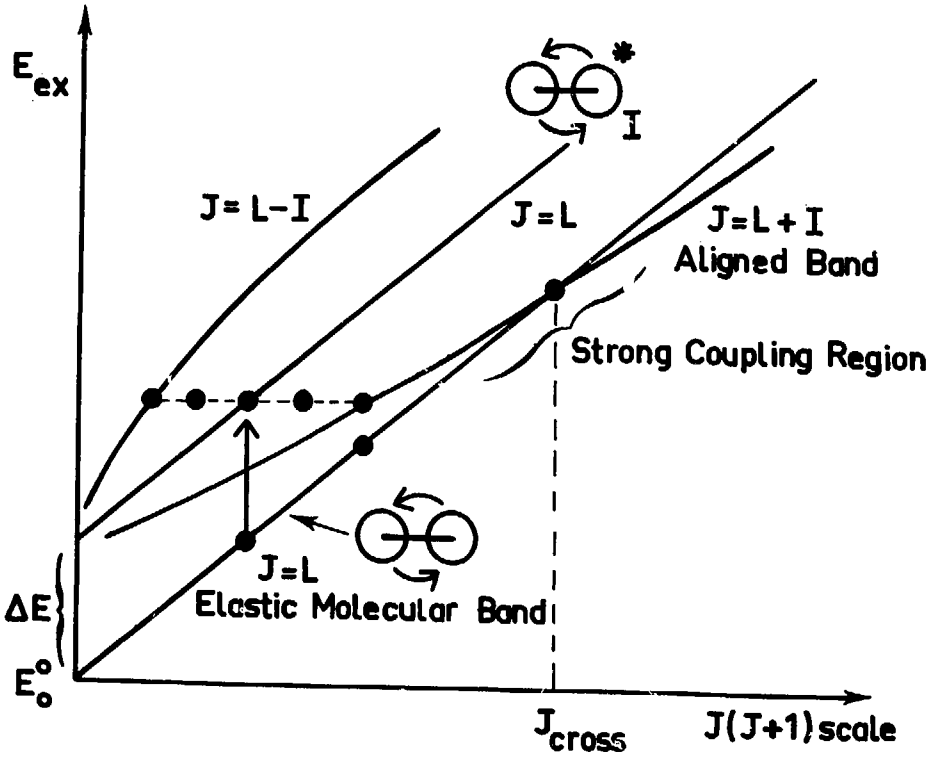

(MeV) Molecular Bands in ^{16}O-^{16}O System
(Microscopic Calculation)
30
20
10
0
V2(m=0.65)
0 2 4 6 8 10 12 14 16 18
l

Fig. 1

Fig. 2


E_ex
J = L − I
J = L
J = L + I
Aligned Band
Strong Coupling Region
I
*
J = L
Elastic Molecular Band
ΔE
E°o
J_cross
J(J+1) scale

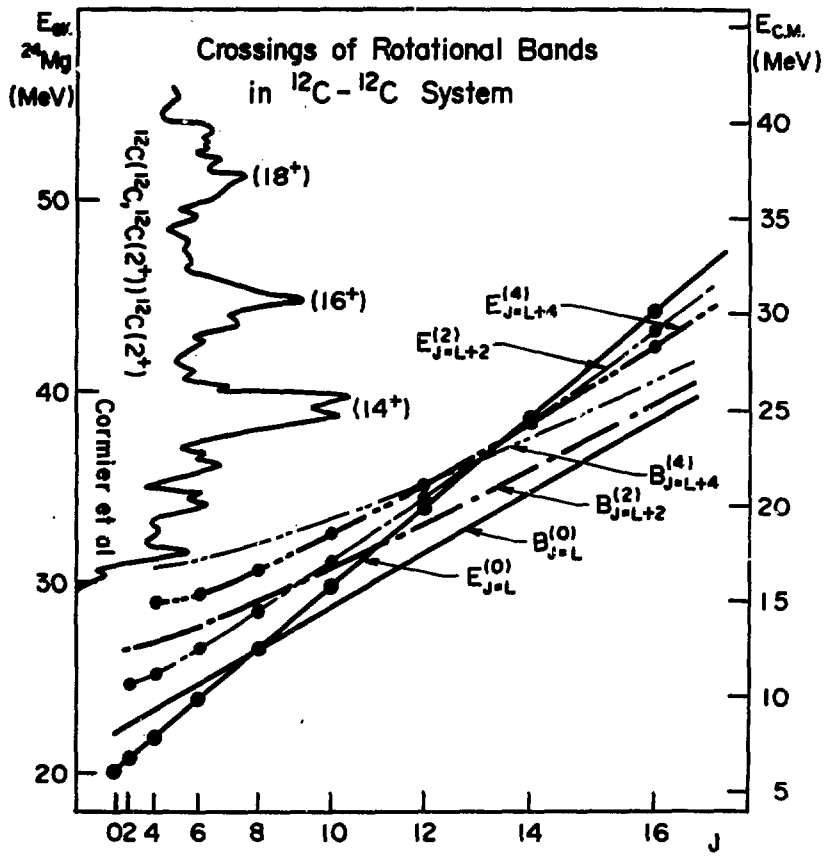

Crossings of Rotational Bands
in $^{12}C-^{12}C$ System
$E_{ex.}$ ^{24}Mg (MeV)
$E_{C.M.}$ (MeV)
$^{12}C(^{12}C,^{12}C(2^+)^{12}C(2^+)$
Cormier et al
(18^+)
(16^+)
(14^+)
$E^{(4)}_{J=L+4}$
$E^{(2)}_{J=L+2}$
$B^{(4)}_{J=L+4}$
$B^{(2)}_{J=L+2}$
$B^{(0)}_{J=L}$
$E^{(0)}_{J=L}$
J

Fig. 3

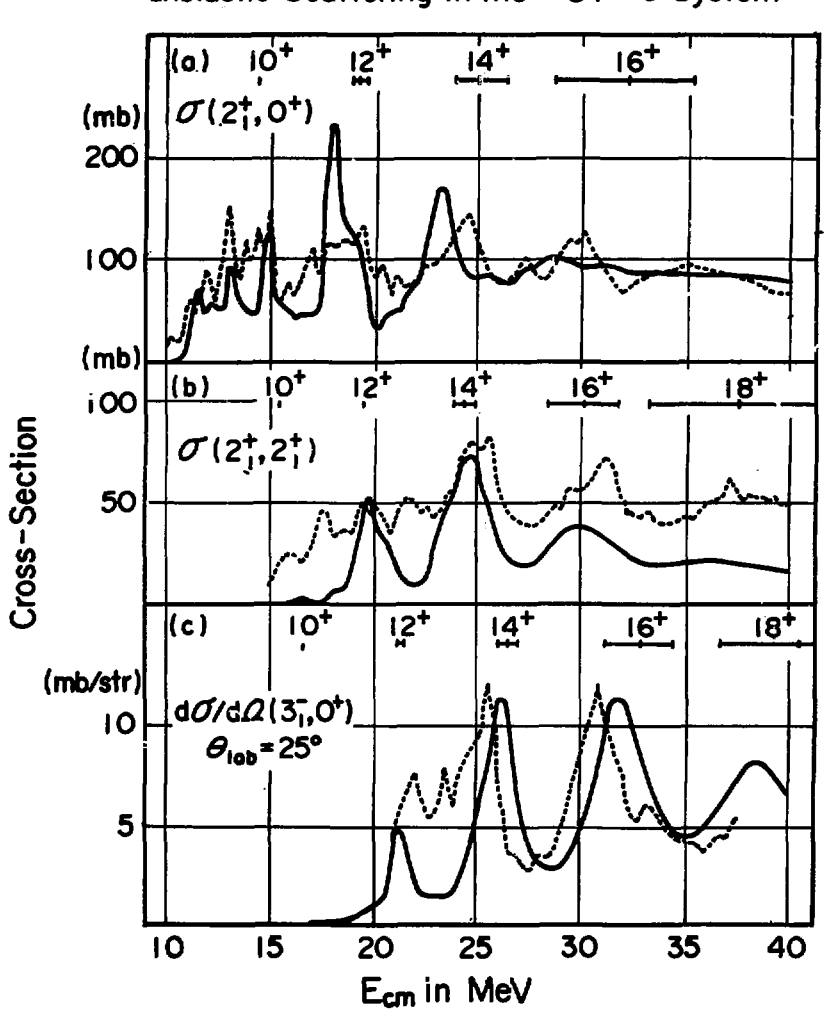
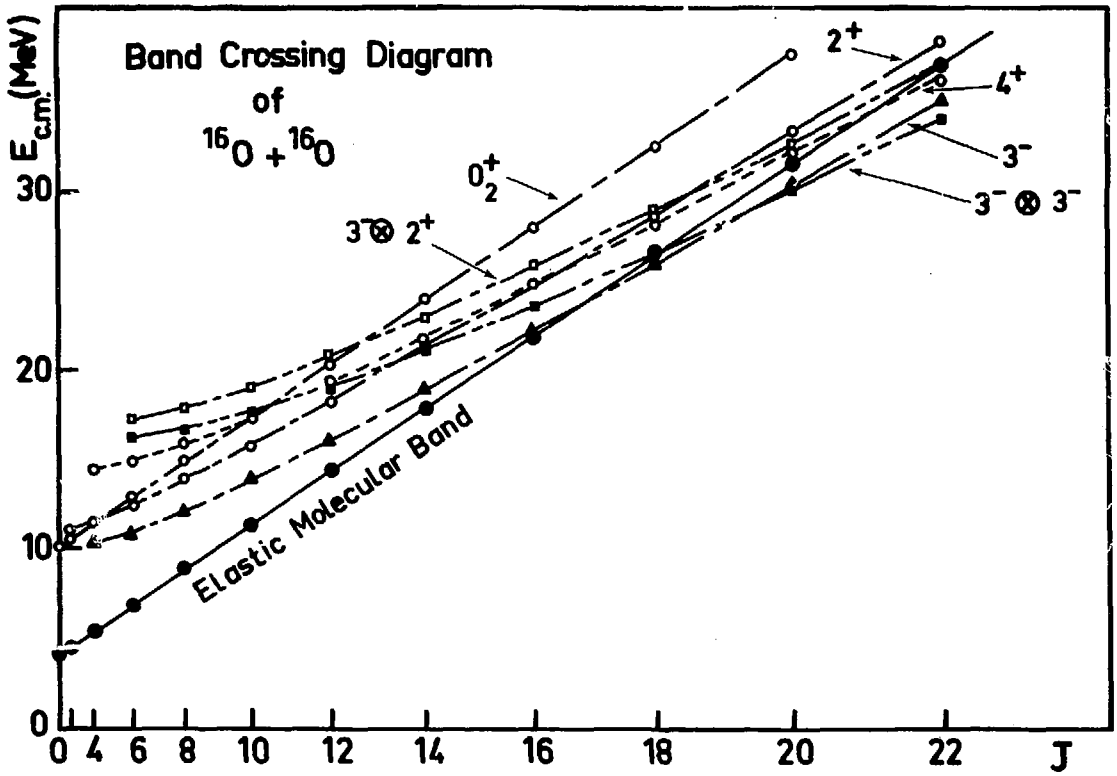

Inelastic Scattering in the $^{12}C+^{12}C$ System
(a) 10^+ 12^+ 14^+ 16^+
(mb)
$\sigma(2_1^+, 0^+)$
200
100
(mb)
(b) 10^+ 12^+ 14^+ 16^+ 18^+
100
$\sigma(2_1^+, 2_1^+)$
50
Cross-Section
(c) 10^+ 12^+ 14^+ 16^+ 18^+
(mb/str)
$d\sigma/d\Omega(3_1^-, 0^+)$
$\theta_{lab} = 25°$
10
5
10 15 20 25 30 35 40
E_{cm} in MeV

Fig. 4

Fig. 5


Band Crossing Diagram
of
$^{16}O + ^{16}O$
$E_{c.m.}$ (MeV)
30
20
10
0
0 4 6 8 10 12 14 16 18 20 22
J
0_2^+
$3^- \otimes 2^+$
2^+
4^+
3^-
$3^- \otimes 3^-$
Elastic Molecular Band

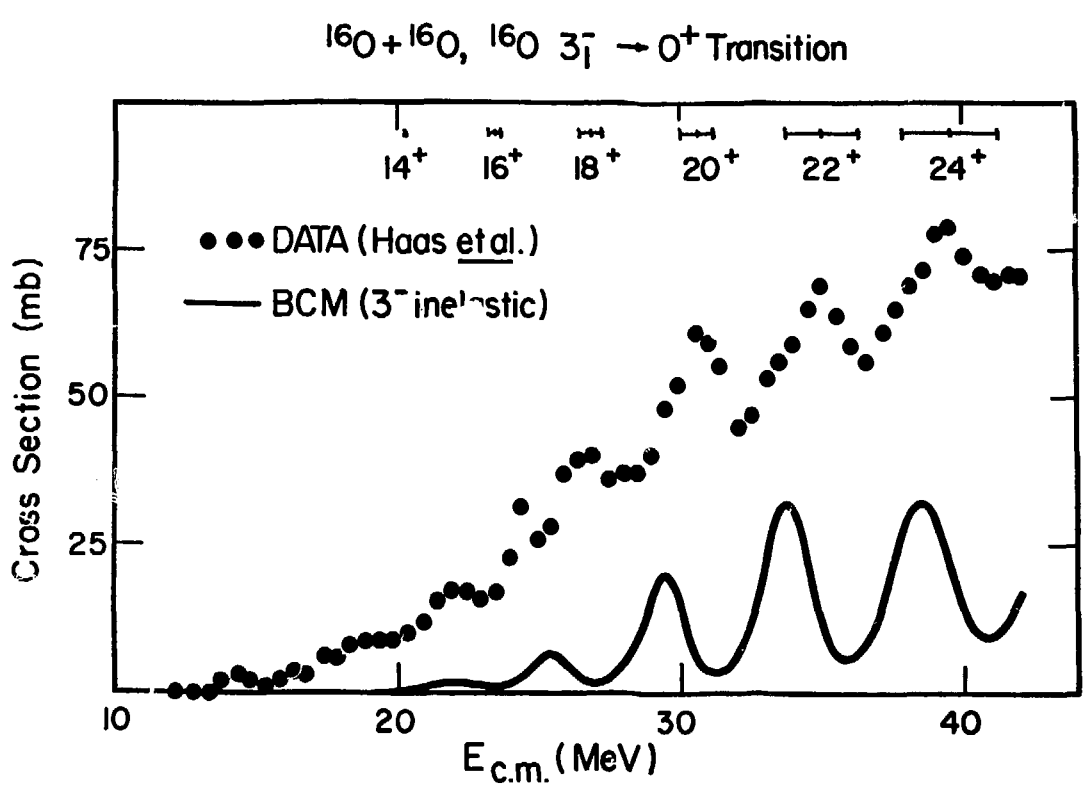

$^{16}O + ^{16}O$, ^{16}O $3_1^- \rightarrow 0^+$ Transition
14^+
16^+
18^+
20^+
22^+
24^+
DATA (Haas et al.)
BCM (3^- inelastic)
Cross Section (mb)
75
50
25
10
20
30
40
$E_{c.m.}$ (MeV)

Fig. 6

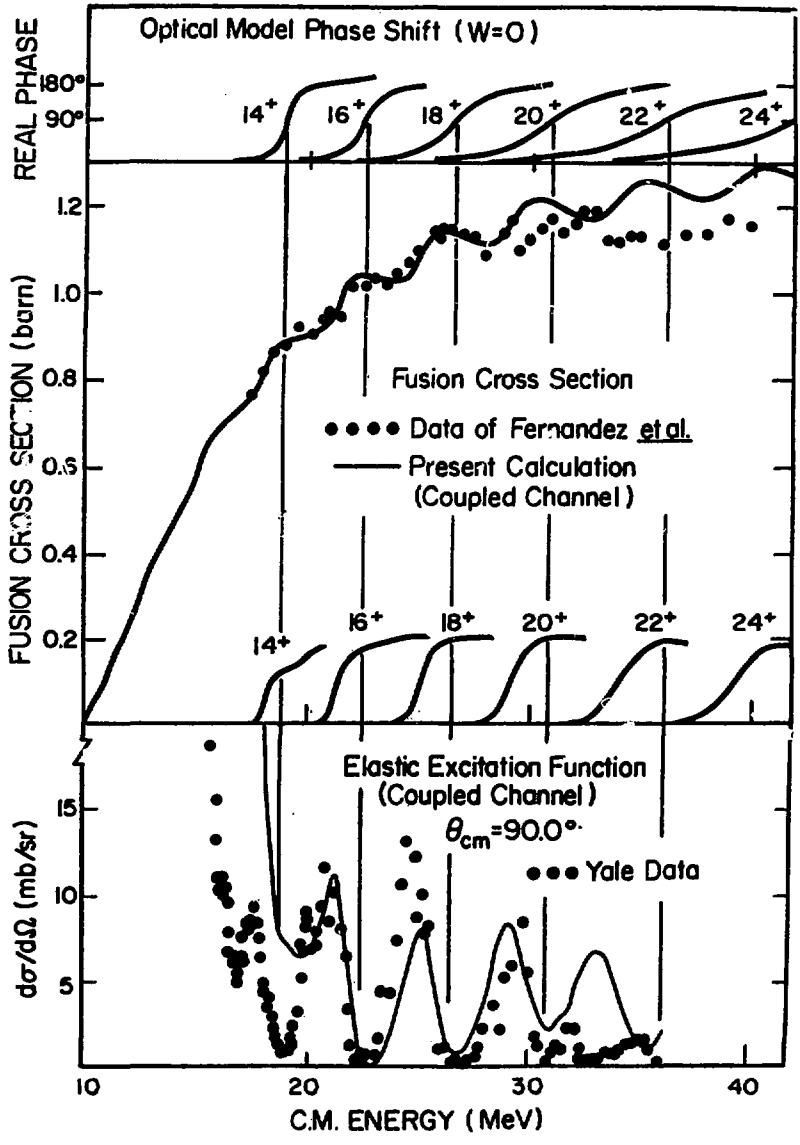

Optical Model Phase Shift (W=0)
REAL PHASE
180°
90°
14+
16+
18+
20+
22+
24+
FUSION CROSS SECTION (barn)
1.2
1.0
0.8
0.6
0.4
0.2
Fusion Cross Section
Data of Fernandez et al.
Present Calculation
(Coupled Channel)
Elastic Excitation Function
(Coupled Channel)
θcm=90.0°
Yale Data
dσ/dΩ (mb/sr)
15
10
5
10
20
30
40
C.M. ENERGY (MeV)

Fig. 7

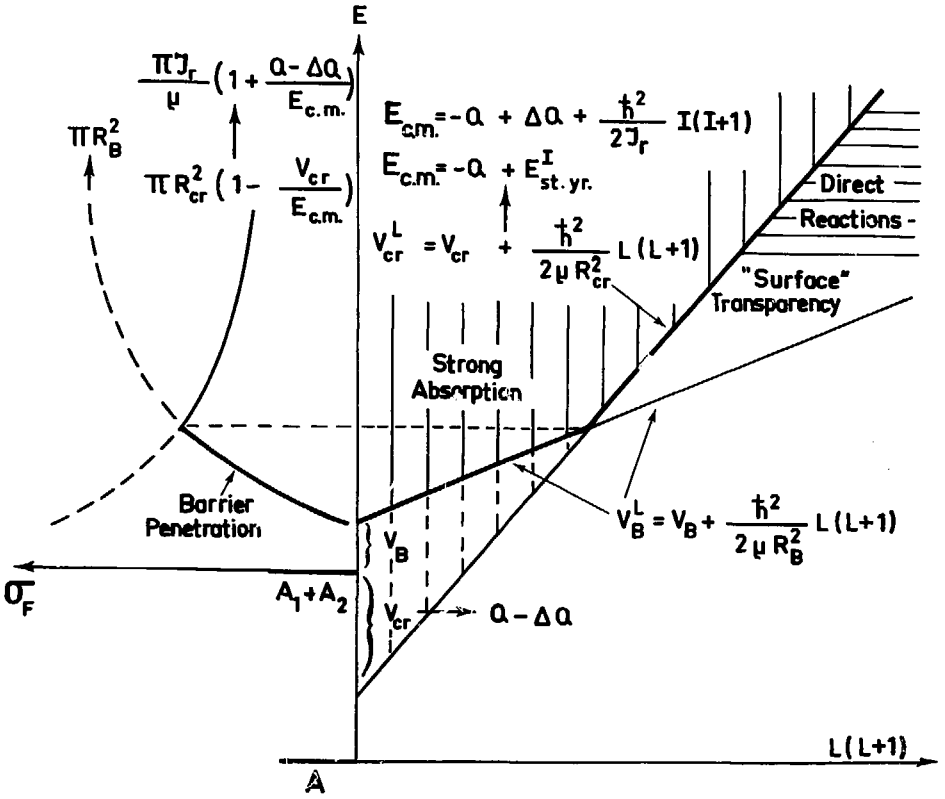

E
$\frac{\pi\hbar^2}{\mu}\left(1+\frac{Q-\Delta Q}{E_{c.m.}}\right)$
πR_B^2
$\pi R_{cr}^2\left(1-\frac{V_{cr}}{E_{c.m.}}\right)$
$E_{c.m.}=-Q+\Delta Q+\frac{\hbar^2}{2\mathcal{J}_r}I(I+1)$
$E_{c.m.}=-Q+E^I_{st.yr.}$
$V^L_{cr}=V_{cr}+\frac{\hbar^2}{2\mu R^2_{cr}}L(L+1)$
Direct
Reactions
"Surface"
Transparency
Strong
Absorption
Barrier
Penetration
$V^L_B=V_B+\frac{\hbar^2}{2\mu R^2_B}L(L+1)$
V_B
σ_F
A_1+A_2
V_{cr}
$Q-\Delta Q$
L(L+1)
A

Fig. 8

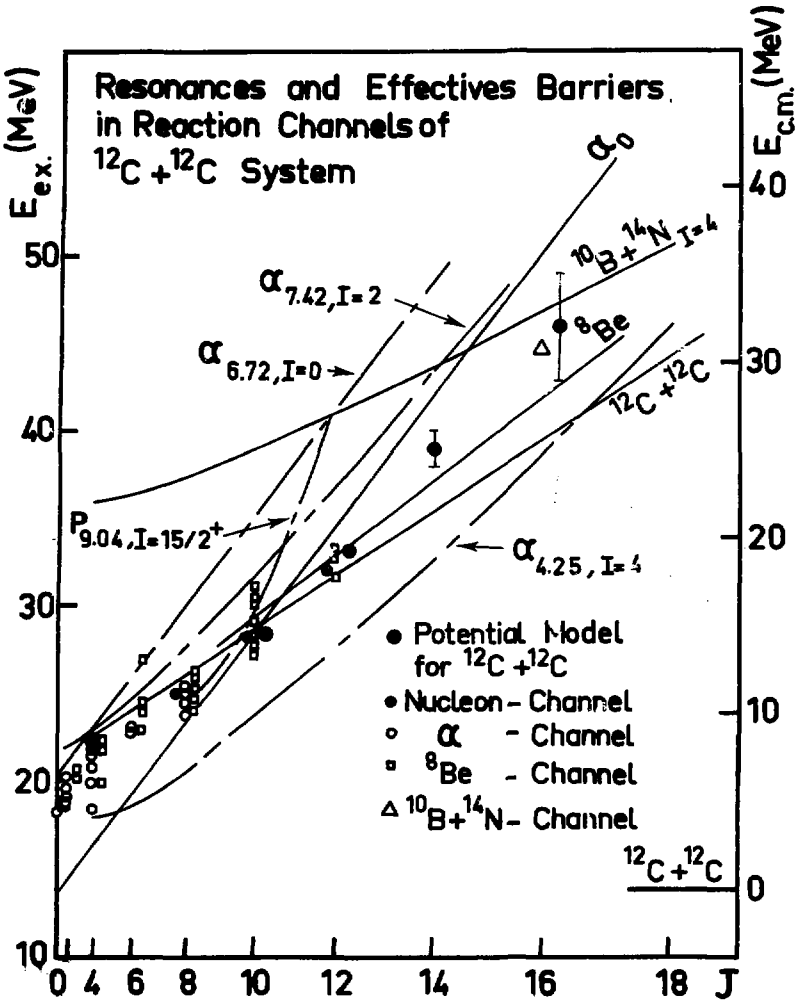

Resonances and Effectives Barriers
in Reaction Channels of
$^{12}C + ^{12}C$ System
$E_{ex.}$ (MeV)
$E_{c.m.}$ (MeV)
α_0
$^{10}B + ^{14}N$ I=4
$\alpha_{7.42, I=2}$
^{8}Be
$\alpha_{6.72, I=0}$
$^{12}C + ^{12}C$
$P_{9.04, I=15/2^+}$
$\alpha_{4.25, I=4}$
Potential Model for $^{12}C + ^{12}C$
Nucleon - Channel
α - Channel
^{8}Be - Channel
$^{10}B + ^{14}N$ - Channel
$^{12}C + ^{12}C$
J

Fig. 9

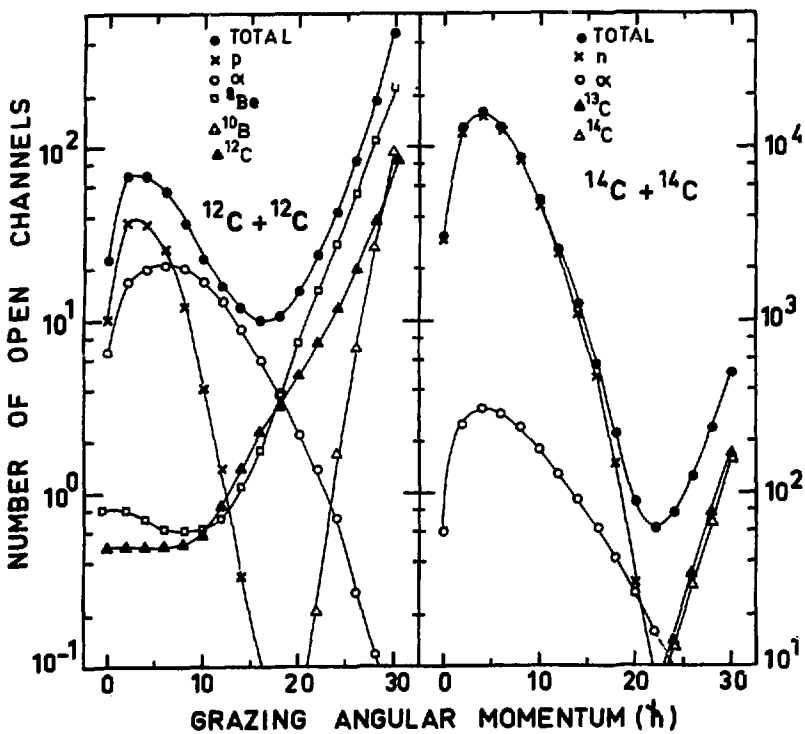

TOTAL
p
α
⁸Be
¹⁰B
¹²C
¹²C + ¹²C
TOTAL
n
α
¹³C
¹⁴C
¹⁴C + ¹⁴C
NUMBER OF OPEN CHANNELS
GRAZING ANGULAR MOMENTUM (ħ)

Fig. 10

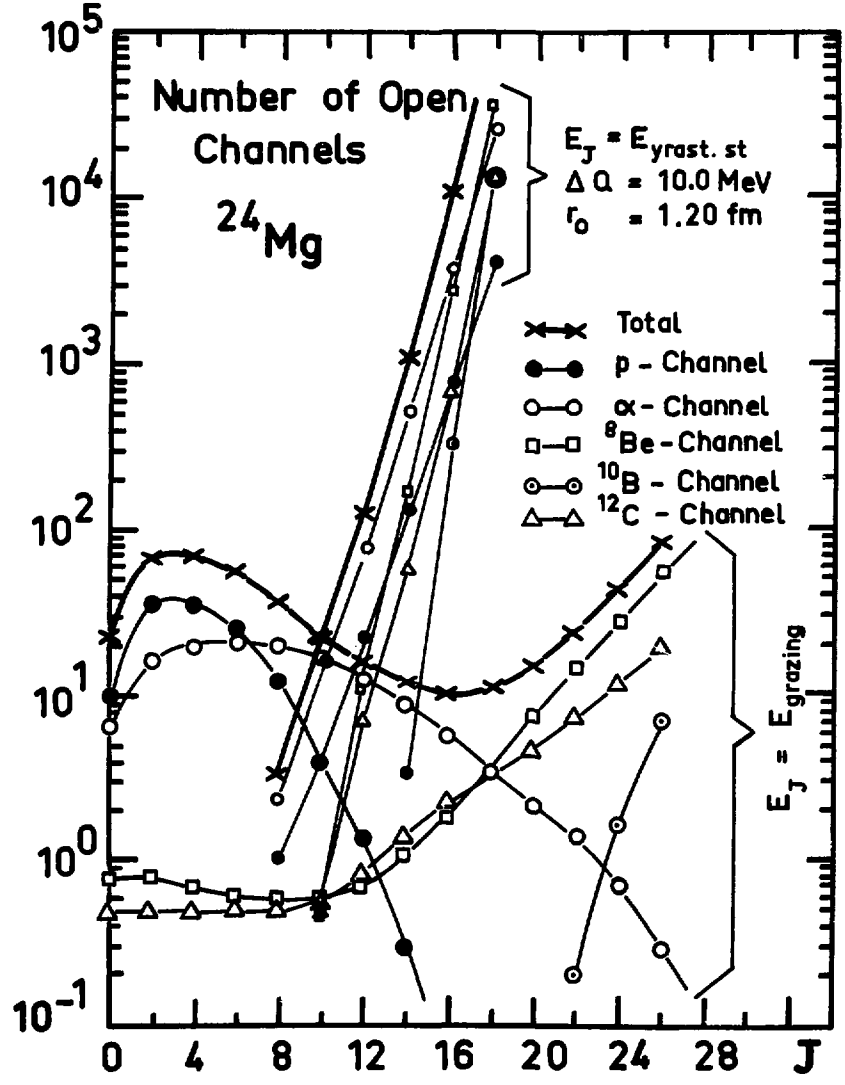

Number of Open Channels
^{24}Mg
$E_J = E_{yrast.\ st}$
ΔQ = 10.0 MeV
r_0 = 1.20 fm
Total
p - Channel
α - Channel
^{8}Be - Channel
^{10}B - Channel
^{12}C - Channel
$E_J = E_{grazing}$
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0
4
8
12
16
20
24
28
J

Fig. 11

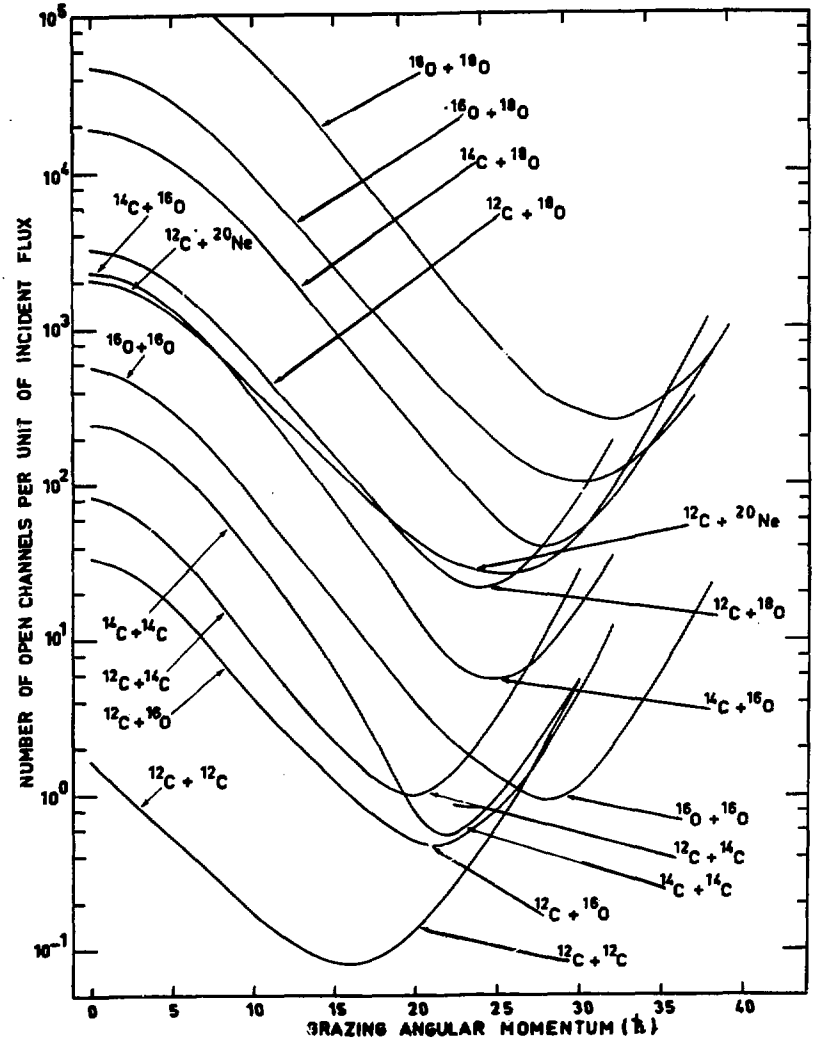

NUMBER OF OPEN CHANNELS PER UNIT OF INCIDENT FLUX
GRAZING ANGULAR MOMENTUM (ħ)
$^{16}O + ^{18}O$
$^{16}O + ^{18}O$
$^{14}C + ^{18}O$
$^{12}C + ^{18}O$
$^{14}C + ^{16}O$
$^{12}C + ^{20}Ne$
$^{16}O + ^{16}O$
$^{14}C + ^{14}C$
$^{12}C + ^{14}C$
$^{12}C + ^{16}O$
$^{12}C + ^{12}C$
$^{12}C + ^{20}Ne$
$^{12}C + ^{18}O$
$^{14}C + ^{16}O$
$^{16}O + ^{16}O$
$^{12}C + ^{14}C$
$^{14}C + ^{14}C$
$^{12}C + ^{16}O$
$^{12}C + ^{12}C$

Fig. 12

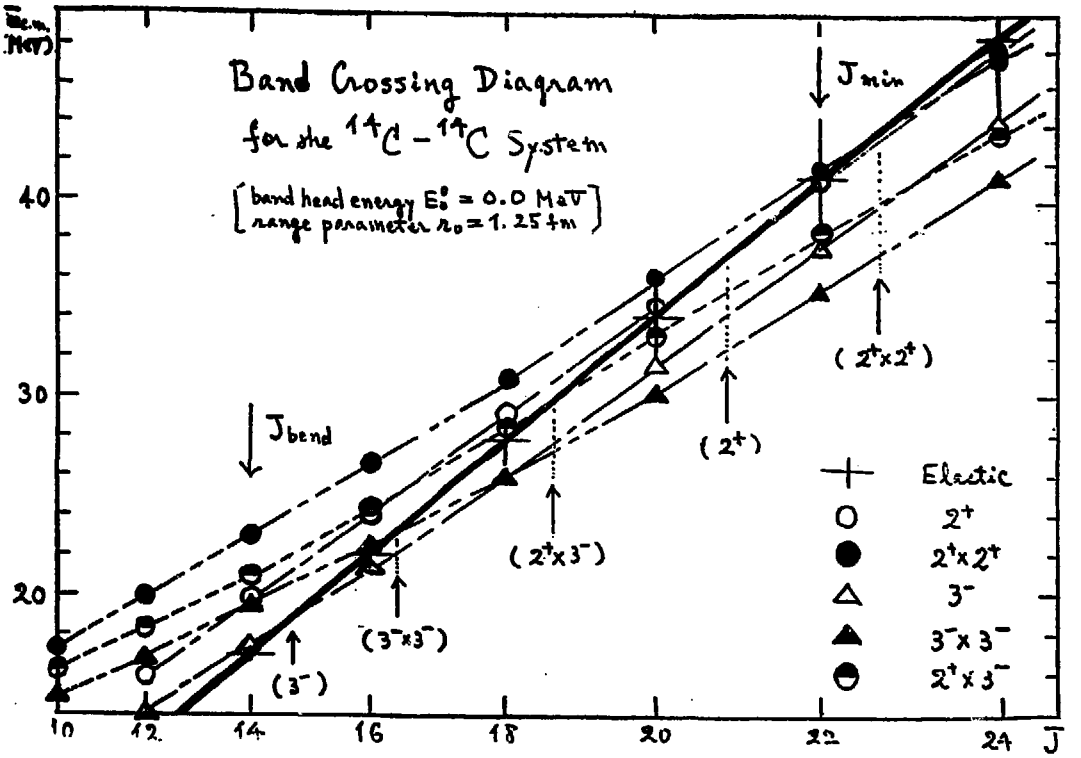

Band Crossing Diagram
for the $^{14}C - ^{14}C$ System
[band head energy $E_0^* = 0.0$ MeV
range parameter $r_0 = 1.25$ fm]
J_{min}
J_{bend}
(3^-)
$(3^-\times 3^-)$
$(2^+\times 3^-)$
(2^+)
$(2^+\times 2^+)$
Elastic
2^+
$2^+\times 2^+$
3^-
$3^-\times 3^-$
$2^+\times 3^-$
40
30
20
10
12
14
16
18
20
22
24
J

Fig. 13

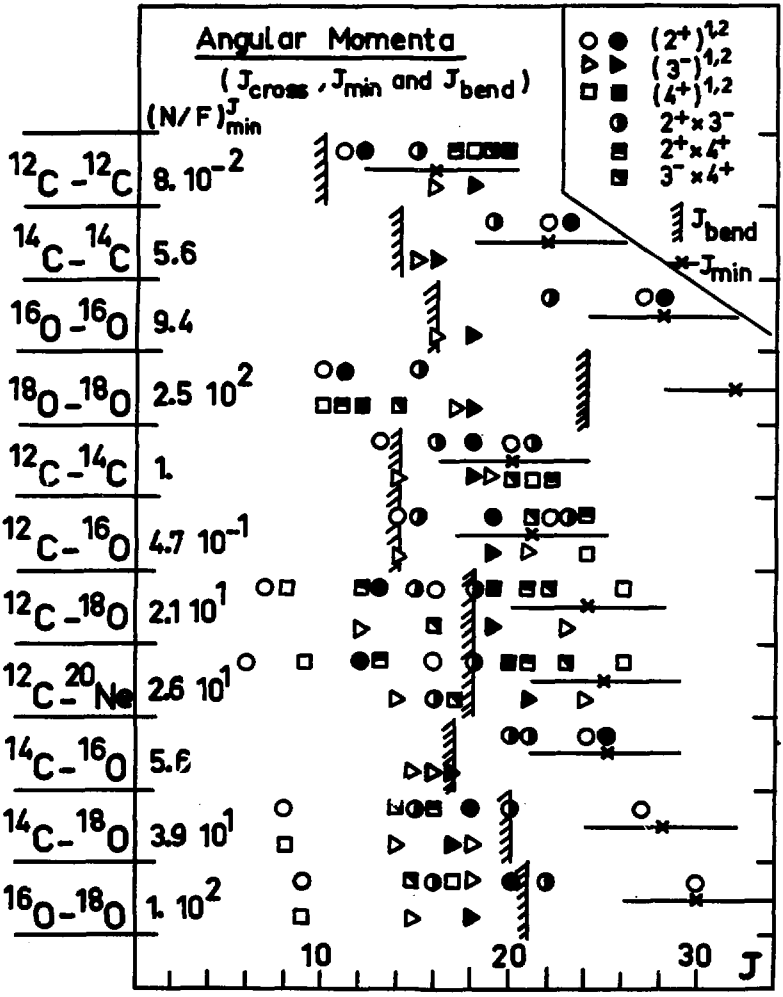

Angular Momenta
(J_{cross} , J_{min} and J_{bend})
$(N/F)^{J}_{min}$
$^{12}C-^{12}C$ 8. 10^{-2}
$^{14}C-^{14}C$ 5.6
$^{16}O-^{16}O$ 9.4
$^{18}O-^{18}O$ 2.5 10^{2}
$^{12}C-^{14}C$ 1.
$^{12}C-^{16}O$ 4.7 10^{-1}
$^{12}C-^{18}O$ 2.1 10^{1}
$^{12}C-^{20}Ne$ 2.6 10^{1}
$^{14}C-^{16}O$ 5.6
$^{14}C-^{18}O$ 3.9 10^{1}
$^{16}O-^{18}O$ 1. 10^{2}
$(2^+)^{1,2}$
$(3^-)^{1,2}$
$(4^+)^{1,2}$
$2^+ \times 3^-$
$2^+ \times 4^+$
$3^- \times 4^+$
J_{bend}
J_{min}
10
20
30
J

Fig. 14

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