INTERMEDIATE STRUCTURE IN LIGHT ION REACTIONS

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Résumé.- Une revue de la théorie et de l'expérimentation concernant la présence ou l'absence de la résonance et de la structure intermédiaire observées dans les sections efficaces de collision des ions légers est présentée.

Abstract.- A review of the theory and experiment regarding the presence and absence of the resonance and intermediate structure presented in the cross-sections for the collision of light ions is presented.

This paper will present a review of the intermediate structure and doorway states which have been discovered in the reactions induced by collision of the light ions $^{12}C + ^{12}C$ and ^{12}C and ^{16}O. An interpretation of the $^{12}C + ^{12}C$ data will be presented as well as arguments explaining the absence of intermediate structure in the interaction of other light ions. It is found that the model proposed by Imanishi and Nogami [1] provides a qualitative understanding of the data. This theory needs further development. A calculation of the total reaction cross-section is particularly required in response to the criticism that the potentials employed by Imanishi have imaginary terms which are too small. However as is pointed out below this does not necessarily mean that the resulting reaction cross-section will be too small because it is necessary to take into account the effects of the coupling of the incident channel to the other channels considered by Imanishi and Kondo, Matsuse and Abe [2] The reader is referred to several excellent review articles by Bromley [3], Cindro [4], Siemssen [5] and Stokstad [6] which I found to be very helpful in the preparation of this paper.

We begin with the $^{12}C + ^{12}C$ system which provides the best and nearly unique examples of resonant structure in the collision of light nuclei. Fig. 1

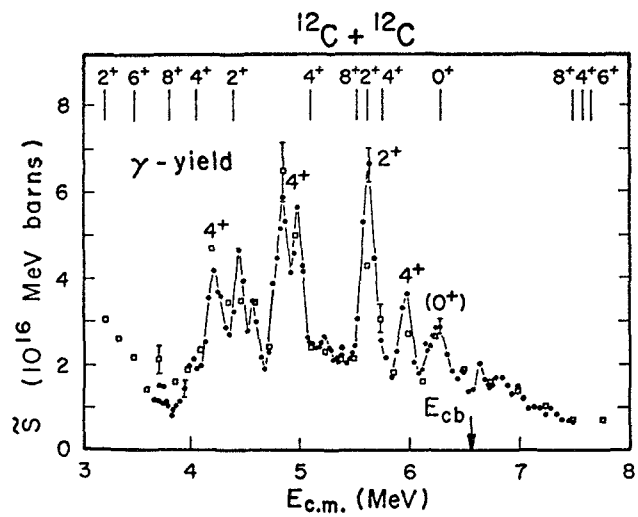

Fig.1 - The total gamma radiation yield in the $^{12}C + ^{12}C$ system. The levels at the top of the figure are those predicted by Kondo et al. $\tilde{S}$ is defined by

$$\sigma = \tilde{S}/E \exp\left[-(2\pi\eta + gE)\right] \text{ where}$$
$$\eta = Z_1 Z_2 e^2/\hbar v \text{ and } g = 1/3\ (mR^3/2Z_1Z_2)^{1/2}$$

shows the results of a measurement of the γ-yield in the $^{12}C + ^{12}C$ reaction as obtained and collected by Spinka et al. [7]. The ordinate is the cross-section divided by the Sommerfeld factor to remove the effects of the Coulomb barrier. This figure summarizes the experimental situation as of the time of the Maryland Conference. The three resonances between

5.5 and 6.5 MeV were first seen by the Chalk River group [8] in 1960 and 1961 while the resonances below were established considerably later by Patterson et al. [9] and by Stephens et al. [10]. The spins of a few of the levels had been determined. It is important to note that the widths are small. For example the 2^+ resonance at 5.6 MeV has a width of 130 keV while the 4^+ resonance at 6.0 MeV width is 100 keV. At the top of the figure are the positions of the resonances on the basis of the extended Imanishi model as calculated by Kondo et al. [2]. The predicted resonances in the region of 7 to 8 MeV have stimulated experimental measurements in this region by both the Saclay and Yale groups.Erb et al. [11] at Yale have looked at the angular distribution of the transitions to low lying states of ^{20}Ne while Basrak et al. [12,13] have used both this reaction and the reaction $^{12}C(^{12}C,p)^{23}Na$. Let us review the data of Erb et al. It will provide an example of the sort of analysis employed by most experimentalists. In fig. 2, the angle integrated cross-sections for transitions to the indicated low lying ^{20}Ne states are plotted. Particular attention should be paid to the sum of the cross-sections at the top of the figure. The sum is useful since it tends to average out "statistical" fluctuations although this method will point up the resonances only if there is a substantial branching ratio to most of the levels involved. There is considerable structure. The authors selected three of the anomalies at 7.71, 9.84, 10.59 MeV to examine as possible resonances because their angular distribution to the ground state of ^{20}Ne exhibited pure $[P_L(\cos\theta)]^2$ distributions (fig. 3). In Fig. 4 two of these are plotted; curve (a) for the 7.71 resonance is just $[P_4(\cos\theta)]^2$ given by the solid line while the 9.84 MeV resonance angular distribution fits the $[P_8(\cos\theta)]^2$. The resonance at 7.71 MeV with a width of 145 keV seems secure because of the strong correlations in the energy dependence, see fig. 2, for the four exit channels. The evidence is quite strong for the 9.84 MeV case where three of the four channels exhibit anomalies. The author did not list the 10.59 MeV case as a resonance. It showed anomalies in two of the four cross-sections.

The summed curve shows other anomalies. The Saclay group in an independent investigation has reported resonances at 7.50, 8.45 and 8.85 MeV. The anomalies which could be associated with the last two are

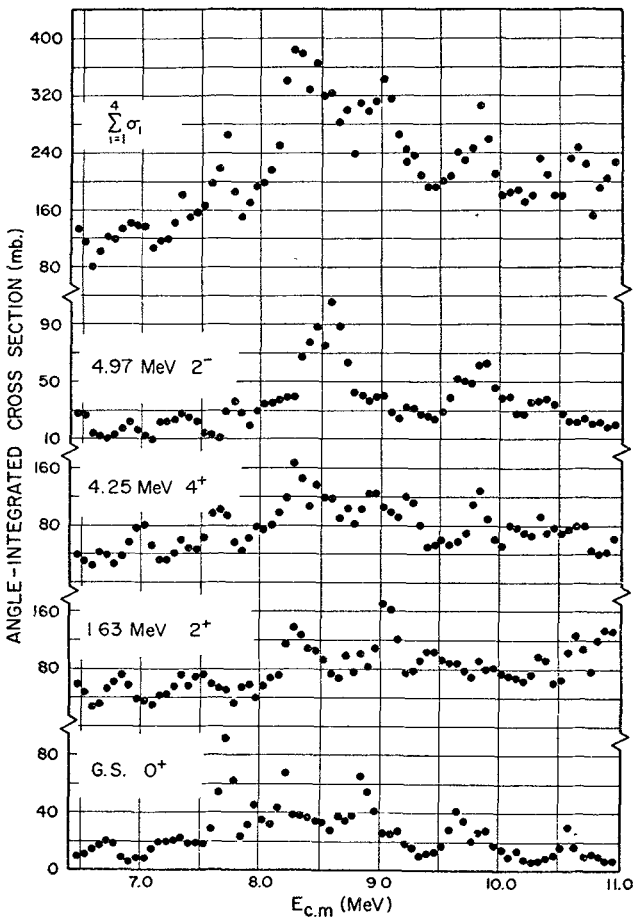

Fig. 2 - Angle integrated cross-sections as function of energy the $^{12}C(^{12}C,\alpha)$ reaction populating low-lying levels of ^{20}Ne.

present in the Yale data but the 7.5 resonance does not seem to be present. The Saclay group reports a minimum on the summed integrated cross-sections including the g.s., the 1.63, 4.25, 4.97 and 6.72 MeV excitation in ^{20}Ne.They also report a peak in the $^{12}C(^{12}C,p)^{23}Na$ reaction. They assign a spin of 6^+ to the 7.50 MeV anomaly, 6^+ for the resonance at 8.45 MeV, and 6^+ or 8^+ for the 8.85 MeV case. Clearly further work needs to be done before one can be sure of the reliability of the results reported. But it is apparent that there is considerable structure and that the widths are narrow.

Encouraged by the existence of the 4^+ resonance as predicted by Kondo et al., the Yale group has attempted to see if the other resonances, the 6^+ and 8^+, are present as well. These resonances would not make their appearance in the alpha particle data because of the barrier effects of the larger spin. They have instead looked at the γ-ray yield depopu-

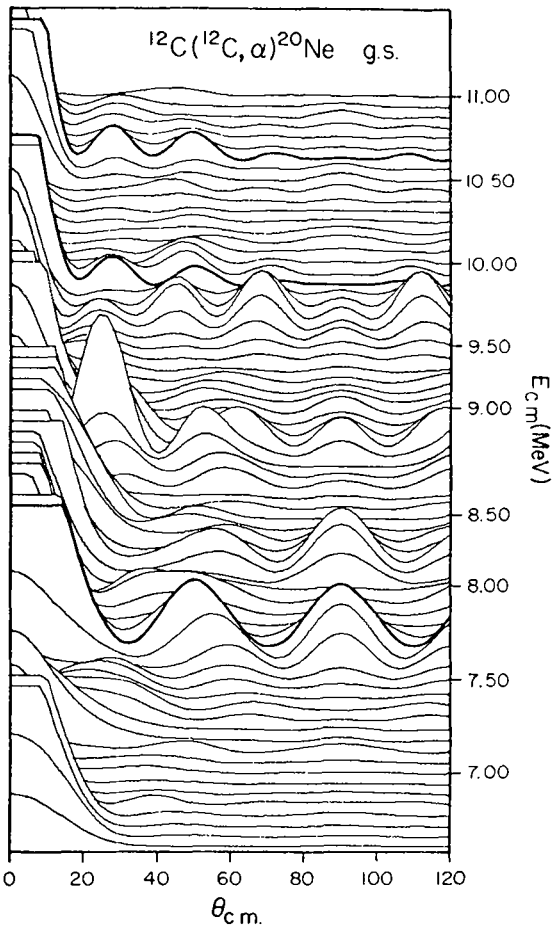

Fig. 3 - Legendre polynomial fits to the measured ground state $^{12}C(^{12}C,\alpha)^{20}Ne$ angular distribution. The cross-section scale is linear with a maximum of 25 mb/sr. Peaks rising above this value are shown as plateaus. The angular distributions of $E_{c.m.}$ = 7.71, 9.84 and 10.59 are drawn with wider lines.

lating the first excited state of ^{20}Ne, ^{23}Na, and ^{23}Mg. This sum reflects, according to the authors, most of the cross-section. The results are shown in Fig. 5. Note that the Coulomb barrier factor used is for a finite nucleus whereas that for Fig. 1 is for a point nucleus. The presence of the resonance at 7.71 keV is clear. But there is considerable additional structure between it and the Chalk River resonance at roughly 6.5 MeV which needs further investigation.

New information is also available in the region below the Chalk River resonances. The data presented in Fig. 1 below $E_{c.m.}$ = 4 MeV shows a strong rise which was of concern to the astrophysicists. It was very difficult to understand. Michaud and Vogt [14] proposed an "absorption under the barrier" mechanism

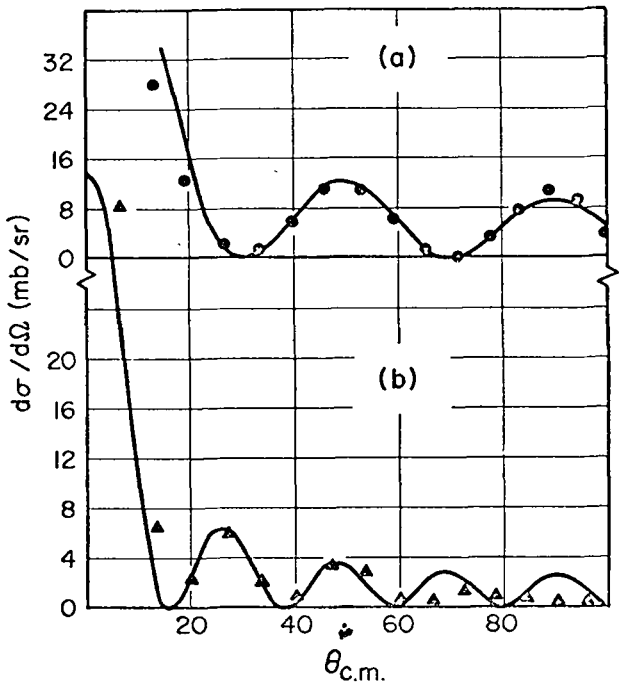

Fig. 4 - The $^{12}C(^{12}C,\alpha)^{20}Ne$ angular distributions are compared with arbitrarily normalized Legendre functions $[P_L(\cos\theta)]^2$ (a) at E = 7.71 MeV (L = 4) and (b) $E_{c.m.}$ = 9.84 MeV (L = 8).

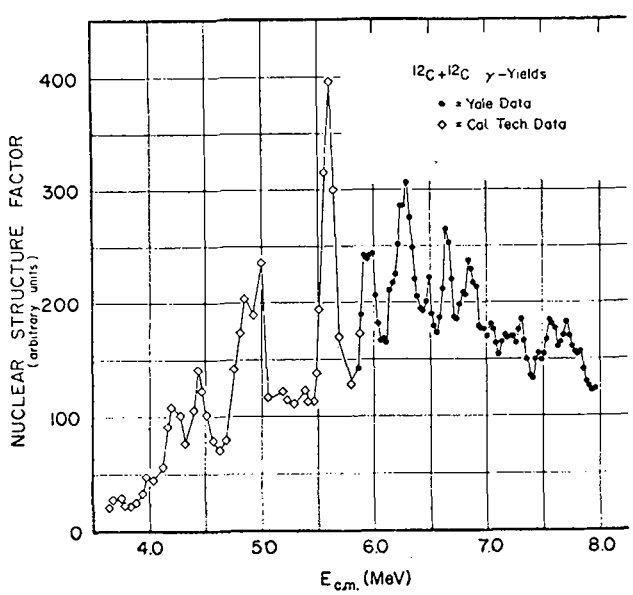

Fig. 5 - $^{12}C + ^{12}C$ gamma ray yield depopulating the first excited states of ^{20}Ne, ^{23}Na, and ^{23}Mg. The nuclear structure factor is defined by

$E\,\sigma(E)/\sum_{L=0}^{10}(2L+1)T_L$ where T_L are the penetrabilities evaluated at $R = 1.4\,(12^{1/3} + 12^{1/3})$ fermi (K. Erb, private communication).

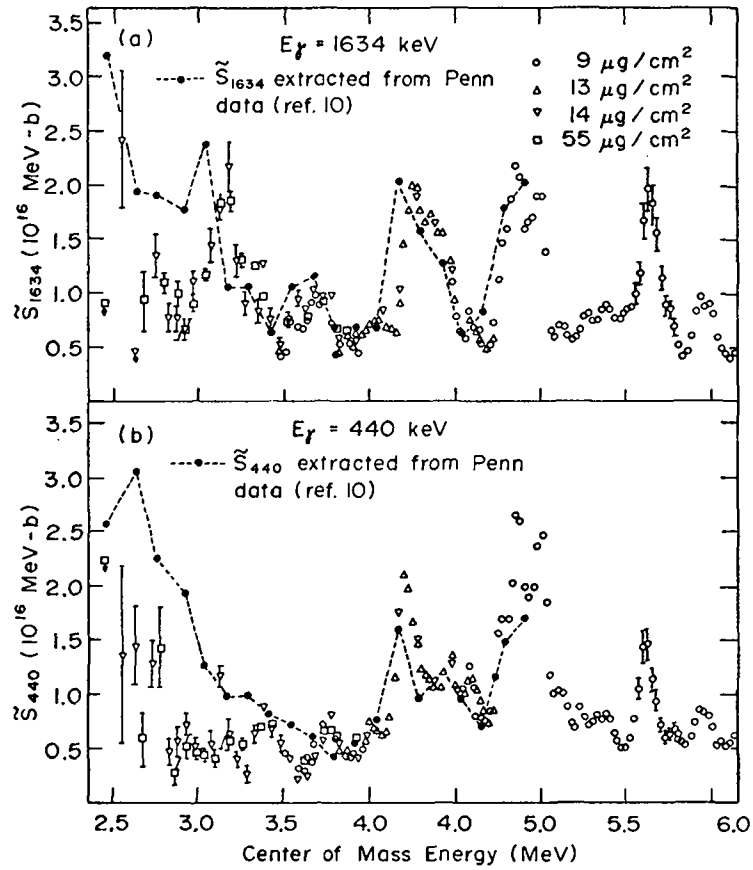

Fig. 6 - $^{12}C + ^{12}C$ gamma ray yield from first excited states of $^{20}Ne(E_\gamma = 1634$ keV) and $^{23}Na(E_\gamma = 440$ keV). The connected points are extracted from the Penn. data [10].

which leads to high fusion cross-sections at low energy. A group from Munster [15] has carefully examined this region by observing the gamma ray transitions from a large number of excited states in ^{20}Ne and ^{23}Na. They report the results for transitions from the first excited states in $^{20}Ne(E_\gamma = 1634$ keV) and $^{23}Na(E_\gamma = 440$ keV). Their results are presented in Fig. 6. The substantial difference from the original Pennsylvania data [16] below 3 MeV is apparent. The rise in the energy decreased turned out to be an artifact of that experiment which was of importance at low energy. This obviates the need for "under the barrier absorption". In addition considerable structure below that visible in Fig. 1 is apparent in that peaks are common to both the ^{20}Ne and ^{23}Na channels.

Resonances of high spin are also seen at considerably higher energies. In this energy domain there is a non-trivial difficulty of proving that the peaks are resonances. There are many cases for which peaks are fluctuations. One can usually eliminate these in view of the absence of correlated peaks in other channels - that is by showing that other channels do not exhibit anomalies at approximately the same energy. One should bear in mind a number of complications. Because of the nature of the stages involved, the branching ratios to some channels may be small so that not all channels need to exhibit correlated resonances. Secondly there is generally a background non-resonant amplitude which can interfere with the resonant amplitude and shift the peak (or valley) and change its character. Of course a shift larger than the width would be very surprising. This effect may cause some difficulties as the coherence length which scales the fluctuations is of the same order as the width, permitting the presence of accidental correlations. However it would be remarkable if this accident were to occur in several channels simultaneously.

Another technique which helps to separate the

signal from the noise identifies the quantum number of the resonance. Angular correlation experiments are an example and we have seen earlier the use of the unique $[P_L (\cos\theta)]^2$ angular distributions. This criterion is on the one hand too severe if resonances overlap and on the other hand not sufficient in itself. It can be the case (this objection applies to all the tests) that we may be dealing with an entrance channel phenomenon. The transmission coefficient may exhibit oscillations because of shape resonances. However these oscillations are of the order of a few MeV. Hence we can dispose of the case if the widths of the resonance are much smaller, e.g., of the order of a few hundred keV. A second problem was pointed out by Rolf Siemssen in a dsicussion earlier this week. If a new channel open up with an amplitude which has a rapidly increasing energy dependence, as will be the case when large angular momenta are involved, and then competition sets in rapidly as will, a peak will be generated. However we can dispose of this problem if there are several such peaks.

An analysis of the type which emphasizes channel correlation has been performed for example by a group from M.I.T., BNL, Argonne and Copenhagen [17] in which they measure the excitation function for $^{12}C(^{12}c,p)$ to a number of states including four of high spin in ^{23}Na. They have also collected the data obtained by other authors. The open channels involving emission of light particles up to and including alpha particles are shown in Fig. 7. We shall later be also discussing the product channel of $^{8}Be + ^{16}O$. In Fig. 8 the results are presented. One immediately sees strong correlations for the levels at 19.3 MeV, at 14.3 and 11.4 MeV. By comparing the various branching ratios these authors concluded that these levels had a spin of 12^+, 10^+ and 8^+ respectively. From the excitation curves for E_x = 14.7, 15.9 + 16.0, and 17.3 one suspects a level at almost 25 MeV. From E_x = 12.30, 8.94, 13.82, 14.40, a level at about 22.5 MeV. Similarly there is possibly a level at 18.5 MeV. The existence of the latter has been verified by Eberhard et al. [18] using the $^{12}C(^{12}C, {}^{8}Be_{g.s.})^{16}O$ g.s. reaction. They obtain a $[P_{L=12} (\cos\theta)]^2$ distribution these identify the spin of the resonance at 12^+. The Florida group [19] has done a very extensive study using the same reaction. Their results together with the ones discussed earlier are collected in Table 1.

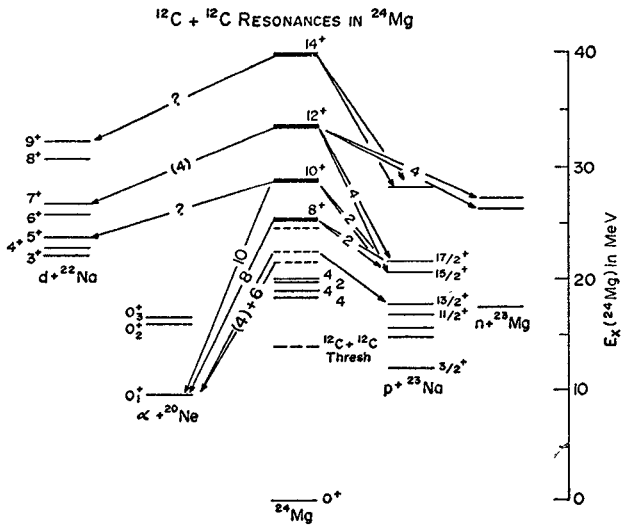

Fig. 7 - Open channels permitting emission of light particles from excited states of ^{24}Mg.

TABLE I

Exit channel	$E_{c.m.}$ (MeV)	$\Gamma_{c.m.}$ (keV)	J^{π}
$^{8}Be + ^{16}O$	11.43	200	8^+
Fletcher et al. [19]	(11.78)	...	(8^+)
	12.0	200	8^+
	12.35	300	8^+
	12.86	350	8^+
	13.35	350	10^+
	13.85	260	10^+
	14.3	280	10^+
	15.3	600*	10^+
	16.2	800*	10^+
	17.15	350	10^+
	17.75	500	12^+
	(18.4)	...	12^+
	18.8	400	12^+
	18.8	< 400	10^+
	19.45	250	12^+
$\alpha + ^{20}Ne^*$	17.9	340±60	
Fortune et al. [20]	18.4	400±30	
	18.6	375±100	
	19.0	310±60	
	19.4	320±30	
$^{8}Be + ^{16}O$	18.5		12^+
Eberhardt et al. [18]			
$p + ^{23}Na^*$	11.4		8^+
Cosman et al. [17]	14.3		10^+
	19.3		12^+
da Silveira [21]	26		(12^+)
$\alpha + ^{20}Ne^*$	7.71	145	4^+
Erb et al. [11]	9.84	small	8^+
$\left\{\begin{matrix}\alpha + ^{20}Ne^* \\ p + ^{23}Na^*\end{matrix}\right\}$	7.50	180	6^+
	8.45		
Basrak et al. [12,13]	8.85		$(6^+,8^+)$

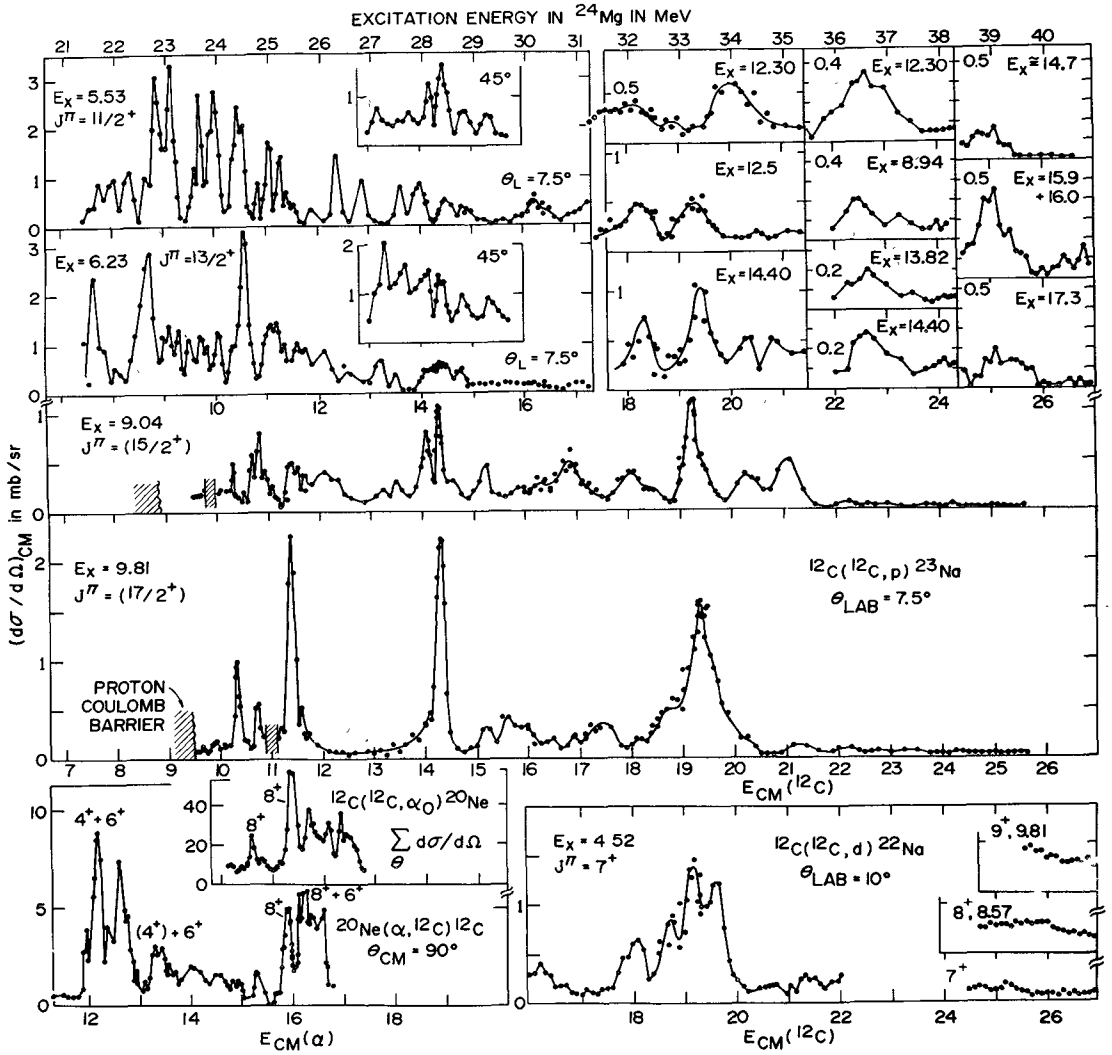

Fig. 8 - Excitation functions of selected $^{12}C + ^{12}C$ reaction channels. The $^{12}C + ^{12}C$ and $^{20}Ne + \alpha$ reaction scales are aligned to correspond to the same $E_x(^{24}Mg)$ values in the figure.

Clearly the issue of why some resonances are seen in one reaction and not in another and which ones are identical although shifted in energy needs to be resolved. But there appears to be much structure with a considerable grouping of levels of a particular spin and parity. The level spacing omitting the possibly unresolved resonances at 15.3 and 16.2 MeV is about 0.5 MeV while the widths are somewhat less, of the order of a few hundred keV. The 10^+ resonances are spread over about 3.8 MeV while the 12^+ resonances extend over about 1.7 MeV but there may be others above the energy range investigated by the Florida group. These data are collected in Fig. 9. The straight line appropriate to a rotational band provides a good average fit but it is apparent that there are several resonances at each values of J rather than just one. We shall come back to this point later.

In comparison to the $^{12}C + ^{12}C$ case, the determination and nature of the resonances of the system $^{12}C + ^{16}O$ have formed more difficult problems. A resonance at 19.71 MeV, width 300 keV, has been found by several groups [22]. The data of the Yale group shown in Fig. 10 includes both elastic and inelastic scattering to excited states of ^{16}O. The resonance is not seen in the exit channel $^{12}C(^{16}O,\alpha)^{24}Mg^*$ but it is seen in $^{12}C(^{16}O,p)^{27}Al^*$. The latter reaction was studied by the M.I.T. - B.N.L. groups. Halbert et al. [23] have seen an anomaly at 13.7 MeV in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction. The Saclay group (Charles et al. [24]), has seen a

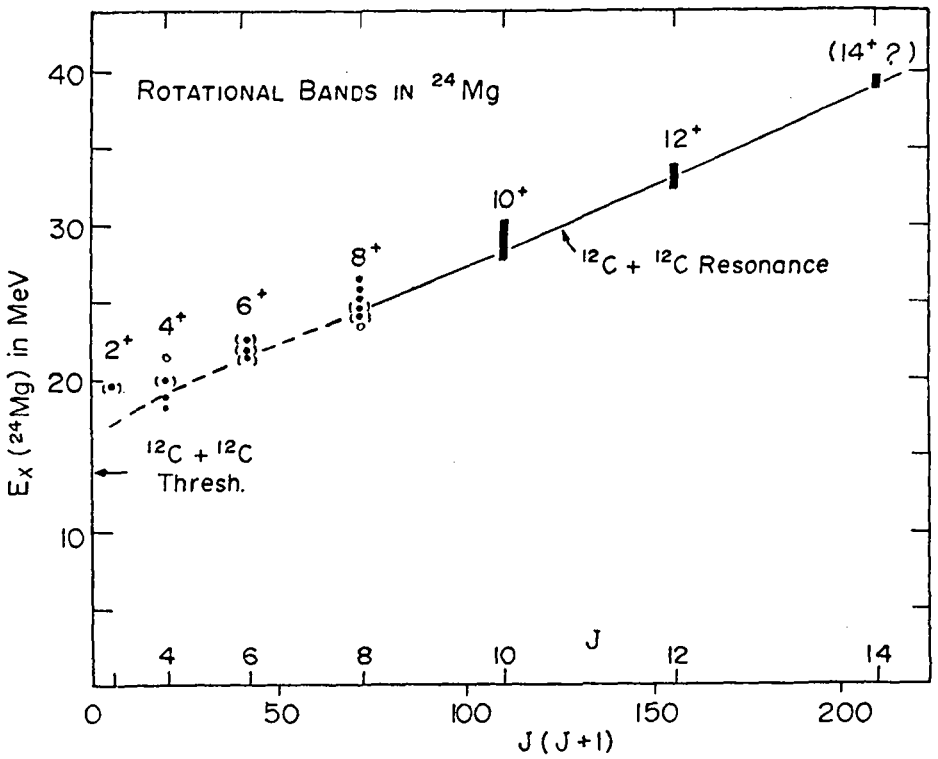

Fig. 9 - A summary of the reported ^{12}C + ^{12}C resonances

resonance at 22.7 MeV. They have reported new levels at 17.3 and 20.8 MeV at this conference [25] from an analysis of the elastic scattering. These need to be observed in other channels. Two levels at 20 and 22.5 MeV, Fig. 11, are reported by Malmin and Paul [26]. Branford et al. [27] have seen one level at 16.0 MeV and report other less certain examples. Recently the Florida group [18] studying the $^{12}C(^{16}O,p)^{27}Al$ reaction has found resonances at 11.83 MeV and 14.36 MeV with widths of the order of 300 keV. James et al. [22] suggest a 12^+ resonance at 19.92 MeV. Structure in the neighborhood of the Coulomb barrier (8.5 MeV) [29], Fig. 12, is not as pronounced as that observed in the ^{12}C + ^{12}C reaction (see Fig. 1). Oscillations in the total reaction cross-section (Fig. 13) [30] are clearly visible. No oscillations are seen in the ^{12}C + ^{18}O reaction (Fig. 14), but for ^{12}C + ^{12}C the oscillations are clearly visible and correlated with known resonances as indicated by arrows. Finally we mention Argonne experiments [31], Fig. 15, which seems to show a broad resonance in the ^{16}O + ^{13}C system with a width of 1 MeV. The reported resonances are summarized in Fig. 16. However the spin and parity of many of these are not known or are uncertain inhibiting any discussion of their significance. Much work obviously remains to be done.

For that reason in discussing the interpretation of the above experimental results we shall focus on the ^{12}C + ^{12}C system. As usual we need first to obtain the insights offered by the elastic scatering. The elastic scattering for a number of light ion systems compiled by Siemssen [5] is shown in Fig. 17, [32]. We observe rather wild oscillations in the ^{12}C + ^{12}C case. Some of the fluctuations are smoothed out in the ^{12}C + ^{16}O system and progressively disappear as we proceed to the ^{18}O + ^{18}O system. The behavior of the ^{12}C + ^{12}C scattering near the Coulomb barrier [33] is shown in Fig. 18. There is some correlation of the peaks in this figure with the observed resonances. It should be noted as well that the oscillatory behavior continues unabated to a rather high energy [34], Fig. 19. The Yale group has fitted the scattering [35] with a combination of Woods-Saxon optical forms for the real and imaginary parts. The results are :

TABLE II

	V(MeV)	R(fm)	a(fm)	W(MeV)	R_I(fm)	a_I(fm)
^{12}C + ^{12}C	14	6.18	0.35	0.4±0.1E	6.41	.35
^{16}O + ^{16}O	17	6.8	0.49	0.8±0.2E	6.40	.15

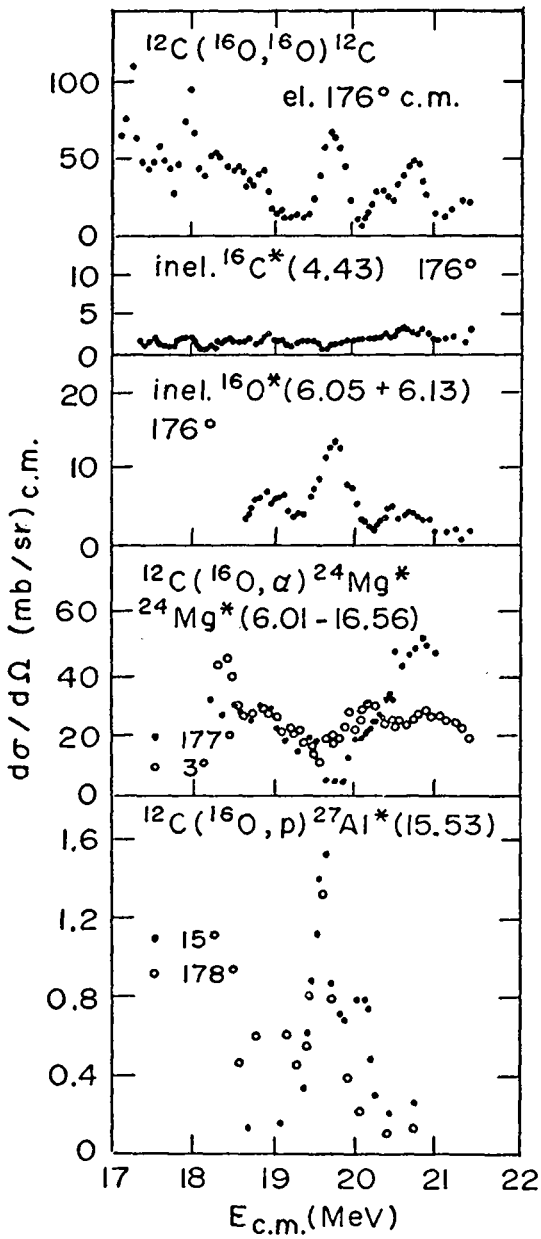

Fig. 10 - $^{12}C + ^{16}O$ reactions in the vicinity of the 19.7 MeV resonance.

The fits obtained with these potentials have the correct character as can be seen from Fig. 20, [36], but are by no means perfect. As can be seen from Fig. 21, [36], at particular energies the angular distribution for $^{16}O + ^{16}O$ are pure $[P_L(\cos\theta)]^2$, the values of L are given on the right hand side of the figure. At these energies the phase shifts are close of $\pi/2$. The width is of the order of 3-4 MeV. The small values of the imaginary potential are essential in order to obtain the observed oscillations in the cross-section and these values of the width of the gross-structure anomaly. One needs only to recall that this width is approximately equal to

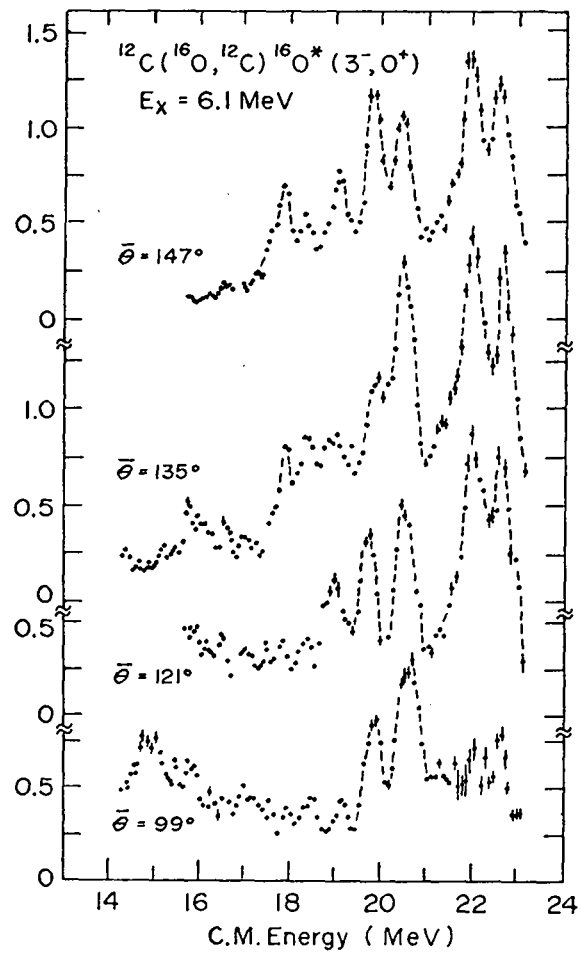

Fig. 11 - Excitation functions for inelastic scattering in the $^{12}C + ^{16}O$ system involving the 3^-, 0^+ doublet at 6 MeV in ^{16}O.

twice the magnitude of the imaginary potential.

The value of energy, $E_{c.m.}$, at which, according to the potential of Table II, the $^{12}C + ^{12}C$ scattering exhibits a gross structure resonance at a given value of L has been determined by Arima et al. [37] using Regge analysis. The straight line of Fig. 22 gives their result. It is remarkable that the measured resonance energies and associated values of L available at that time fall close to the values predicted from the Yale $^{12}C + ^{12}C$ potential. However their suggestion that the observed resonances are simply shape resonances is untenable since the width of a shape resonance is of the order of a few MeV whereas the observed resonances have widths of the order of a few hundred keV. Moreover we now have many resonances for each value of J. Recall the results contained in Fig. 9 presented earlier. I would like to propose the following interpretation. The incident wave in a given L state,

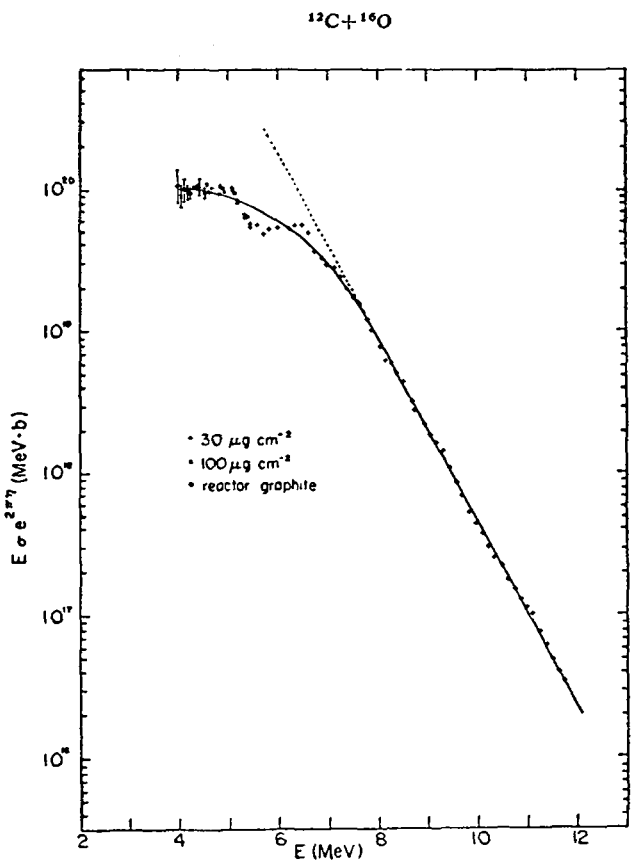

Fig. 12 - The quantity $S = E\,\sigma \exp(2\pi\eta)$ as a function of E where σ is the total reaction cross-section for $^{12}C + {}^{16}O$.

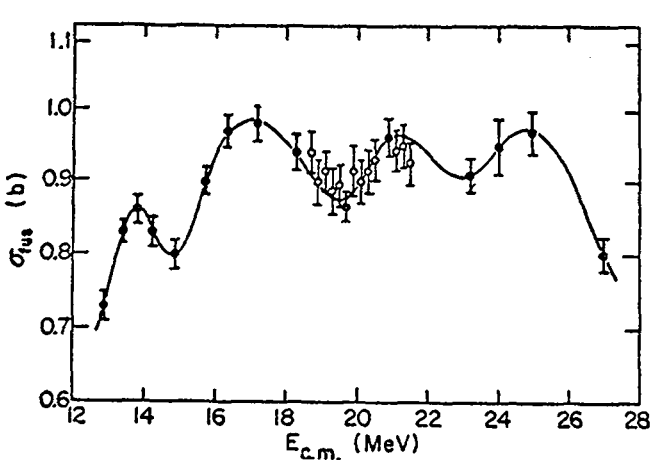

Fig. 13 - Total fusion cross-section for $^{16}O + {}^{12}C$.

at a shape resonance we have just been discussing, is weakly coupled, and I emphasize the weakness of the coupling, to excited states of the system. The result is a fragmentation† of the shape resonance into a number of components, see Fig. 23. A rough check on this idea is given by the fact that the sum of all the widths of the 10^+ states which fall close to the Arima line is 2.65 MeV of the order of magnitude of the gross structure width. We shall come back to this description later in this paper.

In the language of the paper with Kerman and Lemmer [38] the ^{12}C and ^{12}C resonance are examples of isolated doorway states. Let me remind you of the equations describing isolated doorway states and of some pertinent properties. The doorway state ψ_d and the incident channel ψ satisfy a pair of coupled equations

$$(E - H_{pp})\,\psi = H_{pd}\,\psi_d$$

$$(E - H_{dd})\,\psi_d = H_{dp}\,\psi$$

These wave functions are energy averaged so that the Hamiltonian operators are complex. The complex part of H_{dd} reflects the spreading width. The complex part of the coupling Hamiltonian gives rise to the asymmetry in the doorway reaction cross-sections. If these imaginary terms are large the resonance will not be seen so that in the $^{12}C + {}^{12}C$ case they must be small. The imaginary part of H_{pp} must be smaller than that which is used in the optical potential to fit the scattering data since there is a contribution to the reaction cross-section from the coupling to the second equation. Thus the imaginary part of H_{pp} must be smaller than $0.4 + 0.1E$.

In order to understand the properties of the doorway states it is necessary to consider their width. For this purpose we can make use of the statistical model, as developed by Kerman , Koonin and myself. That part of this formalism which is relevant in the present context was present at the Munich Conference [39]. I of course do not have the time to review it here but shall restrict the

†Subsequent to the presentation to this conference, this writer found the same suggestion in the paper [19] of the Florida group.

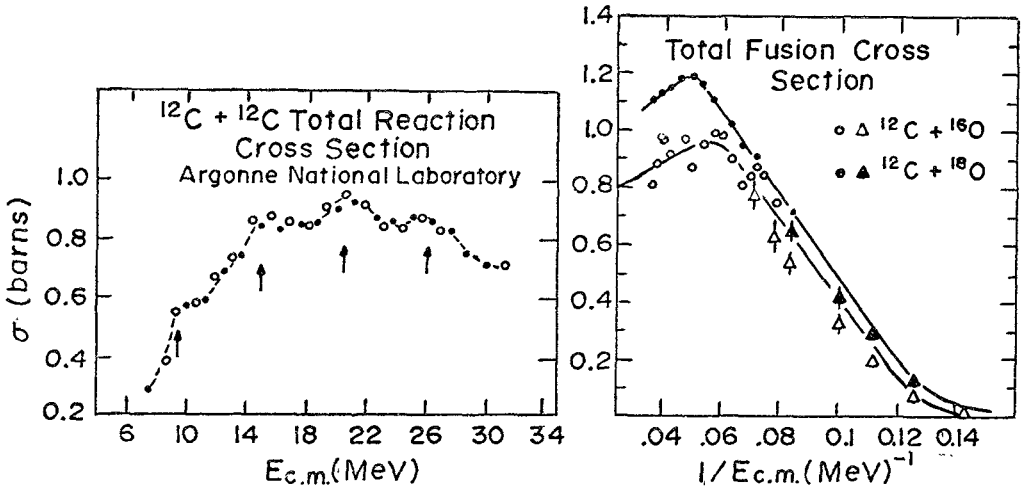

Fig. 14 - Total reaction and fusion cross-section measurements. The arrows indicate where corresponding maxima occur in the elastic scattering excitation functions. The solid lines are the optical model predictions.

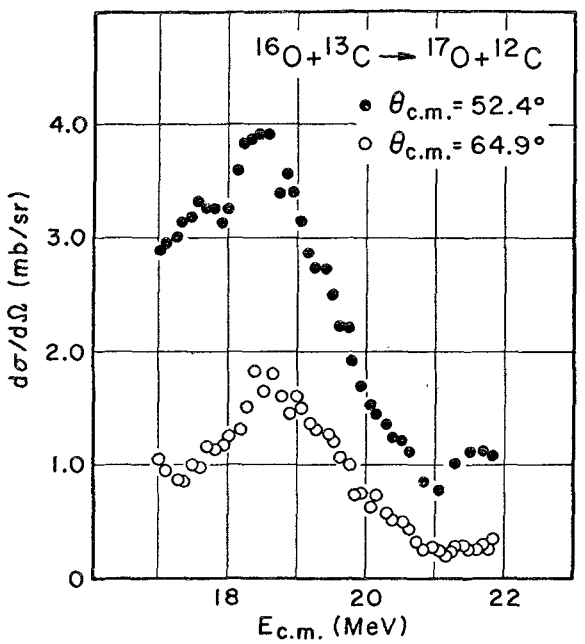

Fig. 15 - Resonant excitation functions in the $^{16}O + ^{13}C$ reaction.

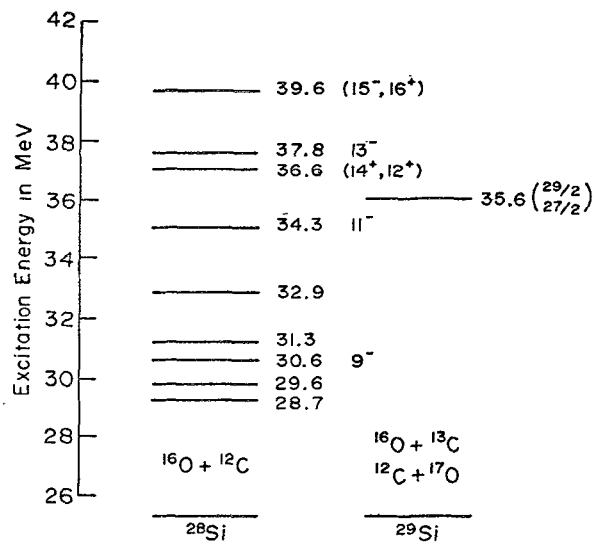

Fig. 16 - Resonances reported for the $^{16}O + ^{12}C$ and $^{16}O + ^{13}C$ systems.

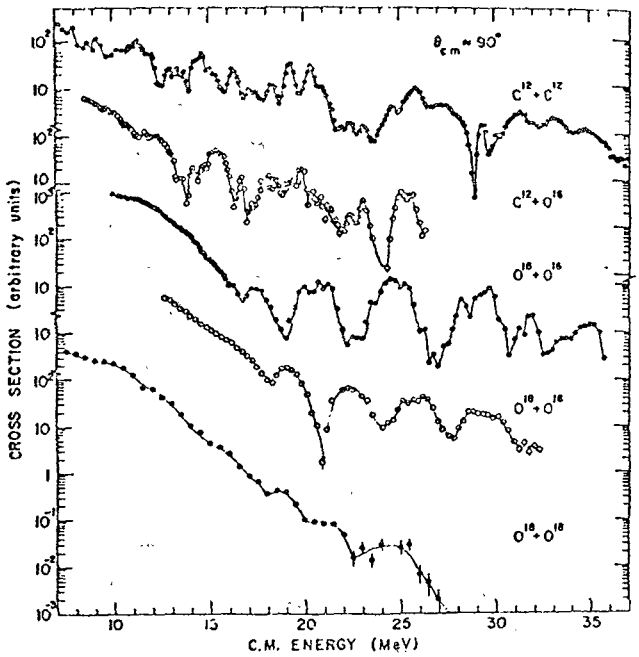

Fig. 17 - The 90° elastic scattering excitation functions for several heavy ion systems.

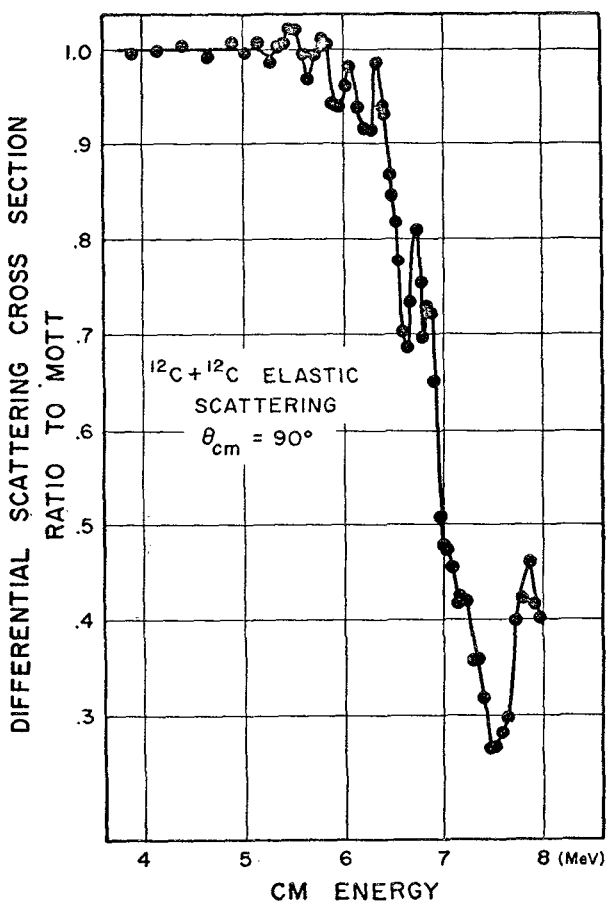

Fig. 18 - ^{12}C + ^{12}C elastic scattering at 90° in the region of the Coulomb barrier

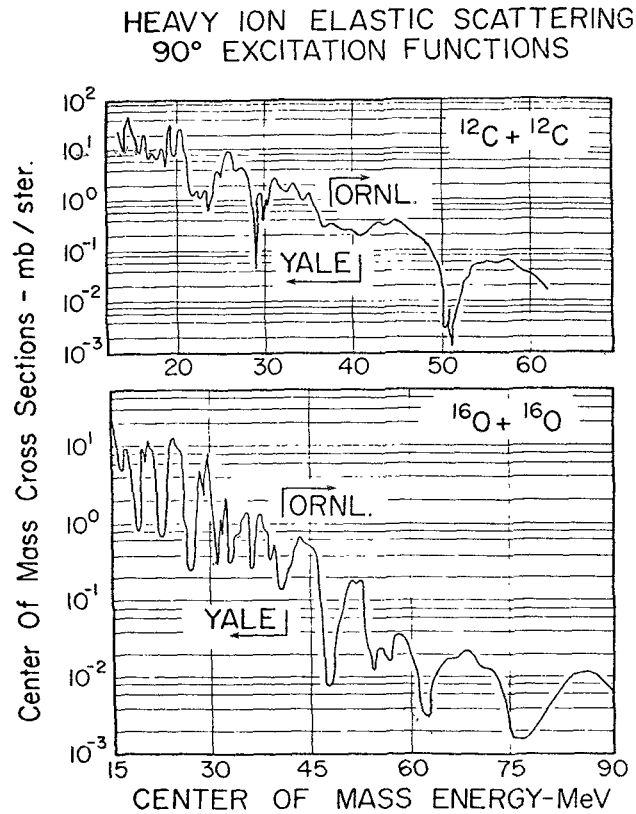

Fig. 19 - The 90° excitation functions for elastic scattering of ^{12}C + ^{12}C and ^{16}O + ^{16}O systems obtained as indicated at Yale and the Oak Ridge Laboratory.

discussion to a few qualitative points. The formalism assumes a sequential process in which the system proceeds from the doorway state to states of higher complexity (see Fig. 24). More precisely it assumes that the residual Hamiltonian can couple the n'th state with only the (n + 1) st or (n - 1) st stage. The escape width of the doorway is given by emission from it while the spreading width involves the sum of the probability of the emission from all the later stages. This result points up one possible source of confusion. The escape width is *not* the sum of all the probabilities of reactions of various kinds connected with the doorway state resonance. Some of these contribute to the spreading width. In the event of strong coupling between the more complex stages, the statistical compound nucleus result is obtained. However more generally it may be necessary to include the contribution of the pre-compound terms.

The size of the doorway state width plays a decisive role with regard to the visibility of doorway state resonance. It will be recalled that although the ^{16}O + ^{16}O elastic scattering cross-

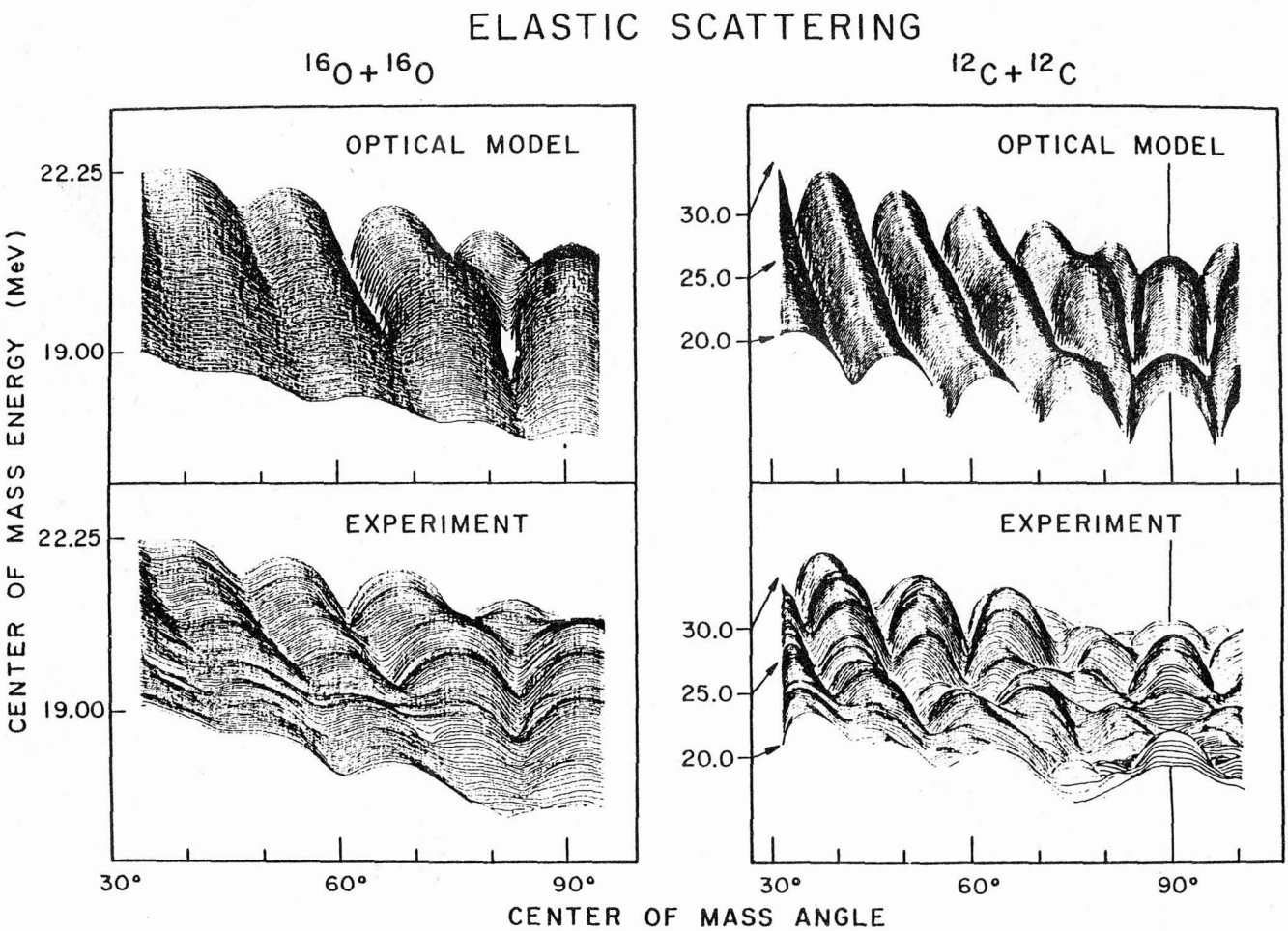

Fig. 20 - Comparison of the experimental angle-energy cross-section surfaces with the corresponding optical model for the $^{16}O + ^{16}O$ and $^{12}C + ^{12}C$ systems.

section exhibits shape resonances there is no evidence for resonances in the reaction channels (Fig. 25, [40]). Even though $^{12}C + ^{12}C$ does resonate, $^{12}C + ^{13}C$ does not as is clear from Fig. 26, [41]. The fusion cross-section of $^{12}C + ^{18}O$ system shows no fluctuations while that of $^{12}C + ^{16}O$ does (Fig. 14). The oscillations in elastic scattering cross-sections are much pronounced in $^{16}O + ^{16}O$ scattering than in $^{16}O + ^{18}O$. We note also that the only systems which do exhibit doorway state resonances are $^{12}C + ^{12}C$ and possibly $^{12}C + ^{16}O$. Vandenbosch et al. [42] showed that the elastic scattering of ^{12}C by ^{20}Ne differs sharply from that of $^{16}O + ^{16}O$ in that both the angular distribution at $E_{c.m.} = 23.3$ MeV and the energy dependence of the cross section are smooth and featureless. This is an interesting case because the binding energy of both systems differs by only 2.4 MeV, they have the same compound nucleus, and the grazing angular momenta differ by no more than one unit of $\hbar$ for the same excitation of the compound nucleus.

The substantial differences amongst these rather similar nuclear systems need to be understood. We have already noted a number of conditions which need to be statisfied if resonances are to be observed. The elastic scattering for the partial L wave in question should have a relatively large amplitude. If this is not the case it will be difficult to pick out effects in the L channel from all the other effects which are simultaneously present. A gross-structure resonance is the best that can occur in this regard. This requires a surface transparency of the nucleus; that is absorption in the nuclear surface is low. We have noted empirical evidence that indicates that surface absorption is low. The fit to the elastic scattering cross-section for $^{16}O + ^{16}O$ is improved if the radius of the imaginary part of the optical potential is smaller than that of the real potential and has a sharp cut off.

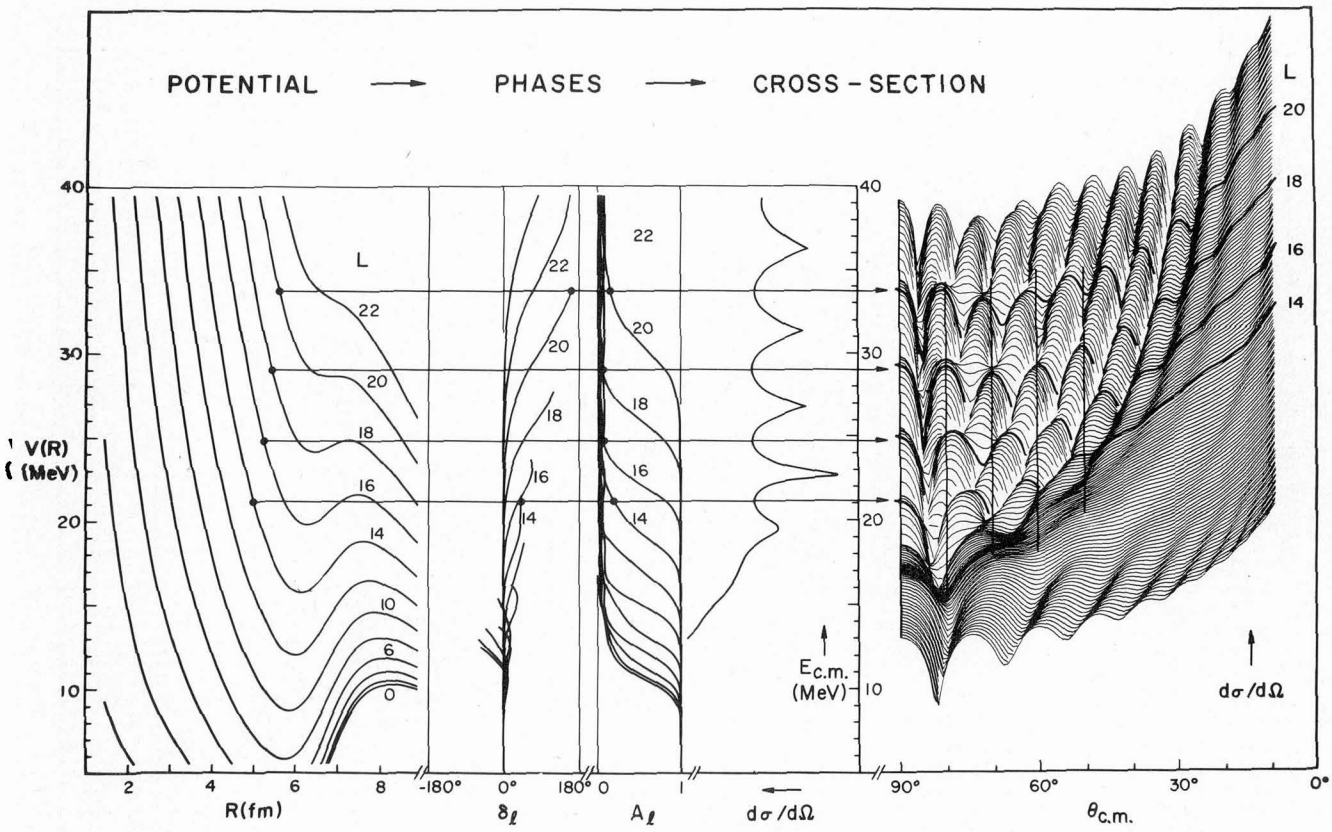

Fig. 21 - An optical model analysis of the $^{16}O + ^{16}O$ elastic scattering. The panel on the left shows the optical model potentials for different partial waves. The central panels show the phase shifts, the attenuation coefficient for each partial wave and the 90° calculated scattering cross-sections. The panel on the right is an energy angle surface for the scattering for the Yale data. The horizontal lines indicate where the different partial waves become dominant. In the panel on the right, the heavy lines, which have been fitted to the experimental data, are squares of the Legendre polynomials of the indicated order.

Many authors have pointed out [43] that at the angular momenta and energies in question there exist very few ways for the system to proceed to higher states of internal excitation with the total angular momentum remaining constant, thus reducing the number of absorption channels.

The density of levels of the compound system as well as the number of channels enter importantly into the value for the doorway state width. The values of these parameters at the Coulomb barrier energy are shown in Table III, as calculated by Hansen et al. [44].

The $^{12}C + ^{12}C$ has the smallest level density and number of open channels, the $^{12}C + ^{16}O$ systems next. However there are other possibilities such as $^{9}Be + ^{12}C$, and $^{12}C + ^{13}C$ yet neither of these systems exhibit resonances. It is clear another mechanism must be operating.

The one I believe to be involved is described as follows. The reader will recall that one of the consequences of the interaction between the colliding ^{12}C nuclei was the fragmentation of the shape resonance for a given L into ones of considerably narrower width. The interaction needed to be weak since the resonances were grouped close to be energy of the shape resonance. A possible explanation of the absence of resonance in other likely systems mentioned above is that in those cases the interaction is strong. As a consequence not only will the L shape resonance be fragmented but the fragments will be substantially displaced. The L strength will be dispersed and far less visible. Vandenbosch [45] has given an example. He has performed a coupled channel calculation for both $^{16}O + ^{16}O$ and $^{18}O + ^{16}O$. The 2^+, 6.9 MeV level and the 3^-, 6.1 MeV level in ^{16}O, were taken into account in the first case while for the second case the 2^+, 1.98 MeV and the 3^-, 5.09 MeV levels of ^{18}O were included. Because of the presence of the low lying 2^+

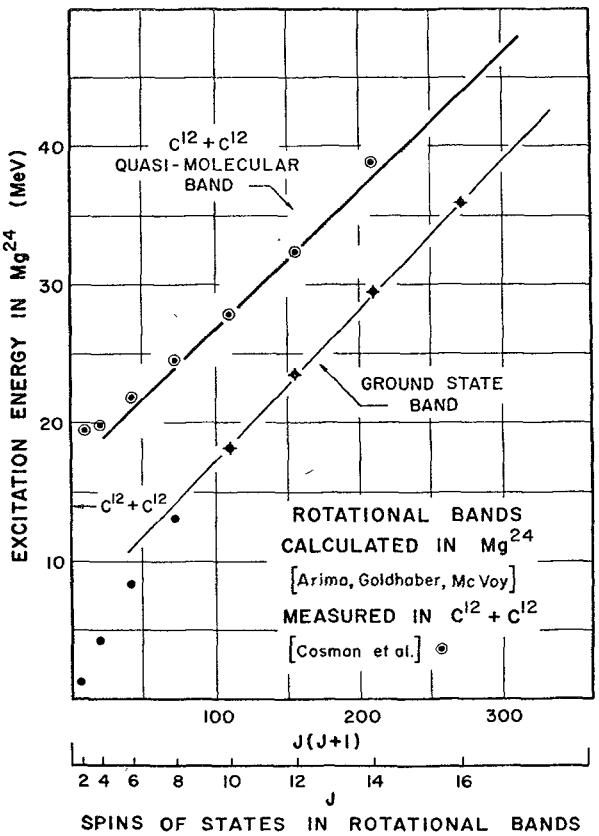

Fig. 22 - Energy and angular momenta of gross structure resonances, compared with values from experiments of Cosman et al. [17].

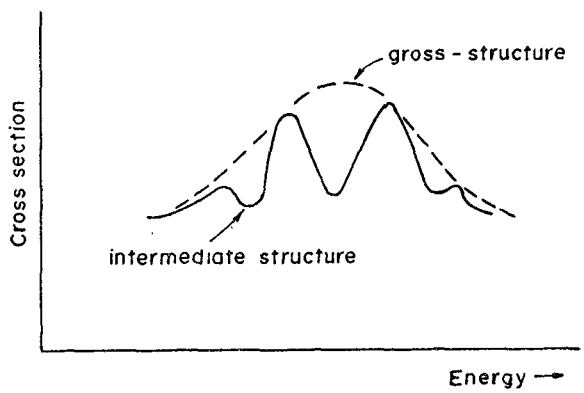

Fig. 23 - Schematic illustration of the fragmentation of a shape resonance.

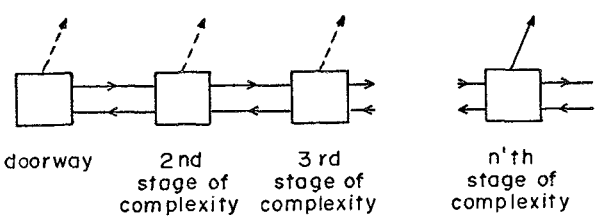

Fig. 24 - Stages in the decay of a doorway state.

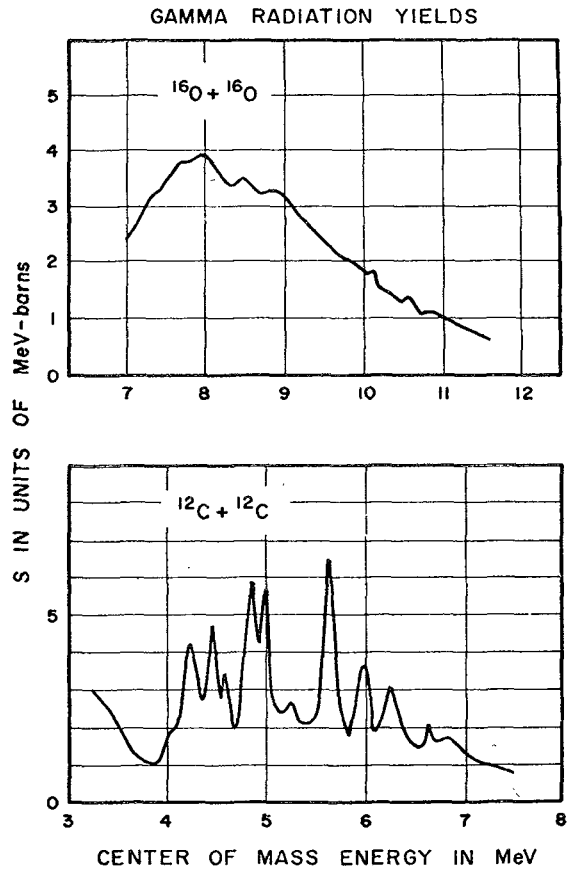

Fig. 25 - Comparison of the gamma radiation yield for the systems $^{16}O + ^{16}O$ and $^{12}C + ^{12}C$.

level in ^{18}O that nucleus is easily polarizable; the coupling is thereby effectively strong. Vandenbosch's calculations show a marked reduction in the amplitude of the $^{16}O + ^{18}O$ oscillations as a function of angle as compared with that of $^{16}O + ^{16}O$.

In these concluding pages, we consider the dynamics involved in the generation of the doorway states. A number of possible mechanisms have been suggested by Imanishi and Nogami [1], Michaud and Vogt [14], Greiner and Schied with various collaborators [46], Leander and Larsson [47], and Baye who reported on his work earlier this week. There are differing examples of the general mechanism which lies behind any description of a resonance - namely the incident channel couples to another degree of freedom of the resonating system. If this second degree of freedom has special states which have a relatively long lifetime, then a resonance will occur whenever the energy of the system equals the energy of these special states. It is important that the system leaves the incident channel and that it spends a considerable period of time in another

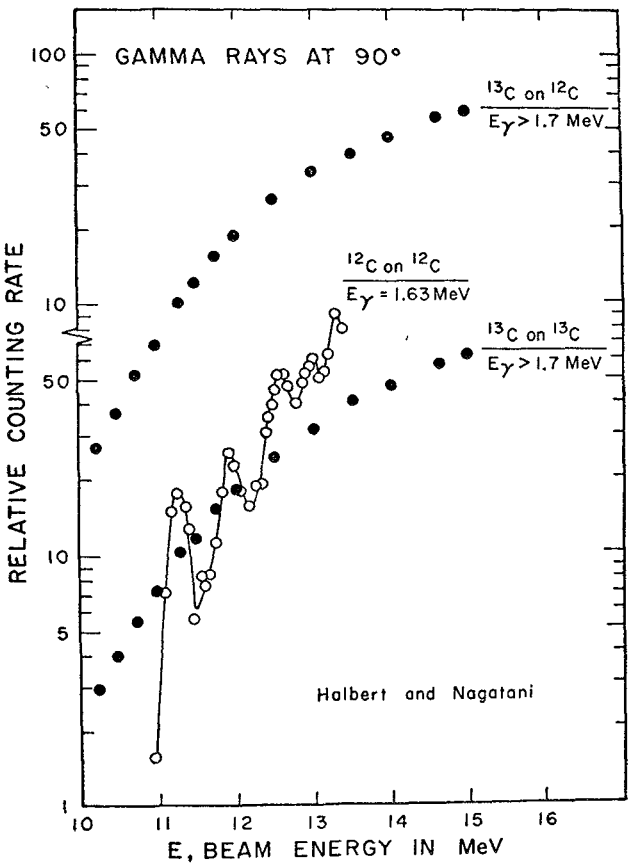

Fig. 26 - Total gamma radiation yield measured at 90° for $^{12}C + ^{12}C$, $^{12}C + ^{13}C$, and $^{13}C + ^{13}C$ systems. For $^{12}C + ^{12}C$ only the 1.63 MeV gamma ray from the first excited state of ^{20}Ne has been measured. For the reactions involving ^{13}C all gamma radiation with energy greater than 1.7 MeV has been measured. Note that the beam energy is given in the laboratory system.

TABLE III

Compound System	Reaction	E_x^{cn} (MeV)	Relative level density	Relative number of open channels
^{20}Ne	$^{10}B+^{10}B$	36.1	37	160
^{21}Ne	$^{9}Be+^{12}C$	21.7	3.3	7
^{22}Na	$^{10}B+^{12}C$	23.0	15	14
^{23}Na	$^{11}B+^{12}C$	23.8	11	14
^{24}Mg	$^{10}B+^{14}N$	35.4	100	350
	$^{12}C+^{12}C$	20.6	1	1
^{25}Mg	$^{12}C+^{13}C$	22.9	7.1	13
^{26}Mg	$^{13}C+^{13}C$	28.9	36	48
	$^{12}C+^{14}C$	25.7	13	12
^{26}Al	$^{12}C+^{14}N$	22.6	23	13
^{27}Mg	$^{13}C+^{14}C$	27.2	44	170
^{27}Al	$^{13}C+^{14}N$	30.7	98	440
^{28}Mg	$^{14}C+^{14}C$	27.4	27	100
^{28}Si	$^{12}C+^{16}O$	25.2	3.8	3.9
	$^{14}N+^{14}N$	35.8	110	300
^{29}Si	$^{13}C+^{16}O$	28.6	59	125
^{30}Si	$^{12}C+^{18}O$	31.9	130	340
	$^{14}C+^{16}O$	31.0	98	220
^{31}P	$^{12}C+^{19}F$	32.1	350	1.8×10^3
^{32}S	$^{12}C+^{20}Ne$	29.1	43	75
	$^{16}O+^{16}O$	27.3	22	34
^{36}Ar	$^{12}C+^{24}Mg$	28.1	130	300
	$^{16}O+^{20}Ne$	31.4	450	1.5×10^3
^{40}Ca	$^{12}C+^{28}Si$	26.7	185	170
	$^{16}O+^{24}Mg$	31.2	1.0×10^3	2×10^3
	$^{20}Ne+^{20}Ne$	36.4	7.9×10^3	2.4×10^4
^{44}Ti	$^{20}Ne+^{24}Mg$	34.8	4.2×10^4	8×10^4
^{48}Cr	$^{24}Mg+^{24}Mg$	36.4	2.8×10^5	2.9×10^5

mode of motion. Only then will there be the long interaction time necessary for the existence of a resonance.

One can classify the various theories according to the manner in which they propose to obtain this long delay time. One method presumes excitation of the ^{12}C nucleus. Imanishi takes into account the excitation of the ^{12}C nucleus to its first excited 2^+ state at 4.44 MeV. Kondo, Matsuse, and Abe [2], took into account the simultaneous excitation of both ^{12}C nuclei. The alpha particle model of Michaud and Vogt [14] amounts to considering the excitation of the ^{12}C nucleus to the 0^+, 7.653 MeV level which lies above the ^{8}Be + threshold although they did not describe it in these terms. The model of Schied, Greiner and Lemmer [45] and Fink, Scheid, and Greiner [43] is essentially identical to that of Imanishi. They provide an important insight which is also explicitly described by Imanishi. A resonance occurs at an energy such that after a consequence of the excitation of one or both of the ^{12}C nuclei, the nuclei are in a quasi-bound state of the appropriate angular momentum. Thus the doorway state consists of excited ^{12}C nuclei trapped in a potential well. This point is established in Fig. 27. There are also models in which one computes the potential energy of the carbon nuclei on the basis of, say, a two center model. One finds that the potential has a valley for certain deformation of the interacting nuclei. The situation is then analogous to the shape isomers which are exhibited by fissionable nuclei. Leander and Larsson have made such a calculation and I believe there are others. As a final example there are the results of Boye and Heenen presented to this Conference who attempt to solve the 24 particle problem.

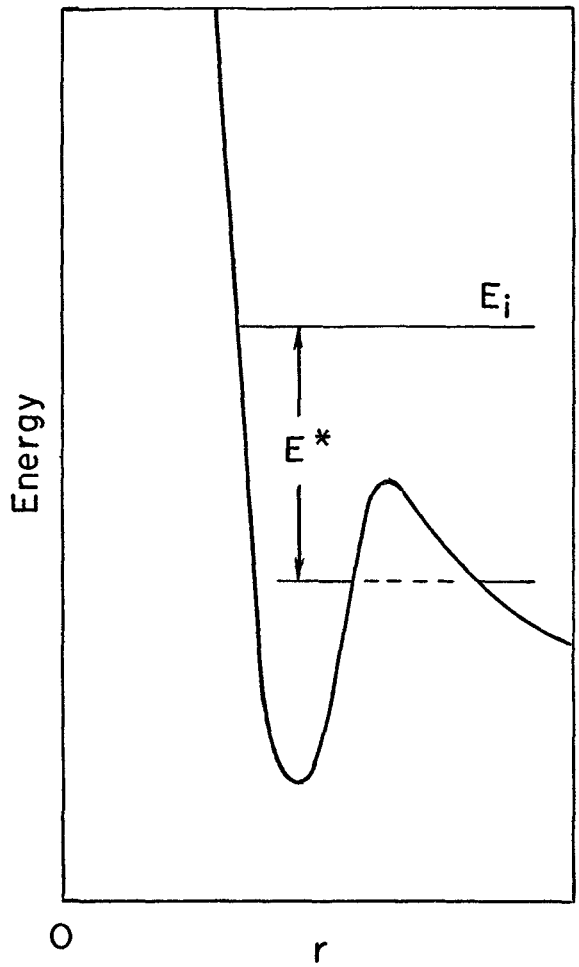

Fig. 27 - E_i is the incident energy, E^* the energy for excitation of the interacting nuclei leading to a quasi bound level in the indicated potential.

Imanishi [1] has carried out a detailed calculation assuming that the incident channel is coupled to a channel in which one of the carbon nuclei is excited to the 4.44 MeV level. The coupling potential is obtained by deforming the optical potential. He finds the doorway states to be isolated. They are listed in Table IV for one of his choices for the optical potential.

TABLE IV

Spin		Energy (MeV)	Width (keV)	Escape width (keV)
2	Theo.	5.66	115	11.5
	Exp.	5.6	130	19.5
4	Theo.	5.90	116	8.2
	Exp.	6.0	100	7.5
0	Theo.	6.37	150	52.1

At the time this was presented there were two complaints. One was that there were too few levels. However as Kondo, Matsube, and Abe [2] showed that there are many more levels, which appear to have roughly the correct approximate density (see Fig.1), if the Imanishi-Nogami model is extended to include the possible simultaneous excitation of both carbon nuclei. Perhaps the most important objection is that Imanishi did not calculate the elastic scattering and show that the results agree with experiment. It was claimed by some that the value of the imaginary potential Imanishi used was much too low. However this objection is premature. The value of the reaction cross-section must include not only the contribution from the incident channel but also that which arises from the other channels. It is hoped that the Japanese group will or have already calculated both the elastic and reaction cross-section. Until this is done and compared with experiment the remarkable agreement recorded in Table IV is not meaningful. Some experimental evidence on the mechanism will also become available if the yield of the gamma rays from the de-excitation of the ^{12}C nuclei is measured. This objective is now being pursued by the Yale group.

The alpha particle model [14] has not been as fully developed theoretically as the one discussed above. It has however been pursued experimentally by both the Erlangen [48] and the Saclay groups [49]. The method employed is illustrated by the following example. In the reaction $^{12}C(^{12}C,\alpha)^{20}Ne$ those states of ^{20}Ne which have a large alpha particle width should be preferentially populated according to the alpha particle model. I will not review this subject as it has been carefully discussed by Siemssen in his review paper [5]. Suffice it to say the evidence is mixed and no hard conclusions can be reached. On the other hand in the $^{12}C + {}^{16}O$ case there is direct negative evidence. In this reaction on the basis of the alpha particle model one would expect preferential excitation of the "4p 4h" 0^+ state in ^{16}O. A measurement has been performed by Malmin and Paul [50]. In fact it turns out that it is the 3^-, 6.13 MeV level which is the more strongly excited. The alpha particle model seems to fail in this case.

In conclusion it seems that the $^{12}C + {}^{12}C$ system is well on its way to be understood as more structure is uncovered and as more correlations are revealed. Obviously a great deal both experimentally

and theoretically remain to be done. Whatever the resolution it is clearly an extraordinary unique system. The carbon nuclei avoid both the Scylla of being too easily polarized and the Charybdis of not being polarizable at all. Once the mechanism involved is completely clarified we will not only find new properties of states of carbon nuclei bu also and more important we may learn how two deformed nuclei interact when they are in close contact as is presumably the case for a shape resonance. We may learn under what circumstances such systems may exist. As of the moment the only other candidate is the $^{12}C + ^{16}O$ systems†.

I am very much indebted to D. Allen Bromley and Eric Cosman for their help in the preparation of this address.

†Intermediate structure has been reported for the reaction $^{10}B(^{14}N,\alpha)^{20}Ne$ [51] but these are seen principally at 0° where however they may reflect diffraction effects rather than resonances.

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