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MOLECULAR DEGREES OF FREEDOM: RESONANCES AND ORBITING

D. SHAPIRA and K. A. ERB
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37830

Studies of orbiting and other gross features of heavy
ion induced reactions show that molecular degrees of
freedom play a significant role. The formation of a
rotating dinuclear molecule appears as a general
feature, and the radii derived for these dinuclear
systems are larger than the radii of the conventional
nucleus-nucleus potential. These large radii for the
molecular bonding potential are similar to those
derived from systematic studies performed recently on
resonances in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems.

Molecular degrees of freedom might well play an important

role in the interaction between two complex nuclei. The

study of molecular degrees of freedom can be carried out

along two different but complementary approaches. The tra-

ditional approach, that we label here "Microscopic"[1] entails

a detailed study of the many individual resonances of

nonstatistical nature that appear in scattering and reaction

channels of the colliding nuclei. The hope is that one can

eventually systematize these many "fingerprints" and thus

build up a model of the underlying molecular structure. An

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alternative approach--Macroscopic--involves a study of the
gross behavior system as a whole. This is done at the
expense of losing some of the more detailed information, but
because of its relative simplicity comparative studies
between different systems of heavy ions become easier. We
shall discuss some of the recent results from these two
approaches.

From a purist's point of view the "Microscopic" method is preferable--especially when a large body of data involving many resonances is available. Such detailed information however is not easily obtained; Figure 1, for example, shows only part of the data needed by Ledoux and collaborators at MIT[2] in order to get detailed information on <u>three</u> resonances in the $^{12}C + ^{12}C$ system. The information listed in Table I underscores the fact that even with these very high quality data some uncertainty and ambiguity remains. It is clear, however, that such data and careful analyses are necessary for attempts to classify the resonances and discern some systematic trends.
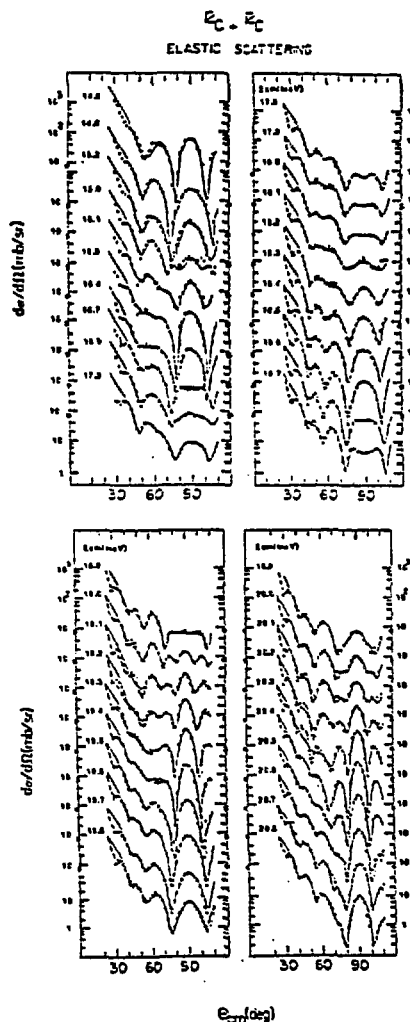

FIGURE 1 $^{12}C + ^{12}C$ elastic angular distributions from ref. 2.

TABLE I ^{12}C + ^{12}C Elastic scattering resonant properties (R. Ledoux et al., MIT).

E_{res}	J^π	η_ℓ^{res}	$\langle \eta_\ell \rangle$	$\Gamma_{Tot}(keV)$	$\Gamma_{e\ell}/\Gamma_{Tot}$	$\gamma_{e\ell}^2(keV)^\dagger$	$\gamma_{e\ell}^2/\gamma_W^{2*}$
IA. "zero phase" solution							
18.4	12^+	.55	.74	400	12.8%	40	12.6%
19.3	12^+	.45	.74	400	19.6%	39	12.2%
20.3	12^+	.50	.74	400	16.2%	23	7.2%
IB. "large phase" solution							
18.4	12^+	.51	.68	450	12.5%	45	14.0%
19.3	12^+	.41	.64	400	18.0%	36	11.4%
20.3	14^+	.53	.74	300	14.2%	100	31.6%

$^\dagger R_c$ = 5.7 fm.

$^* \gamma_W^2$ (for R = 5.7 fm) = 318 keV.

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Another recent example of precise $^{12}C + ^{12}C$ resonance data appears in a study of the reaction $^{20}Ne(\alpha, ^{12}C)^{12}C$ by Charles Davis from the University of Wisconsin.[3] His measurements, made in 10 keV steps over the range of 20 to 26 MeV excitation in ^{24}Mg (the compound nucleus) with very high resolution were followed up with a careful phase shift analysis. All the resonances with a significant $\sqrt{\Gamma_\alpha \Gamma_c/\Gamma_{tot}}$ ratio are shown in Figure 2. The triangle centroids represent the energies of the resonances; while their areas are proportional to the partial widths products. The well established tendency of states with the same spin to cluster over a limited energy range (~ 3 MeV c.m.) appears clearly and is attributed by Davis et al. to barrier top resonances in the C+C exit channel.
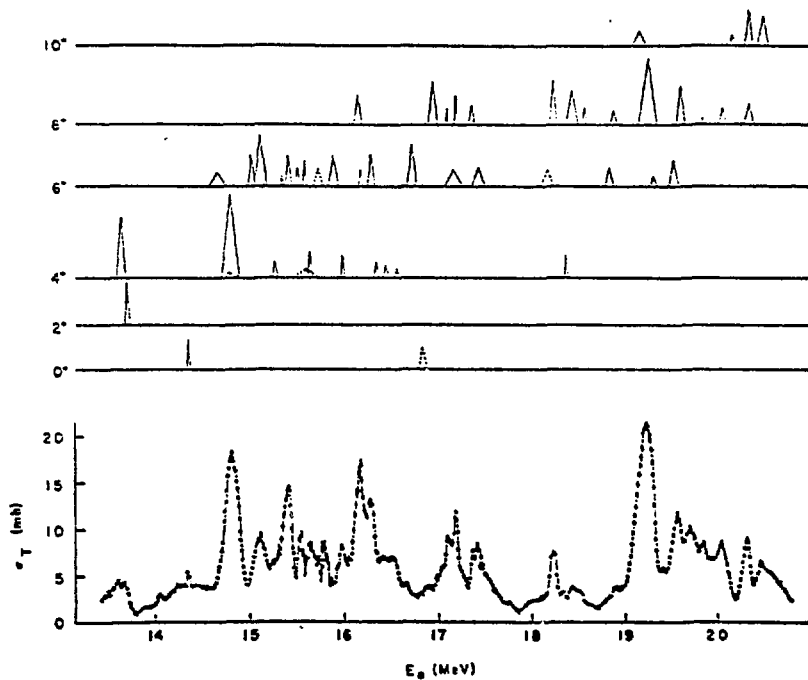

FIGURE 2   Integrated yield curve for the $^{20}Ne(\alpha, ^{12}C)^{12}C$ reaction with summary of resonance data.

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There is now an enormous body of data delineating the properties of resonances in the $^{12}C + ^{12}C$ system. Erb and Bromley[4] and Iachello[5] have suggested two years ago a simple classification for molecular resonances in the $^{12}C + ^{12}C$ system in terms of a vibrational and a rotational quantum number. The choice of energy functional

$$E(\nu,L) = -D + a(\nu+1/2) - b(\nu+1/2)^2 + CL(L+1) \qquad (1)$$

represents an approximate expression for energy levels in a bonding potential that can be represented adequately around the region of its minimum at $r = r_o$ by

$$V(r) = V_o + 1/2 A(r-r_o)^2 + B(r-r_o)^4 + \ldots \qquad (2)$$

Iachello has also shown[5] that the expression (1) for energy levels is appropriate for any Hamiltonian having certain basic symmetry properties [U(4) symmetry] that are a general feature of molecular interactions. The parameters used in Figure 3 were those obtained by Erb and Bromley[4] from a fit to 28 levels, of known spin, with spins ranging up to J=8 (full circles). The open circles correspond to resonances in that energy range for which no spin assignment has been made. Recently available data are also shown in Figure 3 together with an extrapolation of the trends derived for lower spins. The resonances found by Davis et al.[3] fit into the pattern nicely. At higher excitation energies the resonances of each spin are more dispersed, making it more difficult to discern evidence for the rotation-vibration behavior. More work needs to be done to resolve a host of questions concerning the higher-spin resonances. Assuming the validity of this scheme the derived parameter values
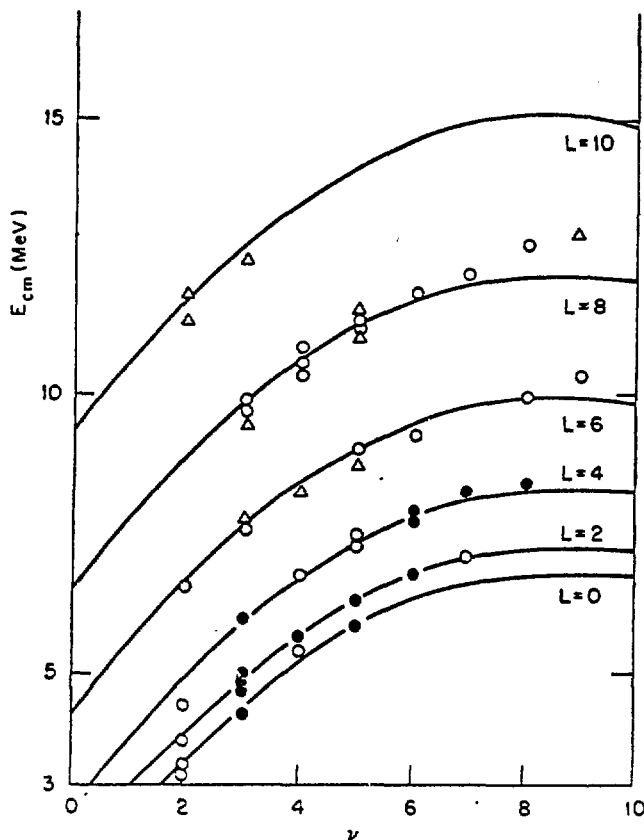
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FIGURE 3   Classification of $^{12}C + ^{12}C$ resonances into
rotational and vibrational bands according to Erb et al.
(ref. 4). The triangles correspond to the new data from
ref. 3.

provide information on the position of the minimum in the
bonding potential and the barrier height. Figure 4 shows
the approximate form of this potential together with the
optical potential for a nonzero partial wave. The minimum
of the molecular bonding potential lines up with the top of
the nucleus-nucleus potential barrier. Clearly this radius
is very large and the many suggestions to account for this
are as yet untested. One class involves excitation (virtual
or real) of the ^{12}C to the first excited 0^+ state that has a
substantial extended 3α chain configuation. Such extreme

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SCHEMATIC POTENTIALS FOR $^{12}C + ^{12}C$
RELATIVE MOTION (OPTICAL) AND FOR
MOLECULAR BONDING

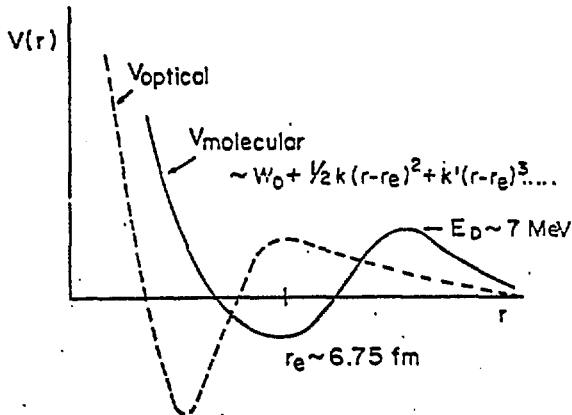

FIGURE 4

deformations might be associated with the attraction at very
large radii.

The $^{12}C + ^{12}C$ system is the system for which the
largest body of detailed resonance data are available.
A fair amount of data exist for the $^{12}C + ^{16}O$ system for
which a similar classification has been achieved.[6] There is
also an increasing body of data on $^{16}O + ^{16}O$ resonances
presently under investigation.[7]

The demarcation between "Microscopic" and "Macroscopic"
approaches to the study of molecular degrees of freedom is
not a sharp one. A case in point are the striking inelastic
data reported five years ago by T. Cormier and collabora-
tors,[8] and shown in Figure 5. These studies still involve
measurements of discrete transitions and their interpreta-
tion is frequently sought in terms of discrete resonances of
the ion-ion scattering. The observed excitation function
structure appears in energy averaged cross sections and
frequently involves (as in Figure 5) a large part of the
total reaction cross section. Our present day knowledge of
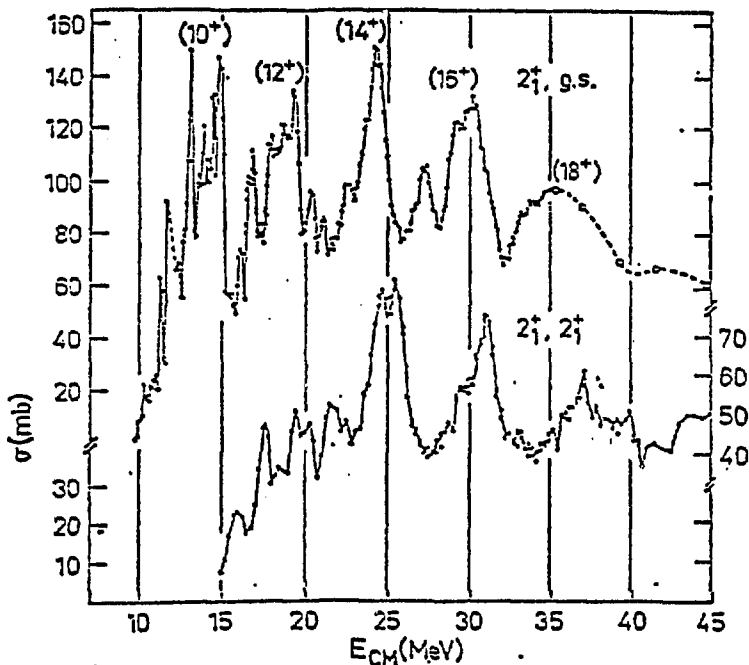
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FIGURE 5 $^{12}C + ^{12}C$ single excitation (2^+) and mutual
excitation ($2^+, 2^+$) inelastic data (ref. 8).

the spins of some of the narrower resonances in this energy
range suggests that the spin assignment proposed for the
broad structure is only approximate, reflecting an average
trend. Several theoretical explanations (or models) were
suggested for the striking gross structure seen in these
data[8,9,10,11] as well as for similar features in the
$^{16}O + ^{16}O$ system.[12] All these models relate the gross
structure in the cross sections to relatively narrow angular
momentum windows around the grazing partial waves. The
models differ in the underlying mechanism which creates the
windows. They also rely on angular momentum matching
between the elastic and inelastic channels. The essence of
these matching arguments for inelastic transitions to well
matched channels is shown in Figure 6, taken from work by
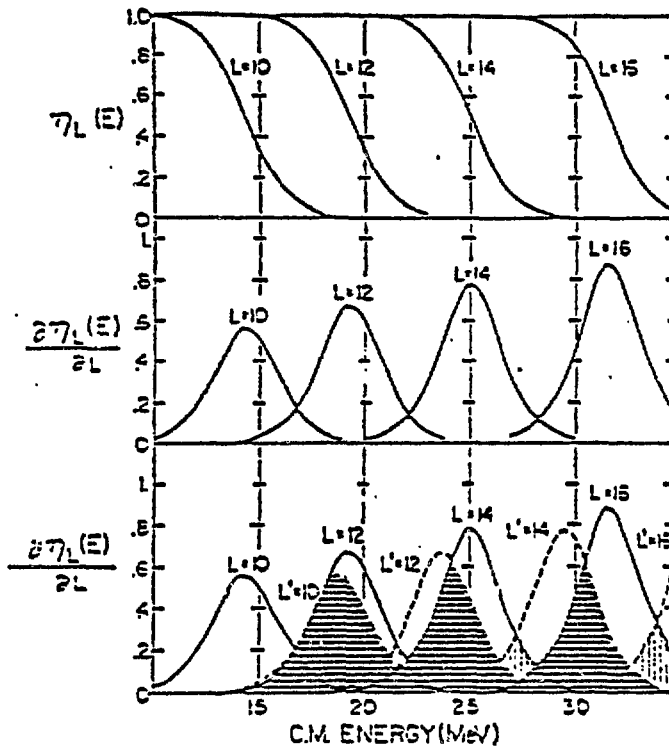
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FIGURE 6 Reflection coefficients and their derivatives
for $^{12}C + {}^{12}C$ scattering in a strong absorption formalism.

Phillips et al.[9] The change in center-of-mass kinetic
energy equals approximately the energy difference between
the nucleus-nucleus potential for partial waves L and L-I
at the matching radius (I is the spin of the state excited
inelastically).

The situation is more complex for poorly matched
channels. Figure 7 shows the excitation functions for
inelastic scattering to the mismatched excited 0^+ channel
and for the mutual excitation of both outgoing nuclei.[12]
The simple matching arguments presented above do not repro-
duce these trends: note that the gross structure in the
$(3^-,3^-)$ channel is not in phase with the single excitation
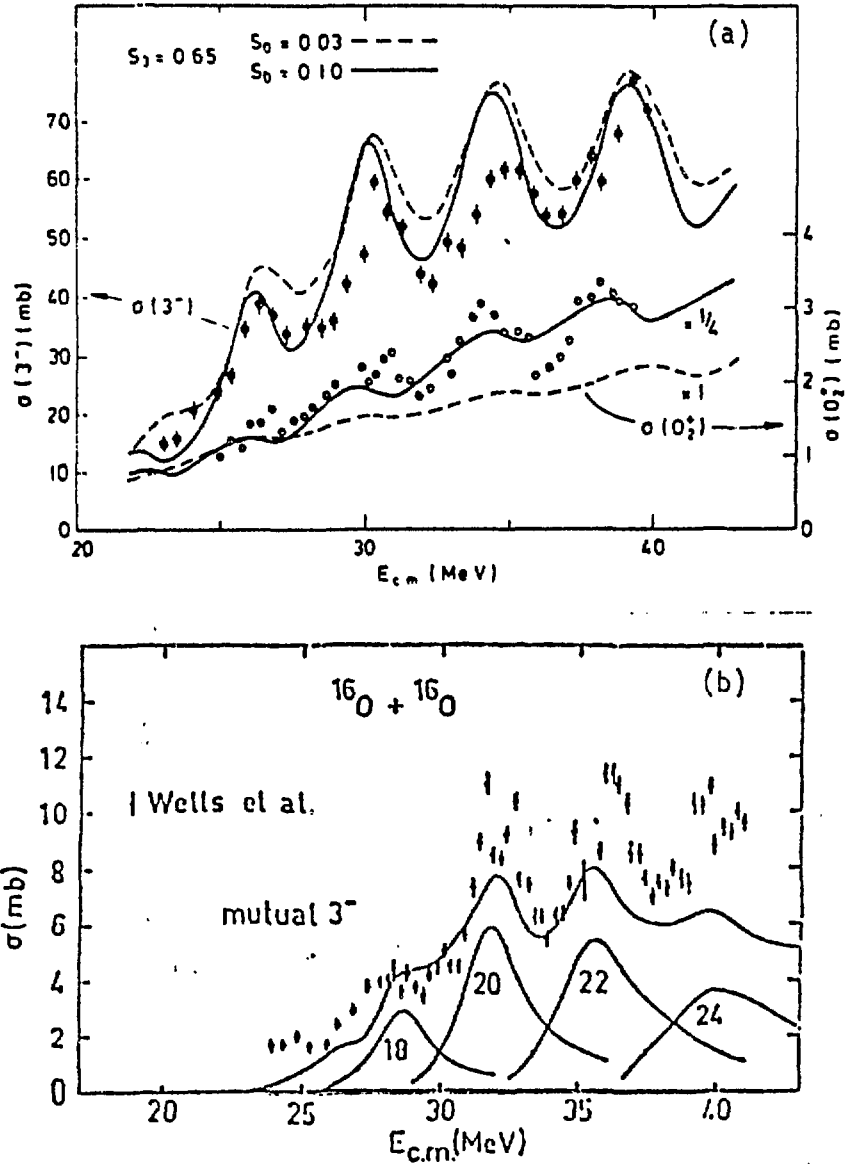
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FIGURE 7 $^{16}O + ^{16}O$ inelastic data and calculated cross
section under a strong coupling assumption. Coupling
strengths to the 0^+ and 3^- states are indicated in the
figure (S_o, S_3) (see ref. 10).

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data. Tanimura and Mosel have shown that the introduction
of strong coupling between the different inelastic
channels shifts the grazing partial waves so as to permit
reproduction of all these structures with their proper
phase.[10]

When the coupling to inelastic channels is strong the
nuclei deform as they approach each other, inducing a change
in the interaction potential. The wave functions obtained
after solving the coupled channels equation were used by
Tanimura and Mosel[10] to calculate this polarization correc-
tion. The resulting effective potentials for $^{16}O + ^{16}O$ are
shown in Figure 8 for five different inelastic channels.
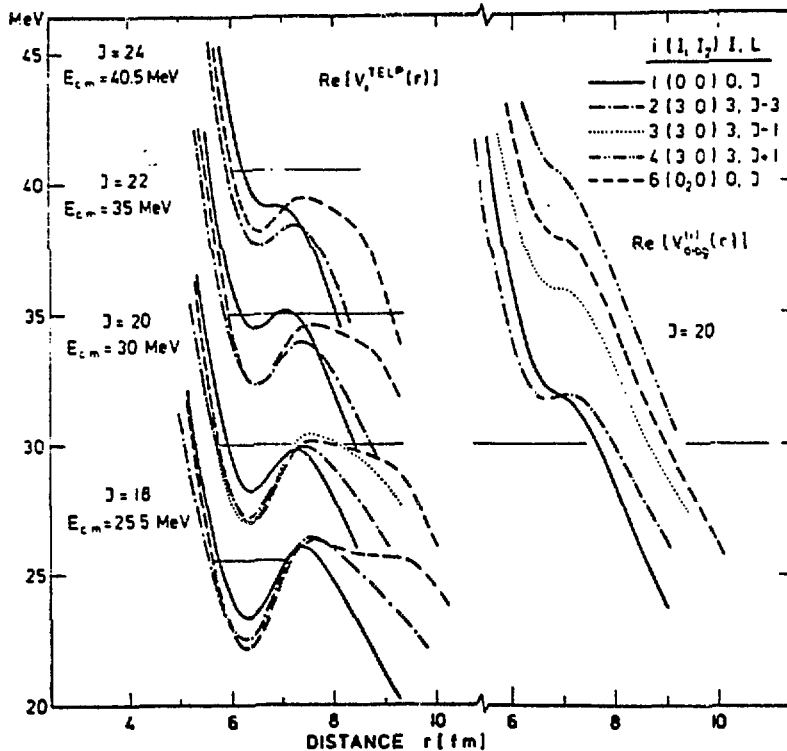The barrier heights for all channels are the same within

FIGURE 8   Equivalent local potentials for different
$^{16}O + ^{16}O$ elastic and inelastic channels.

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±1 MeV--and the barrier top positions coincide with the
positions of the maxima in the inelastic cross sections.
This may be another indication that molecular bonding
reflects the behavior of the interaction at distances well
outside the pocket in the nucleus-nucleus potential and
close to the barrier-top region, rather than in the vicinity
of the pocket minimum.

The study of molecular degrees of freedom in systems
other than $^{12}C + ^{12}C$, $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$ is considera-
bly more difficult, especially when approached within the
"Microscopic" context. At this juncture it has not yet been
settled whether the lack of intermediate width resonances in
the majority of reactions between light heavy ions reflects
a diminished role of molecular degrees of freedom or simply
the availability of many open channels which have large
parentage with molecular configuration. Under such circum-
stances the resonance yields to individual channels may be
small in comparison to the background from other processes.[13]

For cases where this argument is true there may be
clear advantages to be gained from studying reaction and
scattering yields in the backward hemisphere. A long-lived
rotating molecular state is expected to decay there with
nondiminished probability, while most peripheral processes
are forward or side-peaked. Backward and forward angles can
be measured separately only if the systems have significant
asymmetry between target and projectile. A good example is
the $^{28}Si + ^{16}O$ elastic scattering study reported several
years ago by P. Braun-Munzinger et al.[14] Shown in Figure 9
is the elastic angular distribution for $^{28}Si + ^{16}O$ measured
over the whole angular range. The large cross sections at
backward angles are not expected for reactions with strong
absorption. The large magnitude of the observed back angle
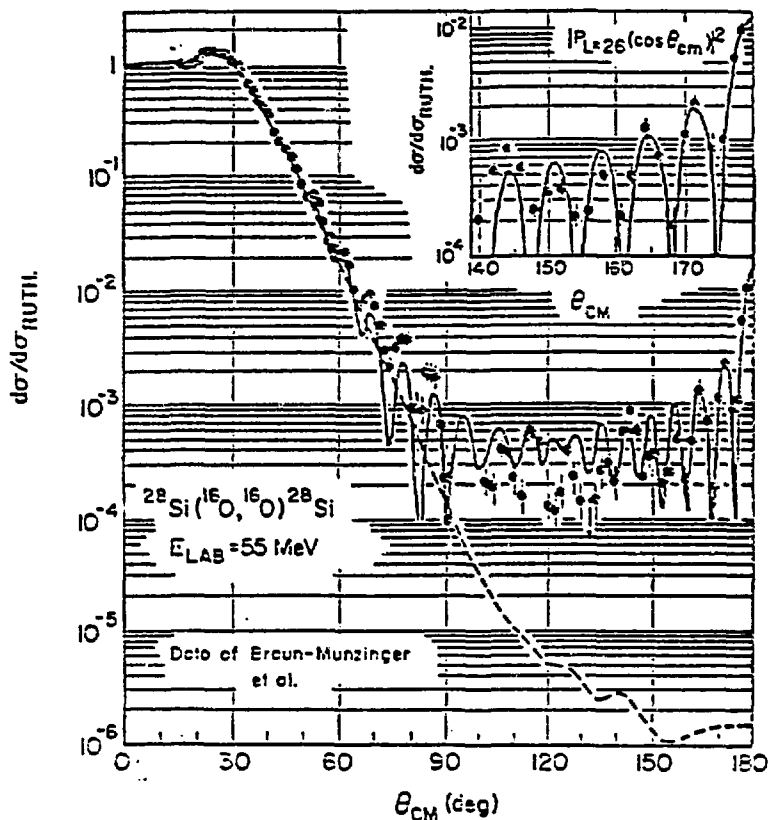
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FIGURE 9   Full angular distribution of ^{28}Si and ^{16}O elastic scattering.

yields precludes their interpretation in terms of small impact parameter phenomena immediately leading to the suggestion,[15] that orbiting resonances of target plus projectile are the source of these angle dependences. This discovery led to a flurry of activity[16] which revealed similar effects in many systems.

Figure 10 shows the elastic and inelastic excitation functions for ^{28}Si + ^{12}C measured close to 180°.[15,17] There is plenty of gross and intermediate structure and much of it seems correlated in the elastic and inelastic channels.
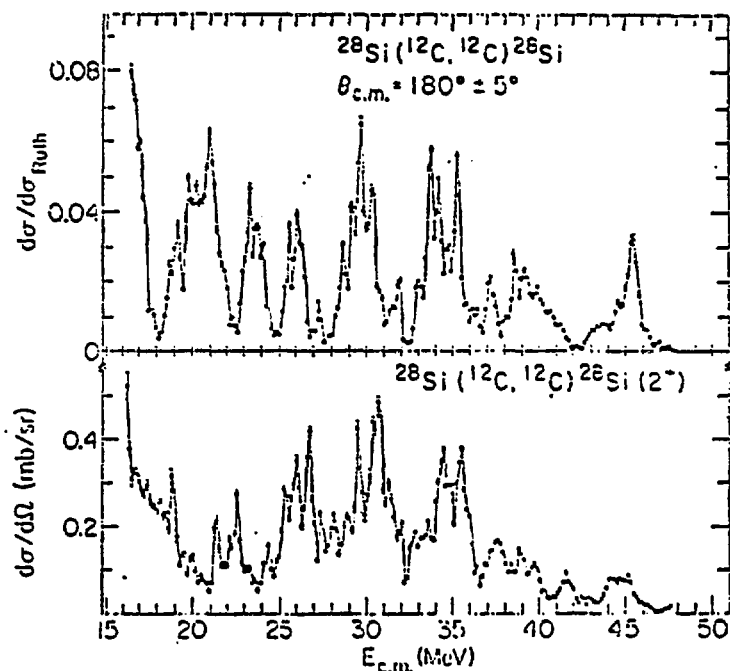
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FIGURE 10 ^{28}Si + ^{12}C elastic and inelastic excitation functions at backward angles.

However, attempts to probe the analogy with ^{12}C + ^{12}C behavior by measuring integrated cross sections proved disappointing. Figure 11 shows the results of a γ-ray measurement of the inelastic yield by Vandenbosch et al.[18] The total inelastic yield shows no significant structure. This could mean either that the structure observed at back angles does not reflect molecular degrees of freedom or that the yield from nuclear molecular processes is distributed over many exit channels and therefore (as discussed above) is not discernible in the presence of the large background.

Figure 12 shows spectra of ^{28}Si + ^{12}C measured at backward angles but over a large range of excitation energy. The "anomalously large" elastic cross section at this backward angle is dwarfed in comparison to the large inelastic
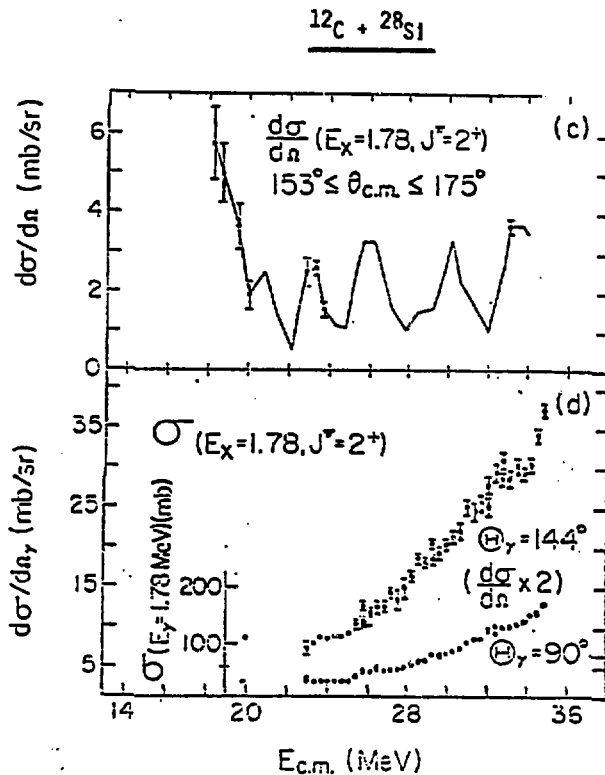
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$$^{12}C + {}^{28}Si$$

FIGURE 11   Integrated cross section for $^{28}Si + {}^{12}C$ inelastic scattering.

yields present. A similar situation prevails also for few nucleon transfer channels. In our studies of the $^{28}Si + {}^{12}C$ and several other systems we have treated the entire yield shown in Figure 12 as originating from one process. This process is depicted schematically in Figure 13: The two nuclei (hard spheres) collide, clutch together, rotate for a while and then separate. When separated the receding fragments will be spinning around their own axes, this results in a reduction of the relative kinetic energy for the separated spheres. Clearly such a description can provide intuitive understanding of our observation but in a

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FIGURE 12 $^{28}Si + ^{12}C$
elastic and inelastic
scattering to backward
angles at different bom-
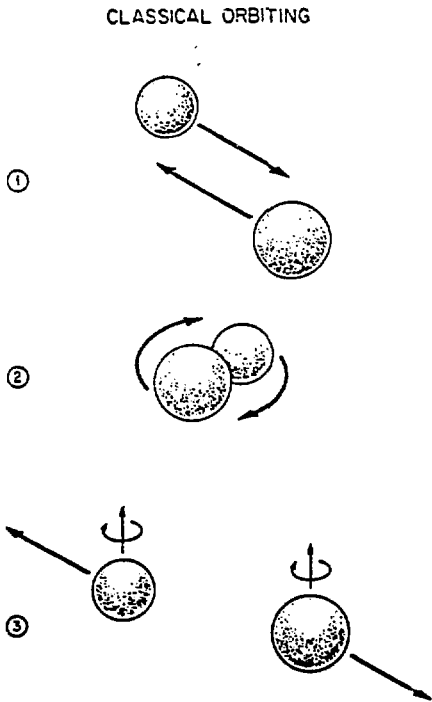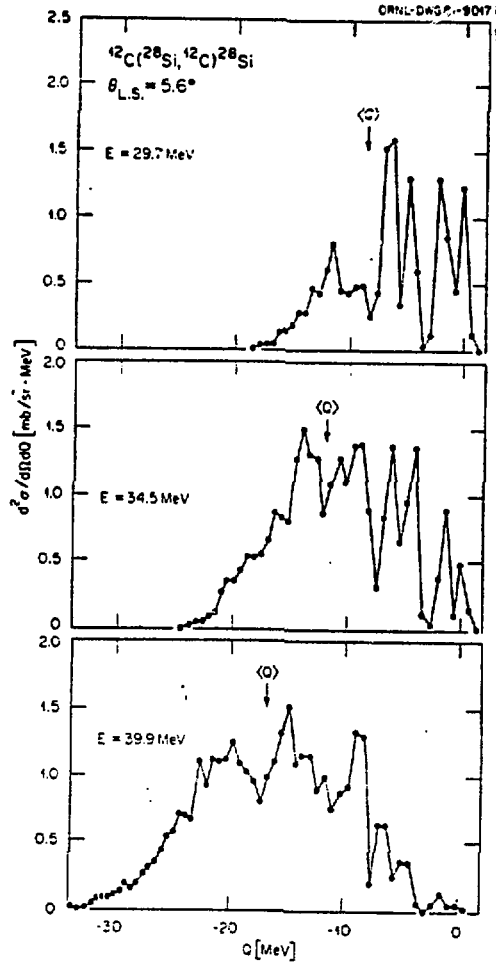barding energies.

CLASSICAL ORBITING

FIGURE 13   Schematic
description of classical
orbiting.

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quantum mechanical system the macroscopic quantities must
be derived from microscopic distributions, and their most
probable values should coincide with the expectation values
of semiclassical macroscopic quantities. Provided the
rotating complex lives long enough ($\sim 10^{-19}$ sec) for many
nuclear degrees of freedom to equilibrate it can be con-
sidered a quasi or nuclear molecule.

In a series of measurements carried out on ^{28}Si + ^{12}C and several other systems[19] the energy and angular distributions of outgoing products were measured in the backward hemisphere. The kinetic energy distributions are shown in Figure 14 for three outgoing channels from Si + C. The most probable kinetic energies (maxima) were found to be independent of emission angle, (see Figure 15) but to depend linearly on bombarding energy (Figure 16). The
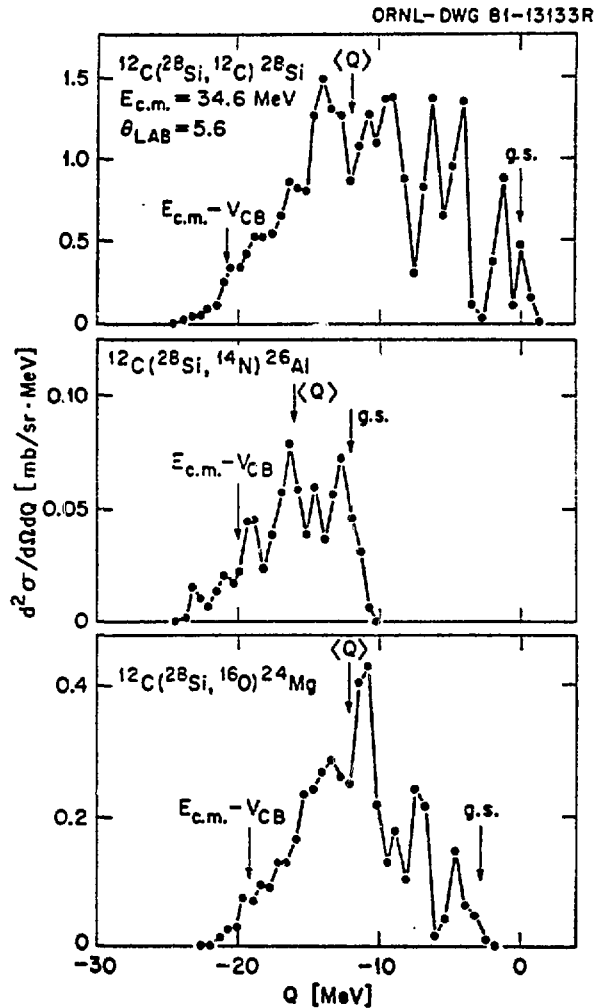
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FIGURE 14. Energy spectra for carbon, nitrogen and oxygen nuclei emerging at backward angles from ^{28}Si + ^{12}C collisions.
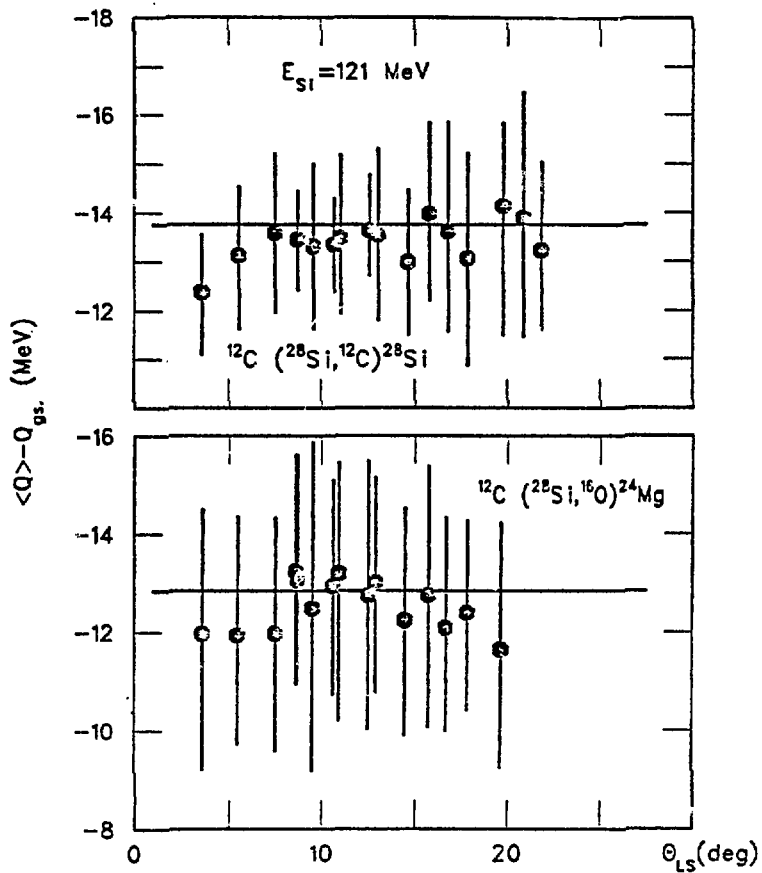
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FIGURE 15   Dependence of most probable Q value on
scattering angle for two outgoing channels at a single bom-
barding energy.

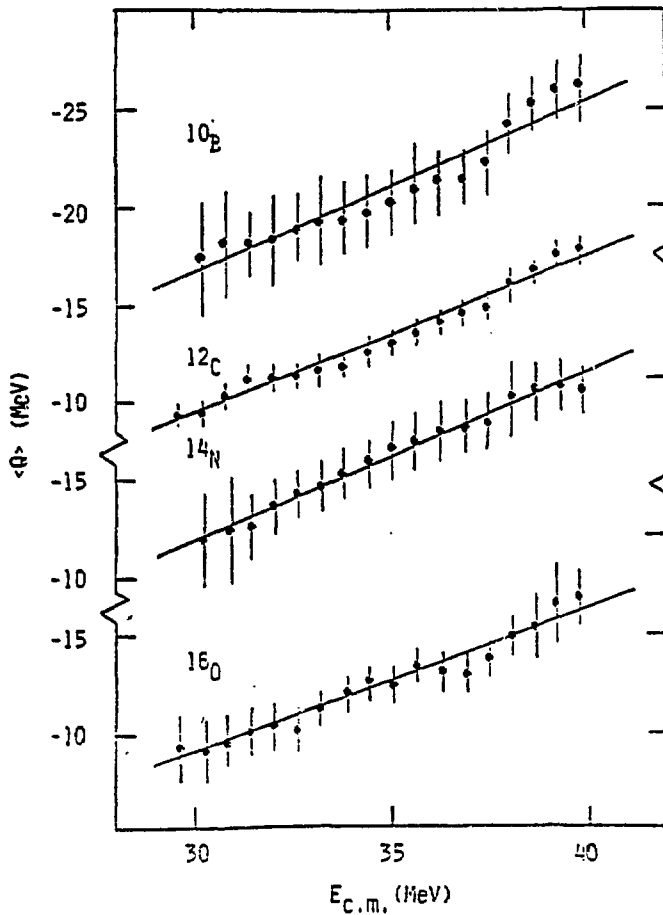MOLECULAR DEGREES OF FREEDOM...

FIGURE 16   Dependence of most probable Q-value on bombarding energy.

angular distribution of the integrated yield is isotropic (Figure 17). A simple quantitative analysis of the data shown in Figure 16 (bombarding energy dependence) with the classical formulae listed in Figure 18 (all the classical macroscopic quantities are identified with the maxima of the measured distributions) yields, among other results, information on the radius of the dinuclear system before scission

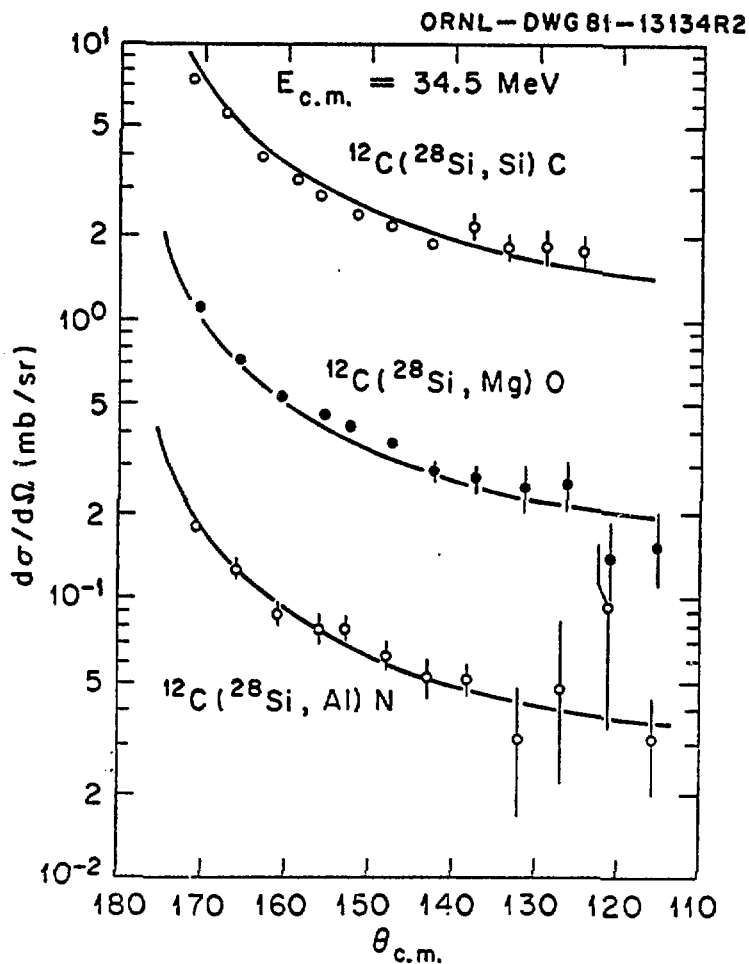D. SHAPIRA AND K. A. ERB

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FIGURE 17   Angular distribution of the integrated carbon, nitrogen and oxygen nuclei yields in the backward hemisphere.

and these results are shown in Table II. These radii may be interpreted with the aid of Figure 19, which shows a $^{28}Si + ^{12}C$ nucleus-nucleus potential. One can see that the radius at which the dinuclear system is formed (or separates) is <u>outside</u> the well of the nucleus-nucleus potential very close to the top of the barrier of that potential.

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$$E^f_{KIN} = \underline{\underline{a_0}} + \underline{a_1\, E^i}$$

$$E^f_{KIN} = V_{COUL}(d) + V_{NUCL}(d) + \frac{\hbar^2}{2\mu d^2}\, \ell_f(\ell_f + 1)$$
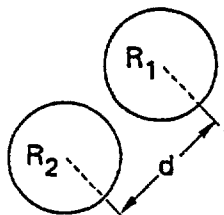
$$d = R_1 + R_2 + X$$

V_{COUL} (d) — CHARGED SPHERES

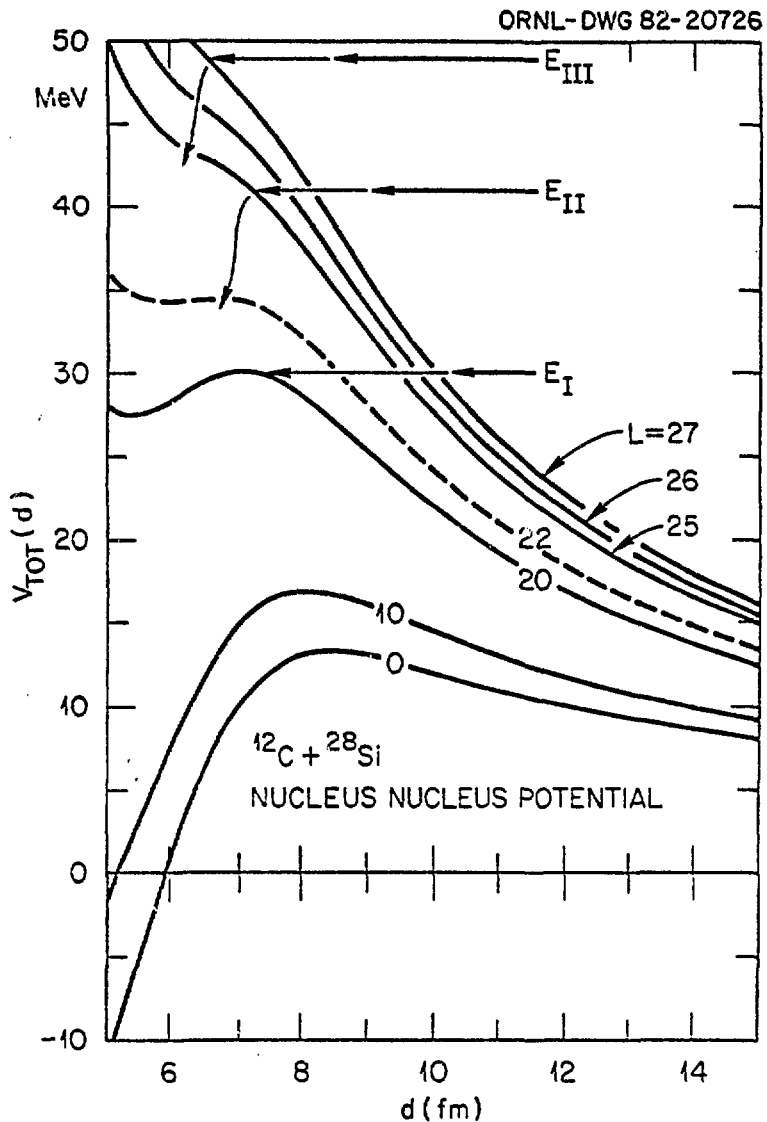V_{NUCL} (d) — PROXIMITY TYPE (BASS)

$\ell_f = f * \ell_i$

ℓ_i = INCOMING ANGULAR MOMENTUM

FIGURE 18

TABLE II   Experimental values for d.

	$a_o = V_{Coul}(d) + V_{Nucl}(d)$	
	$d = R_1 + R_2 + X$	X
B + P	7.8 ± .5	2.1
C + Si	8.2 ± .3	3.2
N + Al	7.2 ± .3	2.0
O + Mg	7.0 ± .3	1.7

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FIGURE 19 $^{12}C + ^{28}Si$ nucleus-nucleus potential.

The macroscopic study of the molecular degrees of
freedom is seen to yield results that agree with these
obtained from the "microscopic" study namely that the radius
of "molecular-bonding" has to be large and is located near
the top of the normal nucleus-nucleus potential. Similar

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studies on other systems such as $^{12}C + ^{20}Ne$,[20] $^{12}C + ^{24}Mg$,[20] $^{16}O + ^{27}Al$[20] and $^{12}C + ^{29}Si$[20] have shown very similar behavior at backward angles, suggesting that dinuclear motion of the type described here is prevalent and probably the rule rather than the exception for light systems. Whether such degrees of freedom can couple to particular states in the composite systems and produce narrow resonances may depend on the structure of the colliding nuclei and the compound system formed. Data on heavier systems such as $^{24}Mg + ^{24}Mg$, $^{28}Si + ^{28}Si$ and other sytems[21] suggest that such narrow resonances are not limited to light systems alone.

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22. R. BETTS, contribution to this conference.

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