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Resonances in the $^{11}B + ^{12}C$ system

A. D. Frawley, J. F. Mateja,* A. Roy,† and N. R. Fletcher
Department of Physics, The Florida State University, Tallahassee, Florida 32306
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Excitation functions have been measured at several angles for the elastic, inelastic, ^{8}Be, and α-particle exit channels of the $^{11}B + ^{12}C$ system. Nine resonances are identified in the energy range $E_{c.m.} = 9.4$ to 17.8 MeV. A comparison with resonance data from the ^{8}Be exit channel of the $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^9Be + ^{12}C$ systems is presented.

[NUCLEAR REACTIONS $^{12}C(^{11}B, ^8Be)$, $^{12}C(^{11}B, \alpha)$, and elastic and inelastic scattering, $E_{c.m.} = 9.4-17.8$ MeV; measured $\sigma(\theta, E)$; deduced resonances.]

I. INTRODUCTION

In spite of the effort put into searches for resonances in heavy-ion systems (see Refs. 1–3 and references therein), there is still no clear picture of the way in which the strengths, widths, and densities of heavy-ion resonances change as one goes from one heavy-ion combination to another. In particular, there is not yet enough information to draw solid conclusions about the effect of adding or removing a nucleon from one of the heavy ions in the strongly resonating α-type systems $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$. At the very least such information should be helpful in evaluating the models proposed to explain resonances in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems.

We report here a study of the $^{11}B + ^{12}C$ system. We have measured excitation functions for the elastic, inelastic, ^{8}Be, and α-particle exit channels of the $^{11}B + ^{12}C$ system over the energy range $E_{c.m.} = 9.4$ to 17.8 MeV. The data show clear evidence for nine narrow resonances in ^{23}Na. The average width is about 300 keV. Two resonances which appear strongly in the elastic scattering channel were reported in an earlier publication,[4] where the elastic scattering and some ^{8}Be data were presented. A comparison with ^{8}Be data from the $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^9Be + ^{12}C$ systems is presented and discussed.

II. EXPERIMENTAL DETAILS

The measurements were made using a ^{11}B beam from the Florida State University (FSU) super-FN Tandem Van De Graaff accelerator, with natural carbon targets. Excitation functions were measured between laboratory energies of 18.8 and 34.1 MeV in steps of approximately 200 keV.

Elastic scattering cross sections were obtained at 10 c.m. angles from 28.0° to 150.8° for the ^{11}B by measuring both ^{11}B and ^{12}C yields at laboratory angles of 14.6°, 19.6°, 24.6°, 49.6°, and 59.6°. A telescope with a 15 μm ΔE detector was used at the three most forward angles; at the two remaining angles, single thin detectors were used so as to minimize the energy loss of light reaction products and prevent them from obscuring the relatively low energy ^{11}B and ^{12}C events. Some data were obtained at 14.6° and 19.6° for two ^{12}C recoil groups from inelastic scattering events.

The ^{8}Be measurements were made using the FSU ^{8}Be detection system.[5] Thin aluminum foils were used in front of the detectors to stop the elastically scattered ^{11}B particles. The ^{8}Be events were detected at 5° intervals from 7.5° to 32.5° in the laboratory. Data were obtained for reactions leading to the g.s. of ^{15}N, the unresolved states at 5.270 and 5.299 MeV, the state at 6.323 MeV, and the unresolved states at 7.154, 7.300, and 7.563 MeV. Because breakup α particles from low energy ^{8}Be events were stopped in the aluminum foils, the lower energy groups were observed only at forward angles. Some data were lost also because of interference from a contaminant group due to the $^1H(^{11}B, ^8Be)^4He$ reaction.

The α-particle measurements were made at the laboratory angles 19.6°, 29.6°, and 39.6°. Data were obtained for reactions leading to the unresolved g.s., 0.110, and 0.197 MeV states, the unresolved 1.35, 1.46, and 1.56 MeV states, and the 2.79 MeV state in ^{19}F.

During all of the measurements discussed above, carbon buildup on the targets was reduced by placing liquid nitrogen traps in the beam line and around the target. Carbon buildup was found to be about 10% over the duration of one excitation function for the elastic scattering and α-particle measurements, and about 20% for the ^{8}Be measurements. The data are not corrected for target thickness increase with time. Absolute cross sections were obtained by measuring the yield of ^{16}O elastic scattering at 20 MeV at angles of 17° to 23° in the laboratory, and normalizing to the calculated Rutherford cross section. The absolute cross sections are believed accurate to within 15%. The target thicknesses were found to be about 60 μg/cm^2 for the elastic scattering and α-particle measurements, and about 80 μg/cm^2 for the ^{8}Be measurements. These correspond to energy losses of 200 and 270 keV in the laboratory at the low energy end of the excitation functions. All c.m. energies given in this paper are corrected for energy loss in the target.

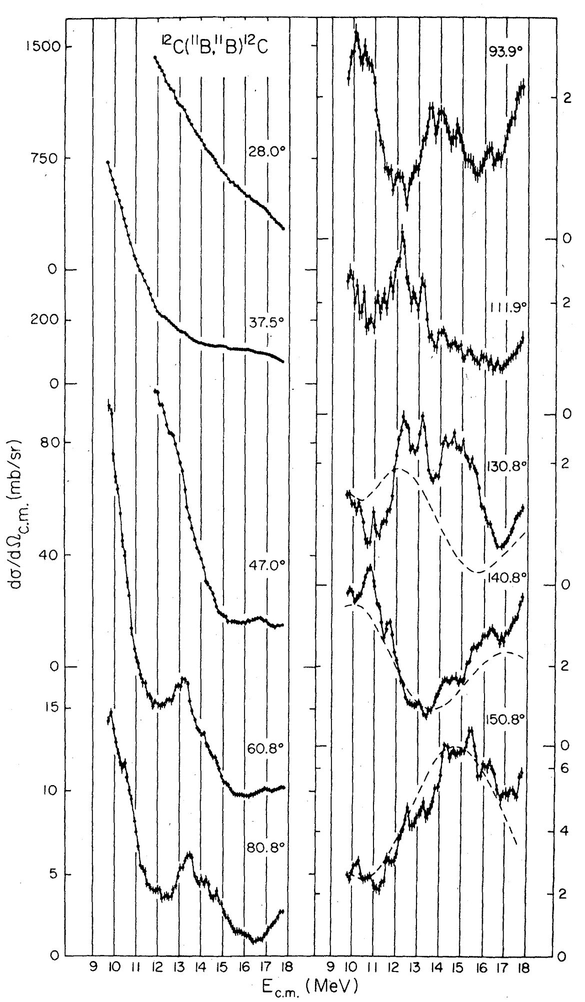

FIG. 1. Center of mass cross sections for elastic scattering of ^{11}B on ^{12}C. The angles are c.m. angles of ^{11}B emission.

III. RESULTS AND DISCUSSION

The elastic scattering excitation functions are shown in Fig. 1 and those for the four ^{8}Be groups in Figs. 2–4. Figure 5 shows the α-particle data, and Fig. 6 the inelastic scattering data.

In the following discussion it is argued that nine resonances may be identified in ^{23}Na on the basis of our data. The arguments are based entirely on correlations over angle and exit channel. To reduce the probability that a chance correlation between peaks due to fluctuations might be mistaken for evidence of a resonance, we consider only structure which is found to be correlated in at least three exit channels. The probability of such a mistake is further reduced in most cases by the observation of correlations over angular ranges much greater than the estimated fluctuation coherence angles ($1/kr \simeq 4°$ for the elastic scattering, for example). In each case, data are compared for the various exit channels at one or two angles where the structure is clearest. The selected data are presented in Figs. 7–9.

10.1 MeV (Fig. 7). Evidence for a resonance at 10.1 MeV may be seen in the cross sections of the

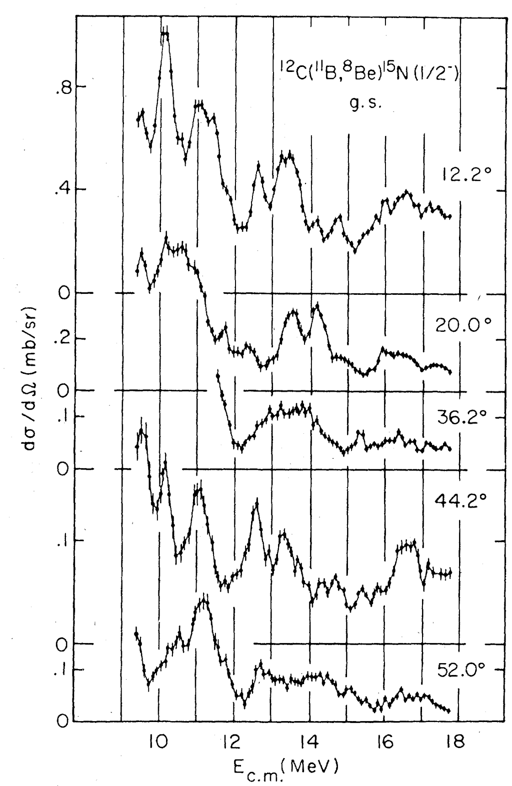

FIG. 2. Center of mass cross sections for the ^{12}C(^{11}B, ^{8}Be)^{15}N (g.s.) reaction. The angles are the c.m. angles at $E_{c.m.}$ = 13.5 MeV incident energy.

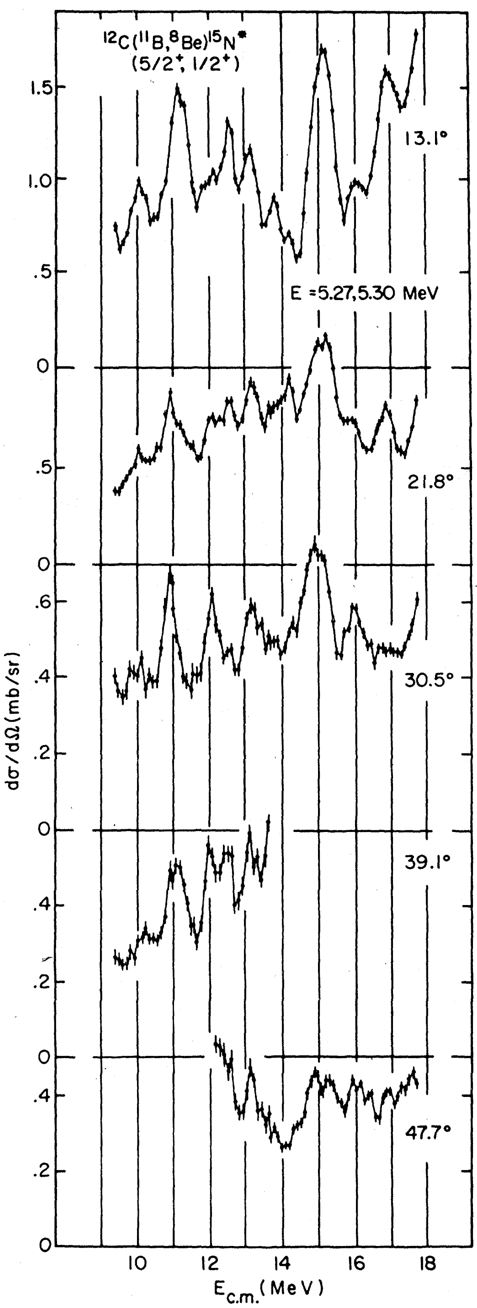

FIG. 3. Center of mass cross sections for the $^{12}C(^{11}B, ^{8}Be)^{15}N^*$ (5.27 and 5.30 MeV) reaction. The angles are the c.m. angles at $E_{c.m.} = 13.5$ MeV incident energy.

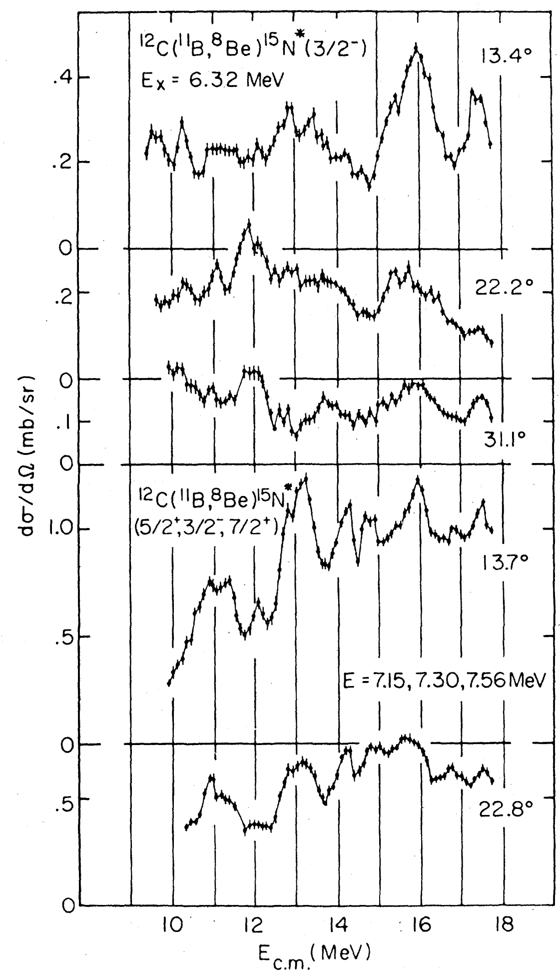

FIG. 4. Center of mass cross sections for the $^{12}C(^{11}B, ^{8}Be)^{15}N^*$ (6.32 MeV) and $^{12}C(^{11}B, ^{8}Be)^{15}N^*$ (7.15, 7.30, 7.56 MeV) reactions. The angles are the c.m. angles at $E_{c.m.} = 13.5$ MeV incident energy.

first two ^{8}Be groups and the second α-particle group. Note that the structure is correlated over about 32° in the c.m. for the ground state ^{8}Be group.

10.9 MeV (Fig. 7). Here, structure is seen in the second and fourth ^{8}Be groups, the first α-particle group, and in the elastic scattering at the three most backward angles. The structure in the first α-particle group is observed at all three angles, a range of about 26°.

11.7 MeV (Fig. 7). The first two α-particle groups and the elastic scattering show structure at this energy. The structure appears over a wide angular range in the first two α-particle groups and is observed at 140.8°, 150.8°, and, weakly, at 93.9° in the elastic scattering.

12.5 MeV (Fig. 8). Structure is observed in the first two ^{8}Be groups, the third α-particle group, and the elastic scattering. The effect in the elastic scattering cross sections is strong and is correlated over about 57°. The structure is correlated over 32° for the first ^{8}Be group and 26° for the

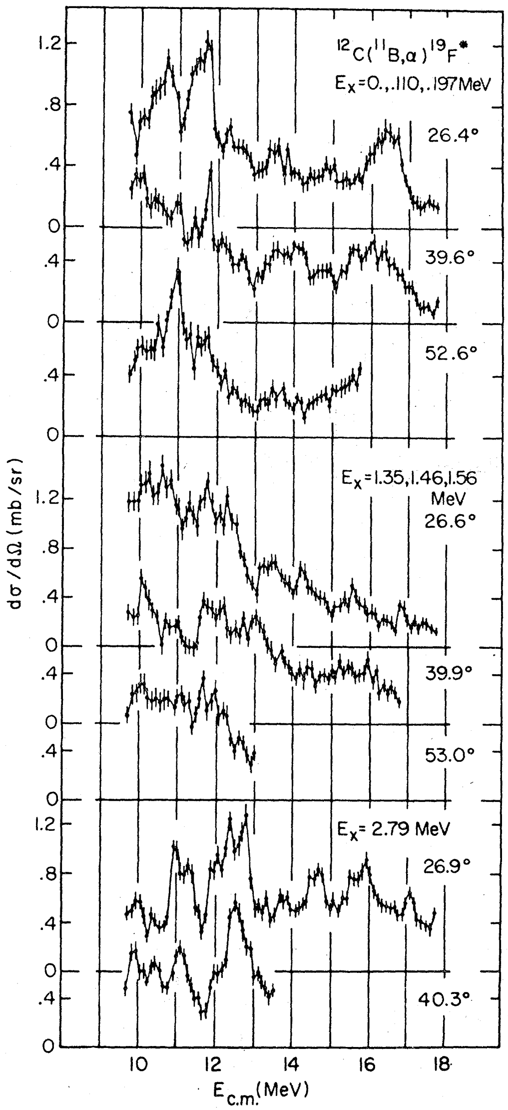

FIG. 5. Laboratory cross sections for the $^{12}C(^{11}B,\alpha)^{19}F$ reactions to the indicated final states. The angles are c.m. angles at $E_{c.m.}$ = 13.5 MeV incident energy.

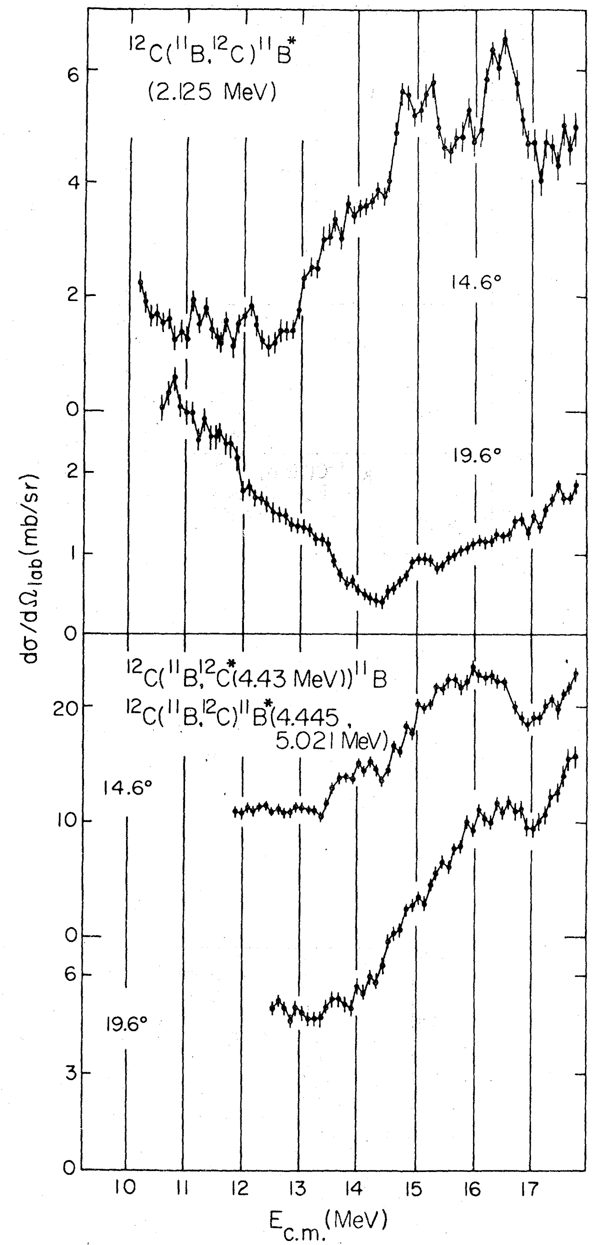

FIG. 6. Laboratory cross sections for the inelastic scattering of ^{11}B from ^{12}C leading to the indicated final states. The angles are laboratory angles.

second ^8Be group. This resonance was reported previously.[4]

13.2 MeV (Fig. 8). Evidence of this resonance appears in the data for the second and fourth ^8Be groups, and in the elastic scattering. Structure is observed in the elastic channel near 13.2 MeV at every angle from 60.8° to 150.8°, and for the second ^8Be group at every angle studied, a range of about 35°. This resonance was also reported previously.[4]

14.2 MeV (Fig. 8). At this energy an effect is seen clearly in the data for the first, second, and fourth ^8Be groups. There is also weak structure in the second α-particle group and in the elastic scattering.

14.8 and 15.3 MeV (Fig. 9). This anomaly, observed at every angle in the data for the second ^8Be group, is the most striking feature in the ^8Be data. It is evidently due to a pair of overlapping resonances having energies of about 14.8 and 15.3 MeV. The inelastic scattering to the first excited

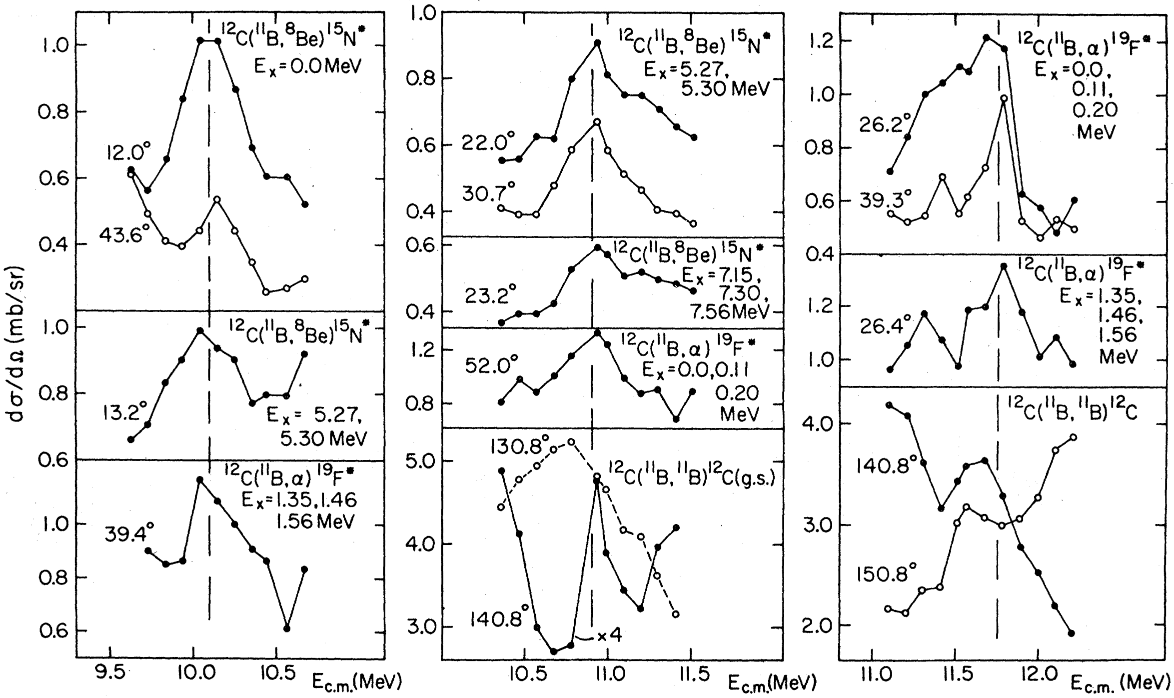

FIG. 7. Comparison of data in various exit channels in the region of the resonances at 10.1, 10.9, and 11.7 MeV. The angles are c.m. angles at the resonance energies. The α-particle cross sections are in the laboratory system, all others are c.m.

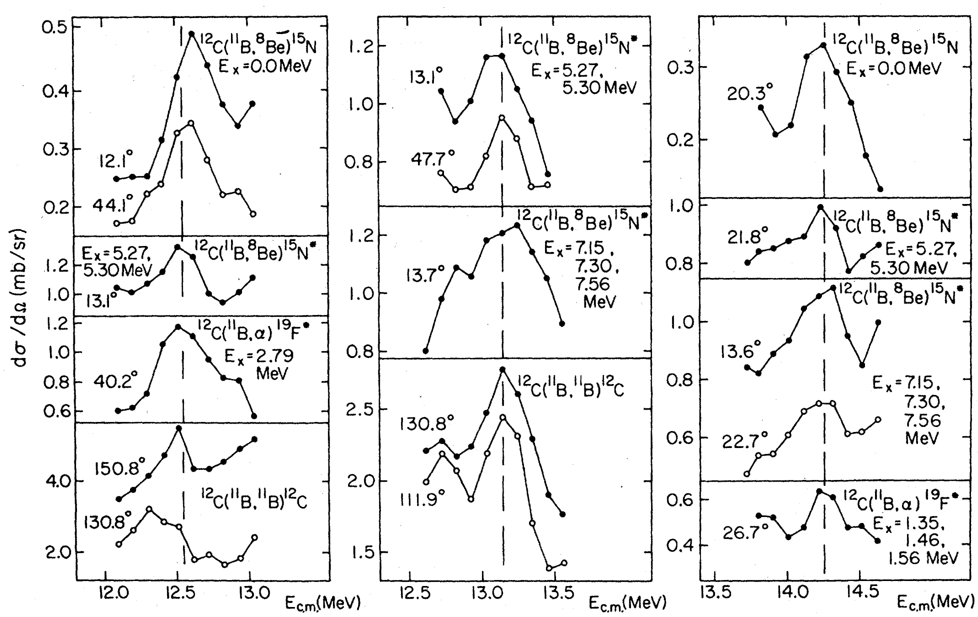

FIG. 8. Comparison of data in various exit channels in the region of the resonances at 12.5, 13.2, and 14.2 MeV. The angles are c.m. angles at the resonance energies. The α-particle cross sections are in the laboratory system, all others are c.m.

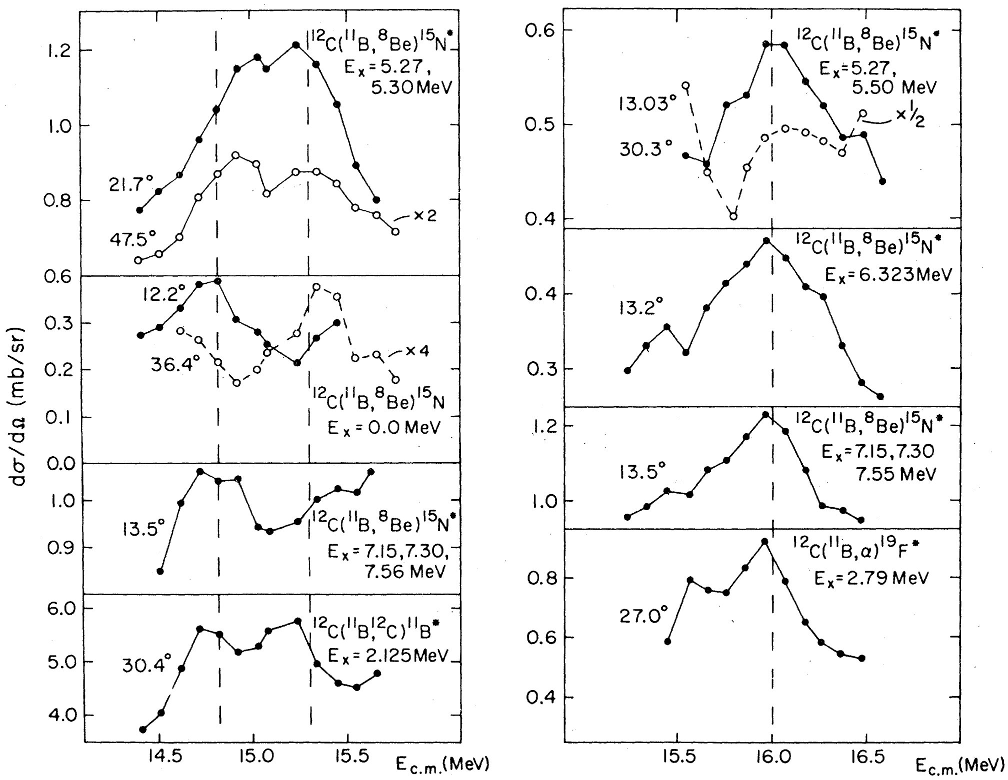

FIG. 9. Comparison of data in various exit channels in the region of the 14.8 and 15.3 MeV resonances, and of the 16.0 MeV resonance. The α-particle and inelastic scattering cross sections are in the lab system, all others are c.m.

state of ^{11}B shows a similar anomaly, slightly shifted in energy. The first ^{8}Be group shows weak structure near 14.8 and 15.3 MeV, the third ^{8}Be group shows an effect near 15.3 MeV, and the fourth ^{8}Be group shows structure near 14.8 MeV.

16.0 MeV (Fig. 9). Structure is seen here in the data for the second, third, and fourth ^{8}Be groups, and for the third α-particle group. The second ^{8}Be group shows an effect at all angles, a range of about 35°. There is also weak structure in the elastic scattering at 93.9° and 150.8°.

In addition to the more or less isolated resonances for which evidence is presented above, there is evidently a group of two or more overlapping resonances near 11.2 MeV. Broad structure, overlapping the position of the 10.9 MeV resonance, is observed for all ^{8}Be groups and also for the third α-particle group. The broad structure changes shape and width from angle to angle and final state to final state, suggesting that it is due to more than one resonance.

There are a number of energies at which structure is observed which is probably due to resonances, but these cases do not meet the criterion employed above, namely, that there be a clear correlation over at least three final states. For example, at about 12.1 MeV structure is present in the data for the second and fourth ^{8}Be groups and also, very weakly, in those for the third ^{8}Be group. Other such examples occur at about 13.5, 17.0, and 17.5 MeV.

Apart from the evidence presented above for the presence of resonances in ^{23}Na, there are some general features of the data which should be mentioned.

Both the elastic and inelastic scattering cross sections (Figs. 1 and 6) show gross structure. For the elastic scattering at far back angles, where the broad structure is very strong, it was found[4] to be consistent with distorted-wave Born approximation (DWBA) calculations of the one proton elastic transfer contribution.

While the elastic scattering, ^{8}Be, and α-particle cross sections all show considerable narrow structure, the inelastic scattering cross sections are relatively smooth. The inelastic scattering data suggest that there is little involvement of the low lying excited states of ^{11}B and the first excited state of ^{12}C in the wave functions of the resonances observed in the other channels. This may be contrasted with the cases of $^{12}C+^{12}C$ (Ref. 6) and $^{12}C+^{16}O$,[7] where it has been found that the

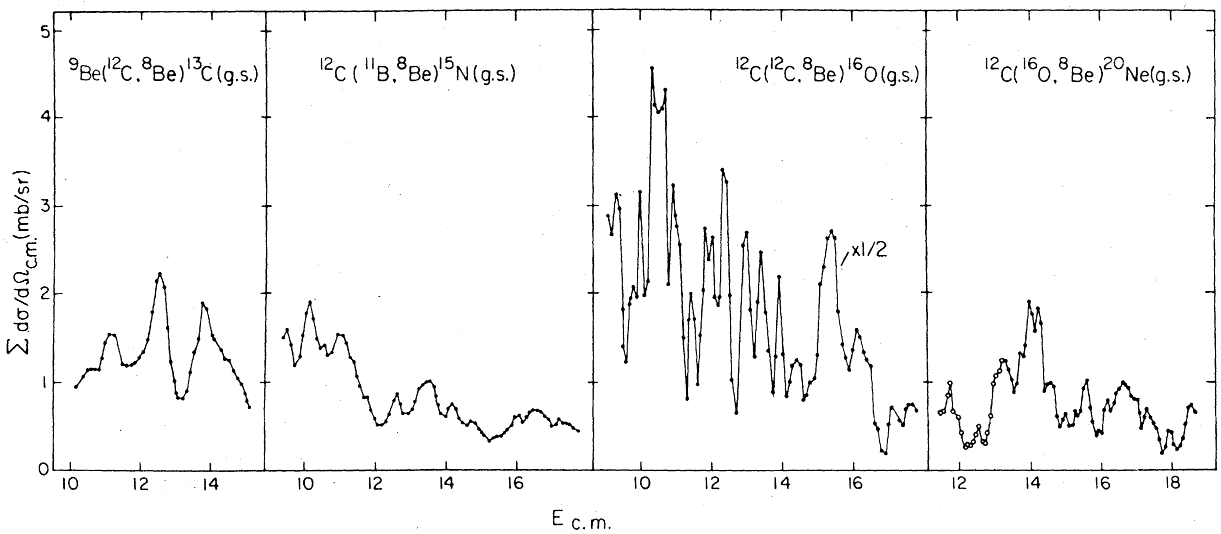

FIG. 10. Comparison of data for the ground state ^{8}Be group from the decay of the $^{9}Be + ^{12}C$, $^{11}B + ^{12}C$, $^{12}C + ^{12}C$, and $^{16}O + ^{12}C$ systems. The c.m. cross sections have been summed over the following laboratory angles:

$$\bullet = \sum_{\theta_{lab}} 7.5°, 12.5°, 27.5°, 32.5°$$

$$\circ = \sum_{\theta_{lab}} 12.5°, 17.5°, 27.5°, 32.5°$$

The values for $^{12}C + ^{12}C$ have been reduced by a factor of 2 for easier comparison with those for the other three systems.

inelastic channels display many strong resonances in a comparable energy range.

Other systems in the mass region of $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ for which resonances have been reported are $^{12}C + ^{13}C$,[8] $^{10}B + ^{14}N$,[9] $^{12}C + ^{14}C$,[10] $^{15}N + ^{12}C$,[11] and $^{9}Be + ^{12}C$.[12] Of these, the claims have been disputed for $^{12}C + ^{13}C$ (Ref. 13) and $^{10}B + ^{14}N$.[14] The study of $^{12}C + ^{14}C$ (Ref. 10) was restricted to the α-particle, triton and deuteron channels, and the study of $^{15}N + ^{12}C$ (Ref. 11) to the α-particle exit channels, but the investigation of $^{9}Be + ^{12}C$ by Mateja *et al.*,[12] who identified five resonances in ^{21}Ne, included a study of the ^{8}Be channels as well as the elastic scattering and α-particle channels. Since there are now four systems for which ^{8}Be data are available in approximately the same energy range, a direct comparison of the ^{8}Be ground state excitation functions is possible. Figure 10 compares our $^{12}C(^{11}B, ^{8}Be)^{15}N$ (g.s.) data with corresponding data from the $^{12}C + ^{12}C$,[15] $^{12}C + ^{16}O$,[16] and $^{9}Be + ^{12}C$ (Ref. 12) systems. The data in each case are summed over the same four laboratory angles to lessen the effect of differences in the angular distributions. While the $^{12}C + ^{12}C$ system resonates much more strongly in the ^{8}Be channel than any of the others, there is little difference in strength between the $^{12}C + ^{16}O$, $^{11}B + ^{12}C$, and $^{9}Be + ^{12}C$ systems.

When making such a comparison, however, the effect of the nonzero channel spins of the $^{11}B + ^{12}C$ and $^{9}Be + ^{12}C$ systems should be considered. It has been found for $^{12}C + ^{12}C$ (Ref. 15) that the resonances of a particular spin are grouped near the energy of the corresponding grazing angular momentum, and that there is very little overlap of groups of resonances of different spin and the same parity. Therefore there is good reason to expect that only one l value will contribute to a given resonance even when the channel spin is not zero. If we assume that resonances are formed by a single l value and decay by a single l value regardless of the channel spins involved, then the angle integrated cross section for a reaction proceeding through an isolated resonance of spin J is given by[17]

$$\sigma_{\alpha\alpha'} = \frac{4\pi}{k_\alpha^2} g_J \frac{\Gamma_{\alpha l}\Gamma_{\alpha' l'}}{\Gamma^2_{\text{total}}}$$

at the resonance energy. The statistical spin factor g_J is defined by

$$g_J = \frac{2J+1}{(2I_1+1)(2I_2+1)},$$

where I_1 and I_2 are the spins of the pair of nuclei in the entrance channel α. The factor

TABLE I. Values of the angular momentum mismatch, defined as $\Delta l = l_{graze}$ (exit channel)$-l_{graze}$ (entrance) for the four reactions compared in Fig. 10. All values are calculated at $E_{c.m.} = 13.5$ MeV.

Reaction	Δl
$^{9}Be(^{12}C, ^{8}Be)^{13}C$ (g.s.)	$3\hbar$
$^{12}C(^{11}B, ^{8}Be)^{15}N$ (g.s.)	$2\hbar$
$^{12}C(^{12}C, ^{8}Be)^{16}O$ (g.s.)	$0\hbar$
$^{12}C(^{16}O, ^{8}Be)^{20}Ne$ (g.s.)	$-2\hbar$

$[(2I_1+1)(2I_2+1)]^{-1}$ accounts for the fact that only part of the entrance channel flux with relative angular momentum l couples to the channel spin (or spins) to form the total angular momentum J. This factor is $\frac{1}{4}$ for $^{11}B+^{12}C$ and $^{9}Be+^{12}C$, and 1 for $^{12}C+^{12}C$ and $^{12}C+^{16}O$. Therefore Fig. 10 suggests that the quantity

$$\frac{(2J+1)}{k_\alpha^{\ 2}} \frac{\Gamma_{\alpha l}\Gamma_{\alpha' l'}}{\Gamma^2_{\text{total}}}$$

is approximately the same for the strongest resonances observed in the ground state ^{8}Be decay channels of the $^{9}Be+^{12}C$, $^{11}B+^{12}C$, and $^{12}C+^{12}C$ systems, while for $^{12}C+^{16}O$ it is smaller by a factor of about 4. This is rather surprising, since it has been generally believed that $^{12}C+^{12}C$ and $^{12}C+^{16}O$ are the only two systems in this mass region which resonate strongly.

In light of the results for $^{12}C+^{12}C$,[15] it is likely that resonances will be strongly inhibited in a reaction where the grazing angular momenta in the entrance and exit channels are very different. We have calculated the difference in grazing angular momentum between the elastic and ground state ^{8}Be channels for the four systems compared above, assuming the grazing angular momentum is given by

$$l_{\text{graze}} = kR\left(1 - \frac{E_B}{E_{\text{c.m.}}}\right)^{1/2},$$

where E_B is the height of the Coulomb barrier and the radius R is calculated from

$$R = 1.6(A_1^{\ 1/3} + A_2^{\ 1/3}) \text{ fm}.$$

The results are presented in Table I for an incident energy of 13.5 MeV c.m. Since the $^{11}B+^{12}C$ and $^{9}Be+^{12}C$ systems both have channel spin $\frac{3}{2}$ in the elastic channel and $\frac{1}{2}$ in the ground state ^{8}Be channel, it is possible for a resonance to have l values in the entrance and exit channels which differe by two units of angular momentum. Therefore these two systems may be considered to be well matched for some combinations of J, l, and l'. The relative weakness of the $^{12}C+^{16}O$ resonances may be due to the grazing angular momentum mismatch of two units between the elastic and ground state ^{8}Be channels.

A similar comparison of elastic scattering data for the four systems is much more difficult, because of strong statistical fluctuations in the $^{12}C+^{12}C$ and $^{12}C+^{16}O$ cases and because of differing background contributions from optical model scattering and from elastic transfer at back angles. However, it is known that both $^{12}C+^{12}C$ (Refs. 6 and 18) and $^{12}C+^{16}O$ (Ref. 19) resonate strongly in the elastic channel. While $^{11}B+^{12}C$ does show substantial resonances in the elastic scattering, they appear to be considerably weaker than those observed in $^{12}C+^{12}C$ and $^{12}C+^{16}O$. It should be remembered that the factor $[(2I_1+1)(2I_2+1)]^{-1}$ appears in the formula for the elastic scattering cross sections also, and so one would expect resonances in the $^{11}B+^{12}C$ and $^{9}Be+^{12}C$ cases to be inhibited by a factor of 4 with respect to those for $^{12}C+^{12}C$, all other things being equal. The $^{9}Be+^{12}C$ elastic scattering[12] shows some weak structure, but no strong resonances are evident. The absence of strong resonances in the $^{9}Be+^{12}C$ elastic scattering suggests that the $^{9}Be+^{12}C$ strength in ^{21}Ne is more strongly fragmented than is the $^{11}B+^{12}C$ strength in ^{23}Na. It has been suggested[3] that the presence of the weakly bound valence neutron might lead to strong fragmentation for such cases as $^{12}C+^{9}Be$ and $^{12}C+^{13}C$. Information on the effect of the valence neutron could be obtained more directly from a comparison of data for the $^{12}C+^{11}B$ and $^{12}C+^{13}C$ systems, since both ^{11}B and ^{13}C have strong ^{12}C parentage. We are now studying the $^{12}C+^{13}C$ system to obtain data for such a comparison.

IV. SUMMARY

Excitation functions have been presented for the elastic, inelastic, ^{8}Be, and α-particle exit channels of the $^{11}B+^{12}C$ system over the energy range $E_{c.m.} = 9.4$ to 17.8 MeV. Nine resonances are identified in ^{23}Na using the criterion that there must be clear structure correlated in at least three of the exit channels. Four of the nine resonances are observed in the elastic scattering, two of them quite strongly. It is found that the inelastic scattering cross sections show very little narrow structure, in contrast with the cases of $^{12}C+^{12}C$ and $^{12}C+^{16}O$. We have compared ^{8}Be data from the $^{11}B+^{12}C$ system with similar data from the $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{9}Be+^{12}C$ systems, and found that, when the effect of the nonzero channel spins is taken into account, the $^{12}C+^{12}C$, $^{11}B+^{12}C$, and $^{9}Be+^{12}C$ systems resonate with approximately the same strength, while $^{12}C+^{16}O$ is weaker by a factor of about 4.

*Now at Tennessee Technological University, Cookeville, Tennessee 38501.

† On leave of absence from Tata Institute of Fundamental Research, Bombay, India.

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