Structure in the $^{12}C+^{12}C$ and $^{8}Be+^{16}O$ fission width distribution of ^{24}Mg observed via the reaction $^{12}C(^{16}O,\alpha)^{24}Mg^{*}\rightarrow X+Y$

A. J. Lazzarini,* S. G. Steadman, R. J. Ledoux, A. Sperduto,† G. R. Young,‡ K. Van Bibber,§ and E. R. Cosman
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 5 October 1982)

Prominent gross and intermediate width structures are observed in the $^{12}C+^{12}C$, $^{12}C+^{12}C^{*}(2^{+})$, $^{12}C^{*}(2^{+})+^{12}C^{*}(2^{+})$, $^{8}Be+^{16}O$, and $^{8}Be+^{16}O^{*}$ $(3^{-},0^{+})$ decay channels following $^{24}Mg^{*}$ population via the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction at $E_{c.m.}=33$ MeV. Evidence that the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction populates states in ^{24}Mg which are associated with $^{12}C+^{12}C$ resonances is presented in the form of correlation analyses between the $\alpha+^{12}C+^{12}C$ three-body spectra and previously measured $^{12}C+^{12}C$ elastic and inelastic excitation functions. Direct determination of $^{12}C+^{12}C$ widths from these measurements is obscured by a background of other strong transitions which appear to be present in the $^{12}C(^{16}O,\alpha)^{24}Mg$ singles spectrum.

[NUCLEAR REACTIONS $^{12}C(^{16}O,\alpha)^{24}Mg^{*}\rightarrow X+Y$; measured $\sigma(\alpha XY)$ three body coincidence, fission widths of states in ^{24}Mg between $E_x=20$ and 40 MeV. Intermediate structure observed.]

I. INTRODUCTION

Much information has become available recently in the study of resonant behavior in the $^{12}C(^{12}C,X)$ reactions at energies well above the $^{12}C+^{12}C$ Coulomb barrier. The first reported data of Cosman *et al.*[1] indicated the presence of several isolated and sharp resonances at $E_x(^{24}Mg)=25.4$, 28.3, and 33.3 MeV in the reaction $^{12}C(^{12}C,p)^{23}Na$. They were seen to decay strongly to a pair of states in ^{23}Na at $E_x=9.04$ and 9.81 MeV. Subsequent analyses of the $^{12}C(^{12}C,p)^{23}Na$ coincidence study[2,3] and of the analogous $^{12}C(^{12}C,n)^{23}Mg$ reaction[4] have indicated that these are high-lying states in ^{23}Na and ^{23}Mg with spins $\frac{15}{2}^{+}$ and either $\frac{15}{2}^{+}$ or $\frac{17}{2}^{+}$. The lower state is a member of the ground-state rotational band. From considerations of the dynamics of proton decay to these two states in ^{23}Na and also from studies of the $^{12}C(^{12}C,\alpha_0)^{20}Ne$ reaction,[5] the three resonances were assigned spins of $J^{\pi}=8^{+}$, 10^{+}, and 12^{+}, respectively. A resonance at $E_x(^{24}Mg)=39$ MeV was seen in the $^{12}C(^{12}C,d)^{22}Na$ reaction and has been tentatively assigned $J^{\pi}=14^{+}$.

More recent studies by Fletcher *et al.*[6] and by Eberhard *et al.*[7] of the $^{12}C(^{12}C,^{8}Be)^{16}O$ reaction have revealed a multiplicity of resonant states in ^{24}Mg; 17 resonances have been reported between $24\leq E_x\leq 34$ MeV. The resonances are closely spaced, with widths equal to 100–400 keV. They are observed to cluster in groups of common spin and parity, the groupings themselves being several MeV in breadth. Most of the states have spins $J^{\pi}=8^{+}$ and 10^{+}; one state at the lower end of the energy range has been assigned as 6^{+} and several at the high end of the range have been identified as 12^{+}. Fletcher *et al.*,[6] and, more recently, Feshbach,[8] have commented on this behavior of the $^{12}C+^{12}C$ system. They point out that this experimental evidence is supportive of the presence of one or more doorway states in ^{24}Mg which have been fragmented over the compound-nuclear states of the system. Such a fragmentation can be accounted for by a weak coupling between a broad shape, elastic resonance in the entrance channel ion-ion potential and the more complex doorway states themselves. The weakness of the coupling is imperative if the spreading width of the resonances into the compound nucleus is to remain small enough for them to be observable.

Cormier *et al.*[9] have observed resonances in $^{12}C+^{12}C$ inelastic scattering. Their data show evidence for strong enhancement of the single and mutual excitation of the ^{12}C ions to the 2^{+} (4.43 MeV) state. As in the case of the $^{12}C(^{12}C,^{8}Be)^{16}O$ reaction, the inelastic scattering samples the resonant strength of entire groups of states. Their earlier study was performed employing a pair of large NaI(Tl) detectors to monitor the 4.43 MeV gamma rays produced in the reaction. The later study was performed via charged particle measurement of the ^{12}C ions themselves. This later experiment had sufficient energy resolution and fine enough step size to observe intermediate structure which is superimposed upon the broader structure. These authors speculated that the gross structure corresponds to groupings of narrower states, all of which have common spin and parity. The broad resonances were hypothesized to constitute a rotational band in ^{24}Mg generated by a quasimolecular interaction of the type first described by Imanishi[10] and later extended to higher energies by Kondo, Matsuse, and Abe,[11] and also by Greiner and Scheid.[12] The fact that the inelastic scattering to the 2^+ state samples the gross structure was interpreted to indicate that the excitation of the 2^+ state is an important part of the reaction mechanism by which the resonances are being produced. A theoretical study by Phillips *et al.*[13] has demonstrated, however, that such gross structure in inelastic scattering can be generated, in part, by nonresonant diffraction; so, the complete explanation of the inelastic functions may involve interference among several mechanisms.

Information has also become available on the $^{12}C+^{12}C$ fusion-evaporation excitation function. Sperr *et al.*[14] performed the first measurement by detecting the evaporation residues with a particle telescope. Recently, the fusion-evaporation excitation function has been determined by Kolata *et al.*[15] by measuring yields of known gamma-ray transitions in the final-state evaporation residues. The agreement between measurements is poor at the lowest bombarding energies, presumably because of particle decays directly to evaporation residue ground states. Nevertheless, both measurements indicate that the fusion-evaporation cross section exhibits an energy dependence which is modulated by a gross structure. The average cross section is found to follow the Glas and Mosel[16] prediction rather well. The gross structure is in good agreement with similar structure observed in the elastic scattering deviation function.[17] It also aligns itself well with the centroids of the resonances reported by Cosman *et al.*[1] and by Fletcher *et al.*[6] In contrast, the inelastic scattering measurements of Cormier *et al.*[9] are distinctly out of phase with these other fluctuations. Indeed, the groups of intermediate states which make up the gross structure of the inelastic scattering reactions may not all have the same spin. Some indication of this is found from examination of individual states seen in the inelastic data[9] which correspond, in many cases, to resonant states reported from the $^{12}C(^{12}C,^{8}Be)^{16}O$ reaction, from which reaction their spins and parities have been inferred.[6]

The role which the gross and intermediate structures play in the spectroscopy of ^{24}Mg is still not clear and furthermore, their interrelationship is not determined. For example, does the gross structure arise from a clustering of several sharper states comprising the intermediate structure, or rather, does it arise from a dynamic window effect originating from the nature of the $^{12}C+^{12}C$ entrance channel, through which window the sharper states of the nucleus ^{24}Mg can be seen? Are the narrower structures relatively isolated intermediate states or are they substantially overlapping high spin states producing a statistical or strong interference behavior in the cross section? There have been recent studies[18–20] which suggest that the structures arise from a fairly sparse population of special high spin states in ^{24}Mg. The first[18] was the examination of high resolution $^{12}C(^{16}O,\alpha)^{24}Mg$ spectra over a wide range of bombarding energies. Here, it was seen that this reaction selectively populates final states at excitation energies which have also been observed in $^{12}C+^{12}C$ reaction excitation functions. The second[19,20] was a correlation analysis between intermediate structures seen in $^{12}C+^{12}C$ elastic and reaction channels. Here, the existence of discrete states in ^{24}Mg with large $^{12}C+^{12}C$ and $\alpha+^{20}Ne^*$ partial widths was observed.

The present experiment was motivated by considerations outlined above and also by the earlier study[18] which indicated that the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction was capable of populating states at high excitation in ^{24}Mg which had also been observed as resonant states in earlier $^{12}C+^{12}C$ reactions. A recent study by Nagatani *et al.*[21] has also shown this to be true for the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction at higher bombarding energies. We present here data which survey the heavy particle decays from states in ^{24}Mg that are populated via the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction; that is, we have measured the three-particle coincidence between α, X, and Y in the reaction $^{12}C(^{16}O,\alpha)^{24}Mg^* \rightarrow X+Y$. Such a three-body reaction could be of importance since it can potentially reveal in a direct way the location of cluster structures in ^{24}Mg involving these species. In addition, this could lead to an experimental determination of the $\Gamma(^{12}C)$ strength function over a large range of excitation in ^{24}Mg and possibly to a determination of the spins of the associated states in ^{24}Mg. In this study we have observed the $^{24}Mg^* \rightarrow ^{12}C^* + ^{12}C^*$ and $^{24}Mg^* \rightarrow ^{8}Be+^{16}O^*$ modes. It is notable that this experiment had been tried by two previous groups, Wieland *et al.*[22] and LeVine *et al.*,[23] at lower energies, viz., $E_{lab}(^{16}O) \cong 56MeV$. They did not find any evidence for structure in ^{24}Mg associated with the $^{12}C+^{12}C$ decays. However, for the reasons stated above we were confident that such structure should be seen at higher energies. In fact, $E_{\rm lab}(^{16}O) = 77$ MeV was chosen here because of the apparently strong population of discrete states observed in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction at this energy. Our measurements have shown abundant ^{24}Mg intermediate and gross structures in several of the $^{12}C(^{16}O,\alpha)^{24}Mg^* \rightarrow X+Y$ channels, but give a preliminary indication of the problems encountered in extracting spectroscopic information from such data.

II. EXPERIMENTAL METHOD

The experiment was performed at the Brookhaven National Laboratory tandem Van de Graaff facility using a 7^+ ^{16}O beam of 77 MeV. Typical beam currents were 10–20 particle nA. The targets employed were natural self-supporting carbon foils (99% ^{12}C, 1% ^{13}C) and were typically 20 $\mu g/cm^2$ in areal density.

Three detectors were used, yielding energy spectra for each of three coincident fragments, two laboratory angles, and the time correlations among the three particles. (See Fig. 1.) These parameters served to specify the final state uniquely. The α was detected at zero degrees in a single element 2000 μm totally depleted surface barrier detector located directly behind a 51 mg/cm^2 tantalum beam stopper foil. Although protons and deuterons could also be observed in the detector, the particle identification could be performed later by using the measured three-body reaction Q value. In similar earlier measurements performed at lower bombarding energies[22,23] the masses of the two heavy fragments observed laterally in coincidence with the light particle at zero degrees were determined kinematically by using the measured energies and angles of the pair in two position sensitive surface barrier detectors. With these quantities it is possible to determine the mass ratio of the two fragments. This technique is not a very clean one experimentally, as the resolution of both the energy and position in the position sensitive detectors (PSD's) directly affect the calculated mass ratio. It was therefore decided to use a somewhat different technique for performing the kinematically complete measurement for the present case. As can be seen in Fig. 1, one counter (hereafter labeled "1") consisted of a gas ΔE solid state E counter telescope.[24] The proportional wire used in the gas ΔE section was a strand of resistive nichrome wire, 10 μm in diameter. The isobutane gas

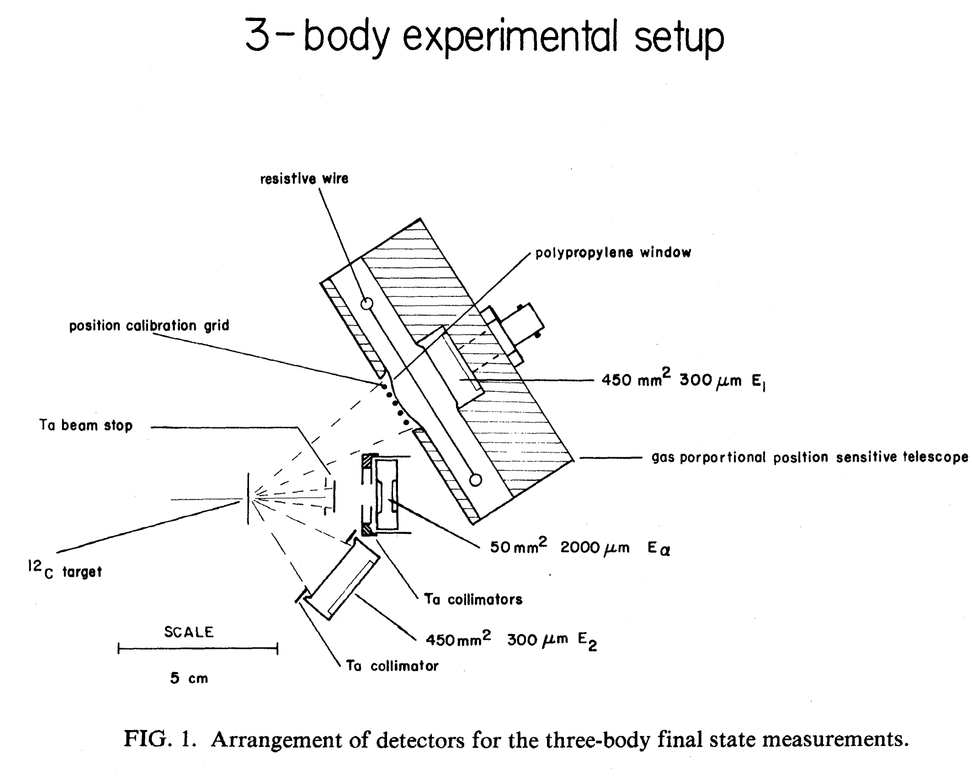

FIG. 1. Arrangement of detectors for the three-body final state measurements.

at 50 Torr pressure and the thin (60–90 $\mu g/cm^2$) stretched polypropylene entrance window represented about 500 $\mu g/cm^2$ of material through which the fragments reaching the solid state detector traversed. The energy detector consisted of a 450 mm^2, 300 μm thick totally depleted surface barrier detector. By performing charge division along the resistive wire, it was possible to obtain a position determination with a resolution of 0.1 mm. From the ΔE-E information only the atomic number of the fragment could be determined. This, however, was used to infer the mass: Thus $Z=6$ implies ^{12}C and $Z=8$ implies ^{16}O. Although the counter could not *per se* resolve isotopes of the elements, the above assignments were reliable because of the differences in reaction Q values for various final states. The third detector (detector 2) was also a large area 450 mm^2, totally depleted 300 μm surface barrier detector. Because of the number of parameters obtained from the telescope, only the energy of this third fragment was needed to determine a three-body final state completely.

The α detector at zero degrees subtended a solid angle of 15 msr. This was defined by a tantalum aperture with a diameter $\phi=7$ mm at a distance of $\sim$2.5 cm from the target. The lateral detectors had large acceptances. These detectors were collimated with circular aperatures and subtended laboratory angles of $\theta_1(\text{lab})=31\pm8.5°$ and $\theta_2(\text{lab})=-42\pm13.5°$, respectively, for detectors 1 and 2.

Data were collected both as singles using the online storage disc of the Brookhaven National Laboratory (BNL) $\Sigma 7$ computer and in coincidence mode event by event using magnetic tape. The coincidence data were of three types: triple coincidence and the two possible sets of twofold coincidences. The latter ones were used off-line for calibration purposes. The singles data included the three energy signals (E_α,E_1,E_2), two time signals ($t\alpha_1$,$t\alpha_2$), the charge spectrum from detector 1 (ΔE-E), and the position spectrum from this same device ($x\Delta E$-ΔE). These signals were collected primarily to observe the on-line performance of the electronics and the detectors during the experiment. The energy losses suffered by the particle at zero degrees and by the slow heavy-ion detected in the telescope were accounted for in the later analysis on an event by event basis using a lookup table derived from Northcliffe and Schilling.[25]

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Discrete three-body final states

The data were first classified by the particle multiplicity in the final state. The time correlations between the α at zero degrees and both lateral detectors were used to discriminate those events for which at least three final states fragments were detected. The true-to-randoms ratio for the experiment was measured to be $\sim$100:1 and random coincidences posed no problem in the interpretation of the results. Those events lying in the triple coincidence peak consist of at least three particles in the final state; the multiplicity could be greater than this. To discriminate against events with greater multiplicities, the total energy spectrum ($E_\alpha+E_1+E_2$) for those events characterized by the individual elemental lines in the ΔE_1-E_1 spectrum was produced. This charge spectrum obtained during the experiment is shown in Fig. 2. The spectrum presented here is the inclusive yield collected during the run; the only appreciable yields observed for threefold coincidences occur for the carbon, oxygen, and neon lines. The ^{20}Ne fragment is in coincidence with two alpha particles; α_0 originating from the α decay of ^{28}Si and α_1 coming from the subsequent decay of ^{24}Mg. Calculations have shown that the expected efficiency of the present geometry for detecting both ^{20}Ne and α fragments in the lateral detectors is nil; the threefold coincidences associated with the ^{20}Ne line come from an observation of the secondary alpha at zero degrees and the primary alpha in the lateral detector. This latter configuration for the three-body final state does not allow the spectroscopy of the intermediate nucleus ^{24}Mg to be studied via the energy spectrum of alphas detected at zero degrees; consequently the $^{20}Ne+\alpha_1+\alpha_0$ final state was not given further consideration.

The total energy spectra for three-body final states are presented in Fig. 3. The channels which have been observed with appreciable yields are the $\alpha+{}^{12}C+{}^{12}C$ and $\alpha+{}^{8}Be+{}^{16}O$ final states. The energy resolution is adequate to resolve transitions

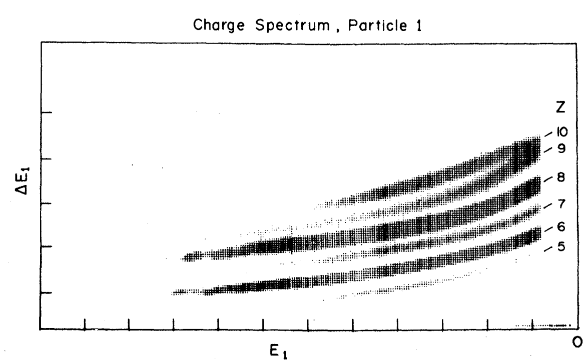

FIG. 2. A typical ΔE-E spectrum obtained with the gas ΔE-solid state E, position-sensitive telescope.

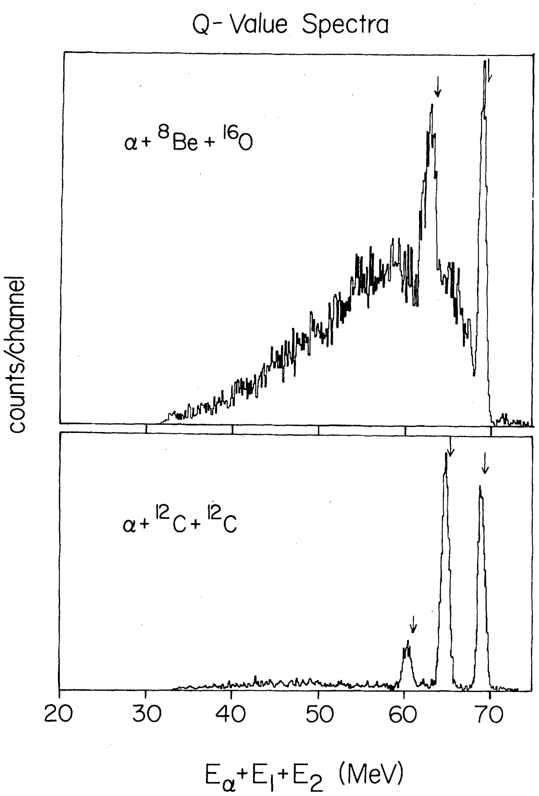

FIG. 3. Q-value spectrum for three-body final states. The arrows indicated expected positions of peaks arising from

$$\alpha_0+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}\ ,$$

$$\alpha+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}^*(6.1\ \mathrm{MeV})\ ,$$

$$\alpha_0+{}^{12}\mathrm{C}_0+{}^{12}\mathrm{C}_0\ ,$$

$$\alpha+{}^{12}\mathrm{C}_0+{}^{12}\mathrm{C}^*(4.43\ \mathrm{MeV})\ ,$$

$$\alpha+{}^{12}\mathrm{C}^*(4.43\ \mathrm{MeV})+{}^{12}\mathrm{C}^*(4.43\ \mathrm{MeV})$$

final states as determined from energy calibrations of the three-detector system.

which proceed through excited states of ^{12}C and ^{16}O (the expected Q values for these states are indicated by arrows in the figure). Here the observed $\alpha+{}^{12}\mathrm{C}+{}^{12}\mathrm{C}$ events correspond to the final states $^{12}\mathrm{C}_{\mathrm{g.s.}}+{}^{12}\mathrm{C}_{\mathrm{g.s.}}$,

$$^{12}\mathrm{C}_{\mathrm{g.s.}}+{}^{12}\mathrm{C}^*(J^{\pi}=2^+,E_x=4.43\ \mathrm{MeV})\ ,$$

and $^{12}\mathrm{C}^*+{}^{12}\mathrm{C}^*$. There is no observed yield to any other states of ^{12}C. The $\alpha+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}$ channel contains Q-value peaks corresponding to $^{8}\mathrm{Be}_{\mathrm{g.s.}}+{}^{16}\mathrm{O}_{\mathrm{g.s.}}$ and

$$^{8}\mathrm{Be}_{\mathrm{g.s.}}+{}^{16}\mathrm{O}^*(J^{\pi}=3^-,0^+,E_x=6.1\ \mathrm{MeV})\ .$$

The continuous background present in the $\alpha+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}$ channel arises from the subsequent decay of the fragment ^{8}Be; the two alphas produced in its decay may not be both detected. The four-body nature of the $\alpha+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}$ breakup then produces a continuous spectrum for the three-particle energy sum. This fact reduces the detection efficiency of the setup for events producing $^{8}\mathrm{Be}+{}^{16}\mathrm{O}$ below that which has been calculated by assuming a three-body final state. The present setup cannot detect three-body final states proceeding through excited states of ^{8}Be.

For each of the discrete three-body final states it is possible to produce the energy spectra of the alpha particles observed at zero degrees. These spectra are presented in Fig. 4. The uppermost histogram labeled "α singles" is the inclusive $^{12}\mathrm{C}(^{16}\mathrm{O},\alpha)^{24}\mathrm{Mg}$ yield at zero degrees for this experiment. The experimental energy resolution is 480 keV and is accounted for by straggling of α particles through the tantalum beam stop. The characteristics of the spectrum—discrete states observable above the evaporative continuum—are quite similar, aside from the inferior energy resolution, to the $E_{\mathrm{c.m.}}=33$ MeV spectrum obtained at $\theta_{\mathrm{lab}}=7.5°$ in an earlier study.[18] This high resolution spectrum at $E_{\mathrm{lab}}=77$ MeV for the $^{12}\mathrm{C}(^{16}\mathrm{O},\alpha)^{24}\mathrm{Mg}$ reaction is shown in Fig. 5. The spectra in Fig. 4 for the $\alpha+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}$ channel have been extracted as follows: The spectrum labeled $\alpha+{}^{8}\mathrm{Be}_{\mathrm{g.s.}}+{}^{16}\mathrm{O}$ arises from those events with a sharp three-body energy sum in the spectrum of Fig. 3. The $\alpha+{}^{8}\mathrm{Be}+{}^{16}\mathrm{O}^*$ yield has been obtained by subtracting an appropriate background from those events in the $Q=6.1$ MeV peak of the energy spectrum. All these data should, in principle, represent states of the ^{24}Mg nucleus which decay via heavy particle fission. That this is indeed the case was found in a detailed study of the $\alpha+{}^{12}\mathrm{C}_{\mathrm{g.s.}}+{}^{12}\mathrm{C}_{\mathrm{g.s.}}$ channel.

B. Three-body analysis of the $\alpha+{}^{12}\mathrm{C}_{\mathrm{g.s.}}+{}^{12}\mathrm{C}_{\mathrm{g.s.}}$ channel

The previous studies of the $^{12}\mathrm{C}(^{16}\mathrm{O},\alpha)^{24}\mathrm{Mg}^*(X,Y)$ breakup reaction[22,23] that were performed at lower bombarding energies have indicated that in these experiments a major contribution to the $\alpha+{}^{12}\mathrm{C}_{\mathrm{g.s.}}+{}^{12}\mathrm{C}_{\mathrm{g.s.}}$ yield arose from the projectile breakup of ^{16}O. At the lower energies the lateral PSD's were exposed to laboratory angles well forward of the grazing angle for $^{12}\mathrm{C}+{}^{16}\mathrm{O}$. The projectile breakup is, by nature, a peripheral process

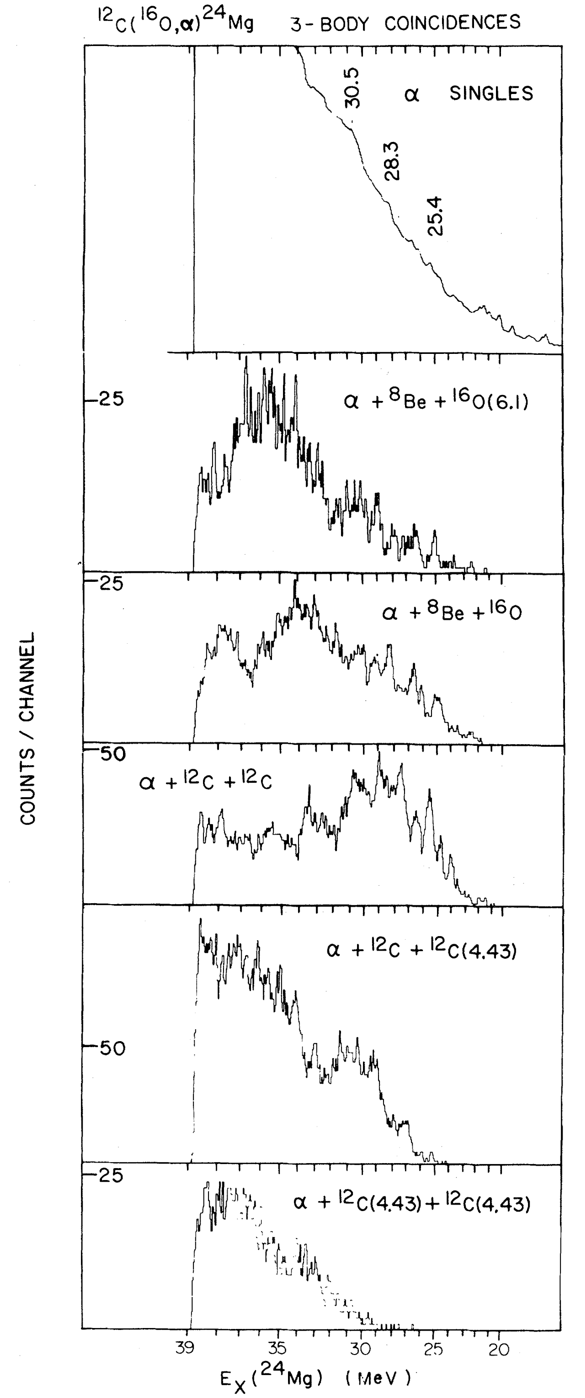

FIG. 4. Energy spectra for 0° α detector gated on labeled three-body final states. Energy scale is in the excitation energy of the $^{24}Mg^*$ system.

and hence has appreciable cross section at or forward of the grazing angle. In the present experiment the $^{12}C + ^{16}O$ grazing angle is calculated to be $\sim 8° - 10°$ in the laboratory. The α-^{12}C angular correlation for breakup processes is known to be quite sharply peaked near $\theta(^{16}O^*) \approx 0°$.[26] The smallest α-^{12}C angle observable by the lateral detectors of Fig. 1 was typically $\sim 25°$ in the laboratory. These considerations make it unlikely that the $\alpha + ^{12}C_{g.s.} + ^{12}C_{g.s.}$ final state in particular, and that the other three-body final states also, arise from peripheral processes involving the breakup of either ^{12}C or ^{16}O.

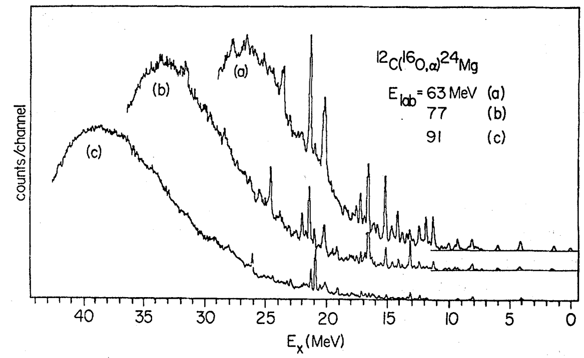

FIG. 5. Singles α-energy spectra for three bombarding energies taken at $\theta_L = 7.5°$ (see Ref. 18). (b) corresponds to the energy used in the present experiment.

In the present study a more detailed analysis of the nature of the $\alpha + ^{12}C_{g.s.} + ^{12}C_{g.s.}$ final state has been performed in the manner of Dalitz[27] and of Chapman and MacLeod.[28] From the parameters determined experimentally it is possible to reconstruct each event in the center of mass. The angles and velocities of the three particles are shown

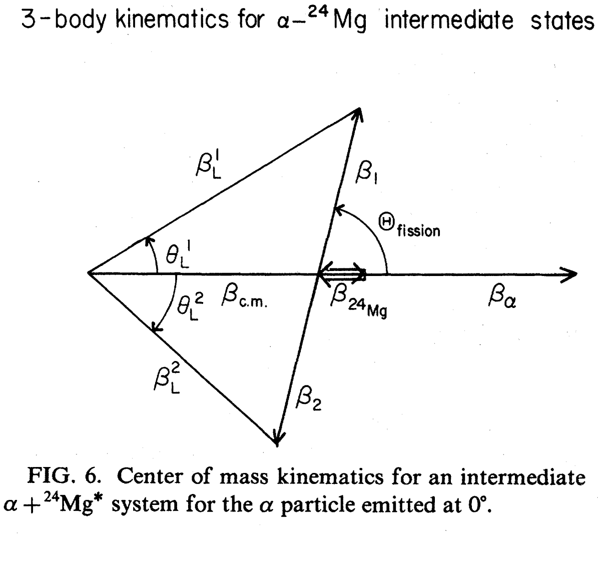

FIG. 6. Center of mass kinematics for an intermediate $\alpha + ^{24}Mg^*$ system for the α particle emitted at 0°.

schematically in Fig. 6. Because the total momentum in this system is zero, the energy and momentum of any one particle can be used to determine the total momentum and energy of the other pair. In so doing, the three-body final state can be reduced to an equivalent two-body final state represented by an intermediate particle which subsequently decays. In this manner the energy of the third particle effectively determines the two-body Q values. Hence, the energy of the alpha particle at zero degrees can be used to determine the effective excitation energy in ^{24}Mg for the ^{12}C(^{16}O,α)^{24}Mg* reaction, while the energy of the ^{12}C observed in the position sensitive detector, $E1$, can be used to determine the effective excitation energy in ^{16}O for the reaction ^{12}C(^{16}O,^{12}C)^{16}O*. Both these reactions can, in principle, produce a three-body $\alpha+{}^{12}C_{g.s.}+{}^{12}C_{g.s.}$ final state. For all three-body events, then, a two dimensional Dalitz plot may be produced, wherein each event is plotted according to its coordinates [$E_x(^{24}\text{Mg}),E_x(^{16}\text{O})$]. In such a graph any tendency for the event to scatter along bands parallel to either axis can be interpreted as evidence for the population of an intermediate state in the nuclei ^{24}Mg* or ^{16}O* prior to the subsequent three-body decay. Figure 7 presents the data in this manner. All events are bounded by the dashed curve representing all accessible points in the phase space of the reaction (4π solid angle). Furthermore, the solid line in the figure corresponds to the calculated region of phase space which is kinematically allowed by the present experiment when the angles of all three detectors are taken into account and when the energy cutoffs represented by the beam stop for the alpha detector and the ΔE gas element of the telescope detecting the ^{12}C are considered.

There is no real evidence for bands parallel to either axis. This is not surprising in the case of ^{24}Mg since the reaction is populating many states in ^{24}Mg at 20–40 MeV of excitation. In the case of ^{16}O, however, this indicates that the present set of data does not include an appreciable yield arising from the reaction $^{16}\text{O}^*\rightarrow\alpha+{}^{12}C_{g.s.}$. The data of Wieland *et al.*[22] indicated the presence of a state in ^{16}O at $\sim$10 MeV which α decayed very strongly. The data of Fig. 7 can be projected onto either axis and these are shown in Fig. 8. The histograms represent excitation energy spectra of the nuclei ^{16}O and ^{24}Mg for the three-body events. There is no appreciable structure in the spectrum of ^{16}O which cannot be accounted for by the statistics. The first α-decaying state in ^{16}O occurs at $E_x\sim9.6$ MeV, while the $\alpha+{}^{12}$C threshold is 7.2 MeV. The histogram at energies below $E_x\sim10$ MeV appears similar to the histogram for energies above this threshold energy, thus indicating that there is no appreciable yield

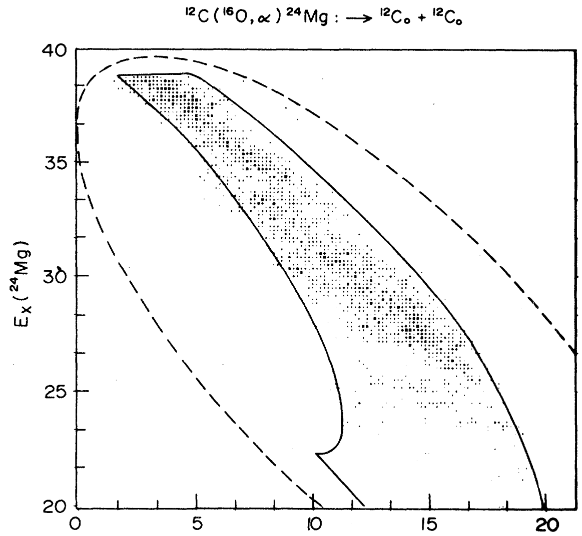

FIG. 7. Dalitz-type plot for $\alpha_0+{}^{12}C+{}^{12}C$ events. For each event the equivalent ^{24}Mg* and ^{16}O* excitation for the three-body final state has been plotted (see text and Refs. 27 and 28). The dashed ellipse represents the limits of the phase space for the three-body final state (4π geometry). The solid curve represents the region sampled by the current experiment.

from the ^{16}O breakup to the three-body events. The spectrum of ^{24}Mg is essentially a transformation of the laboratory spectrum presented in Fig. 4.

Calculations indicated by the solid lines in Fig. 8

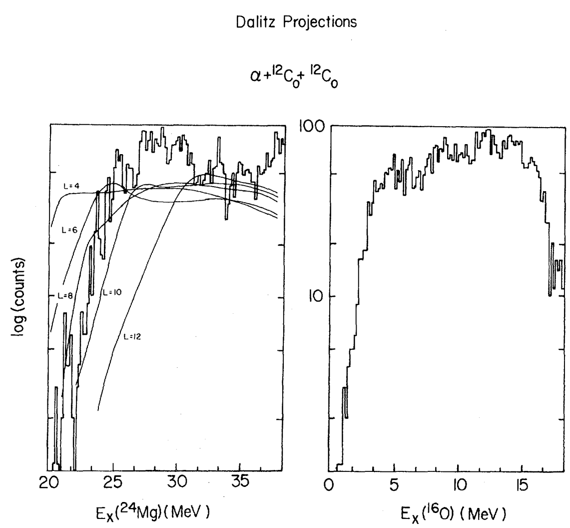

FIG. 8. Projections of the data of Fig. 7 onto the two axes. The curves in the left-hand figure correspond to calculations for emission from a state in ^{24}Mg at the corresponding excitation and for angular momentum as labeled on the curves.

show that the $\alpha+{}^{12}C_{g.s.}+{}^{12}C_{g.s.}$ yield is consistent with the fission of states in ^{24}Mg between $20\leq E_x\leq 40$ MeV with $J^{\pi}=6^+,8^+,10^+$, and possible 12^+. The curves of Fig. 8 were produced by taking a product of the three-body phase space for a given value of angular momentum in ^{24}Mg with the appropriate transmission coefficient, $T_J(E_x)$ for $Mg\rightarrow{}^{12}C+{}^{12}C$. These functions were derived from the elastic scattering code ABACUS-2 with optical model parameters of the Yale group. All curves are normalized to the data. The characteristics of the threshold between $E_x\approx$ 20 and 25 MeV indicate that it is unlikely any large contribution is coming from states with spins less than $J=6$. It may be concluded, then, that the $\alpha+{}^{12}C_{g.s.}+{}^{12}C_{g.s.}$ yield arises from the fission of states in ^{24}Mg at reasonably high spin that are populated via the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction.

C. Structure in the coincidence spectra

The three-body coincidence spectra in Fig. 4 show pronounced gross structure and intermediate structure for all five ^{24}Mg fission channels measured. This suggests that we are seeing real variations in the fission width distributions for these channels. Important questions to be answered therefore are the following: (a) Are there correlations in energy between the structures seen in any of these channels and structures observed previously in $^{12}C+{}^{12}C$ resonance reactions; and (b) are there cross correlations in energy between the structures seen in two or more different fission channels from the present experiment? The answers to these questions would clarify whether the structures in the three-body spectra arise from individual ^{24}Mg states or whether there exist significant interference effects which would tend to obscure the nuclear structure.

First we shall consider the gross structure in the fission channels, that is, the structure with widths of order 2–3 MeV. Such structure is evident in all five of the ^{24}Mg decay channels shown in Fig. 4. It has been determined that they are not due either to threshold effects or to instrumental ones. From a visual examination of the spectra, it does not appear that there are cross correlations in this gross structure between any two of these channels. Comparing these spectra to previously reported $^{12}C+{}^{12}C$ inelastic[9] and fusion[14,15] excitation functions, there does not appear to be any obvious gross structure correlations with them either. Figure 9 shows the sum of the three-body spectra of Fig. 5 together with $^{12}C+{}^{12}C$ fusion data from Sperr *et al.*,[14] and with $^{12}C+{}^{12}C$ elastic scattering deviation function data

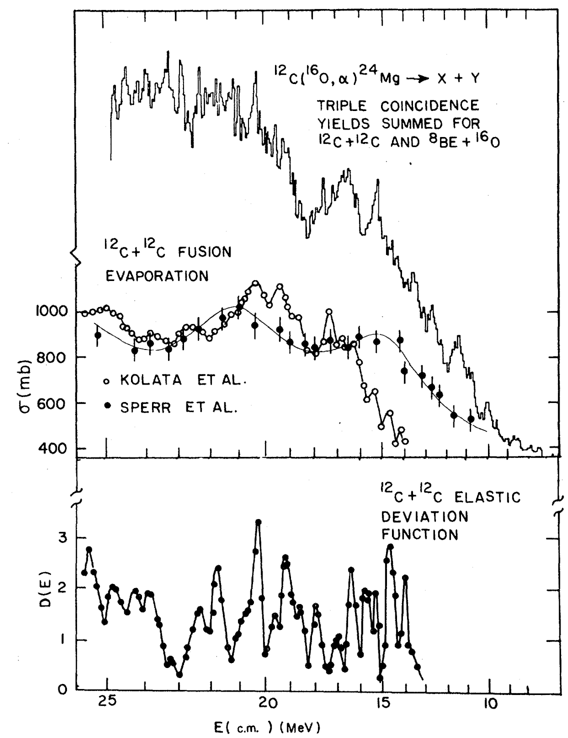

FIG. 9. Comparison of our summed three-body yields (over five three-body final states) with reported fusion excitation functions for $^{12}C+{}^{12}C$. Also shown is the $^{12}C+{}^{12}C$ elastic scattering deviation function on this energy domain.

from Shapira *et al.*[17] The latter results are chosen as possible indicators of gross structure effects such as shape resonances, should these exist in ^{24}Mg. Weak evidence for broad enhancements near $E_x(^{24}Mg)=30$ and 34 MeV may be seen in all these data. It would be expected that the enhancements in the $^{12}C+{}^{12}C$ reaction data, which could be indicative of the $^{12}C_{g.s.}+{}^{12}C_{g.s.}$ strength function, should show up most clearly in the present $\alpha+{}^{12}C_{g.s.}+{}^{12}C_{g.s.}$ states significantly. The fact that this is not the case casts some doubt on the origin of the gross structure in our data as being specific to the interaction of the two ions X and Y of the particular $\alpha+X+Y$ spectra in Fig. 4. An alternate explanation is that the gross structure in the $^{12}C+{}^{12}C$ channels arises from the sequential mechanisms of the inelastic excitation of the ^{16}O to excited states in the continuum $^{16}O^*$, and subsequent decay to $^{12}C+\alpha$. The 0° alpha spectrum would then still reflect the discrete energies of the excited $^{16}O^*$ recoiling to forward angles. The mechanism has been argued by Rae *et al.*[26] to be very important, at least for α-^{12}C coincidence measurements involving ^{12}C ions emitted below $\theta(\text{lab})=30°$. In this paper we have not addressed this question in any quantitative way to explain the gross structure seen in Fig. 4.

It was the objective of this study to determine whether a value of $^{12}C+{}^{12}C$ widths from ^{24}Mg states could be deduced from identification of the same transition in the $^{12}C(^{16}O,\alpha)^{24}Mg$ singles spectrum and in the coincidence $\alpha+{}^{12}C+{}^{12}C$ decay spectra. We have determined, however, that a direct comparison between coincidence yields and singles yields is very difficult, at least at this bombarding energy. The most strongly populated states in the singles spectrum do not have very large carbon widths and thus obscure those states seen most strongly in the coincidence spectra. As an example, consider the peak which appears at $E_x=25.4$ MeV in the $\alpha+{}^{12}C_{g.s.}+{}^{12}C_{g.s.}$ yield. There is also a peak at 25.4 MeV in the singles spectrum. Assuming the two are one and the same state, one obtains

$$\Gamma(^{12}C)/\Gamma_{tot}\approx[0.05]^{+0.05}_{-0.025} .$$

This is in disagreement with a recent study of the same quantity from Breit-Wigner analysis of the elastic scattering,[19,20] which indicates that

$$\Gamma(^{12}C)/\Gamma_{tot}\sim 0.25 .$$

Furthermore, a triple coincidence measurement of the $^{12}C(^{16}O,2\alpha)^{20}Ne$ channel[29] indicates that there is a state at 25.18 MeV in ^{24}Mg which is strongly populated by α decay from ^{28}Si, and which also α decays to excited states in ^{20}Ne. This is at odds with the measured α_0 width of the $^{12}C+{}^{12}C$ resonance at 25.4 MeV, which appears strongly in the $^{12}C(^{12}C,\alpha_0)^{20}Ne(g.s.)$ reaction.[5] Thus although this resonant state is seen in a $^{12}C_{g.s.}+{}^{12}C_{g.s.}+\alpha$ spectrum, it is masked in the singles spectrum, probably by the state at 25.2 MeV, and this precludes making a straightforward determination of $\Gamma(^{12}C)/\Gamma_{tot}$ for the resonant state. Furthermore, Branford *et al.*[29] report that the state at $E_x=25.18$ MeV has a total width of 163 ± 6 keV, whereas the ^{24}Mg state at $E_x\approx25.4$ MeV known from resonance reactions appears to have a width of greater than 200 keV. This further supports the conclusion that the α singles spectrum itself is dominated by transitions which do not correspond to the $^{12}C+{}^{12}C$ resonant states, and, that the latter states populated by the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction are obscured in the α singles spectrum. The argument about the widths must, however, be tempered by the fact that a very fine-stepped excitation over the $^{12}C+{}^{12}C$ resonance near $E_x=25.4$ MeV has not been done to evaluate whether its reported width is an average and whether finer structure might reveal fragments that are more in line with the widths of Branford *et al.*

Thus, our conclusion here is that a direct observation at this single bombarding energy of known $^{12}C+{}^{12}C$ resonance states in the $^{12}C(^{16}O,\alpha)^{24}Mg$ singles spectrum is not possible.

However, this conclusion does not rule out the observation of $^{12}C+{}^{12}C$ resonant states in the $\alpha+X+Y$ coincidence spectra since these should be a drastically constrained subset of the entire α-singles spectrum. To ascertain the degree to which this is true, we have performed a correlation analysis between the $\alpha+X+Y$ spectra of Fig. 4 and reported $^{12}C+{}^{12}C$ excitation functions for the $^{12}C+{}^{12}C$ elastic[17] and inelastic[9] reactions. This is shown in Fig. 10. $C_{ij}(E)$ is the cross-channel correlation function and is defined as

$$C_{ij}(E)=\frac{\langle\sigma_i(E)\sigma_j(E)\rangle}{\langle\sigma_i(E)\rangle\langle\sigma_j(E)\rangle}-1 .$$

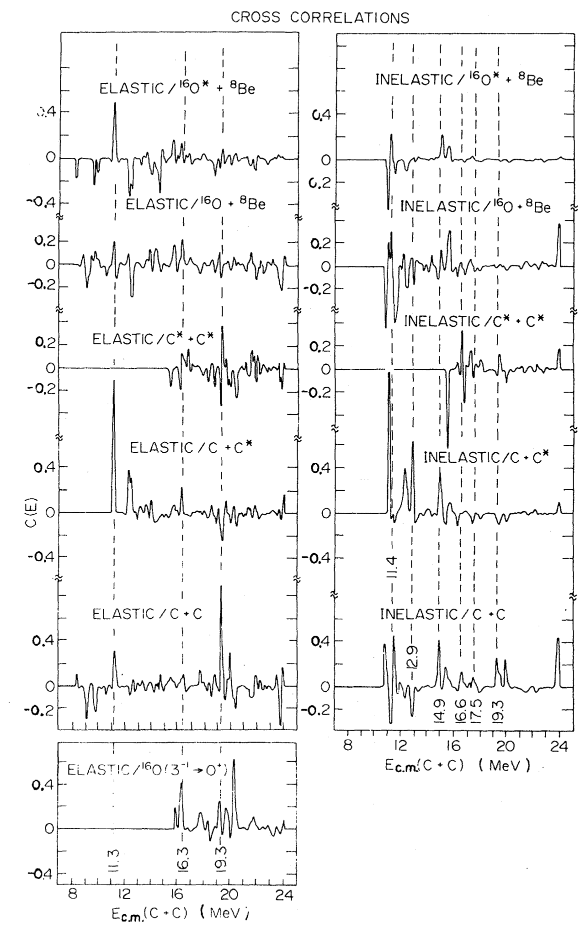

FIG. 10. Cross correlation functions between the present three-body data and other $^{12}C+{}^{12}C$ reported data.

The evidence for correlation appears strongest in the elastic versus $\alpha+^{12}C_{g.s.}+^{12}C_{g.s.}$ and the inelastic versus $\alpha+^{12}C_{g.s.}+^{12}C_{g.s.}$ cases. The degree of correlation in these graphs can be compared to the graph in the lower left of Fig. 10 which presents the same calculation between two $^{12}C+^{12}C$ reaction channels which are known to manifest resonant structure; namely, the $^{12}C+^{12}C$ 90° c.m. elastic channel excitation function and the

$$^{12}C(^{12}C,\alpha)^{20}Ne^{*}\rightarrow{}^{16}O^{*}(3^{-}\rightarrow 0^{+})+\alpha$$

channel excitation function of Kolata *et al.*[15] The enhancements in the correlation functions occur at energies where there have been reported $^{12}C+^{12}C$ resonances; viz., $E_{c.m.}=13.3$, 14.9, 16.3, and 19.3 MeV.

We conclude, therefore, that the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction does populate some of the same ^{24}Mg states seen as $^{12}C+^{12}C$ resonances, but it is not possible, in view of the above discussion, to make a quantitative statement about how strongly they are populated or what the carbon widths for these states are.

We now address ourselves to the cross correlations among the five $\alpha+X+Y$ channels of Fig. 4. The calculations are shown in Fig. 11, where $C_{ij}(E)$ is the same function defined above. There is weak evidence of cross correlations between the $C+C/C+C^{*}$ and $C+C/C^{*}+C^{*}$ channels, and these occur at the same energies that we quote above for $^{12}C+^{12}C$ resonances. Sums of pairwise correlations, examples of which are shown in the upper right hand figure, are relatively structureless, but this reflects the fact, however, that the individual graphs exhibit both positive and negative excursions which will average out in a sum of several such functions. This can occur despite the presence of large correlations because there will be minor energy shifts of the same resonance maximum in each channel caused by differing interference patterns between the resonance amplitudes and background amplitudes for each channel. The interferences produce a fore-aft asymmetry of the resonance shape, giving rise to the above mentioned shifts. Since the shifts need not be the same for each channel, positive and negative variations of $C(E)$ may readily occur.

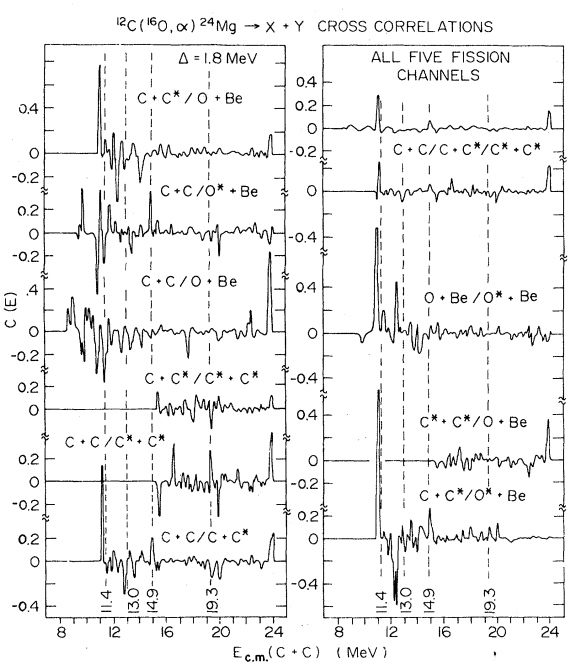

FIG. 11. Cross correlation functions, averaged over 1.8 MeV (in $^{12}C+^{12}C$ c.m. energy), for the five three-body final states observed in this experiment.

As a final comment, we note that the degree of population of $^{12}C+^{12}C$ states in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction may vary significantly within a few MeV in $^{12}C+^{16}O$ incident energy if resonances in this entrance channel affect the process. In fact, resonances in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction excitation functions and recent analysis[30] have revealed that $E_{c.m.}=33$ MeV may not have been a favorable bombarding energy for this reaction. The excitation functions show that $E_{c.m.}=33$ MeV is a minimum between resonances in the $^{16}O+^{12}C$ system. Had the incident energy been equal to one of these ^{28}Si resonance energies, there might have been a proportionate increase in the selectivity of the three-body reaction if there were a structural similarity between the $^{12}C+^{16}O$ and the $^{12}C+^{12}C$ resonances themselves.

IV. SUMMARY

In summary, we find evidence that the $^{12}C(^{16}O,\alpha)^{24}Mg\rightarrow X+Y$ coincidence reaction at $E_{c.m.}=33$ MeV does populate ^{24}Mg states associated with $^{12}C+^{12}C$ resonances at $E_{c.m.}=11.3$, 14.9, 16.3, and 19.3 MeV observed in other works, i.e., states with large $^{12}C+^{12}C$ decay widths. This is based on correlation functions between the $\alpha+^{12}C_{g.s.}+^{12}C_{g.s.}$ coincidence spectrum and excitation functions of $^{12}C+^{12}C$ elastic and inelastic scattering. Further support for this conclusion comes from the cross channel correlations between $^{12}C(^{16}O,\alpha)^{24}Mg\rightarrow X+Y$ final channels, particularly between the channels $X+Y=^{12}C+^{12}C$ and $^{12}C^{*}+^{12}C^{*}$. It also appears that at $E_{c.m.}=33$ MeV the $^{12}C(^{16}O,\alpha)^{24}Mg$ singles spectrum also contains relatively strong transitions corresponding to known states in ^{24}Mg between $E_x(^{24}\text{Mg})=20$ and 40 MeV which have relatively weak ^{12}C + ^{12}C decays. The presence of these transitions makes it difficult to isolate those transitions in the $\alpha+{}^{24}$Mg singles spectrum which have significant ^{12}C + ^{12}C decays, and thus it was not possible in this study to derive directly any quantitative ^{12}C + ^{12}C decay widths in ^{24}Mg by comparison of singles and coincidence spectra.

ACKNOWLEDGMENTS

The authors thank Derek Branford for informing us about his results prior to publication. This work was supported in part by the U.S. Department of Energy Contract No. DE-AC02-76-ER03069.

*Present address: Nuclear Physics Laboratory, University of Washington, Seattle, WA 98195.

†Deceased.

‡Present address: Oak Ridge National Laboratory, Oak Ridge, TN 37830.

§Present address: Stanford University, Stanford, CA 94305.

[1]K. Van Bibber, E. R. Cosman, A. Sperduto, T. M. Cormier, and T. N. Chin, Phys. Rev. Lett. 32, 687 (1974); E. R. Cosman, T. M. Cormier, K. Van Bibber, A. Sperduto, G. Young, J. Erskine, L. R. Greenwood, and O. Hansen, *ibid.* 35, 265 (1975).

[2]T. M. Cormier, E. R. Cosman, L. Grodzins, O. Hansen, S. Steadman, K. Van Bibber, and G. Young, Nucl. Phys. A247, 377 (1975).

[3]G. J. Kekelis, A. H. Lumpkin, and J. D. Fox, Phys. Rev. Lett. 35, 710 (1975).

[4]P. Sperr, D. Evers, G. Denhöfer, W. Assmann, A. Harasim, P. Konrad, C. Ley, and K. Rudolph, Z. Phys. A 280, 287 (1977).

[5]E. Almqvist, J. A. Kuehner, D. McPherson, and E. W. Vogt, Phys. Rev. 136, 1384 (1964); E. W. Vogt, D. McPherson, J. Kuehner, and E. Almqvist, *ibid.* 136, 1399 (1964).

[6]N. R. Fletcher, J. D. Fox, G. J. Kekelis, G. R. Morgan, and G. A. Norton, Phys. Rev. C 13, 1173 (1976).

[7]K. A. Eberhard, E. Matliak, J. Settmeier, W. Tronibik, A. Weidinger, L. N. Musterfeld, and K. G. Bernhardt, Phys. Rev. Lett. 56B, 445 (1975).

[8]H. Feshbach, J. Phys. C 37, 5—177 (1976); Europhysics Conference on Medium Mass Nuclei, 1977 (unpublished).

[9]T. M. Cormier, J. Applegate, C. M. Berkowtiz, P. Braun-Munzinger, P. M. Cormier, J. W. Harris, C. M. Jachcinski, and L. L. Lee, Jr., Phys. Rev. Lett. 38, 940 (1977); T. M. Cormier, C. M. Jachinski, G. M. Berkowitz, P. Braun-Munzinger, P. M. Cormier, M. Gai, J. W. Harris, J. Barrette, and H. E. Wegner, *ibid.* 40, 924 (1978).

[10]B. Imanishi, Nucl. Phys. A125, 33 (1969).

[11]Y. Kondo, Y. Abe, and T. Matsuse, Phys. Rev. C 19, 1356 (1979).

[12]W. Greiner and W. Scheid, J. Phys. C 32, 6—91 (1971); H. J. Fink, W. Scheid, and W. Greiner, Nucl. Phys. A188, 259 (1972); W. Scheid and W. Greiner, Z. Phys. 226, 364 (1969).

[13]R. L. Phillips, K. A. Erb, D. A. Bromley, and J. Weneser, Phys. Rev. Lett. 42, 566 (1979).

[14]P. Sperr, S. Vigdor, Y. Eisen, W. Henning, D. G. Kovar, T. R. Ophel, and B. Zeidman, Phys. Rev. Lett. 36, 405 (1976); P. Sperr, T. H. Braid, Y. Eisen, D. G. Kovar, F. W. Prosser, Jr., J. P. Schiffer, S. L. Tabor, and S. Vigdor, *ibid.* 37, 321 (1976).

[15]J. J. Kolata, R. M. Freeman, F. Haas, B. Hensch, and A. Gallmann, Phys. Lett. 65B, 333 (1976); J. J. Kolata, R. C. Fuller, R. M. Freeman, F. Haas, B. Hensch, and A. Gallmann, Phys. Rev. C 16, 891 (1977).

[16]D. Glas and U. Mosel, Phys. Rev. C 10, 2620 (1974).

[17]D. Shapira, R. G. Stokstad, and D. A. Bromley, Phys. Rev. C 10, 1063 (1974).

[18]A. J. Lazzarini, E. R. Cosman, A. Sperduto, S. G. Steadman, W. Thoms, and G. R. Young, Phys. Rev. Lett. 40, 1426 (1978).

[19]E. R. Cosman, R. Ledoux, and A. Lazzarini, Phys. Rev. C 21, 2111 (1980).

[20]E. R. Cosman, R. J. Ledoux, M. J. Bechara, C. E. Ordonez, and H. A. Al-Juwair, in *Resonances* in *Heavy Ion Reactions,* edited by K. A. Eberhard (Springer, Berlin, 1982), p. 112.

[21]K. Nagatani, T. Schinodo, D. Tanner, R. Tribble, and T. Yamaya, Phys. Rev. Lett. 43, 1480 (1979).

[22]R. Wieland, R. Stokstad, A. Gobbi, D. Shapira, L. Chua, M. W. Sachs, and D. A. Bromley, Phys. Rev. C 9, 1474 (1974); D. A. Bromley, L. Chua, A. Gobbi, P. R. Maurenzig, P. D. Parker, M. W. Sachs, D. Shapira, R. G. Stokstad, and R. Wieland, J. Phys. 32, C6-5 (1971).

[23]M. J. LeVine, D. Schwalm, and M. G. Littman, J. Phys. 32, C6—219 (1971).

[24]R. J. Markham, S. M. Austin, and H. Laumer, Nucl. Instrum. Methods 129, 141 (1975).

[25]L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables 7, Nos. 3,4 (1970).

[26]W. D. Rae, R. G. Stokstad, B. G. Harvey, A. Dacal, R. Legrain, J. Mahoney, M. J. Murphy, and T. J. Symons, Phys. Rev. Lett. 45, 884 (1980).

[27]R. H. Dalitz, Phys. Rev. 94, 1046 (1954).

[28]R. Chapman and A. M. MacLeod, Nucl. Phys. A94, 324 (1967).

[29]D. Branford, M. J. LeVine, J. Barrette, and S. Kubono, Phys. Rev. C 23, 549 (1981).

[30]M. J. Bechara, A. Lazzarini, R. J. Ledoux, and E. R. Cosman, Phys. Rev. C (to be published).

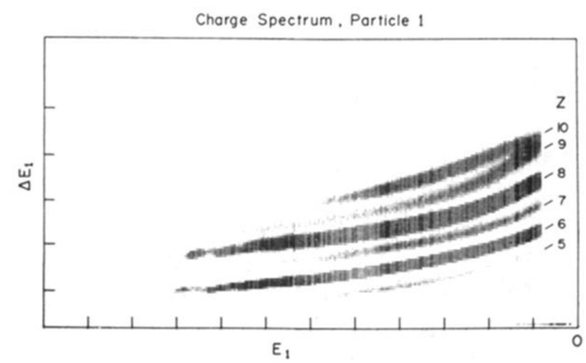

FIG. 2. A typical ΔE-E spectrum obtained with the gas ΔE-solid state E, position-sensitive telescope.