ANL/PHY/CP--84543
Conf-940974--1

EXPERIMENTAL SEARCHES FOR EXOTIC ALPHA-CLUSTER CONFIGURATIONS

A. H. Wuosmaa
Physics Division
Argonne National Laboratory
Argonne IL 60439 USA

Exotic and unusual shapes have recently been suggested to occur in light nuclei composed of alpha particle sub-units. Typically, these occur at very high excitation energy, where the nucleus is unbound with respect to decay into many charged particles. As a result these structures have been generally inaccessible to experiments conducted using conventional nuclear physics techniques. A new generation of detector devices now permits the simultaneous detection of many charged particles emerging from such an event with high efficiency, combined with excellent spatial and energy resolution. Such measurements for the first time allow us to make detailed experimental tests of theoretical predictions of extremely deformed alpha-cluster nuclei. We apply these techniques to the study of extremely deformed configurations predicted to exist at high excitation energy in the nucleus ^{24}Mg

Invited Paper Presented at CLUSTER 94 - Clusters in Nuclear Structure and Dynamics, Strasbourg France, Sept. 6-9, 1994.

DISCLAIMER

Many new theoretical developments in the field of alpha-particle clustering have suggested that evidence for quite unusual cluster configurations in light nuclei might be found by studying nuclear reactions that result in final states consisting of large numbers of charged particles. Specifically, highly deformed alpha-particle cluster configurations in light nuclei such as ^{24}Mg have been suggested to occur at excitation energies that are high enough so that the nucleus becomes unbound with respect to decay into its alpha-particle constituents. In the past, these decay modes have been unobservable, due to the experimental difficulties of exctracting spectroscopic information about complicated many-particle final states. Recently, however, new detector devices have become available which for the first time permit the detailed examination of reactions that lead to such many-body final states. As a result, many new and potentially interesting results have been obtained for cluster configurations that were impossible to study using older, more conventional experimental methods.

In this contribution, we will describe some methods that permit the determination of excitation energies, decay branches, and spin, for highly excited levels which decay into several charged particles. We will present some examples of these measurements applied to the nucleus ^{24}Mg, where a wide variety of theories predict many different coexisting alpha-particle cluster configurations at high excitation energy. These measurements demonstrate how this new generation of detector devices opens up a new window for the study of very exotic, deformed alpha-particle cluster nuclei.

One of the most unusual predictions of models of alpha-clustering behavior in light, alpha-particle nuclei is that strongly deformed structures should exist in these nuclei which resemble linear assemblies of alpha particles, also known as alpha-chain configurations. States of this kind were noted by Morinaga in 1956 in relation to the nucleus ^{16}O [1], and have emerged from many types of calcuations using, for instance, alpha-cluster formalisms[2,3], the deformed shell model[4], and also the Hartree-Fock approximation[5]. These deformed states are predicted to exist in alpha-particle nuclei ranging from ^{8}Be to ^{24}Mg, and in some lighter nuclei certain levels have already been associated with configurations of this type. For example, the ground state of ^{8}Be is naturally described as a two-alpha chain, and in ^{12}C the first excited 0^+ level at 7.65 MeV has long been suggested to correspond to a deformed cluster configuration in that nucleus[6,7]. In ^{16}O, resonances observed in the reactions $\alpha+^{12}\mathrm{C}\rightarrow^{8}\mathrm{Be}+^{8}\mathrm{Be}$ and $\alpha+^{12}\mathrm{C}\rightarrow\alpha+^{12}\mathrm{C}(0_2^+)$ have been associated with a 4-α chain structure[8,9]. In heavier nuclei where the observation of such configurations would provide significant confirmation of the most exotic predictions of the different nuclear structure models, the experimental difficulties of unravelling complicated particle final states have made such observations quite difficult.

One calculation, performed using the Cranked Cluster Model (CCM) of Marsh and Rae[3)] predicts that the deformed chain structure in ^{24}Mg exists at excitation energies between 40 and 50 MeV, approximately 12 to 22 MeV above the 6α decay threshold for ^{24}Mg. Simple phase-space arguments strongly favor the decay of such an object into initially binary decay channels, however, and one expects that the constituents of these binary final states would have a similar deformed structure. One exit channel whose study might provide some insight into this behavior is the $^{12}C(0_2^+)+^{12}C(0_2^+)$ final state. The observation of resonance or resonance-like behavior in the $^{12}C(^{12}C,^{12}C(0_2^+))^{12}C(0_2^+)$ reaction could serve as a signature for the population of these elongated configurations in the composite nucleus ^{24}Mg. A 6α chain configuration in ^{24}Mg might also have non-symmetric decay branches, and one promising candidate is the mode in which the ^{24}Mg decays by emitting a ^{8}Be, leaving ^{16}O in an excited configuration corresponding to one of the deformed states identified as resonances in $\alpha+^{12}$C scattering.

In order to study these reactions, we must use a detector system which is capable of detecting and identifying many charged particles simultaneously, while providing a high resolution measurement of their energies and scattering angles in the laboratory. One device which is ideally suited to these types of measurements is known as the double-sided silicon strip detector (DSSD). These detectors are available in a variety of configurations; for the measurements described here, they were fabricated from 5×5 cm^2 wafers, 500μm thick with the implanted junction layers on the two sides divided into two orthogonal sets of 16 strips. The readout of signals from each segment from each side of the DSSD is accomplished in part using instrumentation developed in part at Argonne National Laboratory [10)]. By correlating the duplicate energy signals from each side of the detector, both X and Y position information for each particle striking the detector can be obtained [10)]. Figure 1 shows a schematic diagram of one configuration of the experimental setup consisting of four DSSDs used at Argonne to study many-particle final states following the decay of ^{24}Mg. With four detectors placed at distances from 15 to 20 cm away from the target, a solid angle coverage of approximately 800 msr, effectively segmented into 1024 pixel regions, is achieved.

In the case of an excited ^{12}C nucleus decaying to three alpha particles, the vector sum of the momenta of the alpha particles from the decaying nucleus immediately determine the kinetic energy and scattering angles in the laboratory for the ^{12}C. In addition, the difference between the sum of the alpha-particle kinetic energies and the kinetic energy of the decaying ^{12}C yields, up to a separation-energy constant, the ^{12}C excitation energy. The same calculations

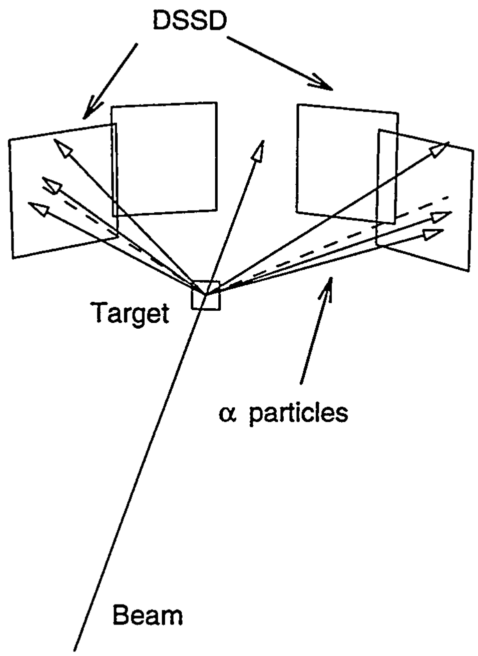

Figure 1: Schematic diagram of the 4-DSSD setup.

can be performed for $^{8}Be_{g.s.} \rightarrow 2\alpha$ or $^{16}O^{*} \rightarrow 4\alpha$. Examples appear in Figure 2. Figure 2a shows a spectrum of ^{8}Be excitation energy obtained from pairs of alpha particles. The ground-state is reconstructed with a resolution of 40-50 keV. For the three-alpha case, the corresponding ^{12}C excitation-energy spectrum appears in Figure 2b. Two states in ^{12}C between 7 and 10 MeV of excitation are apparent, the 0_2^+ level at 7.65 MeV, and the 3^- state at 9.64 MeV. The yield for the 3^- state is suppressed in this case due to the wider breakup cone for the alpha particles from this level, thus reducing the three alpha-particle detection efficiency for this level.

For $^{12}C+^{12}C$ scattering final states, reconstruction of a particular excitation in one of the two nuclei serves as particle identification, and we possess half the information required to extract the two-body scattering state from the many-particle exit channel. In the $^{12}C+^{12}C$ system, all that remains is to calculate the two-body scattering Q value from the kinematic relationship between the reconstructed kinetic energy and scattering angle of the reconstructed ^{12}C nucleus. Figure 3 shows spectra of the reconstructed two-body Q value for $^{12}C+^{12}C$ scattering for events in which the reconstructed ^{12}C nucleus was found to be either in its excited 0^+ level (a) or its 3^- level (b). In each spectrum, four peaks are apparent, corresponding to the situation where the unobserved ^{12}C nucleus was left either intact, in it ground state or 2^+ state, or at more negative Q values, also dissociated into three alpha particles. The final state

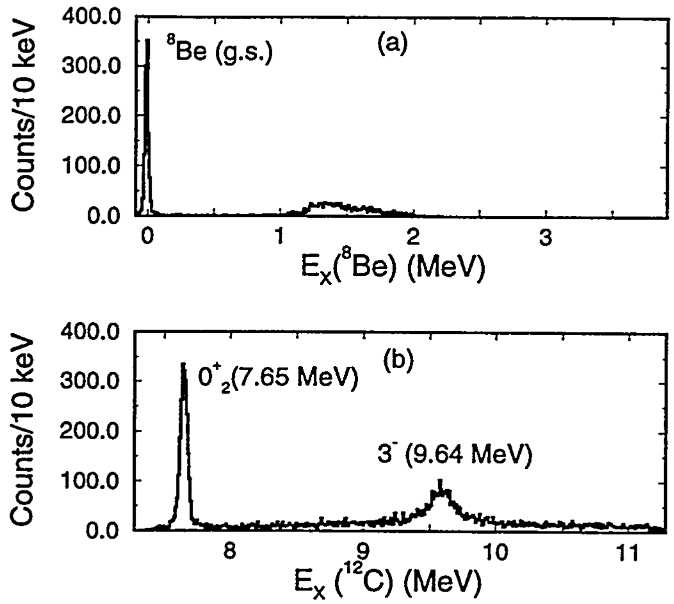

Figure 2: ^{8}Be and ^{12}C excitation-energy spectra

of interest in the context of studying alpha-particle chain structures in ^{24}Mg, the mutual $0_2^+ + 0_2^+$ final state, is easily identified at Q=-15.30 MeV. The width of the peaks in Figure 3 is due almost entirely to kinematic broadening effects, and is well reproduced by a Monte-Carlo simulation of the detector setup[11)], as illustrated by the dashed histogram in Figure 3a, calculated for the 0_2^++g.s. excitation.

Figure 4 shows the excitation function obtained for the mutual $0_2^+ + 0_2^+$ excitation [12)]. There is a strong enhancement of the yield, peaked at a center-of-mass energy of 32.5 MeV, corresponding to an excitation energy of 46.4 MeV in ^{24}Mg. This energy is precisely in the range where the Cranked Cluster Model of Marsh and Rae predicts that unusual phenomena related to the population of extremely deformed configurations in ^{24}Mg might be observed in this reaction[3)]. It is surprising that such a strong feature might be observed in a reaction channel with an angular-momentum mismatch of more that six units. With such a large mismatch, if becomes difficult to understand such behavior in the context of a reaction-model phenomenon, although some interesting efforts have been made in this direction[13,14)].

Angular-distribution data obtained on and off the peak of the excitation-function structure appear in Figure 6 [11)]. The oscillations in the data suggest dominant angular momenta in the range of 14-16 $\hbar$. Immediately, the most striking characteristic of the angular distribution obtained at the excitation-function peak is the very prominant interference maximum at a scattering angle of 90°, which dissappears completely at the higher energy. Such a peak implies constructive interference between a large number of contributing partial waves at this energy.

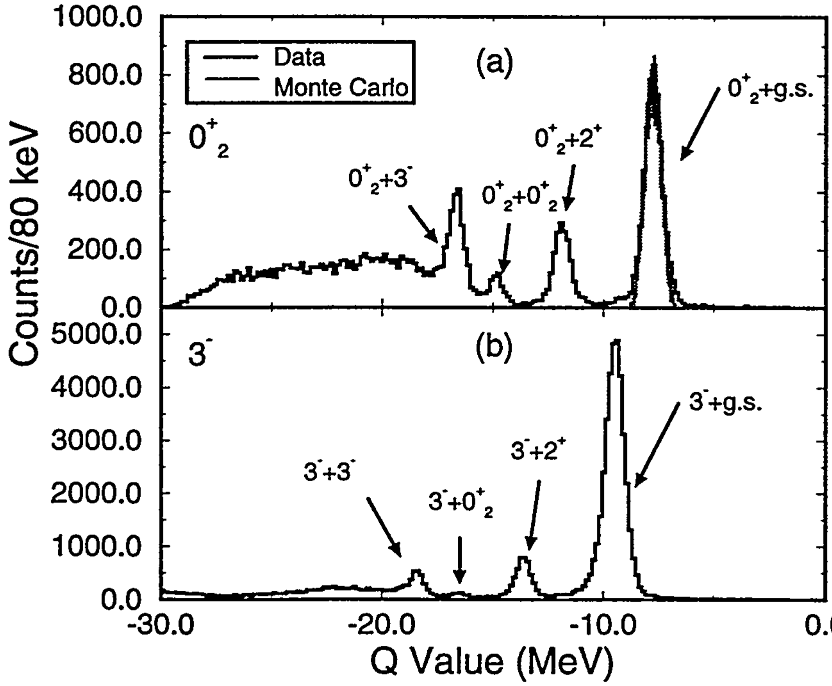

Figure 3: Q-value spectra for $^{12}C+^{12}C$ scattering.

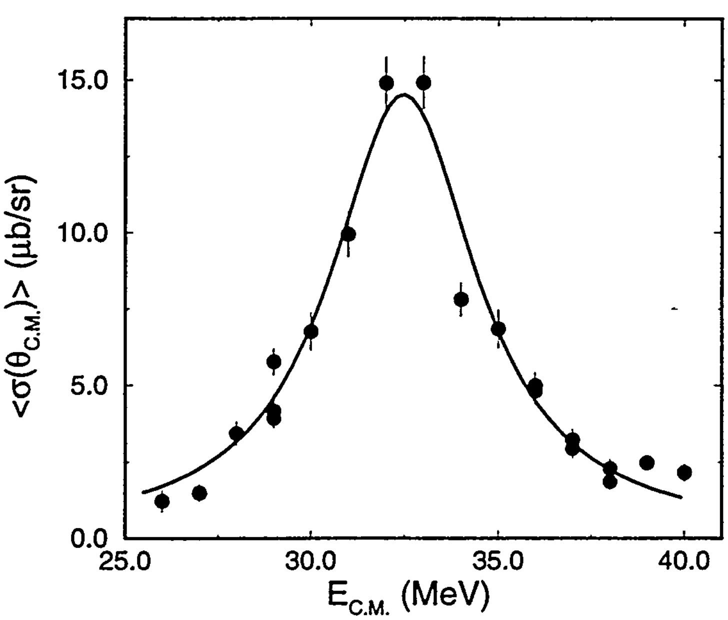

Figure 4: Excitation function for $^{12}C(0_2^+)+^{12}C(0_2^+)$ inelastic scattering[12].

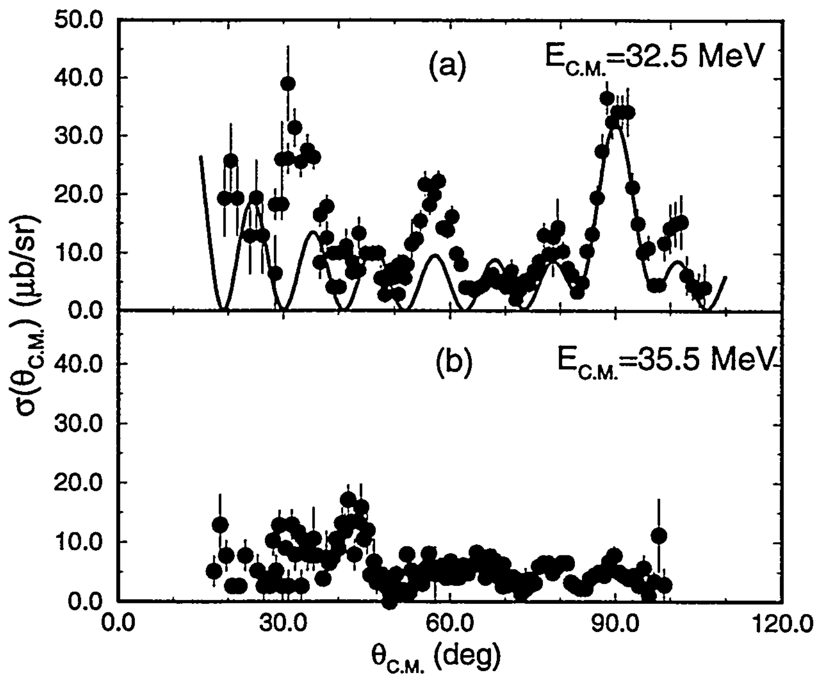

Figure 5: $^{12}C(0_2^+)+^{12}C(0_2^+)$ inelastic scattering angular distributions[11].

Rae, Merchant and Buck have interpreted this maximum in terms of a simple picture where all members of a degenerate rotational band built upon a cluster structure in the compound system are populated[15]. The cluster nature of the band imposes the appropriate phase relationship between adjacent even partial waves needed for constructive interference at $\theta_{C.M.}$=90°. The result of this calculation appears as the solid line in Figure 5a. The agreement between the calculation and data is surprisingly good considering the simplicity of the model. While other interpretations of the behavior of the cross section in the mutual $0_2^+ + 0_2^+$ final state are certainly not ruled out, all the observed data are at least consistent with the idea that strongly deformed cluster configurations in the compound nucleus could play a role in this reaction.

If the structures observed in the inelastic scattering measurements described above do correspond to the decay of a deformed complex in the ^{24}Mg compound nucleus, then this configuration should possess additional decay branches. In particular, we can search for the population of deformed cluster configurations in ^{16}O identified as resonances in $\alpha+^{12}$C inelastic scattering [8,9]. Such a measurement is significantly more difficult than study of inelastic scattering in the $^{12}C+^{12}C$ system, however, as now at least five alpha particles must be detected in each event, rather than only three for the $^{12}C+^{12}C$ case. The reason for this requirement is that not only must the primary ^{8}Be nucleus be identified, but we also must isolate the decay

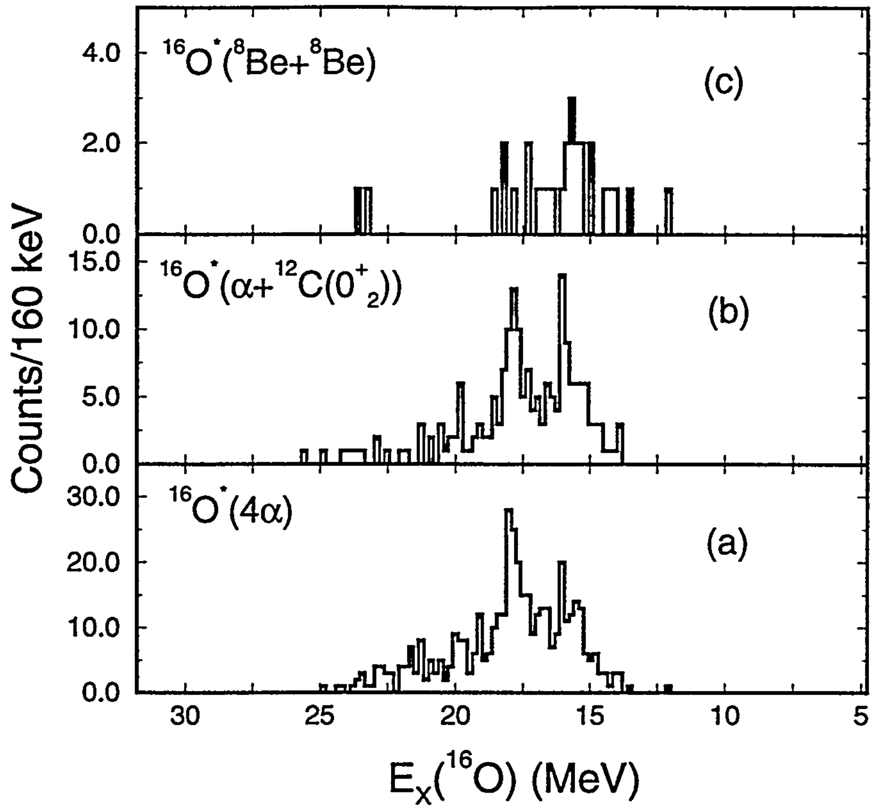

Figure 6: ^{16}O excitation-energy spectra for various decay branches.

sequence for the excited ^{16}O nucleus.

Some of the results of our measurements of the $^{12}C+^{12}C\rightarrow^8Be+^{16}O^*(4\alpha)$ reaction are summarized in Figure 6, which shows excitation-energy spectra for ^{16}O nuclei that decay via different many-particle decay modes. In Figure 6a, the ^{16}O decays to any combination of four alpha particles. In Figure 6b, the ^{16}O alpha decays, leaving a ^{12}C in its first excited 0^+ state, and finally in Figure 6c, the decay is to two ^8Be nuclei. In each case there exists evidence for what appear to be discrete levels in ^{16}O at excitation energies between 17 and 20 MeV, although for the $^8Be+^8Be$ case the statistics are somewhat marginal. The interesting possibility raised by these results is that these are the same levels populated as resonances in inelastic alpha-particle scattering on ^{12}C leading to the $^8Be+^8Be$ and $\alpha+^{12}C(0^+_2)$ final states. Should this association prove correct, a likely interpretation might be that we are observing non-symmetric decays of an elongated complex in the composite ^{24}Mg system.

While the excitation energies and decay properties of these levels in ^{16}O are similar to the resonances observed in $\alpha+^{12}C$ scattering, in order to more firmly establish this association it is important to determine the spins of these states. To determine the spins of these levels, we must resort to particle-particle angular correlation measurements. While we do not have these

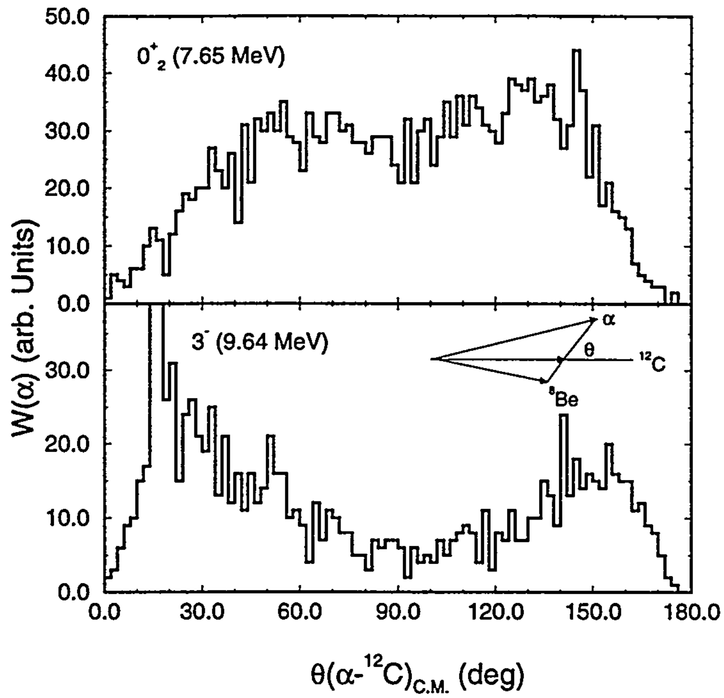

Figure 7: Angular correlations for $^{12}C^{*} \rightarrow \alpha + ^{8}Be$.

data at present, we can still demonstrate that spin variables can be extracted from correlation measurements for many-body final states. As an example, we turn to the case of ^{12}C. Another example of strip detectors used to study spin observables in the $^{12}C + ^{12}C$ system can be found in [16].

Figure 7 shows the yield for the decay of the 0_2^+ (a) and 3^- (b)levels in $^{12}C \rightarrow \alpha + ^{8}Be$, plotted as a function of the center-of-mass angle between the α particle and the direction of the decaying ^{12}C. These data are preliminary and uncorrected for efficiency effects, but still show that this angular correlation displays sensitivity to the angular momentum of the decaying state. For the 0_2^+ case, which should be isotropic in the center-of-mass system, the correlation is relatively flat around 90°. The decrease in yield at forward and backward angles is a consequence of the size of the pixels in the DSSD. At these angles, the three alpha particles from the ^{12}C decay are focussed foward in the laboratory in a cone which is smaller than the size of the detector segments, and hence can no longer be separately identified. For the 3^- case, the angular correlation is quite different, with the yield strongly supressed near $\theta_{C.M.}$=90°. This behavior is expected for a correlation that is dominated by spherical harmonics of order three. While these results will be modified somewhat by efficiency corrections, clearly such correlations contain information that is sensitive to the spins of such particle unbound levels.

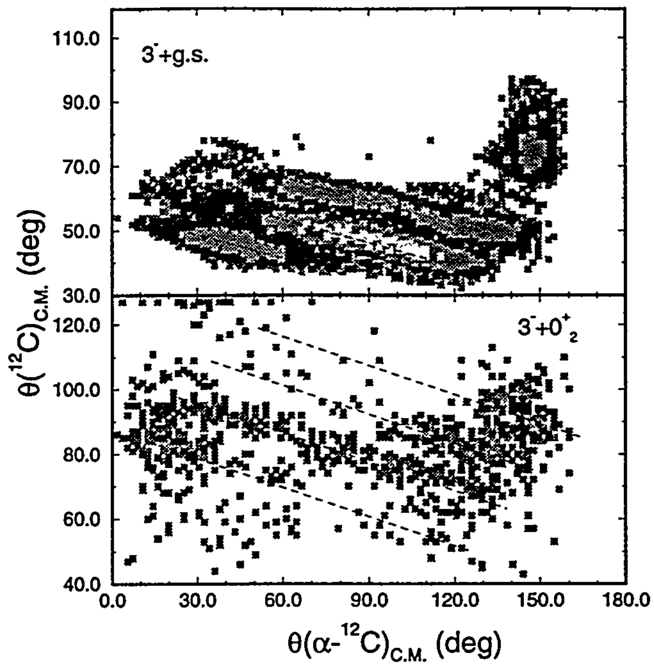

Figure 8: Two-dimensional angular correlation data for $^{12}C+^{12}C$ inelastic scattering.

We can also use these correlations to learn about the mechanism of scattering reactions involving decaying nuclei with non-zero spin. For example, in order to make detailed comparisons between the predictions of reaction models and data for heavy-ion scattering, an important quantity is the orbital angular momentum. The usual method for determining the contributing partial waves for a final state involving spinless particles is to study the angular distribution of the scattering yield. If the particles involved have non-zero spin, however, often the contribution of different magnetic substates washes out the structure in the angular distribution, even if only a single l value is present. By combining the angular correlation measurement described above and an angular distribution measurement, some of this information can be recovered. Figure 8 contains data for $^{12}C+^{12}C$ scattering to the 3^-+g.s. and $3^-+0_2^+$ exit channels. The data are plotted in a two-dimensional matrix where the X axis represents correlation angle described above, and the Y axis is the center-of-mass scattering angle in the ^{12}C-^{12}C system. The data are aligned in bands, as indicated by the dashed lines in Figure 8, and the the slope of the band is sensitive to the ratio between the spin of the decaying level and the orbital angular momentum in the $^{12}C+^{12}C$ system[17,18]. A projection along these contours produces a featured angular distribution, whose oscillations can yield information about the orbital angular momentum in the scattering state[17,18].

These results demonstrate that considerable information can be gained from final states that contain as many as six charged particles. With the availability of highly segmented detectors, these final states can now be fully analysed. This technique has considerable potential for improvement; the only restrictions on how sensitive measurements could be are solid angle coverage of the detector array, and experimental complexity. Experiments underway currently at Argonne consist of arrays containing as many as six DSSDs, resulting in 192 detector channels. For larger, more highly segmented arrays with even greater efficiency, which would be necessary, for example, for very low count rate experiments that might be conducted at a radioactive ion beam facility, the number of detector channels rises into the thousands. In order to instrument this many channels, new read-out systems involving large-scale integrated circuits must be developed. Many efforts in this direction are already underway, and there exist many potential opportunities in the future for this type of investigation using new, powerful experimental techniques. Work supported by the U.S. DOE, Nuclear Physics Division, under contract W-31-109-ENG-38.

References:

[1)]H. Morinaga, Phys. Rev. **101** 254 (1956).

[2)]D. M. Brink, H. Freidrich, A. Weiguny, and C. W. Wong, Phys. Lett. **B33**, 143 (1970).

[3)]S. Marsh and W. D. M. Rae, Phys. Lett. **B180**, 185 (1986).

[4)]G. Leander and S. E. Larsson, Nucl. Phys. **A239**, 93 (1975).

[5)]H. Flocard, P. -H. Heenen, S. J. Kreiger and M. S. Weiss, Prog. Theo. Phys. **72**, 1000 (1984)

[6)]N. Takigawa and A. Arima, Nucl. Phys. **A168**, 593 (1971).

[7)]P. Chevallier *et al.*, Phys. Rev. **160** 827 (1967)

[8)]W. Ames, PhD Thesis, University of Wisconson (1979).

[9)]A. H. Wuosmaa, *et al.*, Nucl. Instr. and Meth. in Phys. Res. **A345** 482 (1994)

[10)]A. H. Wuosmaa, *et al.*, in press in Phys. Rev. C

[11)]A. H. Wuosmaa, *et al.*, Phys. Rev. Lett.**68**, 1295 (1992).

[12)]L. Satpathay and P. Sarangi, J. Phys. G**20**, L37 (1994)

[13)]Y. Abe, contribution to this conference

[14)]W. D. M. Rae, A. C. Merchant, and B. Buck, Phys. Rev. Lett. **69** 3709 (1992).

[15)]N. J. Davis, *et al.*, Nucl. Instr. and Meth. **A330** 165 (1993) .

[16)]R. K. Bhowmik, *et al.*, Phys. Lett. **B136** 194 (1984) .

[17)]W. D. M. Rae, *et al.*, Phys. Lett. **B156** 167 (1985).