Evidence for $^{16}O + ^{12}C$ cluster structure in ^{28}Si

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A study of the $^{12}C(^{20}Ne,^{12}C^{16}O)^{4}He$ reaction has revealed $^{16}O+^{12}C$ breakup from states in ^{28}Si. These states may correspond to highly deformed shape isomeric configurations.

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In recent years a number of studies have been reported on the breakup of ^{24}Mg to $^{12}C + ^{12}C$. These have included breakup induced by scattering of electrons [1], protons [2], and α particles [3], as well as inverse reactions where a ^{24}Mg projectile is scattered from a ^{12}C target [4,5]. All these experiments revealed peaks in the relative energy spectrum of the two ^{12}C fragments, suggesting that the breakup was occurring from discrete states in the ^{24}Mg nucleus. Although one of the principle aims of these studies was to look for a link with the resonances observed in $^{12}C + ^{12}C$ scattering studies, confirmation of this association has only recently emerged [6].

More recently, the inverse scattering technique has been used to extend the breakup spectrum to higher excitation energy [7] and the spins of the breakup states have been determined from a measurement of the angular correlation of the decay fragments [8]. This latter measurement revealed an energy-spin systematics consistent with a rotational structure and lead to the speculation that the breakup could be associated with bands based on highly deformed shape isomers. Such configurations are predicted to occur in the relevant excitation energy region in ^{24}Mg in a number of different theoretical calculations; for example, the Hartree-Fock calculations of Flocard *et al.* [9], the cranked α cluster model calculations of Marsh and Rae [10], and the Nilsson-Strutinsky calculations of Leander and Larsson [11]. The recent observation of the same breakup states following excitation of the ^{24}Mg nucleus by α transfer has suggested [12] an association with one specific isomeric configuration: a hyperdeformed (3:1) prolate shape with an α-^{16}O-α structure, as this has a predominantly $4p4h$ configuration.

The same theoretical models which predict the existence of deformed shape isomers in ^{24}Mg also suggest that they will exist in other neighboring *sd* shell nuclei. It is therefore of interest to see whether such structures can be observed experimentally. One of the likely candidates is ^{28}Si, as evidence (although with very poor statistics) was reported in an earlier measurement [5]. In addition, a number of studies have reported resonances in the scattering of $^{12}C+^{16}O$ similar to those observed in $^{12}C+^{12}C$ scattering. In this paper we present evidence for $^{12}C+^{16}O$ cluster structure in the ^{28}Si nucleus.

The data were obtained during an experiment performed at Lawrence Berkeley Laboratory. A 160 MeV ^{20}Ne beam was used to bombard a natural carbon foil of 240 $\mu g\ cm^{-2}$ and coincident ^{12}C and ^{16}O nuclei were detected from the $^{12}C(^{20}Ne,^{12}C^{16}O)^{4}He$ reaction. The detector setup employed six telescopes mounted three on each side of the beam axis. The three telescopes on each arm were mounted in a vertical arrangement with the top and bottom telescopes 10° above and 10° below the horizontal plane, hence forming three diametrically opposite pairs. Each telescope consisted of three silicon detectors — a thin (30 μm) ΔE detector, an intermediate (510 μm) E detector, and a final (2000 μm) EB stopping detector. The ΔE and E detectors were position sensitive with their position axes crossed to give both X and Y readout. Hence the in-plane and out-of-plane angle of each fragment could be determined. The detectors were 10 mm x 10 mm and the front face of the ΔE detector was mounted 120 mm from the target. The ^{20}Ne beam current averaged around 30 e nA for the duration of the experiment and data was obtained for five settings of the arms.

Figure 1 shows the E_{tot} spectrum for coincident ^{12}C and ^{16}O nuclei for all five angle settings for one of the out-of-plane detector pairs. E_{tot} is the total energy in the exit channel (the summed energy of the two detected fragments plus that of the unobserved recoiling particle calculated from the missing momentum) and hence is a measure of the Q value of the reaction. The highest energy peak corresponds to those events where all three particles

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(^{16}O, ^{12}C, and ^{4}He) emerge in their ground state. The next lowest energy peak corresponds to the two breakup particles emerging in their first excited states (4.44 MeV in ^{12}C and 6.05/6.13 MeV in ^{16}O) which are not resolved, and below this a peak corresponding to the mutual excitation of these states is visible.

Gating on the highest energy peak, we can calculate the relative energy ($E_{\rm rel}$) of the two fragments, which relates directly to the excitation energy in the ^{28}Si nucleus from which the breakup has occurred. Figure 2 shows the summed spectrum from all angle settings, showing breakup from the region 30–40 MeV. The overall profile of the spectrum is determined by the varying detection efficiency at different excitation energies, which reflects the choice of detector angles.

Within the efficiency profile, the excitation spectrum shows a number of peaks superimposed on an underlying

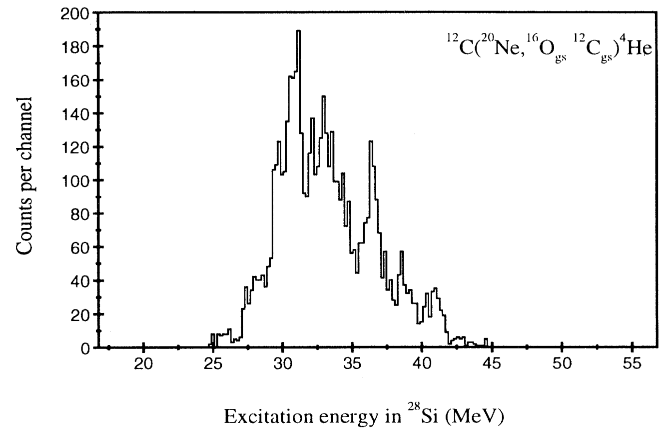

FIG. 2. Excitation spectrum for the states in ^{28}Si breaking up to ^{16}O+^{12}C.

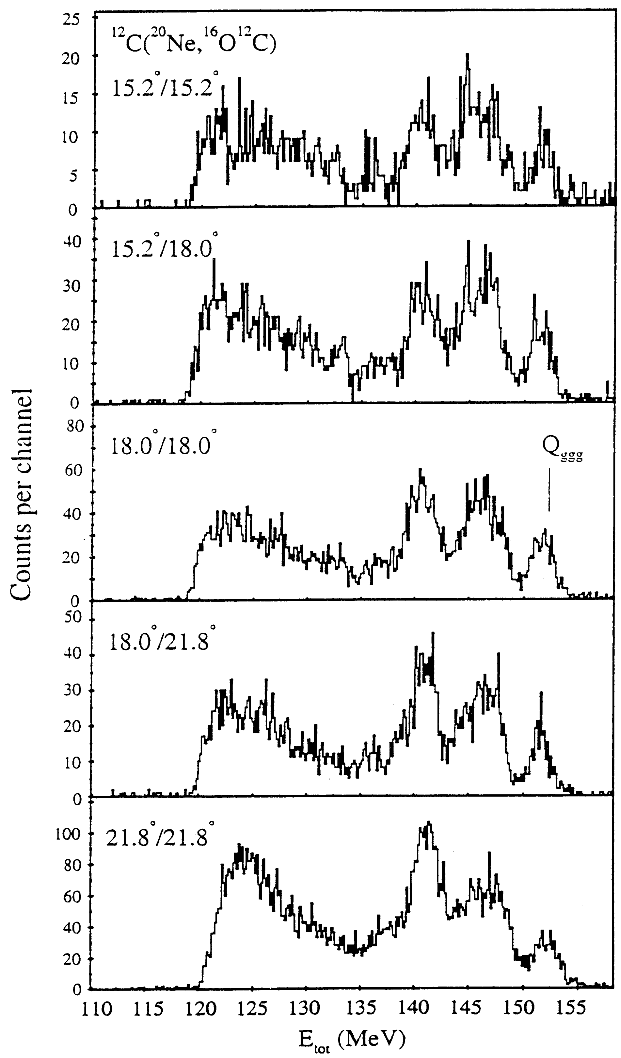

FIG. 1. $E_{\rm tot}$ spectra for ^{16}O+^{12}C coincidences at all angles in one of the out-of-plane detector pairs. The peak marked Q_{ggg} in the middle spectrum shows the peak corresponding to all particles emerging in their ground state.

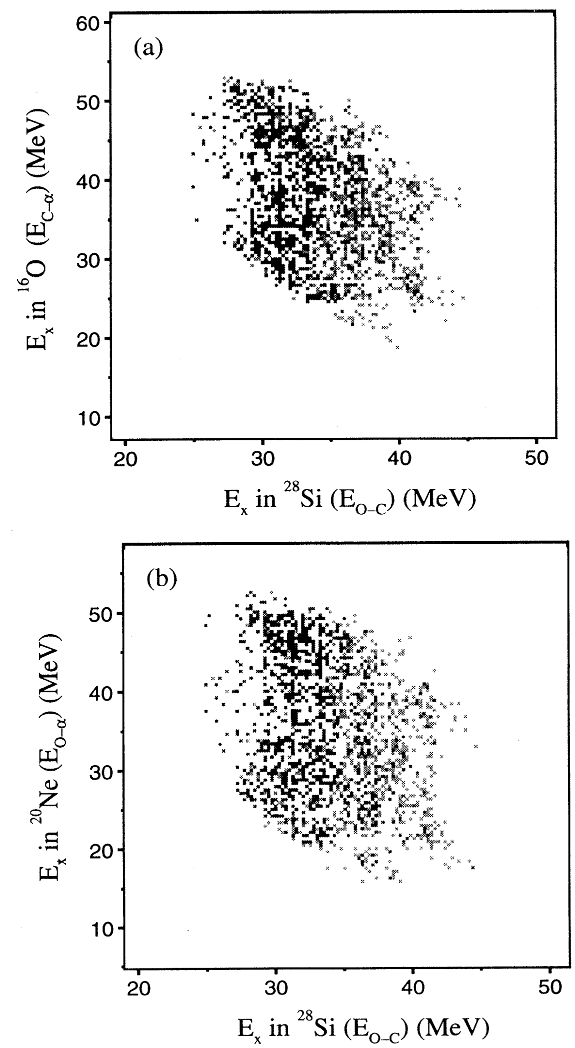

FIG. 3. Two-dimensional plots of (a) $E_{\rm C-\alpha}$ vs $E_{\rm O-C}$ and (b) $E_{\rm O-\alpha}$ vs $E_{\rm O-C}$. The vertical locii in each plot indicate a ^{16}O-^{12}C final-state interaction.

continuum. This structure in the breakup yield suggests the breakup is occurring from discrete states at high excitations in the ^{28}Si nucleus which have a pronounced ^{12}C + ^{16}O cluster structure. These results are remarkably similar to those obtained in the previous measurements of ^{12}C + ^{12}C breakup from ^{24}Mg, and hence suggest a similar structural origin.

Inherent in this analysis is the assumption that the observed yield arises from ^{16}O + ^{12}C breakup of an excited ^{28}Si nucleus formed in the ^{12}C(^{20}Ne,^{28}Si*)^{4}He reaction. The same exit channel particles could, however, arise from a number of different reaction processes, for example, α + ^{12}C breakup from ^{16}O formed in the ^{12}C(^{20}Ne,^{16}O*)^{16}O α stripping reaction or α + ^{16}O breakup of ^{20}Ne formed in the ^{12}C(^{20}Ne,^{20}Ne*)^{12}C inelastic scattering reaction. Since in both these reactions one of the heavy fragments will be emitted at backward angles in the center-of-mass frame and hence have a low laboratory energy in the forward angle region where it is detected, the yield might be expected to be low. Nevertheless, either process can, in principle, contribute to the measured ^{12}C + ^{16}O coincidence yield.

If either of the above two reactions occur then we could expect to see peaks in the $E_{\rm rel}$ calculated between the ^{12}C + α or ^{16}O + α, corresponding to breakup from specific excited states in the ^{16}O or ^{20}Ne nucleus, respectively. Figure 3 shows two-dimensional plots of (a) $E_{\rm C-\alpha}$ vs $E_{\rm O-C}$ and (b) $E_{\rm O-\alpha}$ vs $E_{\rm O-C}$. While the vertical locii corresponding to the ^{16}O+^{12}C states in ^{28}Si are visible, in neither plot is there any indication of horizontal locii which would imply a ^{12}C-α or ^{16}O-α final-state interaction.

If the breakup is from states in ^{28}Si, then in principle it should be possible to see some states in the other breakup channels evident in Fig. 1. Unfortunately, the resolution in the measurement is insufficient to resolve the decays to the first excited states in ^{12}C and ^{16}O (the second peak in Fig. 1) and although the data for the mutual excitation decay channel are clear, the breakup is occurring from an excitation region some 11 MeV higher and so does not overlap the spectrum shown in Fig. 2.

The breakup of ^{28}Si to ^{12}C + ^{16}O has been observed in the ^{12}C(^{20}Ne,^{12}C^{16}O)^{4}He reaction. The breakup spectrum shows yield from a number of discrete states in the ^{28}Si nucleus at high excitation. The similarity of the structure in the ^{16}O + ^{12}C spectrum to that observed in the ^{12}C + ^{12}C breakup of ^{24}Mg suggests a similar underlying structure. Both Nilsson-Strutinsky calculations and cranked cluster model calculations suggest that highly deformed shape isomeric states exist in ^{28}Si in the relevant excitation energy region. One key feature which might help associate the breakup states with these structures would be the observation of a rotational band with the relevant moment of inertia. Unfortunately, the limited statistics of the present measurement preclude spin determinations from the breakup angular correlation. A higher statistics measurement would clearly be of interest to see if a rotational sequence is present as in the ^{24}Mg nucleus.

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[1] A. M. Sandorfi, J. R. Calarco, R. E. Rand, and H. A. Schwettman, Phys. Rev. Lett. **45**, 1615 (1980).
[2] C. A. Davis, G. A. Moss, G. Roy, J. Uegaki, R. Abegg, L. G. Grenniaus, D. A. Hutcheon, and C. A. Miller, Phys. Rev. C **35**, 336 (1987).
[3] S. Lawitzki, D. Pade, B. Gonsior, C. D. Uhlhorn, S. Brandenburg, M. N. Harakeh, and H. W. Wilschut, Phys. Lett. B **174**, 246 (1986).
[4] J. Wilczynski, K. Siwek-Wilczynska, Y. Chan, E. Chavez, S. B. Gazes, and R. G. Stokstad, Phys. Lett. B **181**, 229 (1986).
[5] B. R. Fulton, S. J. Bennett, C. A. Ogilvie, J. S. Lilley, D. W. Banes, W. D. M. Rae, S. C. Allcock, R. R. Betts, and A. E. Smith, Phys. Lett. B **181**, 233 (1986).
[6] N. Curtis, N. M. Clarke, B. R. Fulton, S. J. Hall, M. J. Leddy, A. St. J. Murphy, J. S. Pople, R. P. Ward, W. N. Catford, G. J. Gyapong, S. M. Singer, S. P. G. Chappell, S. P. Fox, C. D. Jones, D. L. Watson, W. D. M. Rae, and P. M. Simmons, Phys. Rev. C **51**, 1554 (1995).
[7] M. J. Leddy, Ph.D. thesis, University of Birmingham, 1994 (unpublished).
[8] B. R. Fulton, S. J. Bennett, M. Freer, J. T. Murgatroyd, G. J. Gyapong, N. S. Jarvis, C. D. Jones, D. L. Watson, J. D. Brown, W. D. M. Rae, A. E. Smith, and J. S. Lilley, Phys. Lett. B **267**, 325 (1991).
[9] M. Flocard, P. H. Heenen, S. J. Krieger, and M. S. Weiss, Prog. Theor. Phys. **72**, 100 (1984).
[10] S. Marsh and W. D. M. Rae, Phys. Lett. B **180**, 185 (1986).
[11] G. Leander and S. E. Larsson, Nucl. Phys. **A239**, 93 (1975).
[12] B. R. Fulton, S. J. Bennett, J. T. Murgatroyd, N. S. Jarvis, D. L. Watson, W. D. M. Rae, Y. Chan, D. DiGregorio, J. Scarpaci, J. Suro Perez, and R. G. Stokstad, J Phys. G **20**, 151 (1994).