Interpretation of Gross Structures in the Energy Spectra of the Reaction $^{12}C(^{16}O,\alpha)^{24}Mg$

A. Szanto de Toledo, M. M. Coimbra, and N. Carlin Filho
Instituto de Fisica da Universidade de São Paulo, São Paulo, Brazil

and

T. M. Cormier and P. M. Stwertka
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

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Recent studies of the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$ at $E(^{16}O) = 145$ MeV have revealed the existence of several broad states with $E_x(^{24}Mg) = 20$ to 60 MeV, which have been interpreted as members of the $^{12}C + ^{12}C$ molecular band $J^\pi = (10^+)$ through $J^\pi = (18^+)$. Subsequent investigation, however, has failed to reveal the expected partial width for $^{24}Mg^* \rightarrow ^{12}C + ^{12}C$. We show that these states can be interpreted as an extension of the ^{24}Mg yrast sequence which is populated by the well understood high-spin selectivity of α-particle evaporation from a ^{28}Si compound nucleus.

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In a recent Letter, Nagatani *et al.*[1] have reported the observation of broad peaks on top of a very strong continuum in the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$ at $E(^{16}O) = 145$ MeV. The positions and widths of these peaks immediately suggest[1] that they are the high-spin $^{12}C + ^{12}C$ molecular resonances observed by Cormier *et al.*[2] in $^{12}C + ^{12}C$ inelastic scattering excitation functions with $E_x(^{24}Mg) = 20$ to 60 MeV. In an earlier similar experiment at lower energies, Lazzarini *et al.*[3] also suggested that several narrow discrete states which survive beam-energy averaging over $E(^{16}O) = 62$ to 110 MeV correspond to various fine-structure resonances seen in the $^{12}C + ^{12}C$ system corresponding to $E_x(^{24}Mg) \simeq 17$ to 40 MeV.

On the basis of the work of Ref. 2, it was anticipated that these states should have significant partial widths for decay into $^{12}C + ^{12}C$ perhaps as large as $\Gamma_c/\Gamma \simeq 35\%$. Such a large decay branch is far greater than the statistical model allows and would be readily observable experimentally. The particle-particle coincidence experiment designed to measure Γ_c/Γ for the states observed by Nagatani *et al.* has recently been reported by Rae *et al.*[4] These authors observe *no* $^{12}C + ^{12}C$ final-state interaction and clearly demonstrate that the $\alpha + ^{12}C + ^{12}C$ channel is dominated by the process $^{16}O + ^{12}C \rightarrow ^{16}O^* + ^{12}C \rightarrow \alpha + ^{12}C + ^{12}C$. Three scenarios are given in Ref. 4 to account for the data of Nagatani *et al.*: (i) Γ_c/Γ is small; (ii) the observed structures are produced by the α decay of discrete states in the strongly forward scattered ^{16}O; and (iii) the excitation and sequential α decay of ^{16}O is a major component of the strong background observed in Ref. 2, and therefore obscures the $^{12}C + ^{12}C$ final-state interaction of the much weaker ^{24}Mg states.

A complete discussion of these three possibilities is beyond the scope of the present Letter. It is important for the following, however, to note that hypothesis (ii) may not be consistent with very recent data[5] which reveal an absence of structures in the reactions $^{13}C(^{16}O, \alpha)$ and $^{14}N(^{16}O, \alpha)$ at $E(^{16}O) = 145$ and 139 MeV, respectively, and, more significantly, the gradual disappearance of structures in the reaction $^{12}C(^{16}O, \alpha)$ at $E(^{16}O) = 180$ and 230 MeV.

On the basis of the above discussions, we conclude that the structures observed by Nagatani *et al.* are states in ^{24}Mg whose structure is not illuminated by the work of Ref. 4. In the present Letter we consider hypothesis (i), namely, that the observed structures are states in ^{24}Mg with small Γ_c/Γ. We are motivated in this by the recent paper of Branford *et al.*,[6] who have repeated the experiment of Lazzarini *et al.* with improved resolution and shown that all of the observed states between $E_x(^{24}Mg) = 22.9$ and 26.5 MeV have total widths Γ which are far smaller than those of molecular states. The total widths of the latter are known from $^{12}C + ^{12}C$ excitation function studies to be $\Gamma > 200$ keV whereas Branford *et al.* measure 13 keV $\leq \Gamma \leq$ 160 keV for states excited in the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$. Figures 1(d) and 1(c) compare the data of Refs. 1 and 3. Both sets have been averaged over $\Delta E_x(^{24}Mg) = 1$ MeV so that the individual discrete states of Ref. 3 are no longer visible. The broad bumps in these two spectra are strongly correlated in their common energy region. It is important to recognize that each broad bump in Fig. 1(c) results from several much narrower states.

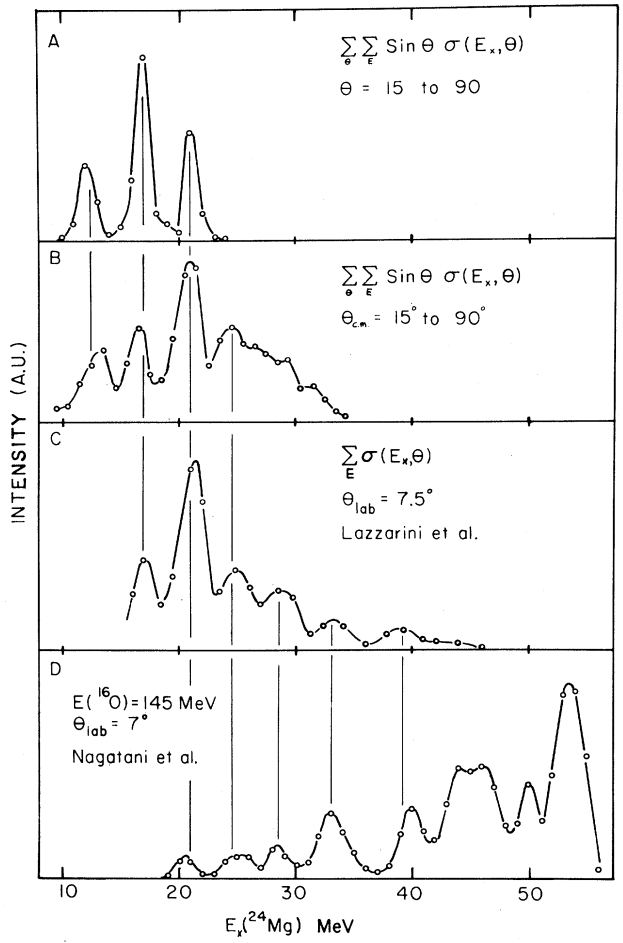

FIG. 1. Background-subtracted energy spectra from the reaction ^{12}C(^{16}O, α)^{24}Mg: (a) Angle-integrated and beam-energy—averaged, E(^{16}O) = 48.8, 54.2, and 58.6 MeV. (b) Angle-integrated and beam-energy—averaged, E(^{16}O) = 55, 60, and 65 MeV. (c) $\theta_{\rm lab} = 7.5°$; beam-energy—averaged, E(^{16}O) = 63, 77, and 91 MeV; data of Ref. 3. (d) $\theta_{\rm lab} = 7°$, E(^{16}O) = 145 MeV; data of Ref. 1.

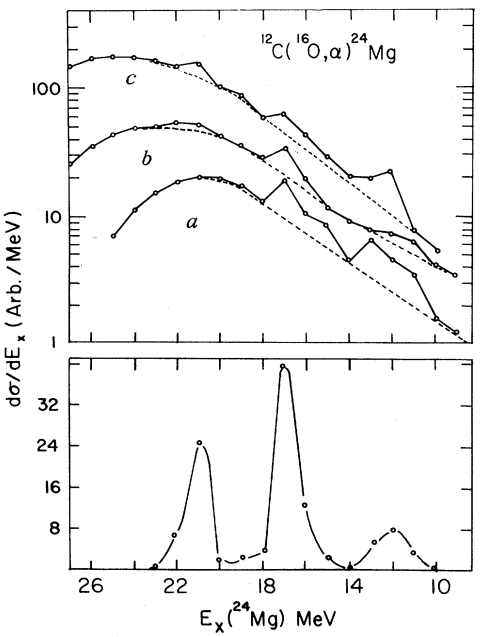

FIG. 2. Top: Angle-integrated energy spectra of the reaction ^{12}C(^{16}O, α)^{24}Mg averaged over ΔE_x (^{24}Mg) = 1 MeV for three of the beam energies studied: E(^{16}O) = 48.8 (curve a), 54.2 (curve b), and 58.6 MeV (curve c). Bottom: Background-subtracted, beam-energy—averaged spectrum.

The recognition that the broad bumps observed by Nagatani *et al.* are also visible at much lower energy has prompted us to extend these measurements to even lower energies, actually below the threshold for ^{12}C + ^{12}C resonances in ^{24}Mg (~ 20 MeV) and in the region where the highest spin discrete states have been identified.[3,6-9] Measurements were made on the University of Saõ Paulo Pelletron and the University of Rochester MP tandem Van de Graff accelerator. α-particle spectra from the reaction ^{12}C(^{16}O, α) were recorded with standard Si surface-barrier detector telescopes at a nominal resolution of ΔE_x (^{24}Mg) ~ 200 keV. Complete angular distributions were measured at E(^{16}O) = 48.8, 54.2, 58.6, 55, 60, and 65 MeV.

To eliminate Ericson fluctuations we form beam-energy—averaged, angle-integrated, background-subtracted α-particle spectra as illustrated in Fig. 2. These spectra are again averaged in E_x (^{24}Mg) = 1 MeV steps as in Figs. 1(c) and 1(d). The resulting average spectra for E(^{16}O) = 49 to 59 MeV and 55 to 65 MeV are shown in Figs. 1(a) and 1(b), respectively.

Remarkably, the pattern observed at E(^{16}O) = 145 MeV apparently extends from E_x (^{24}Mg) = 12 to 56 MeV. It is known from Ref. 6 that the component levels (which when averaged produce the broad bumps in Fig. 1) are not molecular in nature below E_x (^{24}Mg) $\simeq$ 27 MeV. It is also known that these component levels are, at least at lower bombarding energies, populated by a compound-nucleus mechanism and that their selectivity results from angular momentum matching. In fact, angular momentum matching provides a natural explanation of the occurrence of the broad bumps.

The Hauser-Feshbach cross section falls steeply with increasing excitation energy above the yrast level for a given J. For example, the predicted cross sections for a $J^\pi = 8^+$ state excited at $E(^{16}O) = 50$ MeV are 19, 7, and 2 mb at $E_x(^{24}Mg) = 12$, 15, and 18 MeV, respectively. Thus the selectivity window for a given J can be a very narrow region just above the yrast level.

This suggests that the broad bumps of Fig. 1 are the ^{24}Mg yrast levels or clusters of a few levels of the same J close to the yrast level. This is supported in the case of the broad bumps at $E_x(^{24}Mg) = 13$, 16.5, and 21 MeV, which are due principally to the states at $E_x = 13.206$ ($J^\pi = 8^+$) (Ref. 7), $E_x = 16.55$ (9^-) (Ref. 8), and $E_x = 20.8$ (10^+), $E_x = 21.6$ (10^+) (Ref. 9).

In Fig. 3(a) we show the E_x vs $J(J+1)$ plane for ^{24}Mg on which the broad bumps of Fig. 1 have been plotted assuming that they follow a $\Delta J = 1$ sequence beginning with $J = 8$ at $E_x \simeq 13$ MeV. The solid line through the data points is an extrapolation of the ^{24}Mg ground-state rotational band. Of course, the $K^\pi = 0^+$ ground-state band contains only even spin but the odd-spin yrast levels apparently lie on the same trajectory.

Figures 2 and 3(a) suggest that the broad bumps which appear in the averaged spectra have a common origin at both low and high $E(^{16}O)$, namely, statistical evaporation of α particles from the ^{28}Si compound nucleus. Also shown in Fig. 3 are the angular momentum matching conditions implicit in the Hauser-Feshbach formalism. The fact that these curves lie at or to the left of the yrast line accounts, of course, for the extreme selectivity of the reaction $^{12}C(^{16}O, \alpha)$. The increasing angular momentum mismatch which is evident at higher bombarding energies is consistent with the absence of structure in the experiments[5] at 230 MeV.

Figure 3(b) shows the results of a statistical-model calculation of the background-subtracted α spectra in which the yrast states have been explicitly added to a conventional Fermi-gas level density ρ_F by taking

$$\rho(E_x, J) = \rho_F(U, J) + \rho_Y(E_x, J)$$

where $U = E_x - \Delta$, and

$$\rho_Y(E, J) = \begin{cases} 2 \text{ levels/MeV}, & E_x \geq E_Y(J), \\ 0, & E_x < E_Y(J), \end{cases}$$

with $E_Y(J) = (\hbar^2/2\mathcal{J})J(J+1)$, Δ the pairing energy, and $\mathcal{J}$ the moment of inertia given by Fig. 3(a). The choice of 2 levels per MeV is consistent with available data[7-9] for $J \lesssim 10\hbar$. The parameters used in this calculation were fixed for all bombarding energies and were taken from Ref. 9, where they were shown to give a detailed account of cross sections to states of known spin.

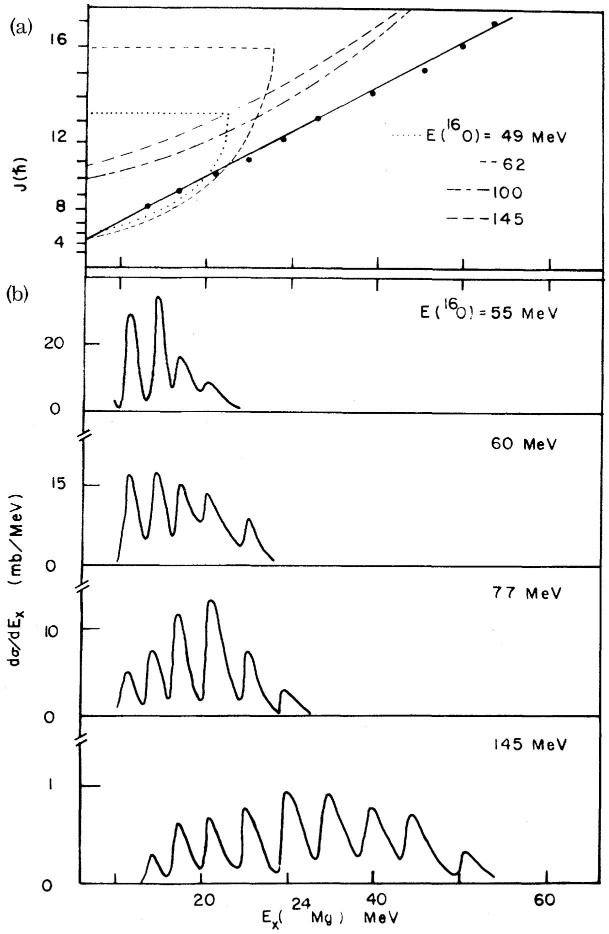

FIG. 3. (a) E_x vs $J(J+1)$ plane for ^{24}Mg. The points are the excitation energies of the broad bumps $E_x = 13$, 16.5, 21, 25, 28.5, 33, 40, 45, 50, and 53.5 MeV plotted assuming $\Delta J = 1$ and $J = 8$ at $E_x = 13$ MeV. The heavy solid line is an extrapolation of the ^{24}Mg ground-state band. The angular momentum matching trajectories for the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$ are shown for various $E(^{16}O)$. (b) Background-subtracted α spectra calculated in the Hauser-Feshbach formalism.

The results presented in Fig. 3(b) are overall in good agreement with the experimental spectra. In particular, the total cross sections are in reasonable agreement with available data[10] and, most significantly, the total widths of the bumps are reproduced except for reasonable variations which may result from the detailed ^{24}Mg level scheme near the yrast line.

The cross sections to yrast states shown in Fig. 3(b) decrease rapidly with increasing beam energy and this is consistent with the absence of structure in recent experiments[5] at $E(^{16}O) = 230$

MeV. Similarly, calculations for ^{25}Mg yrast states excited in the reaction ^{13}C(^{16}O, α) show a reduction of a factor of at least 7 at $E(^{16}\mathrm{O}) = 145$ MeV depending somewhat on the parameters of the Fermi-gas level density.

Thus, a consistent interpretation of the broad structures seen at $E(^{16}\mathrm{O}) = 145$ MeV can be given by relating them to similar structures observed at much lower bombarding energies where the reaction mechanism is well understood. At lower excitation energies where the high-spin states are well separated ($\Gamma/D \ll 1$) it is necessary to explicitly average over excitation energy to make the broad structures visible. In the statistical model these broad structures arise from angular momentum matching, which creates narrow windows of excitation energy above the yrast level within which a state of spin J can be excited with significant probability. The spacing of broad structures suggests the $\Delta J = 1$ sequence plotted in Fig. 3. It must be emphasized that this plot is not unique, however. New data at $E(^{16}\mathrm{O}) = 145$ MeV (Ref. 5) suggest the possibility that the broad structures at $E_x(^{24}\mathrm{Mg}) = 45$ and 53.5 MeV may be doublets. This implies that the sequence plotted in Fig. 3 may be incorrect above $E_x \simeq 45$ MeV. Further high-energy measurement including absolute cross section will be necessary to substantiate the statistical-model description of these data and determine the shape of the ^{24}Mg yrast line.

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Higher-Order Deformations of ^{232}Th and ^{234,236,238}U

R. M. Ronningen, R. C. Melin,[a] J. A. Nolen, Jr., and G. M. Crawley
Physics Department and Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

and

C. E. Bemis, Jr.
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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We have measured the inelastic scattering of 35-MeV protons from ^{232}Th and from ^{234,236,238}U. Angular distributions were extracted for $J^\pi = 0^+ - 8^+$ members of the ground-state rotational bands, and were analyzed with use of coupled-channels calculations for scattering from a deformed optical potential. The deformation parameter β_6 is positive for ^{232}Th and ^{234}U, nearly zero for ^{236}U, and negative for ^{238}U. The trends of the deformation parameters and multipole moments are explained qualitatively by a simple model.

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The actinide nuclei accessible to scattering experiments are known to be intrinsically deformed and thus their charge and matter (proton and neutron) distributions possess nonzero multipole moments. The moments best studied experimentally and theoretically are the quadrupole and hexadecapole ("2^λ pole," where $\lambda = 2$ and 4, respectively). Very little information currently exists on