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preprint

IFUSP/P-256

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

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Abstract

Recent studies of the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction at $E(^{16}O) = 145$ MeV have revealed the existence of several broad states with $E_x(^{24}Mg) = 20$ to 60 MeV. The energies of these states have been taken as evidence that they are members of the $^{12}C + {}^{12}C$ molecular band $J^{\pi} = (10^+)$ through $J^{\pi} = (18^+)$. Subsequent investigation of the properties of these states, however, has failed to reveal the expected partial width for $^{24}Mg^* \rightarrow {}^{12}C + {}^{12}C$.

In the present letter 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.

†This work was supported in part by the National Science Foundation and CNPq
* FAPESP

FEB/81

In a recent letter, Nagatani et al.[1] have reported the observation of broad peaks on top of a very strong continuum in the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction 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.

Based on the work of Ref. (2), it was anticiapted 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 <u>no</u> $^{12}C + {}^{12}C$ 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 and therefore the observed structures are not molecular states; (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) is <u>not</u> consistent with very recent data[5] which reveal an absence of structures in the $^{13}C(^{16}O, \alpha)$ and $^{14}N(^{16}O, \alpha)$ reactions at $E(^{16}O)$ = 145 MeV and 139 MeV respectively and, more significantly, the gradual disappearance of structures in the $^{12}C(^{16}O, \alpha)$ reaction at $E(^{16}O)$ = 180 MeV and 230 MeV.

On the basis of the above discussion, 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 $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction. Fig. 1d and 1c compared the data of Ref. (1) and Ref. (3). Both data 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. 1c results from several much narrower states.

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. Measurements were made on the University of Saõ Paulo Pelletron and the University of Rochester MP Tandem. Alpha particle spectra from the $^{12}C(^{16}O, \alpha)$ reaction were recorded with standard Si-surface barrier detector telescopes at a nominal resolution of $\Delta E_x(^{24}Mg) \sim 200$ 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. 1c and 1d. The resulting average spectra for $E(^{16}O)$ = 49 to 58 MeV and 55 to 65 MeV are shown in Figs. 1a and 1b 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 $E_x(^{24}Mg) \approx 27$ 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 occurance 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 mb, 7 mb, 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, 21 MeV which are due principally to the E_x = 13.206 $J^{\pi} = 8^{+}$ Ref. (6), E_x = 16.55 (9^{-}) Ref. (7), and E_x = 20.8 (10^{+}), E_x = 21.6 (10^{+}) Ref. (8).

In Fig. 3 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 they follow a $\Delta J = 1$ sequence beginning with J = 8 at $E_x \approx 13$ 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.

Figs. 2 and 3 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 right of the Yrast line accounts, of course, for the extreme selectivity of the $^{12}C(^{16}O, \alpha)$ reaction. 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.

Thus, a consistent interpretation of the broad structures seen at $E(^{16}O) = 145$ MeV can be given 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 ($\Gamma/D < 1$) it is necessary to explicitly average over excitation energy to make the broad structures visible. In the statistical model these broad structures may arise from angular 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 $E(^{16}O) = 145$ MeV Ref. (5) suggest the possibility that the broad strucutres at $E_x(^{24}Mg) = 45$ MeV and 53.5 may be doublets. This implies that the sequence plotted in Fig. 3 may be incorrect above $E_x \approx 45$ MeV. Further high energy measurements including absolute cross sections 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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Figure Captions

1. Background-subtracted energy spectra from the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction:

   (A) Angle integrated and beam energy averaged $E(^{16}O)$ = 48.8, 54.2, 58.6 MeV.

   (B) Angle integrated and beam energy averaged $E(^{16}O)$ = 55, 60, 65 MeV.

   (C) $\theta_{Lab} = 7.5°$, beam energy averaged $E(^{16}O)$ = 63, 77, 91 MeV, data of Ref. (3).

   (D) $\theta_{Lab} = 7°$, $E(^{16}O)$ = 145 MeV, data of Ref. (1).

2. Top: Angle integrated energy spectra of the $^{12}C(^{16}O, \alpha)^{24}Mg$ averaged over $\Delta E_x(^{24}Mg)$ = 1 MeV for three of the beam energies studied: $E(^{16}O)$ = 48.8, 54.2, and 58.6 MeV.

   Bottom: Background subtracted, beam energy averaged spectrum.

3. E_x vs. $J(J + 1)$ plane for ^{24}Mg. The open points are the excitation energies of the broad bumps E_x = 13, 16.5, 21, 25, 28.5, 33, 40, 45, 50, 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 $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction are shown for various $E(^{16}O)$.

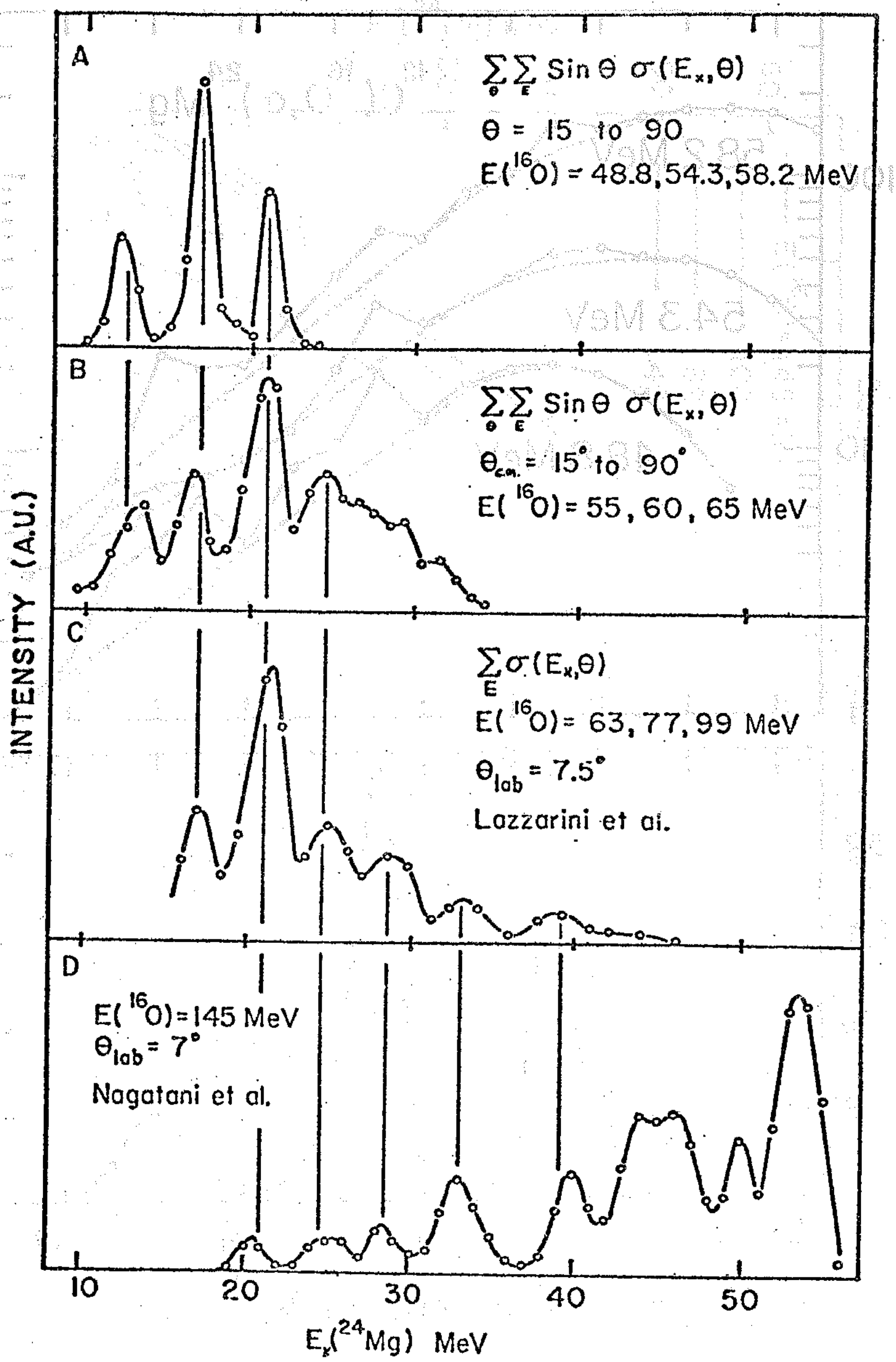
A
$\sum_{\theta}\sum_{E} \sin\theta\ \sigma(E_x,\theta)$
θ = 15 to 90
E(^{16}O) = 48.8, 54.3, 58.2 MeV
B
$\sum_{\theta}\sum_{E} \sin\theta\ \sigma(E_x,\theta)$
$\theta_{c.m.}$ = 15° to 90°
E(^{16}O) = 55, 60, 65 MeV
C
$\sum_{E} \sigma(E_x,\theta)$
E(^{16}O) = 63, 77, 99 MeV
θ_{lab} = 7.5°
Lazzarini et al.
D
E(^{16}O) = 145 MeV
θ_{lab} = 7°
Nagatani et al.
INTENSITY (A.U.)
10
20
30
40
50
$E_x(^{24}Mg)$ MeV

Figure 1