Reaction ^{12}C(^{16}O, α)^{24}Mg Leading to Nuclear Molecular Resonances

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The reactions ^{12}C(^{16}O,α)^{24}Mg and ^{13}C(^{16}O,α)^{25}Mg were investigated at an incident energy of 145 MeV. In the reaction with the ^{12}C target, broad peaks are observed at forward angles which correspond to the molecular resonance states of the ^{12}C + ^{12}C system, while the spectra with ^{13}C target show only a smooth continuum.

Intermediate-structure resonances observed in the ^{12}C-^{12}C system have been studied for nearly two decades since they were first discovered by Almquist, Bromley, and Kuehner[1] in light-particle emission channels following ^{12}C-^{12}C fusion. Subsequent experimental studies have revealed and extended the observation of these structures via excitation-function measurements of many outgoing channels. In particular, a detailed study by Cormier et al.[2] leading to single or mutual excitation of ^{12}C to the first 2^+ state shows a series of resonance structures in the excitation function extending to a c.m. bombarding energy of over 40 MeV. The resonances have been tentatively assigned as a rotational band; the last member of this band would correspond to an 18^+ state. Their energetics indeed follow the $I(I+1)$ rule with a moment of inertia corresponding to that of the molecularlike configuration of two ^{12}C nuclei, hence the name molecular resonances. The existence of these resonances poses two distinct problems for which theoretical understanding is not yet established: (1) the reaction mechanism leading to the resonances, and (2) the existence of such exotic structure states in the ^{24}Mg system. It should be noted that resonancelike structures have not been observed in the neighboring system ^{12}C + ^{13}C.[3]

Experimental measurements have so far been restricted to observations of excitation functions for various outgoing channels following directly from the ^{12}C + ^{12}C incident channel. Therefore, it is desirable to investigate other more versatile techniques to produce such resonance states. In this Letter, we present the first experimental observation of these high-spin resonance states via the transfer reaction ^{12}C(^{16}O, α)^{24}Mg.

A beam of 145-MeV ^{16}O^{4+} from the Texas A&M University 224-cm cyclotron was used to bombard a 200-μg/cm^2 natural carbon target. The beam was focused through a series of collimators in order to ensure that no spurious events were detected. α particles were detected in an Enge split-pole magnetic spectrograph with an 86-cm-long focal-plane detector. Covering the excitation energy range needed to observe the high-spin–state resonances required several magnetic field settings even with this broad-range spectrograph and long-focal-plane detector. Several absorber foils located between the target and detector were utilized to optimize the clean detection of α's. In particular, an absorber foil inserted between the two dipole magnets eliminated the detection of secondary events caused by ^{16}O^{6+} elastics hitting the front window foil of the detector. Other possible problems, such as irregularities in the position determination and changes in detector efficiency along the focal plane, were carefully checked by overlapping spectra with successive magnetic field settings.

In Fig. 1, two energy spectra are compared: The high-energy end of the spectrum from the reaction ^{12}C(^{16}O, α)^{24}Mg is shown in (a), while in (b) a spectrum from the reaction ^{13}C(^{16}O, α)^{25}Mg,
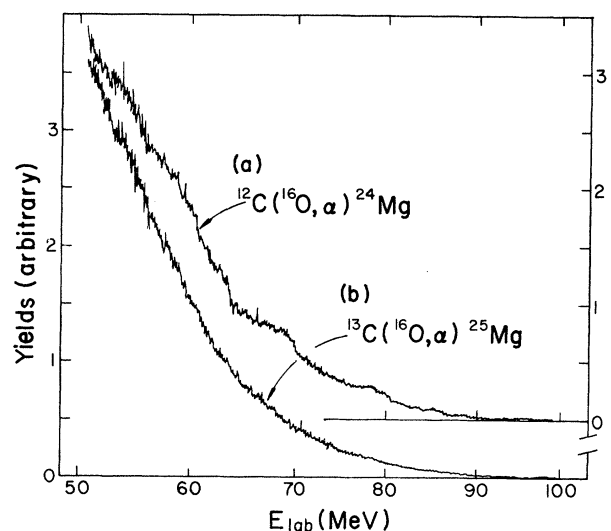
FIG. 1. Energy spectra of ^{12}C(^{16}O,α)^{24}Mg and ^{13}C(^{16}O,α)^{25}Mg at 7° for comparison.

utilizing exactly the same setup as in (a) except for a 300-μg/cm^2 ^{13}C target in place of the ^{12}C target, is displayed. As can be seen, the spectrum from the ^{12}C target shows definite structures on top of an underlying continuum while the spectrum from the ^{13}C target only shows the smooth continuum. This contrast convincingly demonstrates that the present reaction selectively populates some distinct final states in the residual ^{24}Mg system. Before describing the results, we note that evaporation α's are expected to provide strong yields even at relatively high energy because of the high velocity of the c.m. system. A simple calculation[4] indicates that there is significant contribution to the spectrum due to compound evaporation. However, at forward angles, the evaporation yield tails off in the high-energy region of the spectrum leaving it free from such compound contribution. The situation becomes more favorable if higher bombarding energies are used. In fact, the interpretation of a similarly motivated study, carried out by Lazzarini et al.[5] at lower bombarding energies ($E \leqslant 110$ MeV), was greatly affected by competition from the compound process. Hence, no clean selective population was observed to the high-spin resonance states.

Results of the present experiments are summarized in Fig. 2. Examples of total-energy spectra obtained are shown in the figure with a logarithmic vertical scale. The yields for these spectra are normalized relatively. Laboratory energies are given on the horizontal axis while excitation energies in the ^{24}Mg system are displayed above the spectra. Below the total-energy spectra, spectra resulting from smooth background subtraction are shown; curves assumed for the shape of the background are also displayed. Since at present we do not have a firm understanding of the nature of the underlying continuum, the subtraction is performed to illustrate more clearly the population of the high-spin resonance states.

Several intriguing features can be ascertained from the spectra in Fig. 2. The broad peaks observed show a striking correlation with the known molecular resonance states as indicated by the spin and parity notation in the figure. They are strongly enhanced at forward angles; beyond $\theta_{lab} = 20°$ we could not discern any strength for the resonance states above the background. In detail, the angular distributions vary for different states. Likely this is due in part to competition with evaporation α's, especially for the
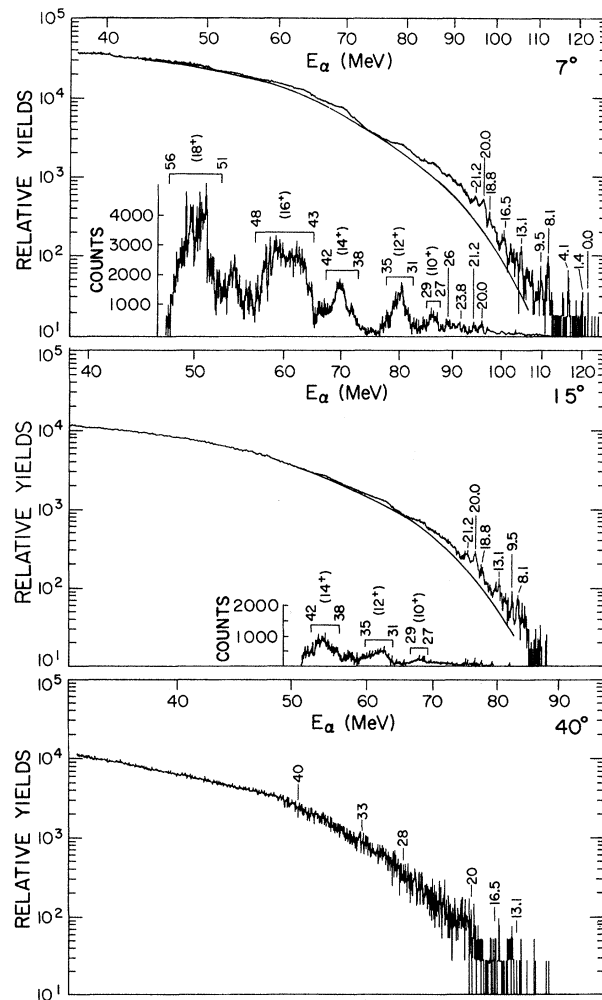

FIG. 2. Energy spectra from the reaction ^{12}C(^{16}O, α)^{24}Mg are shown with a logarithmic scale. The smooth curves under the raw spectra at 7° and 15° indicate the background. The background-subtracted spectra are shown with a linear display below the raw spectra. Excitation energies are indicated together with the spins and parities previously assigned for the molecular resonances.

higher-lying levels such as the 16$^+$ and 18$^+$ states. Absolute cross sections are difficult to assign because of uncertainties in the background subtraction. In addition, possible fine structure interferes with a clean definition of the resonance states. Simply ignoring these problems at present, we quote the laboratory cross sections for the 18$^+$ and 16$^+$ resonances at 7 deg as 12.8 and 8.1 mb/sr, respectively, assuming the limits for the state as shown in the figure.

Another interesting feature of the data is that weak but definite transition strengths can be ob-

served to the low-lying states in ^{24}Mg. For ex-
ample, it appears that the transitions to the mem-
bers of the ground-state band of ^{24}Mg(0.0, 1.4,
4.1, 8.1, and 13.1 MeV) are seen. If the reaction
process is the ^{12}C transfer on ^{12}C, these transi-
tions would indicate a direct overlap of the ^{12}C
+ ^{12}C configuration to low-lying states in ^{24}Mg.
Recent studies by Sandorfi et al.[6] of electron-
induced fission of ^{24}Mg into two ^{12}C nuclei, and
direct-capture γ-ray measurements of ^{12}C on
^{12}C, already demonstrate the existence of such
large cluster components. The present reaction
may provide a more versatile way to extract
such spectroscopic information.

We have presented experimental evidence that
the reaction ^{12}C(^{16}O, α)^{24}Mg populates high-spin
molecular resonance states and, in addition,
some of the low-lying states. In the absence of
a quantitative theoretical understanding of the
reaction mechanism, we can only state that the
data are highly suggestive of a direct transfer.
Clearly there remain several outstanding ques-
tions. In particular, what is the underlying con-
tinuum? Does the reaction provide any particular
selectivity? The latter question is especially
pertinent to the apparent observation of only even-
spin states. It is well known that in a complex
cluster transfer the transferred particle need
not be in its ground state.[7] This is especially
important for the present reaction since the ^{16}O
ground states contain[8] a strong component of
$[^{12}C*(2^+) \otimes \alpha]$ which should destroy any even-spin
selectivity.

A number of possibilities for future experimen-
tal work are opened up by this investigation. As
we have already mentioned, the use of higher
bombarding energies would be beneficial to move
the interesting region of high-spin resonances
away from the strong compound contributions.
We have already made a preliminary investiga-
tion at higher bombarding energies and the re-
sults are quite encouraging. In addition, a num-
ber of other cases can be pursued by changing
the projectile and target. Through such measure-
ments, we could hope to make a systematic study
of the molecular resonance phenomenon.

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