Search for a direct large-cluster-transfer process in the ^{12,13}C$(^{20}$Ne$,\alpha)$ reaction

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The ^{12,13}C$(^{20}$Ne$, \alpha)$ reactions were measured at $E = 140.2$ MeV in order to search for a direct ^{16}O-cluster-transfer process. In the reaction with the ^{12}C target, prominent broad peaks were observed, while the spectrum with the ^{13}C target shows a smooth continuum with much smaller structures in the high excitation region. Kinematics of the structures in the ^{12}C$(^{20}$Ne$, \alpha)$ reaction demonstrates that most of them do not arise from a large cluster transfer, but rather they originate from a sequential ejectile decay.

Investigations of nuclear molecular resonances have been carried out in the past few years using the reaction $(^{16}$O$,\alpha)$ on light nuclei.[1–4] These studies were initiated by the experimental discovery of broad peaks in the continuum region of the ^{12}C$(^{16}$O$,\alpha)$ reaction.[1] Since the excitation energies of those peaks were closely correlated to energies of the ^{12}C$+^{12}$C intermediate, or nuclear molecular resonances found in the excitation function of the ^{12}C$+^{12}$C channel, a direct-like reaction mechanism populating such special states was proposed to explain the structures. However, detailed studies revealed that the observed structures are mainly coming from sequential α-decay processes from ^{20}Ne* and ^{16}O*, excited by the α-pickup reaction and inelastic scattering.[4–6] The existence of these strong competing processes obscures the ^{12}C transfer process even if it proceeds.

It is known that the ground state of a ^{20}Ne nucleus has a strong α-^{16}O clustering strength. Therefore, a ^{20}Ne induced reaction might have appreciable amount of a direct ^{16}O transfer process. The ^{12}C$+^{16}$O system is generally accepted to have intermediate-structure resonances and has been intensively studied, while there is no strong evidence that the neighboring ^{13}C$+^{16}$O system has resonance-like structures. Therefore we studied the $(^{20}$Ne$,\alpha)$ reaction on these two carbon isotopes in order to find out whether an ^{16}O-cluster-transfer reaction can be observed.

140.7 MeV ^{20}Ne^{6+} beams from the Texas A&M University Cyclotron were used to bombard self supporting 196 μg/cm^2 natural carbon and 115 μg/cm^2 enriched (99%) ^{13}C targets. In order to get reasonable counting rates the ^{13}C target was tilted 45° with respect to the beam direction. The beam energy was estimated to be 140.2 MeV at the center of the targets. Typical beam intensity on target was 60 e nA, and special care was taken in the beam optics to minimize spurious events such as slit scattering, etc. α particles were detected at 4° with the Enge split-pole magnetic spectrometer and a 1.2-m-long focal-plane detector.[7] The solid angle and the angular acceptance were 1.3 msr and $\pm 1°$, respectively. The detecting system gave us unambiguous particle identification. A foil system was used to eliminate heavy particles that would produce high count rates in the detectors.[4] The energy calibration was obtained via ^{1}H$(^{20}$Ne$,$p$)$ and ^{1}H$(^{20}$Ne$,\alpha)$ reactions on a Mylar target. The ambiguity in the absolute calibration was estimated to be less than 300 keV. Due mainly to large energy loss in

the target, the energy resolution in the α-particle spectra was approximately 800 keV which is large but certainly adequate in the present experiment to observe relatively broad peaks. The position spectra were obtained by an on-line PDP-15 computer and converted to double differential cross sections in the off-line analysis. The uncertainties in the absolute cross section were estimated to be 20%, which includes uncertainties in the charge collection, target thickness, detector efficiency, and background subtraction.

Energy spectra in the laboratory system from the ^{12}C and ^{13}C targets are shown in Figs. 1(a) and 1(b), respectively. The raw spectra are displayed with a logarithmic scale and the background-subtracted spectra are shown below with a linear scale. The method of subtracting background was described in detail in Ref. 1. Excitation energies in the residual nucleus are shown on the top of each spectrum. These energy spectra are very similar to those observed in ^{12,13}C$(^{16}$O$, \alpha)$ reactions.[2] Characteristic peaks over the entire continuum region were observed with the ^{12}C target while except at the high excitation, a smooth continuum was observed with the ^{13}C target. The shapes of the peaks in the spectrum from the ^{12}C target are also quite similar to those observed in the ^{12}C$(^{16}$O$,\alpha)$ reaction, broad peaks with possible fine structure. Another feature in common with the $(^{16}$O$,\alpha)$ reaction is the increasing strengths of these peaks toward the low α energy. The energy (in the laboratory system) of the structures in the spectrum from the ^{13}C target (labeled A, B, and C) are well correlated with the ones observed with the ^{12}C target (except the structure labeled C') and the strengths are about a factor of 2 smaller.

Since in the ^{12}C$(^{16}$O$,\alpha)$ reaction the continuum background was well explained by a compound process, we expected that a similar process could be used to explain the background in the ^{12}C$(^{20}$Ne$,\alpha)$ reaction. Evaporation contributions were calculated using the Monte Carlo code EVA (Ref. 8) which follows the Hauser-Feshbach formalism. The successive evaporation of neutrons, protons, and α particles was included in the calculation. The level densities used are from the prescription of Pühlhofer.[9] The parameters used in EVA were the same as the default values of the code CASCADE.[9] The transmission coefficients were obtained by using Fermi functions, where parameters were adjusted to reproduce the results of the optical model calculations for the n-^{31}S, p-^{31}P, and α-^{28}Si systems. (Optical potentials

were from Refs. 10–12, respectively.) For the spin cutoff, we calculate the moment of inertia of the residual nucleus using $r_0 = 1.32$ fm. The results of the Hauser-Feshbach calculations which include the multistep evaporation contributions are shown in Fig. 1 by dotted lines. During the calculations, only the critical angular momentum value l_c was adjusted to fit the experimental data. Using $l_c = 19\hbar$, both the shape and magnitude of the smooth components of the experimental spectra for ^{12,13}C targets are well reproduced. However, this critical angular momentum value is about $6\hbar$ smaller than the one obtained by Saint-Laurent et al.[13] There are several possible reasons for this discrepancy. (1) Even though the technique is straightforward, the fusion cross section might have been overestimated in Ref. 13, because it is difficult to separate events belonging to direct processes at high incident energy such as 7 MeV/nucleon. (2) Very little is known about the level densities of the residual nuclei at the high excitation energies involved in these experiments. Therefore, the result of the present calculation might have an uncertainty more than 20%. It should be noted that the statistical yrast-line model[14] with the parameters $r_0 = 1.15$ fm, $\Delta Q = 12.5$ MeV, which we used for the ^{12}C(^{16}O,α) reaction,[4] predicts $l_c \simeq 21.5\hbar$ for the
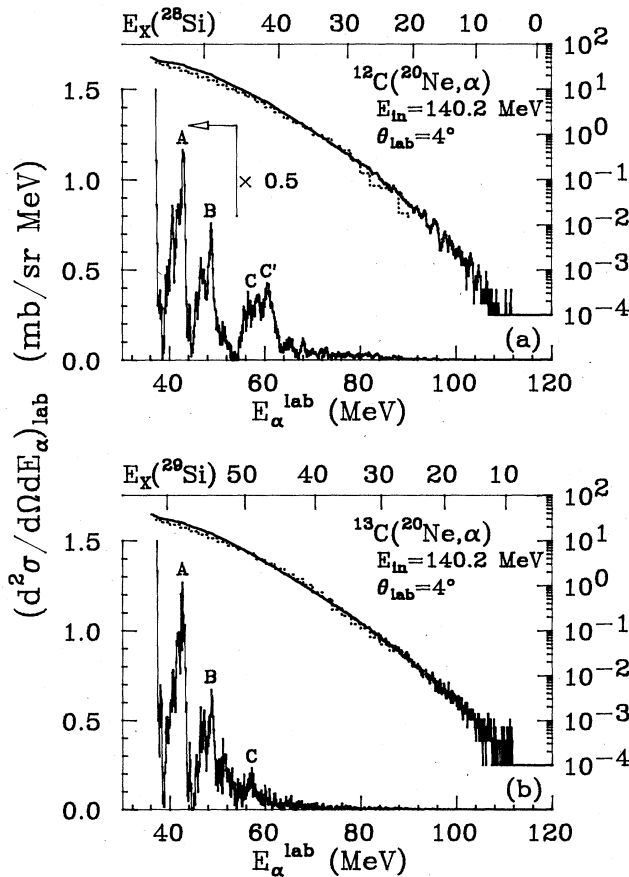
^{12}C(^{20}Ne,α) reaction. This value is in between the one obtained by Saint-Laurent et al. and the one used in the present analysis. In any case, in order to solve this problem we would need to measure at least the other evaporated particle spectra, namely, n and p spectra, and compare them to the prediction of the statistical model. Although there are still some unsolved puzzles, it appears that the continuum background is primarily due to the compound process.

Strong similarities with the (^{16}O,α) reactions reported in earlier references (Refs. 1–4) imply that the prominent structures in the spectra might also come from sequential ejectile α-decay processes. In fact, Ost et al. reported the dominance of a sequence of two binary processes in the ^{12}C(^{20}Ne,α^{16}O)^{12}C and ^{12}C(^{20}Ne,α^{20}Ne)^{8}Be reactions at $E_{lab} = 160$ MeV.[15] From the kinematical features they suggested that those events originated from a fast interaction between target and projectile leading to excited systems ^{20}Ne* and ^{24}Mg* that decay by α emission. More recently, Rae et al. clearly observed that the relative kinetic energy spectra of α-^{16}O from the ^{12}C+^{20}Ne reaction at E_{lab} (^{20}Ne) $= 175$ MeV showed narrow peaks at E_x (^{20}Ne) $= 6.73$, 7.16, 7.37, 7.78, 8.44, 8.79, 9.01, 9.44, 10.26, 10.80, 12.05, 12.72, and 15.37 MeV.[16]

In order to examine these possibilities, additional measurements of the ^{12}C(^{20}Ne,α) reaction were performed at $E_{lab} = 140.2$ MeV, $\theta_{lab} = 8°$ and $E_{lab} = 119.6$ MeV, $\theta_{lab} = 2.75°$. The spectra from those measurements are shown in Fig. 2 with a logarithmic scale together with the results of the Hauser-Feshbach calculation. Again the statistical model gives a reasonable account of the continuum background in the spectra. The background-subtracted spectra in the center-of-mass system are shown in Fig. 3 with a linear scale together with the spectrum at $E_{lab} = 140.2$ MeV, $\theta_{lab} = 4°$. The reported intermediate structures in the ^{12}C+^{16}O system[17–19] are also shown in the top column of the figure for comparison.

From these spectra, it is obvious that the structures A, B, C, and C' do not represent excitations in ^{28}Si, since their excitation energies vary with angle and incident beam energy. The sequential α-decay processes of ^{20}Ne* and ^{24}Mg*, excited by an inelastic scattering and an α-pickup reaction,
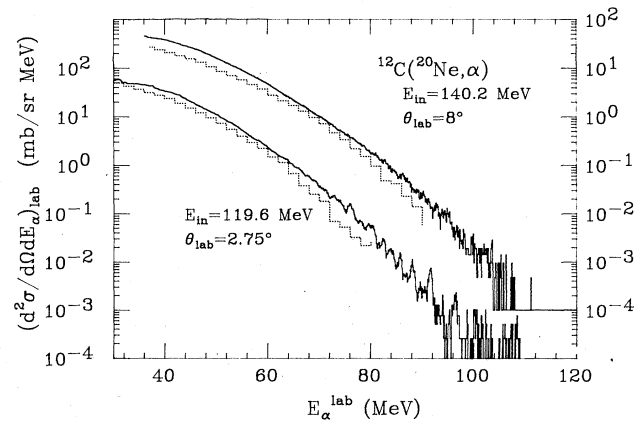

FIG. 1. Energy spectra of the ^{12,13}C(^{20}Ne,α) reaction at $E_{lab} = 140.2$ MeV, $\theta_{lab} = 4°$. The raw spectra are displayed in the top of each frame with a logarithmic scale. The background-subtracted spectra are shown below them with a linear scale. The dotted histograms show the theoretical spectra of the multistep compound evaporations.

FIG. 2. Raw energy spectra of the ^{12}C(^{20}Ne,α) reaction at $E_{lab} = 140.2$ MeV, $\theta_{lab} = 8°$ and $E_{lab} = 119.6$ MeV, $\theta_{lab} = 2.75°$. The dotted histograms are the theoretical spectra obtained by the Hauser-Feshbach calculation. The critical angular momenta used are $19\hbar$ for the 140.2-MeV case and $17\hbar$ for the 119.6-MeV case.

are considered by using the simple kinematical calculation described in Ref. 4. We assume that the only ejectiles which are scattered within 5° of the beam axis in the laboratory system affect the inclusive α spectrum. It turns out that α particles coming from the sequential decay of ^{20}Ne* and ^{24}Mg* have similar kinematics which explain the movement of the structures quite well. Therefore it is clear that at least one of these sequential α-decay processes produces those structures. The α decay of the excited states of ^{20}Ne at $E_x(^{20}\text{Ne}) = 7.16$, 9.01, and 12.72 MeV, which were prominent peaks in the α-^{16}O relative energy spectrum,[16] gives us an excellent account of the structures A, B, and C. For example, the decay of the $E_x(^{20}\text{Ne}) = 7.16$ MeV state is predicted to appear at $E_x(^{28}\text{Si}) = 55.0$, 53.8, and 46.8 MeV in Figs. 3(b), 3(c), and 3(d), respectively. Considering that the structures A, B, and C can be seen on the ^{13}C target with half of the strength, we suggest that the origin of the structures A, B, and C is the sequential α decay of ^{20}Ne*. The structure C' might come from the sequential decay of ^{24}Mg*, because a similar structure is missing on the ^{13}C target. We assumed here that the formation of ^{20}Ne*, i.e., inelastic scattering, does not have strong target dependence, while the formation of ^{24}Mg*, i.e., an α-pickup reaction, might have large target dependence as was found in the case of the ^{12,13}C(^{16}O,α) reactions.[6]

Even in the much lower excitation energy region where we expect to see the known molecular resonances,[17–19] i.e., $E_x(^{28}\text{Si}) = 25$–35 MeV, the energies of many of the structures vary as a function of the angle. These structures likely originate from high excitations of ^{20}Ne* and/or ^{24}Mg*. A few candidates for the molecular resonances, which appear at both angles at $E(^{20}\text{Ne}) = 140.2$ MeV, are not strongly correlated to any reported molecular resonances. Moreover, they do not appear in the spectrum at $E(^{20}\text{Ne}) = 119.6$ MeV. These facts suggest that the $(^{20}\text{Ne},\alpha)$ reaction does not selectively populate ^{12}C + ^{16}O molecular resonances.

In summary, the ^{12,13}C(^{20}Ne,α) reactions at $E = 140.2$ MeV were measured to determine whether a direct ^{16}O transfer occurs in the $(^{20}\text{Ne},\alpha)$ reaction. No experimental evidence was found that ^{12}C + ^{16}O resonance states were populated by the ^{12}C(^{20}Ne,α) reaction. Instead of the ^{16}O cluster transfer, strong structures coming from the sequential ejectile α-decay processes, i.e., ^{20}Ne* $\rightarrow$ ^{16}O+α, and/or ^{24}Mg* $\rightarrow$ ^{20}Ne $+\alpha$, were found as in the case of the $(^{16}\text{O},\alpha)$ reaction.[4–6] The existence of these intrusive processes clearly prevents us from locating the possible large-cluster-transfer process. Therefore we conclude that the $(^{20}\text{Ne},\alpha)$ reaction is not usable as a spectroscopic tool to search for
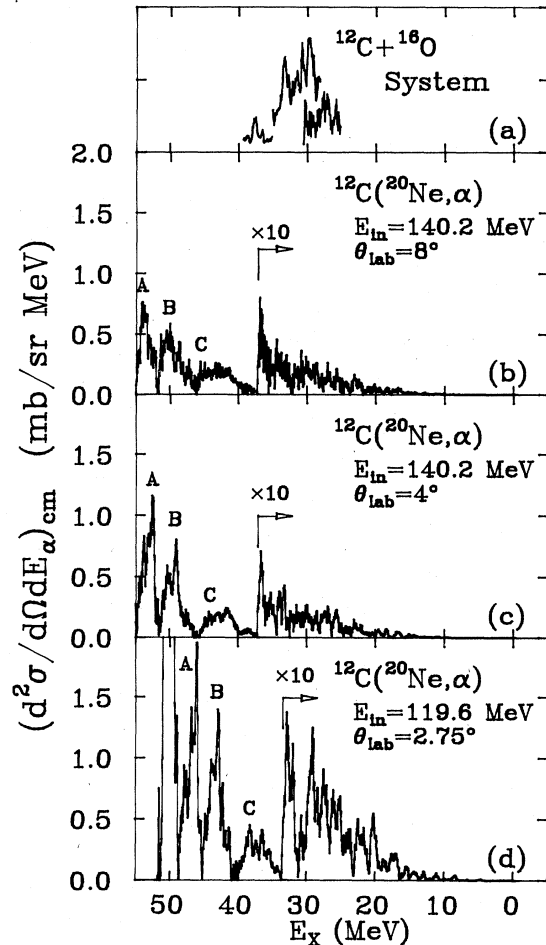

FIG. 3. Background-subtracted α spectra of the ^{12}C(^{20}Ne,α) reactions in the center-of-mass system. Also shown is the background-subtracted excitation function for the total reaction cross section of the ^{12}C + ^{16}O system $[E_x(^{28}\text{Si}) = 25.3$–30.7 MeV] (Ref. 17) and the excitation functions for the angle summed cross section of the ^{12}C (^{16}O,^{8}Be)^{20}Ne(g.s.) $[E_x(^{28}\text{Si}) = 35.3$–39.4 MeV] (Ref. 18) and ^{16}O(^{12}C,^{8}Be)^{20}Ne(g.s.) $[E_x(^{28}\text{Si}) = 28.2$–35.2 MeV] (Ref. 19) reactions using arbitrary units.

the molecular resonances.

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