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New Resonances in the Low-Energy ^{12}C-^{12}C Spectrum*

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Angular distributions of transitions to low-lying states in ^{20}Ne have been measured for the reaction ^{12}C(^{12}C, α) in 62.5-keV steps for $6.5 \leq E_{\mathrm{c.m.}} < 11$ MeV. Two new nonstatistical structures are identified at $E_{\mathrm{c.m.}} = 7.71$ and 9.84 MeV, with $J^\pi = 4^+$ and 8^+, respectively. These observations support the quasimolecular interpretations of the low-energy structure in the ^{12}C-^{12}C interaction.

The resonances in the low-energy ^{12}C-^{12}C interaction, first observed some fifteen years ago and postulated to result from the formation of nuclear molecules,[1] have been a subject of continuing interest and speculation. The sustained interest results from the general agreement that the sub-Coulomb structures reflect a new type of nuclear interaction; this interest has been heightened recently through the discovery of additional possible quasimolecular structures at much higher excitation in the nuclear continuum[2] and by a growing realization that this type of interaction may be a more general feature of heavy-ion interactions than had earlier been suspected. The importance of the ^{12}C + ^{12}C system in nuclear astrophysics and the crucial role of the possible resonant structures in determining the extrapolation of the interaction from the measured energies to thermonuclear ones provide additional motivation for study of this particular system.

Theoretical efforts to reproduce the sub-Coulomb structure in the ^{12}C + ^{12}C system have proceeded along several distinct lines. The earliest works[1,3,4] discussed the sub-Coulomb structures in terms of single-particle resonances in an effective ^{12}C + ^{12}C potential. Imanishi[5] found that the energies and widths of the then known resonances could also be reproduced by a model in which carbon-carbon quasimolecules were formed as a result of the coupling between the elastic channel and inelastic excitations. The failure of these early models to account for the subsequent observation[6-8] of additional lower energy structures implied that a mechanism with additional degrees of freedom was required. A suggestion by Michaud and Vogt[9] that the resonances resulted from the formation of intermediate α clusters satisfied this requirement; and it also offered an appealing explanation of some observed exit-channel branching ratios. Besides encompassing *qualitatively* the presence of additional resonances, the α clustering in the Michaud-Vogt model leads to an optical potential which supports "absorption under the barrier," thus profoundly affecting the estimates of stellar carbon burning rates.

Several recent calculations[10-12] have revived interest in the nuclear molecule models by showing that they *can* indeed accommodate a large number of resonances. A noteworthy aspect of these new calculations with Imanishi-type models is that the increase in barrier penetrability at energies of astrophysical significance results from the presence of isolated resonances, rather than from absorption under the barrier. Furthermore, at higher energies, new resonances are predicted, the presence or absence of which would test the validity of the model calculations.

The purpose of the present work is to determine, in particular, whether there exists a group of resonances with $J^\pi = 4^+, 6^+$, and 8^+, as predicted by Kondo, Matsuse, and Abe[11] between $E_{\mathrm{c.m.}} = 7$ and 8 MeV. Previous measurements in this energy region include elastic scattering[13-15] and also a study[16] of α particle and proton yields at two angles. The latter work reported a resonance of unknown spin at $E_{\mathrm{c.m.}} = 7.55$ MeV.

We have measured angular distributions as a function of beam energy for the reaction ^{12}C(^{12}C, α) populating the low-lying levels of ^{20}Ne. Data were obtained at 5° intervals in 125-keV steps over the range $10° \leq \theta_{\mathrm{lab}} \leq 80°$ and $13 \leq E_{\mathrm{lab}} \leq 22$ MeV (above 18 MeV, measurements were also made at $\theta_{\mathrm{lab}} = 5°$). The targets were 30 μg/cm^2

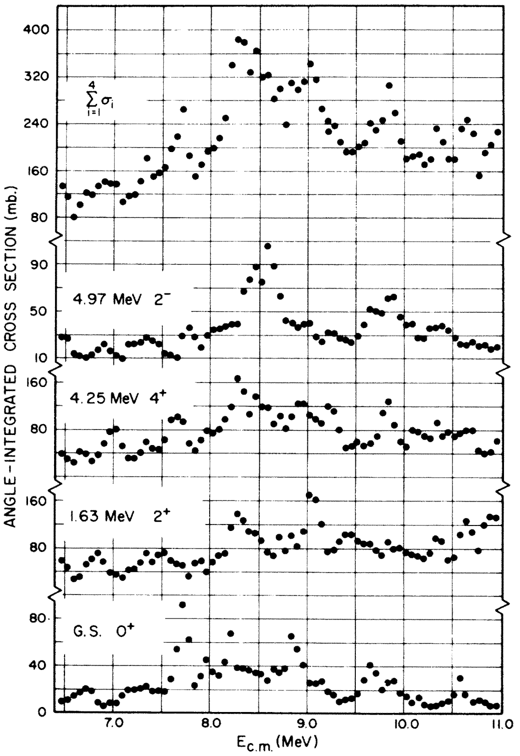

FIG. 1. Angle-integrated cross sections as functions of energy for the reaction ^{12}C(^{12}C, α) populating low-lying levels of ^{20}Ne.

carbon foils, which produced a total beam energy loss of approximately 160 keV. An array of five silicon surface-barrier detectors, just thick enough to stop the α particles and covered with thin nickel foils to stop the scattered carbon ions, permitted an unambiguous identification of the reactions leading to states in ^{20}Ne below 6 MeV in excitation. Absolute cross sections were obtained by comparing yields measured at the higher energies with those reported by Almqvist *et al.*[17]

The total cross sections measured for the lowest four levels in ^{20}Ne are shown as functions of energy in Fig. 1. Of particular interest in the present context are the yields at $E_{\text{c.m.}} = 7.71$, 9.84, and 10.59 MeV. The peak at $E_{\text{c.m.}} = 7.71$ MeV with a width of approximately 145 keV dominates the ground-state excitation function; and, near this energy, smaller peaks are also evident in the 2^- and 4^+ data. While these three peaks may or may not represent correlated structures, the fact that a bump is prominent at 7.71 MeV in the summed excitation function (Fig. 1, top) suggests that something more than an Ericson fluctuation may be present. More conclusive information, however, is gained through an examination of the magnitude and angular distribution of the ground-state cross section at 7.71 MeV.

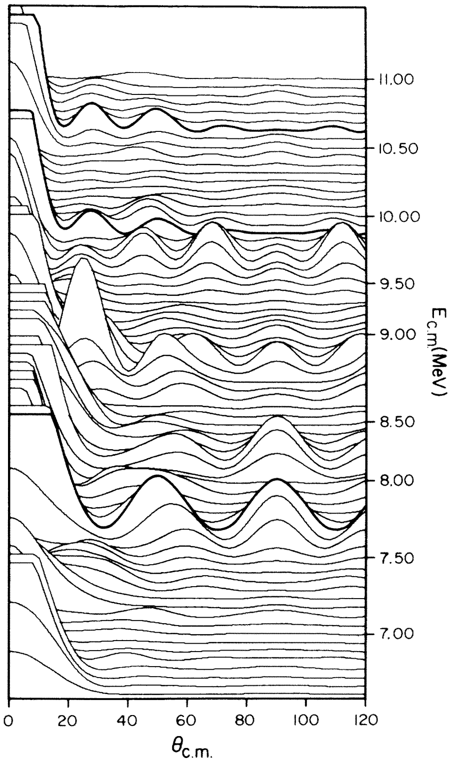

FIG. 2. Legendre polynomial fits to the measured ^{12}C(^{12}C, α)^{20}Ne ground-state angular distributions. The cross section scale is linear, with a maximum of 25 mb/sr. Peaks rising above this value are shown as plateaus. The angular distributions at $E_{\text{c.m.}} = 7.71$, 9.84, and 10.59 MeV are drawn with wider lines.

The Legendre polynomial fits to the measured ground-state angular distributions are shown as functions of energy in Fig. 2. The 7.71-MeV data are emphasized here by a wide curve and, as Fig. 3(a) shows, are very well characterized by a pure $|P_4(\cos\theta)|^2$ shape. With all channel spins being zero, the pure $|P_4(\cos\theta)|^2$ shape at $E_{\text{c.m.}} = 7.71$ MeV indicates that any resonant structure contributing to the cross-section peak must have $J^\pi = 4^+$. That the shape of the angular distribution might arise simply through a nonresonant $L = 4$ grazing partial wave predominance can be ruled out by a consideration of the cross-section magnitude. For a transmission coefficient for the $L = 4$ partial wave of 0.5, corresponding to a grazing collision, the partial absorption cross section becomes $\sigma_{\text{abs}}(L=4) = 2\pi\lambda\!\!\!^{-2}(2L+1)T_L = 127$ mb. The peak resonant cross section at $E_{\text{c.m.}} = 7.71$ MeV in the ground-state ^{20}Ne exit channel is 85± 15 mb; and it is difficult to imagine a nonresonant mechanism, whereby nearly two thirds of the grazing entrance-channel flux would appear in a

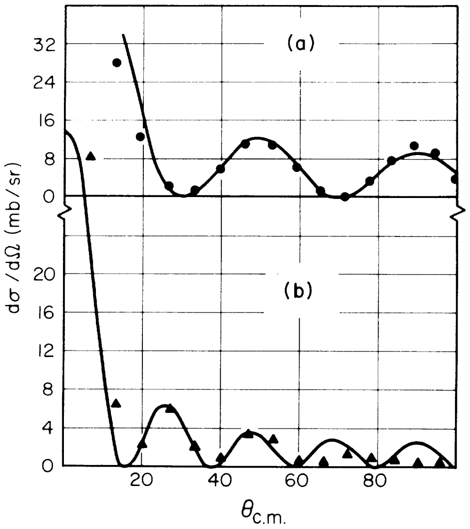

FIG. 3. ^{12}C(^{12}C, α)^{20}Ne ground-state angular distributions are compared with arbitrarily normalized Legendre functions $[|P_L(\cos\theta)|^2]$: (a) at $E_{\text{c.m.}} = 7.17$ MeV ($L = 4$); and (b) $E_{\text{c.m.}} = 9.84$ MeV ($L = 8$).

single exit channel.

These considerations, which rule out geometrical factors as the cause of the bump, also argue against the Ericson fluctuation interpretation. Calculations by Vogt *et al.*[18] have shown that the statistical compound nucleus model reproduces the average cross sections in the reaction ^{12}C(^{12}C, α)^{20}Ne over the energy interval 10–13 MeV (c.m.); and further predict that the average $L = 4$ partial cross section populating the ^{20}Ne ground state at $E_{\text{c.m.}} = 7.5$–8 MeV is roughly 3 mb. Thus our observation of 85± 15 mb for the $L = 4$ component of the cross section represents a fluctuation of the order of 20 or 30 from the average value. Such a fluctuation in the *angle-integrated* cross section presumably could be accommodated within the Ericson model, but only with a very small probability. (Ericson[19] has shown that compound nuclear fluctuations are damped in angle-integrated yields.) We have therefore concluded that the anomaly at $E_{\text{c.m.}} = 7.71$ MeV most probably results from the presence of nonstatistical $J^\pi = 4^+$ structure in the $^{12}\text{C} + {}^{12}\text{C}$ system at this energy.

Assuming an isolated resonance of the Breit-Wigner shape, the observed cross section and width of the peak lead to the constraint on the partial widths of $\Gamma_{^{12}\text{C}}\Gamma_\alpha \approx 1700$ (keV)^2, which further implies that $\Gamma_{^{12}\text{C}} \geqslant 13$ keV. To put this observation into perspective, we note that an extreme upper limit for this width is given by the single-particle expression $\hbar^2/mR^2 = 72.5$ keV using the radius of Ref. 1; our lower limit thus represents 18% of this maximum value. A further comparison with the width of 0.5 keV which is obtained from a simple statistical compound nucleus model for $J = 4$ carbon decay lends support to the identification of this resonance as a carbon-carbon quasimolecular state.

The ^{12}C width of 65 keV predicted in Ref. 11 is entirely consistent with our observed lower limit of 13 keV, but the very shallow imaginary potential (50 keV) required to reproduce the observed total widths, in both these and the original Imanishi calculations, represents a continuing puzzle. We are currently measuring the elastic scattering angular distributions in an attempt to determine $\Gamma_{^{12}\text{C}}$ better, and hence, the molecular character of the 4^+ resonance.

A structural aspect of the resonance is reflected in the preferential decay to the ^{20}Ne ground state. This behavior is in complete contrast to that of the resonances at $E_{\text{c.m.}} = 5.6$, 6.0, and 6.3 MeV, for which large branching ratios to excited 0^+ levels in ^{20}Ne have been observed and interpreted[20] in terms of α cluster formation. (The choice of detectors and absorbers in the present experiment prevented a proper study of these transitions, but we were able to determine that, at least at forward angles, the 0^+ level at 6.72 MeV in ^{20}Ne does not resonate at $E_{\text{c.m.}} = 7.71$ MeV.)

Except in the vicinity of 7.71 MeV, the only energies between 6.5 and 11 MeV at which the ground-state angular distributions can be characterized by a single Legendre polynomial are 9.84 and 10.59 MeV. As previously observed by the Chalk River group,[17,21] the ground-state data at the latter energy are characteristic of $|P_8(\cos\theta)|^2$, and have been interpreted variously as resulting from a quasimolecular resonance[21] and from an Ericson fluctuation.[17] Here we merely note that our data, which are consistent with those from Chalk River but include two additional exit channels, contain no evidence of correlated structures. Furthermore, the strength arguments which lead to our identification of the 7.71-MeV peak as a resonance are certainly not applicable to the much weaker 10.59-MeV peak. We note that the peak location is correlated with a deep minimum in the 90° elastic scattering excitation function for $^{12}\text{C} + {}^{12}\text{C}$,[13-15] but the present data provide no basis for drawing any conclusions regarding possible nonstatistical behavior at this energy.

The ^{20}Ne ground-state data at $E_{\text{c.m.}} = 9.84$ are shown in Fig. 3(b) also to be consistent with a

$|P_8(\cos\theta)|^2$ shape. A prominent peak appears at this energy with a width of approximately 125 keV in the summed yields at the top of Fig. 1; correlated structure can be discerned in each of the measured excitation functions. Furthermore, at the same energy the 90° ^{12}C-^{12}C scattering cross section[13-15] goes through a deep minimum, and the 90° inelastic scattering[15] increases rapidly as the channel effectively opens. Because these observations of strongly correlated structures are characteristic of nonstatistical entrance channel resonances, we would suggest the possibility that the 9.84-MeV 8^+ resonance may be the same one predicted by Kondo, Matsuse, and Abe[11] to occur near $E_{\mathrm{c.m.}} = 7.5$ MeV. By applying the Breit-Wigner expression for an isolated resonance to the summed cross section data we obtain $12 \leq \Gamma \leq 113$ keV for this resonance.

We are continuing our search for additional resonances—and in particular the 6^+ predicted by Kondo, Matsuse, and Abe in the vicinity of 7.5 MeV—through a study of the excitation functions for total γ radiation from the ^{12}C-^{12}C interaction.

The location of the 4^+ and 8^+ resonances, we believe, provides significant support to the validity of the general molecular approach typified in the Imanishi models and therefore to the physical reality of this interaction mode. It also suggests the use of this model in an extrapolation of the measured cross sections to thermonuclear temperatures, yielding a substantially lower ^{12}C-^{12}C interaction rate than would result from absorption under the barrier.

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