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Nonstatistical structure in $^{12}C(^{14}N,\alpha)^{22}Na$

L. C. Dennis and S. T. Thornton
Department of Physics, University of Virginia, Charlottesville, Virginia 22903

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Correlated structure has been found in the forward-angle excitation functions of the $^{12}C(^{14}N,\alpha)^{22}Na$ reactions. An attempt is made based on the strong correlations observed to determine the origin of the structure. It is found that several explanations including statistical fluctuations, direct mechanisms, and the population of isolated high-spin yrast states are unlikely.

[NUCLEAR REACTIONS $^{12}C(^{14}N,\alpha)^{22}Na$; $E_{c.m.}=10.1-15.9$ MeV, $\theta=7°$; correlated nonstatistical structure found; resonances discussed.]

Despite the fact that the first experimental evidence for the existence of nuclear molecules was obtained in 1960 by Almqvist, Bromley, and Kuehner,[1] the question of whether or not nuclear molecules exist still receives considerable discussion. In particular the question of whether resonances should exist in systems containing non-alpha-particle nuclei almost always produces a heated debate. Resonance effects have been reported for several non-alpha-particle systems[2-5]: $^{12}C+^{9}Be$, $^{13}C+^{12}C$, $^{14}N+^{10}B$, and $^{14}N+^{14}N$, but the resonance character of observed structures in the last three systems has been questioned.[6-8] Additional measurements[6,7] showed that the structures in $^{12}C(^{13}C,\alpha)^{21}Ne$ and $^{10}B(^{14}N,\alpha)^{20}Ne$ are not correlated in angle thus making them different from the structures in the $^{12}C+^{12}C$ and $^{16}O+^{12}C$ systems. The $^{12}C(^{14}N,\alpha)^{22}Na$ reaction is an excellent non-alpha system in which to look for nonstatistical effects. The relatively small number of open channels for this system means it is more likely to show resonances than many other non-alpha-particle systems.[8]

We previously[9,10] found for the $^{12}C(^{14}N,\alpha)^{22}Na$ reaction that there are several energy regions where correlated nonstatistical structures exist. The data analyzed were excitation functions for 20 groups of states populated in the $^{12}C(^{14}N,\alpha)^{22}Na$ reactions that were measured at $\theta_{lab}=7°$ and covered a center of mass bombarding energy range from 10.15 to 15.88 MeV. Figure 1(a) shows the summed excitation functions for all states less than 6 MeV excitation energy. The statistical model gives a good average description of the population of all final states of ^{22}Na for which spins are known.[9] However, there is at least one energy region around $E_{c.m.}=10.5\pm0.1$ MeV (and possibly two more—near $E_{c.m.}=13.3$ and 13.7 MeV) where the compound nucleus formalism including Ericson's fluctuation theory do not appear adequate to describe the large enhancements. These are approximately the same energies where the total reaction cross section shows very slight deviations which were excluded by Hanson *et al.*[8] as an example of intermediate structure because "it is not sufficiently pronounced to reliably assign a characteristic width."

To indicate the nonstatistical nature of these structures we have also shown in Fig. 1(a) the statistical model predictions for the magnitude of fluctuations. In making these predictions we have used a center of mass averaging interval of 2.5 MeV and determined the number of effective channels from the autocorrelation function when spins were not known (or two or more states were unresolved) and from the theoretical expression when spins were known. The summed distributions were then estimated using Monte Carlo techniques. Further statistical analyses of these data showed[10] 18 of the 20 groups of excitation functions exhibit maxima within 90 keV of $E_{c.m.}=10.52$ MeV. The Ericson model probability for such a correlation is less than 10^{-6}. The correlated maxima at $E=13.3$ and 13.7 MeV have statistical probabilities of about 10^{-3}.

Two energy regions ($E_{c.m.}=11.6$ and 12.9 MeV) show a relatively large number of correlated minima with probabilities of occurrence of about 10^{-4}. Near 15.2 MeV there is a third correlated minimum whose probability of occurrence is less than 0.01. The presence of these correlated minima may indicate that the nonstatistical nature of this reaction is a property extending over a broad energy range and not just a property of a few isolated energies. The energy dependent correlation coefficient,[10] Fig. 1(b), gives a qualitative indication of the correlations. These structures also appear nonstatistical in the deviation function[10] in Fig. 1(c). Because all three statistical tests indicate correlations, they confirm our belief that

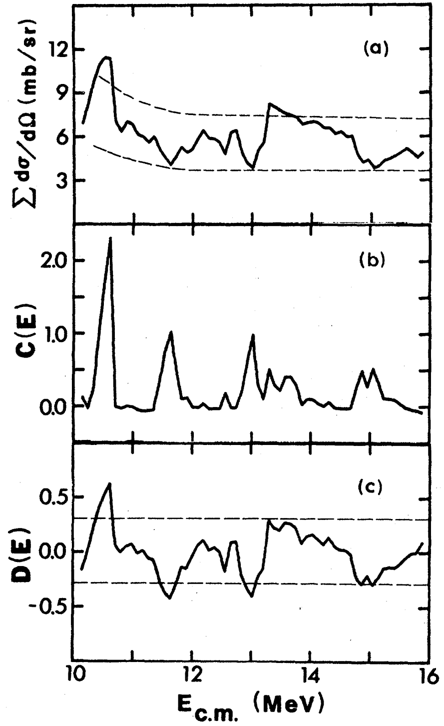

FIG. 1. (a) The solid line gives the summed excitation functions (uncertainties ±3%) for all states with excitation energies less than 6.0 MeV populated by the $^{12}C(^{14}N,\alpha)^{22}Na$ reactions. The dashed line gives the magnitude of the cross section (uncertainty ±7%) outside of which statistical fluctuations occur with a frequency of less than one in a thousand. (b) The energy dependent correlation coefficient for the same group of states as in (a). (c) The deviation function for these excitation functions is given by the solid line. The dashed line gives statistical model predictions for deviations that should occur with a probability of 10^{-3} or less. Typical uncertainties are ±8% for $D(E)$ and ±2% for the predictions near $E_{c.m.} = 10.5$ MeV.

these structures are not dominated by large fluctuations for a few final states but rather result from correlations between states.

The fact that these structures are not readily explained by the statistical theory does not mean they are resonances. There are several other possible explanations including

(1) direct reactions,

(2) population of isolated high-spin states (yrast states in the compound nucleus),

(3) l-dependent effects in the entrance and/or exit channels.

To further add doubt to a resonance interpretation of these data other cases where "resonances" have been seen in forward angle excitation functions have met with criticism because they could be the result of direct reactions or interference between compound and direct processes. There is one feature of these data that is not present to such a large extent in previous cases that makes those explanations unlikely here, and that is the correlation among so many final states.

Direct contributions are usually smooth functions of energy which can be incorporated into fluctuation analyses. The presence of smooth direct components results in a damping of the fluctuations. Direct plus compound interference should be uncorrelated between various final states. Heavy particle transfer mechanisms have been postulated by Noble[11] that predict strongly energy dependent cross sections. This energy dependence results from interference between the transfer of heavy particles in several different excited states. These structures are not likely to be correlated among many different final states. There is some evidence[12] in the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction that such transfers have occurred leading to selective population of 8p-4h residual states in ^{20}Na. The selectively populated final states were not correlated in the manner seen here. These states also showed average cross sections that were well above the Hauser-Feshbach predictions over a wide energy range. Because these two features are not present in this case, we feel it is very unlikely for the structures observed here to be the result of heavy particle transfer processes.

To gain more understanding of the mechanism involved we examined the level density of the compound nucleus ^{26}Al and the critical angular momenta involved to determine the spins of the states being populated in the compound nucleus. The level densities were obtained using the spectral moment method,[13] and the moments used were taken from Ref. 14. The critical angular momenta were obtained from Hauser-Feshbach analyses[9] at low energies and from fusion cross sections[15] at energies above $E_{^{14}N} = 34$ MeV. Figure 2 summarizes the level densities and critical angular momenta.

At $E_{c.m.} = 10.5$ MeV the highest spin values for the states strongly populated from the $^{12}C + ^{14}N$ entrance channel should be $l_{gr}+1$, where l_{gr} is the grazing angular momentum in the entrance channel (channel spin = 1). Using the optical model parameters of Delic[16] one finds the grazing angular momentum to be $8\hbar$ at this energy. Figure 2 shows that at this excitation energy in ^{26}Al ($E_x = 25.6$ MeV) the yrast states have spin values of $13-14\hbar$, well above the $9\hbar$ that can be populated from the $^{12}C + ^{14}N$ entrance channel. Such an increase in spin above the grazing angular momentum implies that the penetrabilities for such states are very small and that such a mechanism would contribute weakly to any exit channel.

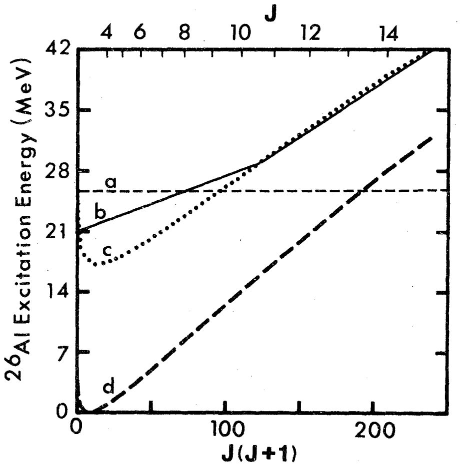

FIG. 2. Curve a shows the ^{26}Al excitation energy of the most prominent structure in the summed excitation functions. Curve b shows the critical angular momentum as a function of the ^{26}Al excitation energy. Curve c shows J_{stat} and curve d gives the yrast line for ^{26}Al as determined by the spectral moment method.

Alternatively, it may be possible, even in the presence of several other levels of the same spin and parity, for one level to give the dominant contribution to the cross section. This could occur whenever the levels do not interfere sufficiently to yield statistically varying cross sections and the resulting excitation functions could contain some resonance characteristics. The average coherence width divided by the average level spacing for each J^{π}, $\Gamma_{J\pi}/D_{J\pi}$, provides a qualitative measure of the interference between neighboring levels of the same spin and parity. The parameter J_{stat}, arbitrarily chosen as the J for which $\Gamma_{J\pi}/D_{J\pi}=2$ is shown in Fig. 2 and provides an indication of the interference present for levels in ^{26}Al. The level density calculations described above indicate that $\Gamma_{J\pi}/D_{J\pi}=2.1\pm0.3$ (approximately 15 states/MeV) for $J=9\hbar$ at E_x (^{26}Al)$=25.6$ MeV, while the Fermi gas model values for $\Gamma_{J\pi}/D_{J\pi}$ range from 2 to 17 depending on one's choice of parameters. While large values (≥ 2) of $\Gamma_{J\pi}/D_{J\pi}$ may ensure that on the average fluctuations predominate, they do not provide the same assurance about the behavior of the cross sections in a very limited energy range. Thus even in cases where the levels being populated are not isolated one cannot rule out resonancelike structures due to one of those levels.

The nonstatistical nature of the largest structure at $E_{\text{c.m.}}=10.5$ MeV is clearly established and five other regions with maxima and minima correlations may also contain nonstatistical fluctuations. Statistical tests, such as those on which these conclusions are based, do not determine the cause of the nonstatistical fluctuations. However, correlations between various final states make this reaction hard to understand in terms of direct reactions or direct plus compound interference. We have shown that it is unlikely that this reaction populates isolated, high-spin states near the yrast line in ^{26}Al. We have recently made studies of the angular distributions in the region around $E_{\text{c.m.}}=10.5$ MeV that we hope will elucidate the mechanisms involved here, but at present there seems to be very little evidence with which to differentiate between nuclear dynamic effects such as molecular resonances and the population of a small number of states of the same spin and parity.

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