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Evidence for a $^{12}C + {}^{12}C$ Collective Band in ^{24}Mg†

E. R. Cosman,* T. M. Cormier, K. Van Bibber, A. Sperduto, and G. Young
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

J. Erskine and L. R. Greenwood
Argonne National Laboratory, Argonne, Illinois 60439

and

Ole Hansen
Niels Bohr Institute, Copenhagen, Denmark

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Excitation functions of the reaction $^{12}C(^{12}C,p)^{23}Na$ reveal a distinct set of resonances in the $\frac{11}{2}^+$, $\frac{13}{2}^+$, $(\frac{15}{2}^+)$, and $(\frac{17}{2}^+)$ members of the ^{23}Na $K^\pi=\frac{3}{2}^+$ ground-state band near $E_x(^{24}Mg) = 25.2$, 28.2, and 33.3 MeV. These plus earlier data suggest the possible existence of an excited collective band in ^{24}Mg with very high deformation and large $^{12}C+{}^{12}C$ width.

As part of a program to search for intermediate structure in (heavy-ion, p) reactions,[1,2] we have measured excitation functions for the reaction $^{12}C(^{12}C,p)^{23}Na$ from $E_{c.m.}(^{12}C) = 6.75$ to 30 MeV, using the tandem Van de Graaff accelerators at Brookhaven National Laboratory (BNL) and Argonne National Laboratory (ANL). The detectors at BNL were the Massachusetts Institute of Technology multigap spectrograph with photographic plates and surface-barrer counter telescopes, and at ANL the Enge split-pole spectrograph with Borkowsky-Kopp focal-plane counter. Over 800 measurements were made on carbon targets of 5 to 10 $\mu g/cm^2$ thickness with typical steps in $E_{c.m.}(^{12}C)$ of 25 to 100 keV. Most data were taken at $\theta_{lab} = 7.5°$. The proton resolution was between 30 and 70 keV and E_x coverage in ^{23}Na was in some cases from 0 up to 20 MeV. Excitation functions for the reaction $^{12}C(^{12}C,d)^{22}Na$ were measured over a more restricted range. Angular distributions were measured for some proton and deuteron groups at selected energies. A full report of these data will be given in a forthcoming paper.

In this Letter we focus on a most striking subset of these data, the unusually strong and correlated enhancements of the proton groups at $E_x = 9.04$ and 9.81 MeV in ^{23}Na near $E_{c.m.} = 11.4$, 14.3, and 19.3 MeV (Fig. 1). Since our earlier report of the 19.3-MeV anomaly,[2] measurements of the reaction $^{12}C(^{12}C,p\gamma)^{23}Na$ indicate that the 9.04- and 9.81-MeV states have high spin and probably carry a large fraction of the strength from the $\frac{15}{2}^+$ and/or $\frac{17}{2}^+$ members of the $K^\pi=\frac{3}{2}^+$ ^{23}Na ground-state rotational band.[3] Thus their apparent special structure, high spin, and correlated excitation functions point to connected resonant states in ^{24}Mg.

Several pieces of information suggest that the above three anomalies are $^{12}C+{}^{12}C$ entrance-

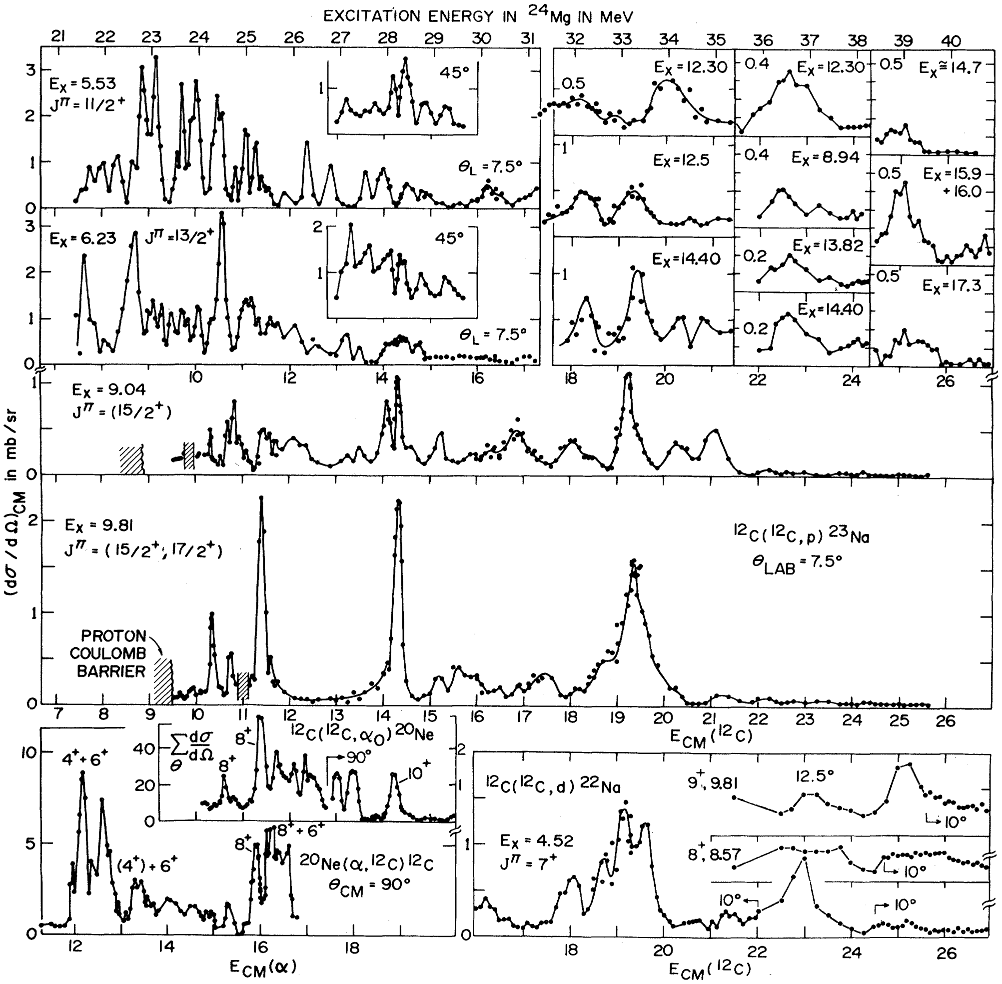

FIG. 1. Excitation functions of selected $^{12}C + ^{12}C$ reaction channels, described in the text. The $^{12}C + ^{12}C$ and $\alpha + ^{20}Ne$ reaction $E_{c.m.}$ scales are aligned to correspond to the same $E_x(^{24}Mg)$ values in the figure.

channel resonances, and more inferentially that their spins form an 8^+-10^+-12^+ sequence.

19.3-MeV resonance.—This anomaly appears in other ^{23}Na channels,[2] in $^{12}C(^{12}C, n)^{23}Mg$,[4] and in the reaction $^{12}C(^{12}C, d)^{22}Na$ to the 7^+ state (4.522 MeV) (present work and KeKelis and Fox[5]). We measured angular distributions at $E_{c.m.} = 19.3$ MeV for the 9.04- and 9.81-MeV states, and fits to them indicate a dominant $l_p = 4$ component. No resonance was found in the weak proton groups to the $\frac{11}{2}^+$ or $\frac{13}{2}^+$ ^{23}Na levels at this energy and $\theta_{lab} = 7.5°$. The decay of the $E_{c.m.} = 19.3$-MeV $^{12}C(^{12}C, d)^{22}Na(7^+)$ resonance is very strong, but there is no enhancement in the transitions to the ^{22}Na (6^+) state at $E_x = 3.708$ MeV or the ^{22}Na (5^+) state at 1.528 MeV. These facts favor $J^\pi = 12^+$ for the resonance.

$E_{c.m.} \simeq 14.3$-MeV resonance.—In this case anomalies are also observed for the $\frac{11}{2}^+$ and $\frac{13}{2}^+$ ^{23}Na states as well as for other channels not shown in Fig. 1. Angular distributions at $E_{c.m.} = 14.325$ MeV reveal $l_p = 2$ components in the proton decays to the 9.04- and 9.81-MeV states. Previous excitation functions[6] for the reaction $^{12}C(^{12}C, \alpha_0)^{20}Ne$ (g.s.) show a clear $J^\pi = 10^+$ enhancement at $E_{c.m.} = 14.3$ MeV with the same width as our anomaly (Fig. 1). These facts favor $J^\pi = 10^+$ for the resonance.

$E_{c.m.} \simeq 11.4$-MeV resonance.—The decays to the 9.04- and 9.81-MeV states have strong $l_p = 2$ components limiting the resonant spin to $J^\pi = 6^+$, 8^+, or 10^+. Earlier angular-distribution excitation functions of the reaction $^{12}C(^{12}C, \alpha_0)^{20}Ne$ (g.s.) show a distinct $J^\pi = 8^+$ enhancement at $E_{c.m.} = 11.4$

MeV, with $\Gamma \simeq 150$ keV[6,7] (Fig. 1), which corresponds well to our 9.04- and 9.81-MeV-state anomalies. Similarly the reaction ^{20}Ne(α, ^{12}C)^{12}C shows a strong effect near this energy[8] with $J^\pi = 8^+$ and $\Gamma = 145$ keV (Fig. 1). These results indicate $J^\pi = 8^+$ for the resonance.

It is interesting to consider the evidence for ^{12}C + ^{12}C resonances from other data. Sub-barrier $J^\pi = 2^+$ and 4^+ ^{12}C + ^{12}C resonances are well known[9] at $E_x = 19.56$ and at 18.16, 18.79, and 19.93 MeV, respectively. The ^{20}Ne(α, ^{12}C)^{12}C data[8] revealed large $J^\pi = 6^+$ strength mixed with $J^\pi = 4^+$ strength at $E_x(^{24}\mathrm{Mg}) \cong 21.5$, 22.0, and 22.7 MeV, and we observe large enhancements for the ^{23}Na($\frac{13}{2}^+$) proton group at $E_x \cong 21.5$ and 22.6 MeV with comparable widths. This information is plotted in Fig. 2. The roughly linear connection of these resonances to the 8^+-10^+-12^+ sequence suggested above is notable but may or may not be significant. The highest 2^+ and 4^+ states at $E_x(^{24}\mathrm{Mg}) = 19.56$ and 19.93 MeV decay preferentially to negative-parity states in ^{23}Na[10] and to the 0_2^+ state at $E_x = 6.72$ and 0_3^+ state at 7.20

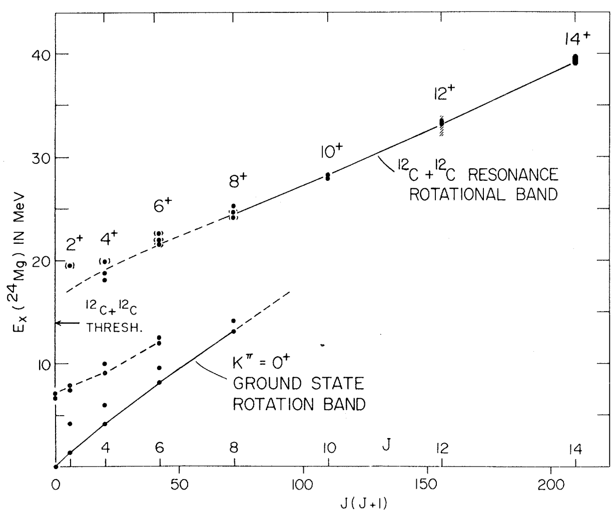

FIG. 2. A summary of known ^{12}C + ^{12}C resonance information. The solid points marked 8^+, 10^+, and 12^+ correspond to anomalies seen in the $E_x = 9.04$- and 9.81-MeV ^{23}Na state transitions in Fig. 1. Their spins are postulated from evidence given in the text and their positions are consistent with a rotational sequence. The points marked 6^+ are based on strength seen in Refs. 6–8 and Fig. 1, and those marked 4^+ and 2^+ are from Ref. 9. The parentheses reflect questions about these points and are discussed in the text. The point at 14^+ corresponds to the correlation seen in selected proton and deuteron transitions (Fig. 1). The solid line for the ^{12}C + ^{12}C band is simply to guide the eye. Some known low-lying levels of ^{24}Mg are also shown.

MeV in ^{20}Ne, so that at least for these states there is an indication of a different structure than for the resonances found here. Other distinct correlated anomalies were observed in the present ^{12}C(^{12}C, p)^{23}Na study. The only one near the expected 14^+ position (see Fig. 2) is at $E_{\mathrm{c.m.}} = 25.1$ MeV observed in three proton groups to states at 14.7, 16.0, and 17.3 MeV (Fig. 1). Data of Conjeaud *et al.*[11] indicate that the deuteron group to the ^{22}Na 9^+ state resonates at the same energy, while the d transitions to the lower-spin states in ^{22}Na do not. This is consistent with a 14^+ assignment for the resonance, but it is not conclusive. Two other anomalies appear at $E_{\mathrm{c.m.}} \cong 18.1$ and 22.6 MeV for ^{23}Na states between $E_x \simeq 8.9$ and 18 MeV (Fig. 1). Since they show little or no effect in the 9.04–9.81-MeV doublet, they may be unrelated to the proposed 8^+-10^+-12^+ sequence.

An appealing explanation of the resonances is that they are $J^\pi = 8^+$, 10^+, and 12^+ members of a rotational band with a large ^{12}C + ^{12}C width. Figure 2 shows that their energies vary nearly linearly with $J(J+1)$ and the slope of the line gives $\hbar^2/2I = 100$ keV which is close to the value for ^{12}C + ^{12}C at grazing distance. The observed resonance widths are considerably narrower than those predicted for shape resonances in a ^{12}C + ^{12}C Woods-Saxon potential well,[12] and may indicate that a minimum in the shell-corrected potential surfaces[13] gives rise to the observed resonances. Some spectroscopic information may also be contained in the observed particle transitions to known final states. For example, the selective proton decays of the $J^\pi = 8^+$, 10^+, and 12^+ resonances to the 9.04- and 9.81-MeV ($J^\pi = \frac{15}{2}^+$ or $\frac{17}{2}^+$) states are striking and could indicate a larger spectroscopic overlap for these states than for neighboring high-spin levels in ^{23}Na.

These data encourage the notion that the fine energy dependence of heavy-ion reactions will reveal simple intermediate structure and new spectroscopy rather than just statistical fluctuations and broad energy behavior. Further, more detailed excitation-function studies are essential to substantiate the existence of such collective states as those suggested here. For example, measurements of the elastic, α, and perhaps γ decays of the ^{12}C + ^{12}C resonances and a search for similar anomalies in complementary entrance channels such as ^{14}N + ^{10}B and ^{16}O + ^{8}Be would be of importance in pinning down the spins and any remaining J^π resonance strength and in determining the decay widths of the postulated ^{24}Mg structure into its quasi-molecular or cluster components.

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Neutron Blocking in α-Particle–Transfer Reactions*

F. D. Becchetti and J. Jänecke
Cyclotron Laboratory, Department of Physics, The University of Michigan, Ann Arbor, Michigan 48105
(Received 5 June 1975)

The $(d,{}^6\mathrm{Li})$ α-transfer reaction on several even-A and odd-A tin isotopes has been investigated at $E_d = 35$ MeV. A significant reduction ($\sim$ factor 2) in transition strength is observed for the odd-A target nuclei. This reduction is attributed to the "blocking" effect of unpaired nucleons and is comparable to that observed in (p,t) reactions.

The effects of the Pauli exclusion principle manifest themselves in a dramatic fashion in two-nucleon–transfer reactions such as (p,t) and (t,p). A recent study of the (p,t) reaction[1] on even-A and odd-A tin isotopes has demonstrated the "blocking" effect of unpaired target nucleons. Typically, the ground-state → ground-state (g.s.) transition strengths are reduced by a factor of about 2 for $J^\pi=\frac{1}{2}^+$ odd-A targets compared with adjacent $J^\pi=0^+$ targets.[1] Recent theoretical models[2] and experiments[3] indicate a close connection between two-nucleon- and α-transfer reactions. As a further test of such a correlation, we have investigated the $(d,{}^6\mathrm{Li})$ reaction on targets of $^{116-120}\mathrm{Sn}$. A preliminary report has been presented elsewhere.[4]

The experiments were performed with a 35-MeV deuteron beam from the University of Mich-