Structure in the $^{12}C(^{12}C,d)^{22}Na$ reaction near $E_{c.m.} = 14.3$ MeV†

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Enhancements are observed in the $^{12}C(^{12}C,d)^{22}Na$ reaction for the population of the $J^{\pi} = 5^+$ and 7^+ states at $E_x = 1.53$ and 4.52 MeV in the energy region from 13.0 to 16.8 MeV (c.m.). A comparison of $^{12}C(^{12}C,^8Be)$ and $^{12}C(^{12}C,d)$ suggests that the selective population of the states in ^{22}Na arises from the deuteron exit channel penetrabilities for grazing partial waves rather than nuclear structure similarities between the $^{12}C + {}^{12}C$ and $d + {}^{22}Na$ systems.

[NUCLEAR REACTIONS $^{12}C(^{12}C,d)$, $E_{c.m.} = 13.0$ to 16.8 MeV; measured E_d and $d\sigma/d\Omega$ at $\theta_{lab} = 10°$ and 20°.]

Recently, a number of studies have been undertaken to determine the mechanisms responsible for the observed structure in the $^{12}C + {}^{12}C$ reaction for the p, n, and d exit channels.[1-7] Special emphasis has been given to the $E_{c.m.} = 19.3$ MeV anomaly where there are correlated enhancements of selectively populated high spin states in ^{23}Na, ^{23}Mg, and ^{22}Na. Some investigators[2,4] have suggested that the selectively populated states indicate a similarity between the $^{12}C + {}^{12}C$ system and the structure excited in the $^{23}Na + p$, $^{23}Mg + n$, and $^{22}Na + d$ systems. In the present work the $^{12}C(^{12}C,d)^{22}Na$ reaction is studied at center-of-mass energies from 13.0 to 16.8 MeV for ^{22}Na states with $E_x < 4.6$ MeV. This excitation energy region in ^{22}Na includes a number of states with various spins which are of related structure in both the rotational and shell-model descriptions.[8,9] Consequently, any selective population displayed in the deuteron channel might be understood on the basis of grazing angular momentum and/or structure arguments. A recent $^{12}C(^{12}C,^8Be)^{16}O$ study[10] provides additional information about the spins in the compound system which allows a qualitative explanation of the relative populations observed in the deuteron channel.

The Florida State University FN tandem Van de Graaff accelerator with an inverted sputter source[11] was used to produce $^{12}C^{+4}$ beams at incident energies of $E_{lab} = 26.0$ to 33.6 MeV in 100 and 200 keV steps. The thicknesses of the self-supporting natural carbon targets (~99% ^{12}C) were from 25 to 35 $\mu g/cm^2$, as determined by elastic proton scattering.[12] The deuterons were detected with approximately 130 keV resolution in two ΔE-E solid state counter telescopes at $\theta_{lab} = 10°$ and 20°. Each telescope was collimated to subtend a solid angle of approximately 208 μsr with an angular acceptance of ±0.14°. The absolute error in the cross sections is about 20% and arises principally from uncertainties in the detector solid angles and target thicknesses. The cross sections include corrections for the varying equilibrium charge state of carbon ions passing through carbon foils since the normalizations were based on integrated charge in a Faraday cup. A monitor detector was used to check these calculations for several of the runs. Because of the large negative Q value (−7.95 MeV) for the reaction, the deuterons populating the 4.52 MeV state are low in energy at beam energies below $E_{c.m.} = 14.0$ MeV, making it difficult to extract reliable data for this state below 14 MeV.

Deuteron spectra at $E_{c.m.} = 14.15$ and 14.30 MeV for $\theta_{lab} = 10.0°$ are shown in Fig. 1. Weak population of a number of the known low-lying states in ^{22}Na is indicated. At $E_{c.m.} = 14.15$ MeV [Fig. 1(a)] the $E_x = 1.53$ MeV (5^+) state is 3 to 4 times stronger than any other state with $E_x \leq 4.6$ MeV. Similar spectra are also observed at $E_{c.m.} = 13.5$ and 14.5 MeV. This selectivity is reminiscent of the selective population of the 4.52 MeV (7^+) state at the $E_{c.m.} = 19.3$ MeV resonance.[3,4,7] At $E_{c.m.} = 14.30$ MeV [Fig. 1(b)] only the 5^+ strength is appreciably reduced, but it is still stronger than any of the other states shown. Since there is a resonance in the proton channel to the 9.04 ($\frac{15}{2}^+$) and 9.80 MeV ($\frac{15}{2}^+$) states in ^{23}Na at the latter center-of-mass energy, competition between the channels is indicated.

The results of the excitation function studies are shown in Fig. 2 for a number of the states at $\theta_{lab} = 10°$ and 20°. The vertical dashed line extending through the figure corresponds to the energy at which the proton yield to the $E_x = 9.80$ MeV state of ^{23}Na is a maximum. The proton spectra were obtained simultaneously in our experiment and thus a relative energy standard is established. Our energy for the proton resonance is $E_{c.m.} = 14.30 \pm 0.05$ MeV in agreement with Cosman *et*

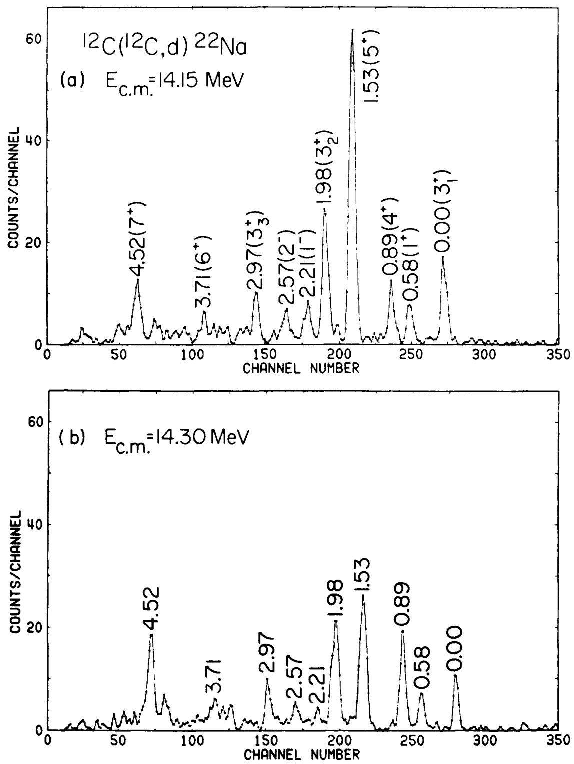

FIG. 1. Deuteron spectra for the $^{12}C(^{12}C,d)^{22}Na$ reaction at $\theta_{lab} = 10°$ at (a) $E_{c.m.} = 14.15$ MeV; (b) $E_{c.m.} = 14.30$ MeV. The excitation energies are given in MeV with the spins in parentheses.

al.'s[4] energy of 14.325 MeV. The most striking feature of Fig. 2 is the preferential population of the 1.53 MeV (5^+) state over the entire range. There are several regions of enhancement which are correlated at these two angles and which are centered near $E_{c.m.} = 13.5$, 14.1, 14.5, 15.6, and 16.0 MeV. Such structure is impressive when compared to the almost smooth behavior of the states at $E_x = 0.59$, 0.89, 1.98, 2.57, 2.97, and 3.71 MeV, whose spins are 1^+, 4^+, 3^+_2, 2^-, 3^+_3, and 6^+, respectively. An Ericson fluctuation interpretation[13] is improbable for these data since the coherence angle can be estimated as $\theta_c = 1/kR \simeq 6°$ in the center-of-mass which is smaller than the angle spacing of the data (the two lab angles correspond to $\theta_{c.m.} \simeq 15$ and 30° for $E_x = 1.53$ MeV), and since several of the states' yields have smooth behavior with beam energy.

The extended shell-model calculations of Preedom and Wildenthal and MacArthur *et al.*,[9] suggest the 0.00 (3^+), 0.89 (4^+), 1.53 (5^+), 3.71 (6^+), and 4.52 (7^+) MeV states may be identified as a "band" with an approximate $J(J+1)$ energy sequence and with enhanced $B(E2)$ transitions between them, so structural differences between them should be minimal. The relatively smooth excitation function of the 0.0 MeV (3^+) state above $E_{c.m.} = 14.1$ MeV and of the 0.89 MeV (4^+) and 3.71 MeV (6^+) states as compared to the 1.53 MeV (5^+) and 4.52 MeV (7^+) states is quite striking. An appealing qualitative explanation for the observed selectivity is based essentially on the angular momentum available. Recently, Fletcher *et al.*[10] have used studies of the $^{12}C(^{12}C,{}^8Be)^{16}O$ (g.s.) reaction to show that the energy region in the compound nucleus from $E_{c.m.} = 26-35$ MeV is dominated by $L = 10$ enhancements. They report a number of 10^+ structures whose approximate positions and widths, full width at half maximum (FWHM), are indicated by the crossed arrows (⟼|⟻) in the $E_x = 1.53$ MeV portion of Fig. 2. Enhancements and their width in the 5^+ yield generally are related to the presence of a 10^+ structure. Penetrability calculations show the $l_d = 4$ partial wave to this state to be dominant by a factor of 100 over $l_d = 6$.

The relative populations of the various ^{22}Na states in the "band" can be qualitatively explained

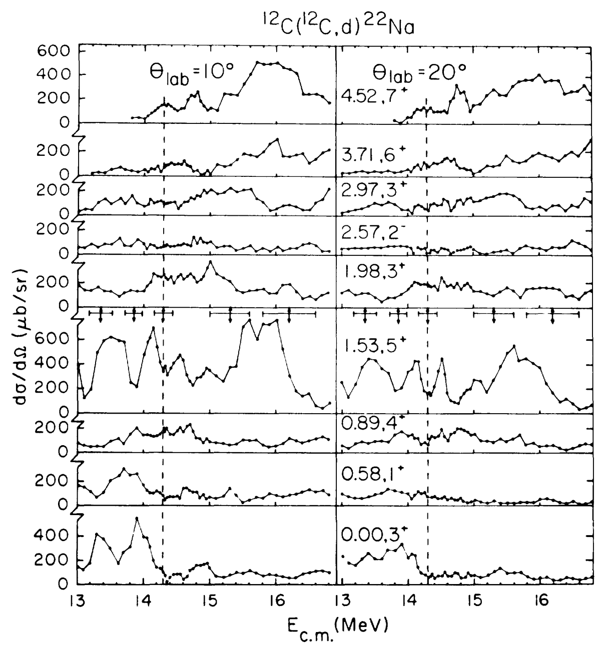

FIG. 2. Excitation functions from the $^{12}C(^{12}C,d)^{22}Na$ reaction at $\theta_{lab} = 10°$ and 20° for a number of states with $E_x < 4.6$ MeV. The vertical dashed line represents the energy $E_{c.m.} = 14.30$ MeV where the 9.80 MeV ($\frac{15}{2}+$) state's yield was observed to be a maximum in the $^{12}C(^{12}C,p)^{23}Na$ reaction data that was obtained in the present experiment. The positions and widths (FWHM) corresponding to 10^+ structure identified in the $^{12}C(^{12}C,{}^8Be)^{16}O$ study (Ref. 10) are indicated by crossed arrows (⟼|⟻) in the 1.53 MeV state portion of the figure.

TABLE I. Results of penetrability (P_{nL}) calculations for ^{22}Na + d and for ^{23}Na + p (which are indicated by a †) channels for values of $E_{c.m.}$, excitation energy (E_x), effective Q value (Q_{eff}), interaction radius $R = r_0(A_1^{1/3} + A_2^{1/3})$, and partial wave ($L$). Penetrabilities are marked by an asterisk in those cases where the minimum partial wave in the exit channel that can populate the state of interest and satisfy angular momentum and parity rules seems predominant.

$E_{c.m.}$ (MeV)	E_x (MeV)	(J^π)	Q_{eff} (MeV)	r_0 (fm)	P_{nL} $L=0$	$L=2$	$L=4$	$L=6$
14.32	1.53	(5^+)	−9.48	1.20	2.007	1.071	*0.101	0.001
				1.40	2.534	1.645	0.300	0.007
	3.71	(6^+)	−11.66	1.20	0.800	0.186	*0.003	1.0×10^{-5}
				1.40	1.138	0.381	0.014	7.2×10^{-5}
	4.52	(7^+)	−12.47	1.20	0.290	*0.035	0.0003	3.7×10^{-7}
				1.40	0.472	0.084	0.001	2.9×10^{-6}
	9.80	($\frac{15}{2}^+$)†	−7.56	1.20	1.896	*0.877	0.045	0.0002
16.00	1.53	(5^+)	−9.48	1.20	2.694	1.807	*0.363	0.009
	3.71	(6^+)	−11.66	1.20	1.767	0.842	*0.059	0.0005
	4.52	(7^+)	−12.47	1.20	1.329	*0.485	0.019	9.7×10^{-5}
19.42	1.53	(5^+)	−9.48	1.20	3.766	3.032	1.327	*0.123
	4.52	(7^+)	−12.47	1.20	2.848	1.981	*0.459	0.014
	9.80	($\frac{15}{2}^+$)†	−7.56	1.20	2.897	1.997	*0.412	0.009

by the "penetrability" (P_{nL}) of the appropriate deuterons that decay to each state. The partial width (Γ_c) for decay into the channel c is given by $\Gamma_c = 2P_{nL}\gamma_c^2$, where P_{nL} is the penetrability for a given partial wave L and γ_c^2 is the reduced width for the channel.[14] The structural dependence of the cross sections due to the overlap of the ^{24}Mg state (^{12}C + ^{12}C) with ^{22}Na + d is in the reduced width and should not vary appreciably within the "band." An inspection of Table I shows that if a 10^+ state were formed in the compound system at $E_x \simeq 28$ MeV which corresponds to $E_{c.m.} \simeq 14$ MeV, the ratio of the penetrabilities for the 5^+ and 6^+ states is $P_{n4}(1.53)/P_{n4}(3.71) \simeq 30$ as compared to an experimental differential cross section ratio of 13 at $E_{c.m.} = 14.15$ MeV and $\theta_{lab} = 10°$. The appropriate penetrability ratio for the 5^+ and 7^+ states is $P_{n4}(1.53)/P_{n2}(4.52) \simeq 3$ as compared to experimental ratios of 8 (2) at $E_{c.m.} = 14.15$ (14.32) MeV. In these cases the minimum partial wave in the exit channel that can populate the state of interest and satisfy angular momentum and parity rules seems predominant and the penetrabilities are marked by an asterisk (*) in the table. The penetrability for the next higher even L is down by a factor of 100 in general and is neglected. In addition, the preferential population of the 9.80 MeV ($\frac{15}{2}^+$) ^{23}Na state compared to the 1.53 MeV (5^+) ^{22}Na state is also reflected in the penetrabilities. The appropriate ratio is $P_{n4}(1.53)/P_{n2}(9.80) \simeq 0.11$ as compared to the experimental ratio of 0.20 at $E_{c.m.} = 14.3$ MeV and $\theta_{lab} = 10°$ (neglecting angular distribution effects). If one considers the $E_{c.m.} = 19.3$ MeV anomaly which is considered to be predominantly a 12^+ structure,[10] the 1.53 (5^+) to 4.52 (7^+) ratio is $P_{n6}(1.53)/P_{n4}(4.52) \simeq 0.27$ as compared to an experimental ratio at 10° of approximately 0.10. If one were to correct for angular distribution differences for $L = 6$ and $L = 4$ at $\theta_{lab} = 10°$, the predicted ratio would be reduced to a value very close to the experimental number.

In conclusion, these data indicate that the structure in the ^{12}C(^{12}C, d)^{22}Na reaction from $E_{c.m.} = 13.0$ to 16.8 MeV is well explained via grazing angular momentum and penetrability considerations. The deexcitation of a set of 10^+ structures in the compound system has a "stretched" character, i.e., the predominant l in the exit channel matches the spin difference between the initial and final states subject to penetrability conditions and, concomitantly, Q values. The enhancements in the 5^+ differential cross sections are correlated at $\theta_{c.m.} = 15°$ and 30° and appear to be nonstatistical in origin. The widths of the enhancements in the deuteron channel are dependent on the compound state and the strength depends on the competition for the flux in the proton and neutron channels. Apparently, the large negative Q value, penetrability conditions, and the presence of only three states with $J \geq 5$ for $E_x < 4.6$ MeV in ^{22}Na combine to make the ^{12}C(^{12}C, d)^{22}Na reaction a sensitive probe of the compound system.

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[1]K. Van Bibber, E. R. Cosman, A. Sperduto, T. M. Cormier, T. N. Chin, and O. Hansen, Phys. Rev. Lett. 32, 687 (1974).

[2]P. Sperr, D. Evers, K. Rudolph, W. Assmann, E. Spindler, P. Konrad, and G. Denhöfer, Phys. Lett. 49B, 345 (1974).

[3]G. J. KeKelis and J. D. Fox, Phys. Rev. C 10, 2613 (1974).

[4]E. R. Cosman, T. M. Cormier, K. Van Bibber, A. Sperduto, G. Young, J. Erskine, L. R. Greenwood, and O. Hansen, Phys. Rev. Lett. 35, 265 (1975).

[5]T. M. Cormier, E. R. Cosman, L. Grodzins, O. Hansen, S. Steadman, K. Van Bibber, and G. Young, Nucl. Phys. A247, 377 (1975).

[6]G. J. KeKelis, A. H. Lumpkin, and J. D. Fox, Phys. Rev. Lett. 35, 710 (1975).

[7]A. H. Lumpkin, G. J. KeKelis, K. W. Kemper, and J. D. Fox, Phys. Rev. C 15, 1152 (1977).

[8]R. H. Spear, R. A. I. Bell, M. T. Esat, P. R. Gardner, D. C. Kean, and A. M. Baxter, Phys. Rev. C 11, 742 (1975), and references therein.

[9]B. M. Preedom and B. H. Wildenthal, Phys. Rev. C 6, 1633 (1972); J. D. MacArthur, A. J. Brown, P. A. Butler, L. L. Green, C. J. Lester, A. N. James, P. J. Nolan, and J. F. Sharpey-Schafer, Can. J. Phys. 54, 1134 (1976).

[10]N. R. Fletcher, J. D. Fox, G. J. KeKelis, G. R. Morgan, and G. A. Norton, Phys. Rev. C 13, 1173 (1976).

[11]K. R. Chapman, Nucl. Instrum. Methods 124, 299 (1975).

[12]A. C. L. Bernard, J. B. Swint, and T. B. Clegg, Nucl. Phys. 86, 130 (1966).

[13]D. Shapira, R. G. Stokstad, and D. A. Bromley, Phys. Rev. C 10, 1063 (1974).

[14]J. B. Marion and F. C. Young, *Nuclear Reaction Analysis* (North-Holland, Amsterdam, 1968).