surprising since the spin dependence of the g factors is very similar in all the three cases below $I=12\hbar$ and consistent with gradual changes in structure while going from ^{170}Yb to ^{174}Yb.

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[1]F. S. Stephens, Rev. Mod. Phys. 47, 43 (1975).

[2]E. Grosse, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 31, 840 (1973), and 32, 74 (1974); L. L. Riedinger, O. Anderson, S. Frauendorf, J. D. Garrett, J. J. Gaardhøje, G. B. Hagemann, B. Herskind, Y. V. Makovetzky, J. C. Waddington, M. Guttormsen, and P. O. Tjøm, Phys. Rev. Lett. 44, 568 (1980).

[3]U. Mosel, in J. Phys. (Paris), Colloq. 41, C10-253 (1980), Proceedings of the International Conference on Nuclear Behavior at High Angular Momentum, Strasbourg, 1980.

[4]H. R. Andrews, O. Häusser, D. Ward, P. Taras, N. Rud, B. Haas, R. M. Diamond, D. Fossan, H. Kluge, M. Niemann, C. Roulet, and F. S. Stephens, Phys. Rev. Lett. 45, 1835 (1980).

[5]D. Ward, O. Häusser, H. R. Andrews, P. Taras, P. Skensved, N. Rud, and C. Broude, Nucl. Phys. A330, 225 (1979).

[6]M. Diebel, A. N. Mantri, and U. Mosel, Nucl. Phys. A345, 72 (1980).

[7]S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I. L. Lamm, P. Möller, and B. Nilsson, Nucl. Phys. A131, 1 (1969).

[8]B. Nerlo-Pomorska, Z. Phys. A293, 9 (1979).

[9]*Table of Isotopes*, edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).

[10]D. Ward, P. Colombani, I. Y. Lee, P. A. Butler, R. S. Simon, R. M. Diamond, and F. S. Stephens, Nucl. Phys. A266, 194 (1976).

[11]S. Cwiok, W. Nazarewicz, J. Dudek, and Z. Szymanski, Phys. Rev. C 21, 448 (1980).

[12]A. L. Goodman, Nucl. Phys. A265, 113 (1976).

[13]We note that using an effective spin gyromagnetic $g_s' = 0.7g_s$ as suggested by A. Bohr and B. R. Mottelson [*Nuclear Structure* (Benjamin, New York, 1975), Vol 2, p. 303] would mainly reduce the difference between the two curves by a factor of 0.7.

[14]R. Bengtsson and S. Frauendorf, Nucl. Phys. A314, 27 (1979).

Entrance-Channel Limitations to $^{10}B + ^{13}C$ and $^{11}B + ^{12}C$ Fusion

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The $^{11}B + ^{12}C$ and $^{10}B + ^{13}C$ total fusion cross sections have been measured over a laboratory energy range from 10 to 54 MeV. It has been found that the limitation in the fusion cross sections for these systems cannot presently be explained by the properties of the compound nucleus.

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It is now well known that heavy-ion reactions for target-projectile systems in the 1p and 2s-1d shells exhibit substantially different maximum fusion cross sections.[1-4] It is unclear, however, whether this limitation in the total fusion cross section is due to properties of the entrance-channel nuclei or whether it is due to equilibrium properties of the compound nucleus formed. In a recent study[2] it was shown that, although the $^{10}B + ^{16}O$ and the $^{12}C + ^{14}N$ entrance channels lead to the same compound nucleus, the fusion cross sections for these two systems differ substantially. This difference was attributed by these authors to differences in the microscopic properties of the entrance-channel nuclei. However, in a subsequent analysis of these data,[3] it was shown that the $^{10}B + ^{16}O$ and the $^{12}C + ^{14}N$ systems approach the same critical angular momentum at high energies so that the difference in the two systems was interpreted as a compound-nucleus effect. The limitation in the critical angular momentum for these systems, and for several other systems which were observed to show this effect,[3-5] is believed to be due either to the position of the compound-nucleus yrast line[3] or to having reached critical density of compound-nucleus states.[4-6] In the present Letter, evidence is presented for fusion cross-section differences that are the result of entrance-channel properties of the interacting nuclei.

We report here experimental results for the reactions $^{11}B + ^{12}C$ and $^{10}B + ^{13}C$, both of which lead to the ^{23}Na compound nucleus. Fusion cross sections for the total and individual mass groups were studied over a center-of-mass energy range from 7 to 28 MeV in approximately 0.5-MeV intervals. The significant feature of these data is that the two entrance channels do not exhibit the same limiting critical angular momentum at higher excitation energies in ^{23}Na. At least for these systems, the mechanism which limits the critical angular momentum, and consequently the total fusion cross section, cannot be due either to the compound-nucleus yrast line or to having reached a critical density of compound-nucleus states, but instead appears to depend on the properties of the entrance-channel nuclei.

Beams of ^{10}B and ^{11}B from the Florida State University tandem Van de Graaf accelerator were used to bombard enriched self-supporting ^{12}C and ^{13}C foils. The fusion products were mass identified with a time-of-flight system which consisted of a microchannel plate detector and a silicon surface-barrier detector separated by 2.7 m. Unit mass separation was obtained at all bombarding energies. Monitors, positioned to the left and right of the beam, allowed an accurate determination of the beam position and target thickness buildup.

Angular distributions of the evaporation residues were measured from 3° to 40° at intervals of 5 and 7 MeV in the laboratory for the $^{11}B + ^{12}C$ and $^{10}B + ^{13}C$ systems, respectively. Excitation functions were measured in approximately 1-MeV steps at a fixed angle (8° for the $^{12}C + ^{11}B$ and 9° for the $^{10}B + ^{13}C$) near the maximum in $(d\sigma/d\Omega) \times \sin\theta$. Since the shapes of the total fusion angular distributions changed smoothly as a function of bombarding energy, the integrated angular distributions were used to obtain the total fusion cross section from the single-angle yields measured in the excitation function.

Absolute cross sections were determined by comparison with ^{16}O elastic scattering and with the elastic yields of either ^{10}B or ^{11}B which were obtained simultaneously with the fusion measurements. At low energies and forward angles all of the elastic scattering was due to Rutherford scattering. The error in the absolute fusion cross section is estimated to be 10%. Since the experimental techniques used to measure the cross sections for the two boron-induced reactions were the same, we believe that the relative fusion cross sections are accurate to 5%.

Evaporation residues with masses between 10 and 22 were included in the total fusion cross sections. For masses 13 and lighter, the energy spectra exhibited discrete peaks at energies near the projectile energy. This yield was assumed to arise from either direct transfer or inelastic scattering and was not included in the fusion cross section, but would have increased the fusion cross section by less than 5% had it been included. No evidence for any mechanism other than fusion was found in the energy spectra of the heavier mass groups.

Furthermore, no fusion yield was found for masses ≤ 9 in either experiment. The mass-10 and -11 fusion cross sections were obscured in the $^{10}B + ^{13}C$ and $^{11}B + ^{12}C$ experiments, respectively, because of the backgrounds present in the elastic channels. However, the fusion yield to the mass-10 group could be measured in the $^{11}B + ^{12}C$ study and was found to be $\leq 1\%$ of the total fusion cross section at all energies. In the $^{10}B + ^{13}C$ investigation there was no apparent fusion cross section above the elastic background. We have, therefore, excluded the mass-10 yield when evaluating the total fusion cross sections for both systems. The mass-11 group could be evaluated in the $^{10}B + ^{13}C$ study. This cross section was found to vary smoothly from 0 to $\simeq 60$ mb over the energy range studied. This cross section is included in the $^{10}B + ^{13}C$ total fusion cross section. A reliable mass-11 fusion yield could not be extracted from the $^{11}B + ^{12}C$ study; thus, it is not included in the total $^{11}B + ^{12}C$ fusion cross section.

The dependence of the total fusion cross sections upon $E_{c.m.}$ for the two entrance channels is presented in Fig. 1. Apparent in both excitation functions are weak broad structures (e.g., $E_{c.m.} = 16$ MeV in the $^{11}B + ^{12}C$ system). This structure does not arise from periodic oscillations in one mass group as is observed in the $^{12}C + ^{12}C$ system for the oxygen exit channel.[1] What occurs in the $^{11}B + ^{12}C$ system is a smooth increase in the cross section of a particular mass group up

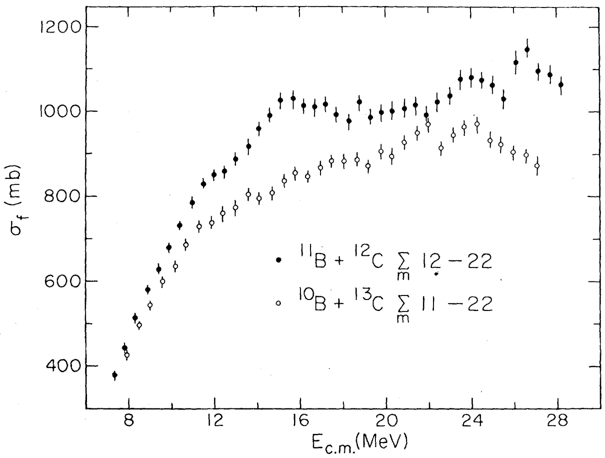

FIG. 1. Total fusion cross sections for the $^{11}B + ^{12}C$ and $^{10}B + ^{13}C$ systems plotted as a function of $E_{c.m.}$.

to a certain energy followed by a smooth decrease in the cross section for this mass with further increases in energy. Such smooth changes in cross section as a function of energy are typical of fusion reactions. At $E_{c.m.} = 16$ MeV two strong exit channels, masses 15 and 18, both reach a maximum cross section in the $^{11}B + ^{12}C$ system to form the structure observed at this energy in the total fusion cross section. The rapid increase in masses 14 and 16 appears to be primarily responsible for the structure at higher energies. A complete presentation of the yields of the individual masses for both entrance channels will be presented in a subsequent publication.

From the total fusion cross sections displayed in Fig. 1, the critical angular momenta for the two entrance channels were extracted using a sharp-cutoff model. In Fig. 2, we present a plot of these angular momenta as a function of excitation energy in ^{23}Na. Also presented in Fig. 2 are the grazing angular momenta for the two entrance channels (upper two solid curves) and a calculated ^{23}Na yrast line (lower solid curve). The $^{10}B + ^{13}C$ grazing angular momenta were obtained from an optical-model analysis of the elastic scattering data obtained simultaneously with the fusion yield. The grazing angular momenta for the $^{11}B + ^{12}C$ system were obtained from an optical-model parametrization of detailed $^{11}B + ^{12}C$ angular distributions measured at ^{11}B bombarding energies of 25, 40, and 50 MeV. Both optical-model parameter sets were energy independent. The ^{23}Na yrast line shown in Fig. 2 was calculated with use of the spectral-moment method of Ayik and Ginocchio,[7] with the

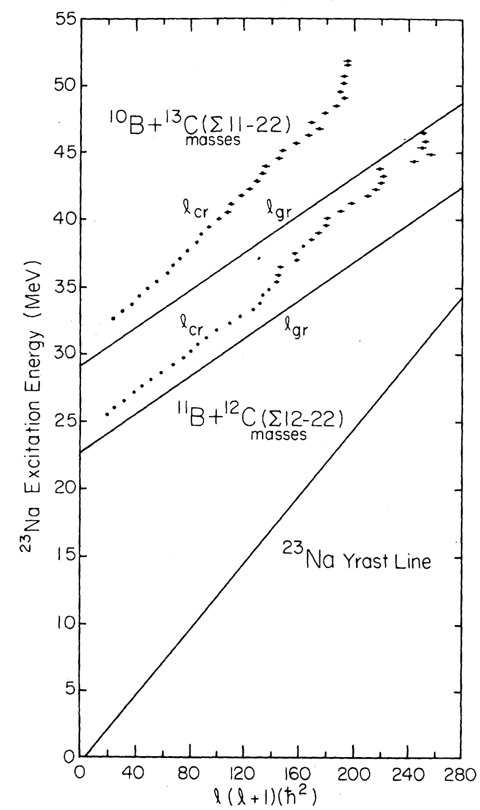

FIG. 2. The critical angular momenta vs ^{23}Na excitation energy. Also shown are the calculated ^{23}Na yrast line (see text) and the grazing angular momenta for the $^{11}B + ^{12}C$ and $^{10}B + ^{13}C$ entrance channels.

moments taken from Ayik.[8]

At excitation energies below approximately 35 MeV in ^{23}Na, the critical angular momentum for each system parallels its entrance-channel grazing angular momentum curve. Above this energy, however, it is clear that the critical angular momenta begin to bend away from the grazing angular momentum lines. The significant feature of the data in Fig. 2 is that in the energy region where the limitation in the fusion cross section is observed, the $^{11}B + ^{12}C$ and the $^{10}B + ^{13}C$ critical angular momenta show no tendency to converge. It must be emphasized that the $^{10}B + ^{13}C$ and the $^{11}B + ^{12}C$ critical angular momenta were extracted from total fusion cross sections which included all the significant fusion yield available for these two systems with the possible exception of the yield to the mass-11 group in the $^{11}B + ^{12}C$ study. However, an increase in the $^{11}B + ^{12}C$ total fusion cross section would result in larger values of the $^{11}B + ^{12}C$ critical angular momenta, which would only increase the separation between the

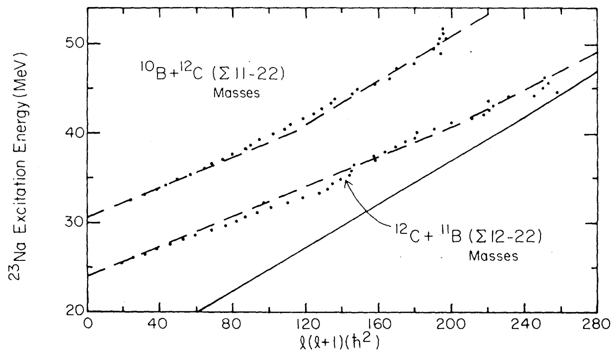

FIG. 3. The critical angular momentum vs ^{23}Na excitation energy. Also shown is the statistical yrast line of Ref. 5 (solid curve) and a Glas and Mosel (Ref. 9) parameterization of the data (dashed lines).

^{10}B + ^{13}C and the ^{11}B + ^{12}C critical angular momentum curves.

Numerous models based either on entrance-channel characteristics or on compound-nucleus properties have been developed to explain limitations in fusion cross sections observed in other systems in this mass region. One of the more recent compound-nucleus–based models[5] suggests that a "statistical yrast line" (corresponding to a critically low density of compound-nucleus levels of suitable spin) is responsible for the fusion cross section limitations. From a study of several fusion systems in this mass region, the authors of Ref. 5 find that this statistical yrast line parallels the compound-nucleus yrast line and lies 10 ± 2.5 MeV higher in energy. If we add 12.5 MeV to the yrast line of Ayik and Ginnochio[7] for ^{23}Na (see Fig. 2), the solid curve in Fig. 3 is obtained. If the ^{11}B + ^{12}C fusion cross section is being limited by the presence of such a statistical yrast line, then clearly the ^{10}B + ^{13}C fusion cross section is not.

In terms of a plot of fusion cross section (σ_f) versus center-of-mass energy, the difference between the present pair of entrance channels in the fusion limitation region and pairs of entrance channels leading to other compound nuclei in this mass region[2-4] is again readily apparent. One finds, in such a plot for other systems in this mass region, that the entrance channel with the larger Q value has the larger total fusion cross section in the fusion limitation region. The opposite is true, however, for the present data. The entrance channel with the smaller Q value (^{12}C + ^{11}B, 18.198 MeV; ^{13}C + ^{10}B, 24.706 MeV) has the larger total fusion cross section in this region (see Fig. 1). This seems to suggest that no microscopic model based on a single Q-value scaling of the fusion cross section can simultaneously describe all of the experimentally measured fusion cross sections.

Finally, one of the entrance-channel models, that of Glas and Mosel,[9] has also been applied to the data (see Fig. 3, dashed curves). The Glas-Mosel parameters required to describe the ^{11}B + ^{12}C (^{10}B + ^{13}C) data are $V_B = 5.6$ (5.6) MeV, $r_B = 1.5$ (1.5) fm, $V_{cr} = -2.0$ (0.0) MeV, and $r_{cr} = 1.2$ (1.2) fm. The relatively small differences in the critical parameters seen here are in contrast with large differences in the critical parameters reported for the ^{10}B + ^{16}O and ^{12}C + ^{14}N systems,[2] a case where the authors of Ref. 3 suggest that a compound-nucleus limitation is indicated by the data.

In summary, the present data indicate that the fusion cross section for ^{10}B + ^{13}C is not limited by any property of the ^{23}Na compound nucleus, but rather by some feature of the entrance channel. Precisely what entrance-channel feature is causing the fusion cross section limitation (e.g., microscopic structure of the interacting nuclei, fragmentation of the target or projectile, etc.) is, at present, unclear.

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[1] D. G. Kovar, D. F. Geesamen, T. H. Braid, Y. Eisen, W. Henning, T. R. Ophel, M. Paul, K. E. Rehm, S. J. Sanders, P. Sperr, J. P. Schiffer, S. L. Tabor, S. Vigdor, and B. Zeidman, Phys. Rev. C 20, 1305 (1979), and references therein.

[2] J. Gomez del Campo, R. A. Dayras, J. A. Biggerstaff, D. Shapira, A. H. Snell, P. H. Stelson, and R. G. Stokstad, Phys. Rev. Lett. 43, 26 (1979).

[3] J. P. Wieleczko, S. Harar, M. Conjeaud, and F. Saint-Laurent, Phys. Lett. 93B, 35 (1980).

[4] F. Saint-Laurent, M. Conjeaud, S. Harar, J. M. Lorseaux, J. Menet, and J. B. Viano, Nucl. Phys. A327, 517 (1979).

[5] S. M. Lee, T. Matsuse, and A. Arima, Phys. Rev. Lett. 45, 165 (1980).

[6] L. C. Dennis and S. T. Thornton, Phys. Rev. C 22, 340 (1980).

[7] S. Ayik and J. N. Ginocchio, Nucl. Phys. A234, 13 (1974).

[8] S. Ayik, Ph.D. thesis, Yale University, 1974 (unpublished).

[9] D. Glas and V. Mosel, Nucl. Phys. A237, 429 (1975).