and Nucl. Phys. A235, 315 (1974); S. Krewald and J. Speth, Phys. Lett. 52B, 295 (1974).
[5]G. F. Bertsch, Phys. Rev. Lett. 31, 121 (1973); G. F. Bertsch and S. F. Tsai, Phys. Rep. 18C, 126 (1975).
[6]A. Schwierczinski *et al.*, Phys. Lett. 55B, 171 (1975).
[7]N. Marty *et al.*, Nucl. Phys. A238, 93 (1975).
[8]T. Kishimoto *et al.*, Phys. Rev. Lett. 35, 552 (1975); D. H. Youngblood *et al.*, to be published.
[9]R. Ligensa and W. Greiner, Nucl. Phys. A92, 673 (1967).
[10]D. Zawischa and J. Speth, Phys. Lett. 56B, 225 (1975).
[11]W. Ogle, S. Wahlborn, R. Piepenbring, and S. Fredriksson, Rev. Mod. Phys. 43, 424 (1971).
[12]P. Koldewijn, private communication.
[13]R. N. Oethberg *et al.*, Nucl. Phys. A219, 543 (1974).
[14]D. G. Burk and B. Elbek, K. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 36, No. 6 (1967).
[15]R. C. Greenwood and C. W. Reich, Nucl. Phys. A223, 66 (1974).
[16]E. C. Halbert, J. B. McGrory, G. R. Satchler, and J. Speth, Nucl. Phys. A245, 189 (1975).

Population of High-Lying Three-Nucleon-Cluster States in ^{19}F and ^{19}Ne†

M. Hamm, C. W. Towsley, R. Hanus, K. G. Nair, and K. Nagatani
Cyclotron Institute and Physics Department, Texas A & M University, College Station, Texas 77843
(Received 24 November 1975)

The analog reactions ^{16}O(^{10}B, ^{7}Li)^{19}Ne and ^{16}O(^{10}B, ^{7}Be)^{19}F at 100 MeV have been utilized to study high-excitation, three-nucleon-cluster states in ^{19}Ne and ^{19}F. Deformed-model calculations have been made in order to predict the energies of such high-lying states in terms of rotational bands with one or more particles in the fp shell. These show that the high-lying levels seen in the data can be explained by $(sd)^2(fp)^1$ and $(fp)^3$ configurations outside an ^{16}O core.

The mass-19 nuclei, particularly ^{19}F and ^{19}Ne, are among the most extensively studied in the light-mass region, both experimentally and theoretically. However, these studies have mainly concentrated on the low-lying positive- and negative-parity states which are now well understood in terms of "bands" arising from $(sd)^3$ and $(p)^{-1}\times(sd)^4$, $(p)^{-3}(sd)^6$, etc. configurations about an ^{16}O core. It has now become possible to explore more exotic configurations with one or more nucleons in higher shells by using heavy-ion-induced multinucleon transfer reactions. It has been well established[1,2] that such reactions tend to enhance high-spin transitions to high excitations. Furthermore, the states populated can be explained in terms of the nucleons being transferred as a cluster into configurations with maximum spatial symmetry.

The present study utilizes ^{10}B-induced three-nucleon transfer reactions on ^{16}O to populate exotic states in the high-excitation region which could have up to three nucleons in the $0f$-$1p$ shell, leaving the sd shell partially or even totally vacant. Since there is no theoretical information available for such states, a simple rotational model[3] has been used to predict energies of excited bands in ^{19}F based on removing one nucleon from various excited bands in ^{20}Ne. The results, as will be discussed, show that bands based on $(sd)^2(fp)^1$ and $(fp)^3$ configurations outside ^{16}O can start at surprisingly low excitations and can account for the high-lying unknown levels seen in the data.

The experimental study was performed using a 100-MeV ^{10}B beam from the Texas A&M University cyclotron and an ^{16}O gas target. Reaction products were detected and identified by a standard ΔE-E solid-state counter telescope. The typical energy resolution in the ^{7}Li and ^{7}Be channels was 250–300 keV. Energy calibrations were obtained from known transitions in various outgoing channels. The resulting uncertainty for excitation energies in the high-excitation region is ± 100 keV.

Figure 1 shows the analog spectra obtained for ^{19}F and ^{19}Ne. Below 8 MeV only the $\frac{9}{2}^+$ and $\frac{13}{2}^+$ members of the ground-state (g.s.) bands are populated strongly as a result of the spin selectivity of the reactions. The direct-transfer nature of the reactions is evident from the fact that the high-spin members of the $K^\pi = \frac{1}{2}^-$ band, arising from a $0p$-shell hole, are seen only very weakly. The weak population of the low-spin members of the g.s. band can be explained by applying the semiclassical theory due to Brink.[1,4] The relative transition strengths for the known members of the g.s. band, calculated assuming cluster transfer and using SU(3) (6,0)-symmetry

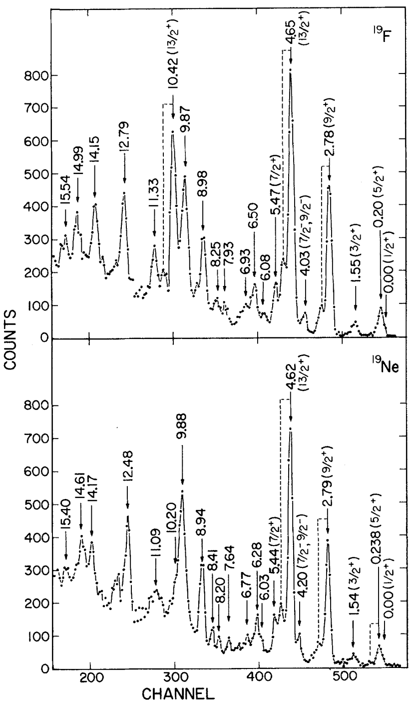

FIG. 1. Energy spectra for the (^{10}B, ^{7}Be) and (^{10}B, ^{7}Li) reactions on ^{16}O at 10.8°. Known states are indicated by spins, and ejectile excitations are indicated by dashed lines. Absolute cross sections for the strong peaks are on the order of 0.1 mb/sr (that of the $\frac{13}{2}^+$ 4.65-MeV level in ^{19}F, for example, is 0.15 mb/sr ± 20%).

predictions for the final-state spectroscopic amplitudes,[5,6] are in quite good agreement with the data. Spectroscopic amplitudes for the projectile breakup into ^{7}Be + t were taken from Kurath and Millener.[7]

In addition to the known members of the g.s. band, shell-model calculations[5,6,8] predict the existence of two more states having large overlaps with the leading SU(3) (6,0) representation. An $\frac{11}{2}^+$ state with ~40% to 60% of the $\frac{11}{2}^+$ (6,0) strength and a second $\frac{13}{2}^+$ state with ~20% to 40% of the $\frac{13}{2}^+$ strength are predicted to lie around 9 to 10 MeV in excitation. A study[9] of ^{16}O(α,p) suggested that these states be assigned to levels seen in the data at 8.9 and 10.5 MeV, respectively. In the present data, strong transitions are seen at 8.98 and 10.42 MeV. The semiclassical calculation of the transition strength indicates that the strength of the 8.98-MeV level is consistent with an $\frac{11}{2}^+$ assignment. The 10.42-MeV level has more than twice as much strength as would be expected for the $(\frac{13}{2}^+)_2$ state. However, Tserruya *et al.*[10] saw a doublet of states at 10.32 and 10.44 MeV, indicating that the present data may contain an unresolved doublet. Thus, a $\frac{13}{2}^+$ level at ~10.4 MeV is still consistent with both the data and the semiclassical strength predictions. More recent studies[11] involving γ-decay schemes of levels in this excitation region indicate that the $(\frac{13}{2}^+)_2$ assignment at 10.42 MeV is almost certain, but none of the levels seen around 9 MeV has the correct behavior for an $\frac{11}{2}^+$ state with a large component of the (6,0) symmetry. Thus, the location of the bulk of the $\frac{11}{2}^+$ (6,0) strength remains in question; however, a possible explanation will be discussed below.

The levels indicated by spin in the ^{19}Ne spectrum have already been established[10,12] as the analogs of the appropriate g.s. band members in ^{19}F. The present data show that these pairs of states have equal yields, within statistical errors, as expected. Other analog pairs which can be assigned on the basis of equal yields and similar energies are as follows: 8.98 (8.94), 11.33 (11.09), 12.79 (12.48), 14.15 (14.17), 14.99 (14.61), and 15.54 (15.54) MeV in ^{19}F (^{19}Ne). It appears at first that the analog of the 10.42-MeV level in ^{19}F is missing in ^{19}Ne. However, the total yield from 8 to 12 MeV is the same in each spectrum, indicating a broadening of one level in ^{19}Ne. Broadening in ^{19}Ne is even more evident from a comparison of the 11.33-MeV level in ^{19}F to the 11.09-MeV level in ^{19}Ne. This can be explained by the differences in proton decay from ^{19}F and ^{19}Ne in this region, which is above the proton threshold for both nuclei. ^{19}Ne can proton decay to ^{18}F where there are several low-lying, high-spin states available. ^{19}F, on the other hand, can proton decay only to the 0^+ g.s. of ^{18}O. Calculations of decay widths, assuming Coulomb penetrabilities and reduced widths of less than 10% of the Wigner limit, indicate that a level with spin $\leq \frac{13}{2}^-$ or $\leq \frac{11}{2}^\pm$ at 10 or 11 MeV would be broadened considerably (500 keV or more) in ^{19}Ne as opposed to ^{19}F. The observation or nonobservation of broadening, therefore, can be an important clue in limiting the possible spins for a level in the high-excitation region. Returning to the problem of locating the analog of the ^{19}F $(\frac{13}{2}^+)_2$ level, a $\frac{13}{2}^+$ level at ~10 MeV in ^{19}Ne is expected to have a small decay width (< 100 keV). Thus the only plausible explanation is that the 9.88-MeV peak in ^{19}Ne contains the unresolved analogs of the 9.87-MeV level and the $\frac{13}{2}^+$ state contained in the 10.42-MeV level of ^{19}F. The underlying broadened level in ^{19}Ne would then correspond to the other state in the 10.42-MeV peak, which must have a spin of $\frac{13}{2}^-$ or $\frac{11}{2}^\pm$ according to the decay widths and semiclassical transition strengths at that excitation energy. It now appears possible that the missing $\frac{11}{2}^+$ state is the other member of the 10.42-MeV doublet in ^{19}F. The same considerations limit the spin of the 11.33-MeV level in ^{19}F (and the corresponding 11.09-MeV level in ^{19}Ne) to either $\frac{13}{2}^-$ or $\frac{11}{2}^{\pm}$.

With the possible exception of the $\frac{11}{2}^+$ strength, the bulk of the SU(3) (6,0) strength is exhausted in the positive-parity states discussed above. Since these reactions populate mainly states with maximum spatial symmetry, the other high-lying peaks are assumed to arise from $(sd)^2(fp)^1$, $(sd)^1\times(fp)^2$, or $(fp)^3$ configurations. These would presumably belong to the leading SU(3) representations (7,0), (8,0), and (9,0), respectively. A full shell-model calculation for such configurations is difficult and has not been attempted because of lack of knowledge about the proper residual interactions to use. However, energies of bands with one or more particles in the *fp* shell can be easily calculated with a deformed, rotational-particle coupling model, including Coriolis mixing terms.[3] Such a model has been used successfully by a number of authors[13] to describe the properties of the $K^\pi=\frac{1}{2}^+$ g.s. bands in ^{19}F and ^{19}Ne based on a hole in the ^{20}Ne g.s. band [see Fig. 2, column *a* and caption]. In the present study, a similar calculation was performed in which the moment-of-inertia parameters were varied to give the best energy fit [see Fig. 2, column *b*]. A shell-model calculation from Wildenthal and Chung[8] is shown for comparison.

The calculations were then extended to predict energies of bands with one or more particles in the (fp) shell. The lowest-energy configuration should be an $(sd)^2(fp)^1$, $K^\pi=\frac{1}{2}^-$ (7,0) band based on an $N=2$ hole in the ^{20}Ne $K^\pi=0^-$ (9,0) band starting at 5.79 MeV. The moment of inertia parameter, $\hbar^2/2\mathscr{I}$, was taken to be 0.109 MeV from the ^{20}Ne band with a deformation δ of 0.5. The $N=2$ single-particle energies were taken from Garrett and Hansen,[13] while the energy of the $\frac{1}{2}^-$ [330] orbital relative to the $\frac{1}{2}^+$ [220] orbital was fixed at 5.79 MeV from the position of the $K^\pi=0^-$ band head in ^{20}Ne. The results are shown in Fig. 2, column *b*.

There is some experimental evidence which tends to support the energies calculated for the first three states in the (7,0) band. Among several states seen in an ^{18}O(^{3}He,*d*) study,[14] three levels at 6.095, 6.792, and 6.93 MeV were assigned to be $l=1$, $l=1$, and $l=3$ transfers, respectively, from the angular distributions, implying that these states could have $(sd)^2(fp)^1$ structures. Weak transitions at 6.08 and 6.93 MeV in ^{19}F are also seen in the present experiment and are indicated by the dashed lines in Fig. 2, column *c*. Because of the resolution, the level at 6.8 MeV could not be resolved. As is evident, the spins and predicted energies of the $\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{7}{2}^-$ members are in quite good agreement with the data.

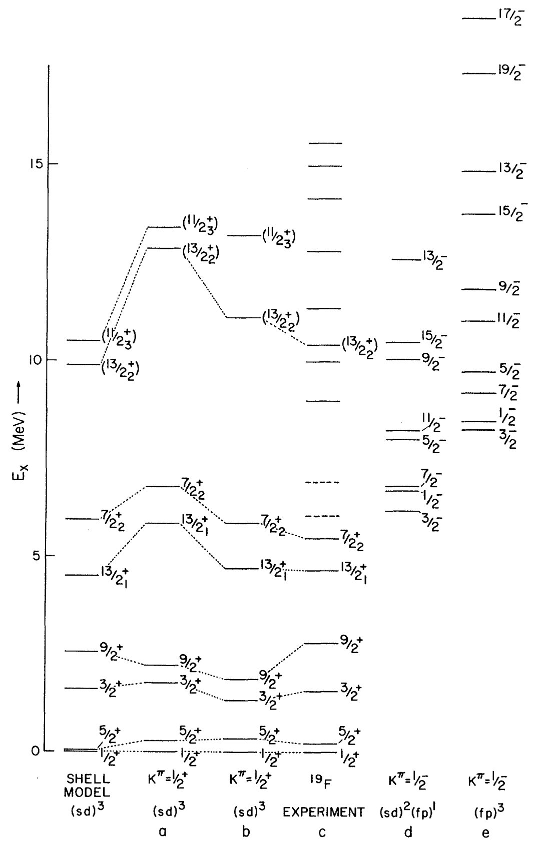

FIG. 2. Comparison of various calculations with the present data. Column *a*, Coriolis mixing results for g.s. band from Garrett and Hansen (Ref. 13); column *b*, Coriolis mixing results of present study (all parameters the same as Ref. 13 except with $\hbar^2/2\mathscr{I}_1=0.171$ MeV); column *c*, levels seen in the present study for ^{19}F; the dashed levels at 6.08 and 6.93 MeV are weak transitions (see text); columns *d* and *e*, energies predicted from the present study for $(sd)^2(fp)^1$ and $(fp)^3$ $K^\pi=\frac{1}{2}^-$ bands, respectively, in ^{19}F (see text).

Since the reaction dynamics favor spins $\leq\frac{11}{2}$ in this region, there are more high-lying levels in the data than can be accounted for by just one band. It is known[15] that the $(fp)^4$ (12,0) band in ^{20}Ne is lower in energy than the $(sd)^2(fp)^2$ (10,0) band, hence it was assumed that an $(fp)^3$ (9,0) band in ^{19}F would be lower in energy than the

(8,0) band. It was found that the Coriolis mixing is small for these higher bands; therefore the adiabatic rotational energy formula including decoupling term[3] was used to calculate the band energies, assuming $\hbar^2/2\mathcal{J}=0.110$ MeV and $\delta=0.75$ from the (12,0) band in ^{20}Ne. The other piece of information needed was the energy difference for three nucleons in the $\frac{1}{2}^-$ [330] orbit at 0.75 deformation relative to three nucleons in the $\frac{1}{2}^+$ [220] orbit at 0.5 deformation, in order to fix the energy of the $(fp)^3$ band head relative to the ^{19}F ground state. The single-particle value was fixed at 2.75 MeV from an extrapolation of binding energies of nucleons in a deformed Woods-Saxon well as referenced by Garrett *et al.*[16] The results, as shown in Fig. 2, column *e*, indicate that such a band could account for the rest of the high-lying transitions in the data.

In summary, the present reactions selectively populate known high-spin states belonging to $(sd)^3$ configurations. In addition, strong transitions are seen in the region of excitation above 8 MeV. The deformed-model calculations can qualitatively account for these high-lying levels in terms of high-spin members of two rotational bands in ^{19}F having $(sd)^2(fp)^1$ and $(fp)^3$ configurations. It is hoped that this work will prompt more detailed theoretical studies of such states in this mass region in order to test the various models which have been successful in describing the more well-known conventional configurations. It is conceivable that a new approach will be necessary, such as an extension of the cluster model[17] used to describe three-nucleon states in mass 15.

The authors wish to thank D. Strottman, D. Kurath, and K. Allen for useful discussions and valuable information. One of the authors (M.H.) also wishes to thank T. Kishimoto for suggesting the deformed-model calculations.

†Work supported in part by the National Science Foundation.

[1]N. Anyas-Weiss *et al.*, Phys. Rep. 12C, 201 (1974).
[2]K. Nagatani *et al.*, Phys. Rev. Lett. 31, 250 (1973).
[3]M. E. Bunker and C. W. Reich, Rev. Mod. Phys. 43, 348 (1971).
[4]D. M. Brink, Phys. Lett. 40B, 37 (1972).
[5]D. W. O. Rogers, Nucl. Phys. A207, 465 (1973).
[6]D. Strottman, private communication.
[7]D. Kurath and D. J. Millener, Nucl. Phys. A238, 269 (1975).
[8]B. H. Wildenthal and W. Chang, unpublished.
[9]A. Van der Woude *et al.*, in Proceedings of the Second International Conference on Clustering Phenomena in Nuclei, University of Maryland, College Park, Maryland, April 1975 (to be published).
[10]I. Tserruya *et al.*, Nucl. Phys. A235, 75 (1974).
[11]K. Allen, private communication.
[12]A. D. Panagiotou and H. E. Gove, Nucl. Phys. A196, 145 (1972); J. D. Garrett *et al.*, Phys. Rev. C 5, 682 (1972); H. G. Bingham and H. T. Fortune, Phys. Rev. C 6, 1900 (1972).
[13]J. D. Garrett and O. Hansen, Nucl. Phys. A188, 139 (1972), and references therein.
[14]C. Schmidt and H. H. Duhm, Nucl. Phys. A155, 644 (1970).
[15]D. Strottman *et al.*, Phys. Lett. 47B, 16 (1973).
[16]J. D. Garrett *et al.*, Nucl. Phys. A164, 449 (1971).
[17]B. Buck, C. Dover, and J. P. Vary, Phys. Rev. C 11, 1803 (1975); B. Buck, private communication.

Experimental Proof for Binary Mass Division of a Composite System with $A \approx 80$

P. Braun-Munzinger, C. K. Gelbke, J. Barrette,* B. Zeidman,† M. J. LeVine,‡
A. Gamp, H. L. Harney, and Th. Walcher
Max-Planck-Institut für Kernphysik, D-69 Heidelberg 1, Germany
(Received 30 December 1975)

The reaction ^{32}S + ^{50}Ti is studied at 140-MeV laboratory energy. By means of a multiparameter coincidence experiment in which two particles are detected and identified, the existence of a fissionlike binary mass division of a composite system with mass $A \approx 80$ is proved. The reaction is accompanied by the evaporation of about three nucleons.

Binary mass divisions, such as fission, are well established for heavy nuclei and many detailed descriptions of these processes have been published.[1] Heavy-ion–induced binary mass divisions have been observed and adequately understood in terms of fission for systems of masses as low as $A \approx 130$.[2] Attempts to establish the existence of binary mass divisions in light nuclear systems ($A \lesssim 70$) did not yield positive results.[3] For masses between these limits the situation is not well defined and the data have been discussed in terms of "deep inelastic," "highly relaxed,"