[7]K. T. R. Davies and R. J. McCarthy, Phys. Rev. C 4, 81 (1971). This paper contains an extensive set of references relating to Brueckner-Hartree-Fock calculations and to occupation factors. From this work we see that the modification of the occupation probabilities due to short-range correlations is only weakly orbit dependent.

[8]We are assuming that the matrices $\gamma_{k,j}$ and

$$\epsilon_{k,l} = t_{k,l} + \sum_{j,j'} \langle kj|K|lj'\rangle \gamma_{j',j}$$

may be simultaneously brought to diagonal form. The exact result is $C_i = \sum_k \epsilon_{i,k}\gamma_{k,i}$; in Ref. 3 it is shown that the *matrix product* $\epsilon\gamma$ may be brought to diagonal form.

Reaction ^{12}C(^{14}N, ^{6}Li)^{20}Ne and the Structure of the Upper $K = 0^+$ Bands

K. Nagatani and M. J. Le Vine
Brookhaven National Laboratory, Upton, New York 11973*

and

T. A. Belote
Massachusetts Institute of Technology,† Cambridge, Massachusetts 02139

and

A. Arima
State University of New York,‡ Stony Brook, New York 11790
(Received 27 July 1971)

The reaction ^{12}C(^{14}N, ^{6}Li)^{20}Ne was studied at 60 MeV and forward-angle reaction data to states of ^{20}Ne were obtained. Different rotational bands were populated with different strengths consistent with cluster transfer processes. The previously questioned structure of the $K = 0^+$ bands starting near 7 MeV is discussed and a new classification for the bands is proposed.

Studies of transfer reactions using heavy ions have become increasingly of interest. In this Letter, the eight-nucleon transfer reaction leading to states in ^{20}Ne is reported. This nucleus is of special interest in the testing of many nuclear structure models and has been the subject of a great deal of study.[1,2]

The lower rotational bands of ^{20}Ne have been extensively studied. However, while the structure of the $K = 0^+$ bands starting near 7-MeV excitation has been the subject of much theoretical interest, little experimental data exist which provide evidence in determining their characteristics.

Because of the expected collective nature of these states they can best be investigated by cluster transfer reactions. The α transfer reactions, ^{16}O(^{6}Li, d)^{20}Ne and ^{16}O(^{7}Li, t)^{20}Ne,[3] have provided vital information about these states. These reactions excite levels having four particles coupled to an ^{16}O core. More complicated states such as those having holes in the $1p$ shell are expected to be excited by the transfer of eight nucleons to ^{12}C. Therefore, the reaction ^{12}C(^{14}N, ^{6}Li)^{20}Ne was studied. A similar experiment has been recently reported by Marquardt *et al.*,[4] but little analysis was made by those authors.

A ^{14}N^{5+} beam was obtained from the Brookhaven tandem facility using a direct-extraction negative-ion source. The incident energy was 60.0 MeV, and a beam of about 1 μA charge current was utilized. A nominal 20-μg/cm^2 natural carbon target was used. The ^{6}Li spectra were obtained using a conventional ΔE-E solid-state counter telescope having an angular resolution of 0.5°. The particle identification and energy calibration was checked by observing recoil ^{6}Li from a ^{6}Li target. The overall laboratory energy resolution was about 300 keV. Spectra were obtained at laboratory angles of 11.0°, 15.0°, 20.0°, 25.0°, 30.0°, and 40.0°. The 20.0° spectrum is shown in Fig. 1 where the peaks are identified by their excitation energies and J^π's. An absolute cross-section scale accurate to about a factor of two was determined; for example, the center-of-mass cross section of the 1.63-MeV (2^+) level at 20.0° (see Fig. 1) was 11 μb/sr.

In the present reaction we expect the mechanism to be dominantly a direct process. Experimentally this assumption is supported by the observation of the smaller yield of ^{7}Li relative to ^{6}Li by about a factor of ten,[5] while a ratio of the decay strengths from the compound state in ^{26}Al is cal-

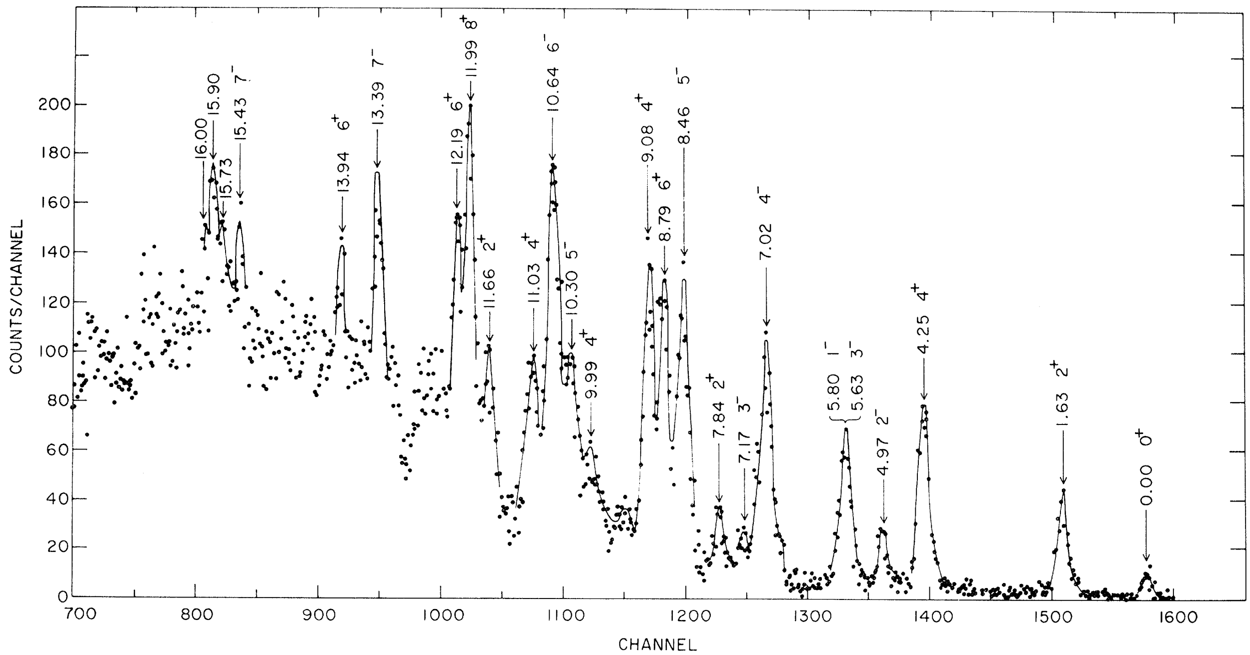

FIG. 1. Energy spectrum at 20.0°. Peaks are identified with the previously known excitation energies with J^{π}'s. The absolute cross sections can be calculated by knowing that for the 1.63-MeV state (11 μb/sr in center-of-mass cross section).

culated to be about 2 ($l=0$ decay) to 5 ($l=10$ decay) using Coulomb penetrabilities with Wigner limits for their reduced widths. Also the angular distributions were observed to be forward peaked consistent with ordinary direct processes. The general features in the present data are very similar to the reaction data of Ref. 4, while the incident energies were 60 and 52 MeV, respectively. Furthermore, such a relatively large cross section for the (^{14}N, ^{6}Li) reaction would be difficult to understand if the reaction was mainly compound, since a simple statistical argument should give an extremely small probability for the compound system decay into ^{6}Li plus ^{20}Ne.

In the absence of a theoretical treatment of the reaction mechanism, we have analyzed the data to obtain transition strengths by the following procedure. In general, the differential cross section can be written as

$$\frac{d\sigma}{d\Omega} \propto \frac{k_f}{k_i}\frac{1}{2J_i+1}\sum_{m_i, m_f}|T|^2,$$

where the notation is standard. The quantity R defined by

$$R \equiv (k_i/k_f)\int(d\sigma/d\Omega)d\Omega$$

represents the integrated cross section with the momentum phase-space factor taken out. The transition amplitude T is a function of $\vec{k}_i$ and $\vec{k}_f$, in general, which in turn is a function of angle. Therefore, R does not exactly correspond to a transition strength; but with a lack of reaction-mechanism theory, this quantity should be of interest. We have calculated experimental values of R for the analyzable peaks by approximating it as

$$R = \sum \frac{k_i}{k_f}\frac{d\sigma}{d\Omega}\sin\theta,$$

where the summation extends over the six measured angles. The values obtained correspond to the strengths in the forward direction, thus precluding major contributions from the process in which a ^{6}Li transfers from ^{12}C to ^{14}N. Since the spin statistical factor has not been taken out of R, it is interesting to compare R with $2J_f+1$, although spin dependence in T destroys the exact meaning of the procedure. It should also be mentioned that this procedure does not preclude a compound mechanism, but deviation from the $2J_f+1$ rule indicates the different structure involved in residual states. This comparison is shown in Fig. 2. The predicted $2J_f+1$ strengths are drawn as rectangular histograms normalized to the 4.25-MeV state; the previously known band classification is also shown.[1]

The following is observed. The ground-state band is populated almost exactly with strengths

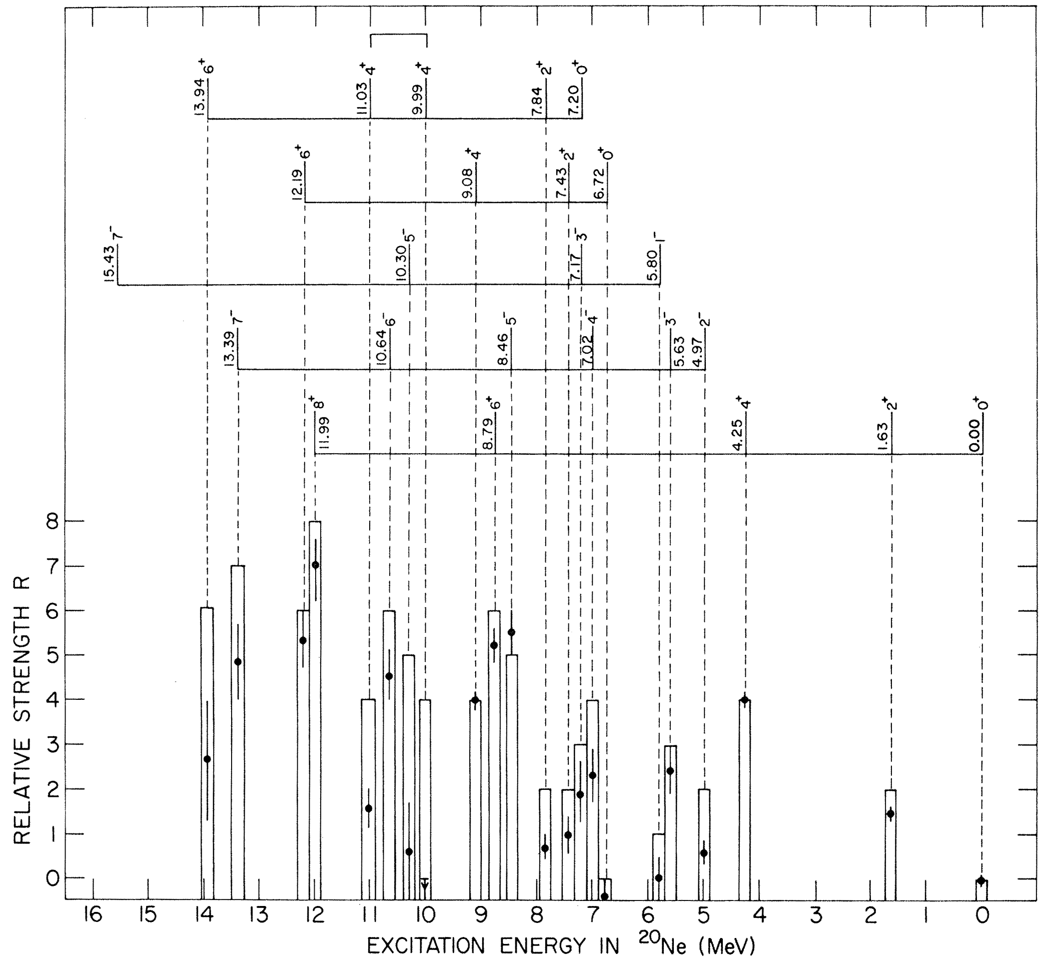

FIG. 2. Extracted strength R and the rotational band classification. Points are the experimentally obtained R's, while histograms correspond to $2J_f+1$ values normalized at the 4.25-MeV state. Strengths for the states at 5.63, 5.80, 7.02, 7.17, 7.84 MeV were taken from Ref. 5. The 7.17- and 7.20 MeV states are still unresolved. We suggest different classifications for the upper $K=0^+$ bands as described in the text.

proportional to $2J_f+1$, suggesting that the procedure is justified. The $K=2^-$ (4.97-MeV) band is populated in the same fashion but possibly with slightly weaker strengths. In the $K=0^-$ (5.80-MeV) band, the 10.30-MeV (5^-) member was weakly excited although the 5.80-MeV (1^-) and 7.17-MeV (3^-) members have stronger strengths. The $K=0^+$ (6.72-MeV) band population is strong, while the $K=0^+$ (7.20-MeV) band is weakly populated. In particular, the 4^+ state at 9.99 MeV was weakest. The weakly populated state at 11.03 MeV is also 4^+ and it may belong to this band. A part of the result shown (the unresolved peaks at 5.63, 5.80, 7.02, 7.17, and 7.43 MeV) were extracted incorporating a high-resolution experiment.[5]

The shell-model calculations[2] show that the ground-state band belongs to the SU(3) classification (8, 0), which contains a large probability of α clusters. The strong population for this band, therefore, is easily explained. The calculation also predicts a $K=0^+$ excited band belonging to the $(sd)^4$ configuration starting at about 7-MeV excitation. Since this band contains largely the SU(3) symmetry (4, 2) and this symmetry has very little probability of α clusters, the members of this band can be excited by neither the α transfer reaction on ^{16}O nor by the two-α transfer reaction on ^{12}C. On the other hand, eight-particle, four-hole (8p-4h) states can be excited by transferring two α's to ^{12}C, while they are not excited by transferring one α to ^{16}O. Several theoretical considerations[2,6,7] predict the 8p-4h states with a 0^+ band head at about 7 MeV. According to the SU(3) model, the most deformed 8p-4h states belong to the representation (8, 8), which contains $K=0^+, 2^+, \cdots, 8^+$. It might be expected that the

$K=2^+$ band can also be excited by the two-α transfer reaction on ^{12}C. The present result strongly suggests that the 9.08-MeV (4^+) and 12.19-MeV (6^+) states belong to the 8p-4h $K=0^+$ band. The indication of the 0^+ and 2^+ states of this band, however, is not conclusive. It has been suggested recently[8] from the study of the reaction ^{12}C(^{12}C, α)^{20}Ne together with the previously known α-particle widths that the 6.72-MeV (0^+) and 7.43-MeV (2^+) states belong to the $(sd)^4$ configuration, and 7.20-MeV (0^+) and 7.84-MeV (2^+) states are the members of the 8p-4h $K=0^+$ band. The 9.99-MeV (4^+) state has a very small yield, which indicates that this state also has the configuration $(sd)^4$. The 11.03-MeV (4^+) and 13.94-MeV (6^+) states were populated, though the strengths were modest. It is worth mentioning that the calculation by Arima and Strottman[2] predicts the 8p-4h $K=2^+$ band in this energy region.

The excitation of the $K=2^-$ band built on the 4.97-MeV (2^-) state is clearly observed in the present reaction. In this band, every other state has unnatural parity and thus can be populated by transferring an excited ^{8}Be* (2^+). The levels with natural parity, on the other hand, can be excited by transferring ^{8}Be in the ground state and/or in the 2^+ excited state. The difference should explain why excitations of the 2^- and 4^- states are relatively weaker than those of the 1^- and 3^- states.[9]

The $K=0^-$ band built on the 5.78-MeV (1^-) state is usually assumed to have the SU(3) symmetry (9, 0) in which three nucleons are in the (sd) shell and the fourth nucleon is in the (pf) shell. If this interpretation is correct, the population of this band should be as strong as that of the ground-state band in the one- and two-α transfer reactions. In fact, the α transfer reaction on ^{16}O demonstrated such characteristics.[3] It was, however, observed here that the present reaction excited this band weakly; in particular, the population of the 10.30-MeV (5^-) state was extremely small. This is inexplicable and remains for further theoretical and experimental studies.

We wish to thank Dirk Schwalm for his experimental assistance.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Work supported in part by the U. S. Atomic Energy Commission, Contract No. AT(30-1)2098.

‡Work supported in part by the U. S. Atomic Energy Commission.

[1]J. A. Kuehner and E. Almqvist, Can. J. Phys. 45, 1605 (1967); W. E. Hunt, M. K. Mehta, and R. H. Davis, Phys. Rev. 160, 782 (1967).

[2]Y. Akiyama, A. Arima, and T. Sebe, Nucl. Phys. A138, 273 (1969); A. Arima and D. Strottman, Nucl. Phys. A162, 423 (1970).

[3]R. Middleton, in *Proceedings of the International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, July 1969,* edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 263.

[4]N. Marquardt, W. Von Oertzen, and R. L. Walter, Phys. Lett. 35B, 37 (1971).

[5]L. L. Lynn, W. H. Moore, A. Sperduto, and T. A. Belote, private communication of measurements using the Massachusetts Institute of Technology multigap spectrograph.

[6]A. Arima, V. Gillet, and J. Ginocchio, Phys. Rev. Lett. 25, 1043 (1970).

[7]S. N. Tewari and G. L. Struble, Phys. Rev. C 1, 1156 (1970).

[8]R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Rev. Lett. 27, 950 (1971). We wish to thank these authors for providing us with their results prior to publication.

[9]K. Nagatani, Phys. Lett. 35B, 286 (1971).

Selective Population of Highly Excited States Seen in the Reaction ^{12}C(^{16}O,p)^{27}Al†

E. R. Cosman, A. Sperduto, W. H. Moore, T. N. Chin, and T. M. Cormier
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 7 July 1971)

The reaction ^{12}C(^{16}O, p)^{27}Al has been studied at $E_{\rm lab}$(^{16}O) = 36 and 60 MeV with high resolution. Narrow levels of ^{27}Al are seen in the region of E_x = 13 to 20 MeV in both measurements, and their locations suggest that the reaction is selectively sampling high-spin states in the region of the yrast line.

In this Letter we report the existence of narrow levels at high excitation in ^{27}Al seen with the reaction ^{12}C(^{16}O, p)^{27}Al, which suggests that this type of reaction may be an effective tool to reveal new and unusual nuclear-structure information. The results are part of a wider program of