$K=2^+$ 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.

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

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The reaction ^{12}C(^{16}O,p)^{27}Al has been studied at $E_{\rm lab}(^{16}{\rm O})=36$ 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 high-resolution measurements of light charged particles emitted from heavy-ion-induced reactions using the Brookhaven National Laboratory (BNL) double model MP tandem accelerators and the Massachusetts Institute of Technology multiple-gap spectrograph which has recently been moved to BNL.[1]

Initial exploration of the reactions $^{12}C(^{16}O,p)^{27}Al$, $^{12}C(^{16}O,d)^{26}Al$, $^{12}C(^{16}O,t)^{25}Al$, and $^{12}C(^{16}O,\alpha)^{24}Mg$ was done at Los Alamos Scientific Laboratory two years ago with $E(^{16}O) = 50$ MeV, particle telescope detectors, and 300-keV resolution.[2] Prominent level structure superimposed on the smooth evaporation background yield was seen for each of these channels. Higher-resolution studies using magnetic spectrographs have since been performed for the proton channel[3] and α channel[4] showing strong transition strengths to a few highly excited states. Here, more extensive data on $^{12}C(^{16}O,p)^{27}Al$ are reported to elucidate further the nature of these states seen in Ref. 3 and the reaction mechanism involved.

Figure 1 shows two $\theta_{lab} = 7.5°$ spectra from $^{12}C(^{16}O,p)^{27}Al$ taken at $E_{lab}(^{16}O) = 36$ and 50 MeV. The target was a self-supporting carbon foil of about 15–20 $\mu g/cm^2$ thickness. The overall resolution is about 140 keV. Also shown, superimposed on the upper figure, are the data of Ref. 3 with $E(^{16}O) = 36$ MeV, $\theta_{lab} = 10°$, where the resolution was about 80 keV because of a thinner target. The remarkable features of the data are the strong proton peaks $[(d\sigma/d\Omega)_{c.m.} \simeq \frac{1}{2}$ mb/sr at 7.5°] at high excitations where the total level density is of the order of 10 000 levels per keV, and the relative absence of yield to states at lower excitations. Their widths are consistent

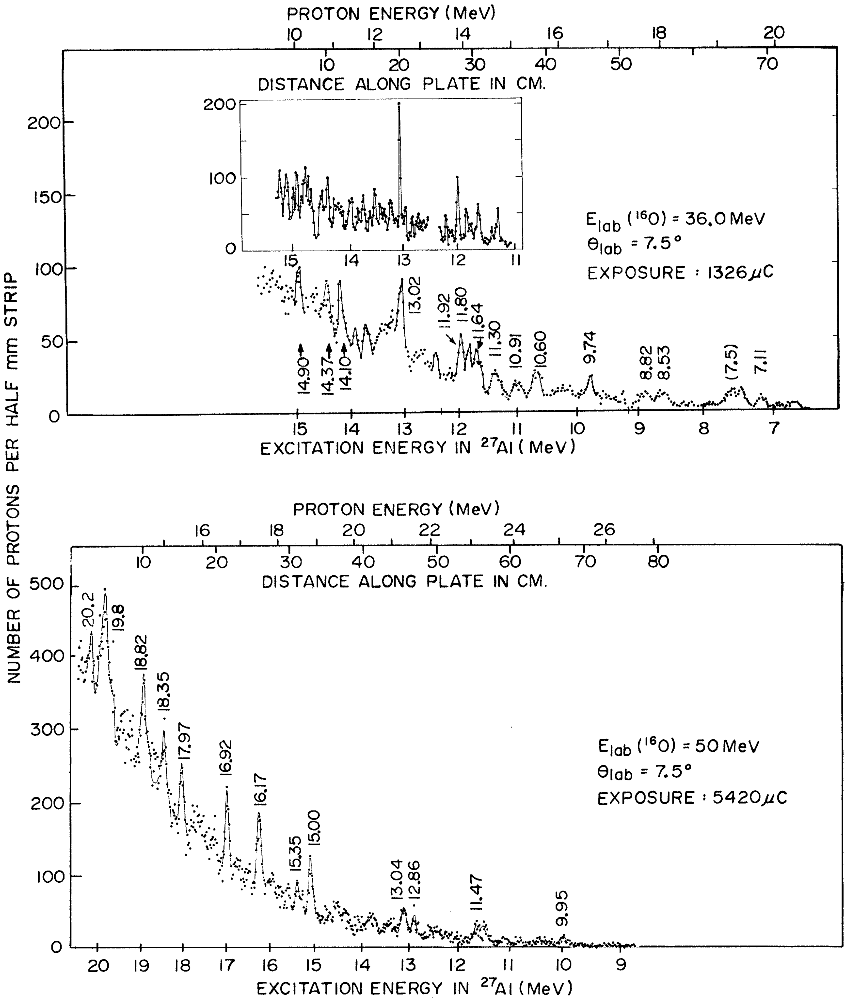

FIG. 1. The spectra of $^{12}C(^{16}O,p)^{27}Al$. The excitation energies for the peaks shown are expected to be accurate to about ±40 keV. The insert (showing data from Ref. 3) is a measurement done with a thinner target and correspondingly better resolution.

with the resolution, suggesting that they correspond to single levels with widths <50 keV. Further, the marked upward shift in excitation energy of the lowest of these states with increased bombarding energy is striking. No previous information on these levels is known from the literature.

Figure 2 displays the forward angular distributions for the most prominent groups seen in the 50-MeV experiment and for the largest group seen in the 36-MeV experiment. They are all forward peaked, as is the underlying evaporation background, and a variety of patterns is evident. No obvious details of the shapes distinguish the 36- from the 50-MeV experiments. The absolute cross-section scale is only approximate ($\pm 40\%$) since carbon buildup on the target during the exposure was substantial, and the initial target thickness was crudely determined by an α thickness gauge.

The appearance of these narrow groups on the evaporation proton background suggests that important nonstatistical nuclear-structure information can be obtained from such selective heavy-ion–induced reactions. Qualitatively, there are three limiting types of reaction mechanisms that could be involved: (1) The process proceeds through compound-nucleus formation which is governed only by transmission factors and statistical level densities; in this case, the residual ^{27}Al states should be enhanced simply because of high spin. (2) It is a direct reaction. If so, the final states would be of an exotic quasimolecular character involving a ^{12}C and ^{15}N cluster. (3) An intermediate structure in ^{28}Si is formed preferentially. This would mean that the final ^{27}Al states would be of some special intrinsic form related to the intermediate structure. In reality, one or more of these may be contributing. The same questions of mechanism are presently being intensely studied for the similar case of ^{12}C(^{16}O, α)^{24}Mg and have not yet been completely resolved. The kinds of measurements that are being applied there, namely, of particle-particle and particle-γ correlations,[5] excitation functions,[6] and complete angular distributions,[7] could also be effectively studied by the reaction ^{12}C(^{16}O, p)^{27}Al in view of the large yields observed here.

Assuming a compound-nucleus mechanism, an important difference between the reactions ^{12}C(^{16}O, p)^{27}Al and ^{12}C(^{16}O, α)^{24}Mg is that the α particle can carry away substantially greater angular momentum than the proton, implying that a much stricter selection of high-spin states in the residual nucleus would be possible in the former case than in the latter. Such a selection of high-spin states may account for the shift in threshold of the strongly populated levels with

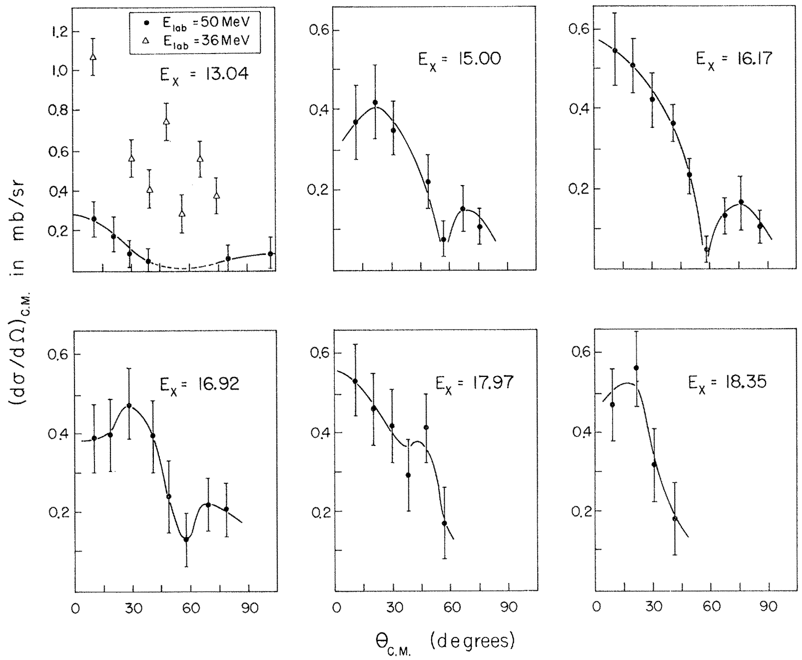

FIG. 2. Angular distributions from ^{12}C(^{16}O,p)^{27}Al for a selection of the strongest peaks seen at $E_{\rm lab}$(^{16}O) = 50 MeV. One peak at E_x = 13.04 MeV appears to be seen in both $E_{\rm lab}$ = 36- and 50-MeV exposures, and its distribution at the lower energy is also given. The solid lines are meant merely as guides to the eye.

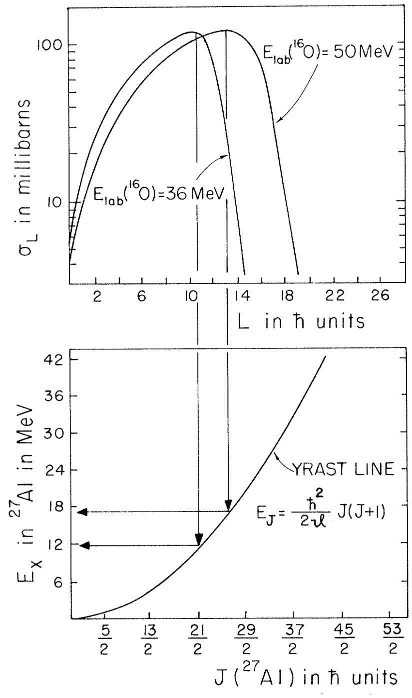

FIG. 3. The upper graph is an optical-model calculation of the reaction cross section for ^{16}O on ^{12}C showing that it peaks strongly with orbital angular momentum L. Since the proton can carry away little angular momentum, one expects a yield threshold for ^{12}C(^{16}O, p)^{27}Al at the lowest state in ^{27}Al with J approximating the most probable L, i.e., at the yrast line. In reality, the threshold would be spread by the distribution of σ_L.

increased bombarding energy mentioned above for ^{12}C(^{16}O,p)^{27}Al. This point is illustrated in Fig. 3. The upper graph shows a plot of the partial compound-nucleus–formation cross sections $\sigma_L{}^{CN}$ as a function of incoming angular momentum L for ^{16}O on ^{12}C at $E_{\mathrm{lab}}(^{16}\mathrm{O}) = 36$ and 50 MeV, or $E_{\mathrm{c.m.}} = 15.5$ and 21.5 MeV, respectively, calculated using a simple optical model.[8] It is found that 80% of the total $\sigma_{\mathrm{total}}{}^{CN}$ arises from $L = L_{\max} \pm 2\hbar$, where $L_{\max}$, corresponding to $\sigma_L{}^{\max}$, is $\simeq 10\hbar$ and $\simeq 14\hbar$ for $E_{\mathrm{lab}} = 36$ and 50 MeV, respectively. Similar calculations for protons indicate that the average angular momentum they can carry off for the energies we are considering here is strongly peaked around the average value of $\bar{l} = 1\hbar$. Thus, one expects maximum yields to states of ^{27}Al with spins J, such that $L_{\max} - \bar{l} - \frac{1}{2} \leq J \leq L_{\max} + \bar{l} + \frac{1}{2}$, i.e., within bands in the plot of E_x for ^{27}Al centered around the vertical lines of $L_{\max}$ in Fig. 3, and therefore a selective sampling of J levels above the yrast energy $E(J)$ (this refers to the energy of the lowest state with a given J), i.e., for $E_x > E(J)$. In Fig. 3, $E(J) = \hbar^2 J(J+1)/2I$, where I is the rigid-nucleus value of the moment of inertia, $I = \frac{2}{5}MR^2$. Of course, a sharp threshold in E_x for the enhanced states is not expected in reality since the angular-momentum limits are diffuse themselves. However, the qualitative feature of thresholds at about the positions expected on the basis of the rotation prediction for $E(J)$ are borne out by the data.

More detailed excitation functions and spin measurements are needed to substantiate this picture. If it is true, (heavy-ion,p) reactions would be a useful tool in locating high-spin states and the yrast line, determining associated structure parameters, and probing compound-nucleus cross sections for high partial waves. Investigation of proton and γ decays from such states would also be interesting since they should also populate high-spin daughter levels with related nuclear structure.

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