[26] J. Damgaard, C. K. Scott, and E. Osnes, Nucl. Phys. A154, 12 (1970); C. W. Wong, Nucl. Phys. A151, 323 (1970); N. Van Giai *et al.*, Phys. Lett. 35B, 135 (1971); N. Auerbach, Nucl. Phys. A229, 447 (1974).

[27] E. Friedman and S. Shlomo, Z. Phys. A283, 67 (1977).

[28] N. Auerbach, J. Hüfner, A. K. Kerman, and C. M. Shakin, Rev. Mod. Phys. 44, 48 (1972).

Evidence for the Excitation of Giant Resonances in Heavy-Ion Inelastic Scattering

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A study of the inelastic scattering of ^{12}C from ^{27}Al at 82 MeV, a bombarding energy at which deep-inelastic collisions occur, suggests the population of giant resonances in the target. This result supports the suggestion of Broglia, Dasso, and Winther regarding the mechanism of deep-inelastic collisions.

It has been proposed[1] that the excitation of giant resonances in the target and projectile may play an important role in the mechanism of deep-inelastic heavy-ion collisions. The suggested means by which kinetic energy of relative motion is converted into excitation energy involves the multiple excitation of those degrees of freedom which are strongly coupled to the target and projectile ground states (i.e., the giant resonances). These degrees of freedom may therefore be considered as "doorways" leading to deep inelastic events and thus provide a link between quasielastic and deep-inelastic collisions.

The probability that either fragment will emerge in a single giant resonance depends on the system being considered. For heavy systems,[2] such as Kr + Pb, the large energy loss observed implies a dominance of multiple excitation of the giant resonances which suggests that it is extremely unlikely that either fragment will actually emerge in a single, and therefore identifiable, giant resonance. We do not therefore expect the direct observation of giant resonances in deep-inelastic scattering of heavy systems. For light systems, however, the situation is somewhat simpler. Shorter collision times and higher excitation energies for the giant resonances combine to make it more likely that the fragments separate with one actually still in a giant resonance. These conclusions are supported by the experimental results for systems like ^{16}O + ^{27}Al, ^{12}C + ^{27}Al, etc., where the energy loss observed in deep-inelastic collisions leads to excitation energies more characteristic of single excitation of the giant resonances in the target and projectile than of multiple excitation.[3,4] The question then is whether or not the giant resonances are, in fact, selectively populated over the continuum background as implied in the model of Ref. 1.

With the above points in mind, we have studied the inelastic scattering of ^{12}C from ^{27}Al at a bombarding energy of 82 MeV. At this bombarding energy, deep-inelastic collisions form a large fraction of the total reaction cross section[3] ($\sigma_{\text{react}} \approx 1700$ mb, $\sigma_{\text{fusion}} = 1000$ mb), and earlier results[3] show that inelastic scattering of beam particles forms the major fraction of the reaction products. This Letter reports the possible observation of two giant resonances in ^{27}Al thus providing evidence in favor of the suggestion of Ref. 1. It is also, to the authors' knowledge, the first time heavy ions have been used to excite giant resonances in any nucleus.

A 400-μg/cm^2 99.7%-pure Al target was bombarded with a beam of 82-MeV ^{12}C ions from the Yale MP tandem Van de Graaff accelerator. The reaction products were detected in a ΔE-E telescope consisting of two silicon surface-barrier detectors (25 and 300 μm). This detector system was easily able to separate the different isotopes of C, and the overall energy resolution was 300 keV. Carbon build-up on the target was reduced to a negligible amount by placing a Cu plate cooled to liquid-nitrogen temperature in the close vicinity of the target. The absence of carbon on the Al was further checked by frequent runs with a carbon target to provide comparison spectra. Data were obtained in 1° steps from 15° to 25° and 5° steps thereafter to 40°.

Spectra for the reaction ^{27}Al(^{12}C, ^{12}C$'$) obtained at angles of 15°, 23°, and 30° are shown in Fig. 1. The raw data have been converted to a Q-value scale thus enabling a direct comparison of the three spectra. Transitions to the low-lying qua-

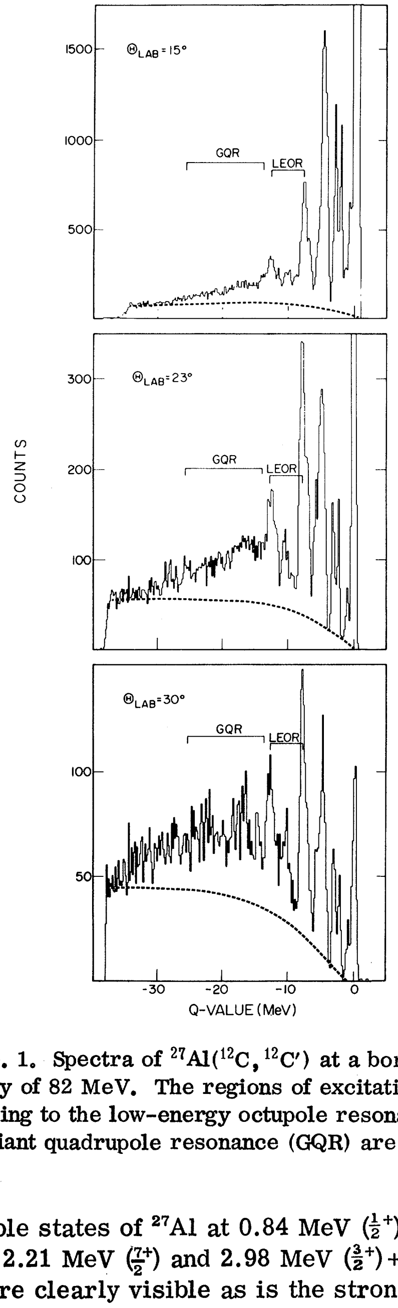

FIG. 1. Spectra of ^{27}Al(^{12}C, ^{12}C$'$) at a bombarding energy of 82 MeV. The regions of excitation corresponding to the low-energy octupole resonance (LEOR) and giant quadrupole resonance (GQR) are indicated.

drupole states of ^{27}Al at 0.84 MeV ($\frac{1}{2}^+$)+1.01 MeV ($\frac{3}{2}^+$), 2.21 MeV ($\frac{7}{2}^+$) and 2.98 MeV ($\frac{3}{2}^+$)+3.00 MeV ($\frac{9}{2}^+$) are clearly visible as is the strong transition to the 4.43 MeV (2^+) state of ^{12}C. Also clear are transitions to broad states or groups of states centered near 7.7, 10.4, and 12.8 MeV, and an excess of strength in the excitation region covering 14–26 MeV. The regions of excitation corresponding to the known[5,6] giant quadrupole resonance (GQR) and the expected location[7] of the low-energy octupole resonance (LEOR) are indicated on the figure. Although the present experiment cannot distinguish between projectile and target excitation or mutual excitation of both fragments, it is possible to assign the transitions at $Q=-7.7$, -10.4, and -12.8 MeV to excitations of ^{27}Al rather than of the projectile. This arises as a result of ^{12}C becoming particle unstable above $E_x=7.37$ MeV and all natural-parity states above this excitation energy therefore have substantial width for particle emission resulting in their decay before reaching the detector telescope. It is also possible to rule out the possibility of the above-mentioned peaks arising from mutual excitation of the target and projectile as no combinations of ^{12}C in its 2^+ state and known ^{27}Al excitations fit the measured Q values. It is possible, however, that the shoulders on the side of the 4.43- and 7.7-MeV peaks result from such mutual excitation processes.

The group at 7.7-MeV excitation in ^{27}Al probably corresponds to the lowest-lying octupole state observed near this excitation energy in nuclei in this mass region [$E_x=6.88$ MeV (^{28}Si), $E_x=6.88$ MeV (^{26}Mg)]. The collective strength will be distributed over a multiplet of states in ^{27}Al thus providing an explanation of the observed width of this transition.

The transitions to groups centered at $E_x=10.4$ and 12.8 MeV lie in the region of excitation expected for the LEOR in ^{27}Al. There is no direct evidence that these are in fact $L=3$ excitations although they most likely correspond to the multiplets formed by the coupling of the odd $1d_{5/2}$ proton hole to states at 10.2 and 13.0 MeV in ^{28}Si which are strongly excited[8] in (α,α') and are most probably 3^- states.[9] We therefore tentatively assign these two groups to belong to the LEOR in ^{27}Al.

The broad structure spanning the excitation range 14–28 MeV coincides with the known position and width of the GQR in ^{27}Al. The background in this region (shown as dashed lines in Fig. 1) was chosen by matching to the observed low-energy spectrum and smoothly extrapolating to zero at the high-energy end. The exact location and spreading of the experimental strength is dependent on the way in which this background is drawn. It is clear, however, that the existence of the broad structure is not in question for any reasonable choice of background. We emphasize here that we believe the background to arise for physical rather than instrumental reasons and as such to be a contribution to the total cross section.

Figure 2 shows angular distributions obtained for the transitions discussed in the previous paragraphs. The more-forward–angle data points for the 4.43-MeV transition were obtained in an earlier experiment with somewhat poorer statistics.

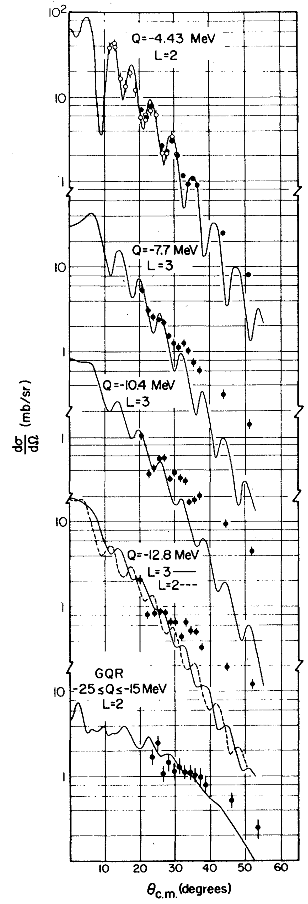

FIG. 2. Angular distributions of transitions to groups with the indicated Q values. The curves are the results of one-step DWBA calculations using a collective form factor. The L values used are shown.

The curves are the results of one-step distorted-wave Born-approximation (DWBA) calculations using a collective form factor of the derivative type and optical-model parameters taken from a preliminary analysis of elastic scattering data measured at this energy.[10] The curves are arbitrarily normalized to the data. The quality of the fit for the 4.43-MeV transitions is excellent. Equally good fits were also obtained for the other low-lying transitions but are not shown here for reasons of space. The calculations for the higher-lying transitions, however, show consistent deviations from the data at larger angles, and in no sense can these calculations be said to describe the data except in the crudest way at forward angles. It is possible that different optical-model prescriptions will be able to remedy this discrepancy. More likely, however, is that the inclusion of the expected strong coupling between inelastic channels, as implied in the model of Broglia, Dasso, and Winther, will provide the solution. These points are under further investigation.

Integrated cross sections for the observed structures were obtained from the measured angular distributions using the DWBA predictions to extrapolate to forward angles. The total cross section obtained is approximately 10 mb which is to be compared with the approximately 200 mb obtained for the total inelastic scattering cross section.[3] This result implies a relatively small probability for the target emerging in a single giant resonance when compared with the total for this channel—it is of interest to see if a calculation of the type discussed in Ref. 2 will be able to reproduce this value.

In summary and conclusion, a study of the inelastic scattering of ^{12}C from ^{27}Al at a bombarding energy at which deep-inelastic scattering occurs has shown that structures corresponding approximately both in energy and width to the expected LEOR and known GQR are excited. This result is in agreement with the expectations of the model of Broglia, Dasso, and Winther and thus provides the first experimental support of their ideas. Clearly of further interest is the study of the detailed mechanism by which these giant resonances are populated, in particular the effect of the expected strong-coupled channels on the angular-distribution shapes and magnitudes. Also of interest in this regard is the energy dependence of the population of the giant resonances particularly in the region just above where the fusion cross section turns over ($E_{\text{lab}} \approx 45$ MeV) which perhaps not coincidentally is approximately the threshold for excitation of these giant resonances ($E_{\text{cm}} - E_{\text{GR}} \approx E_{\text{Coul}}$).

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[1] R. A. Broglia, C. H. Dasso, and Aa. Winther, Phys. Lett. 61B, 113 (1976).

[2] R. A. Broglia, O. Civitarese, C. H. Dasso, and Aa. Winther, to be published.

[3] R. R. Betts, W. A. Lanford, M. H. Mortensen, and R. L. White, in Proceedings of the Symposium on Macroscopic Features of Heavy-Ion Collisions, Argonne, Illinois, 1976, edited by D. G. Kovar, ANL Report No. ANL/PHY-76-2 (to be published), p. 433, and to be published.

[4] T. M. Cormier, A. J. Lazzarini, M. A. Newhausen,

A. Sperduto, K. Van Bibber, F. Videbaek, G. Young, E. B. Blum, L. Herreid, and W. Thoms, Phys. Rev. C 13, 682 (1976).

[5] D. H. Youngblood, C. M. Rozsa, J. M. Moss, D. R. Brown, and J. D. Bronson, Phys. Rev. C 15, 1644 (1977).

[6] A. Djaloeis, A. Kiss, C. Mayer-Böricke, M. Rogge, P. Turek, and S. Wiktor, Kernforschungsanlage Jülich, Annual Report, 1975 (unpublished), p. 10.

[7] J. M. Moss, D. J. Youngblood, C. M. Rozsa, D. R. Brown, and J. D. Bronson, Phys. Rev. Lett. 37, 816 (1976).

[8] T. Bauer, H. Breuer, A. Kiss, K. T. Knöpfle, C. Mayer-Böricke, P. Paul, M. Rogge, and G. J. Wagner, Kernforschungsanlage Jülich, Annual Report, 1975 (unpublished), p. 17.

[9] P. M. Endt and C. Van der Leun, Nucl. Phys. A214, 1 (1973).

[10] R. R. Betts, S. DiCenzo, M. H. Mortensen, and R. L. White, to be published.

Rotation-Alignment Mechanism and the Second Discontinuity in the Yrast Level Spacing

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We report the result of a calculation of the yrast levels for a system of four nucleons in the $i_{13/2}$ shell, interacting via a pairing force, and coupled to a strongly deformed, axially symmetric core. In addition to an initial backbend at $I=12$, a second smaller backbend occurs at $I=38$. The structure of the wave functions at the second discontinuity indicates that it arises because of the decoupling of all four nucleons and subsequent alignment with the core angular momentum.

In a recent Letter, Lee *et al.*[1] have reported on a study in which high-spin yrast levels up to $I=32$ have been observed in ^{158}Er. When they plot the moment of inertia versus the square of the rotational frequency in the usual way for this yrast sequence, they observe a new discontinuity in the curve at $I=28$, in addition to the previously observed backbend at $I=14$. Several explanations have been offered for the existence of the first backbend in many nuclei.[2] An especially attractive suggestion was made by Stephens and Simon[3] who attribute the backbend to the breaking of a pair of $i_{13/2}$ neutrons and a subsequent realignment of their angular momentum with the rotational angular momentum. The question immediately arises whether the second discontinuity now observed in the ^{158}Er sequence can be explained as an alignment of an additional pair of $i_{13/2}$ neutrons. Below, we report on a model calculation which suggests that this may be the case.

In a previously reported calculation,[4] we considered a simple system composed of N identical valence nucleons bound to an axially symmetric, strongly deformed core. We assumed further that all valence nucleons are in orbitals which can be specified by one definite j quantum number, in particular, the $i_{13/2}$ unique-parity orbital. Our model Hamiltonian is

$$H=\vec{R}^2/2\mathscr{I}+\sum_{i=1}^{N}H_{\mathrm{sp}}(i)+H_{\mathrm{pair}}. \qquad (1)$$

The first term is the rotational Hamiltonian for the deformed core with moment of inertia $\mathscr{I}$. $H_{\mathrm{sp}}(i)$ is the single-particle Hamiltonian for the ith valence nucleon moving in the field of the deformed core. (In our calculation, we choose a deformed oscillator potential to represent the core.) The only interaction between valence nucleons which we include is a simple pairing interaction, H_{pair}.

The energy spectrum and wave functions for the yrast levels of our model system were then calculated using the basis $|(j)^N J, R; I\rangle$ in the lab system; the valence particles are coupled to a definite J which is then coupled to a definite (even) core angular momentum R to yield definite I. Because of the many J values possible for the $(i_{13/2})^N$ configuration, we restricted ourselves to include only those basis states which have the lowest seniorities, $v=0$ or 2 when N is even. The result of that calculation led to a backbend at $I=10$ for $N=2$, and at $I=18$ for $N=4$. The $N=2$ calculation was exact. The $N=4$ calculation, however, was performed with a truncated basis. We have since attempted to assess the importance of those $V=4$ states which were previously omitted from the latter calculation. This omission turns out to be extremely important due to the large core deformation ($\beta=0.3$) which was chosen.

For the $N=4$ case, only $v=0$, 2, and 4 is possible. Thus, an inclusion of the $V=4$ states and