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§Research supported by the National Science Foundation under Grant No. GP-16565.

‖ Work supported by the U. S. Energy Research and Development Administration.

[1]J. Elias *et al.*, Phys. Rev. 177, 2075 (1969), and Refs. 1–9 therein. See also S. Galster *et al.*, Nucl. Phys. B 32, 221 (1971).

[2]G_{Ep} and G_{Mp} are taken from F. Iachello, A. Jackson, and A. Lande, Phys. Lett. 43B, 191 (1973); G_{En} from Galster *et al.*, Ref. 1; and G_{Mn} from K. Hanson *et al.*, Phys. Rev. D 8, 753 (1973), and from W. Bartel *et al.*, Nucl. Phys. B58, 429 (1973).

[3]M. Chemtob, E. Moniz, and M. Rho, Phys. Rev. C 10, 334 (1974); R. Adler and S. Drell, Phys. Rev. Lett. 13, 349 (1964); R. Adler, Phys. Rev. 141, 1499 (1966); the recent measurement by B. Gobbi *et al.*, Phys. Rev. Lett. 33, 1450 (1974), of the decay width $\Gamma_{\rho\pi\gamma}$ decreases the prediction of Chemtob, Moniz, and Rho by $\sim\frac{1}{4}$ at $q^2=4$ GeV^2 in Fig. 2.

[4]R. Blankenbecler and J. Gunion, Phys. Rev. D 4, 718 (1971).

[5]A. Jackson, A. Lande, and D. Riska, Phys. Lett. 55B, 23 (1975).

[6]J. Gunion and L. Stodolsky, Phys. Rev. Lett. 30, 345 (1973); V. Franco, Phys. Rev. D 8, 826 (1973).

[7]R. Reid, Ann. Phys. (N.Y.) 50, 411 (1968).

[8]The overlap integrals were kindly provided by Professor E. Lomon. Very-low-q^2 e-d elastic data slightly favor FL-15 over FL-5: R. Berard *et al.*, Phys. Lett. 47B, 355 (1973).

[9]F. Gross, Phys. Rev. D 10, 223 (1974); J. Hornstein and F. Gross, Phys. Lett. 47B, 205 (1973); F. Coester and A. Ostebee, Phys. Rev. C 11, 1836 (1975); J. Friar, Ann. Phys. (N.Y.) 81, 332 (1973).

[10]H. Arenhovel and H. Miller, Z. Phys. 266, 13 (1974); V. Neudatchin *et al.*, Phys. Rev. C 11, 128 (1975); J. Vary, Phys. Rev. C 7, 521 (1973).

[11]S. Brodsky and G. Farrar, Phys. Rev. D 11, 1309 (1975); see also V. Matveev, R. Muradyan, and A. Tavkhelidze, Lett. Nuovo Cimento 7, 719 (1973).

[12]S. Brodsky, SLAC Report No. SLAC-PUB-1497, 1974 (to be published).

Evidence for the Isoscalar Giant Quadrupole Resonance in ^{16}O

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(Received 16 June 1975)

The spectra of 146-MeV α particles scattered inelastically from ^{16}O exhibit a giant-resonance-type structure between excitation energies of 15.9 and 27.3 MeV. The analysis of angular distributions shows its quadrupole nature and yields a strength exhausting about 65% of the isoscalar $E2$ energy-weighted sum rule.

Recently, several experimental[1-5] and theoretical[6-11] investigations have been published concerning giant quadrupole resonances (GQR) in ^{16}O. Some of these papers deal especially with the question of an isoscalar ($T=0$) GQR excited in (α,γ_0) capture[2] and inelastic scattering,[4,5] however, without arriving at completely conclusive results.[12] The (α,γ_0) investigation suffered mainly from the fact that only one decay channel was studied. The ^{3}He inelastic scattering,[4] on the other hand, is not completely isospin selective. A recent study of inelastic α-particle scattering[5] at 97 MeV which was not subjected to these restrictions has only been able to exclude the existence of a resonance at $63A^{-1/3}=25$ MeV predicted by the hydrodynamical model.[11] Recent theoretical investigations[7-10] expect the isoscalar GQR in the energy range between 20- and 25-MeV excitation energy. In this Letter we present results from an ^{16}O(α,α') experiment at 146

MeV showing a large concentration of isoscalar $E2$ strength centered at 21 MeV with a width [full width at half-maximum (FWHM)] of about 7 MeV. This observation was possible mainly because of a reduced and flatter background compared to that of the 97-MeV experiment.

The experiments have been performed with the unanalyzed 146-MeV α beam from the Jülich cyclotron. Natural oxygen gas was contained in a gas cell with 2-mg/cm^2 Havar windows at a pressure of about 200 Torr. Reaction products were detected and identified with cooled ΔE-E telescopes consisting of four 2-mm Si surface-barrier counters. The beam energy spread, straggling in the target, and reaction kinematics limited the overall energy resolution to 350–650 keV depending on the scattering angle. Spectra were taken at lab angles from 5° to 40° mostly in steps of 1°. At extreme forward angles, where the gas target presented some difficulties, supplementary normalization runs were performed with a 350-μg/cm^2 Mylar target yielding an overall resolution of 220 keV. The absolute cross sections of the two measurements agreed within the estimated error of 10%. In order to exclude the possibility that the interesting structures were produced by slit scattering, check runs were made with hydrogen and helium fillings of the gas target.

The spectra of scattered α particles show strong groups which are attributed to the excitation of known[13] levels at 6.13 MeV ($J^\pi = 3^-$),[14] 6.92 MeV (2^+),[15] 8.87 MeV (2^-),[16] and 11.52 MeV (2^+). The groups at 13.1 and 15 MeV arise from several unresolved levels. The 18.4 ± 0.05-MeV peak probably corresponds to the 18.3-MeV (2^+) resonance of Ref. 2 and the 18.5-MeV (2^+) group of Ref. 3. The most interesting feature of Fig. 1 is the gross structure between 16 and 27 MeV which clearly stands out against the background and persists at all angles with minor changes of shape. We have evaluated the angular distribution of this structure by subtracting a linear background, as indicated in Fig. 1 (dashed lines). The endpoints are well defined at all angles by a minimum at 15.9 MeV and an abrupt change of the slope at 27.3 MeV. A parabolic background shape which one might prefer could reduce the peak area by about 20%; on the other hand, the peak area would increase by 25% if one were to completely remove the remaining oscillatory structure of the background angular distribution (see Fig. 2).

The resulting angular distribution of the structure between 15.9 and 27.3 MeV together with

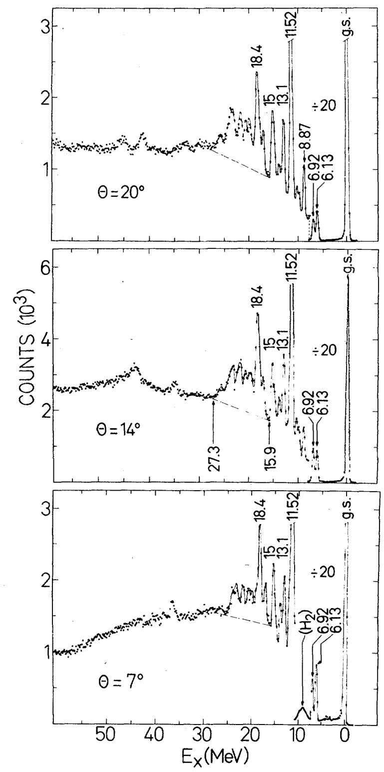

FIG. 1. Spectra of the $^{16}O(\alpha,\alpha')$ scattering at 146 MeV. The isoscalar GQR between 15.9 and 27.3 MeV clearly stands out against the background at all angles. The smooth curves have been drawn to guide the eye.

those of the strongest α groups are shown in Fig. 2. The cross section of the strong 18.4-MeV group has been evaluated separately (background line taken between the minima) to demonstrate the similarity of both patterns. For c.m. angles less than 30° well-structured angular distributions have been found which allow a straightforward determination of the angular momentum transfer L. Very good fits to the data are obtained by distorted-wave Born approximation (DWBA) calculations using collective form factors[17] with complex coupling, if one assumes $L = 3$ transfer for the 6.13-MeV group and $L = 2$ for all the others, neglecting possible $E0$ contributions. Even the less pronounced structure and the less rapid falloff of the angular distributions of higher excited states, which we had suspected as being due to contributions of other L values, are readily reproduced by the DWBA calculations (Fig. 2). Concerning the gross structure between 16 and 27 MeV, statistics and resolution of the spectra are not adequate to evaluate the individu-

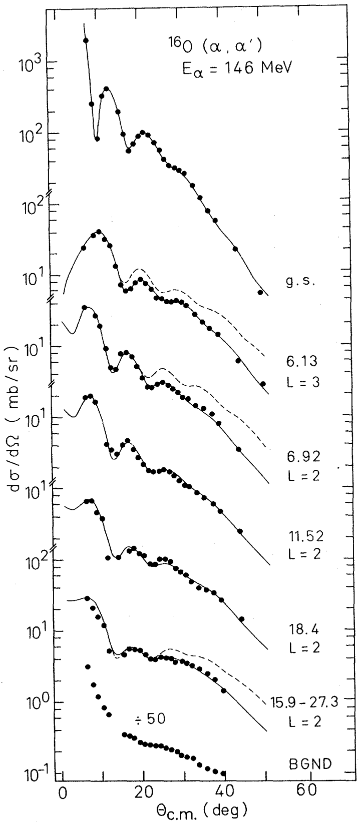

FIG. 2. Angular distributions of the strongest α groups and of the structure above the background (dashed line in Fig. 1) between 16 and 27 MeV. The cross section of the 18.4-MeV states has been substracted from the latter. The solid curves represent complex-coupling DWBA calculations. The dashed lines are typical examples of real-coupling DWBA calculations. The angular distribution of the background between 16 and 27 MeV is also shown.

TABLE I. Deformation lengths $\beta_L R$ and corresponding fractions S(IS) of the isoscalar energy-weighted sum rule in comparison with values S(EM) from electromagnetic transition rates.

E_x (MeV)	J^π ($T=0$)	$\beta_L R$ (fm)	S(IS) (%)	S(EM) (%)
6.13	3^-	1.41	8	13 ± 2^a
6.92	2^+	0.95	11	11 ± 1^a
11.52	2^+	0.75	11	13 ± 2^a
13.1	2^+	0.37^b	$\leq 3^b$	$6, \leq 8^c$
18.4	2^+	0.52	9	$11, 4^d$
15.9 to 27.3	2^+	1.22^e	58 ± 25^e	21 ± 9^f

[a]Ref. 13.
[b]With contributions from the 13.02- (2^+) and 13.14-MeV (2^+) levels. We give an upper limit only to allow for a possible contribution from the 13.13-MeV (3^-) level.
[c]Refs. 2, 20.
[d]Refs. 2, 3.
[e]With the strength of the 18.4-MeV group subtracted.
[f]Ref. 3; $E2$ strength in the region of 20–30 MeV excitation energy.

al fine-structure peaks with the aim to definitely exclude small contributions from other L values. The optical-model parameters of the assumed Woods-Saxon potential ($V=109.7$ MeV, $r_v=1.16$ fm, $a_v=0.82$ fm, $W=14.7$ MeV, $r_w=1.80$ fm, $a_w=0.77$ fm) were derived from a least-squares fit to the elastic cross sections (see Fig. 2).

Deformation parameters $\beta_L=[d\sigma(\theta)_{\rm exp}/d\sigma(\theta)_{\rm DW}]^{1/2}$ and the corresponding deformation lengths $\beta_L R$ have been extracted (see Table I) using real-coupling DWBA calculations[18] which gave fits of comparable quality in the diffraction region (see Fig. 2). In this way we avoided the ambiguities in the deformation lengths $\beta_L R$ arising from the largely different real and imaginary radii. Fractions of the isoscalar $E2$ energy-weighted sum rule (EWSR) have been calculated accounting for Fermi mass distributions through the application of method II from Bernstein.[19] For the low-lying states, Table I shows a satisfactory agreement between our isoscalar strengths and the electromagnetic values. This is very gratifying since all trivial criticism of the applied procedure (e.g., choice of the optical potential, real or complex coupling) would lead only to a simultaneous renormalization of all transition strengths. Therefore, unless the use of the identical collective form factors for all transitions is questioned, reasonable confidence can be attached to the value of $(67\pm\pm25)\%$ of the ($T=0$) $E2$ EWSR found in the isoscalar GQR region (Table I). The errors are estimated from the uncertainties of the absolute cross sections and of the background subtraction.

This strength is not at variance with previous experiments. It seems to indicate, however, that most of the $E2$ strength observed in the (p,γ_0) channel[1] is isoscalar. This has already been suggested on the basis of inelastic ^{3}He scattering[4] where, however, a $T=1$ contribution could not be ruled out. An attempt to disentangle the dipole and quadrupole strength excited in this reaction has led to an estimate[4] of 75% of the isoscalar EWSR for $L=2$ in the region between 17 and 27 MeV. Only an analysis of electron-scattering data,[3] which are also affected by the presence of the GQR, has yielded noticeably smaller $E2$ strength exhausting $(27 \pm 10)\%$ of the EWSR between 16 and 30 MeV.

In conclusion, for the first time a large concentration of isoscalar $E2$ strength has been located definitely between 16 and 27 MeV of excitation energy in ^{16}O, centered at 20.7 MeV with a width (FWHM) of 7.5 ± 1 MeV. Because of the high selectivity of the (α, α') reaction and a background which is less important than in the 97-MeV experiment[5] this strength is directly visible in the spectra as a giant resonance with appreciable fine structure. The total observed isoscalar $E2$ strength exhausts about 90% of the $(T=0)$ $E2$ EWSR.

Theoretically the semiempirical resonance analysis[6] of scattering data yields a maximum of the $E2$ strength (isoscalar and/or isovector) at 24 MeV with a width (FWHM) of about 5 MeV. It is remarkable that three calculations[7,8,10] of the isoscalar GQR predicted the position correctly within 1 MeV even if the strengths are overestimated and the widths (if any) are underestimated.

[1]S. S. Hanna *et al.*, Phys. Rev. Lett. 32, 114 (1974).

[2]K. A. Snover, E. G. Adelberger, and D. R. Brown, Phys. Rev. Lett. 32, 1061 (1974).

[3]A. Hotta, K. Itoh, and T. Saito, Phys. Rev. Lett. 33, 790 (1974).

[4]A. Moalem, W. Benenson, and G. M. Crawley, Nucl. Phys. A236, 307 (1974).

[5]J. M. Moss *et al.*, Phys. Rev. Lett. 34, 748 (1975).

[6]H. V. Geramb, R. Sprickmann, and G. L. Strobel, Nucl. Phys. A199, 545 (1973) and to be published.

[7]S. Krewald *et al.*, Phys. Rev. Lett. 33, 1386 (1974), and Phys. Lett. 52B, 295 (1974).

[8]H. Flocard and D. Vautherin, Phys. Lett. 55B, 259 (1975).

[9]Y. Abgrall and E. Caurier, Phys. Lett. 56B, 229 (1975).

[10]G. F. Bertsch and S. F. Tsai, to be published; see also Fig. 19 of S. S. Hanna, in *Proceedings of the International Conference on Nuclear Structure and Spectroscopy, Amsterdam, The Netherlands, 1974*, edited by H. P. Blok and A. E. L. Dieperink (Scholar's Press, Amsterdam, 1974), Vol. II, p. 249.

[11]A. Bohr and B. Mottelson, in *International Symposium on Neutron Capture Gamma Ray Spectroscopy, 1969* (International Atomic Energy Agency, Vienna, Austria, 1969).

[12]A review of the situation has been given by Hanna, Ref. 10.

[13]F. Ajzenberg-Selove, Nucl. Phys. A188, 1 (1971).

[14]A strong excitation of the unresolved 0^+ state at 6.06 MeV can only be ruled out by the clear $L=3$ pattern of the angular distribution. In a parallel ^{12}C(α, α') experiment, we have found that an $L=0$ angular distribution is out of phase with an $L=3$ distribution.

[15]With the higher resolution achieved with the solid target we found that the 1^- level at $E_x = 7.12$ MeV does not contribute noticeably except in the minima of the angular distribution of the 6.92-MeV level.

[16]The excitation of an unnatural-parity state shows the existence of reaction amplitudes other than direct one step. The angular distribution of this state is bell shaped with a maximum of 0.35 mb-sr at $\theta_{c.m.} \simeq 23°$. At $\theta_{c.m.} \simeq 8°$ where we adjusted the DWBA curves of the natural-parity states the cross section of the 2^- state is less than 0.1 mb/sr. This suggests a negligible influence of higher-order amplitudes on the extracted strengths.

[17]G. R. Satchler, Nucl. Phys. A195, 1 (1972), and ORNL Report No. ORNL-TM-4347, 1973 (unpublished).

[18]Of two optical potentials which gave equivalent fits to the elastic scattering data the one with $V=88.4$ MeV, $r_v=1.4$ fm, $a_v=0.70$ fm, $W=18.1$ MeV, $r_w=1.82$ fm, $a_w=0.62$ fm turned out to be superior for the real-coupling calculations.

[19]A. M. Bernstein, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum, New York, 1969), Vol. III, p. 325.

[20]J. C. Kim, R. P. Singhal, and H. S. Caplan, Can. J. Phys. 48, 83 (1970).