PHYSICAL REVIEW C VOLUME 11, NUMBER 3 MARCH 1975

$E1$ transitions in ^{17}F. II. The region of the giant resonances*

M. N. Harakeh and P. Paul
Department of Physics, State University of New York, Stony Brook, New York 11794

Ph. Gorodetzky†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 5 November 1974)

The giant dipole resonance of ^{17}F was studied by radiative proton capture. An observed integrated strength of 10 MeV mb, presumably mostly $T=\frac{1}{2}$, is centered at 22 MeV with a width of ~ 5 MeV. Calculations were performed for odd-parity 2p-1h, 1p excitations in a basis of good isospin. These calculations predict correctly the observed strength distribution. Some general rules for the T components of the $E1$ collective state are consistent with the microscopic calculation. The $f_{7/2} \rightarrow d_{5/2}$ strength was located near 18 MeV, in agreement with other experimental evidence.

NUCLEAR REACTIONS ^{17}F, ^{16}O(p,γ), E_p = 15.75–31.66 MeV. Measured $d\sigma/d\Omega$ (90°). Measured angular distributions deduced $E_{T=1/2}$ of GDR. Calculated $1p$ and 2p-1h states of ^{17}F. Compared with experimental results.

I. INTRODUCTION

The work presented here is part of a study of isospin effects on collective electric dipole states in light nuclei. While the isospin splitting of the giant dipole resonances (GDR) is well understood in heavy nuclei and follows some general rules,[1] the situation is somewhat more complex in light nuclei with $|T_z| = \frac{1}{2}$, where the $T=\frac{1}{2}$ and $T=\frac{3}{2}$ components of the $E1$ strength are not completely separated into directly recognizable peaks. In addition, various estimates have been given for the systematic trend of the splitting which differ greatly for light nuclei.[2,3]

The present line of attack has been threefold: (1) To compute the distribution of $E1$ strength in a reliable microscopic model in good isospin and compare the results from these calculations with the various general predictions. (2) To test the model calculations with the $E1$ transitions of the low-lying $T=\frac{3}{2}$ excited states in ^{17}F. These experimental and theoretical results have been published in a previous paper[4] (henceforth referred to as I). (3) To compare the model calculations with the $E1$ strength distribution in the GDR of ^{17}F. These theoretical and experimental results on the collective states are presented here.

No photonuclear data were available on mass 17 nuclei for obvious reasons. We have used the inverse (capture) reaction ^{16}O$(p,\gamma)^{17}$F to obtain the $E1$ strength distribution in the GDR of ^{17}F. Although only about 10% of the GDR actually decays into the capture channel, it has proven correct in all known cases that the (p,γ) reaction faithfully reflects the $E1$ strength distribution of the collective excitations.

II. EXPERIMENT AND RESULTS

The ^{16}O$(p,\gamma)^{17}$F reaction was studied for bombarding energies varying between 15.75 and 31.66 MeV using the proton beam of the three-stage tandem accelerator at Brookhaven National Laboratory. The target was a 30.5-cm long gas cell with 75-μm Kapton entrance and exit foils and filled with natural oxygen to a pressure of 318 Torr. Behind the cell the beam entered a gradually expanding Faraday cup and was stopped in a shielded 25-cm diam dump 20 m behind the target. Nowhere in the target room did the beam strike any material except the target windows. This care was necessary because the Q value of this reaction is lower than the Q value of proton capture on any other material, hence any γ-ray background would be higher in energy than the γ rays of interest.

The central 7.5 cm of the gas target were viewed by the collimator of a 25-cm by 25-cm γ detector with anticoincidence shield, at 90° to the beam axis, so that the windows are shielded from view. The γ detector was similar to that previously described,[5] with only minor improvements. The effective thickness of the target seen by the detector was 100 keV at 21-MeV incident proton energy. Beam currents between 15 and 60 nA were acceptable. The total spectrum (all γ rays detected in the NaI crystal) and the accepted one (total less those rejected by the shield) were recorded for each run. The typical accepted spectrum in Fig. 1

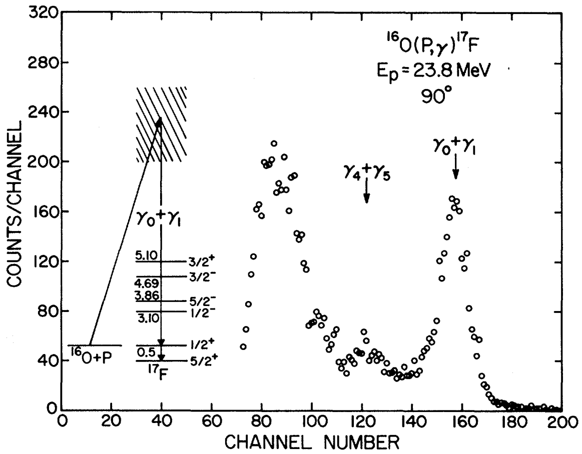

FIG. 1. Typical γ-ray spectrum obtained in the proton bombardment of an ^{16}O gas target at E_p = 23.8 MeV. The arrows indicate the expected position of summed transitions to ground and first excited state, and fourth and fifth excited states, respectively.

shows the unresolved transitions to ground state and first excited state at 500 keV, clean of all background. Even the total spectra were clean enough to obtain a good curve for the ratio of accepted to total counts in the peak as a function of γ-ray energy. This curve which enters into the detector efficiency is plotted in Fig. 2. For the present detector geometry this ratio varies between 63 and 53%.

The summed yield of γ_0 and γ_1 was obtained from each accepted spectrum by a line fitting procedure, and the cross section was calculated absolutely, correcting for the detector efficiency and γ absorption in material between target and crystal. The over-all systematic error of the procedure is estimated to 20%, in addition to the statistical errors which will be shown explicitly.

The 90° yield for the summed γ_0 and γ_1 transitions is shown in Fig. 3 as a function of bombarding energy. The curve displays the typical wide giant resonance feature which is the $T=\frac{1}{2}$ component of the GDR in ^{17}F if isospin is a good quantum number. The peak occurs approximately in the region expected from the GDR in ^{16}O, but contains all spin components from $\frac{1}{2}^-$ to $\frac{7}{2}^-$. One would not, in general, expect any one of the peaks to be associated with a particular J value.

Nevertheless, angular distributions were taken at various specific peaks at E_p = 17.14, 18.15, 20.98, and 22.19 MeV indicated by arrows in Fig. 3. The changing geometry of the target was taken into account for each angle. The resulting angular distributions and the extracted normalized Legendre coefficients a_1, a_2, a_3 are shown in Fig. 4. The large a_2 coefficients and absence of an observable

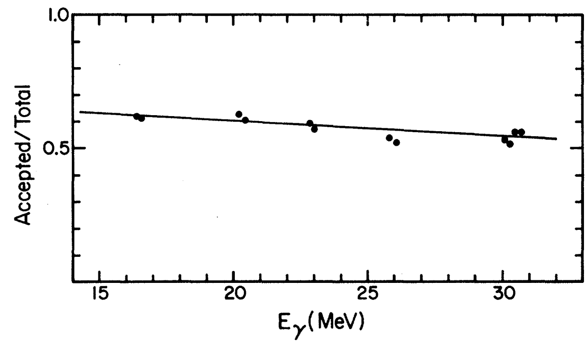

FIG. 2. Fraction of the total detected events which is accepted by the anticoincidence system, as a function of γ-ray energy.

a_4 coefficient support the dipole character of the observed transitions. The large positive a_1 and negative a_3 coefficients are typical for many giant resonances and indicate strong interference between $E2$ radiation (and perhaps some $M1$) and the dominant $E1$ mode. In fact, at excitation energies of E_x = 19.42 and 21.07 MeV, positive-parity states with spins $\frac{5}{2}$ and $\frac{1}{2}$, respectively, have been reported[6] in the reactions ^{14}N(τ, α), ^{14}N(τ, τ), and ^{14}N(τ, γ).

Assuming the average observed value a_2 = −0.59 to be valid throughout the GR region and all the strength due to γ_0, detailed balance yields an upper limit of 10.2 MeV mb for the photonuclear reaction ^{17}F(γ, p_0)^{16}O. The center of the photonuclear strength in ^{17}F integrated from 15.4 to 30.4 MeV lies at 22.0 MeV. This contains, of course, the GDR built on the 500-keV excited state. For comparison, the equivalent center of strength of the GDR in ^{16}O, calculated from the experimental data of Refs. 7 and 8, lies at 22.4 MeV.

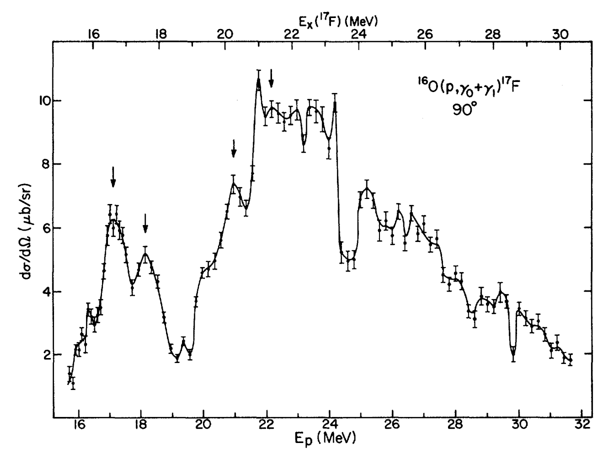

FIG. 3. Excitation curve for the summed transitions $\gamma_0+\gamma_1$. The solid line is drawn through the data to guide the eye. Arrows indicate energies where angular distributions were taken.

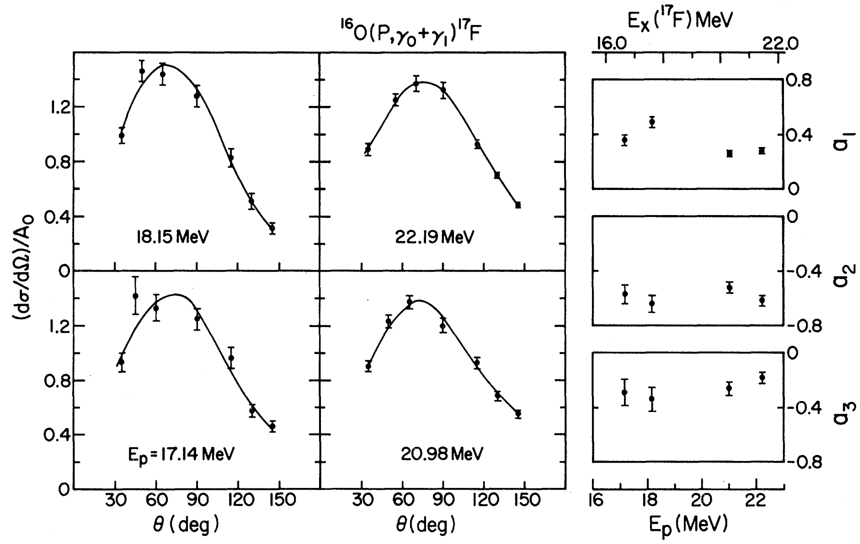

FIG. 4. Angular distributions of the $\gamma_0+\gamma_1$ yield at 17.14, 18.15, 20.98, and 22.19 MeV, i.e., the energies indicated by arrows in Fig. 3. Solid curves are fits with Legendre polynomials up to and including P_3 terms. The normalized Legendre coefficients a_1, a_2, and a_3 obtained from the fits are plotted on the right-hand side of the figure.

III. THEORETICAL PREDICTIONS

We have calculated the negative-parity states up to $J=\frac{7}{2}$ in $A=17$ in a basis of good isospin. The procedure and results for the low-lying $T=\frac{3}{2}$ states have already been reported in I. These states were considered in a 2p-1h basis. For the present case, which includes the $T=\frac{1}{2}$ states this basis has been extended to include the 1p states also. The entire $(2s, 1d)$ and $(1f, 2p)$ shells are active for the particles. The entire $(1p)$ shell is active for the hole. The unperturbed single-particle (s.p.) and single-hole (s.h.) energies were taken[9] from the level spectra of ^{17}O and ^{15}O and are listed in Table I. For the $(1f, 2p)$ s.p. energies two sets were used. One set is proposed by Jolly[9] based on the experimental results of Hardie, Daugle, and Oppliger[10] predicting the $1f_{7/2}$ single-particle strength to lie at around 18-MeV excitation in ^{17}F. He then assumed a spin-orbit splitting of ~7 MeV to establish the position of the $1f_{5/2}$ s.p., then arbitrarily assumed the positions of the $2p_{3/2}$ and $2p_{1/2}$ s.p. to preserve the following order: $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$. Interpretation of recent experimental evidence[11] from elastic proton scattering seems to support Jolly's conjecture in placing $1f_{7/2}$ s.p. strength in ^{17}F at ~18 MeV excitation. This will be referred to as Set I and is shown in the first row of Table I. The other set, which has recently been used[12] in theoretical calculations for ^{16}O and its neighbor nuclei hereafter referred to as Set II, is shown in the second row of Table I. In this set the energies of the highly unbound $(1f, 2p)$ orbitals are generated in the potential which fits the bound orbitals. We note that the energies in Sets I and II differ by 10 MeV or more for the unbound orbitals.

The p-p and p-h residual interactions were computed using the realistic Kuo-Brown interaction[13] with details given in I. The Coulomb interaction was omitted but should have little effect. The spurious center-of-mass effects, which must be considered for the $T=\frac{1}{2}$ states, have been removed following the procedure given by Giraud.[14]

Three sets of calculations were performed which differ in the following manner. Case I: The calculations are performed in a 2p-1h and 1p basis using the s.p. energies of Set I. Case II: Calculations are performed in a 2p-1h and 1p basis using the s.p. energies of Set II. Case III: Calculations

TABLE I. Neutron s.p. energies (in MeV) relative to the ^{16}O ground state which were used in the 1p and 2p-1h states calculations.

	$1p_{3/2}$	$1p_{1/2}$	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$	$1f_{7/2}$	$2p_{3/2}$	$1f_{5/2}$	$2p_{1/2}$
I	−21.74	−15.60	−4.15	−3.28	0.93	15.0	20.0	22.0	23.0
II	−21.74	−15.60	−4.15	−3.28	0.93	6.62	3.59	8.88	4.05

TABLE II. Theoretical $B(E1\downarrow)$, obtained from case I, in $e^2\,\text{fm}^2$ to the ground state of ^{17}F [only those $B(E1\downarrow) \geq 0.02\ e^2\,\text{fm}^2$ are listed].

J^π	$\frac{3}{2}^-$ E_x (MeV)	$B(E1\downarrow)$	$\frac{5}{2}^-$ E_x (MeV)	$B(E1\downarrow)$	$\frac{7}{2}^-$ E_x (MeV)	$B(E1\downarrow)$
$T=\frac{1}{2}$	17.543	0.02	21.677	0.05	9.092	0.04
	21.164	0.06	22.324	0.02	13.814	0.03
	21.466	0.15	23.970	0.07	16.917	0.09
	22.393	0.02	25.165	0.05	17.945	0.09
	23.811	0.06	25.724	0.05	19.694	0.03
	25.562	0.02	26.267	0.04	20.954	0.04
	26.163	0.04			22.117	0.02
	31.624	0.02			23.642	0.03
					24.093	0.10
					25.621	0.03
					26.697	0.03
					27.241	0.02
$T=\frac{3}{2}$	23.196	0.41	21.662	0.03	23.024	0.51
	26.171	0.09	24.729	0.36	24.517	0.03
	26.808	0.07	25.645	0.03	26.970	0.04
	28.079	0.16	26.267	0.11		
	28.639	0.02	26.486	0.19		
	33.555	0.02	27.576	0.03		
			28.205	0.06		
			29.364	0.06		

TABLE III. Theoretical $B(E1\downarrow)$, obtained from case I, in $e^2\,\text{fm}^2$ to the first excited state of ^{17}F [only those $B(E1\downarrow) \geq 0.02\ e^2\,\text{fm}^2$ are listed].

J^π	$\frac{1}{2}^-$ E_x (MeV)	$B(E1\downarrow)$	$\frac{3}{2}^-$ E_x (MeV)	$B(E1\downarrow)$
$T=\frac{1}{2}$	14.612	0.02	11.828	0.03
	17.822	0.03	17.543	0.02
	21.608	0.07	18.410	0.02
	21.959	0.06	21.164	0.07
	23.089	0.07	22.393	0.02
	24.273	0.03	22.603	0.05
	24.420	0.07	23.524	0.03
	24.801	0.02	24.105	0.09
	27.395	0.02	25.562	0.02
	28.763	0.06	26.163	0.03
	29.535	0.05	28.442	0.02
			28.721	0.05
$T=\frac{3}{2}$	23.818	0.19	22.344	0.09
	24.531	0.29	23.196	0.07
	25.939	0.03	24.774	0.02
	28.773	0.07	26.171	0.45
	30.740	0.10	26.808	0.02
			28.079	0.07

are performed in a 2p-1h basis ignoring $(1f, 2p)$ s.p. states.

The $B(E1)$ matrix elements were computed using harmonic oscillator wave functions with $\hbar\omega = 41A^{-1/3}$ MeV. The ground and first excited states are assumed good single-particle $d_{5/2}$ and $s_{1/2}$ states, respectively. Tables II and III list the energies of these resulting dipole states, for case I, which have $B(E1\downarrow)$ values (where $\downarrow$ indicates de-excitation) in excess of $0.02\ e^2\,\text{fm}^2$. The concentration of dipole strength in the GDR region is readily apparent.

IV. DISCUSSION

The present experiment measures only the capture strength $\Gamma_p\Gamma_\gamma$ rather than the radiative width. Nevertheless, if Γ_p does not change much over the region of interest, a valid relative comparison between the experiment and the theory can be made. In Fig. 5 the summed $\gamma_0+\gamma_1$ data are compared

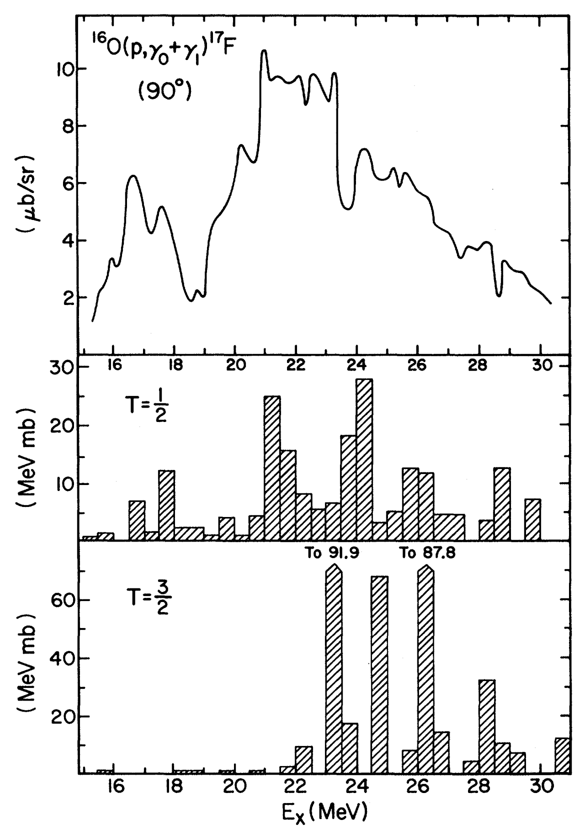

FIG. 5. Comparison of the experimental excitation curve and the theoretical predictions from case I calculation. The lower two distributions are obtained for $T=\frac{1}{2}$ and $T=\frac{3}{2}$, respectively, by summing the integrated decay strength to the ground and first excited states of ^{17}F over intervals of 500 keV. The experimental curves should be predominantly related to the $T=\frac{1}{2}$ part of GDR.

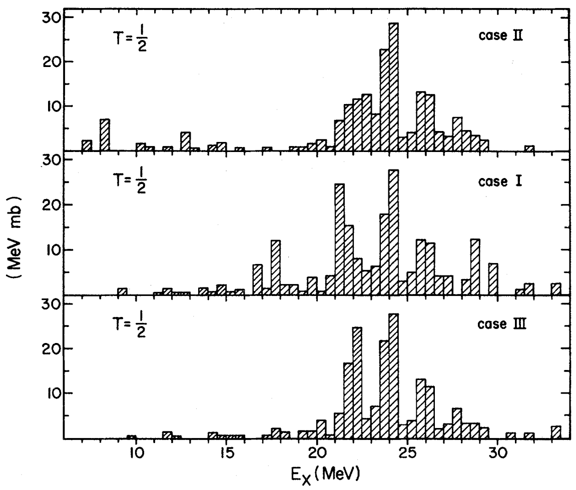

FIG. 6. Comparison of theoretical predictions for the integrated cross sections for the γ decay to the ground and first excited states of ^{17}F of the $T=\frac{1}{2}$ part of GDR for three cases of calculations. Case I: Jolly's $(1f, 2p)$ s.p. energies are used; this gives better agreement with the experiment. Case II: widely accepted $(1f, 2p)$ s.p. energies are used, clearly evident is the absence of strength observed experimentally ~ 18 MeV. Case III: s.p. $(1f, 2p)$ states are ignored.

with the corresponding sum of calculated integrated γ decay cross sections which are derived from the computed $B(E1\downarrow)$ values, for case I, by the equation

$$\int \sigma dE = \frac{16\pi^3}{9\hbar c} \sum_k E_{\gamma_k} B(E1\downarrow)_k .$$

Here E_{γ_k} is the energy of the γ ray resulting from the transition of the kth level to either the ground or first excited state of ^{17}F and $B(E1\downarrow)_k$ is the corresponding reduced decay transition rate. All possible spin values are included and all integrated cross sections are summed within 500-keV bins. The predictions for $T=\frac{1}{2}$ and $T=\frac{3}{2}$ are indicated separately; the $^{16}O(p,\gamma)^{17}F$ reaction should only populate the $T=\frac{1}{2}$ components.

The following points can be made: (1) The observed GDR is well reproduced by the calculations. We note that no free parameters were adjusted, and that these same calculations explained well the spectrum and effective $E1$ charges of the low-lying $T=\frac{3}{2}$ states. (2) The pygmy resonance centered at 17.5 MeV comes out from the calculation only if single-particle excitations are included with the s.p. energies in the $(1f, 2p)$ shell taken from Set I (case I). This is verified by the three different calculations.

Figure 6 compares the predictions with (cases I and II) and without (case III) inclusion of the s.p. excitations. The $E1$ strength associated with the $f_{7/2} \rightarrow d_{5/2}$ transition is not small compared to the particle-hole strength and inclusion of the single-particle states affects the predicted theoretical spectrum. Inclusion of the s.p. excitations in case I concentrates the $f_{7/2}$ strength into two states, at 16.92 and 17.95 MeV and removes some of the main strength seen at 22 MeV in case III (in which s.p. states are ignored) down to 21 MeV giving better agreement with the data. The input into case I calculations assumes the s.p. $1f_{7/2}$ ex-

TABLE IV. Summary of theoretical and experimental results.

	General rules	1p and 2p-1h calc. [a]	Exp.
$\sigma_0 = \int \sigma\, dE$ (MeV mb)	$=60\ NZ/A$ 254	$\sigma_0(T=\frac{1}{2})=129$ $\sigma_0(T=\frac{3}{2})=221$ $\sigma_0(\text{total})=350$	$\sigma_0(\gamma, p_0)$ ≤ 10.2
$\sigma_{-1} = \int \sigma/E dE$ (mb)	$=0.36A^{4/3}$ 15.7	$\sigma_{-1}(T=\frac{1}{2})=6.0$ $\sigma_{-1}(T=\frac{3}{2})=8.9$ $\sigma_{-1}(\text{total})=14.9$	
$\sigma_{-1}(T+1)/\sigma_{-1}$	0.60 [b] 0.59 [c]	0.60	
$E_{\text{GDR}}=\sigma_0/\sigma_{-1}$ (MeV)		$E_{T=1/2}=21.4(20.4)$ $E_{T=3/2}=24.8$	$E_{T=1/2}=22.0(15.4-30.4\text{ MeV})$ $E_{T=1}(^{16}O)=22.4(16.8-29\text{ MeV})$ [d]
$\Delta E = E_{T=3/2}-E_{T=1/2}$ (MeV)	$=U(T_0+1)/A$ $=5.3\ (U=60\text{ MeV})$ [e] $=1.8\ (U\approx 20\text{ MeV})$ [f]	3.4(4.4) $\rightarrow U=39$ MeV	

[a] Numbers in this column are from case I calculation except for numbers in parenthesis, which are from case II.
[b] See Ref. 17.
[c] See Ref. 18.
[d] Calculated from experimental data of Refs. 7 and 8.
[e] See Ref. 2.
[f] See Ref. 3.

citation near 18 MeV, the value extracted from the experiment. In most theoretical calculations which use model-generated s.p. energies, the $1f_{7/2}$ state comes much lower, around 10 MeV, and the $2p_{3/2}$ state even lower at 7.7 MeV. Hardie *et al.*[10] point out that their smoothed set of optical-model parameters obtained from proton elastic scattering on ^{16}O does not predict a $2p_{3/2}$ single-particle level at 7.7 MeV. Nevertheless using these s.p. energies (case II), the $f_{7/2}$ strength is moved down into two states around 8.28 and 12.77 MeV; the strength around 22 MeV is redistributed, but the calculated spectrum does not come near to explaining the pygmy resonance around 17.5 MeV.

In Table IV, a few gross properties which emerge from our data and the calculations are compared to some systematic predictions or general rules. The theoretically derived properties are for GDR states built on the ground state of ^{17}F with $B(E1\downarrow) \geq 0.01\ e^2\,\mathrm{fm}^2$, from the case I calculations. The integrated absorption cross section so obtained is larger than the classical dipole sum rule prediction by a factor of 1.4 as is commonly the case with shell-model calculations.[15] The experimental integrated absorption cross section of 10.2 MeV mb between 15.4 and 30.4 MeV for the partial photonuclear reaction $^{17}\mathrm{F}(\gamma, p_0)$ is consistent with other reported results in light nuclei.[16]

The bremsstrahlung-weighted cross section σ_{-1} of 14.9 mb compares very well with the Levinger estimate[15] of $0.36A^{4/3}$ mb. The consistency of our calculations is further exemplified by the good agreement between the $T=\frac{3}{2}$ fraction of the bremsstrahlung-weighted cross section $[\sigma_{-}(T+1)/\sigma_{-}]$ given by our calculations and those derived from the sum rules.[17,18] Our calculation predicts an energy splitting of the GDR strength into two gross components, $T=\frac{1}{2}$ and $T=\frac{3}{2}$, centered at 21.4 MeV (20.4 MeV for case II calc.) and 24.8 MeV, respectively. This results in an isospin splitting of $\Delta E = E(T=\frac{3}{2}) - E(T=\frac{1}{2}) = 3.4$ MeV (4.4 MeV for case II). Often the phenomenological expression $\Delta E = (U/A) \times (T+1)$ is used and several estimates for the symmetry potential U have been published. The largest value is $U = 60$ MeV[2] which gives $\Delta E = 5.6$ MeV. The smallest value $U = 20$ MeV taken from Leonardi,[3] yields $\Delta E = 1.8$ MeV. The microscopic theory gives a value in between the two estimates. Recently Leonardi and Lipparini[19] proposed a rather model-independent upper limit on U which was derived from sum rule limits for $T=\frac{1}{2}$ nuclei. Applying this limit to the present case yields $U \leq 38$ MeV, very close to the value which is actually obtained from the present calculations.

The experimentally observed center of $T=\frac{1}{2}$ capture $\gamma_0 + \gamma_1$ strength, integrated from 15.4 to 30.4 MeV, lies at 22.0 MeV, compared to 21.4 MeV from the present calculations. One notes that the calculated center of strength built on the first excited state lies at 22.4 MeV for the $T=\frac{1}{2}$ part, supporting the picture of a s.p. excitation weakly coupled to the collective state. Removal of the γ_1 contribution thus brings the data into even better agreement with the calculation.

V. CONCLUSION

It has been demonstrated that the $T=\frac{1}{2}$ collective dipole states in ^{17}F are well described by the same model which yields the positions and $E1$ transition strengths for the low-lying $T=\frac{3}{2}$ states. No parameters were adjusted in the present calculation. Although the $T=\frac{3}{2}$ collective strength remains to be identified, the success of the calculations makes the model sufficiently believable to test the general rules of isospin splitting against the model. It is found then, as one expected, that the effective symmetry potential for collective $E1$ states which has a value[1] of 55 ± 15 MeV in nuclei with large neutron excess, must be reduced to about 40 MeV for the $T_z = \frac{1}{2}$ case, still quite a large value.

It was found that a pygmy resonance below the GDR can only be explained by inclusion of the $d_{5/2} \rightarrow f_{7/2}$ single-particle excitation into the calculation. The energy location of the $f_{7/2}$ orbital which is needed to obtain the observed peak is in agreement with experimental results from elastic proton scattering[10,12] which puts the $f_{7/2}$ strength near 18 MeV.

The authors would like to thank J. D. Vergados for clarifying some questions about phases.

*Work supported in part by the National Science Foundation and the Atomic Energy Commission.

†Present address: Laboratoire Spectrometic Nucléaire, Strassburg, France.

[1]P. Paul, in *Proceedings of the Conference on Photonuclear Reactions and Applications, Asilomar 1973*, edited by B. L. Berman (Lawrence Livermore Laboratory, Univ. of California, Livermore, 1973), CONF-730301.

[2]R. O. Akyüz and S. Fallieros, Phys. Rev. Lett. 27, 1016 (1971).

[3]Renzo Leonardi, Phys. Rev. Lett. 28, 836 (1972).

[4]M. N. Harakeh, P. Paul, and K. A. Snover, preceding paper, Phys. Rev. C 11, 998 (1975).

[5]E. M. Diener, J. F. Amann, S. L. Blatt, and P. Paul, Nucl. Instrum. Methods 83, 115 (1970).

[6]T. Mo, R. A. Blue, and H. R. Weller, Nucl. Phys. A197, 290 (1972).
[7]W. J. O'Connell, Ph.D. thesis, Stanford Univ., 1970 (unpublished).
[8]N. W. Tanner, G. C. Thomas, and E. D. Earle, Nucl. Phys. 52, 45 (1964).
[9]H. P. Jolly, Jr., Phys. Lett. 5, 289 (1963).
[10]G. Hardie, R. L. Dangle, and L. D. Oppliger, Phys. Rev. 129, 353 (1963).
[11]B. M. Skwiersky, C. M. Baglin, and P. D. Parker, Phys. Rev. C 9, 910 (1974).
[12]G. F. Bertsch and S. F. Tsai, unpublished; S. Krewald and J. Speth, Phys. Lett. (to be published).
[13]T. T. S. Kuo and G. E. Brown, Nucl. Phys. 85, 40 (1966); private communication.
[14]B. Giraud, Nucl. Phys. 71, 373 (1965).
[15]E. Hayward, Photonuclear Reactions (NBS Monograph No. 118, 1970).
[16]R. E. Segel, Z. Vager, L. Meyer-Schützmeister, P. P. Singh, and R. G. Allas, Nucl. Phys. A93, 31 (1967).
[17]S. Fallieros and B. Goulard, Nucl. Phys. A147, 593 (1970).
[18]E. Hayward, B. F. Gibson, and J. S. O'Connell, Phys. Rev. C 5, 846 (1972).
[19]R. Leonardi and E. Lipparini, unpublished.