reaction, we obtain an upper limit of 3% for the neutron branch of He^8. If He^8 exists, this indicates that the transition to the 3.22-MeV level of Li^8 has a log *ft* value greater than 4.0 (using the He^8 mass estimated in Ref. 5).

To search for neutrons from B^{13}, the decay curve from the N^{15} target was reanalyzed with the addition of an 18.6-msec component and an upper limit of 5 μb was obtained. Estimating a $(p,3p)$ cross section from our previous work,[1] we obtain an upper limit of 0.3% for the delayed neutron branch of B^{13}, which is somewhat lower than the previous limit of Marques *et al.*[4]

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Study of the Gamma-Ray Spectra Emitted in the Resonance Capture of Neutrons by ^{19}F†

J. R. Bird,* J. A. Biggerstaff, J. H. Gibbons, and W. M. Good
Oak Ridge National Laboratory, Oak Ridge, Tennessee

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Gamma-ray spectra have been measured at the 27-keV (2^-) and the 49-keV (1^-) resonances of $^{19}F(n,\gamma)^{20}F$. The $E1$ transition to ground is virtually absent at both resonances, while the other $E1$'s have strengths that appear normal when compared with heavier nuclei in which the radiation widths are proportional to level spacing. A description is given of the two-parameter instrument by means of which it is possible to measure simultaneously the neutron energy (flight time) and gamma-ray pulse-height spectra for radiative neutron capture.

I. INTRODUCTION

Spectra of prompt gamma rays emitted following capture of thermal neutrons by nuclei have been studied for more than ten years.[1] These studies have (a) revealed the location of many hitherto unobserved bound states, (b) established spins, parities and lifetimes of states in certain situations where conditions were particularly favorable, and (c) revealed by means of certain systematic features of the spectra, characteristic trends in nuclei with mass number and aspects of the mechanism of neutron capture.

Measurements of the type just described have utilized the copious sources of thermal neutrons that reactors provide. As interest in the subject has grown and instrumentation progressed, the study of *resonant* neutron-capture spectra became possible; the first success was with electron linac neutrons,[2] but more recently reactor neutrons have also been successfully employed.[3] These experiments have been most successful at neutron energies below about 2 keV, although some work has been done with fast neutrons.[4]

It would be especially interesting to be able to extend (n,γ) measurements into the keV region and higher because many resonance levels with known angular momentum and parity occur in nuclei for which level spacings are of the order of kilovolts. Such nuclei appear either at the lower quarter of the nuclear-mass scale or in the neighborhood of closed shells. Study of neutron-capture gamma-ray spectra in such nuclei affords at once the opportunity of studying the mechanism of neutron capture at resonances of known spin and parity and of assigning spin and parity to additional levels.

In the earliest studies on thermal-neutron capture,[5] it was found that strong ground-state gamma rays were the exception rather than the rule. This finding might at first have been expected on the basis of the statistical model that the transition probabilities are expected to be proportional to the density of final states. However, strong gamma rays were observed to low-lying levels when those levels were p states according to the shell model. These transitions generally corresponded to $E1$ transitions. Particularly notable exceptions were ^{20}F and ^{28}Al in which strong high-energy transitions of type

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* Present address: Australian Atomic Energy Commission, Sutherland, N. S. W., Australia.

[1] L. V. Groshev, V. N. Lutsenko, A. M. Davidov, and V. I. Pelekhov, *Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, Inc., New York, 1959).

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$M1$ appeared.[5,6] Stripping measurements had established in the case of ^{20}F that the low-lying levels were positive parity,[7,8] with the lowest negative-parity levels at 2.87 and 2.97. It was observed that $E1$ transitions to the latter (which might have been expected to be strong for thermal capture) were not detected. In spite of this type of behavior, intensity arguments are often used in an attempt to deduce the spins and parities of levels.

For ^{20}F the suggestion[9] was made that the "thermal" spectrum might actually have been dominated by the presence of resonant-neutron capture of opposite parity. The resonances in question have been observed in neutron transmission studies and their spins, parities and widths are well established. We describe in this paper a study of the capture gamma-ray spectra of the 27- and 49-keV resonances in ^{19}F(n,γ) and describe the techniques for making such measurements.

II. EXPERIMENTAL TECHNIQUE

The basic difficulty encountered in extending capture measurements into the keV neutron-energy range is that of intensity. Capture cross sections are typically $>10^4$ mb for thermal neutrons, $<10^2$ mb for keV neutrons and available neutron fluxes are $\lesssim 10^{13}$ cm^{-2} sec^{-1} for thermal neutrons but $\leq 10^4$ cm^{-2} sec^{-1} for keV-range neutrons. Thus, high-resolution instruments such as pair spectrometers or crystal diffraction spectrometers, suitable in the case of thermal capture, must be replaced by relatively poor resolution but much more efficient detectors (such as a total-absorption spectrometer) when dealing with kilovolt neutrons. The system here described consists of a terminal pulsed Van de Graaff accelerator, a large NaI(Tl) total-absorption gamma-ray spectrometer, and a two-parameter analysis system for simultaneous recording of *counts* versus *gamma-ray energy* versus *neutron flight time.*

Protons from a duo-plasmatron ion source[10] were pulsed in the terminal of the ORNL 3-MV Van de Graaff so as to yield proton bursts of $\leq$10-nsec duration at a repetition rate of 1 Mc/sec. Neutrons were produced using the ^{7}Li$(p,n)^7$Be reaction near threshold.[11–13] Neutron flight paths ranging from 15 to 51 cm were employed. The time resolution obtained using the NaI detector and a crossover pick-off circuit was approximately 15 nsec (full width at half-maximum) for a decade range in pulse height.

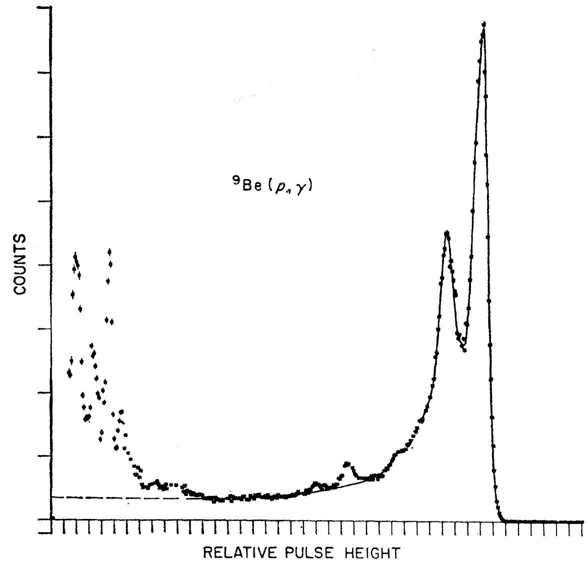

FIG. 1. Response function for the 9 in.×12 in. NaI crystal to the 7.48-MeV ground-state gamma rays from proton capture on ^{9}Be. Peaks that depart from the solid or dotted curve are due to other gamma rays.

The spectrometer was a 9 in.×12 in. NaI(Tl) crystal. The light pulses were viewed by six photomultipliers connected in parallel. The crystal was housed in a 4-in.-thick lead cask, surrounded on all sides (both inside and outside) except the front by a total of several inches of paraffin mixed with boron or lithium. Gamma rays from the capture sample passed through a neutron shield (^{6}LiH) and were collimated by an 8-in.-diam aperture in the lead shield. The crystal axis was about 100° from the forward direction. The solid angle subtended by the collimated spectrometer was about 2.6% of 4π. Under these conditions, the kinematics of the ^{7}Li(p,n) reaction were such that it was possible to produce at least 50-keV neutrons without the primary neutrons bombarding the shielding. If greater than 50-keV neutrons are produced, the background in general rises.

For interpretation of spectra it is necessary to know in detail the spectrometer's response to monoenergetic gamma rays. These were determined by means of (p,γ) or $(p,\alpha\gamma)$ reactions on ^{9}Be, ^{12}C, ^{13}C, ^{15}N, and ^{19}F, which yielded reasonably pure lines at 7.48, 2.365, 9.17, 4.43, and 6–7 MeV, respectively.[7] For such measurements, the proton target position was moved to the site of the neutron target by suitably extending the proton beam tube. A typical response curve for a monoenergetic gamma ray through the 8-in. collimator is shown in Fig. 1. Response curves for other energies were obtained by interpolation techniques.

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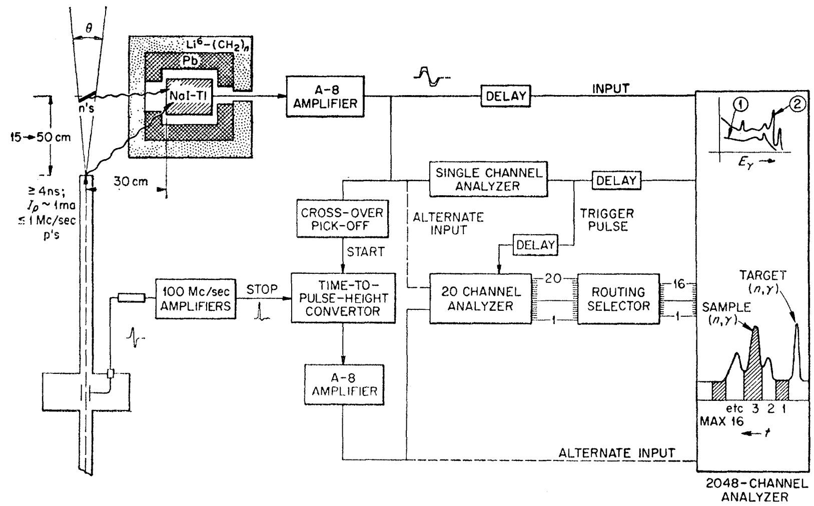

FIG. 2. Block diagram of the two-dimensional time versus gamma-ray pulse-height spectrometer.

The proton-beam pulsing system has been described elsewhere.[14] The two-parameter analyzer was rather a rudimentary one in that it consisted of a RCL-2048 combined with a 20-channel stacked discriminator analyzer. The RCL analyzer is a vacuum tube analyzer modified so that it could be gated into 2, 4, 8, or 16 memory sections. It was thus possible to utilize the 20-channel analyzer to furnish the gate signals, and in this way to use the system as a 16×128 channel analyzer. By interchanging the time and gamma pulse inputs and repeating a measurement it was possible to operate with an effectively larger number of channels per parameter. Figure 2 is a block diagram of the electronics for the system.

III. MEASUREMENTS

The sample was in the form of a 6-in.-diam disk of CF_2, $\frac{1}{2}$ in. thick. The neutron flight path was 51 cm.

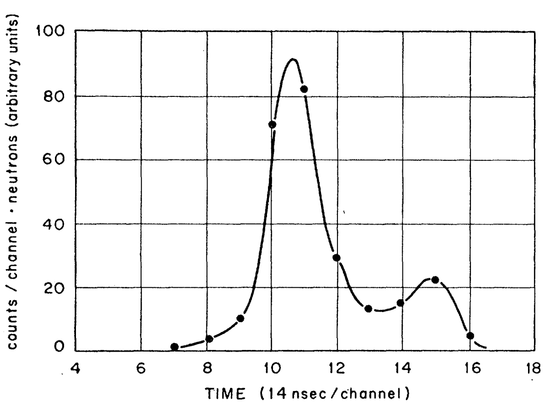

FIG. 3. Time spectrum of $^{19}F(n,\gamma)^{20}F$ as observed on the 20-channel dimension simultaneously with the gamma-ray spectra in the 128-channel dimension. The larger peak corresponds to the 27-keV resonance and the smaller one to the 49-keV resonance.

Data were recorded in the 16×128 channel analyzer with neutron flight time recorded in the 16-channel dimension and gamma-ray energy in the 128-channel dimension. The background-corrected time spectrum (for all gamma-ray energies) is given in Fig. 3. Neutron flight time is measured from right to left. Counts per channel were normalized for equal neutron intensities by use of a cadmium standard for relative flux determination. Two well-known resonances appear at neutron energies of 27 and 49 keV.

The dependence of background on flight time was obtained from measurements with a carbon sample which has negligible capture at these neutron energies. The gamma-ray energy dependence of the background did not change with flight time for energies between 2.5 and 7 MeV. Background-corrected results for gamma-ray spectra for each of the two resonances are shown in Figs. 4 and 5.

Gamma-ray intensities were obtained by least-squares fitting of response curves to the data under the constraint of allowable values for the individual gamma rays. Corrections were made for the efficiency of the spectrometer and the absorption of gamma rays in the ^{6}LiH shield. The results are given in Table I together with the results for thermal-neutron capture.[6,15]

The third and fourth columns in Table I give the energy, angular momentum and parity of low-lying levels in ^{20}F which can be reached by transitions with the observed energies.

In Table II partial radiation widths are given for the 27- and 49-keV resonances by assuming total radiation widths of 1.1 and 1.6 eV, respectively.[16] For thermal capture a "radiation width" of 1 eV was used and although there is little justification for this value it allows a comparison to be made between the thermal and resonance results. The gamma-ray widths are expressed as fractions of the extreme single-particle

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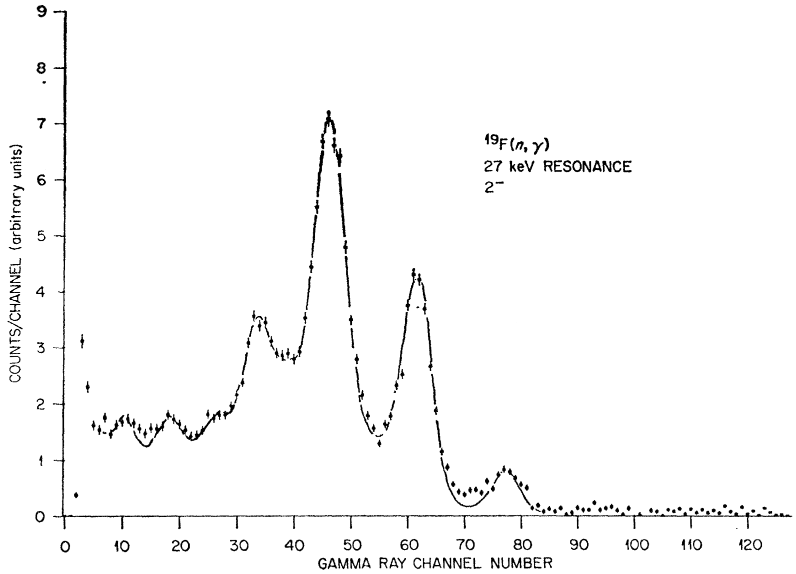

FIG. 4. Pulse-height spectrum from gamma rays observed at the 27-keV neutron resonance $^{19}F(n,\gamma)$. The solid curve is a pulse spectrum based upon individual line shapes and the gamma rays in Table I.

"Weisskopf" width, viz.,

$$\Gamma_{\gamma_i}(E1)=|\mathfrak{M}(E1)|^2\Gamma_{\gamma_w}(E1),$$

$$\Gamma_{\gamma_i}(M1)=|\mathfrak{M}(M1)|^2\Gamma_{\gamma_w}(M1),$$

where the "single-particle" widths (in eV) are obtained[17] from

$$\Gamma_{\gamma_w}(E1)=0.068A^{2/3}E_\gamma^3,$$

$$\Gamma_{\gamma_w}(M1)=0.021E_\gamma^3, \quad E_\gamma=[\text{MeV}]$$

by using a nuclear radius $r_0=1.2$ F. Wilkinson[17] found

TABLE I. Relative intensities of the gamma rays emitted following neutron capture by ^{19}F. Gamma-ray energies (Col. 2) observed in this experiment, excepting those given in parentheses,[a] are estimated to be accurate to $\pm 1\%$. Column 3 gives the probable final states observed in the transitions. Column 4 gives the probable J^π assignments according to Rout *et al*,[b] and Nadjakov.[c]

	Interpretation			Intensities as gammas per 100 captures			
				Thermal $0^+, 1^+$ 6.60 MeV		27 keV 2^- 6.63 MeV	49 keV 1^- 6.65 MeV
	E_γ (MeV)	E_{ex} (MeV)	J^π				
1	6.60	0	2^+	8.5[c]	25[d]	<1	<1
2	6.019	6.019		8	13		
3	5.95	0.65	$1^+, 2^+, 3^+$			4	5
4	5.77	0.83	$1^+, 2^+, 3^+$				(2)
5	5.65	0.99	$1^+, 2^+, 3^+$				5
6	(5.59)	1.06	$(0^+), 1^+$	5	20		
7	5.54						
8	5.32	1.31	$1^+, 2^+, 3^+$	7.5	23	25	5
9	5.28						
10	5.10	5.04	$0^-, 1^-, 2^-$		14	3	
11	(4.83)					1	3
12	4.66	1.97				22	5
13	4.60	2.05	$1^+, 2^+, 3^+$			25	20
14	(4.50)			(5)			
15	4.38	2.22	$1^+, 2^+, 3^+$			4	6
16	4.15	4.08	$0^+, 1^+$	(1)		4	4
17	3.95	3.95		4			
18	3.74	2.87	$2^-, 3^-, 4^-$			3	
19	3.61	2.97	$0^-, 1^-, 2^-$				11
20	3.52	3.52	$0^+, 1^+$	15		5	10
21	(3.24)			(2)			
22	3.11	3.52					
23	3.02	2.97		20			

[a] Values given in parentheses indicate doubt as to the existence of this gamma ray.
[b] V. M. Rout, W. M. Jones, and D. G. Waters, Nucl. Phys. **45**, 369 (1963).
[c] E. G. Nadjakov, Nucl. Phys. **48**, 492 (1963).
[d] Averages of values given in L. V. Grocher *et al.*, *Atlas of Gamma-Ray Spectra from Radiation Capture of Thermal Neutrons* (Pergamon Press, Inc., New York, 1959).

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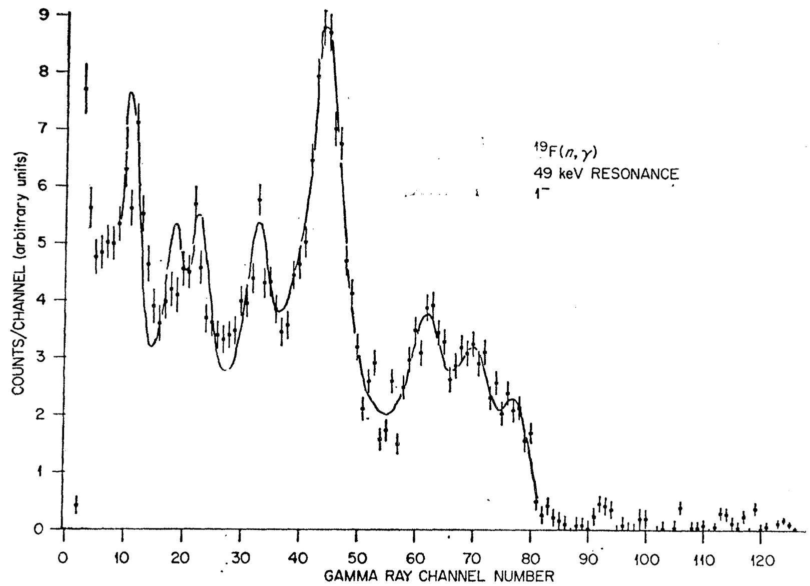

FIG. 5. Pulse-height spectrum from gamma rays observed at the 49-keV neutron resonance $^{19}F(n,\gamma)$. The solid curve is a pulse spectrum based upon individual line shapes and the gamma rays in Table I.

that in this representation the average value of the "transition strength," $|\mathfrak{M}|^2$ for $E1$ and $M1$ radiation was about 0.045 and ≈ 0.15, respectively, with a rather wide distribution about the mean value in the case $M1$. Our results for the resonances indicate values for $\langle|\mathfrak{M}|^2\rangle$ of 0.003 and 0.245 respectively, for $E1$ and $M1$ radiation.

Thus the $M1$ reduced widths appear about "normal" compared to Wilkinson's survey of nuclei with $A \leq 20$ *but the* $E1$ *reduced strengths have of the order of 5% of the value found in lighter elements.*

Wilkinson showed that the distribution of $E1$ reduced widths surveyed by him were about what would be expected for an intermediate coupling description of the nuclei in question. The small values for $|\mathfrak{M}(E1)|^2$ in Table II for ^{20}F may be indicative of failure, correspondingly, of the intermediate coupling model. As a matter of fact, it has been shown that in the region of ^{20}F, the intermediate coupling, even when employing the effective interactions of Talmi, is no longer valid.[18] From another point of view, it is possible to compare the reduced widths in ^{20}F with those in heavier nuclei in the manner adopted by Bartholomew.[19] In this comparison, the reduced widths are related to the partial widths

TABLE II. Reduced radiation widths for the gamma-ray transitions listed in Table I.[a] Uncertainties in the partial radiative widths range from about ±10% for the most intense lines to ±25% for intermediate intensity lines. Intensities in parentheses imply large uncertainties (±50%).

			Thermal ($J^\pi=0^+, 1^+$)			27 keV, $J^\pi=2^-$ $\Gamma_\gamma=1.1$ eV			49-keV resonance $J^\pi=1^-$, $\Gamma_\gamma=1.6$ eV		
E_γ (obs) (MeV)	E_γ (initial) (MeV)	Multipole of E_γ (initial) for negative parity capture	$\Gamma_{\gamma i}$ (meV)	$\lvert\mathfrak{M}(E1)\rvert^2 \times 10^3$	$\lvert\mathfrak{M}(M1)\rvert^2 \times 10^3$	$\Gamma_{\gamma i}$ (meV)	$\lvert\mathfrak{M}(E1)\rvert^2 \times 10^3$	$\lvert\mathfrak{M}(M1)\rvert^2 \times 10^3$	$\Gamma_{\gamma i}$ (meV)	$\lvert\mathfrak{M}(E1)\rvert^2 \times 10^3$	$\lvert\mathfrak{M}(M1)\rvert^2 \times 10^3$
6.60	6.60	$E1$	250		41.5	(<15)	(<0.10)		(<20)	(<0.14)	
5.95	5.95	$E1$				55	0.52		96	0.90	
(5.77)	(5.77)	$E1$							(48)	(0.50)	
5.65	5.65	$E1$							96	1.07	
(5.59)	(5.59)	$E1$							(<48)	(<0.55)	
5.54	5.54	$E1$	200		56						
5.32	5.32}	$E1$				286	3.8		112	1.5	
5.28	5.28}		230		74						
5.10	1.6	$M1$	140	82		33		465			
(4.83)	(4.83)	...				(11)			(48)		
4.66	4.66	...				253			112		
4.60	4.60	$E1$				286	5.6		416	8.5	
4.38	4.38	$E1$				44	1.0		128	3.0	
4.15	2.55	$E1$				44	1.2		80	2.2	
3.74	3.74	$M1$				33		30			
3.61	3.61	$M1$							240		240
3.52	3.11	$E1$				55	3.7		208	14	

[a] Excluding thermal results, the average values are $\langle|\mathfrak{M}(E1)|^2\rangle = 3\times10^{-3}$ and $\langle|\mathfrak{M}(M1)|^2\rangle = 245\times10^{-3}$.

[18] I. Unna, Phys. Rev. **132**, 2225 (1963).

[19] G. A. Bartholomew, *Electromagnetic Lifetimes and Properties of Nuclear States* (National Academy of Science and National Research Council, Washington, D. C., 1962).

by

$$\Gamma_{\gamma_i}(E1)=k(E1)E_\gamma^3A^{2/3}D,$$
$$\Gamma_{\gamma_i}(M1)=k(M1)E_\gamma^3D,$$

where Γ is in eV, E and D are in MeV. Thus

$$k(E1)=0.068|\mathfrak{M}(E1)|^2/D;$$
$$k(M1)=0.021|\mathfrak{M}(M1)|^2/D.$$

The average value of $k(E1)$ for ^{20}F for results given in Table II, taking $D=40$ keV, is about 5×10^{-3}, in agreement with the average value of Bartholomew's survey. Thus we see that compared with lighter nuclei (mostly proton capture) ^{20}F has a small ($E1$) radiation width, but, when compared with heavier nuclei in which level spacing is taken into account, the radiation width for ($E1$) is about normal. It must be noted in the same context, however, that the average $k(M1)$ for ^{20}F, 0.13, is more than fifteen times the average according to the Bartholomew survey. Bartholomew has pointed out[19] that the probability of finding gamma rays with values of k ten times the average is very small provided the reduced widths do in fact follow a chi-squared distribution. Our results may indicate therefore a significant $M1$ enhancement.

IV. DISCUSSION

The results in Tables I and II show a dramatic difference between s-wave (thermal) and p-wave neutron capture (two resonances). It is clear, to begin with, that the thermal results cannot be explained (as suggested by Gabbard *et al.*[9]) by the possible presence of resonance neutrons in the thermal beams. A difference between the thermal and resonant gamma-ray spectra is to be expected since most of the low-lying levels in ^{20}F have positive parity and electric dipole transitions are possible to these levels following p-wave resonant capture but not following s-wave thermal capture. Thus, most of the strong transitions observed in the two resonance spectra are electric dipole and their strengths are distributed around the average value observed by Bartholomew. The same is not true for thermal capture and there are a number of singular features which arise out of experiments involving ^{20}F:

(a) For thermal capture, strong transitions are observed to the ground state and to the level at 1.06 MeV, although these transitions involve no parity change ($M1$ and/or $E2$). In contrast, transitions are lacking to these and other levels for resonance capture, although such transitions would be electric dipole.

(b) The strongest gamma rays observed for resonance capture include transitions to levels at 1.31 and 1.97 MeV which do not show characteristic stripping distributions when studied by the ^{19}F$(d,p)^{20}$F reaction. The highest reduced width for $l_n=2$ in the (d,p) reaction is observed for the 2.05-MeV level which also receives strong transitions in both resonances. The ground state shows very weak stripping. Thus there is no clear correlation between the results for (n,γ) and (d,p) reactions.

(c) Fluorine has a large p-wave strength function that suggests that the observed p-wave resonances may have dominant single-particle configurations. If, as a result of this, strong transitions occur to other single-particle states a correspondence would be expected with the stripping results.

^{20}F has three neutrons and one proton outside closed shells and its structure is expected to be relatively complex. Also, neighboring nuclei are known to be deformed so that collective motions may have a strong influence on the behavior of ^{20}F. A description of the ground state of ^{20}F in terms of a modified multiplet shell model has been given by Dazai,[20] and in terms of the rotational model by Macfarlane and French,[21] and Kurath.[22] Both descriptions predict negligible reduced width for the ground state in the (d,p) reaction and a complex configuration for the ground state. This may explain the absence of ground-state transitions in resonance capture, but not the strong transition for thermal capture.

The absence of known positive-parity levels near 6-MeV excitation (apart from possible weak levels observed by Hibdon[23]) makes it unlikely that the thermal-capture cross section is dominated by one resonance. If a number of distant levels contribute, random fluctuations in matrix elements for a particular transition would tend to be averaged out and would not provide a suitable explanation for the thermal-capture spectra.

V. CONCLUSIONS

^{20}F shows evidence for both single-particle and collective type level configurations and a corresponding complexity in the observed gamma-ray transition rates. There are some points of similarity between the results for p-wave neutron capture and the $l_n=2$ stripping results for the (d,p) reaction in ^{19}F. However, most of the neutron-capture results do not show this similarity and there is a clear need for further study, both theoretical and experimental, in order to throw more light on the properties of the ^{20}F nucleus. The ability to make measurements for individual neutron resonances makes possible a considerable extension to the amount of information that can be obtained for such nuclei.

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[23] C. Hibdon, Phys. Rev. **133**, B353 (1964).