$C^{12}(\gamma,n)C^{11}$ reaction but a break at 21.6 Mev in our curve might be a combination of the last two resonances. On the basis that only "strong" breaks are likely to be resolved (except possibly near threshold), it is reasonable to suppose that most of the corresponding resonances involve electric dipole absorption. Thus the strong resonances in C^{12} would have one unit of angular momentum and odd parity. It is believed that the ground state of B^{11} is $\frac{3}{2}^-$. Thus the capture of S-wave protons should lead to 1^- and 2^- levels in C^{12}, and the capture of protons with higher orbital angular momentum would lead to additional kinds of states. For this reason one would expect many more resonances to be found in the $B^{11}(p,n)C^{11}$ reaction than in the $C^{12}(\gamma,n)C^{11}$ reaction. The fact that the opposite is true is somewhat disturbing, but Blaser *et al.* did not have high-energy resolution for their protons, and it is possible that they missed many resonances.

Goward and Wilkins[12] have examined the $C^{12}(\gamma,3\alpha)$ and $O^{16}(\gamma,4\alpha)$ reactions using nuclear plates and have found fine structure in the cross sections for these reactions. In the $C^{12}(\gamma,3\alpha)$ reaction they found cross section peaks at 19.6, 20.7, 21.9, 23.1, and 24.3 Mev [as well as some below our (γ,n) threshold]. They were not able to resolve any levels in the oxygen reaction over the energy region covered by our experiments. It is difficult to estimate the accuracy to which the positions of these C^{12} levels have been determined. The authors state that their resolution was probably of the order of 1 Mev, and possibly for this reason our results indicate about twice as many levels in the same energy range.

[12] F. K. Goward and J. J. Wilkins, Atomic Energy Research Establishment Report A.E.R.E. G/M 127 Harwell, Berks, England, March 24, 1952 (unpublished).

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Fine Structure in the Neutron Yield Curves from (γ,n) Reactions in Li^7, C^{12}, O^{16}, and F^{19}

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Fine structure previously observed in the β^+ activation curves of C^{11} and O^{15} resulting from the betatron induced reactions $C^{12}(\gamma,n)C^{11}$ and $O^{16}(\gamma,n)O^{15}$ is shown to be present in the neutron yield curves from these reactions by detecting the emitted neutrons. The position of this fine structure as a function of betatron operating energy is the same in both cases to within experimental accuracy. The $Li^7(\gamma,n)Li^6$ and $F^{19}(\gamma,n)F^{18}$ were examined and discontinuities in the neutron yield curves were found at 9.6, 10.8, 12.4, 14.0, and 17.5 Mev for the first reaction and 11.0, 11.5, 11.9, and 15.3 for the second.

INTRODUCTION

IN the accompanying paper we report on the fine structure observed in the *activity* curves resulting from the $C^{12}(\gamma,n)C^{11}$ and $O^{16}(\gamma,n)O^{15}$ reactions induced by betatron irradiation. In those experiments the activity of the residual nuclei C^{11}(20.5 min) and O^{15}(2.0 min) are plotted as a function of maximum bremsstrahlung energy. Since the presence of fine structure in the curves was indicated by changes in slope, their real existence and precise location requires that they be reproduced under varying experimental conditions and with different measuring techniques. For this reason and because many of the light nuclei do not have convenient half-lives for measuring their residual activity an apparatus previously built for detecting neutrons emitted in (γ,n) reactions[1] was slightly modified to give a high counting rate for improved accuracy and neutron yields for a number of elements were examined for fine structure. The results of these measurements are reported in this paper.

EXPERIMENTAL TECHNIQUES

To measure the fine structure reported in this paper an energy stability of ± 5 kev in the control of the maximum bremsstrahlung energy is imperative during any one irradiation. A dispersion of over ± 30 kev, though not wiping out this fine structure, certainly makes it very difficult to detect. Recent experiments have indicated that a change of 1°C in the operating temperature of the betatron core, or a change in frequency of 0.15 cps in our 180-cps supply corresponds to an energy change of about 5 kev. All measurements reported were taken under conditions where we believe a stability of ± 5 kev was achieved.

A sketch of the experimental setup with all pertinent dimensions is shown in Fig. 1. The operation of this system has been previously described.[1] To obtain high counting rates two BF_3 counters were connected in parallel and large samples were used. Photon absorption in the samples does not alter the neutron yield curve

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[1] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).

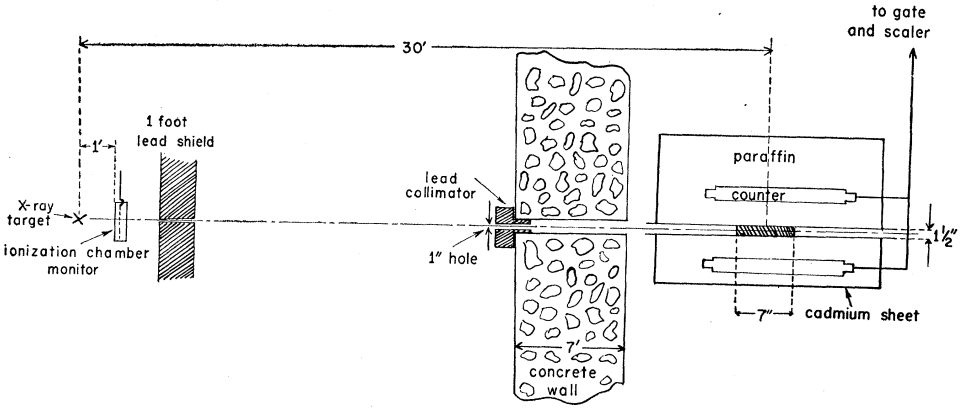

FIG. 1. Experimental arrangement.

shape, since at these energies the effective electronic absorption coefficients do not change appreciably with energy.[1] The background counting rate amounted at most to 1 percent of the number of recorded counts in an actual run.

Monitoring of the delivered dose was done with a flat chamber close to the betatron. Separate runs were also made with a monitor which subtended the same solid angle at the betatron target as the sample had under irradiation conditions. This convinced us that the presence of the observed fine structure was not the result of our monitoring procedure.[2]

RESULTS

The neutron yield curves for the reactions $Li^7(\gamma,n)Li^6$ and $F^{19}(\gamma,n)F^{18}$ are shown in Figs. 2 and 3. The discontinuities or "breaks" are clearly visible and the energies at which they occur are marked on the figures.

The results of these experiments are summarized in Table I. Taylor, Robinson, and Haslam[3] have examined the fine structure in the $F^{19}(\gamma,n)F^{18}$ activation curve by measuring the 1.87-hr F^{18} positron activity. Their results are also included in Table I. Since their method is more sensitive near threshold, they have been able to resolve two extra breaks at 10.6 and 11.2 Mev. They also found a level at 12.2 Mev which careful experiments failed to reveal in our work. This is particularly puzzling since this level is in an energy region where our neutron detection method has a sensitivity equal to the beta detection method.

In order to prove that the breaks were in no way dependent on our experimental technique or the characteristics of the betatron, measurements were repeated on the neutron yields for lithium and fluorine in the energy range from 13 to 15 Mev. These measurements were made on the same night when experimental conditions might be expected to have remained reasonably unchanged. Each curve was measured twice in two independent runs. The results are shown in Fig. 4. As expected from our previous results, it is apparent from this figure that a break occurs at 14 Mev in lithium but not in fluorine. This conclusion is substantiated in a more concise way through fitting straight lines by least squares to the points right and left of the arrow (Fig. 4).

The neutron yield curve for the $C^{12}(\gamma,n)C^{11}$ reaction is shown in Fig. 5. This reaction had been previously examined by detecting the positron activity from C^{11} and present results confirm those previously obtained, within the limitations of our method. Some of the levels were not found exactly in the same position, but this depends on the calibration of the betatron energy scale at the time of the experiment and variations of ± 0.1 Mev are certainly to be expected. A similar experiment on the neutron yield from the $O^{16}(\gamma,n)O^{15}$ reaction confirmed the breaks previously found by residual activity at 19.1, 20.7, and 21.9 Mev. The results of these measurements are shown in Fig. 3 of the preceding paper.

TABLE I. Positions of breaks in lithium and fluorine neutron yield curves and comparison with other data.

Lithium		Fluorine		
			$F^{19}(\gamma,n)F^{18}$	
$Li^7(\gamma,n)Li^6$ (Mev)	$Li^7(\gamma,t)He^4$ (Mev)	$O^{18}(p,n)F^{18}$ (Mev)	Present work (Mev)	Taylor *et al.*[a] (Mev)
9.6	9.6	10.59	—	10.6
10.8	—	10.84	—	—
12.4	—	10.99	11.0	10.9
14.0	~14	11.07	—	—
17.5	16.7	11.18	—	11.2
		11.27	—	—
		11.6	11.5	11.5
		12.0	11.9	11.9
		—	—	12.2
		12.8, 13.3, 13.8, 14.3	—	—
		—	15.3	15.3

[a] See reference 3.

[2] It has been found by some investigators (D. W. Kerst, private communication) that under certain conditions the γ-ray beam suffered a sudden change in its direction of emergence from the betatron. This change was related to the energy at which the betatron was operated. Such sudden displacement of the beam would result in a break in the activation curve if the monitor and sample were not in line with the betatron target even though each subtended the same angle at the target. In our case the breaks were reproducible under a variety of monitoring procedures.

[3] Taylor, Robinson, and Haslam, Can. J. Phys. **32**, 238 (1954).

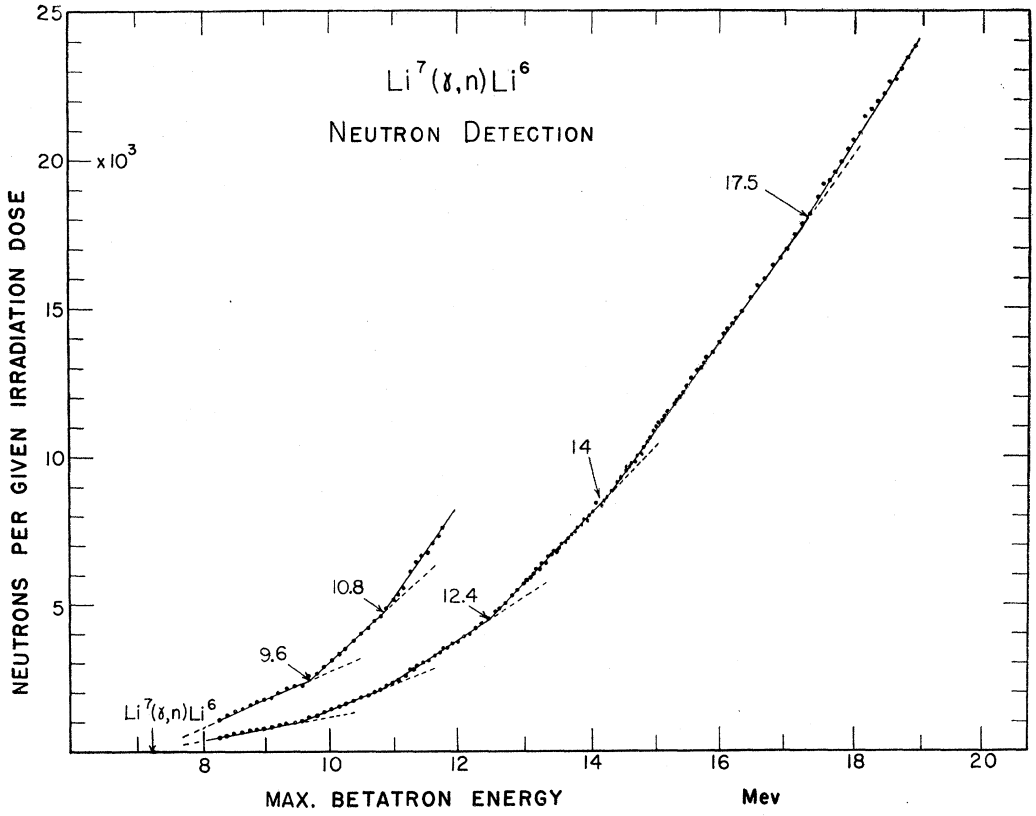

FIG. 2. Neutron yield curve of lithium showing the positions of the observed breaks. The break at 14 Mev is shown in Fig. 4 in greater detail.

A level found previously at 20.7 Mev in carbon has been carefully examined in steps of 11 kev, whereas usually steps of 44 kev are used. The results of this more detailed experiment are shown in Fig. 6 and by

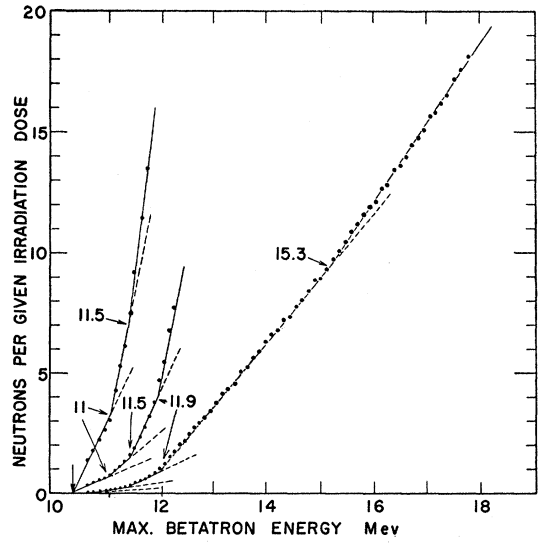

FIG. 3. Neutron yield curve of fluorine showing the positions of the observed breaks. The lower-energy region is shown on an enlarged scale.

themselves constitute strong evidence for the existence of "breaks" in neutron yield curves. The difficulty in fitting a smooth curve to the points is evident.

DISCUSSION

We interpret the breaks in these curves to indicate that nuclear photon absorption takes place, at least in part, into discrete levels in the target nuclei. The reason for this belief stems from the following considerations: the cross section for the nuclear reaction may be written as follows,

$$\sigma_{\gamma,n}=\sigma_c(\gamma)G(n),$$

where $\sigma_{\gamma,n}$ is the cross section for the (γ,n) reaction, $\sigma_c(\gamma)$ is the cross section for photon absorption, and $G(n)$ is the probability that a neutron will be emitted in preference to any other de-excitation process. The number of neutrons emitted during any betatron irradiation is given by the equation

$$\alpha(E_0)=\int_0^{E_0} P\sigma_{\gamma,n}dE=\int_0^{E_0} P\sigma_c(\gamma)G(n)dE,$$

where P is the number of photons of energy E incident on the sample per unit area when the betatron is operated at an energy E_0. The presence of fine structure

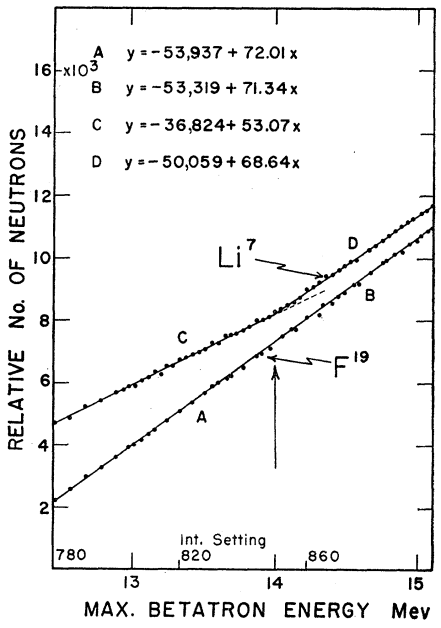

FIG. 4. A comparison of the neutron yields from fluorine and lithium in the energy range of 12 to 15 Mev. Each sample was measured twice in two independent runs and all four measurements were made in the same evening. The presence of a break in one curve and not in the other definitely establishes that the breaks are characteristic of the samples used. That is, they are not the result of instrumentation. The equations of straight lines fitted by least squares to the four parts A, B, C, and D are given in the upper part of this curve. These equations show that the slopes in A and B are the same, to within experimental accuracy, but are different in C and D.

in $\alpha(E_0)$ can thus be attributed to experimental technique or discontinuities in P, $\sigma_c(\gamma)$, or $G(n)$. The various experiments reported in this note eliminate any effect due to technique or P, and thus the observed breaks have their origin in either $\sigma_c(\gamma)$ or $G(n)$.

It is difficult to see how discontinuities in $G(n)$ can result in an increase in $\alpha(E_0)$ with energy. The usual picture is to visualize the outset of new competing processes with increasing energy, thereby causing a decrease in $\alpha(E_0)$. We are thus forced to conclude that the observed discontinuities imply fine structure in $\sigma_c(\gamma)$, that is, discrete photon absorption levels in the parent nucleus.

Applying the same type of analysis as in the case of C^{12} and O^{16}, it is possible to calculate the approximate integrated cross section $G\int\sigma_i dE$ associated with each of these levels. The values so calculated are summarized in Table II. From Eq. (4) of the previous paper it will be seen that the value of $P(E_i,E_0)$ near the bremsstrahlung peak is necessary for such calculations. This isochromat is not known with any degree of accuracy and the values listed in Table II are probably not accurate to better than a factor of 2.

TABLE II. Integrated cross section of the levels.

Lithium		Fluorine	
E_i (Mev)	$G\int\sigma_i dE$ (Mev-barn)	(Mev)	$G\int\sigma_i dE$ (Mev-barn)
9.6	0.2×10^{-3}	11.0	0.2×10^{-3}
10.8	0.3	11.5	0.3
12.4	0.7	19.5	0.9
14.0	0.6	15.3	0.5
17.5	0.8		1.9×10^{-3}
	2.6×10^{-3}		

The sum of the integrated cross sections for these levels may be compared to the same cross section previously calculated by the photon difference method[4] from the activation curves as if they had no fine structure. In the case of lithium we find ~0.003 Mev-barn for the levels and 0.020 Mev-barn for $\int_0^{17.5}\sigma_{\gamma,n}dE$.[1] The fluorine levels yield a sum of 0.002 Mev-barn,[5] whereas the integrated $\sigma_{\gamma,n}$ cross section to 15.5 Mev (region over which levels are summed) is 0.010 Mev-barn, estimated from the curve published by Horsley, Haslam, and Johns.[6] The reasons for the large difference in these values is not known at present. The use of the photon difference method to evaluate the exact cross-section shape may not apply to the reactions being studied here, but should certainly give the correct integrated cross section corresponding to the observed activation curve. On the other hand, our measurements have surely detected all the larger levels in the energy region investigated. We are thus led to conclude that there are many weak levels which have not been resolved or

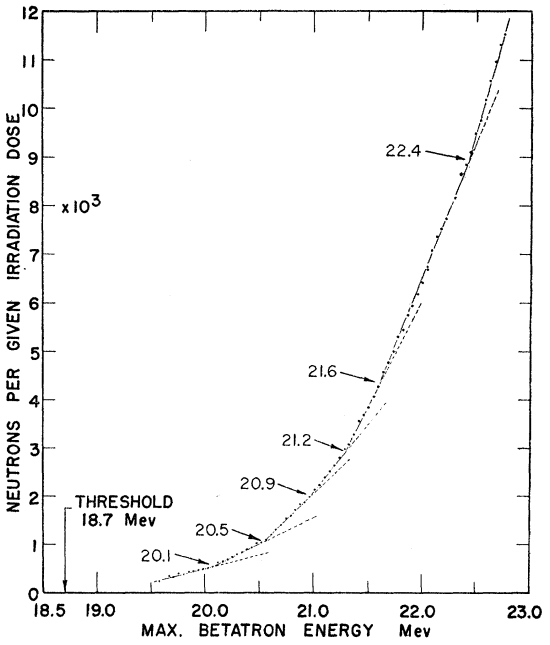

FIG. 5. Neutron yield curve from the reaction $C^{12}(\gamma,n)C^{11}$. The positions of the breaks are the same to within experimental accuracy as found by measuring the residual activity.

[4] L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).
[5] Contributions from the levels at 10.6 and 11.2 Mev found by Taylor *et al.* (see reference 3) have been included in this value.
[6] Horsley, Haslam, and Johns, Phys. Rev. **87**, 756 (1952).

that the levels observed are superposed on a continuum of photon absorption.

From the foregoing discussion, it will be seen that our work to date constitutes only a spectroscopic exploration of the absorption levels in the nuclei investigated. Some of the levels observed by us are substantiated by other measurements. Titterton and Brinkley,[7] working with photographic plates, obtained some levels in the absorption of γ rays by Li^7 nuclei. They measured the reaction $Li^7(\gamma,t)He^4$ and obtained levels at the energies 9.6 and 16.7 Mev with an unresolved level around 14 Mev. We obtain levels in lithium at the energies of 9.6, 10.8, 12.4, 14.0, and 17.5 Mev. The significance of the greater number of levels found in the (γ,n) reaction compared with the (γ,t) reaction has been analyzed by Peaslee and Telegdi[8] in the light of the isotopic spin formalism. They conclude that the measurements favor the hypothesis of charge independence against that of charge symmetry.

Measurements of fluorine using the $O^{18}(p,n)F^{18}$ reaction gave the levels listed in Table I.[9] Though considerably more levels were observed in this reaction, the agreement between the two sets of measurements is excellent. Since the ground state of F^{19} has a spin of $\frac{1}{2}$ and even parity, dipole photon absorption, which is the process usually assumed in these photonuclear reactions, will lead to levels of spin $\frac{1}{2}$, $\frac{3}{2}$ and *odd* parity. The ground state of O^{18} is given as 0^+.[9] Thus *s*-wave protons should lead to levels of $\frac{1}{2}^+$ and *p*-wave protons

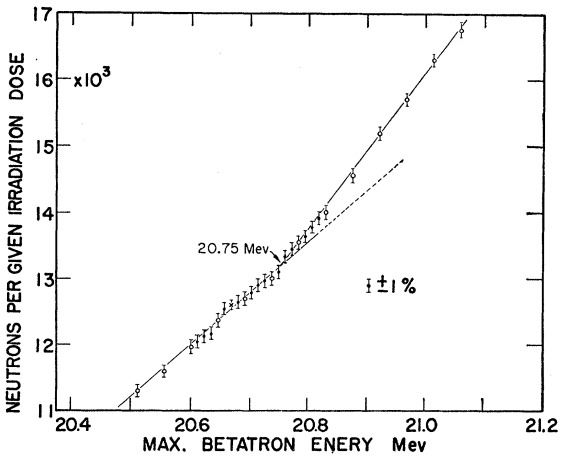

FIG. 6. $C^{12}(\gamma,n)C^{11}$. The break in the carbon yield curve at 20.75 Mev examined in detail.

to levels of $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Capture of protons of higher orbital angular momentum should result in levels of higher spin. Where the two sets of measurements overlap, the levels can be assumed to have either spin $\frac{1}{2}$ or $\frac{3}{2}$ and *odd* parity. Furthermore, these levels cannot be reached by *s*-wave protons or for that matter by any protons of even orbital angular momentum.

It may be worth while to report that measurements with copper and heavier elements failed to show fine structure in their activation curves. Owing to the crudeness of our experimental method we can only conclude that the excitation levels in these elements, if present, are very close together (closer than 0.2 Mev) or represent a negligible fraction of photon absorption.

[7] E. W. T. Titterton and T. A. Brinkley, Proc. Phys. Soc. (London) **66**, 398, 194 (1953).
[8] D. C. Peaslee and V. L. Telegdi, Phys. Rev. **92**, 126 (1952).
[9] F. Ajenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).