Eq. (6) (as well as certain terms which vanish in the statistical theory). An analysis to this end of existing theoretical eigenfunctions[8] is in progress.

In addition to the first and second moments, we have also studied the entire empirical distribution of G for many elements and found it to be fairly close to Gaussian in a majority of cases. The situation is illustrated in Fig. 1 for the 123 odd levels of Ru I. (The plot is actually a superposition of six histograms, one for each value of J.) On the theoretical side, we merely note that the discussion preceding Eq. (4) can evidently be extended to all higher moments, and this defines, at least formally, an entire distribution of G. The third moment is given by

$$\frac{\langle (G-\langle G\rangle)^3\rangle}{\langle (g-\langle g\rangle)^3\rangle}=\frac{8}{(N+2)(N+4)}, \tag{7}$$

which, like Eqs. (2) and (4), has the interesting form of a ratio of corresponding quantities in the LS and intermediate coupling schemes.

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"Breaks" in the Activation Curve of the $P^{31}(\gamma,n)P^{30}$ Reaction

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Discontinuities in the slope of the activation curve of the $P^{31}(\gamma,n)P^{30}$ reaction were found while using two large NaI(Tl) crystals to detect the annihilation gammas from P^{30}. These breaks correspond well with resonances found recently in the $Si^{30}(p,n)P^{30}$ reaction. The correspondence between breaks and known resonances in some light nuclei is discussed. Such a correspondence was found to exist in the case of N^{14}, F^{19}, and P^{31} and is in doubt in the case of C^{12}. The detection system used allowed accurate measurements of the thresholds of the $P^{31}(\gamma,n)P^{30}$ reaction (12.23±0.04 Mev) and the $Cl^{35}(\gamma,n)Cl^{34}$ reaction (12.66±0.04 Mev).

I. INTRODUCTION

SINCE 1952 "breaks" in the activation curves of some light elements irradiated with gamma rays from a betatron have been found. These breaks were attributed to narrow resonances in the photon absorption cross section.[1–6]

The breaks of P^{31} were found only by Schull[2] in 1955 with a poor counting efficiency using Geiger counters. (One break in P^{31} was found by Geller *et al.*[7]) However, mass data and detecting systems recently made available permit us to calibrate the energy scale of the betatron with a better precision than that obtained by Schull. Our sensitive way of detecting the activity combined with the good energy stability of the betatron allowed us to determine these breaks to ±40 kev.

Recently the doubt about the origin of the breaks, in general was emphasized when Gove *et al.*[8] could not find any resonance in the $B^{11}(p,n)C^{12}$ reaction although such a resonance should have been observed[5] because of the breaks detected in the $C^{12}(\gamma,p)B^{11}$. This will be discussed in the light of our results.

II. EXPERIMENTAL PROCEDURE

A. Activity Measurements

Cylindrical samples of red phosphorus, 4.2 cm in diameter and 5 cm in height, were placed at a distance of 25 cm from the anticathode of the betatron. After irradiation, the sample was placed between two NaI(Tl) crystals of 5-in. diam and 4-in. high. A single-channel analyzer and a coincidence circuit ensured that only the two annihilation gammas from the 2.5-min β^+ of P^{30} were counted.

In practice, the crystals were placed in a lead castle 15-cm thick. A brick of lead provided with a cylindrical hole to contain the sample, was placed between the two crystals to prevent false coincidences between photons entering one crystal and being scattered to the other.

The identity of the samples was tested by irradiating each with an energy much higher than its threshold energy, and counting its activity.[1] The samples used were identical within ±0.2%.

The samples were irradiated and their activity was measured for a period of 8 min, pausing 30 sec between the end of the irradiation and the beginning of counting.

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The electronic instruments were kept working continuously for many months at a constant temperature. Tests of stability in time with Na^{22} source showed that the counting efficiency was stable with an accuracy of better than 0.1%.

The advantages of our counting system are a high "true counts to background" ratio and a better efficiency in comparison to previously used systems. For energies below threshold we count 10 counts per minute (compared to 325 counts/min given by Geller *et al.*[7]). This count is doubled for an energy of only 20 kev above threshold.

B. Dose Measurement

The dose received by the samples was measured simultaneously by two different methods. An ionization chamber, covering the same solid angle as the sample, was placed at a distance of 2 m from the anticathode. The unwanted electrons from the betatron were deflected by a 3000-gauss magnetic field and did not reach the chamber. The current from the chamber was amplified and was registered mechanically. The area under this current curve gives a relative measurement of the dose. This method permits us to check whether the intensity of the gamma rays from the betatron was stable during irradiation. We did not take into consideration one percent of the irradiations where the occurrence of instabilities in the intensity were observed.

Together with the sample of phosphorus we irradiated a sample of copper and we counted the activity of the copper with the same electronic system. The counting was started one minute after the end of the measurement of the phosphorus activity. As the activation curve of the photoneutronic reaction of copper does not show any break and is well known in this energy region,[9] we could use this information about the activity in the calculation of the relative dose.

The advantages of this way of measuring the relative dose are twofold: (1) Using a nuclear reaction, the result is independent of the pressure and room temperature and also independent of the stability of the circuits used for detecting the activity. (2) The total count measured for one irradiation of copper was 10^5; thus the statistical error is 0.3% (one order of magnitude better than the error introduced by an ionization chamber). A good correspondence was found between the two independent ways of measuring the relative dose.

TABLE I. The energy of the breaks in the $P^{31}(\gamma,n)P^{30}$ reaction compared to the results of other groups.

Our results $P^{31}(\gamma,n)P^{30}$ ±0.04 Mev	Schull[a] $P^{31}(\gamma,n)P^{30}$ ±0.05 Mev	Geller *et al.*[b] $P^{31}(\gamma,n)P^{30}$ ±0.026 Mev	Bromley *et al.*[c] $Si^{30}(p,n)P^{30}$ ±0.007 Mev[d]
12.23			
12.37	12.33	12.39	12.41[e]
			12.44
			12.49
12.47	12.58	12.55	12.53[e]
			12.56
			12.63
12.68			12.66[e]
			12.73
			12.76
12.78	12.75		12.80[e]
12.83	12.90		
12.98			
13.18	13.18		
13.32	13.38		

[a] See reference 2.
[b] See reference 7.
[c] See reference 14.
[d] Results extracted from Bromley's graphs.
[e] Strong resonances.

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C. Calibration of the Betatron

Calibration of the betatron was carried out by using the thresholds of the following reactions: $F^{19}(\gamma,n)F^{18}$ (10.40±0.011 Mev—from mass data given by Mattauch[10]), $Cu^{63}(\gamma,n)Cu^{62}$ (10.78±0.007 Mev[10,11]), $O^{16}(\gamma,n)O^{15}$ (15.65±0.007 Mev[4,11,12]), and $C^{12}(\gamma,n)C^{11}$ (18.721±0.006 Mev[10]).

To locate these thresholds we measured the activity of the residual nuclei by the same technique as described before. In the case of the $C^{12}(\gamma,n)C^{11}$ threshold, we irradiated crystals of anthracene and their activity was measured using a photomultiplier and a single-channel analyzer.[6]

Thresholds were easily detected because the increase of activity after threshold was abrupt and linear. In the case of copper we had to take the square root of the activity to obtain the threshold. This threshold value was taken from the work of Penfold[12] who did not calibrate his betatron with threshold reactions and took, as we did, the square root of the activity in order to find the energy of this threshold.

Although it is not accurate to use light nuclei to calibrate the energy scale of the betatron,[7,12] we think our calibration to be correct for the following reasons: (1) Using three points of calibration: photoneutron thresholds of Cu^{63} and C^{12} and the break of 17.18 Mev in O^{16}, we obtained the same calibration line as when calibrating with the four points described above. Katz,[13] when treating the problem of calibration with threshold reactions, used these three points of calibration and found this calibration line sufficiently accurate. (2) Using as sensitive a detecting system as ours, we believe that we approach as nearly as possible the neutron separation energy. As a matter of fact, King and Katz,[4] having a good detection efficiency, were able to observe an increase in activity at the neutron separation energy of O^{16}.

The error in the energy scale in the region of 12–14 Mev is 40 kev, taking into account errors in determining the place of the break and in the energy calibration of the betatron.

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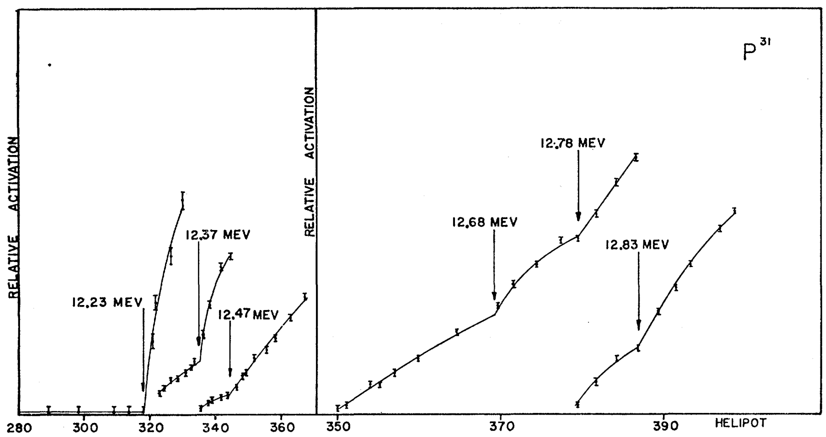
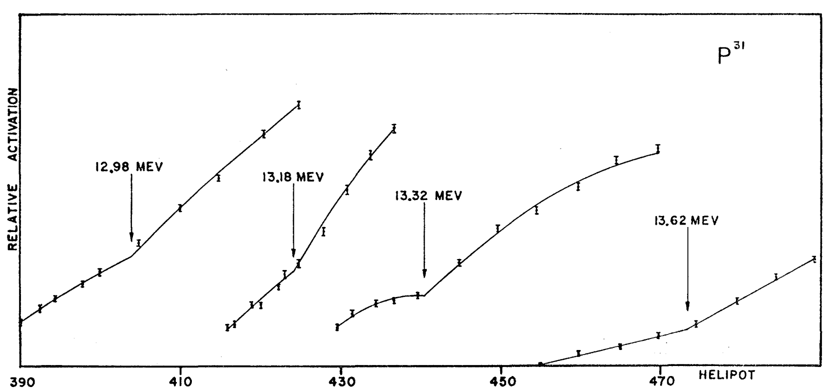


FIG. 1. "Breaks" in the activation curve of the $P^{31}(\gamma,n)P^{30}$ reaction.



Regular measurements of the activity of boric acid samples permit us to state[1] that the day-to-day energy stability of the betatron is better than 5 kev.

III. EXPERIMENTAL RESULTS

The results of our measurements are given in Fig. 1 and in Table I. For reasons of convenience we traced the breaks one beside the other, on different scales of activity. Every one of these breaks was found at least three times on different occasions and always at the same energy (±20 kev).

In Table I we give our results compared with those of Schull[2] and those of Geller *et al.*[7] The first used Geiger counters and the second used two small NaI(Tl) crystals, without coincidence, in order to detect the two annihilation gammas. These two groups are the only ones known to have investigated this reaction.

In Table II we give our results for the threshold of the $P^{31}(\gamma,n)P^{30}$ and the $Cl^{35}(\gamma,n)Cl^{34}$ reactions, compared with known results. In order to investigate the $Cl^{35}(\gamma,n)$-Cl^{34} reaction we used cylinders of compressed NaCl which had the same dimensions as the phosphorus samples. Their activity was measured with the same counting system described above. We found the threshold and the first break of this reaction.

The energy of our first break, at 12.75 Mev, corresponds to the threshold found by Schull[2] at 12.79 Mev. It must be assumed that because of his insensitive measuring system, Schull could only detect the marked increase of activity after the first break. A similar consideration can be made for the phosphorus threshold.

TABLE II. Thresholds (in Mev) of the $P^{31}(\gamma,n)P^{30}$ and $Cl^{35}(\gamma,n)Cl^{34}$ reactions compared to the results of other groups.

References	$P^{31}(\gamma,n)P^{30}$	$Cl^{35}(\gamma,n)Cl^{34}$
Our results[a]	12.23 ±0.04	12.66±0.04
Schull[b]	12.33 ±0.05	12.79±0.05
Chidley *et al.*[c]	12.50 ±0.05	
Wapstra (mass data)[d]	12.40 ±0.08	12.71±0.12
Everling (mass data)[e]	12.316±0.02	12.57±0.04

[a] These results are given in the laboratory system. In the center-of-mass system the results will not decrease more than 3 kev.
[b] See reference 2.
[c] Can. J. Phys. **36**, 407 (1956).
[d] Physica **21**, 367 (1955).
[e] Nuclear Phys. **15**, 342 (1960).

Our first break at 12.37 Mev corresponds to that of 12.39 Mev found by Geller[7] which was thought to be the threshold. Chidley and Katz found their threshold at 12.50 Mev where we found our second break (12.47 Mev).

IV. DISCUSSION

Comparing our results for the energy of the breaks to the results for the resonances in the $Si^{30}(p,n)P^{30}$ reaction, we can see that to every strong resonance we can attribute a break within the limits of error. For this comparison we must take into consideration that the correspondent level is Γ Mev higher than the break[3] (Γ=level width at half maximum).

Although the resonances as found by Bromley *et al.*[14] are too dense to permit a unique correspondence, it is clear that if a break is found in the neighborhood of some resonances it corresponds to the strongest one.

As our results show, there are clearly fewer breaks than there are resonances near threshold. The reason is that we used bremsstrahlung gamma rays. A break can be seen only when the change in its slope is at least equal to the change in the slope of the previous break.[3] Thus, breaks corresponding to weak resonances cannot be distinguished in the background of the previous breaks.

The same considerations are valid when we compare breaks in the activation curves of the $N^{14}(\gamma,n)N^{13}$ and $F^{19}(\gamma,n)F^{18}$ reactions[15] with known levels in the N^{14} and F^{19} nuclei.

On the other hand, in the $C^{12}(\gamma,n)C^{11}$ reaction both Thorson and Katz[5] and Sadeh[6] found, in the region near threshold, more breaks than levels. The levels at 18.85 Mev and at 19.26 Mev were found by four authors,[16] using three types of reactions, (p,γ), (p,n), and (p,p). Although these authors used a Van de Graaff generator with a resolving power of 5 kev, which is obviously superior to a betatron, they did not find any level between the two levels mentioned, where Thorson and Katz[5] had found 5 breaks at 18.90(18.86), 18.96 (18.96), 19.08(19.10), 19.17, and 19.30 Mev (the values in parentheses represent the results of Sadeh[6]). Even the resolving power of the two machines were the same, more resonances should be discerned when exciting with a Van de Graaff generator than with a betatron, because the three p reactions can excite more levels than the gamma reaction [a zero-spin level, for example, can be reached by a (p,n) reaction and not by the gamma reaction; see also Katz[1]].

A further point which increases the doubt about the identity between the breaks of C^{12} and levels listed is the level width. All levels listed,[16] with the exception of the one at 19.42 Mev, have a width greater than 90 kev. According to Penfold,[3] levels as wide as this probably should not cause a change in slope sharp enough to be detected as a break.

Gove *et al.*[8] searched thoroughly for resonances in the $B^{11}(p,\gamma_0)C^{12}$ reaction between 21 and 23.5 Mev (energy in the compound nucleus). They failed to find any fine structure although their energy resolution is a few kev. In this region five breaks were found.[5] There is one strong break at 21.58 Mev[5] which was specially investigated by Gove, but in vain. Detailed balancing would imply that resonances should have been observed where such structure has been found[17] for the $C^{12}(\gamma,p)B^{11}$ reaction.[5]

These considerations throw a certain doubt on the origin of the breaks in C^{12}, and it appears that the breaks do not correspond to known levels in C^{12} which had been reached by other reactions.

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