expression

$$1-\beta/2l \text{ when } l \geqslant \beta; \quad l/2\beta \text{ when } l \leqslant \beta. \tag{1}$$

In particular, the total fraction that escape; i.e., the fraction that have traversed any thickness of material up to ρ is

$$1-(\beta/2\rho). \tag{2}$$

We may use the above formulas together with a range-velocity relationship to find both the total fraction of fragments that escape and the thickness of the foil relative to the range; i.e., β/ρ.

A range-velocity relation which agrees with experiment well enough for these purposes is $(v/v_0)=(1-l/\rho)$. From this equation we calculate the value of l/ρ corresponding to 6 Mev, taking an average initial energy of the fragments to be 81 Mev. From Eq. (1) and the measured escape fraction we find $\beta/\rho=0.26$. Inserting this value of β/ρ in Eq. (2) we find that the total fraction of fragments which escape from the foil is $E=0.435$.

The uniformity of the UF_4 deposit was measured by cutting 24 one-inch squares from the foil and alpha-counting them. The standard deviation in thickness of the foil was 18 percent. We have assigned an uncertainty of this magnitude to E in computing the error of our final result.

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Distribution of Slow Neutrons in Free Atmosphere up to 100,000 Feet*†

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Two identical proportional counters filled with boron trifluoride of 96 percent B^{10} have been sent aloft up to an altitude of 102,000 ft at a geomagnetic latitude of 51° 46′ N by means of free balloons. One counter was shielded with 0.030 in. of cadmium, and the other enclosed in tin of the same thickness for the compensation of possible effects caused by "stars" produced in the cadmium shield. The difference in the counts of the two counters is due only to slow neutrons ($E\leqslant 0.4$ ev). The counts and the pressure and temperature were radioed down by an FM telemetering system. Up to about 20 cm of Hg the counts increase exponentially with altitude according to an absorption depth $\lambda=156$ g/cm², in agreement with previous measurements, and roughly with the increase of "stars" in the atmosphere. The counts of both counters as well as their difference show a maximum at high altitude, as expected theoretically. The maximum for the cadmium difference counts appears at about 8.5-cm Hg pressure and drops down sharply to about one-fourth of its maximum value at 1 cm Hg. The counter sensitivity was calibrated against a standard neutron source and the absolute number of slow neutrons absorbed per gram and second in the atmosphere is computed and compared with the number of protons produced at the same altitudes.

I. INTRODUCTION

A CONSIDERABLE number of measurements have been made on the neutron intensity in cosmic radiation by various investigators in this field.[1–9] The essential results thus far show an exponential increase of the neutron intensity as a function of altitude. Since neutrons in the cosmic radiation cannot be considered as primary particles because of their short lifetime, they must be produced in the atmosphere. Thus one can expect that there exists a maximum in neutron intensity distribution as a function of altitude. The position of the maximum has been calculated by Fluegge[10] and recently by Bagge and Fincke[11] on a theoretical basis by considering the absorption, scattering, and diffusion of neutrons in the atmosphere. This maximum is expected to exist at about 10 cm Hg, assuming that the atmospheric neutrons are originally produced in the processes of nuclear disruptions or "stars." However, measurements in the past[7] show a continuous increase in the neutron intensity up to 2 cm Hg. This discrepancy between theory and experiment[7] can probably be attributed to spurious counts obtained at high altitudes because of corona discharge at the high voltage terminals of the proportional counter. As will be described later, a completely pressurized system for the high voltage supply and the counters was employed[12] in the present experiment to eliminate such possible corona effects.

The object of the present experiment is not only to obtain the intensity distribution of the slow neutrons ($E\leqslant 0.4$ ev) in the atmosphere, but also to attempt to measure their absolute intensities at various altitudes.

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† A preliminary report of the present work appeared in Phys. Rev. **77**, 728 (1950); Phys. Rev. **74**, 504 (1948).
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[12] Luke C. L. Yuan, Phys. Rev. **74**, 504 (1948).

A complete description of the measurements made at high altitudes will be given here. Experimentation at lower altitudes is still in progress.[13]

II. APPARATUS

A. Gondola Equipment

The present measurements were carried out at Princeton, New Jersey (geomagnetic latitude 51° 46′ N), by sending aloft two identical proportional counters 5 cm in diameter and 20 cm in length up to an altitude of 102,000 ft (corresponding to a pressure of 0.75 cm Hg) by means of free balloons. The counters were made of glass of low boron content (less than 0.02 percent boron) and they were filled with purified boron trifluoride gas containing 96 percent B^{10} at a pressure of 20 cm Hg in the first flight (April, 1948) and at a pressure of 50 cm Hg in the second (July, 1948) and third (January 8, 1949) flights. They were operated at

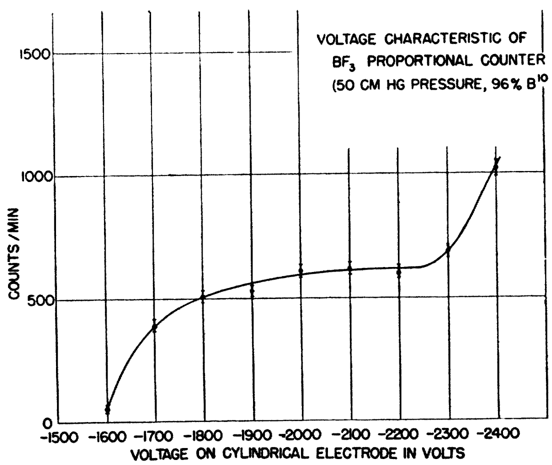

FIG. 1. Voltage plateau characteristic of proportional counter.

a voltage plateau centered at 800 v and 1850 v, respectively. A preliminary report on the results of the first flight has appeared.[12]

A typical voltage plateau characteristic of the proportional counter is shown in Fig. 1, where the counting rate is plotted against the negative high voltage on the outer electrode (cathode) of the counter. The width of the plateau is about 200 volts with a slope of about 3 percent per 100 v. A counter operated at such a plateau region has a very high alpha-to-gamma-ray discrimination, and so pulses due to single gamma-rays are easily biased off.

Of the two counters used in the flight, one counter was shielded with 0.030 in. of cadmium. Owing to the possibility of stars being produced in the cadmium shield at high altitudes, a tin shield of the same mass as the cadmium shield was put around the second counter to compensate for any such effect. Tin was

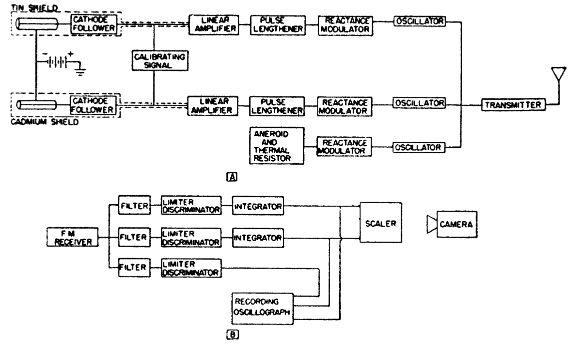

FIG. 2. Block diagram of telemetering and receiver system.

chosen as the material for the compensating shield simply because its atomic number ($Z=50$) is close to that of cadmium ($Z=48$) and because its absorption cross section for neutrons is exceedingly small. The calculated absorption of the tin shield for thermal neutrons amounts to about two percent.

The output pulse amplitude of these counters due to disintegration of B^{10} by neutrons at 1850 volts is of the order of a few millivolts, which is a thousand times smaller than that of a Geiger-Mueller counter. In view of this fact, a series of tests were made to determine the possible effect of corona on the counter at high altitudes and the means of eliminating such effect. This was done by putting the counter and its high voltage battery supply in a large vacuum chamber. Various methods of insulation were applied to the high voltage leads and terminals and to the battery itself, and corona effects were determined as the chamber was pumped down. With the best insulation method tried, corona still began to show up at about 4- or 5-cm Hg pressure, and its effect increased as the pressure decreased. This would give rise to a false increase in the neutron counts as the altitude increased if the corona effect were not completely eliminated.

In order to eliminate any possible corona discharge under high altitude conditions, a pressurization system was adopted such that both counter shields as well as the high voltage battery container were sealed airtight and were maintained at atmospheric pressure throughout the flight. The high voltage leads were fed through long pressurized copper tubings which connected the high voltage battery container with the two counter shields.

A cathode follower stage using a 2E41 subminiature tube was placed at one end of each counter shield. The output from the counter tube was fed directly from the anode (the axial wire) of the counter, which was at approximately ground potential, to the grid of the 2E41. The output of the cathode follower was then fed through Kovar seals and long shielded leads to the input of a three-stage inverse-feedback linear amplifier, which was placed about $2\frac{1}{2}$ ft away from the counter. Each counter was followed by a separate cathode

[13] For preliminary results, see reference 8, also Luke C. L. Yuan, Phys. Rev. 76, 1267 (1949) and Phys. Rev. 76, 1268 (1949).

follower and linear amplifier channel as shown in the block diagram in Fig. 2(A).

The output of each amplifier was fed into a pulse lengthening circuit which converted a pulse of a certain amplitude into a corresponding square pulse such that the width of the latter was made to vary as the logarithm of the amplitude of the original pulse. These square pulses were employed to drive a reactance tube which frequency modulated a subcarrier oscillator. The frequency of the subcarrier oscillator was thus changed by a small, fixed amount for a time proportional to the logarithm of the original counter pulse amplitude.

The gain of the amplifiers was so adjusted that the amplitudes of gamma-ray pulses from a 15-mc Ra-Be source at one foot away from the counter were just below the threshold voltage required to operate the pulse lengthener. Thus, the gamma-ray pulses, as well as the noise background of the amplifier circuits, were not transmitted through the telemetering system.

A calibrated fixed signal of constant amplitude was switched into the input circuit of the linear amplifiers every 15 min for a period of 8 sec. This served as a check on the constancy of the amplifier gain and the performance of the whole system during the course of the flight. The calibrated fixed signal was produced by a relaxation oscillator employing a small neon bulb painted black which gave a constant signal output over a long period of time and a wide temperature range.

The above described frequency-modulated telemetering system has a very good noise discrimination characteristic which is independent of signal fading and frequency drift within wide limits. A circuit diagram of the complete system[14] employed in the balloon flight is shown in Fig. 3.

Before each flight the whole gondola containing the entire system was put into a vacuum tank which was pumped down gradually to $\frac{1}{2}$-cm Hg pressure to detect the presence of any possible corona discharge. When the background counts of the two counters remained unchanged during a period of one hour at $\frac{1}{2}$-cm Hg as well as during the pumping down period, the gondola was then ready for flight.

The gondola frame was made of magnesium angle strips. The total weight of the gondola, including all of its equipment, was about 43 lb. The gondola was wrapped in a thin sheet of cellophane paper painted partially black, and the temperature inside remained fairly constant throughout the flight.

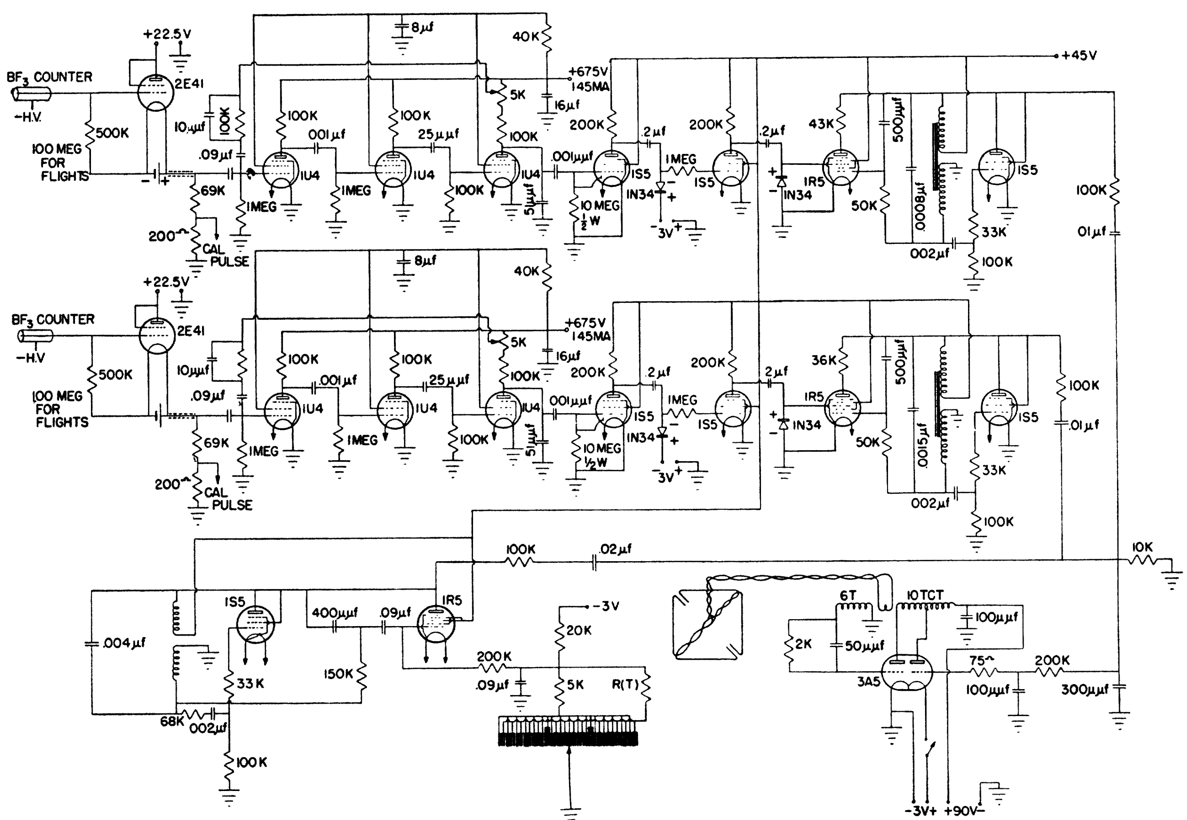

FIG. 3. Schematic circuit diagram of counters and associated telemetering system.

[14] A detailed description of the telemetering system is given in a paper by T. Coor which has been submitted for publication in Rev. Sci. Instr.

TABLE I. June 9, 1948, balloon flight. Counting rates in counts per minute (counter background subtracted).

(1) Pressure in cm Hg	(2) Tin-shielded counter	(3) Cd-shielded counter	Cd difference (2)−(3)	Cd ratio (2)/(3)
69.0	1.5±0.8			
57.4	0.9±0.8	0.4±0.6	0.5±1.0	2.3±3.9
47.5	3.3±1.0	0.5±0.6	2.8±1.2	6.6±6.9
38.3	7.5±1.5	3.3±1.1	4.2±1.9	2.3±0.9
30.8	13.5±1.7	6.3±1.3	7.2±2.1	2.1±0.5
24.7	24.1±2.2	11.5±1.6	12.6±2.7	2.1±0.4
19.7	35.9±2.7	14.7±1.8	21.2±3.2	2.4±0.4
15.8	50.5±3.2	18.3±2.0	32.2±3.8	2.8±0.4
12.7	54.5±3.3	20.7±2.1	33.8±3.9	2.6±0.3
10.2	61.7±3.6	26.1±2.4	35.6±4.4	2.4±0.3
8.27	65.5±3.6	32.7±2.6	37.8±4.4	2.0±0.2
6.75	68.1±3.7	29.3±2.5	38.8±4.5	2.3±0.2
5.45	62.9±3.6	33.9±2.6	29.0±4.4	1.8±0.2
4.5	62.2±3.2	32.3±2.3	29.9±3.9	1.9±0.2
4.17	63.5±3.6	31.5±2.6	32.0±4.4	2.0±0.2
4.17	60.9±3.5	28.9±2.5	32.0±4.3	2.1±0.2
4.36	65.9±3.7	32.5±2.6	33.4±4.5	2.0±0.2
4.8	68.5±3.7	28.1±2.4	40.4±4.4	2.4±0.2
5.38	60.1±3.5	31.5±2.6	28.6±4.4	1.9±0.2
6.05	70.9±3.8	28.5±2.4	42.3±4.5	2.5±0.3
6.83	60.2±3.1	35.6±2.4	24.6±3.9	1.7±0.1
7.75	58.9±3.4	34.1±2.7	24.8±4.4	1.7±0.1
9.92	59.7±3.5	30.7±2.5	29.0±4.3	1.9±0.2
10.7	63.9±3.6	25.9±2.4	28.0±4.4	2.5±0.3
12.5	58.5±3.4	25.3±2.3	33.2±4.1	2.3±0.3
14.5	50.5±3.2	24.1±2.3	26.4±3.9	2.1±0.2
16.8	43.7±3.0	18.3±2.0	25.4±3.6	2.4±0.3
19.3	39.1±2.8	17.1±1.9	22.0±3.4	2.3±0.3
22.1	29.5±2.5	14.7±1.8	14.8±3.1	2.0±0.3
25.0	22.7±2.2	10.1±1.5	12.6±2.6	2.2±0.4
28.2	19.5±2.0	8.5±1.4	11.0±2.4	2.3±0.4
31.8	10.9±1.6	6.9±1.3	4.0±2.1	1.6±0.4
36.0	12.7±1.7	4.3±1.1	8.4±2.0	2.9±0.9
40.6	4.9±1.3	2.3±0.9	2.6±1.6	2.1±1.0

TABLE II. July 25, 1948, balloon flight. Counting rates in counts per minute (counter background subtracted).

(1) Pressure in cm Hg	(2) Tin-shielded counter	(3) Cd-shielded counter	Cd difference (2)−(3)	Cd ratio (2)/(3)
60	2.2±0.8	1.6±0.7		
51	3.8±1.0	4.4±1.0		
42.5	10.6±1.5	7.0±1.3	3.6±2.0	1.5±0.4
35.5	18.2±2.0	10.8±1.5	7.4±2.5	1.7±0.3
29	31.2±2.5	20.0±2.0	11.2±3.2	1.6±0.2
23	63.8±2.9	31.0±2.5	32.8±4.6	2.1±0.2
18.2	82.8±4.1	52.0±3.2	30.8±5.2	1.6±0.1
14	118.3±5.4	64.8±4.0	53.5±6.7	1.8±0.1
11	130.4±5.1	73.6±3.8	56.8±6.3	1.8±0.1
8.5	128.2±5.1	79.4±4.0	48.8±6.5	1.6±0.1
7	149.0±5.5	80.0±4.0	69.0±6.8	1.9±0.1
5.9	145.2±5.4	82.6±4.1	62.6±6.8	1.8±0.1
5.5	135.4±5.2	81.4±4.0	54.0±6.5	1.7±0.1
4.9	138.6±5.3	79.4±4.0	59.2±6.6	1.8±0.1
4.7	122.0±2.3	77.2±1.8	44.8±2.9	1.6±0.1
5	131.0±5.7	82.0±5.2	49.0±7.7	1.6±0.1
5.3	134.2±5.2	87.2±4.2	47.0±6.7	1.5±0.1
6.1	141.2±5.3	86.6±4.2	54.6±6.8	1.6±0.1
6.8	136.0±3.9	82.0±3.0	54.0±4.9	1.7±0.1
7.5	139.0±3.9	88.2±3.2	50.8±5.0	1.6±0.1
8.4	130.2±3.6	80.0±2.8	50.2±4.6	1.6±0.1
9.6	131.2±5.8			
11.7	126.0±4.6			
13.2	123.4±5.0			
14.8	105.6±4.6			
16.6	87.0±4.7			
19	84.2±4.1			
21.5	66.8±3.7	40.2±2.9	26.6±4.7	1.7±0.2
24.3	46.2±3.1	25.4±2.3	20.8±3.9	1.8±0.2
27.5	38.0±2.8	19.0±2.0	19.0±3.4	2.0±0.3
32	26.0±2.3	12.4±1.6	13.6±2.8	2.1±0.3
36.3	18.6±2.0	10.0±1.5	8.6±2.5	1.9±0.3
41.4	11.6±1.6	4.8±1.1	6.8±1.9	2.4±0.6
46	7.8±1.3	2.6±0.8	5.2±1.5	3.0±0.1
51	5.0±1.1			

B. Receiving Equipment

A Navy type RBF-3 FM receiver with a rotatable directional antenna was used for signal reception. As shown in Fig. 2(B), the audio signal output from the receiver was fed into three separate channels, each containing a band-pass filter corresponding to one of the three subcarrier frequencies. The filters are followed by limiter stages, which minimize the effect of radio signal amplitude variations, and then by an FM discriminator which gives a voltage proportional to that particular subcarrier frequency.

In the two neutron channels the transmitted square pulses after detection are integrated and converted back into regular pulses whose heights were proportional to the duration of the square pulses and hence to the logarithm of the amplitudes of the original pulses from the proportional counter.

These pulses, together with the pressure and temperature signals, were recorded on a galvanometer type recorder on three separate channels. In parallel with this galvanometer type recorder, two-decade scaler units with a predetermined bias were connected to register the neutron counts from the two counters. The readings of these two scaler units were photographed at one-minute intervals in synchronization with the timing signals of the galvanometer recorder. Thus, the counting rate can be read directly from the photographic records if the gain of the linear amplifiers, as shown by the calibrated fixed signal, remains constant.

III. RESULTS AND DISCUSSION

During the first two flights the balloons ascended to a maximum altitude of about 67,000 ft (4.2-cm Hg pressure) and then descended gradually. Measurements were made during the descent as well as during the ascent; thus the data in the descent served as a good check on the results in the ascent. In the third flight the balloon-borne equipment reached an altitude of 102,000 ft (0.75-cm Hg pressure) and floated at or near that altitude for approximately two hours. After five hours of continuous reception, the signal was lost before the equipment descended appreciably from its maximum altitude.

In analysis of the results, counting rates averaged over five-minute intervals were used as the mean counting rate corresponding to the mean pressure in that interval.

The results of the three flights are collected in Tables I, II, and III, where the background counts of each counter were subtracted from the actual counting rate. These background counts were measured at ground level by shielding the counters with a cadmium shield;

TABLE III. January 8, 1949, balloon flight. Counting rates in counts per minute (counter background subtracted).

(1) Pressure in cm Hg	(2) Tin-shielded counter	(3) Cd-shielded counter	(4) Cd difference (2)–(3)	(5) Cd ratio (2)/(3)
60.3	1.6±0.7	0.4±0.6	1.2±0.9	4.0±6.3
54.3	4.6±1.1	1.0±0.7	3.6±1.3	4.6±3.4
48.3	8.4±1.4	4.2±1.0	4.2±1.7	2.0±0.6
43.3	13.0±1.7	6.0±1.2	7.0±2.0	2.2±0.5
38.7	18.8±2.0	7.2±1.3	11.6±2.4	2.6±0.5
34.3	29.2±2.5	12.0±1.6	17.2±3.0	2.4±0.4
30.3	35.6±2.7	19.0±2.0	16.6±3.4	1.9±0.2
26.7	51.6±3.2	17.8±1.9	33.8±3.7	2.9±0.4
23.5	64.2±3.6	28.0±2.4	36.2±4.3	2.3±0.2
20.3	84.1±4.1	40.4±2.9	44.4±5.0	2.1±0.2
17.5	95.6±4.4	45.6±3.1	50.0±5.4	2.1±0.2
15.2	126.3±5.2	52.6±3.3	74.2±6.2	2.4±0.2
12.7	144.4±5.4	65.0±3.6	79.4±6.5	2.2±0.1
11.1	148.6±5.5	75.2±3.9	73.4±6.7	2.0±0.1
9.5	165.8±5.7	79.4±4.0	86.4±7.0	2.1±0.1
8.1	173.6±5.9	82.4±4.1	91.2±7.2	2.1±0.1
7.0	172.2±5.9	91.0±4.3	81.2±7.3	1.9±0.1
5.8	168.6±5.7	87.1±4.1	81.5±7.0	1.9±0.1
5.0	153.4±5.5	82.4±4.1	71.0±6.9	1.9±0.1
4.3	161.8±5.7	85.8±4.2	76.0±7.1	1.9±0.1
3.5	136.6±5.2	84.0±4.1	52.6±6.6	1.6±0.1
3.0	130.8±5.1	81.2±4.0	49.6±6.5	1.6±0.1
2.5	125.4±5.0	67.4±3.7	58.0±6.2	1.9±0.1
2.2	108.8±4.7	56.6±3.4	52.2±5.8	1.9±0.1
1.8	103.4±4.6	56.8±3.4	46.8±5.7	1.8±0.1
1.6	98.0±4.4	56.8±3.4	41.2±5.6	1.7±0.1
1.4	98.6±4.5	63.0±3.6	35.6±5.8	1.6±0.1
1.3	86.0±4.2	55.8±3.4	30.2±5.4	1.5±0.1
1.2	81.4±4.1	53.8±3.3	27.6±5.2	1.5±0.1
1.1	77.4±4.0	55.2±3.4	22.2±5.3	1.4±0.1
1.0	101.3±3.2	65.2±2.6	36.1±4.1	1.6±0.1
0.9	82.6±2.9	61.1±2.5	21.5±3.8	1.4±0.1
0.8	83.0±4.1	53.0±3.3	30.0±5.3	1.6±0.1
0.9	93.1±0.6	67.2±0.5	25.9±0.8	1.4±0.01

they amount to about one count per minute for the counters employed. They were due mainly to the alpha-contamination of the surface of the counter electrode.

The altitude dependence of the neutron intensity in the atmosphere obtained during the three balloon flights is shown in Figs. 4, 5, and 6, where the counting rate is plotted against the pressure in centimeters of Hg. Figure 4 represents the data obtained by means of two identical 20-cm-Hg-pressure BF_3 counters with a calibrated effective cross section of 6.3 ± 0.6 cm^2 for thermal neutrons (see Appendix A). The upper curve A gives the counting rates obtained from the tin-shielded counter, curve B that from the cadmium-shielded counter, and curve C that from the difference of the two. Figures 5 and 6 show the results obtained with similar BF_3 counters but with 50-cm Hg pressure, i.e., counters with about twice as great efficiency. The results obtained from the three flights agree well among themselves in the positions of the maxima as well as in the rate of increase, which is also in good agreement with that obtained previously at lower altitudes.[8,9]

The tin-shielded counter (curve A) shows a maximum counting rate at 7.5 cm Hg; the cadmium-shielded counter (curve B) shows a maximum at 6.5 cm Hg; and the cadmium difference (curve C) has a flat maximum around 8.5 cm Hg. The slow neutron ($E\leqslant 0.4$ ev) intensity, N, increases exponentially with decreasing atmospheric depth to a pressure of about 20 cm Hg. The absorption depth, i.e., the quantity λ in the expression $N=N_0e^{-x/\lambda}$, is $\lambda=156$ g cm^{-2}. The corresponding absorption coefficient is $\mu=1/\lambda=6.4\times10^{-3}$ cm^2/g. Both the tin counter (which measures fast as well as slow neutrons plus the effect due to recoils and stars produced in the shield, etc.) and the cadmium counter (which measures only the fast neutrons plus the effect due to recoils, stars, etc.), show the same slope of increase in counting rate[14a] up to about 20 cm Hg. Above the maximum, the counting rate of the tin counter decreases much more rapidly with increasing altitude than that of the cadmium counter, with the result that the slow neutron intensity (curve C, Fig. 6) drops sharply to about one-fourth of its maximum value at 0.75 cm Hg. If one extrapolates this curve up to the very top of the atmosphere, approaching zero pressure, one finds that the slow neutron intensity drops almost to zero.

For comparison, the values of absorption depth λ, obtained in other processes involving the production of neutrons, are as follows. (1) For ionization bursts by Rossi, Williams, Bridge, and Hulsizer[15] below 20-cm Hg pressure, $\lambda=138$ g/cm^2; by Coor,[14] $\lambda=160$ g/cm^2. (2) For nuclear disruptions or stars in photographic plates by Perkins[16] between sea level and 44 cm Hg, $\lambda=140$ g/cm^2, and by George,[17] $\lambda=150$ g/cm^2.

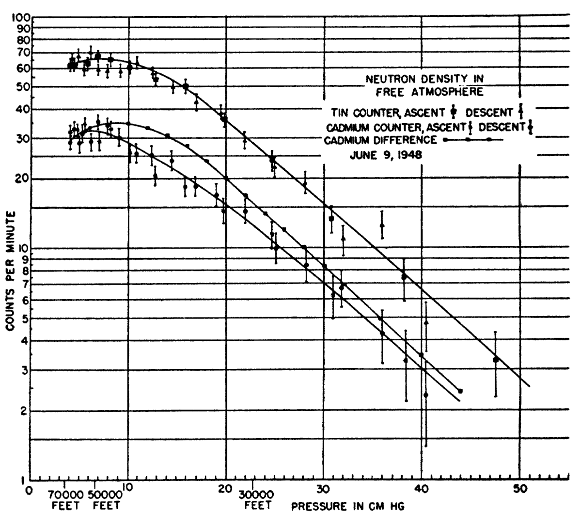

FIG. 4. Balloon flight made at geomagnetic latitude 51° 46′ N on June 9, 1948, using a pair BF_3 counters (20 cm Hg pressure).

[14a] The balloon floated at an altitude corresponding to about 0.9-cm Hg pressure for nearly two hours and the average value for the cadmium difference obtained for this altitude was 25.9 ± 0.8 counts per minute.

[15] B. Rossi and R. W. Williams, Phys. Rev. **72**, 172 (1947); H. Bridge and B. Rossi, Phys. Rev. **71**, 379 (1947); R. I. Hulsizer, Phys. Rev. **73**, 1252 (1948).

[16] D. H. Perkins, Nature **160**, 707 (1947); Nature **163**, 319 (1949).

[17] E. P. George, private communication.

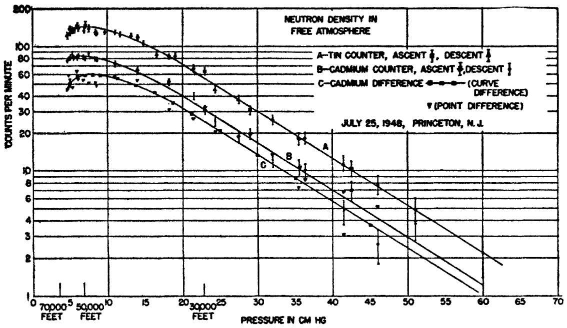

FIG. 5. Balloon flight made at geomagnetic latitude 51° 46′ N on July 25, 1948, using a pair of BF_3 counters (50 cm Hg pressure).

For further comparison, the position of the maximum in the vertical intensity distribution for the soft component of the cosmic radiation at geomagnetic latitudes greater than 45° N is at about[18] 11.5 cm Hg and that for the total radiation[18] is at about 10 cm Hg, according to measurements made by Millikan, Pfotzer, *et al.*,[19] by means of balloon-borne equipment up to an altitude of about 2.5 cm Hg. The maximum for the integrated total intensity of the cosmic radiation is about 4.1 cm, according to the measurements of Van Allen, *et al.*,[20] using V-2 rockets up to an altitude above the appreciable atmosphere at a geomagnetic latitude of 41° N.

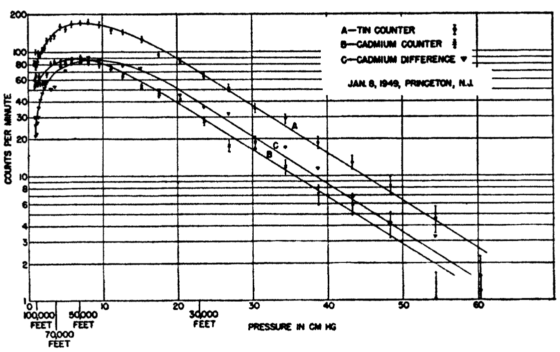

FIG. 6. Balloon flight made at geomagnetic latitude 51° 46′ N on January 8, 1949, using a pair of BF_3 counters (50 cm Hg pressure).

As will be described later, the counters used in the flights were calibrated experimentally against a standardized neutron source. Those employed in the second flight (July, 1948) had an effective cross section of 11.3 ± 1.1 cm² and those employed in the third flight (January, 1949) had an effective cross section of 12.6 ± 1.2 cm², all for neutrons of thermal energy. Division of the observed counting rates by these effective cross sections would give the neutron flux in particles per cm² and per unit time, if the neutrons had thermal energy. Actually they do not. The $1/v$ absorption of nitrogen cuts out the lowest energies, and the most probable energies will be of the order of 0.1 ev, instead of 0.02 ev. This circumstance greatly complicates the determination of the absolute neutron flux. Fortunately, a quantity of greater physical interest than the flux, *the number of neutrons, s, absorbed per gram of air and per second*, is much less affected by uncertainties in the form of the spectrum of slow neutrons. More specifically, one may note that 193 grams of air have the same absorption cross section for thermal neutrons as does a counter with an effective response cross section of 10.6 cm² for thermal neutrons. For slow neutrons of other energies the boron trifluoride counter will of course have a *different* cross section, but will still be equivalent in neutron absorbing power to the *same* mass of air. This result is an obvious consequence of the fact that both nitrogen and boron follow the $(1/v)$ law at the low energies which are of interest here. We conclude that the number of counts in the boron counter gives directly the number of neutrons absorbed per second in a certain mass of air which is fixed once and for all and which may be considered for our purposes to be independent of the shape of the neutron spectrum.

However, when the cadmium-difference counts are used instead of the counting rate obtained from a single unshielded counter, the air mass equivalent of the counter as described above must be corrected in order that it may be applied to the cadmium-difference counts. A brief description of the correction procedure is given below.

Let $A(E)=(1/v_{\mathrm{thermal}})\Sigma_a v\sigma_a$ for all atoms in one gram of air, where v is the velocity of neutrons and σ_a is the absorption cross section of air atoms. For low energy neutrons $A(E)$ is constant and is found to be 0.055 cm²/gm, since σ_a follows $(1/v)$ law in this energy region.

Let $B(E)=(v/v_{\mathrm{thermal}})\times$effective cadmium-difference response cross section of boron counter to an isotropic flux. Then the air mass equivalent of the cadmium-difference counter is given by

$$\int B(E)(df_a/dE)dE \Big/ \int A(E)(df_a/dE)dE = \int B(E)(df_a/dE)dE/0.055, \quad (1)$$

where (df_a/dE) represents the fraction of the neutrons in 1 cc of air which lie in a unit energy range at E. [The same result can be expressed alternatively by introducing the conception of "sweepage," that is, the product of cross section by neutron velocity. This quantity is the most convenient measure of absorbing power of an atom or material which follows the $1/v$ law. It has the physical dimensions of cm/sec. In the present considerations what matters is, of course, the ratio of

[18] B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).
[19] Millikan, Neher, and Pickering, Phys. Rev. **63**, 234 (1943); G. Pfotzer, Z. Physik **102**, 23 (1936); H. Carmichael and E. G. Dymond, Proc. Roy. Soc. (London) **A171**, 321 (1939).
[20] J. A. Van Allen and H. E. Tatel, Phys. Rev. **73**, 245 (1948); Gangnes, Jenkins, Jr., and Van Allen, Phys. Rev. **75**, 57 (1949).

the sweepage by the counter and the sweepage by one gram of air. The ratio will obviously be unaltered by dividing the two sweepages by the same constant. The quotient of the sweepage of a gram of air divided by thermoneutron velocity, which received above the name $A(E)$, this quantity having the dimension of square centimeters, is a little easier to visualize than the sweepage itself. Similarly, B represents the counter-sweepage divided by the same constant.]

For convenience, we compute the effective cadmium-difference response cross section $(v_{\text{thermal}}/v)B(E)$, for two limiting idealized cases: *viz*, (a) for a boron counter of spherical geometry and (b) for the opposite limiting case of a layer of BF_3 gas confined between two infinite parallel sheets.

(*a*) *Spherical counter.* Consider a spherical boron trifluoride counter of radius R. The response cross section of the whole counter with no cadmium present is equal to $(v_{\text{thermal}}/v)\times 10.6$ cm^2. Therefore, the response cross section of one cm^3 of counter$=(v_{\text{thermal}}/v)\times(3\times 10.6/4\pi R^3)$cm^2, which holds either for isotropic flux or for flux in the x-direction because of the spherical symmetry.

Now consider the case of unit flux in the x-direction with cadmium present. Then the effective response cross section owing to neutrons striking surface between angular limits θ to $\theta+d\theta(0<\theta<\pi/2)$ is

$$4\pi R^3 \cos^2\theta \sin\theta d\theta \frac{v_{\text{thermal}}}{v}\frac{3\times 10.6}{4\pi R^3} \times\exp\frac{-\text{Cd}(E)}{t}\{[R^2\cos^2\theta+t(2R+t)]^{1/2}-R\cos\theta\}$$

where $\exp[-\text{Cd}(E)]$ is the fraction of a normally incident neutron beam of velocity v which penetrates a sheet of cadmium of thickness t. Hence, the response cross section of the cadmium covered counter is, after substituting $u=\cos\theta$,

$$\frac{v_{\text{thermal}}}{v}10.6\int_0^1 3u^2\exp\frac{-\text{Cd}(E)}{t} \times\{[R^2u^2+t(2R+t)]^{1/2}-Ru\}du. \quad (2)$$

Consequently, we conclude that in the idealized case of spherical geometry the cadmium-difference response cross section of the boron counter is

$$\frac{v_{\text{thermal}}}{v}B(E)=\frac{v_{\text{thermal}}}{v}10.6\left(1-3\int_0^1 u^2\exp\frac{-\text{Cd}(E)}{t} \times\{[R^2u^2+t(2R+t)]^{1/2}-Ru\}du\right). \quad (3)$$

The quantity $B(E)$ is plotted as a function of energy in Fig. 7 (curve A) by taking $R=5$ cm, which was obtained from the effective volume of the cylindrical counter used in the measurements. The values of the exponential integral were obtained by numerical integration. The quantity Cd(E) represents the decrement in napiers of a normally incident neutron beam and was calculated from the thickness, 0.305 g/cm^2, of the cadmium foil, and from the curve of cadmium cross section as a function of energy given by Rainwater, Havens, and Wu.[21]

From the values of $B(E)$ given in Eq. (3) and using the values for the neutron distribution in the atmosphere calculated by Kouts,[22] we get,

$$\int_0^\infty B(E)(df_a/dE)dE=2.78 \text{ cm}^2. \quad (4)$$

(*b*) *Parallel plane counter.* Now consider the limiting idealized case of a layer of boron trifluoride gas confined between two infinite parallel sheets of cadmium, the analogous calculation gives, for case of isotropic incidence the cadmium-difference response cross section

$$(v_{\text{thermal}})(B(E)=(v_{\text{thermal}}/v)10.6 \times\left\{1-\int_0^{\pi/2}\sin\theta\exp[-\text{Cd}(E)/\cos\theta]d\theta\right\} \quad (5)$$

or by substituting $u=\cos\theta$, we have

$$B(E)=10.6\left[1-\text{Cd}(E)\int_{\text{Cd}(E)}^\infty u^{-2}\exp(-u)du\right]. \quad (6)$$

The values of $B(E)$ given by Eq. (6) are also plotted in Fig. 7 (curve B). Hence

$$\int_0^\infty B(E)(df/dE)dE=2.93 \text{ cm}^2. \quad (7)$$

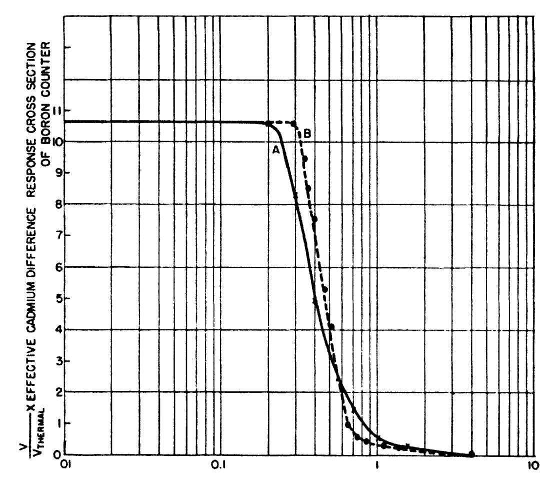

FIG. 7. Calculated effective *cadmium-difference* response cross section of a spherical and a parallel plate counter. Curve A is for the spherical counter, and curve B is for the parallel plate counter.

[21] Rainwater, Havens, and Wu, Phys. Rev. **71**, 65 (1947).
[22] Kouts, Wheeler, and Whyte, to be published.

TABLE IV. Air mass equivalents of counters used, calculated on basis of thermal neutron cross section of 5.30×10^{-2} cm² per gram of air.[a]

Counter name	Observed effective response cross section for thermal neutrons from pile (cm²)	Calculated air mass equivalent (grams)
Standard	10.6	52.0
June, 1948, flight	6.3	30.8
July, 1948, flight	11.3	55.5
January, 1949, flight	12.6	62.0

[a] This value was given as the most probable absorption cross section of nitrogen for thermal neutrons by H. H. Goldsmith, Committee on Nuclear Science, National Research Council.

It is seen from Fig. 7 that the difference between the curves for the idealized spherical and plane counters is small. Moreover, in the energy range where the difference is greatest, the equilibrium neutron density in air has fallen to a very low value. From Eqs. (4) and (7) the integral $\int B(E)(df_a/dE)dE$ has in the two idealized limiting cases, respectively, the values 2.78 cm² and 2.93 cm², a difference of only 5 percent. We adopt the average value

$$\int_0^\infty B(E)(df_a/dE)dE=2.86 \qquad (8)$$

for the actual intermediate case of cylindrical geometry. Thus, we get the air mass equivalent of the particular cadmium difference counter:

$$2.86/0.055=52.0 \text{ g}. \qquad (9)$$

Similar calculations for the air mass equivalent of other counters used in these experiments give the results listed in Table IV.

Thus it is only necessary to divide the tabulated air mass equivalent of the appropriate counter into the observed cadmium difference counting rates (Figs. 4, 5, and 6) to obtain the absolute number, s, of neutrons absorbed per gram of air and per unit time.

In order to compare the results represented by the curves A, B, and C in Figs. 4, 5, and 6, one must take into account the respective air mass equivalents in the two cases. From Fig. 6, curve C, the actual counting rate of the slow neutrons at the maximum (at 8.5 cm Hg) is 86±4 counts/min (January counter), and its counting rate reduced to the same July counter sensitivity as in Fig. 5 amounts to 78±7 counts/min. The slow neutron counting rate from curve C, Fig. 7, at 8.5 cm Hg is 60±6 counts/min (June counter) and the counting rate from Fig. 6(c) reduced over to the July counter is 63±5 counts/min. Thus, the slow neutron intensity measured in the January, 1949, flight is higher by about 20 percent than that obtained in the June and July, 1948, flights; but the difference between these results is so close to the statistical error of the experiment that one cannot draw a definite conclusion, even though the June and July results are in very good agreement. On the other hand, if this difference is real, it might conceivably be attributed to the time variation of the neutron component of the cosmic radiation. In regard to the time variation of cosmic radiation, Jesse[23] found an approximate 14 percent increase in the total cosmic radiation intensity at high altitude in early spring over early summer at Chicago between October, 1938 and November, 1939. Millikan and Neher[24] observed a similar increase in the total intensity of about 9 percent in December, 1938, over September, 1937, at Omaha, Nebraska.

The cadmium ratio, obtained by taking the ratio between the counts from the tin-shielded counter to those from the cadmium-shielded counter is of the order of 2 over the depth of 50 cm Hg to 4 cm Hg. Figure 8 (A, B, and C) shows the values of the cadmium ratio obtained at various altitudes for the three flights, respectively. It seems to show that the cadmium ratio is approximately constant above 4 cm Hg, having a

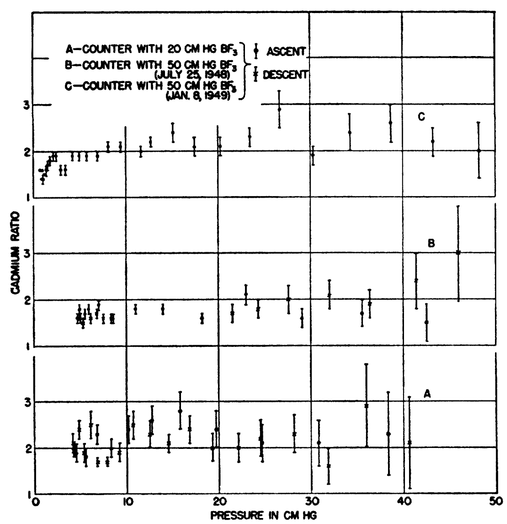

FIG. 8. Cadmium ratio as a function of altitude.

value of about 2, but then decreases gradually as the pressure decreases and reaches a ratio of 1.4 at 0.9 cm Hg. This is probably due to the increasing contribution of the non-neutron counts and to the decrease in the slow neutron counts when approaching the top of the atmosphere. On the other hand, the cadmium ratio calculated from Eq. (8) is $10.6/(10.6-2.86)=1.4$, which is lower in value than the experimental ratio of 2. This difference is probably due to the neglect of the molecular scattering of slow neutrons in the moderation process in calculating the energy distribution of the air neutrons.[22] The molecular scattering effect is difficult to estimate but Bagge and Fincke[11] have shown that such effects can improve the agreement between the theoretical and experimental cadmium ratios.

In the present experiments two identical counters were used simultaneously, one enclosed in tin, the other

[23] W. P. Jesse, Phys. Rev. 58, 281 (1940).
[24] R. A. Millikan and H. V. Neher, Phys. Rev. 56, 491 (1939).

in cadmium. The non-neutron counts are of the same magnitude in both counters, and they cancel out. Consequently, the difference of the counts should give the true counting rate due to slow neutrons.

From the above results and from the air mass equivalents of the counters one can calculate the absolute number of slow neutrons absorbed in one gram of air per second. For example, at a pressure of 20 cm Hg there were observed 0.83 counts per second, in the January counter, for which the equivalent air mass is calculated to be 62.0 cm^2; thus, *we find for s, the slow neutron absorption rate in air amounts to* 1.3×10^{-2} *per gram per second*. This would be, in equilibrium, the neutron production rate in the atmosphere if (1) no fast neutrons were captured by nitrogen and oxygen and (2) no fast neutrons were lost (or gained) by diffusion to (or from) other levels in the atmosphere. At the 20-cm level the curve of neutron intensity (not the logarithm of neutron intensity) as a function of altitude is neither strongly convex upward, as at the maximum, nor strongly concave upward as lower in the atmosphere. Consequently, it is reasonable to conclude that neutron diffusion has relatively little effect at this altitude in redistributing the neutrons. In view of the losses during moderation it is therefore to be expected that the slow neutron absorption rate at 20 cm is a lower limit on the neutron production rate at this elevation.

It is of some interest to compare this value with the proton production rate in the atmosphere. At 8.9-cm Hg pressure the value for the proton production rate obtained by Coor[14] is 0.015/g-sec and the lower limit of the neutron production rate extrapolated to this altitude is 0.034/g-sec. The ratio of the proton to neutron production rate thus calculated is 0.015/0.034 =0.44. Actually, the ratio must be smaller still because the figure 0.034 employed here is the lower limit of the neutron production rate.

By integration of the slow neutron counts from the ground up to the top of the atmosphere, one finds the number of *slow* neutrons absorbed per cm^2 of the earth's surface per second at the latitude of Princeton is 7.1.

The author wishes to express his sincere gratitude to Professor R. Ladenburg, with whom this series of neutron experiments was initially started, for his generous advice and helpful suggestions; to Professor John A. Wheeler for his constant encouragement and many valuable discussions; to Messrs. T. Coor and F. J. Darago for their technical assistance in the construction and adaptation of the telemetering system to the present experiment; to Mr. David Hill for his kind assistance in carrying out the measurements and calculations of the counter calibration at the pile of the Argonne National Laboratory and for the contribution of Appendix B; to Mr. Herbert Kouts, who kindly let the author use his theoretical results on the energy distribution of air neutrons; to Dr. N. Hilberry, Associate Director of the Argonne Laboratory, for the opportunity to secure a calibration of our counters; to Dr. D. J. Hughes and Mr. C. Eggler for their help in fitting this measurement into the Argonne program.

APPENDIX A. STANDARDIZATION

Although the cross section of boron for neutrons of various energies is well known and one can calculate the efficiency of a BF_3 counter theoretically, it is necessary in practice, owing to factors such as the geometry and the effective volume of the counter, absorption due to counter walls, etc., to calibrate the counter sensitivity experimentally. In this way were obtained the values of counter cross section which are referred to in the preceding section.

Through the courtesy of the Argonne National Laboratory, the sensitivity of the BF_3 counters used here was calibrated against its standardized neutron source. A brief description of the calibration procedure is given below. The detailed computation for the calibration was carried out by D. Hill, and is described in Appendix B.

The counter to be calibrated was placed in a beam of thermal neutrons of known intensity distribution emitted from the pile at the Argonne Laboratory. It was a 50-cm-Hg-pressure BF_3 counter (96 percent B^{10}) and was operated at its voltage plateau region under the same conditions under which it was being used in the experiment.

The counter was checked with a Ra-Be source (15 mc) surrounded by a paraffin cylinder at a fixed geometry both before and after the standardization to make certain that the performance of the counter remained unchanged throughout the calibration.

A similar counter used by Agnew, Bright, and Froman[6] was lent to the author and was put beside our counter separated by a distance of one foot.

A comparison of the sensitivities of the two counters was made by using the same electronic circuits and by operating in the respective plateau regions. An average of six measurements at six different angular positions of the counters was taken in order to eliminate the effect due to anisotropy of the neutron beam. For the same neutron flux, the counter used by the author was found to give 2.32 times the counting rate of that used by Agnew, Bright, and Froman, whereas the ratio of the sensitivities calculated from gross volume and pressure is 2.48.

The above measurement with the 15-mc Ra-Be source also gave a secondary standardized neutron source for subsequent calibrations.

APPENDIX B. CALIBRATION OF BF_3 COUNTER

The BF_3 counter was calibrated by observation of its counting rate in a spray of thermal neutrons scattered by a graphite wall 10 cm thick placed in a beam emerging from the Argonne heavy water pile, and by comparison of this counting rate with the saturated beta-activity acquired by indium foils placed about the boron counter in such a manner that their average activation should correspond to the average neutron flux impinging upon the counter. It was found that the bare counter presented an effective cross section of 9.6 cm^2 to thermal neutrons; but this result is subject to two small corrections deriving from the fact that the response of the indium foils (1) involves the influence of the moderator present upon the self-absorption in the foils, and (2) depends upon the isotropy of the neutron atmosphere.

The calibration of the indium foils themselves is made by irradiating them in a solid graphite pile at a position in which the thermal neutron flux is known and isotropic. On the other hand, in our counter calibration the foils under irradiation are supported upon a light sheet metal structure suspended in mid-air. The difference in scattering materials about the foils in the two cases must be expected to change the perturbation in the neutron density caused by the absorption of neutrons in indium. To establish the amount of this effect, Mr. C. Eggler kindly performed a subsidiary measurement in which he compared the specific saturated activity for irradiations in air and in graphite of a standard indium foil (92.3 mg/cm²) with that of a very thin indium deposit (0.423 mg/cm²; negligible self absorption) on an iron foil finding

$$\frac{(A\ \text{thin})}{(A\ \text{stan})}\bigg/\frac{(A\ \text{thin})}{(A\ \text{stan})} = 0.95.$$
$$\text{(air)} \qquad \text{(graphite)}$$

If all of the neutrons striking the boron counter-indium foil assembly were monodirectional, proceeding from the primary scatterer only, the activity induced in the indium foils would be, as is easily computed, 1.29 times greater for the arrangement chosen, in which the normal to the indium foils made an angle of 55° with the line from the foils to the primary scatterer, than the activity if the neutrons were isotropic. The degree of isotropy was easily checked by observation of the counting rate in a boron counter which was sheathed in cadmium over all of its surface except one end; it was found that the counting rate changed in a gradual manner from a maximum when the counter window pointed directly toward the primary scatterer to a minimum, equal to one-fourth the maximum, when the window pointed away from the primary scatterer. We thus conclude that most of the neutrons striking the indium foil assembly have been scattered in by objects other than the primary graphite scatterer. We also note that the unshielded boron counter responds in approximately the same manner as do the indium foils to deviations from isotropy, since the arrangement kept the axis of the counter parallel to the planes in which the foils were mounted; but the effect in the counter is smaller from the circumstance that neutrons passing perpendicularly through the counter along a diameter experience a fractional reduction in intensity of 0.05, whereas for neutrons passing perpendicularly through a standard indium foil the reduction is 0.092. This study leads us to estimate the effect of nonisotropy in the neutron atmosphere as producing a correction of about 5 percent.

These two corrections then lead us to write for the detection cross section of the counter: 10.6 ± 1 cm².

Adopting for the mean cross section of a nitrogen molecule for absorption of thermal neutrons the figure $2\times 1.7\times 10^{-24}$ cm², we may say that the number of counts is the same as the number of neutrons absorbed in a mass of air of 10.6 cm²/(0.055 cm²/gm air) = 193 gm air (for single unshielded counter).

This air mass equivalent of the counter is derived from calibration for thermal neutrons. As the cross sections of both boron and nitrogen follow the $1/v$ law, the same air mass equivalent will apply for unshielded counters to slow neutrons of all energies.

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$(n,2n)$ and (n,p) Cross Sections*

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Cross sections of several $(n,2n)$ and (n,p) reactions were measured by bombarding samples with a known flux of neutrons and measuring the induced beta-activity, making elaborate corrections for self-absorption of the beta-rays. Using the known energy spectrum of the incident neutrons, calculations were made of the cross sections to be expected from Weisskopf's statistical theory, and the agreement was satisfactory. The results indicate that level densities in odd-odd nuclei are greater than those in even-even nuclei by a factor of 3 ± 1. Applications of the method to shielding and the use of threshold detectors are discussed.

I. INTRODUCTION

An interesting result of nuclear statistical theories is the prediction of cross sections of nuclear reactions which predominantly proceed through energy states of excitation sufficiently high that resonances are very closely spaced and can thus be meaningfully averaged over. $(n,2n)$ and (n,p) reactions are particularly simple examples of these, since the incident particle faces no Coulomb barrier, whence the cross section for the formation of the compound nucleus is πr^2 (r is the nuclear radius). The cross section for an $(n,2n)$ reaction is then πr^2 times the probability that the compound nucleus will decay by emission of two neutrons which, considering neutron emission as much more probable than any other mode of decay, is just the probability that the first neutron is emitted with low enough energy to leave emission of a second neutron energetically possible. Considering the first neutron to be emitted with an energy spectrum approximating a Maxwell distribution with temperature, T, gives[1]

$$\sigma(n,2n)=\pi r^2[1-(1+\Delta E/T)\exp(-\Delta E/T)], \quad (1)$$

where $\Delta E=E-B$, E = energy of incident neutron, and B = threshold of the reaction.

In the case of (n,p) reactions, emission of a proton is impeded by the coulomb barrier, causing it to be much less probable than emission of a neutron (inelastic scattering) with which it competes, whence

$$\sigma(n,p)=\pi r^2 f_p/(f_n+f_p)\simeq\pi r^2 f_p/f_n, \quad (2)$$

where f_p and f_n are the relative probabilities of the compound nucleus decaying by emission of a proton and neutron. Methods of calculating these quantities are given by Weisskopf.[1]

* Assisted by the ONR.

† A section of doctoral dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Science.

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[1a] V. Weisskopf, *Lecture Series in Nuclear Physics* (U. S. Govt. Printing Office, Washington, D. C., 1947). [b] V. Weisskopf and Ewing, Phys. Rev. **57**, 472 (1940). [c] V. Weisskopf and J. M. Blatt, M.I.T. Technical Report No. 42 (May 1, 1950), unpublished.