Delayed Neutrons from U^{235} After Short Irradiation*

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The decay curve of the delayed neutrons from U^{235} after an approximately 10-millisecond irradiation is measured for times from 0.2 second to 10 minutes. This curve is resolved into 5 periods, and their relative intensities are determined. When the data are converted to the conventional case of infinite irradiation, we may represent the decay curve on a relative basis by the following formula where t is in seconds.

$$N(t)=0.076\exp(-t/0.52)+0.279\exp(-t/2.5)+0.297\exp(-t/7.9)+0.294\exp(-t/32.4)+0.054\exp(-t/79.9).$$

Indications of a 6-millisecond delayed neutron period are found. These 6-millisecond period neutrons seem to amount to only 2 percent of the delayed neutrons when irradiated to saturation.

I. INTRODUCTION

AT the end of 1944, O. R. Frisch *et al.* built a chain-reacting assembly nicknamed "The Dragon" at Los Alamos Laboratory. The essential feature of Frisch's device was that a slug of active material[1] was made to fall through a core of active material in such a fashion that momentarily a chain reaction sustained by the neutrons emitted instantaneously in fission (prompt neutrons) alone took place. This gave rise to an intense burst of neutrons lasting a very short time; for example, the bursts lasted some milliseconds and gave rise to about 10^{14} neutrons per burst.

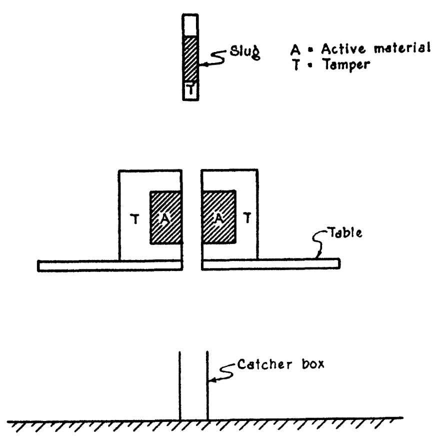

FIG. 1.

Delayed neutron periods of U^{235} had been measured by this time or were being worked on by several investigators,[2] but all these measurements were made with rather long irradiation times. In consequence, the resolution of the shorter periods was questionable. The dragon, or drop experiment as it was also called, was the first opportunity to realize exceedingly short irradiations of U^{235} and then measure the decay curve of the delayed neutrons.

II. EXPERIMENTAL ARRANGEMENT

A. General Set-Up

In the drop experiment essentially three different assemblies were used. Such an assembly is sketched in Fig. 1 (not to scale). The "slug" contained about 10 percent of the active material. The three assemblies shall be referred to as assembly *I*, *II*, and *III*. Their essential characteristics as they affect this investigation are given in Table I.

It will be noted that assemblies *I* and *II* used a BeO reflector and consequently, in addition to the delayed neutrons, neutrons after the main pulse were produced by the $\gamma-n$ reaction in Be.

There were essentially two places where delayed neutrons could be detected: (a) near the core (i.e., on the "Table") or, (b), near the

* This work was completed on April 6, 1945, and filed as a classified report of the Los Alamos Scientific Laboratory. The results only of this work were reported previously as a Letter to the Editor in this journal (Phys. Rev. 73, 636 (1948)).

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[1] By active material is meant a mixture of U^{235} and moderator.

[2] Snell, Nedzel, Ibser, Levinger, Wilkinson, and Sampson, Phys. Rev. 72, 541 (1947); W. C. Redman and D. Saxon, Phys. Rev. 72, 570 (1947); Hughes, Dabbs, Cahn, and Hall, Phys. Rev. 73, 111 (1948).

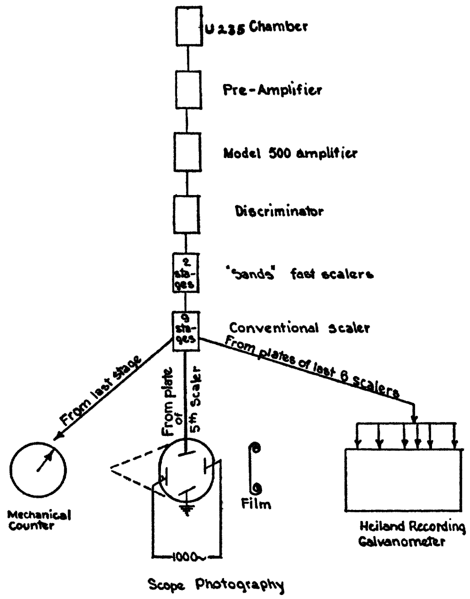

FIG. 2.

catcher box. If one observes the decay curve by means of a neutron-detecting device on the table, it has the advantage that one can record immediately after the main burst is past; i.e., from about 10 milliseconds on. The disadvantage of the table position is that it presents a distorted picture of the decay curve, since the core and reflector form a highly multiplicative system even without the slug; in addition, the neutrons from the $\gamma-n$ reaction of the fission product γ's on the Be further distort the decay curve.

A chamber which is placed near the catcher box and measures delayed neutrons emitted from the slug does not so distort the decay curve, but it does not permit the measurement of the source sooner than about 200 milliseconds after the main pulse, the time required for the slug to arrive and come to rest in the catcher box.

In consequence of the above considerations it was decided to measure the true decay curve from 200 milliseconds on out by measuring the delays emitted from the slug in assembly *III*, where no $\gamma-n$ reaction or multiplicative system would interfere.

To obtain an idea about possible delay periods in the region between several milliseconds and 200 milliseconds, a neutron detector was located on the table in all three assemblies with the clear understanding that it might give a somewhat distorted picture but would show up any important effects.

TABLE I. Characteristics of the assemblies.

Assembly No.	Neutron reflector	Effective width B of main pulse
I	BeO	$\sim$3 milliseconds
II	BeO—sheet of Cd between core and tamper	$\sim$3 milliseconds
III	Graphite and polythene	$\sim$11 milliseconds

B. Neutron Detecting and Recording Equipment

The chambers used throughout were two flat U^{235} fission chambers[3] filled with an argon+CO_2 mixture and using electron collection for rapid response.

For measurements on the slug, a chamber was placed close to the catcher box and surrounded by 2 to 3 inches of paraffin. The top and sides were covered with cadmium and paraffin to stop the neutrons emitted from the core on the table.

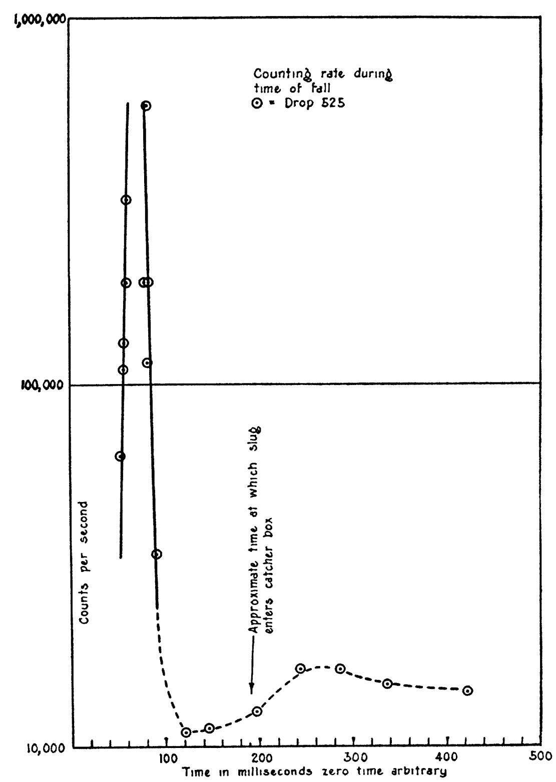

FIG. 3.

[3] Constructed by H. Daghlian and M. Holloway.

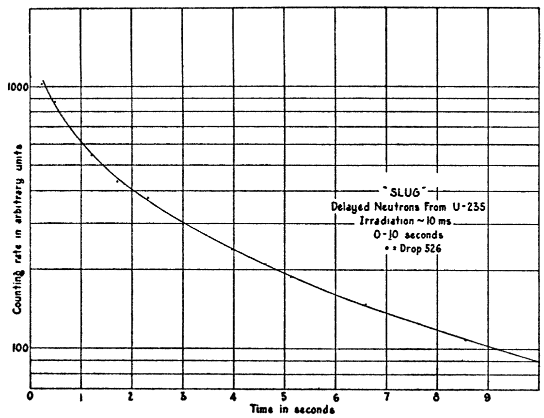

FIG. 4.

The table chamber was placed in different positions on the three assemblies. In assembly *I* and *II* it was placed at the interface of core and reflector; in assembly *III*, it rested on the outside of the polythene reflector.

The amplifying and recording arrangement is depicted in a block diagram in Fig. 2. By suitable adjustments of the time constants the resolution of the system was made about $\frac{1}{2}\mu$-second.[4] Each stage represents a scale of two. As can be seen, three methods of recording were employed. For counts over many minutes, to obtain the long periods, a conventional mechanical counter was read at proper intervals and the interpolation lights recorded when necessary. For the recording of the decay curve after 200 milliseconds, use was made of a 6-channel Heiland recording galvanometer. All six channels were used, since it was convenient to have different scales available at different time intervals.

For the very short times the counts were put on the vertical deflection plates of a Dumont Model 247 oscilloscope, which was swept by a 1000-cycle sweep and photographed by means of a General Radio camera.[5, 6]

III. EXPERIMENTAL RESULTS

The results of this section will be presented under the headings "Slug" and "Table" data:

A. "Slug" Data

In Fig. 3 the counting rate of the slug chamber as a function of time is shown for the time during which the slug falls, and slightly thereafter. It can be seen that the main pulse is recorded in spite of the shielding, since it is so strong; as a matter of fact, the scaler saturated during the peak of the pulse. As the slug approaches the catcher box and is decelerated in it, the counting rate rises again. When the slug comes to rest the counting rate begins to fall with the true decay period. It can be seen that from about 200 milliseconds after the main pulse the curve can be trusted to represent the decay of the neutrons from the slug.

Figures 4–6 show a composite curve obtained from three drops (drop numbers 526, 534, and 537) on assembly *III*. The zero of time chosen corresponds to the midtime of the main pulse.

Drops 526 and 537 were normalized to match drop 534. The arbitrary scale chosen for the *Y* axis is thus counts/second on drop 534. The conversion factors for the other drops were:

$$(534)/(526) = 1.22\times10^{-1},$$
$$(534)/(537) = 1.251\times10^{-2}.$$

That is, the observed intensities were multiplied by these factors in order to obtain one curve for all three measurements.

Since some of these counting rates were quite high, a counting loss correction was applied. This figure was obtained experimentally by making

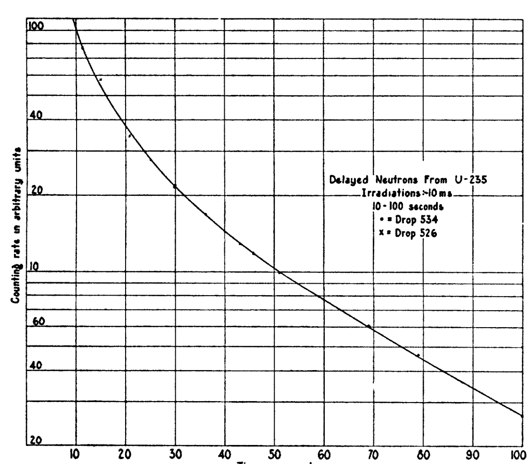

FIG. 5.

[4] Our thanks are due the members of the Los Alamos Electronics Group, and particularly to Matthew Sands for building much of the equipment and suggesting many of the techniques used.

[5] See Appendix for further details.

[6] We are greatly indebted to B. Brixner for help in all photographic aspects of the problem.

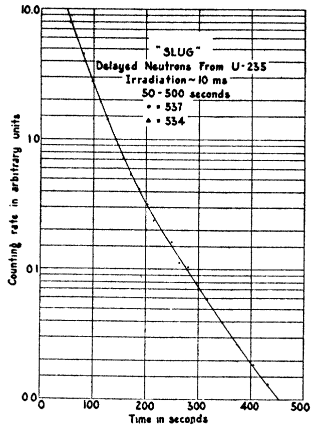

FIG. 6. (The symbol appearing at the bottom of the ordinate should read 0.01.)

the assembly supercritical and allowing the neutron intensity to rise with a period of about one second. This exponentially rising intensity was recorded and plotted on semilog paper; the deviation from a straight line gives the counting loss correction. In the drops 526, 534, and 537 the counting rate was never greater than 60,000 counts/sec., where the correction was 3 percent.

For drops 526 and 534 the records were taken from the Heiland camera, whereas drop 537 was recorded by reading the mechanical counter.

A small background resulting from the presence of a Po-Be source in the assembly was checked before each drop and deducted. The

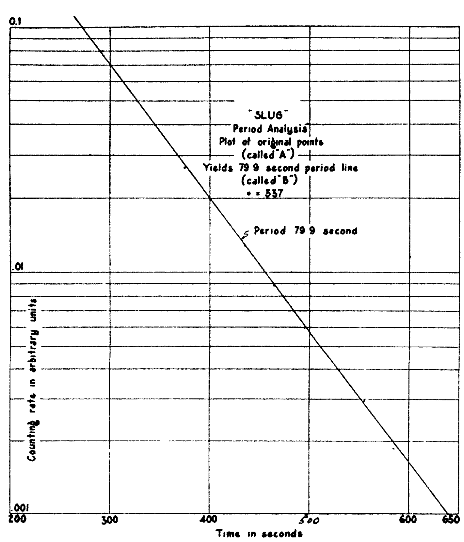

FIG. 7.

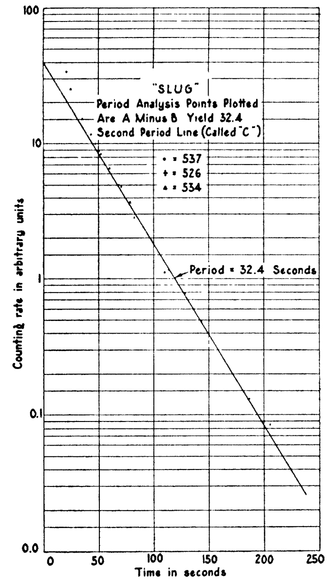

FIG. 8.

effect of delayed neutrons excited by preceding drops was always negligible.

The accuracy of the plotted points is as follows:

Drop 526: 2048 counts for each point.
Drop 534: 3000–8000 counts for each point.
Drop 537: up to 300 seconds—each point represents 15 seconds counting; after 300 seconds—each point represents 30 seconds counting.

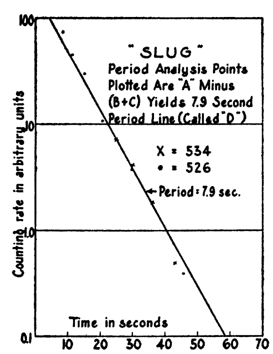

FIG. 9.

The smoothed curve drawn on Figs. 4–6 was the curve that best fitted these points. Supporting evidence not presented here was gained from several additional drops, which showed temporary breakdown of the scalar system but were trustworthy in certain limited time regions.

The analysis into periods was performed by using the *smoothed* curve and "peeling" succes-

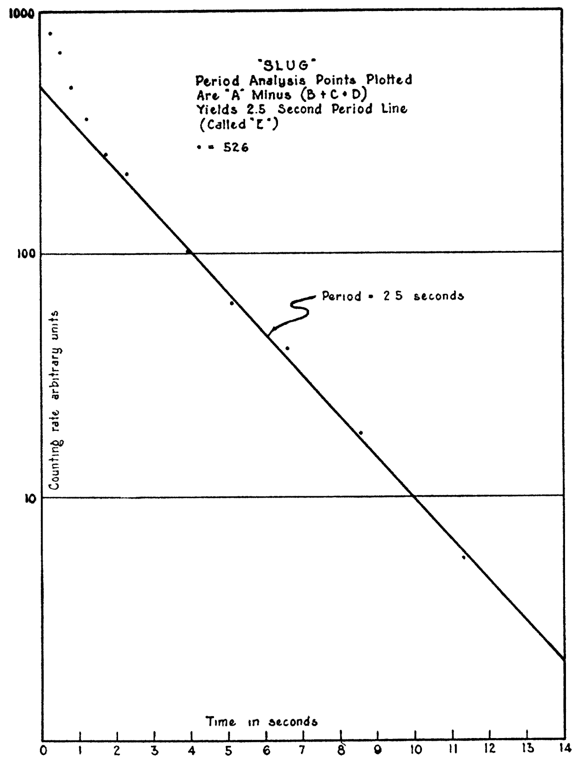

FIG. 10.

sive periods in the conventional fashion. Figures 7–11 serve to illustrate this process and show the period lines obtained from the smoothed curve with the ***original*** points scattering around it.

Table II shows the result of this analysis. We represent the counting rate as a function of time by

$$N(t)=\sum_i A_{0i}\exp(-t/\tau_i),$$

where 200 milliseconds $<t<$ 10 minutes. A_{0i} is thus the intensity of the period τ_i at zero time.

Since it is conventional to represent this curve in case of irradiation to saturation, we convert our relative intensities to this standard. Since our irradiation was infinitely short compared with any of the periods in Table I, we merely have to form the product $A_{0i}\tau_i$ to achieve this purpose. The column entitled r_i normalizes the products $A_0\tau_i$ so that $\sum_i r_i=1$. The probable errors indicated on the periods obtained are guesses based on the "peelings" as shown and on evidence from the analysis of drops not presented here.

B. "Table" Data

Figures 12–14 show three drops on assemblies *I* and *II*. They clearly indicate the presence of a short period. In order to analyze this portion of the curve we treat all other periods as a single one, as shown by the straight and almost horizontal line into which the curve merges. This is justified since the next period is very long compared with our time scale. In the insert of each of these figures are plotted the experimental points with the values from the straight line, representing the long periods, subtracted off. The points are rather inaccurate since each represents only 64 to 320 counts, save that the long-period line is much better established. Appropriate counting rate corrections were applied, but these were difficult to ascertain accurately for such enormous counting rates and were really guesses for rates above 200,000 counts/second. The average value of the period is 6.3 ± 1 milliseconds.

Figure 15 shows two samples of the type of curves obtained with assembly *III*. The left side, i.e., the rise of the main burst, was plotted for one drop only. The short period is much less in

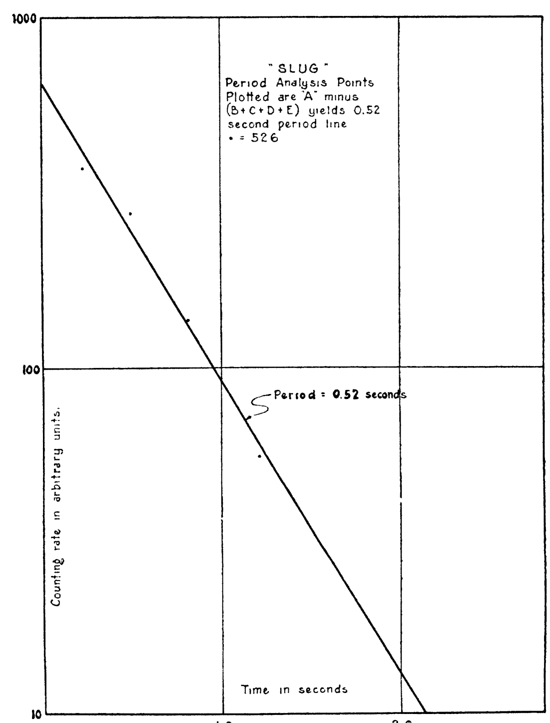

FIG. 11.

evidence here. However, this is to be expected since the main pulse is much broader and hence the short period would have decayed considerably by the time at which it becomes possible to observe it. The dotted curves indicate the intensity expected on the basis of a 6.3-millisecond period with an intensity averaged from Figs. 12–14, and it is seen to agree reasonably well with the observed points.

In calculating the curve, allowance was made for the different length of irradiation in the different assemblies. The rise and fall of the neutron intensity during the main burst corresponds to a Gaussian[7] function $\exp(-t^2/B^2)$, where B is the equivalent width of the burst as given in Table I. If a neutron emitter of period τ is produced by such an irradiation, the activity at the time $t(t^2 \gg B^2)$ is $A_0 \exp(-t/\tau) \exp(B^2/4\tau^2)$, where A_0 is the initial activity which would be produced by an infinitely short irradiation of the same integrated intensity. The correction factor $\exp(B^2/4\tau^2)$ is 1.02 for $\tau = 6.3$ milliseconds and $B = 3$ milliseconds (assemblies *I* and *II*), and 1.275 for $\tau = 6.3$ milliseconds and $B = 11$ milliseconds (assembly *III*). Hence the intensity of the short period was multiplied by $1.275/1.02 = 1.25$ before constructing the dotted line in Fig. 15.

The fact that all these assemblies indicate a short period of about the same length and intensity makes it seem unlikely that it should be spurious. If it were, for instance, caused by neutrons which have been diffusing in the neutron reflector for some time, it should be most prominent in assembly *III*, in which thermal neutrons are very important, and least in assembly *II*, in which they hardly contribute to the reaction. If it were caused entirely by a $\gamma - n$ reaction in the BeO tamper, it should be absent in assembly *III*. On the other hand, γ-rays of a similar period have been found by P. B. Moon,[8] and these may produce some photo-neutrons in assemblies *I* and *II*, which would contribute to our short period.

The initial intensity of the short period after an infinitely short irradiation is about 10 times that of the other periods together. If irradiated to equilibrium however, it amounts to only 2 percent of all delayed neutrons, or about 0.01 percent of all the neutrons.

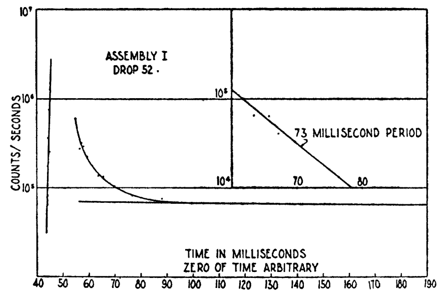

FIG. 12.

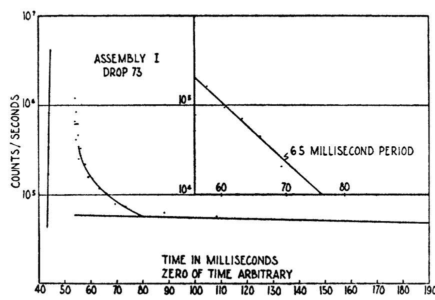

FIG. 13.

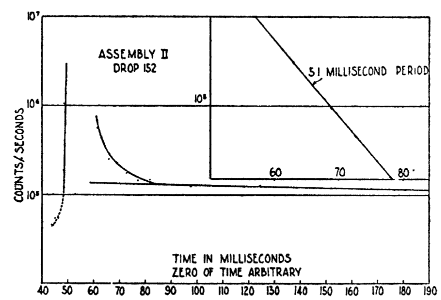

FIG. 14.

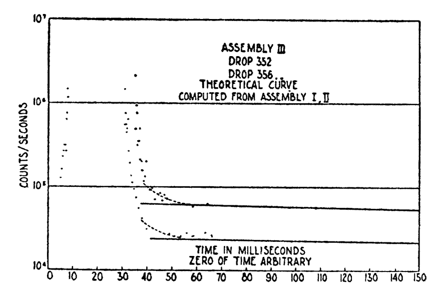

FIG. 15.

[7] This follows from theory and is borne out by the measurements on the dragon; O. R. Frisch, private communication.

[8] Private communication.

TABLE II. Results of analysis into periods.

τ_i	A_{0i}	$A_{0i}\tau_i$	r_i
79.9 ±1.0 seconds	2.99	239	0.054
32.4 ±0.6 seconds	40.0	1296	0.294
7.9 ±0.5 seconds	165	1308	0.297
2.5 ±0.3 seconds	490	1225	0.279
0.52±0.1 seconds	640	333	0.076

IV. DISCUSSION OF RESULTS

A comparison of the above results with the measurements of D. J. Hughes *et al.*[1] is shown in Table III.[9]

It is seen that the results are in substantial agreement in the delayed neutron periods reported. However, the discrepancies in the values of r_i are greater than the experimental errors of these measurements would seem to warrant. Only part of this discrepancy can be attributed to the inherent inaccuracies of the "peeling" technique. The explanation for the divergence in the reported r_i's probably lies in the fact that the energies of the delayed neutrons emitted in the different periods vary over a rather wide range.[10] Hence, for an absolute evaluation of the strengths of the various periods, account must be taken of the varying efficiency of the neutron detectors used with the energies of the different delayed neutron periods. Such corrections have not been applied to our measurements, while the values of Hughes *et al.* are corrected for the energies of the delayed neutrons.

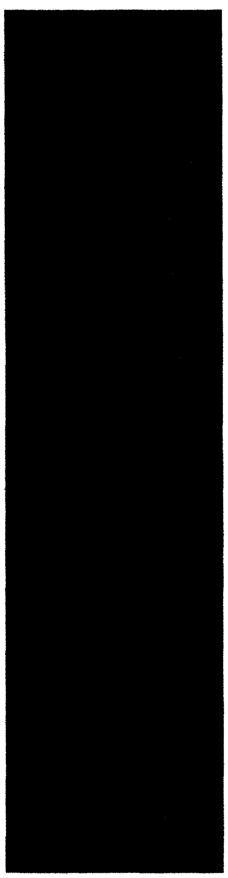

FIG. 16. Typical oscilloscope pattern.

TABLE III. Comparison of results with those of Hughes.*

This paper		Hughes	
τ_i	r_i	τ_i	r_i
79.9	0.054	80.2	0.035
32.4	0.294	31.7	0.227
7.9	0.297	6.51	0.292
2.5	0.279	2.19	0.330
0.52	0.076	0.62	0.116

* See reference 1.

Although the evidence for the 6.3-millisecond delay period seems rather strong, the fact that the effect measured is a very small tail on the exceedingly strong primary neutron pulse makes the interpretation of the results rather uncertain. We cannot, therefore, claim great accuracy for either the value of the period or for its relative intensity. Certainly we cannot exclude the possibility that the period observed is really a super position of many short periods.

Our experiments show no evidence for a 50-millisecond delayed neutron period, as reported by Hughes *et al.* While the accuracy of our measurements of the 6.3-millisecond group is not very great, and it would have been quite difficult for the above-mentioned authors to have observed such a short period, it seems unlikely that we would have missed a 50-millisecond period of the intensity reported by them.

We would like to thank Professor O. R. Frisch for helpful advice during the course of this experiment.

This paper is based on work performed at the

[9] We have compared our values with those of Hughes, since his measurements are the most recent, and have been corrected for the different energies of the delayed neutron periods. We have not included the very short 6.3-millisecond period in our results, nor the 50-millisecond period reported by Hughes, in computing the r_i's.

[10] See the paper by D. J. Hughes of reference 1 for values.

Los Alamos Scientific Laboratory of the University of California under Government Contract No. W-7405-eng-36, and the information contained therein will appear in Division V of the National Nuclear Energy Series (Manhattan Project Technical Section) as part of the contribution of the Los Alamos Laboratory.

APPENDIX

Figure 2 shows that the plate of the 5th "Higginbotham" Scaler was tapped and the signal fed to the vertical sweep plates of a blue-screen 5-inch DuMont oscillograph, Model 247. On the horizontal plates a specially built linear sweep was imposed and adjusted to a frequency of 1000 cycles/second. The screen was photographed by means of a continuously moving film, with the film moving vertically. The camera used was a General Radio Company oscillograph camera. The developed films showed a pattern like the sample shown in Fig. 16.

This pattern can be interpreted easily, since the first stage of the scaler contains a "flip-flop" circuit, and consequently its output changes from a maximum to a minimum and back to a maximum with successive pulses. Thus a shift of the height of the line on the scope (or film) will indicate that a pulse has registered. It should be clearly understood that with the use of this scheme the length of time between "breaks" (i.e., shifts in line-height) is the time elapsed between the appearance of two consecutive pulses and not the duration of a single pulse.

It is important that the sweep return be very fast in order that pulses may not be lost between the end of one and the beginning of another sweep. Since a signal pulse in between two sweeps is easily detected because of the shift in line-height, and, further, since two pulses within that time are rather unlikely because of the limitations in the resolving time of the amplifier, this sweep was found entirely adequate. Both the sweep and incoming signal were put directly on the respective sets of plates of the oscilloscope in order to by-pass the comparatively long time constants of the internal scope amplifiers. The incoming pulse height was regulated by means of a volume control between scaler and oscilloscope. It was so adjusted as to make the pulse height about a quarter of the distance between consecutive sweeps on the film, as can be seen in Fig. 16. This volume control had to be varied, of course, when a different film speed was used. The developed film is easily read on a Recordak Microfilm Reader.

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The Capture Probability of Negative Mesotrons*

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Disintegration curves of positive and negative mesotrons stopping in H_2O, NaF, Mg, Al, and S have been determined. The relative counting rates of positive and negative disintegration electrons support the view that the change of the mean life of negative mesotrons can be interpreted as due to a competition between the processes of spontaneous disintegration and nuclear capture. The mean-life values of positive mesotrons in the various materials are in agreement and yield a mean of $\tau_+ = 2.11 \pm 0.10$ μsec. From the mean life values of negative mesotrons the capture probabilities of mesotrons in the neighborhood of the absorber nuclei are calculated and shown to obey an empirical law of the form kZ^a with $a = 3.7 \pm 0.85$.

INTRODUCTION

Two years ago, the author carried out a determination of the mean life of cosmic-ray mesotrons at an altitude of 11,500 feet[1] to investigate whether there might exist a variation of the mean life with altitude. The experimental method was similar to that used by Nereson and Rossi.[2] The absorber stopping the mesotrons was aluminum, and the mean life obtained was 1.78 ± 0.10 μsec. However, since a sea level check of the apparatus also yielded a value slightly lower than 2.15 ± 0.07 μsec., the best sea level value of Nereson and Rossi, an altitude variation of the mean life could not be considered as established. When the results of the experiment of Conversi, Pancini, and Piccioni on the disintegration of negative mesotrons in light materials became known,** it seemed more reasonable to

* Assisted by the joint program of the Office of Naval Research and Atomic Energy Commission.
[1] H. Ticho, Phys. Rev. **72**, 255 (1947).
[2] N. Nereson and B. Rossi, Phys. Rev. **64**, 199 (1943).

** Private communication by Prof. Amaldi.

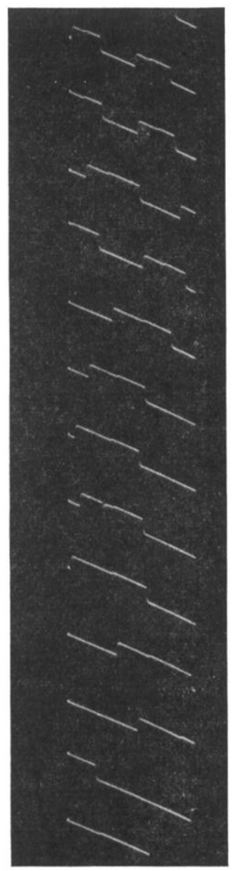

FIG. 16. Typical oscilloscope pattern.