Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium, and Thorium*

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The periods, relative abundances, and absolute yields of delayed neutrons from "fast" fission of six nuclides (U^{235}, U^{233}, U^{238}, Pu^{239}, Pu^{240}, and Th^{232}) and thermal fission of three nuclides (U^{235}, U^{233}, and Pu^{239}) have been measured. "Godiva," the bare U^{235} metal assembly at Los Alamos, was the neutron source. Six exponential periods were found necessary and sufficient for optimum least-squares fit to the data. Despite evident perturbations, general agreement among delayed-neutron periods was obtained for all nuclides. The absolute total delayed-neutron yield for each nuclide has been measured for fast and thermal fission; a spectral effect was not observed. Representative of general delayed-neutron periods (half-lives) and abundances are the U^{235} fast-fission data:

Half-life (sec)	Rel. abundance	Half-life (sec)	Rel. abundance
54.51±0.94	0.038±0.003	2.23 ±0.06	0.407±0.007
21.84±0.54	0.213±0.005	0.496±0.029	0.128±0.008
6.00±0.17	0.188±0.016	0.179±0.017	0.026±0.003

These data have been corroborated in detail by independent period-*vs*-reactivity measurements on the bare U^{235} assembly. A comparison of the present results with a phenomenological theory of delayed-neutron emission has been made. This treatment has led to the prediction of several new short-period delayed-neutron precursors.

I. INTRODUCTION

SOON after the discovery of delayed neutrons in 1939 by Roberts *et al.*[1] the Bohr-Wheeler liquid-drop nuclear model was advanced,[2] thus providing a plausible mechanism for the experimental fact of delayed-neutron emission. Since the original work of Roberts, many investigations have been made on the characteristics of delayed neutrons; both accelerators and reactors have been used as neutron sources, with main interest in thermal fission of U^{235} and Pu^{239}. For a résumé of previous investigations, reference is made to a recent review[3] summarizing all delayed-neutron work prior to 1956. A preliminary report on status of the comprehensive delayed-neutron program at Los Alamos was presented at the Geneva Conference, August, 1955.[4]

II. EXPERIMENTAL ARRANGEMENT AND MEASUREMENT TECHNIQUES

The complex decay of delayed-neutron activity is capable of most direct and accurate analysis when the irradiation time of the fissile material is (a) "instantaneous"; i.e., short compared to the shortest delayed-neutron period, or (b) "infinite"; i.e., long compared to the longest delayed-neutron period. To minimize neutron multiplication within the sample, only a small amount (a few grams) of fissile material should be irradiated; this, in turn, implies the use of extremely high-intensity irradiations to provide adequate counting statistics. The bare U^{235} metal assembly at Los Alamos—"Godiva"[5]—is well suited to these requirements. With this assembly appropriately modified, both "infinite" and "instantaneous" irradiations, each consisting of $\sim 10^{16}$ total fissions, are used to emphasize the longer- and shorter-period contributions, respectively.[6] In addition, the insantaneous irradiations provide an independent method of determining absolute total yield of delayed neutrons from the different fissile elements (see Sec. III-C).

Measurements have been made on the delayed neutrons from fast fission of six nuclides: U^{235}, U^{233}, U^{238}, Pu^{239}, Pu^{240}, and Th^{232} and from thermal fission of three nuclides: U^{235}, U^{233}, and Pu^{239}. The Godiva central spectrum (for "fast"-neutron irradiations) is a slightly degraded fission-neutron spectrum[7]; the "thermal"-neutron spectrum is obtained within an 8-in. cubic polyethylene block, Cd shielded and mounted near

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[1] Roberts, Meyer, and Wang, Phys. Rev. **55**, 510 (1939); Roberts, Meyer, Hafstad, and Wang, Phys. Rev. **55**, 664 (1939).

[2] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939). See also J. Frenkel, J. Phys. U.S.S.R. **1**, 125 (1939).

[3] G. R. Keepin, *Progress in Nuclear Energy I* (Pergamon Press, London, 1956). For recent work on delayed neutron energies, see also R. Batchelor and H. R. McK. Hyder, J. Nuclear Energy **3**, 7 (1956).

[4] G. R. Keepin and T. F. Wimett, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1955), Paper 831, Vol. IV, p. 162.

[5] R. E. Peterson and G. A. Newby, Nuclear Sci. and Eng. **1**, 112 (1956).

[6] "Infinite" irradiations refer to delayed-critical operation; "instantaneous" irradiations are super-prompt-critical radiation bursts of $<\frac{1}{4}$-millisecond duration. Characteristics of these bursts are discussed in references 3 and 8. The initial delayed-neutron activity is proportional to $a_i\lambda_i$ following an instantaneous irradiation, and proportional to a_i for an infinite irradiation. (a_i and λ_i are the abundance and decay constant, respectively, of the ith delayed-neutron group.) This effective weighting of initial activity by the factor λ_i for an instantaneous irradiation is clearly advantageous in studying the short-period delayed-neutron groups.

[7] L. Rosen, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1955), Paper 582 (15A). See also Cranberg, Day, Rosen, Taschek, and Walt, *Progress in Nuclear Energy I* (Pergamon Press, London, 1956).

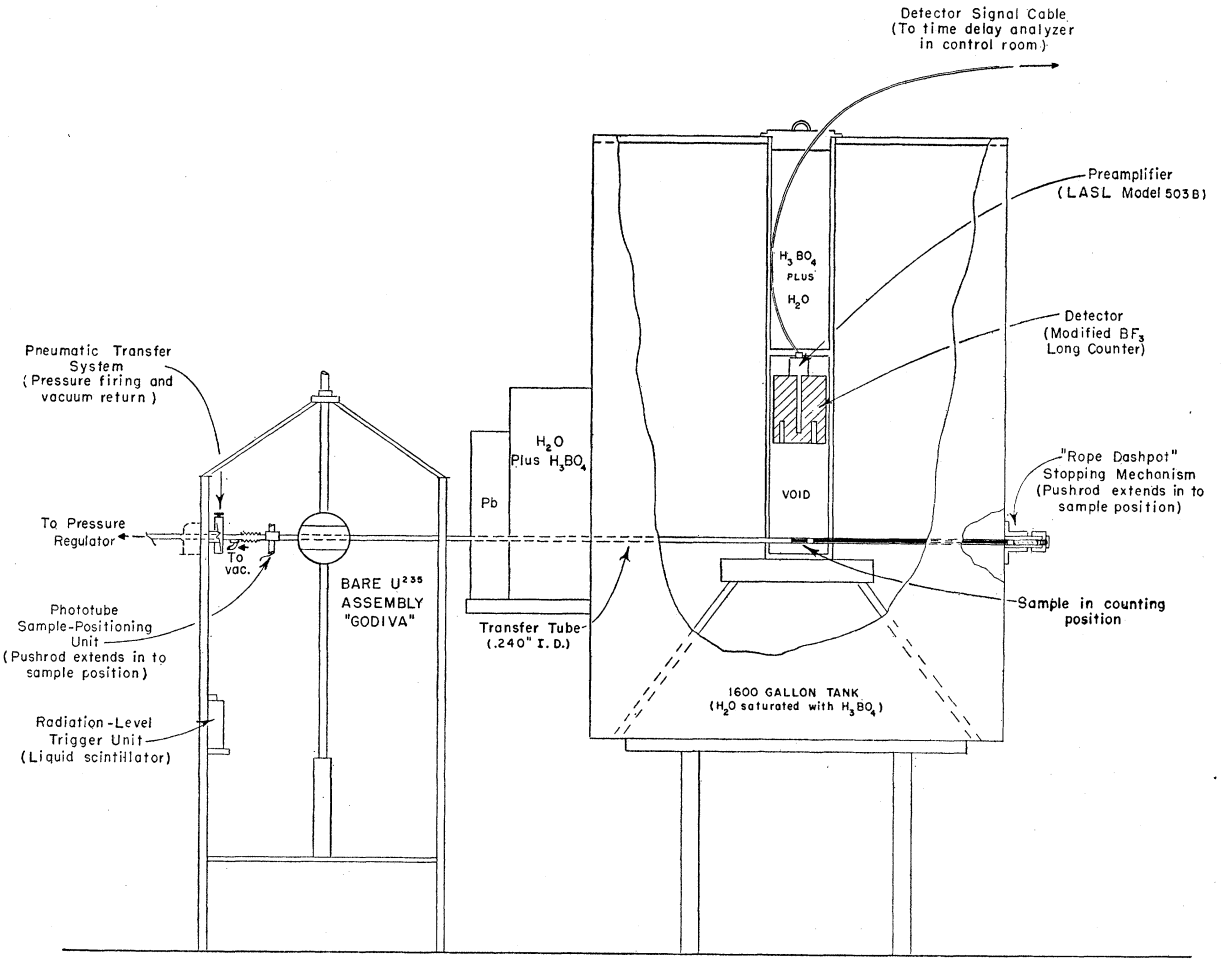

FIG. 1. Schematic diagram of the experimental arrangement for delayed-neutron studies at Los Alamos.

Godiva. The cadmium ratio of this moderator geometry was measured by U^{235}-foil activation as ~ 75, thus assuring a high preponderance of thermal fissions.

A schematic diagram of the general experimental arrangement for fast irradiations is shown in Fig. 1. The Godiva assembly, sample transfer system, and detection equipment are located in an assembly building ("Kiva") which is remotely operated from a control center $\frac{1}{4}$ mile distant.[8] A pneumatic system transfers a 2–5 g sample of fissile material from the point of irradiation to a 4π-shielded counting geometry in ~ 50 msec. Ni-coated samples (Pu and U^{233} with high specific α-activity) are protected from shock and abrasion by enclosure in thin titanium cans. A simple phototube arrangement ensures reproducible positioning of the sample within the center of Godiva (or polyethylene geometry) during irradiation. For instantaneous irradiations, the output of a scintillation detector is used to generate (at a preset radiation level) a "trigger" pulse which initiates sample transfer and counting. After the irradiated slug is counted for 500 sec, it is returned to Godiva by a remote-control vacuum system, thus completing an irradiation cycle.

The neutron detector used in the present work is a $\frac{1}{2}$-inch-diameter $B^{10}F_3$ proportional counter in "long" geometry, modified to give "flat" response within 5% from ~ 23 kev to ~ 1.5 Mev.

The decay of delayed-neutron activity (corrected for detector dead-time ~ 1 μsec) is monitored by a multichannel recording time-delay analyzer[9] with 0.001-, 0.01-, 0.1-, 1-, and 10-sec channel widths following in automatic sequence; the number of channels of each width is variable, thus permitting selection of the most suitable channel-width distribution for a given decay curve. Two identical analyzers were built and operated in parallel, providing a continuous check on proper operation of the two independent systems. Accurate time-delay analysis is thus assured through independent checks on time-channel width, correct counts in each channel, and correct total counts.

[8] H. C. Paxton, Nucleonics **13**, No. 10, 48 (1955).

[9] Koontz, Johnstone, Keepin, and Gallagher, Rev. Sci. Instr. **26**, 546 (1955).

III. ANALYSIS OF DATA, AND RESULTS

A. Analysis of Delayed-Neutron Data

It may be assumed that the decay of delayed-neutron activity with time can be represented by a linear superposition of exponential decay periods. The general exponential decay problem was linearized (by Taylor's series expansion) and coded for iterative least-squares analysis on the IBM 704 computer at Los Alamos. The number of periods required was *not* an initial constraint; six exponential periods were determined to be necessary and sufficient for optimum least-squares fit to the data. When one uses five (or fewer) periods, satisfactory convergence is not obtained and the indicated errors are very large. When an arbitrary seventh period is introduced, the calculated abundance of this group is not significantly different (within two standard deviations) from zero. (See note added in proof).

Two approaches to analysis of delayed-neutron decay data have been investigated. The first is a simultaneous solution of all periods and abundances (12×12 matrix) from prompt-burst (instantaneous) irradiation data. The second is a determination of the four long-period groups from long-irradiation data and determination of the four shorter-period groups from burst-irradiation data; the two sets of yields are then normalized at an appropriate point. The latter method was found to give more accurate values of a_i and λ_i (smallest calculated errors) and has been used throughout the program. That the final period and abundance values are unique has been demonstrated convincingly by varying these values (as much as a few hundred percent) and then repeating the least-squares analysis. The iteration invariably converges on the unique ("best fit") values of period and abundance.

Concurrently with the primary computation, standard deviations for both period and abundance values are computed from the inverse of the matrix which occurs in the solution of the normal least-squares equation. These calculated errors indicate (as expected) that the two longer half-lives T_1 and T_2 are determined more accurately from long irradiations, while T_3 to T_6 are better determined from prompt-burst irradiations. It is believed that the computer least-squares calculation completely eliminates subjective errors in decay-curve analysis. Accepting the least-squares criterion for curve fitting, the computer gives unique period and abundance values which are *by definition* the "best fit" to a given set of experimental data.

B. Group Periods and Relative Abundance Values

A summary of the results for high-energy ("fast") fission is given in Table I. Relative abundance values include correction (<3%) for energy variation of the BF_3 detector response. Values of T_1, T_2, and the abundance ratio a_1/a_2 are taken from final long-irradiation data; all other values are obtained from prompt-burst irradiation results. Data were accumulated and analyzed in groups of 10 irradiations each to give the most direct indication of experimental spread in the data. With few exceptions, the observed experi-

TABLE I. Fast-fission delayed-neutron data.[a–e]

Group index i	Half-life, T_i	Relative abundance, a_i/a	Absolute group yield (%) (for pure isotope)
	U^{235} (99.9% 235; $n/F=0.0165\pm0.0005$)		
1	54.51 ±0.94	0.038±0.003	0.063±0.005
2	21.84 ±0.54	0.213±0.005	0.351±0.011
3	6.00 ±0.17	0.188±0.016	0.310±0.028
4	2.23 ±0.06	0.407±0.007	0.672±0.023
5	0.496±0.029	0.128±0.008	0.211±0.015
6	0.179±0.017	0.026±0.003	0.043±0.005
	U^{238} (99.98% 238; $n/F=0.0412\pm0.0017$)		
1	52.38 ±1.29	0.013±0.001	0.054±0.005
2	21.58 ±0.39	0.137±0.002	0.564±0.025
3	5.00 ±0.19	0.162±0.020	0.667±0.087
4	1.93 ±0.07	0.388±0.012	1.599±0.081
5	0.490±0.023	0.225±0.013	0.927±0.060
6	0.172±0.009	0.075±0.005	0.309±0.024
	U^{233} (100% 233; $n/F=0.0070\pm0.0004$)		
1	55.11 ±1.86	0.086±0.003	0.060±0.003
2	20.74 ±0.86	0.274±0.005	0.192±0.009
3	5.30 ±0.19	0.227±0.035	0.159±0.025
4	2.29 ±0.01	0.317±0.011	0.222±0.012
5	0.546±0.108	0.073±0.014	0.051±0.010
6	0.221±0.042	0.023±0.007	0.016±0.005
	Pu^{239} (99.8% 239; $n/F=0.0063\pm0.0003$)		
1	53.75 ±0.95	0.038±0.003	0.024±0.002
2	22.29 ±0.36	0.280±0.004	0.176±0.009
3	5.19 ±0.12	0.216±0.018	0.136±0.013
4	2.09 ±0.08	0.328±0.010	0.207±0.012
5	0.549±0.049	0.103±0.009	0.065±0.007
6	0.216±0.017	0.035±0.005	0.022±0.003
	Pu^{240} (81.5% 240; $n/F=0.0088\pm0.0006$)		
1	53.56 ±1.21	0.028±0.003	0.022±0.003
2	22.14 ±0.38	0.273±0.004	0.238±0.016
3	5.14 ±0.42	0.192±0.053	0.162±0.044
4	2.08 ±0.19	0.350±0.020	0.315±0.027
5	0.511±0.077	0.128±0.018	0.119±0.018
6	0.172±0.033	0.029±0.006	0.024±0.005
	Th^{232} (100% 232; $n/F=0.0496\pm0.0020$)		
1	56.03 ±0.95	0.034±0.002	0.169±0.012
2	20.75 ±0.66	0.150±0.005	0.744±0.037
3	5.74 ±0.24	0.155±0.021	0.769±0.108
4	2.16 ±0.08	0.446±0.015	2.212±0.110
5	0.571±0.042	0.172±0.013	0.853±0.073
6	0.211±0.019	0.043±0.006	0.213±0.031

[a] Total data for each nuclide were obtained from 40 prompt-burst irradiations and 40 long irradiations with the exception of the U^{235} fast-fission data which were obtained from 80 prompt-burst irradiations and 80 long irradiations.

[b] Indicated for each nuclide (in parentheses) are: (1) isotopic purity of sample used for period and abundance measurements, and (2) $n/F \equiv$ total absolute yield in delayed neutrons per fission; note that n/F values (and absolute group yields) have been corrected to 100% isotopic purity; see Sec. III-C.

[c] Uncertainties indicated are calculated probable errors (from IBM-704 computer).

[d] T_1, T_2, and the ratio a_1/a_2 are taken from final long-irradiation data (see Sec. III-B).

[e] $\Sigma a_i = a = n/F \equiv$ total delayed neutrons per fission. Abundance values reported include correction (<3%) for detector response.

mental spread between corresponding group parameters for a given fissile nuclide lies within the calculated probable errors for these parameters. The final results given in Table I are obtained from a separate least-squares fit to all data—*not* an average of individual data groups.

Thermal fission results are summarized in Table II. The analysis of these data is identical with that for fast fission.

Figure 2 shows the agreement between the experimental data for fast fission of U^{235} and a curve calculated from the periods and abundances reported for U^{235} in Table I. Agreement of this kind was obtained for the delayed-neutron decay curve fo each fissile nuclide studied.

C. Absolute Delayed-Neutron Yields

Absolute delayed-neutron yields may be measured by using either prompt bursts or infinite (delayed-critical) irradiations. The former method is considerably more accurate since in this case the yield is determined from neutron *total counts* following a burst, whereas in the second method the yield can be determined only from initial ($t=0$ extrapolation) neutron counting *rate* following a saturation irradiation.

The basic data for determining absolute yield by the prompt-burst method are (1) $\Sigma_{NC}\equiv$total neutron counts (corrected for detector loss and background) following an instantaneous irradiation, (2) $\epsilon\equiv$absolute efficiency of the neutron detector, and (3) $F_s\equiv$total fissions in the sample irradiated. Total fissions are determined by standard counting of the 67-hour β-activity from Mo^{99} which has been chemically separated from the irradiated sample. Measured β-yield is then converted to number of fissions which occurred in the sample by an appropriate "K-factor." K-factors for the various fissionable materials are determined from a primary calibration of number of fissions in a thin fissile foil of known weight against Mo^{99} β-yield from a thick foil also of known weight; both foils are irradiated in the same neutron flux. Thus, for an instantaneous irradiation,

$$\Sigma_{NC}=F_s\epsilon\sum_{i=1}^{6}\int_0^\infty a_i\lambda_i e^{-\lambda_i t}dt=F_s\epsilon\sum_{i=1}^{6}a_i, \qquad (1)$$

where t is measured from the time of the burst, a_i=abundance of ith group in delayed neutrons per fission, λ_i=decay constant of ith group, and $\Sigma a_i=n/F$ ≡absolute yield in total delayed neutrons per fission. Therefore[10]

$$\text{absolute yield}=(n/F)=\Sigma_{NC}/F_s\epsilon.$$

A small correction (order of 1%) must be applied to n/F values as obtained above, due to the self-multiplication of the sample irradiated. Final values of absolute total yields, corrected to 100% isotopic purity, are presented in Table III.

Within the error of these measurements, no "spectral effect" (dependence on energy of neutron inducing fission) was observed for the absolute yields of U^{235}, U^{233}, or Pu^{239}. The values given in Table III are tabulated in order of increasing yield to emphasize two interesting regularities: (1) total yield increases with mass number for a given element and (2) total yield generally decreases with atomic number [except in extreme cases where (1) predominates over (2), e.g., Pu^{240} *vs* U^{233}].

The yield n/F (U^{235})=0.0165±0.0005 from Table III may be compared with the value n/F (U^{235})=0.0164 ±0.0006 determined from independent measurements[11]

TABLE II. Thermal-fission delayed-neutron data.[a–e]

Group index i	Half-life, T_i	Relative abundance, a_i/a	Absolute group yield (%)
	U^{235} (99.9% 235; n/F=0.0158±0.0005)		
1	55.72 ±1.28	0.033±0.003	0.052±0.005
2	22.72 ±0.71	0.219±0.009	0.346±0.018
3	6.22 ±0.23	0.196±0.022	0.310±0.036
4	2.30 ±0.09	0.395±0.011	0.624±0.026
5	0.610±0.083	0.115±0.009	0.182±0.015
6	0.230±0.025	0.042±0.008	0.066±0.008
	Pu^{239} (99.8% 239; n/F=0.0061±0.0003)		
1	54.28 ±2.34	0.035±0.009	0.021±0.006
2	23.04 ±1.67	0.298±0.035	0.182±0.023
3	5.60 ±0.40	0.211±0.048	0.129±0.030
4	2.13 ±0.24	0.326±0.033	0.199±0.022
5	0.618±0.213	0.086±0.029	0.052±0.018
6	0.257±0.045	0.044±0.016	0.027±0.010
	U^{233} (100% 233; n/F=0.0066±0.0003)		
1	55.00 ±0.54	0.086±0.003	0.057±0.003
2	20.57 ±0.38	0.299±0.004	0.197±0.009
3	5.00 ±0.21	0.252±0.040	0.166±0.027
4	2.13 ±0.20	0.278±0.020	0.184±0.016
5	0.615±0.242	0.051±0.024	0.034±0.016
6	0.277±0.047	0.034±0.014	0.022±0.009

[a] Total data for each nuclide were obtained from 40 prompt-burst irradiations and 40 long irradiations.
[b] Indicated for each nuclide (in parentheses) are: (1) isotopic purity of sample used for period and abundance measurements, and (2) $n/F\equiv$total absolute yield in delayed neutrons per fission; note that n/F values (and absolute group yields) have been corrected to 100% isotopic purity; see Sec. III-C.
[c] Uncertainties indicated are calculated probable errors (from IBM-704 computer).
[d] T_1, T_2, and the ratio a_1/a_2 are taken from final long-irradiation data (see Sec. III-B).
[e] $\Sigma a_i=a=n/F\equiv$total delayed neutrons per fission. Abundance values reported include correction (<3%) for detector response.

TABLE III. Absolute total yields of delayed neutrons.

Fissile nuclide	Absolute yield (delayed neutrons/fission for pure isotope) Fast fission	Thermal fission
Pu^{239}	0.0063±0.0003	0.0061±0.0003
U^{233}	0.0070±0.0004	0.0066±0.0003
Pu^{240}	0.0088±0.0006	···
U^{235}	0.0165±0.0005	0.0158±0.0005
U^{238}	0.0412±0.0017	···
Th^{232}	0.0496±0.0020	···

[10] Absolute total yields are sometimes reported as β (or f), the delayed-neutron fraction of total neutrons from fission. [$\beta=\bar{\nu}^{-1}(n/F)$, where $\bar{\nu}$ is the average number of neutrons emitted per fission.]
[11] Data from H. C. Paxton, Los Alamos.

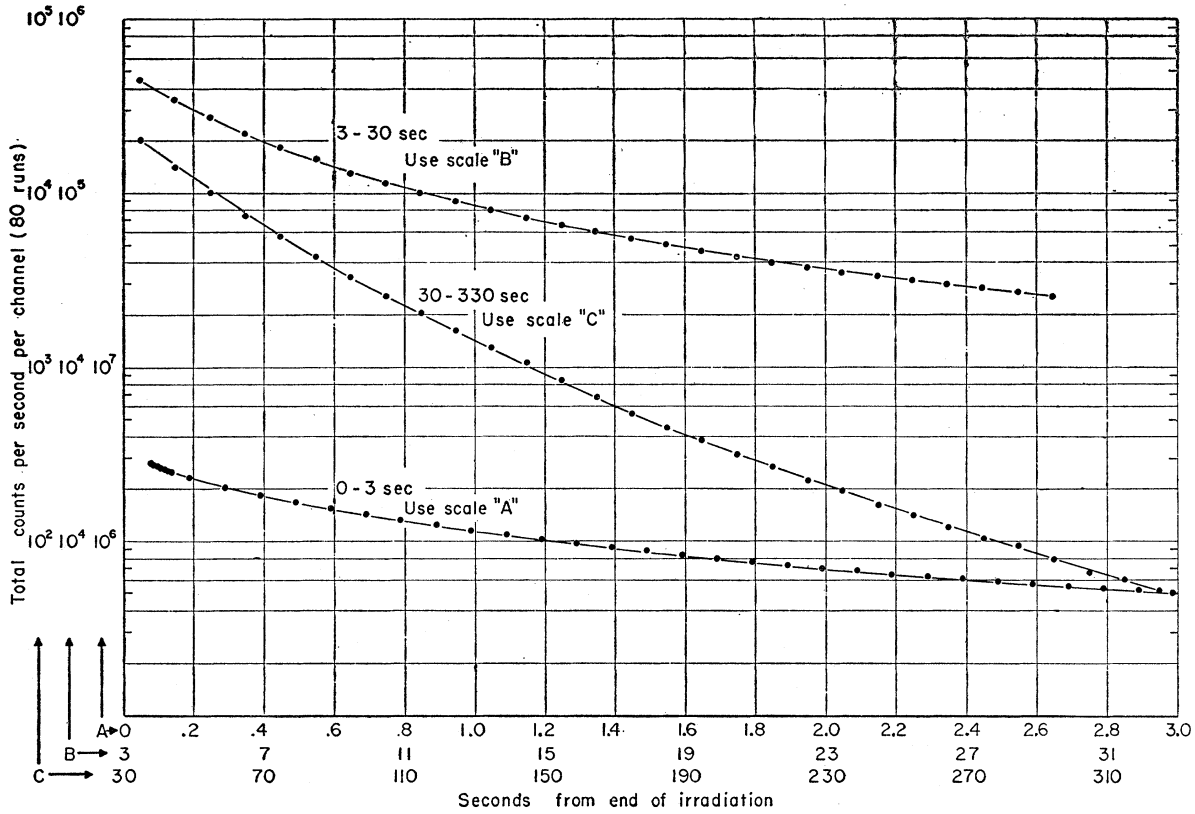

FIG. 2. Delayed-neutron decay following instantaneous irradiations of U^{235} (fast-fission). Cumulative data (●) from 80 prompt-burst irradiations of 3-gram sample of 99.9% U^{235}; the curve is calculated from the U^{235} periods and abundances of Table I.

of the mass increment between delayed and prompt critical conditions for the bare U^{235} assembly.

IV. DISCUSSION OF RESULTS

In summary Tables I and II, the individual group periods for the various nuclides studied are seen to be in general agreement. A comparison of individual delayed-neutron groups among the various nuclides shows that (1) variation among group yields is much greater than variation among group periods, and (2) the increase of total yield with mass number is due mainly to greater contribution from the shorter-period groups.

The period and abundance values for U^{235} have been corroborated in detail by independent period-*vs*-reactivity measurements on the "Godiva" assembly.[12] The excellent agreement between experiment and theory ("inhour equation" of reactor kinetics) in the reactivity region of prompt critical provides (1) a sensitive check on accuracy of short-period delayed-neutron data, and (2) good evidence against the existence of a seventh, shorter delayed-neutron period of appreciable abundance (i.e., less than $\sim 5\times 10^{-4}\%$ yield in U^{235} fission).

Further experimental evidence in support of short-period (especially sixth-group) values is given by recent studies on the detailed shape of super-prompt-critical radiation bursts from the bare U^{235} assembly.[8,13]

General agreement will be noted among the measured periods and abundances for thermal fission in Table II and corresponding data for fast fission in Table I. Small spectral differences (especially for fifth- and sixth-group values) could, of course, result from the variation in fission mass-distribution with incident neutron energy. It will be recalled (Table III) that no spectral effect is observed for absolute total delayed-neutron yields.

A comparison of U^{235} data with the earlier work of Hughes *et al.*[14] has been made.[3] Notable differences (mainly in third- and fourth-group periods) were attributed largely (1) to different amounts of data in the appropriate time interval—5 to 40 sec and (2) to the different methods of analysis—least-squares fit *vs* the more subjective graphical "exponential peeling" method.

Despite the general agreement among group periods, there do exist mechanisms whereby real differences can arise (I) between measured delayed-neutron periods

[12] Similar measurements (at lower reactivity) have been made on a bare Pu^{239} metal assembly as a check on delayed-neutron data for Pu^{239}. Period-*vs*-reactivity measurements will also be made on a bare U^{233} assembly soon to be installed at the LASL critical assemblies laboratory.

[13] Wimett, Graves, and Orndoff, Nuclear Sci. and Eng. (to be published).

[14] Hughes, Dabbs, Cahn, and Hall, Phys. Rev. **73**, 111 (1948).

and their corresponding precursor β-decay periods and (II) between corresponding delayed-neutron periods for the different fissile nuclides. Delayed-neutron precursors can be formed either directly as primary fission products or by cascade β decay. In the latter case, precursor activity (and hence delayed-neutron activity) would exhibit a growth-decay characteristic with time which could lengthen the observed precursor period, depending on the β periods involved.

The differences in corresponding delayed-neutron periods for the six fissile nuclides (difference II above) arise basically from variations in independent nuclide yield. For a given nuclide this yield is determined by the appropriate yield-mass and charge distributions. Both of these quantities are in turn dependent on the indentity of the fissile nuclide and the energy of the neutrons inducing fission. It follows that differences in observed periods (and abundances) could be introduced (a) by changes in the growth-decay characteristics of a fission chain "feeding" a given precursor and/or (b) by the small differential contributions of minor delayed-neutron precursors (i.e., other than the six main precursors).

Heretofore it has been generally supposed[3,15–17] that delayed-neutron precursors of appreciable yield should exhibit even neutron numbers slightly above the 50 or 82 stable-shell configuration. These precursors then decay by β emission to excited states in odd-neutron-numbered nuclides which, having particularly low binding energies for the last neutron, exhibit the greatest probability for neutron emission. This is an energetics argument based solely on the difference between Q_β, the total β-decay energy of the precursor, and B_n, the neutron binding energy of the emitter. However, if one considers odd-N (and odd-Z to maximize Q_β) precursors, decaying to shell-plus-2,4, etc. emitters, it is found that the energy excess, $Q_\beta - B_n$, is still appreciable in many cases.[18,19] Thus prospective delayed-neutron precursors (major and minor contributors) may be sought among fission products having either odd or even neutron numbers.

Effects due to these and other smaller perturbations are, of course, assimilated in the least-squares analysis, thus perturbing slightly the final period and abundance values. Nevertheless, since the decay of delayed-neutron activity from the various fissile nuclides can be satisfactorily fitted by six periods having approximately the same values, it is reasonable to conclude that six *main* precursors do predominate despite evident "perturbations."

In contrast to the relative constancy of delayed-neutron periods, the observed variations in both relative and total yields among the different fissile nuclides are large indeed (see Tables I and II). The essential problem then is to explain individual group yield values—these being the product of relative group yields and total absolute yields. Calculations of precursor yields for the various fissionable nuclides have been made in terms of appropriate mass- and charge-distributions, including shell effects. Comparison of precursor yields thus calculated with measured delayed-neutron yields for the various nuclides then gives neutron-to-β branching ratios ("P_n values") which may be related to theoretical branching ratios. This treatment provides criteria which have proved useful in predicting probable precursor(s) associated with a given delayed-neutron group. The predictions resulting from preliminary calculations have been given.[20] Refined calculations, now in progress, of theoretical P_n values are expected to narrow further the choice of possible precursors for each delayed-neutron group.[21]

Note added in proof.—Br^{88} has recently been identified radiochemically as a second-group delayed neutron contributor by Perlow and Stehney [to be published; see also Bull. Am. Phys. Soc. Ser. II, **2**, 16 (1957)]. They have measured the half-life of Br^{88} as 15.5 ± 0.4 sec and have redetermined the half-life of I^{137} as 24.2 ± 0.2 sec. We have made several attempts to distinguish a 15.5 sec delayed neutron contributor in neutron-decay-curve analysis. Initial abundance coefficients were varied between 1/7 and 1/2 of the total second-group abundance; in no case could a 15.5 sec contribution be detected using either graphical analysis or the iterative least squares method. Thus it appears difficult if not impossible to distinguish the 15.5 sec Br^{88} and the (dominant) 24.2 sec I^{137} components of the second delayed neutron group without the aid of chemical separation (e.g., isolation of fission product bromine as performed by Perlow and Stehney).

A considerably more detailed account of the measurements, analysis method, and results reported here (together with associated reactor-kinetics studies) is being published elsewhere (Keepin, Wimett, and Zeigler, J. Nuclear Energy in press).

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[15] M. G. Mayer, Phys. Rev. **74**, 235 (1948).

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[18] Q_β for odd-Z, odd-N precursors exceeds that for odd-Z, even-N precursors by the difference $\delta_A - \epsilon_A \approx 2$ Mev,[19] which largely compensates for the increased binding energy of even-N emitters. For example, in the case of 16-sec Br^{88} and 5.8-sec I^{138}, the calculated values are $Q_\beta(Br^{88}) = 9.8$ Mev, $B_n(Kr^{88}) = 7.4$ Mev, $Q_\beta(I^{138}) = 8.4$ Mev, and $B_n(Xe^{138}) = 5.6$ Mev. Similar comparisons can be made for other odd-N, odd-Z prospective delayed-neutron contributors.

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[21] The results of these calculations are included in a subsequent paper on theoretical interpretation of delayed-neutron phenomena [G. R. Keepin, J. Nuclear Energy (to be published)].