# PROMPT NEUTRON DECAY FOR DELAYED CRITICAL METAL SPHERES OF PU, AND NATURAL-URANIUM-REFLECTED PU AND HEU

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## ABSTRACT

Prompt neutron decay constants at delayed critical have been measured by Oak Ridge National Laboratory for unmoderated natural-uranium-reflected uranium and plutonium metal spheres (FLATTOP) and an unreflected and unmoderated plutonium metal (4.5% $^{240}$Pu) sphere (JEZEBEL) at the Los Alamos National Laboratory (LANL) critical experiments facility. The average prompt neutron decay constants obtained from hundreds of Rossi-α and randomly pulsed neutron measurements with $^{252}$Cf at delayed criticality are $3.868 \pm 0.007$ x$10^5$ sec $^{-1}$, $2.219 \pm 0.002$ x$10^5$ sec $^{-1}$, and $6.450 \pm 0.010$ x$10^5$ sec $^{-1}$, respectively. These values were measured with a variety of source detector-locations in the diametral holes of the JEZEBEL and FLATTOP assemblies. These values are in agreement with previous prompt neutron decay constant measurements at delayed criticality by LANL for FLATTOP and JEZEBEL ($3.8 \pm 0.1$; $2.14 \pm 0.05$ and 2.29 (uncertainty not reported); and $6.4 \pm 0.1 \times 10^5$ sec$^{-1}$, respectively) but have smaller uncertainty because of the larger number of measurements. For the FLATTOP and JEZEBEL assemblies there is agreement between measurement and calculations. Traditionally, the calculated decay constants for bare uranium metal sphere GODIVA I and the Oak Ridge sphere have been higher than the experimental by ~10% whereas other measured quantities for the bare uranium sphere that depend on energy distributions have calculated to experimental ratios with ~1% of unity.

## 1. INTRODUCTION

Prompt neutron decay constants at delayed criticality have been obtained from a series of measurements of the ratio of correlated counts per $^{252}$Cf fission in a randomly pulsed neutron measurement[1] with $^{252}$Cf to the correlated counts per count in a Rossi-α measurement[2] for an unmoderated unreflected sphere of plutonium metal[3] (JEZEBEL), and unmoderated and natural-uranium-metal-reflected enriched uranium (~93%) and plutonium (4.5% $^{240}$Pu) spheres[3] (FLATTOP). These prompt neutron decay constant measurements were performed in the Summers of 1971 and 1972 at the Los Alamos National Laboratory's Critical Experiments

Facility at the Pajarito Site*. In these delayed critical systems, the prompt neutron decay can be represented by a single exponential decay. The prompt neutron decay constant (α) at delayed criticality equals the effective delayed neutron fraction divided by the prompt neutron lifetime. The prompt neutron time decay can be calculated by both Monte Carlo and transport theory methods in a variety of ways: by codes which solve an α-eigenvalue problem such as $S_N$ transport theory,[4] or methods which rely on the assumption that the time dependent term in the transport equation is exponential. The prompt neutron decay can also be obtained by Monte Carlo methods[5] that directly calculate the prompt neutron time behavior in both the Rossi-α and randomly pulsed neutron measurements. Thus, these measured prompt neutron decay constants can be used to benchmark calculational methods. These results obtained by ORNL are compared with previous measurements by Los Alamos National Laboratory (LANL) for these assemblies. All of the details of these assemblies can not be presented here. The intent of this paper is to provide measured data and not all the details required for benchmarking calculations. Detailed descriptions of these assemblies have been published and can be used with the measured results presented here to verify calculational methods.

## 2. SOURCE-DETECTOR-TIME ANALYZER

The $^{252}$Cf sources used in these measurement contained less than 0.15 μg of $^{252}$Cf, which was electroplated on one plate of a parallel plate ionization chamber, and thus served as a time source of fission neutrons. There were three ionization chambers with spontaneous fission rates of 12.5, 25, and 86 thousand fissions per second. Two were 0.5 × 0.5-in-diam right circular cylinders, and the other was a 0.375-in.diam, 0.5-in.-high cylindrical chamber. The detector was a spiral fission counter (SFC) that contained ~93 wt% $^{235}$U metal and was a 0.5-in.-high, 0.5-in.diam right circular cylinder. The 0.5-in.diam source ionization chambers and the SFC had 0.125-in.-diam shafts which contained the voltage and signal cables. Both these chambers were designed to be used in the diametral hole of both JEZEBEL and FLATTOP with the existing split fissile plugs to surround the shaft of the detectors. The 0.375-in.-diam source ionization chamber had a large diameter shaft (0.25 in.) for the signal and voltage cable, and it was only used external to the cores.

The time analyzer (Type I, Ref. 6) was a two channel shift register (designed and built by R. L. Strait of LANL in 1968) that had 19 time bins with selectable width as short as 0.25 μsec. It could operate with a single (SFC) input or a double ($^{252}$Cf and SFC) input. Pulses come into the register at time bin 1 and are shifted in time steps to time bin 19. In the single input mode (single detector Rossi-α), each time a pulse shifted to the end of the shift register (out of time bin 19) the remaining pulses in the shift register are stored in memory according to their location in the register. In the double input mode, each time a pulse is shifted out of the time bin 19 of the register for channel one, it stores the time distribution of pulses in the 19 time bins for the second channel in the memory. In the double input mode, it can perform a two-channel Rossi-α measurement or a randomly pulsed neutron measurement if the $^{252}$Cf source fission pulses are

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input to channel 1. In addition, the analyzer stores the number of times 1, 2, 3, 4, and 5 pulses occur in the register (channel 2 for two-channel operation) as well as the number of times the registers store data, i.e. the number of times the register is triggered to store data. This register has the limitation that only one pulse could be counted in each time bin and is useful at low counting rates. The source detector diametral hole configurations were varied and are given in the tables of results for the measurements with the JEZEBEL assembly and FLATTOP with a $^{235}$U and a Pu core.

## 3. MEASUREMENTS WITH JEZEBEL

The JEZEBEL assembly is a bare and unmoderated assembly of delta phase Pu metal with 4.5 wt% $^{240}$Pu. It consist of three major parts: an upper section, a central section, and a lower section. Assembly to delayed critical was achieved by lowering the upper section until it rested on the central section which was independently supported and then raising the lower section at two speeds, the last 0.2 inch of motion at a rate of 0.050 in. per minute. The central and lower sections contain cylindrical cavities at the upper surface, that for these experiments contained five and eight mass adjustment buttons, respectively. In addition, at the upper surface of the central section, there was a control rod. There were provisions for two polar discs, a thin and thick disc at the upper pole on top of the upper section and a thin and thick disc at the lower pole at the bottom of the lower section. Split Ni-plated Pu plugs were used around the shafts of the SFC and $^{252}$Cf source ionization chamber when they were in the diametrical holes with solid Pu plugs everywhere else in the hole.

The nominal configuration of this assembly for these measurements was one thick and one thin disc at both poles with all mass adjustment holes filled, one of which holds half plutonium and half uranium (~93 wt %). Delayed criticality was achieved by positioning the control rod at the appropriate location with the particular diametrical hole loading of source and/or detector. The total inherent neutron source for this assembly from $^{240}$Pu is about $8 \times 10^5$ n/sec which is much larger than from the highest source intensity Cf source, ~ $3 \times 10^5$ n/sec. To reduce the background from fission chains not correlated with the spontaneous fission of $^{252}$Cf in the randomly pulsed neutron measurements, the top section of the assembly was cycled as follows. With the lower section adjacent to the central section, the lowering of the top section would, after a slight delay, initiate the time analyzer acquisition of the randomly pulsed neutron data. The analyzer would acquire data for a specified time. It would stop acquiring data; the top section would move up to its upper limit for a specified time to allow the fission rate to decay; and then, the process would be repeated by lowering the top section. This cycling process was automatically controlled with the time of the data acquisition and the shutdown time selectable. For each successive cycle, the average fission rate was increasing linearly with time since every neutron entering the delayed critical assembly remains. After several cycles, the randomly pulsed neutron measurement was stopped and the fission rate allowed to decay before the Rossi-$\alpha$ measurement was initiated. For the Rossi-$\alpha$ measurement, the system was not cycled but continuously assembled for the duration of the measurement. The randomly pulsed neutron and Rossi-$\alpha$ measurements were alternately performed with many pairs of measurements making up a sequence.

The system was cooled by moving air across the outer surface and the temperature of the sphere monitored by an internal thermocouple. The internal alpha particle heating source was ~36 watts. The air temperatures in the facility generally increased slightly during the day. This temperature variation and assembly of the system caused variations in the temperature of the Pu during the measurements. Periodically, during the measurements the reactivity of the system was verified by raising the fission rate of the system by control rod motion and the reactivity determined by one of three ways. For one, at the end of the sequence of prompt neutron decay constant measurements the major sections of JEZEBEL remained assembled, the control rod was fully inserted, and the positive stable reactor period measured at a fission rate much higher than source fission rates so that source effects were small. The excess reactivity was obtained from the stable reactor period using the inhour equation and was compared with that previously measured. At the end of this measurement, the control rod was withdrawn to the position for the previous sequence of prompt neutron decay constant measurements and the stable reactor period again measured for the second reactivity determination. This was the preferred method. After this, the control was positioned as necessary to maintain the system at delayed criticality. Reactivity change from the previous control rod setting could then be obtained from the control rod calibration curve and this was the third method. The system was then shutdown by raising the upper section to allow the fission rate to decay before the next sequence of several cycling measurements. Not all three methods were used due to time constraints. These reactivity changes were at most a few cents but usually a small fraction of a cent (~0.2) and usually decreased due to rising temperature of the Pu in the assembled condition. The reactivity difference from delayed criticality was assumed to be linear with time between adjustment to delayed critical and the reactivity measurement some time later. This reactivity verification was performed as often as three times per day.

The prompt neutron decay constants were obtained by nonlinear least-squares fitting of the data. The average values are given in Table I. The uncertainty in the decay constants from the randomly pulsed neutron measurement is much larger than for the Rossi-α measurements because only fission chains initiated by $^{252}$Cf fission contribute to the time decay in this randomly pulsed neutron measurement and all fissions chains contribute to the background. In the Rossi-α measurements, all fission chains contribute to the time decay. The total correlated counts in a typical Rossi-α measurements was ~ 25,000 counts and ~10,000 total correlated counts for the randomly pulsed neutron measurement. The total number of background counts in the 19 channels was ~10,000 for the Rossi-α measurements and ~600,000 for the randomly pulsed neutron measurement. These values are with the Cf source at the center and the spiral fission counter at a radius of 2.21 in. As a result of this high background from fission chains not correlated with the $^{252}$Cf source (i.e., those initiated by delayed neutrons from previous fission and inherent source fission), the uncertainty in the prompt neutron decay constants from each randomly pulsed neutron measurements was usually about a factor of 5 to 10 higher than in each Rossi-α measurement. The average prompt neutron decay constant at delayed criticality was obtained from the measured values and the reactivity assuming that the percentage correction to the prompt neutron decay constant was the value of the reactivity deviation from delayed criticality in cents (a decrease for negative reactivity and an increase for a positive reactivity). This results from the fact that near delayed criticality the prompt neutron decay constant varies like one minus the reactivity in dollars. In obtaining the average values, the individual values were weighted with the inverse of the variance.  As a result of this weighting, the Rossi-α data mainly determined the average prompt neutron decay constant.

Table I.  Prompt Neutron Decay Constants at Delayed Criticality for JEZEBEL for a Variety of Source-Detector Locations

| Radial Source Location[a] (in.) | Radial Detector Location[b] (in.) | Propmpt Neutron Decay Constant[c] (x $10^5$ $sec^{-1}$) |
|---|---|---|
| 0 | 2.21 | 6.415 ± 0.015 |
| 1.0 | 2.21 | 6.393 ± 0.026 |
| 1.75 | 0 | 6.528 ± 0.017 |
| Average for all locations. | | 6.450 ± 0.010 |

[a]Approximate radial location of the Cf deposit.
[b]Location of the center of the spiral fission counter.
[c]Average prompt neutron decay constant weighted with the inverse of the variance from each individual measurement.  Uncertainty is the one standard deviation of the mean.

The average prompt neutron decay constant for JEZBEL at delayed criticality is $6.45 \pm 0.01 \times 10^5$ $sec^{-1}$ and this is in excellent agreement with the value previously measured by LANL[7] of $6.4 \pm 0.1 \times 10^5$ $sec^{-1}$.  The uncertainty for the ORNL measurements is the standard deviation of the mean and the uncertainty is less because of the large number (126) of measurements performed, approximately half Rossi-α and half randomly pulsed neutron with $^{252}$Cf.

## 4. FLATTOP MEASUREMENTS

The FLATTOP assembly is a natural uranium metal reflected fissile metal assembly with three control rods in the natural uranium reflector.  It has three fissile cores:  $^{235}$U, $^{233}$U, and $^{239}$Pu.  For these measurements, the $^{239}$Pu and $^{235}$U cores were utilized.  The FLATTOP reflector consists of three major sections:  a fixed hemispherical section and two movable sections, the A block and the B block which were each one fourth of the spherical reflector.  At the center of this reflector, the fissile core was mounted on a core support pedestal of natural uranium, which could be cranked out along a track by hand for major core loading changes.  There are one large (F) and two small (E and G) natural uranium control rods in the reflector for reactivity adjustment.  In all these measurements, rods F and G were normally fully inserted, and rod E was used to adjust to delayed criticality.  For these measurements the B block was cycled to reduce the fission rate for the randomly pulsed neutron measurement with $^{252}$Cf and between alternate measurements.   The three methods to measure reactivity variations between sequences of measurements were essentially the same as for the JEZEBEL assembly.

## 4.1. FLATTOP CONFIGURATIONS

### 4.1.1. $^{239}$Pu Core (4.5 wt% $^{240}$Pu)

The configuration of the Pu (δ phase) was with a natural uranium cap in place and with six natural uranium adjustment buttons in the pedestal cap. Control Rods F and G were fully inserted and control rod E was again used to adjust to delayed criticality. For this configuration, the SFC was at the center of the diametral hole. Split plugs of Ni plated Pu were used around the shaft of the SFC or Cf source when they were in the core.

### 4.1.2. $^{235}$U Core

The configuration at delayed criticality for the measurements with the $^{235}$U core was as follows. The $^{235}$U cap was on the top and the natural uranium ring was at the outer core surface at the midplane. There were five highly enriched uranium (~93) mass adjustment buttons and six natural uranium mass adjustment buttons in the core support pedestal. Rods F and G were always fully inserted and Rod E was used to adjust to delayed criticality. For this configuration the SFC was at the center of the diametral hole. The number of mass adjustment buttons was varied depending on the source-detector location in the diametral hole. Split plugs of enriched uranium were used around the shaft of the SFC or Cf source when they were in the core.

## 4.2. PROMPT NEUTRON DECAY

### 4.2.1. Pu Core (4.5 wt% $^{240}$Pu)

Again, the uncertainty in the prompt neutron decay constants for the randomly pulsed neutron measurements was much larger than for the Rossi-α measurements because of the background source from $^{240}$Pu fission and increasing fission rate compared to the $^{252}$Cf source. Typically, the total correlated counts in a typical Rossi-α measurement was ~ 40,000 counts and 11,000 counts for the randomly pulsed neutron measurement. Typically, the total number of background counts in the 19 registers was 11,000 for the Rossi-α measurements and 900,000 counts for the randomly pulsed neutron measurements. These values were with the spiral fission counter in the center and the Cf source at the core reflector interface. As a result of this high uncorrelated count rate which was partially reduced by cycling, the uncertainty in the prompt neutron decay constants was approximately a factor of 5 to 10 higher in the randomly pulsed neutron measurements than for the Rossi-α. The measured values were corrected for small deviation in reactivity from delayed criticality which were measured as described in the measurements for JEZEBEL. Again in obtaining the average values given in Table II the individual measurements were inversely weighted with the variances in the individual values from the non-linear least-squares analysis. As a result, the average values were mainly determined by the Rossi-α data. Instead of the 19 channel shift register described in section 2, a 30 channel time analyzer was also used to acquire data which were least squares fitted to obtain prompt neutron decay constant and the value agreed with that from the data for the 19 channel shift register (Table 2 Footnote). The average prompt neutron decay constant for all measurements at delayed criticality for FLATTOP with a Pu core is $2.219 \pm 0.002 \times 10^5$ sec$^{-1}$. However, the average prompt neutron decay constant for the randomly pulsed neutron measurements was $2.204 \pm 0.009\times10^5$ sec$^{-1}$. The average value for all measurements is slightly larger than the value measured by LANL of 2.14 ± $0.05 \times 10^5$ $sec^{-1}$ reported by Hansen[7] but lower than the value reported by Orndoff[8] of 2.29 $x10^5$ $sec^{-1}$ (uncertainty not reported) at a reactivity of +0.3 cents above delayed criticality. The uncertainty is less for the ORNL measurement because of the large number (116) of measurements performed.

Table II. Prompt Neutron Decay Constants at Delayed Criticality
for FLATOP With a Pu Core

| Radial Source Location[a] (in.) | Radial Detector Location[b] (in.) | Prompt Neutron Decay Constant[c] (x $10^5$ $sec^{-1}$) |
|---|---|---|
| Core-reflector interface | 1.0 | 2.247 ± 0.005 |
| Core-reflector interface | 5 | 2.331 ± 0.004[d] |
| 0 | Core-reflector interface | 2.126 ± 0.005 |
| Core-reflector interface | 0 | 2.095 ± 0.005 |
| Average for all locations. | | 2.219 ± 0.002 |

[a]Approximate radial location of the Cf deposit.
[b]Location of the center of the spiral fission counter.
[c]Average prompt neutron decay constant weighted with the inverse of the variance from each individual measurement. Uncertainty is the one standard deviation of the mean.
[d]Simultaneous data from a 30 channel time analyzer resulted in an average value of $2.331 \pm 0.003\times10^5$ $sec^{-1}$.

4.2.2. Prompt Neutron Decay for the $^{235}U$ Core[†]

The total correlated counts in a typical Rossi-α measurement was ~ 30,000, and 20,000 for the randomly pulsed neutron measurement. The total number of uncorrelated counts in the 19 registers was 10,000 for the Rossi-α measurements, and 100,000 for the randomly pulsed neutron measurements. These values are with the spiral fission counter in the center of the diametral hole and the $^{252}Cf$ source at the core reflector interface. The uncertainty in the prompt neutron decay constants for the randomly pulsed neutron measurements are only slightly larger than for the Rossi-α measurements because there is no large inherent source in this assembly. The measured values were corrected for small reactivity deviations from delayed critical that were measured as previously described. The average prompt neutron decay constants are given in Table III. The average prompt neutron decay constants at delayed criticality for FLATTOP with a $^{235}U$ core is $3.868 \pm 0.007 \times 10^5$ $sec^{-1}$ and this is in agreement with the value measured by LANL[7] of $3.8 \pm 0.1 \times 10^5$ $sec^{-1}$. The uncertainty is less for the ORNL measurement because of the large number (136) of measurements performed.

[†] The previously measured prompt neutron decay constants for the bare HEU metal sphere are 1.109 ± 0.001 $x10^6$ $sec^{-1}$ for the Oak Ridge sphere[9], and 1.10 ± 0.01 $x10^6$ $sec^{-1}$for GODIVA I at LANL.

Table III. Prompt Neutron Decay Constants at Delayed Criticality for FLATOP With a U (~93) Core

| Radial Source Location[a] (in.) | Radial Detector Location[b] (in.) | Prompt Neutron Decay Constant[c] (x $10^5$ $sec^{-1}$) |
|---|---|---|
| 0 | Core Reflector Interface | 3.851±0.028 |
| Core Reflector Interface | 0 | 3.879±0.008 |
| Average for all locations. | | 3.868±0.007 |

[a]Approximate radial location of the Cf deposit.
[b]Location of the center of the spiral fission counter.
[c]Average prompt neutron decay constant weighted with the inverse of the variance from each individual measurement. Uncertainty is the one standard deviation of the mean.

## 5. AGREEMENT BETWEEN MEASUREMENTS AND CALCULATIONS

The prompt neutron decay constant at delayed criticality can be used to verify calculational methods. These comparisons for the systems reported here show agreement between measurements and calculations.[7, 10] However, for a bare metal $^{235}U$ sphere there is a 10% difference.[7, 10] Why the measurement and calculation ($S_N$ $\alpha$-eigenvalue method) agree for natural uranium reflected $^{235}U$ metal core and not for a unreflected uranium metal sphere is not well understood. Measurements have been performed by two laboratories (ORNL and LANL) for all four systems and are in excellent agreement for all systems except FLATTOP with a Pu core where the ORNL value is slightly higher. The measurements by both national laboratories for the systems reported here were for the same assemblies. For the bare HEU metal sphere, there were two assemblies, GODIVA I and the Oak Ridge sphere of different but similar materials.

## 6. CONCLUSIONS

The measured prompt neutron decay constant at delayed criticality for JEZEBEL (an unreflected Pu metal sphere) and for FLATTOP with a Pu and $^{235}U$ core are: $6.45 \pm 0.01$ x$10^5$ $sec^{-1}$, $2.219 \pm 0.002$ x$10^5$ $sec^{-1}$, and $3.868 \pm 0.007$x$10^5$ $sec^{-1}$ by Oak Ridge National Laboratory, respectively. These values can be compared to the values measured previously by Los Alamos National Laboratory which were $6.4 \pm 0.1$ x$10^5$ $sec^{-1}$; $2.14 \pm 0.05$ x$10^5$ $sec^{-1}$ and 2.29 x$10^5$ $sec^{-1}$ (uncertainty not reported); and $3.8 \pm 0.1$ x$10^5$ $sec^{-1}$, respectively. Similar value for the bare uranium (~93) metal sphere at ORNL and LANL are $1.109 \pm 0.001$x$10^6$ $sec^{-1}$ and $1.10 \pm 0.01$ x$10^6$ $sec^{-1}$; respectively. The agreement between laboratories is good and verified the accuracy of the measurements. The prompt neutron decay constant at delayed criticality is equal to the effective delayed neutron fraction divided by the prompt neutron lifetime. These measurements can be used to verify calculational methods. Calculated and measured values agree except for the bare uranium (93) metal sphere where the difference is 10%. This is not understood especially since the measured and calculated values for the natural uranium metal reflected enriched uranium metal sphere agree.

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