THE DELAYED-NEUTRON FRACTION IN A PULSED SPALLATION NEUTRON SOURCE

by

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TABLE OF CONTENTS

Page

LIST OF FIGURES

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ABSTRACT

The fraction of delayed neutrons β (with $T_{1/2} \gtrsim 0.025$ s) in slow-neutron beams from a ^{238}U pulsed spallation neutron source is 0.0053 for 300-MeV protons.

This appears to be the first measurement of this quantity. The result indicates that, for most classes of measurements, the delayed-neutron background in time-of-flight instruments will be unimportant, and places constraints on the physics description of spallation targets. The measurement was performed at the prototype pulsed spallation neutron source, ZING-P', at Argonne National Laboratory.

INTRODUCTION

When fissionable material (^{238}U, ^{232}Th, etc.) is used as target in a pulsed spallation neutron source,[1] delayed neutrons are produced from certain "precursor" fission fragments which decay by neutron emission following one or more steps of beta decay. Energetic photons emitted from beta-decaying products of fission and spallation processes can also induce delayed neutrons through (γ, n) reactions in materials such as ^{9}Be and ^{2}D which may be close to the primary source. The delay half-lives[2] range from fractions of a second to 1 min for precursor fission fragments, and from a few seconds up to several days, with 98% less than 1 min for fission product gamma rays interacting with ^{9}Be. When the interpulse time is short by comparison with these delay times,

1

delayed neutrons constitute a nearly steady source (unless there exist yet-undiscovered, shorter-lived precursors) of neutrons between source pulses. Unless there is a substantial amount of material (^{235}U, or accumulated ^{239}Pu, or ^{233}U) fissionable by low-energy neutrons, these neutrons are not multiplied as in a pulsed reactor, nor is a fast-decaying "tail" developed on the primary source pulse.

Although the energies of delayed neutrons are typically lower ($\sim$ .5 MeV) than those of prompt fission, evaporation or cascade neutrons, one may assume that they are moderated and emerge in neutron beams with approximately the same probability and the same spectrum as prompt source neutrons.
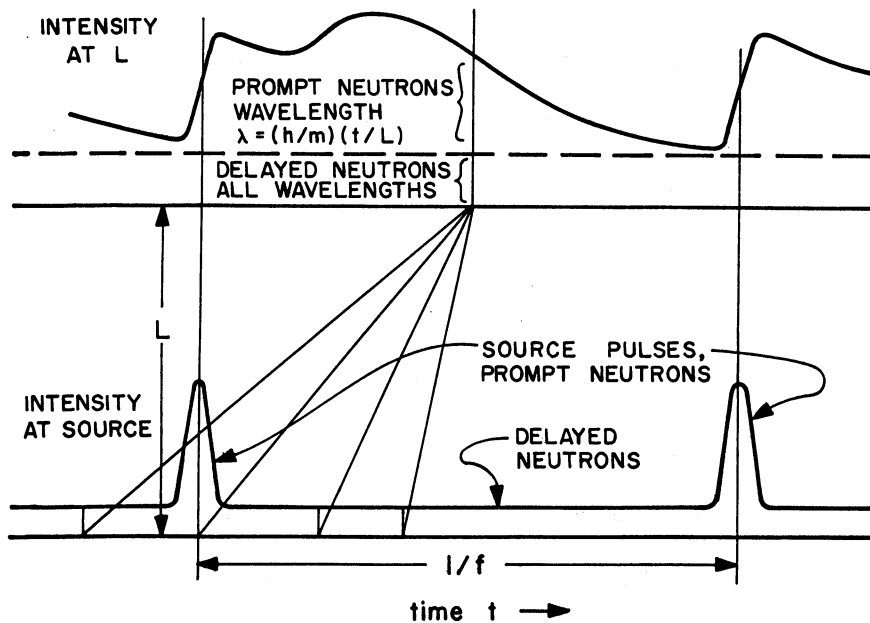
Fig. 1. Combined Neutron Time Schedule and Diagrams of the Intensity Distribution of Source Neutrons and of the Counting Rate in a Detector. Neutrons of energy E = (m/2)L^2/t^2 arrive at the detector at time t after the source pulse. Delayed neutrons of all energies arrive continuously in a similar spectrum unresolved in time.

Figure 1 indicates how these delayed neutrons produce a background in a neutron beam. At distance L, prompt neutrons from the source pulse spread out according to wavelength, λ = (h/m)t/L, arriving to produce a time distribution

that reflects the wavelength distribution. Delayed neutrons of all wavelengths arrive continuously in a spectrum that is identical in shape at energies below source energies, but not resolved in time.

MEASUREMENT

Two runs were made. For the "SIGNAL" run, the detector was open to the beam from the moderator, and surrounded by B_4C and ^{10}B shielding as shown in Fig. 2. For the "BACKGROUND" run, the detector was surrounded by the same shielding, but closed to the beam by 10 cm of ^{10}B shielding. A 1-mm-thick Corning 7740 boron glass filter plate (6.4×10^{20} B/cm^2) was placed in the beam to diminish the counting rate due to long-wavelength neutrons from the prompt pulse, which would obscure the delayed neutrons at long times. The detector was a low-efficiency BF_3 beam monitor detector. The measurement was made in beam V-2 of the ZING-P' prototype pulsed spallation neutron source.[3] The target was an 8.2-cm-dia, 15-cm-long cylinder of ^{238}U (0.4% ^{235}U). The moderator was a $10 \times 10 \times 5$-cm^3 slab of polyethylene at 300 K decoupled by 4×10^{21} $^{10}B/cm^2$. The assembly was surrounded by beryllium reflector material material. The proton energy was 301. MeV.

The counting rates for the two runs are

$$c_s(t) = \frac{\bar{S}_{NP}}{f} \frac{A_{det}}{L^2} I^P(E)\eta(E) \frac{2E}{t} + \bar{S}_{ND} \frac{A_{det}}{L^2} \int_0^\infty I^D(E)\eta(E)dE$$

$$+ Q \int_0^\infty \phi^P(E,t)V_{det}\Sigma_{det}(E)dE + Qf \int_0^\infty \phi(E,t)V_{det}\Sigma_{det}(E)dEdt + c_{noise}$$

and

$$c_B(t) = + Q \int_0^\infty \phi^P(E,t) + Q\int_0^\infty \phi(E,t)V_{det}\Sigma_{det}(E)dE$$

$$+ Qf \int_0^\infty\!\int_0^\infty \phi^D(E,t) V_{det}\Sigma_{det}(E)dEdt + c_{noise}.$$

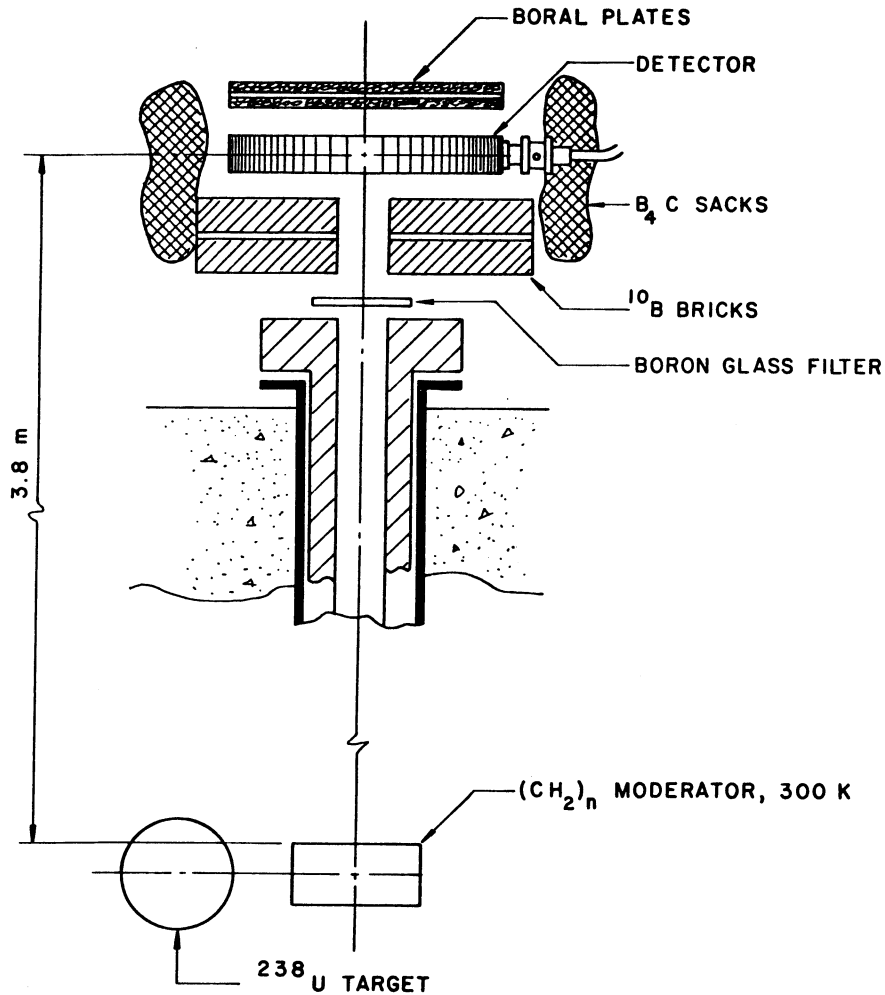Fig. 2. The Arrangement of Source, Moderator, and Detector in the Measurement

Here, $c_S(t)$ and $c_B(t)$ are the counting rates at time t after a pulse, L is the distance from moderator to detector, $I^{P(D)}(E)$ is the number of neutrons per in the beam steradian, per unit energy, per prompt (delayed) source neutron, A_{det} is the area of the beam, $n(E)$ is the number of counts per neutron of energy E

(including the attenuation due to the glass filter plate) in the beam,
$E = (m/2)L^2/t^2$, and $\bar{S}_{NP(D)}$ is the time-average rate of prompt (delayed)-neutron
production by the source. Also, $\phi^{P(D)}(E, t)$ is the flux of extraneous prompt
(delayed) neutrons (skyshine) at the detector, per unit energy around energy E,
at time t, per source proton. Q is the number of protons per pulse and f is the
pulsing frequency. V_{det} is the sensitive volume of the detector, and Σ_{det}
is the probability per unit length, that neutrons of energy E cause a count in
the detector. The counting rate due to electronic noise, detector radioactivity,
cosmic-ray-induced neutrons, etc., is c_{noise}. The value of $\phi^D(E,t)$ is
expected to be very small since most delayed neutrons originate in the target.

The net counting rate is

$$c_{net}(t) = c_S(t) - c_B(t)$$

$$= \frac{\bar{S}_{NP}}{f} \frac{A_{det}}{L^2} I^P(E)\eta(E) \frac{2E}{t} + \bar{S}_{ND} \frac{A_{det}}{L^2} \int_0^\infty I^D(E)\eta(E)dE \quad,$$

since the extraneous background is not affected by the additional shielding in
the beam direction in the background measurement, and since the average proton
charge per pulse during the total counting time was approximately the same
during signal and background counting.

The total number of counts in a time channel Δt wide around time t_n
measured from the time of the source pulse, after counting time T at pulsing
frequency f, is $C_n = c(t_n)\Delta t f T$. The prompt neutron part $c_P(t)$ is

$$c_P(t) = (\frac{\bar{S}_{NP}}{f}) \frac{A_{det}}{L^2} I^P(E)\eta(E) \frac{2E}{t} \quad,$$

and the delayed-neutron part (essentially constant) is

$$c_D = \bar{S}_{ND} \frac{A_{det}}{L^2} \int_0^\infty I^D(E) \eta(E) dE \ .$$

The total number of counts per pulse due to prompt neutrons is

$$C_P = \int_0^\infty c_P(t) dt$$

Thus,

$$C_P = \frac{\bar{S}_{NP}}{f} \frac{A_{det}}{L^2} \int_0^\infty I^P(E) \eta(E) dE \ .$$

If L is small enough, the delayed neutrons can be observed in the interval between pulses, after the long-wavelength tail of the prompt pulse disappears. The total number of counts per pulse due to delayed neutrons is

$$C_D = c_D \frac{1}{f} \ .$$

We define β, the delayed-neutron fraction for source neutrons, as the ratio of production rates,

$$\beta = \frac{\bar{S}_{ND}}{\bar{S}_{ND} + \bar{S}_{NP}} \ .$$

The ratio of counting rates β_{beam} is the true indicator of the extent to which delayed neutrons affect beam measurements. It is also the accessible quantity, and nearly equal to β; that is,

$$\beta_{beam} = \frac{C_D}{C_D + C_P} = \frac{\bar{S}_{ND} \int I^D_\eta \, dE}{S_{ND} \int I^D_\eta \, dE + S_{NP} \int I^P_\eta \, dE}$$

$$= \frac{\beta}{1 + (1 - \beta)(\frac{\int I^P_\eta dE}{\int I^D_\eta dE} - 1)} \approx \beta \quad ,$$

since over the range in which $\eta(E)$ is significant, the spectra I^P and I^D are identical.

The measured distribution of counts after background subtraction is shown in Figs. 3 and 4. The total number of counts in the time channel interval $1 \le n \le n_1$ after fT pulses is

$$M_1 = C_P fT + c_D \Delta t \, \Delta n_1 \, fT \ .$$

The average delayed-neutron counting rate is established in the interval $n_1 < n \le n_2$ after the long-wavelength tail of $c_P(t)$ disappears,

$$M_2 = c_D \Delta t \Delta n_2 fT$$

where

$$\Delta n_1 = n_1 \text{ and } \Delta n_2 = n_2 - n_1 \ .$$

Thus

$$C_D = \frac{1}{fT} \frac{M_2}{f \Delta n_2 \Delta t}$$

and

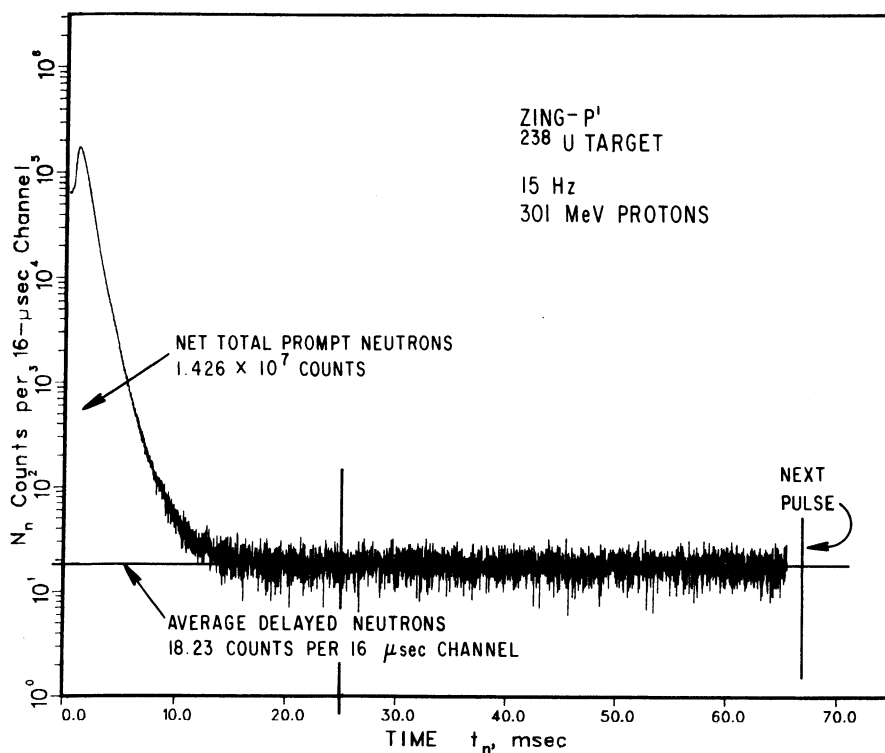$$C_P = \frac{1}{fT} (M_1 - M_2 \frac{\Delta n_1}{\Delta n_2}) \ .$$

Fig. 3. The Distribution of Net Counts (above background) in the Measurement. A total of 381,000 pulses were accumulated.

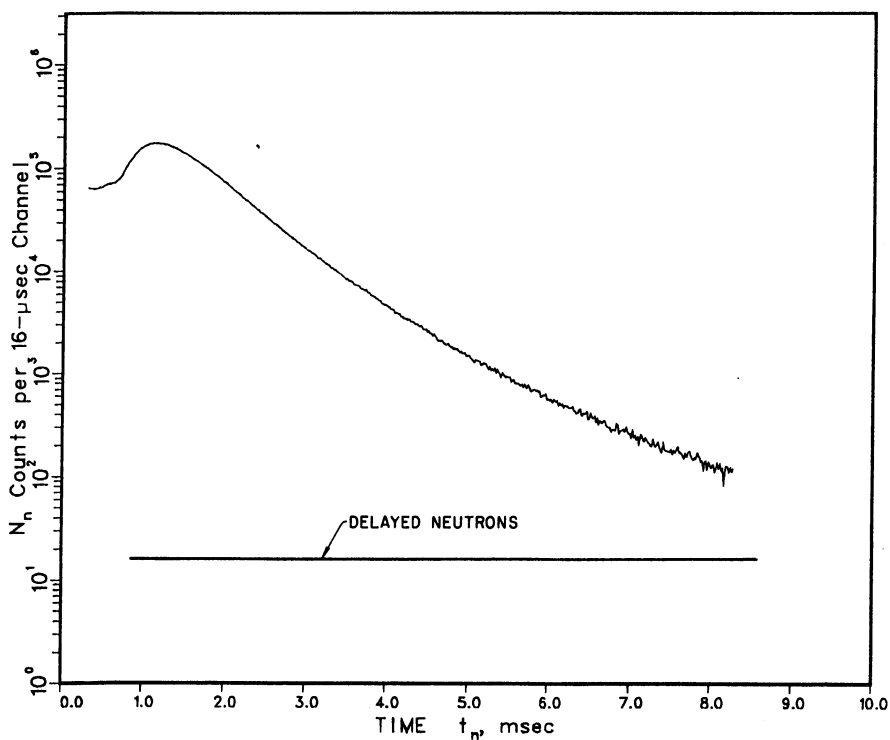Fig. 4. The Distribution of Net Counts in the Measurement, Showing $\eta(E)\phi(E)\ dE/dt$ in detail

Corrections have been made for losses due to dead time in the counting system, which amounted to about 2% in the channels with highest counting rates. Background due to neutrons other than those in the beam ("skyshine") and detector electronic background were small. The detector and electronic systems are insensitive for about 200 μs after the source pulse, as they must recover from the very large ionization pulse produced by recoiling atoms struck by fast neutrons. A correction has been incorporated into M_1 to account for ^{10}B capture events that are obscured in this interval, by extrapolating $c(t)$ smoothly to $t = 0$. The correction amounted to about 10% of the corrected value of M_1. The counting rate is constant within statistical accuracy in the interval Δn_2. Interval Δn_1 may contain delayed neutrons with short delay times. Therefore, delayed neutrons that are distinguishable in this measurement are those with delay times $T_{1/2} > n_1 \Delta t$.

The final results, taking $n_1 = 1550$ and $n_2 = 4090$ are

$C_p = 37.45$ counts per pulse,

$C_D = 0.1995$ count per pulse,

and

$\beta_{beam} = 0.0053$

The minimum delay time distinguishable in the measurement is $T_{1/2} \simeq n_1 \Delta t = 24.8$ ms. The delayed-neutron fraction is expected to be rather insensitive to the energy of incident protons.

DISCUSSION and CONCLUSIONS

The total neutron yield ν from neutron-induced fission of ^{238}U increases linearly with neutron energy as $\bar{\nu} = 2.41 + 0.139E_n$ (MeV) neutrons/fission.[2] The delayed-neutron yield also varies with neutron energy,[4]

$$\bar{\nu}_D = \begin{cases} 0.046\,n/f; \ E_n < 4 \text{ MeV} \\ 0.046 - 0.005\,(E_n - 4 \text{ MeV}); \ 4 \text{ MeV} \leq E_n \leq 8 \text{ MeV} \\ 0.026; \ E_n > 8 \text{ MeV} \end{cases}$$

Thus the delayed-neutron fraction for neutron-induced fission varies from $\beta = \bar{\nu}_D/\bar{\nu} = 0.0180$ at 1 MeV to 0.0068 at 10 MeV with an average for the fission-neutron spectrum of 0.0157.[2] In the present case, prompt neutrons are produced by neutron- and proton-induced fission, as well as produced directly and evaporated in the high-energy nucleon cascade and by prompt (n,xn) and (γ,n) reactions in both target and beryllium reflector materials. The behavior of $\bar{\nu}$ and $\bar{\nu}_D$ for neutron-induced fission indicates that the present result is consistent with the assertion that a substantial fraction of neutrons from a ^{238}U spallation target, about half, arise from high-energy nucleon-induced fission. Since in the present case $\beta = 0.0053$, delayed-neutron background will not be troublesome in most slow-neutron experiments using beams from a ^{238}U pulsed spallation neutron source. Due to the strong dependence of $\bar{\nu}_D$ on neutron energy (nuclear excitation energy), measurements such as this may place useful constraints on the physics description of high-energy, nucleon-induced fission.

ACKNOWLEDGEMENTS

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2. Reactor Physics Constants, ANL-5800 (July 1963). See Ch. 1.

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4. Delayed Neutron Data--Review and Evaluation, S. A. Cox, ANL/NDM-5 (1974).

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