ON THE DETERMINATION OF THE SLOWING DOWN LENGTH IN ORDINARY WATER USING A PULSED NEUTRON SOURCE

BY R. RAMANNA AND M. P. NAVALKAR
(Atomic Energy Establishment, Bombay)

Received November 22, 1956
(Communicated by Prof. B. Peters, F.A.S.C.)

INTRODUCTION

A method of determining the slowing down age in ordinary water from a fast neutron source to thermal energy, using a pulsed neutron source is described. The fast neutrons were produced from the D-Be reaction using a cascade generator. This reaction emits neutrons of maximum energy of 4.5 Mev with a peak at about 3.5 Mev. Pulsed neutron methods have been used by earlier workers in the measurement of the mean life of thermal neutrons in water (Haworth et al., 1942), (Von Dardel et al., 1953), (Antonov et al., 1955), the diffusion length of ordinary water and other substances (Von Dardel, 1953), the diffusion parameters of ordinary water (Von Dardel et al., 1954) and the diffusion and the slowing down constants of ordinary water and beryllium oxide (Ramanna et al., 1956).

THEORY

The slowing down of neutrons in a moderating medium can be explained either on the Age Theory or Multi-Group Theory. The Age Theory assumes a continuous process of energy loss of source neutrons to thermal energy whereas in the Multi-Group Theory the energy interval from source to thermal is divided into finite number and there is no energy degradation of neutrons in any group until they go over to the next group. The Multi-Group Theory approximates to the Age Theory when the number of energy intervals tend to infinity. But in the case of light moderators like water where the number of collisions to thermalise is small, the Age Theory is a poor approximation to the slowing down process.

The spatial and time distribution of thermal neutrons from a pulsed source of fast neutrons has been given on the two theories as follows (Mani and Iyengar, 1957):  

**Age Theory**

\[
\rho_\theta(r, t) = \frac{S_\theta}{8\pi\tau_{\text{th}}} e^{-(t-\tau_{\text{th}})/\tau_{\text{th}}}
\]
Slowing Down Length in Ordinary Water using a Pulsed Neutron Source

\[
\exp. \left[ \frac{-4 \left( \tau_0 + L_s^2 \left( t - \tau_{ef} \right)/\tau_{cs} \right)}{\left[ \tau_0 + L_s^2 \left( t - \tau_{ef} \right)/\tau_{cs} \right]^{1/2}} \right] \times \left( t - \tau_{ef} \right) \frac{\tau_0}{\tau_{ef}} \] (1)

where

- \( \tau_{ef} \) = Slowing down time of source neutrons to thermal energy.
- \( \tau_{cs} \) = Mean life of thermal neutrons in the moderator.
- \( \tau_0 \) = Age of source neutrons to thermal energy.
- \( L_s \) = Diffusion length of thermal neutrons in the moderator.
- \( S_o \) = Source strength.

Two Group Theory

\[
\rho_s \left( r, t \right) = \frac{\tau_{cs} S_0}{2\pi^2 \beta r} \left[ \frac{-t}{r_{cs}} I \left( a_s, \sqrt{\mu} \right) - \frac{-t}{r_{sf}} I \left( a_f, \sqrt{\mu} \right) \right] \] (2)

where

\[
\beta = \tau_{cs} - \tau_{ef} \quad \mu = \frac{\tau_{cs} L_f^2 - \tau_{ef} L_s^2}{\beta} \]
\[
a_s = \frac{L_s^2 t}{\tau_{cs}} \quad a_f = \frac{L_f^2 t}{\tau_{ef}} \]
\[
I \left( a, \sqrt{\mu} \right) = \frac{\pi}{4\mu \sigma} e^{\frac{r}{2\sqrt{\mu}}} \left\{ 1 - \text{erf} \left( \frac{\sqrt{a}}{\mu} - \frac{r}{2\sqrt{a}} \right) \right\} \]
\[
- \frac{r}{2\sqrt{\mu}} \left\{ 1 - \text{erf} \left( \frac{\sqrt{a}}{\mu} + \frac{r}{2\sqrt{a}} \right) \right\} \] (3)

and

\[
\frac{\sqrt{\pi}}{2} \text{erf} \left( x \right) = \int_0^x e^{-u^2} du. \]

where the subscript 's' denotes the slow term and 'f' denotes the fast term.

I \left( a, \sqrt{\mu} \right) \approx e^{\frac{a}{\sqrt{\mu}}} e^{-\frac{r}{\sqrt{\mu}}} \quad \text{upto a time } t_1 \text{ after which it decreases rapidly. Since } \tau_{ef} \ll \tau_{cs} \text{ after a time } t_2, I \left( a_f, \sqrt{\mu} \right) \ll I \left( a_s, \sqrt{\mu} \right) \text{ and can be neglected. Hence between } t_1 \text{ and } t_2, t_3, t_4 \text{ being less than } t_1.

\[
\rho_s \left( r, t \right) = \frac{\tau_{cs} S_0}{4\pi^2 \beta r^2} \frac{-r}{r_{cs}} e^{\frac{-r}{r_{cs}}} \left[ 1 - \frac{L_s^2}{L_s^2} \right] \] (4)
and so
\[
\frac{d}{dt} \log \rho_s(r, t) = -\frac{1}{\tau_{cs}} \left[ 1 - \frac{\tau_{cf}}{\tau_{cf}L_s^2} \frac{\tau_{cs}}{\tau_{cs}L_f^2} L_s^2 \right]
\]
(5)

Unlike the Two Group Theory, the Age Theory expression does not show such an exponential character in any interval of time.

Also
\[
\frac{d}{dr} \log \frac{r^2 \rho_s(r, t)}{S_0} = -\frac{1}{\sqrt{\mu}}
\]
(6)

But
\[
\mu = \frac{\tau_{cs}L_f^2 - \tau_{cf}L_s^2}{\tau_{cs} - \tau_{cf}}
\]
(7)

\[
\approx L_f^2 \quad \text{(since } \tau_{cf} \ll \tau_{cs})
\]

where \( L_f^2 \) = Square of the slowing down length of source neutrons to thermal energy.

Therefore, \( L_f \) can be determined using the above expression from a measurement of the spatial distribution of neutron from a pulsed source.

**Experimental Arrangement**

*The neutron pulsing system.*—The fast neutron bursts were produced by pulsing the extraction electrode of the radio frequency ion source of the cascade generator. The pulse width was kept at 19 \( \mu \)-sec. and the repetition rate at 560 cycles per second.

*Detector.*—The thermal neutrons were detected by means of a lithium iodide scintillation counter. The crystal (1.25 cm. in diameter, 1 cm. long) was mounted at the end of a long perspex rod (3 ft. long, 1 in. in diameter) which was attached to the photo cathode of a 6262 E.M.I. photo multiplier. The pulse from the disintegration of lithium due to thermal neutrons is much higher than the background radiation and can thus be easily discriminated. The light guide assembly was provided with a spigot at its end so that the position of the crystal could be fixed at known distances and in the same plane from the centre of the target. This was done by inserting the spigot into various positions on a perspex strip attached to the target holder. The strip was provided with holes at fixed positions to take in this spigot and was so arranged that it was kept at the centre of the assembly. A rectangular tank (60 cms. cube) of perspex was filled with approx. 55 gallons of distilled water. The sides and bottom of the tank were covered with \( \cdot 5 \) mm.
thick cadmium on the outside to absorb thermal neutrons entering or leaving the tank. The block diagram of the experimental set-up is given in Fig. 1.

The Time Analyser.—The thermal neutrons were analysed in time by a 10 channel time analyser (Iyengar, 1956). For the experiment each channel width was adjusted to 54 µ-sec, with an initial delay of 200 µ-sec. In order to get more points in between, the initial decay was shifted to 227 µ-sec, keeping the channel width same. The two sets of readings were normalised by the thermal neutron counts taken in the same interval of time for both the delays. In this case the interval of time was 0–150 µ-sec.

Experimental neutron distribution for some of the detector positions is shown in Fig. 2a and 2b while the theoretical curves on both the Age and the Two Group Theory for \( r = 30 \) cms. are given in Fig. 2c. It is
noticed that in the region between 200 and 500 μ-sec. the experimental distribution plotted on a log scale is a straight line when the detector is at 22·5 cms. from the source. The straight line portion increases in time duration as the detector is moved away from the source. The values of the decay constants at various detector positions from the source have been determined by least square fitting and are given in Table I.

Calculations of the decay constant were made on both Age and Two Group Theories. The constants used in the calculations were as follows: Using Marshak's formula for the age of source neutrons to indium energy and correcting it for thermal energy, the value obtained for age is about 39 cms.² for 3 Mev. and 44 cm.² for 3·5 Mev. mono-energetic neutrons. Taking a value of about 41 cms.² for age, \( \tau_{cs} = 216 \mu\text{-seconds} \), \( \tau_{ef} = 10 \mu\text{-seconds} \), \( L_s = 2·88 \text{ cms.} \) and using expression (5), the Two Group Theory gives a decay constant of 0·0037 μ-sec.⁻¹ which is in better agreement with the experimental value. Unlike the Two Group Theory, the Age Theory gives different decay constants at different detector positions while those obtained
experimentally are independent of the detector positions as long as they are greater than 22.5 cms., thus showing that the Two Group Theory
applies better than Age Theory in case of water. The disagreement of Age Theory is to be expected since it is well known that the Age Theory is inapplicable in case of light moderators like water. The experimental value of the decay constant is in agreement with the value obtained previously, (Ramanna et al., 1956).  

The values of the decay constants at detector distances of 10 and 15 cms. from the source are much higher than expected on the Two Group Theory. This may be explained on the basis that at such close distances there is a large concentration of fast neutrons which decay more rapidly than thermal neutrons and hence give higher value of the decay constant. The decay constant therefore decreases with distance from the source and then remains constant.

Fig. 3 shows $\log \frac{r^2 p^s(r,t)}{S_0}$ against $r'$ and is seen to be a straight line. The slope of this line at various times is given in Table II. Using the average value of these slopes and taking $\tau_{cs} = 216 \mu$-sec, $^{9} \tau_{ef} = 10$ micro-sec.
Slowing Down Length in Ordinary Water using a Pulsed Neutron Source

SLOWING DOWN LENGTH FOR SOURCE NEUTRONS TO THERMAL ENERGY

SLOPE = 0.15334 ± 0.00022 cm⁻¹

t = 416 µSECS

Fig. 3
and $L_s = 2.88$ cms. in expression (7), we get the age of source neutrons to the thermal energy as $41.05$ cms. The value of the age changes to $39.47$ cms. when $\tau_{cf}$ is taken as $20 \mu$-sec. If we use the approximation in expression (7), i.e., $\tau_{cf} = 0$, we obtain $42.65$ cms. as the value for the age. It can be noticed that in altering the value of $\tau_{cf}$, the value of the age does not change more than $\pm 4.0\%$. The statistical error due to counting is very small compared to the above error and can be neglected. It is unlikely that the value quoted above for age $41.05$ cms. has been determined to better than $\pm 4.0\%$, taking into account both the approximations involved in theory and the experimental errors introduced due to the finite dimensions of the detector, the source and the moderator assembly. It can, therefore, be concluded that the experimental value obtained for age by this method is consistent with the value expected for the D-Be neutrons.

We wish to express our thanks to Mr. S. B. D. Iyengar, Mr. G. S. Mani and Mr. P. K. Iyengar for helpful discussions. Our thanks are also due to Mr. S. K. Ambardkar for running the accelerator and Mr. F. R. Bhathena for his help in taking readings with the time analyser.

### REFERENCES

Slowing Down Length in Ordinary Water using a Pulsed Neutron Source

5. Von Dardel, G. F. and Sjostrand, N. G. 

6. Ramanna, R., Mani, G. S., Iyengar, P. K., Iyengar, S. B. D. and Joshi, B. V.

7. Iyengar, S. B. D. and Mani, G. S.

8. Iyengar, P. K.

9. Glasstone, S. and Edlund, M.
   *The Elements of Nuclear Reactor Theory*, 1952.