foils. The activity of the foils was counted with single-channel $\gamma$ spectrometers using the $Hg^{196}$ 412-keV line in the case of gold and the 105-keV $Pa^{233}$ line in the case of thorium.

The results of the measurements were evaluated by the well-known equation

$$\left(\frac{I}{\sigma_{eff}}\right)^{Th} = \left(\frac{I}{\sigma_{eff}}\right)^{Au} \frac{R_{cd}^{Au} - 1}{R_{cd}^{Th} - 1}$$

where

$I$ is the resonance integral

$\sigma_{eff}$ the effective thermal cross section.

$R_{cd}$ the cadmium ratio.

We found

$$R_{cd}^{Au} = 8.40 \pm 0.05$$

$$R_{cd}^{Th} = 10.80 \pm 0.05$$

and thus

$$\left(\frac{I}{\sigma_{eff}}\right)^{Th} = \left(\frac{I}{\sigma_{eff}}\right)^{Au} \left[0.7543 \pm 0.0066\right].$$

Using $I = 1461.8$ barn and $\sigma_{eff} = 99.3$ barn for gold foils[3] and $\sigma_{eff} = 7.45 \pm 0.15$ barn for thorium[4], we get

$$I^{Th} = 82.7 \pm 1.8 \text{ barn}$$

for the infinite dilute resonance integral of thorium under 1 mm cadmium. This value is in good agreement with that obtained by Johnston[5]. From the resonance parameters published in BNL - 325, one calculates 96 barn for this quantity (including a correction of 3.89 barn for unresolved $s$-resonances and 2.86 barn for the $1/v$ part).

*M. Brose**

Institute für Neutronenphysik und Reaktortechnik
Kernforschungszentrum Karlsruhe
Germany

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*Present address: 3202 Bad Salzdefurth, Horststrasse 24.

[3]M. BROSE, "Zur Messung und Berechnung der Resonanzabsorption von Neutronen in Goldfolien," *Nukleonik* (in print).

[4]E. HELLSTRAND and J. WEITMANN, "The Resonance Integral of Thorium Metal Rods," *Nucl. Sci. Eng.* **9**, 507-518 (1961).

[5]F. J. JOHNSTON *et al.*, "The Thermal Neutron Absorption Cross-section of $Th^{233}$ and the Resonance Integrals of $Th^{232}$, $Th^{233}$ and $Co^{59}$," *J. Nucl. Energy, Part A: Reactor Sci.* **11**, 95-100 (1960).

## Age to 1.44 eV for (*D,D*) Neutrons in Concrete

Concrete is by far the material most commonly used for shielding. Fast neutrons are slowed down to thermal energies and are absorbed in the concrete. Gamma rays are emitted during the absorption process and the production of gamma rays will be proportional to the flux of thermal neutrons. The distribution of gamma-ray sources can be calculated assuming the results of age theory[1], and calculated values for the age of fission neutrons to thermal energies in a number of different concretes are reported[1].

All concretes contain hydrogen and it is indeed this element that is mostly responsible for the slowing down of neutrons. Age theory will therefore be a poor approximation and, if used, may result in big discrepancies between calculated and measured values of the age. No measurements of neutron age in concrete are reported in Reference 1, and we have found no other references to such measurements. We therefore decided to carry out such a measurement, the result of which is reported here. For practical reasons it was necessary to work with a $(D, D)$ neutron source and to measure the age to the indium resonance at 1.44 eV.

Deuterons were accelerated in a SAMES J accelerator to an energy of 150 keV. The target consisted of a foil of zirconium in which deuterium was absorbed. Thus a true deuterium target was formed. It was circular with a diameter of 2 cm and the source strength was about $5 \cdot 10^7$ neutrons/sec.

Bricks of concrete with dimensions (50×25×10) $cm^3$ were used to build a block as shown in Figure 1. The concrete block was situated on the floor below the target. This was itself enclosed in concrete as far as possible.

Indium foils, 2 cm × 2 cm and 90 mg/$cm^2$ thick, were enclosed in boxes of 0.5-mm-thick cadmium plates and placed in small cavities along the axis of the block. The distance from the target to the nearest cavity was 9.3 cm. Otherwise the positions of the cavities were as indicated in Figures 1 and 2. Four or five foils were irradiated simultaneously, one of them being always at the 9.3-cm position. The activity at any point was thus always determined relative to the activity at the 9.3 cm position. Between 8 and 10 different measurements were made for each point. All irradiations lasted for $2\frac{1}{2}$ hours.

[1]A. ARONSON and C. N. KLAHR, Neutron Attenuation, Chapter 9 in *Reactor Handbook, Vol. III, Part B.* Editors: E. P. BLIZARD and L. S. ABBOTT, Interscience Publishers, New York (1962).

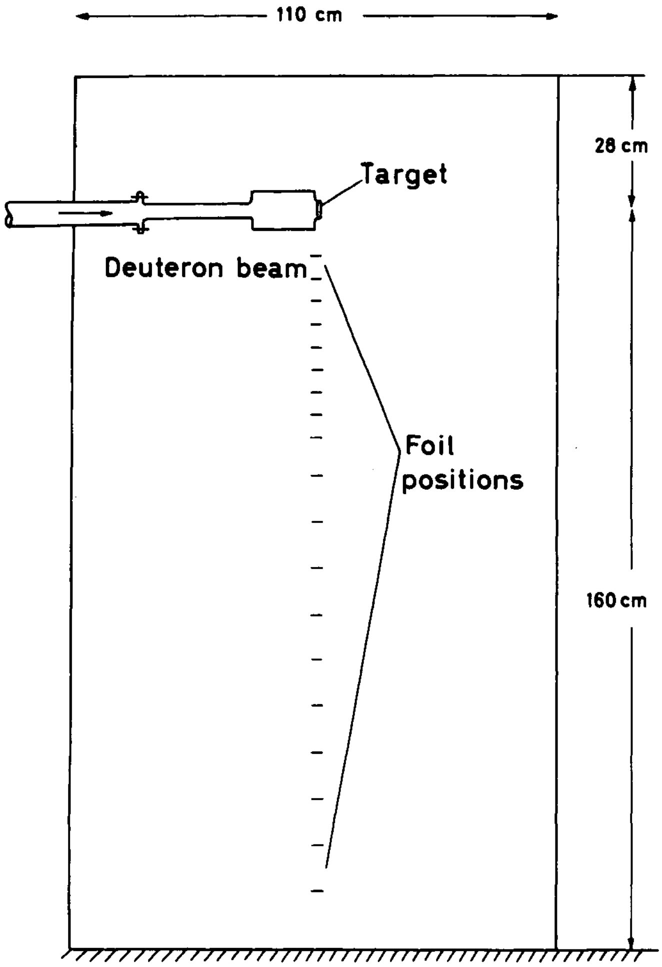


Fig. 1. Vertical cross section of experimental arrangement.

The induced activities were measured with *G-M* counters and the distribution of 1.44-eV neutrons was assumed to be proportional to the measured activities. In principle, corrections should be made for activities induced by neutrons with energies different from 1.44 eV. Spiegel and Richardson[2] have measured this correction for $(D, D)$ neutrons in heavy water with 90 mg/cm$^2$ indium foils. They report an increase in the age of 0.5%. This is a small value and no attempt was made to measure this correction in the present investigation.

For an isotropic point source and a moderator of infinite extension, the slowing-down age is defined as

$$\tau = \frac{1}{6}\frac{\int_0^\infty A(r)r^4dr}{\int_0^\infty A(r)r^2dr} . \qquad (1)$$

[2]V. SPIEGEL, Jr., and A. C. B. RICHARDSON, *Nucl. Sci. Eng.* **10**, 11 (1961).

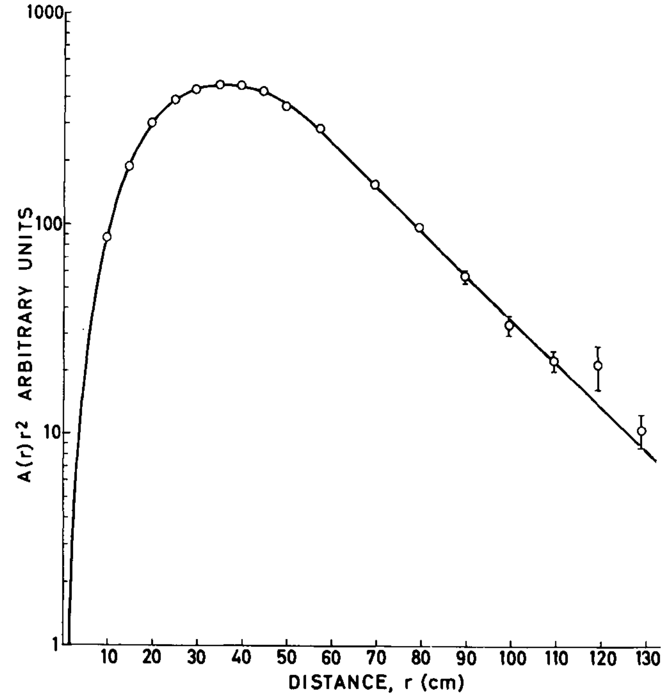


Fig. 2. Measured distribution of 1.44-eV neutrons in concrete.

In the present case neither of the conditions mentioned above is fulfilled. Nevertheless a quantity $\tau$ may be determined from the measured distribution according to (1). This quantity does not represent the true neutron age, but rather the "non-isotropic finite second moment". Figure 2 shows the function $A(r)r^2$ where $A(r)$ is a measure of the activity and $r$ is the distance between the indium foil and the target. In order to carry out the integration to an infinite distance, the usual extrapolation was applied. In the asymptotic region, $A(r)r^2$ was put equal to $Ce^{-r/\lambda}$ where $\lambda$ was determined to be $(21.08 \pm 2.75)$cm. The extrapolated part of the integrals

$$\int_0^\infty A(r)r^4dr \quad \text{and} \quad \int_0^\infty A(r)r^2dr$$

amounted to respectively 25% and 6% of the total. The value obtained for $\tau_{In}$ was:

$$\tau_{In} = (444 \pm 11)\text{cm}^2 .$$

A number of questions may be raised concerning the significance of this value. First of all, the energy of $(D,D)$ neutrons varies with their angle of emission. For neutrons emitted at an angle of 90° with respect to the deuteron beam, the energy is 2.5 MeV with a deuteron energy of 0.15 MeV. However, not all the neutrons which reach the indium foils have left the source at this angle.

The problem of slowing down of $(D, D)$ neutrons in heavy water has been examined experimentally by Spiegel and Richardson[2] and theoretically by Goldstein and Certaine[3]. The results published by these authors indicate that the measured $\tau$ in the 90° direction will be less than 2% smaller than the theorectical $\tau$ calculated for a monoenergetic neutron source with neutron energy equal to the energy of neutrons emitted in the 90° direction.

Secondly, the accelerator tube passes through the concrete block and the cavity thus introduced in the moderator gives rise to a certain error. Cooper[4] has treated this problem for $(D, D)$ neutrons in water and heavy water. His results indicate that the absolute duct correction for the neutron age, expressed in cm$^2$, is about the same for water and heavy water —i.e., it should not depend too much on the moderating medium. At an angle of 90° the duct correction is about 3 cm$^2$ (which should be subtracted) for a duct radius of 1 cm. In our case the duct radius is more than 3 cm and the correction will be considerably greater, but it could hardly exceed 10% of the measured value of $\tau$.

Finally, the concrete block has a finite volume. However, measurements in paraffin[5] indicate that the neutron distribution in a block of moderating material with linear dimensions equal to or larger than $4\sqrt{\tau}$ is about the same as in an infinite medium. Here again one should not expect an error of more than 10%.

From the considerations presented above, we conclude that within 15% our measured age is equal to the age that would be measured with an ideal geometry for 2.5-MeV neutrons in concrete.

The neutron age to be expected from our measurements might be calculated by Monte Carlo methods, but we had no possibilities to perform such a calculation. Instead we have tried to compare our measured distribution with the distribution given by the Fermi age theory. According to this theory the neutron age is given as:

$$\tau = \int_{u_0}^{u} \frac{du}{3\sum_i (\Sigma_i(1 - \bar{\mu}_i)\sum_i (\Sigma_i \xi_i)} \quad . \qquad (2)$$

Here

$i$ refers to element No. $i$,

$\Sigma$ is the macroscopic scattering cross section,

$\bar{\mu}$ the average cosine of the scattering angle,

$\xi$ the average logarithmic energy decrement per collision and

$u = \ln(E_0/E)$ is the lethargy.

[3]H. GOLDSTEIN and J. CERTAINE, *Nucl. Sci. Eng.* **10**, 16 (1961).

[4]J. W. COOPER, *Nucl. Sci. Eng.* **10**, 1 (1961).

[5]B. GRIMELAND, S. MESSELT and L. SUND, *Nucl. Sci. Eng.* **13**, 261 (1962).

The elemental composition of the concrete was determined by a chemical analysis, (Table I). The content of water is of special importance. It was determined several times and rather large deviations between the individual results were observed. It is believed, however, that the figure given for the hydrogen content is correct within 10%.

With values of the cross sections taken from BNL 325[7], the neutron age from 2.5 MeV to 1.44 eV has been calculated for the present concrete according to (2). The result is:

$$\tau = 224 \text{ cm}^2 .$$

According to age theory, the distribution of neutrons with energy $E = E_0 e^{-u}$ should be proportion to $\exp(-r^2/4\tau)$. Curves showing this function for $\tau$ = 224 cm$^2$ and $\tau$ = 444 cm$^2$ are given in Figure 3. Both curves were normalized to go through the point at $r$ = 9.3 cm. The experimentally determined points are given too. Also shown on the figure is a curve corresponding to $\tau$ = 297 cm$^2$. This curve gives a very good fit to the experimentally determined distribution for $r$ less than 60 cm.

Our results indicate then that age theory will give a fairly good approximation to the neutron distribution in concrete for values of $r$ less than about $3\sqrt{\tau}$. One should, however, use a value of $\tau$ some 25% higher than the one calculated from (2).

In practical shielding problems, fission neutrons are of main importance. Measurements with $(D,D)$ neutrons and fission neutrons in water[8,9] and heavy water[2,10] indicates that the age measured in the 90° direction for $(D, D)$ neutrons is somewhat higher than the age measured for fission neutrons.

TABLE I

Elemental Composition of Concrete

| Element | Density in g/cm$^3$ |
|---|---|
| H | 0.010 |
| O | 1.025 |
| C | 0.023 |
| Mg | 0.015 |
| Al | 0.112 |
| Si | 0.587 |
| K | 0.042 |
| Ca | 0.155 |
| Fe | 0.041 |
| Na | 0.038 |
| Other | 0.009 |
| Total | 2.057 |

[6]A. M. WEINBERG and E. P. WIGNER, *The Physical Theory of Neutron Chain Reactors*, p. 321, University of Chicago Press, (1958).

[7]D. J. HUGHES and R. B. SCHWARTZ, "Neutron Cross Sections," BNL 325, (1958).

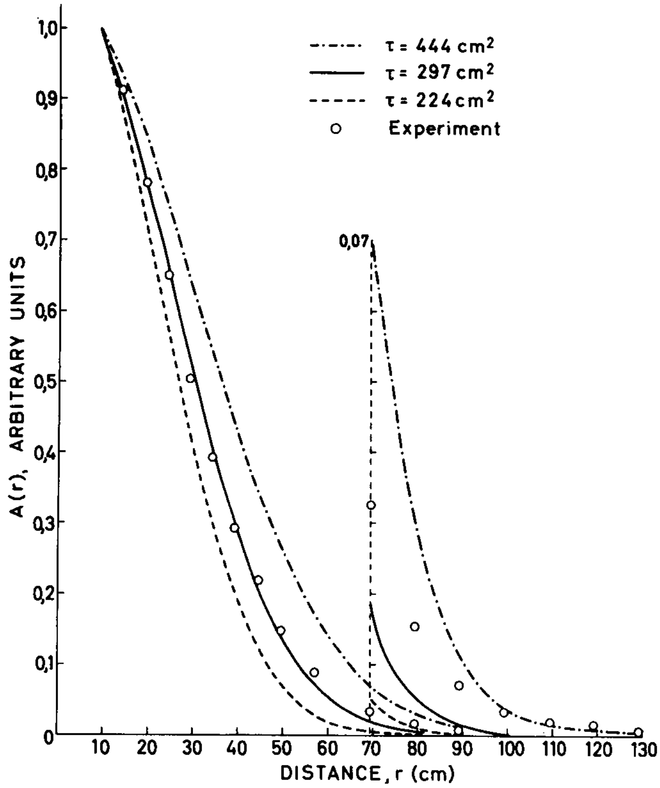


Fig. 3. Fermi age distribution, $C \cdot \exp(-r^2/4\tau)$ for $\tau = 224\ cm^2$, $\tau = 297\ cm^2$ and $\tau = 444\ cm^2$.

In water the difference amounts to about 19%, in heavy water to about 8%. The difference between the neutron age in concrete for $(D, D)$ neutrons measured in the 90° direction and fission neutrons could hardly exceed the 19% met with in water, and most probably it is smaller.

*B. Grimeland and S. Dönvold*

Institute of Physics
University of Oslo
Blindern, Norway

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[8] V. SPIEGEL, D. W. OLIVER and R. S. CASWELL, *Nucl. Sci. Eng.* **4**, 546 (1958).
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[10] J. E. WADE, *Nucl. Sci. Eng.* **4**, 12 (1958).

## Relation of the Neutron Diffusion Length to Neutron-Pulse Parameters in $H_2O$*

The well known expression[1,2,3] for the behavior of the time constant $\omega$ of a thermal-neutron pulse

$$\omega = \omega_0 + DB^2 - CB^4 + \ldots , \quad (1)$$

can be inverted for $\omega = 0$ and $B^2 = -L^{-2}$ to give the neutron diffusion length $L$,

$$L^2 \cong (D/\omega_0)\{1 + C\omega_0/D^2\} , \quad (2)$$

provided $4\omega_0 C \ll D^2$.

This has been used (e.g. Reference (4)) to determine the diffusion length from measured pulse parameters.

The fractional correction $C\omega_0/D^2$ for $H_2O$ has been calculated for the Nelkin model[5] from the values given[3]. This is given as a function of temperature in Table I. For room temperature $C\omega_0/D^2$ is 1.1%. However, Kerr[6] has calculated the same correction for the Nelkin model by means of a ten-group eigenvalue calculation and obtained a value of 3.4%.

To resolve this discrepancy, eigenvalue calculations have been carried out using the method of Reference (3) and a group structure with 39 groups. Specifically, that value of $B^2 = -L^{-2}$ has been found which implies $\omega = 0$. In Table I are compared values of $L^2$ obtained from Equation 2 and those obtained from the eigenvalue calculation as a function

TABLE I. Correction Term and Diffusion Lengths for the Nelkin Model for $H_2O$

| $t$(°C) | $C\omega_0/D^2$ | $(D/\omega_0)\{1+C\omega_0/D^2\}$ | $L^2$(eigenvalue) |
|---|---|---|---|
| 23 | .0114 | 7.878 | 7.875 |
| 50 | .0098 | 8.544 | 8.545 |
| 100 | .0082 | 10.222 | 10.223 |
| 140 | .0072 | 11.886 | 11.889 |
| 180 | .0065 | 13.982 | 13.990 |
| 220 | .0060 | 16.796 | 16.804 |
| 260 | .0055 | 20.632 | 20.648 |
| 300 | .0051 | 26.067 | 26.110 |

$\omega_0$ is based on an absorption of 0.3322 barns per H atom in $H_2O$ at 2200 m/s.

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[1] G. F. von DARDEL and N. G. SJÖSTRAND, *Phys. Rev.* **96**, 1245 (1954).
[2] M. NELKIN, *Nucl. Sci. Eng.* **7**, 210 (1960).
[3] W. W. CLENDENIN, *Nucl. Sci. Eng.* **18**, 351, (1964).
[4] W. M. LOPEZ and J. R. BEYSTER, *Nucl. Sci. Eng.* **12**, 190 (1962).
[5] M. NELKIN, *Phys. Rev.* **119**, 741 (1960).
[6] B. A. KERR, GEAP-3943 (1962).