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DETERMINATION OF DIFFUSION COOLING IN GRAPHITE
BY MEASUREMENT OF THE AVERAGE NEUTRON VELOCITY

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Measurement of the Average Neutron Velocity

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ABSTRACT

The diffusion cooling coefficient in graphite has been determined by measuring the change in the asymptotic average velocity with buckling, by pulsed neutron methods. The times necessary to establish equilibrium spectra in graphite and heavy water have been measured and are reported.

Theory

If a moderator has been injected with a burst of neutrons, the asymptotic decay constant is given by

$$\lambda = \lambda_0 + \overline{Dv} B^2 [1 - C'B^2 + \dots] \quad (1)$$

which if D is constant can be rewritten

$$\left[\frac{\lambda - \lambda_0}{B^2 D} \right] = \bar{v} - \bar{v}_0 [1 - C'B^2 + \dots] \quad (2)$$

Therefore a direct measurement of the average velocity as a function of buckling will yield the diffusion cooling coefficient.

The average of a given neutron velocity distribution can be measured by comparing the response of two detectors with sensitivities which differ in behavior as a function of velocity. The measurements described below were done using BV_3 detectors: one in which every neutron is counted, and a second which has a $1/v$ neutron response sensitivity.

The rate of absorption of neutrons in either detector is given as

$$\Sigma \phi = \int \Sigma(E) \phi(E) dE \quad (3)$$

where Σ is the absorption cross section.

The flux ϕ can be expanded in a set of time eigenfunctions of the form

$$\phi(E, t) = \sum_n A_n \phi_n \cdot e^{-\lambda_n t} \quad (4)$$

Equation (3) then becomes

$$\Sigma \phi = \sum_n A_n \langle \Sigma \phi_n \rangle \cdot e^{-\lambda_n t} \quad (5)$$

where

$$\langle \mathcal{L} \phi_n \rangle = \int \phi_n \mathcal{L} dE$$

The absorption cross section $\mathcal{L}$ depends on the nature of the detector. The ratio R of count rates of two different detectors will be given from equation (5) as

$$R = \frac{\sum_n A_n \langle \mathcal{L}_1 \phi_n \rangle e^{-\lambda_n t}}{\sum_n A_n \langle \mathcal{L}_2 \phi_n \rangle e^{-\lambda_n t}} \quad (6)$$

Rewriting the summation and factoring out the lowest eigenfunction ϕ_0 leads to

$$R = \frac{\langle \mathcal{L}_1 \phi_0 \rangle}{\langle \mathcal{L}_2 \phi_0 \rangle} \left[\frac{1 + \frac{A_1}{A_0} \frac{\langle \mathcal{L}_1 \phi_1 \rangle}{\langle \mathcal{L}_1 \phi_0 \rangle} e^{-(\lambda_1 - \lambda_0)t} + \dots}{1 + \frac{A_1}{A_0} \frac{\langle \mathcal{L}_2 \phi_1 \rangle}{\langle \mathcal{L}_2 \phi_0 \rangle} e^{-(\lambda_1 - \lambda_0)t} + \dots} \right] \quad (7)$$

At sufficiently long times, the summation can be approximated by the expression involving the first order terms. If the denominator is small, it can be expanded in a power series:

$$R = \frac{\langle \mathcal{L}_1 \phi_0 \rangle}{\langle \mathcal{L}_2 \phi_0 \rangle} \left[1 + \frac{A_1}{A_0} \left(\frac{\langle \mathcal{L}_1 \phi_1 \rangle}{\langle \mathcal{L}_1 \phi_0 \rangle} - \frac{\langle \mathcal{L}_2 \phi_1 \rangle}{\langle \mathcal{L}_2 \phi_0 \rangle} \right) e^{-(\lambda_1 - \lambda_0)t} \right] \quad (8)$$

This equation relates the eigenfunctions ϕ and eigenvalues λ to R , to the ratio of the counting rates in the two detectors. At long times, R

reduces to

$$R = \frac{\langle L_1 \phi_0 \rangle}{\langle L_2 \phi_0 \rangle} \quad (9)$$

Equation (9) will then give the value of the ratio R after equilibrium is reached for a given size of moderator. Since L_1 is assumed to be constant for an energy range $0 \rightarrow E_1$ and L_2 varies as $1/v$ in this same interval, R is proportional to the density weighted average velocity $\bar{v}$. If the lowest eigenfunction ϕ_0 is a maxwellian form, the error introduced by integrating from $0 \rightarrow \infty$ instead of to the finite limit E_1 is in our case about 1%.

During the transient period after the burst of neutrons, the ratio R will change. The approach to equilibrium will be governed by the decay constant $(\lambda_1 - \lambda_0)$.

Detectors

The detectors were two physically identical BF_3 proportional counters, filled to 70 cm pressure. The black detector contained 96% enriched Boron 10, and the grey detector contained 11% depleted Boron 10. The counters were placed in a sleeve of cadmium inside an annular cylinder of borated paraffin 3" in thickness. The leakage spectrum from a block of moderator was passed through a collimator of cadmium in the end of the sleeve, and into the detector parallel to its length.

Apparatus

The same pre-amplifier, amplifier and voltage supply were used for the two detectors, so as to eliminate any error associated with different electronics. Both detectors were operated at the same voltage plateau and discriminator settings. The neutron pulses were fed into a 100 channel time analyser. To normalise runs with separate detectors, a monitor BF_3 detector

was used to record the total number of neutron counts. The burst of neutrons was obtained from a 1 MEV Van de Graaff generator by means of the $\text{Be}^9 (d, n) \text{Be}^{10}$ reaction.

Procedure

The variations of detector sensitivities with energy were measured through use of neutrons from a crystal spectrometer. The variation of the ratio with energy is shown in figure 1. If R is assumed to be linear with velocity in the range 1.5×10^5 cm/sec to 4×10^5 cm/sec, the average value $\bar{R}$ for a maxwellian spectrum at 20°C differs by about 5% from the value of $\bar{R}$ obtained by using the general equation of the curve in figure 1, and averaging over the same maxwellian. Therefore the approximation of the linearity of ratio with velocity is justified for the range of this experiment.

The average velocity was determined for the sizes of graphite moderator listed in table 1. The graphite stacks were placed in an enclosure of cadmium covered boral to eliminate the effect of room return neutrons. The source was situated in the moderator. The collimator was aligned parallel to the graphite bars, so that the neutrons leaking out of a beam hole in one of the graphite bars entered the end of the detector in a direction parallel to the detector axis. The data were accumulated by the time analyser, and the ratio was normalized by the ratio of total monitor counts obtained during the same time interval. The value of the ratio $\bar{R}$ for one of the stack sizes is shown in figure 2. Two different channel widths were used to record the data from each detector, to substantiate that the asymptotic value of $\bar{R}$ was reached, and to test the calibration of the time analyser.

Results

The values of the asymptotic ratio as a function of buckling are tabulated in table 1 and plotted in figure 3. The value of the diffusion cooling coefficient for graphite was found to be $38 \pm 5 \times 10^5$ cm/sec.

The time necessary for $\bar{R}$ to reach the equilibrium value appears to be independent of buckling; and is approximately 2 milliseconds for graphite. Hence, this is the minimum waiting time in order to measure the fundamental decay constant in pulsed neutron experiments with graphite.

The time rate of change of $\bar{R}$ is shown in figure 4. It was obtained by subtracting the asymptotic value $\bar{R}$ from the curve of R as a function of time. Since the accuracy of the measurement is not extremely good, no attempt has been made to determine if the decay constant associated with $\frac{d\bar{R}}{dt}$ is buckling dependent. The decay constant given in figure 4 is an average for the five stacks shown. If the black triangles of stack 6 are typical of the decay constant, then the value of 1995 sec^{-1} should represent $(\lambda_1 - \lambda_0)$ at a buckling of .00959. This may be compared with the values of λ_0 and λ_1 obtained from the decay data of one of the detectors. We find the asymptotic decay constant λ_0 is 1690 sec^{-1} while λ_1 is approximately 3500 sec^{-1} . The value of $(\lambda_1 - \lambda_0)$ is then 1800 sec^{-1} which agrees very well with the value obtained from the measurement of time rate of change of $\bar{R}$.

The time for equilibrium has also been determined in a tank of heavy water, with the measurement showing that approximately $600 \mu\text{sec}$ is necessary for the higher modes to die away. From the value of the ratio obtained for this one tank, which had an equivalent buckling of .0076, and with the value of $\bar{v}$ at $B^2 = 0$, an estimated value of the diffusion

cooling coefficient of heavy water is $5 \times 10^5 \text{ cm}^2/\text{sec}$.

Conclusion

The technique of using the average ratio of the two detectors is ideally suited to pulsed neutron measurements, if only to measure the time necessary to wait in order to determine the fundamental decay constant. The technique also yields information about thermalization beyond simply the equilibrium time. More information about the thermalization process can be obtained with improved systems of detectors.

Acknowledgment

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Figure Captions

1. Ratio B^{10}/B^{11} Vs Velocity cm/sec - Neg. # 12-339-61.
2. Ratio Vs Time - Neg. # 12-198-61.
3. Average Neutron Velocity as a Function of Buckling - Neg. # 12-197-61.
4. Change of Average Velocity as a Function of Time - Neg. # 12-199-61.

FIG. 1

898 13

FIG. 2

BNL Neg. No. 12-198-61

AVERAGE NEUTRON VELOCITY AS A FUNCTION OF BUCKLING

FIG. 3

BNL Neg No. 12-197-61

818 14

CHANGE OF AVERAGE VELOCITY AS A FUNCTION OF TIME

FIG. 4

D

TABLE I
Tabulation of Measured Ratio

Stack No.	R ($\bar{\nu}$)	B ² (cm ⁻²)	Stack Size (cm)
1	6.20 $\pm$ .25	.001765	128 x 128 x 122
2	5.77 $\pm$ .35	.00220	109 x 108 x 122
3	5.85 $\pm$ .20	.00295	89 x 89 x 122
4	5.87 $\pm$ .65	.00366	69 x 89 x 122
5	5.00 $\pm$ .40	.00770	49 x 49 x 122
6	4.75 $\pm$ .35	.00959	49 x 49 x 59
7	5.54 $\pm$ .30	.00550	69 x 89 x 59
8	4.50 $\pm$ .25	.01139	49 x 39 x 59
9	3.00 $\pm$ .50	.01505	29 x 49 x 59
10	4.20 $\pm$ .40	.01320	39 x 39 x 59

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