INVESTIGATION OF THE DIFFUSION AND THERMALIZATION OF NEUTRONS IN WATER AND IN ICE BY PULSE METHOD IN A WIDE TEMPERATURE RANGE*

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The article describes an apparatus for the investigation of the process of transient diffusion of neutrons in liquids at various temperatures, including temperatures above the boiling point up to 300°C. The resulting experimental variation of the diffusion parameters of water with temperature in the interval 0.5-286°C can be approximated by second-degree polynomials. The article considers the process of thermalization of neutrons in water by the Dardel method and compares the results with those obtained by other methods. The diffusion parameters are determined, and a preliminary estimate is given for the slowing-down time of neutrons in ice at the temperature of liquid nitrogen.

Introduction

In recent years the process of diffusion and thermalization of neutrons in water at various temperatures has been studied in a number of investigations [1-8]. Data were obtained on the temperature dependence of the diffusion parameters (the diffusion constant, the lifetime, and the diffusion cooling coefficient) for water temperatures below the boiling point (10-90°C).

The investigation of water used as a coolant in a wide temperature range is of interest both for the study of the interaction of neutrons with matter and for an understanding of the physical process taking place in nuclear reactors. In the present investigation the temperature dependence of the diffusion parameters was studied for water temperatures of 0.5-286°C. In the course of this work we also investigated the process of transient diffusion and thermalization of neutrons in ice at a temperature of -196°C. The data of such experiments are important in determining the limits of temperatures at which thermal equilibrium can be established between the neutron gas and the ice, and they can be used to develop highly efficient sources of cold neutrons.

The work was carried out by means of a pulse method of transient diffusion proposed by Dardel [1] and I. M. Frank [2]. The essence of the method is the following: A block of the moderator under investigation is irradiated with a short burst of fast neutrons. Some time after the conclusion of the slowing-down process the neutron density in the block is attenuated exponentially, with an attenuation decrement.

$$\alpha = \frac{1}{T} + D\Omega - (C - d)\Omega^2. \quad (1)$$

Here $T$ and $D$ are the lifetime and the diffusion constant of the neutrons in an infinite medium; $C$ is the diffusion cooling coefficient [1, 3]; $\Omega$ is a geometric parameter (the smallest eigenvalue of the Laplace operator for a system with given shape and dimensions); $d$ is the non-diffusion correction term obtained by Sjöstrand in the investigation of the solution of the one-velocity kinetic equation by a $P_3$ approximation [9].

For water we may assume that approximately

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\[ d = \frac{1}{15} D \lambda_{tr}^2 (1 + 4 \cos \theta), \] 

where \( \cos \theta \) is the average cosine of the neutron angle and \( \lambda_{tr} \) is the transport mean free path.

The geometric parameter \( \Omega \) for the cylindrical geometry we used is obtained from the formula

\[ \Omega = \left( \frac{2.405}{R} \right)^2 + \left( \frac{\pi}{H} \right)^2, \]

where \( R \) and \( H \) are the extrapolated radius and altitude. In order to determine the extrapolation length we used the expression from Sjöstrand's article \[9\]

\[ x_0 = 0.7051 \lambda_{tr} \left[ 1 - \lambda_{tr}^2 \Omega \right. \times \left( 0.0256 - 0.2825 \cos \theta + 0.08993 \cos \theta^2 \right). \]

From the experimentally determined attenuation decrement \( \alpha \) for various values of the geometric parameter \( \Omega \), on the basis of Eq. (1), we find the diffusion parameters \( T, D, \) and \( \alpha - d \).

**Apparatus and Measurements**

We used the \( T(d, n)He^4 \) reaction to obtain the pulsed neutron flux. The deuterons were accelerated by means of a 200-kv horizontal tube. The discontinuity of the fast neutron flux was obtained by modulation of the ion current of the accelerator source. The duration of the fast neutron pulses was 15 microseconds at a repetition frequency of 250 pulses per second.

A boron proportional counter filled with \( B^{10}F_2 \) was used for recording the thermal neutrons. The pulses from the counter, after amplification, were transmitted to the input of a 20-channel time analyzer*, which was started simultaneously with the beginning of neutron generation. The channel widths of the analyzer were 10, 20, 40, 80, 160, and 320 microseconds, while the delay times of the start of recording (the "distances") were 20, 40, 80, 160, and 640 microseconds. The dead time of the analyzer is about 10 microseconds.

**Measurements with Water.** A schematic diagram of the apparatus for the water measurements is given in Fig. 1. A water-filled steel vessel was placed inside a hermetically sealed steel container; the vessel was divided into an upper and a lower section by a piston having the form of a hollow box filled with boron carbide. The internal surface of the vessel and the external surface of the piston were covered with cadmium foil. A cut was made in the cadmium cover of the bottom of the vessel, and the counter was placed next to this cut. The diffusion of neutrons in the working volume under the piston is independent of the presence of water above the piston; this water acts as a reflector of the fast neutrons. The geometric parameter was varied from 0.05 to 1 cm\(^{-1}\) by vertical movement of the piston.

In order to obtain the necessary water temperature we used a spiral coil welded onto the measuring vessel. When the water was cooled below room temperature, a cooled aqueous

* The analyzer was developed by I. V. Shtranikh, A. E. Voronkov, A. M. Volkov, and K. P. Dudareva.