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# CROSS SECTION FOR THE INTERACTION OF SLOW NEUTRONS WITH $CO_2$ NEAR THE VAPORIZATION CRITICAL POINT

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UDC 539.125.52:536.44

The results of studies of the temperature dependence of the total cross section for the interaction of slow neutrons with $CO_2$ in a wide temperature range, including the vaporization critical point, are presented.

The development of atomic energy requires that the technologies for utilizing new coolants in reactor loops be perfected [1]. To create such technologies it is necessary to know the equation of state of the coolant in a wide temperature range, including the critical temperature. In recent years, the method of transmission of slow neutrons has been used in studies of the equation of state near the vaporization critical point for individual substances [2] and solutions [3, 4]. In this case, it is assumed that the total cross section for interaction of neutrons with molecules of the substance is independent of the temperature and does not have singularities at the point of the liquid—vapor phase transition. At the same time, experimental data indicating monotonic growth of the total cross section for the interaction of slow neutrons in some hydrogen-containing compounds with increasing temperature and the presence of a jump in the cross section at boiling points are presented in [5]. The purpose of this work is to study at different temperatures the cross section for the interaction of slow neutrons with a substance near its vaporization critical point.

The temperature dependence of the total cross section for the interaction of slow neutrons with a material can be obtained by determining the transmission of the neutrons by the material under study with mass m = const at different temperatures. In the slow neutron transmission method the well-known relation [6] between the intensity of the neutron before the sample $I_0$ and after the sample I is used:

$$I = I_0 \exp\{-N\sigma x\}. \quad (1)$$

The solution of this problem is complicated by the fact that near the critical point, because of the increase in the compressibility of the sample under the action of the gravitational field, there appears a characteristic distribution in the height distribution of the density — the gravitational effect [7]. Because of this the quantities N and I in formula (1) are functions of the height of the layer under study.

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0022-0841/86/5005-0526$12.50

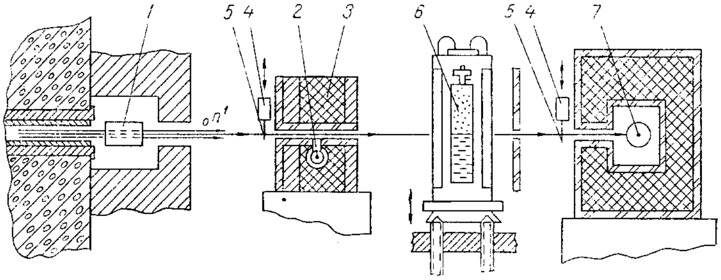

Fig. 1. Arrangement of the experiment.

Taking into account the scattering of the neutrons by the walls of the sample, for T = const we find the total cross section σ from the system of equations

$$p_0 = \exp\{-\Sigma l\}, \quad p_1 = \exp\{-\overline{N}\sigma_1 x - \Sigma l\},$$
$$p(h, T) = \exp\{-N(h, T)\sigma(T)x - \Sigma l\}, \quad \int_0^H N(h, T)\, S dh = m. \qquad (2)$$

The solution of the system of equations (2) gives

$$\frac{\sigma(T)}{\sigma_1} = \frac{\int_0^H \ln[p(h, T)/p_0]\, dh}{H \ln[p_1/p_0]}. \qquad (3)$$

The experiment was carried out on the VVR-M reactor at the Institute of Nuclear Research, Academy of Sciences of the Ukrainian SSR. The object of study was carbon dioxide gas, whose critical parameters ($T_{cr}$, $\rho_{cr}$) are well known [8]. To realize the critical state, the sample with internal dimensions of 20 × 50 × $10 \cdot 10^{-3}$ m was filled with $CO_2$ with an average filling density equal to the critical density. The arrangement of the experiment is shown in Fig. 1. From the reactor the neutron beam entered a shielded monochromator 1. For the monochromator we used a Pb single crystal, which separated neutrons with wavelength $\lambda = 1.5 \cdot 10^{-10}$ m. With the help of a system of collimators 3, a vertically narrow, about $0.5 \cdot 10^{-3}$ m, neutron beam was formed; this beam entered the sample 6, placed in a thermostat. The neutron beam passing through the sample was detected by the detector 7. The intensity of the neutron flux incident on the sample was monitored by the monitor 2. To determine the detector background and the monitor background the drivers 4 covered the direct neutron beam with cadmium screens 5. The thermostat containing the samples under study was placed on a raising device, which enabled inserting the sample into the neutron beam and moving it vertically with a minimum step of $10^{-4}$ m. The temperature of the sample was maintained constant by a two-stepped temperature-control system to within ±0.002°K over a period of one day. We measured the temperature of the sample with the help of a platinum resistance thermometer and an R-363 potentiometer. The temperature gradient over the height of the sample, which was equal to $200 \cdot 10^{-3}$ m, was recorded with a 16-junction copper–Constantan thermocouple and did not exceed $10^{-4}$ K/m. The intensity of the neutron beam passing through the sample was equal to $10^4$ $sec^{-1}$, which enabled determining the transmission with a statistical error of ~0.1% in a time of 300 sec. During the course of the measurements, isotherms of the height dependence of the neutron transmission in $CO_2$ were obtained for different reduced temperatures τ in the interval $2 \cdot 10^{-5} < |\tau| < 2.7 \cdot 10^{-2}$ (Fig. 2).

The transmission data obtained were analyzed using the formula (3). To calculate the integrals of the height dependence of the transmission for different temperatures a computer program consisting of two subprograms was developed; the first subprogram enables interpolation of the experimental data obtained on the transmission with the help of a natural cubic spline [9], and the second subprogram carries out the integration with the help of spline quadratures [10]. The results of the analysis are shown in Fig. 3. As is evident from the figure, to within 1% the scattering cross section per $CO_2$ molecule is independent of the proximity to the critical temperature in a wide temperature range including the critical temperature.

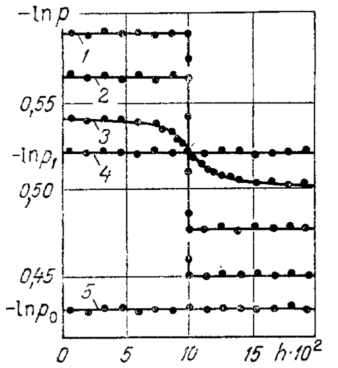

Fig. 2

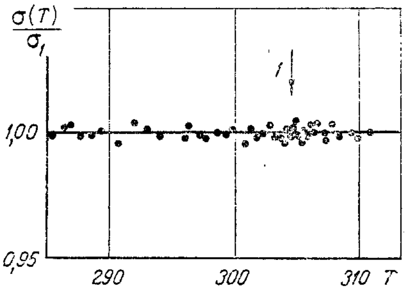

Fig. 3

Fig. 2. Height dependence of the transmission of slow neutrons by the sample filled with $CO_2$ at temperatures T, K: 1) 295.45; 2) 297.52; 3) 304.255; 4) 311.39; 5) transmission of an empty sample. h, m.

Fig. 3. Temperature dependence of $\sigma(T)/\sigma_1$. The arrow in the figure marks $T_{cr}$ for $CO_2$. T, K.

The results obtained enable applying, in a substantiated manner, the slow-neutron transmission method for studying the equation of state near the critical point of vaporization of individual substances.

## NOTATION

T, temperature; m, mass of the substance under study; $I_0$ and I, intensity of the neutron beam before and after the sample; σ, cross section for the interaction of slow neutrons per molecule; N, number of molecules per unit volume; x, thickness of the sample; h, height of the layer under study relative to the bottom of the sample; Σ, cross section for the interaction of neutrons with the walls of the sample; ℓ, thickness of the walls; $p_0 = i/i_0$, transmission of an empty sample; $i_0$, i, values of $I_0$, I; $p_1$, transmission of the filled sample for $T_1 \gg T_{cr}$, when $\bar{N} = N_A m/\mu$; $N_A$, Avogadro's number; μ, molecular weight of the substance under study; p(h, T), transmission of the sample under study at temperature T and height h; S, cross-sectional area of the sample; H, total height of the sample; $\sigma_1$, cross section for the interaction of slow neutrons with molecules of the substance under study at a temperature $T_1$; $T_{cr}$, critical temperature; $\rho_{cr}$, critical density; $\tau = (T - T_{cr})/T_{cr}$, reduced temperature.

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