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ON THE RATE OF FORMATION OF NEUTRONS UNDER THE ACTION OF COSMIC RADIATION NEAR THE EARTH'S SURFACE

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SUMMARY

This work presents the results of investigations of the transient effect below the interface atmosphere-water and also the latitude and altitude dependences near ground with the view of determining the background of natural neutrons due to cosmic radiation near the Earth's surface, for possible applications in prospecting for economic mineral deposits. The instrumentation used is described.

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When searching and prospecting for economic mineral deposits, the methods based upon the registration of nuclear radiations, and, in particular of neutron radiation, are more and more broadly applied. In the course of these investigations it is necessary to take into account the natural neutron background which determines the methods' threshold response. It may be considered as established at present that at points on the ground with normal content in radioactive elements the main share of neutron background is constituted by neutrons formed by cosmic radiation in the atmosphere, as well as in underlying rock formations. In order to correctly appraise the magnitude of the natural neutron background, it is necessary to take into account the barometric, altitude, latitude effects, the rate of formation of neutrons by cosmic radiation in rocks as a function of atomic weight, the distortion of the neutron field near the ground above the air-ground interface and below it, and also other factors [1 - 21].

Expounded in the present work are the results of investigations of the transient effect below the interface atmosphere-water, and also of the latitude and altitude dependences near the Earth's surface.

Proportionate counters, filled with enriched boron (B^{10} enrichment up to 85%) at pressure to 0.4 atm, with effective length of 94.2 cm and operational diameter of 3.4 cm, were used as neutron indicators. Four BF_3 counters, arranged parallelwise with preamplifier input, were placed in a horizontal plane in duralumin tubes (42 mm external and 38 mm internal diameter), at a distance of 10 cm from one another. The tubes were linked with a thin-walled waterproof box, in which the preamplifier was placed.

The amplifying-registering part of the device was constructed according to the scheme, worked out for a semiconductor neutron monitor [16, 22]. The block-diagram of the device consists of the following elements: preamplifier, amplifier, anticoincidence circuit (to eliminate interferences and spurious pulses), scaler (scaling factor 8) and an output cascade to trigger the electromechanical type MES-54 counter. The feed was assured by batteries guaranteeing a continuous operation of the device during 500 hours.

The measurements of the spatial distribution of the density of cosmic radiation neutrons, decelerated in the water, were conducted at the following points:

1) Ladoga Lake (56° N.lat., sea level, average distance from the shore of about 700 m., water depth of about 7 m);

2) Balkhazh Lake (37° N.lat, altitude above sea level 350 m);

3) a small high-mountain lake (2150 m altitude, 33° N.lat.).

In order to eliminate the effect of salt water, the neutron monitor was placed on the Lake Balkhazh in a special tank of 180 x 150 x 150 cm dimensions, filled with fresh water. In order to separate the flux of thermal neutrons, measurements were conducted at all points with the use of cadmium screens 1 mm thick, surrounding the counters from all sides. The counters' proper background was determined by way of comparison of effects measured in water at depths of more than 30 cm with those of cadmium screen at sea level and in the mountain lake. The value of the background conditioned by admixtures of radioactive elements in counter materials, was found to be 2.1 pulses/min for the above-indicated detector made of four counters.

The measured neutron counting rates in water at depths from 0 to 400 cm (Lake Ladoga) are plotted in Fig.1. The results of measurements for two other points at depths from 0 to 60 cm are brought out in Fig.2. The obtained counting rates for each point are corrected for the fluctuations of atmospheric pressure. The values of the barometric factor was then assumed equal to − 0.96% per 1 mm. Hg. The indicated depths are related to the axis of counters.

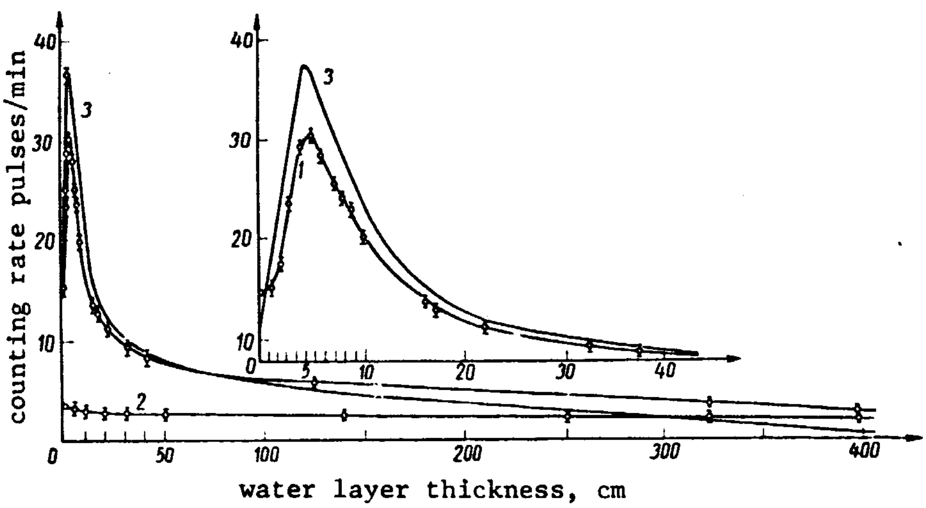

Fig.1. Measurement of counting rates of cosmic radiation neutrons decelerated in water. The measured rates correspond to sea level (Lake Ladoga)

1, 2, 3 are respectively the counting rates registered by means of unshielded counters, shielded with cadmium and corrected for counters' proper background and the effect of neutron field distortion induced by the immersion of BF_3 counters in the water

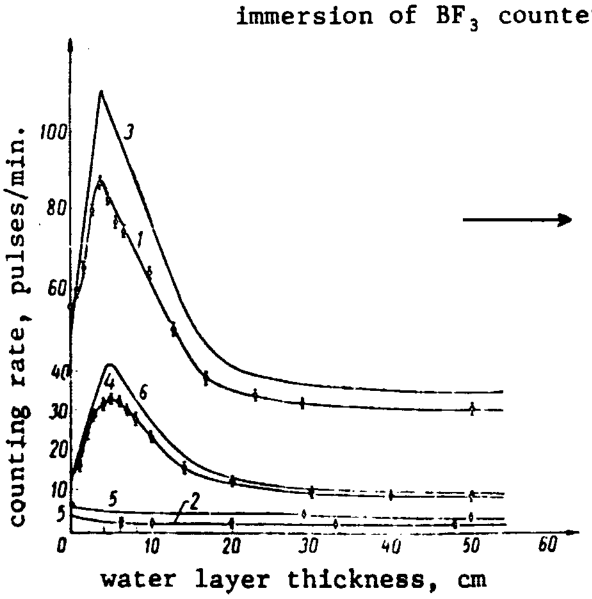

Fig.2. Same measurement in the high-altitude lake (1 - 3) and in the Lake Balkhash (4 - 6)

1, 4 are respectively the counting rates registered with unshielded counters in the mountain and Balkhash lakes; 2 - 5 are the counting rates corrected for the background and neutron field distortion effect.

These measurements were all conducted from June to August 1966.

The measured counting rates of neutrons must also be corrected for the distortion effect in water of the neutron field, caused by boron counters and partially by the duralumin casing. The correction factor, determined by the relation

$$F = \overline{\Phi}_V / \Phi_0,$$

where $\overline{\Phi}_V$ is the flux of thermal neutrons averaged over the entire volume of the counter, Φ_0 is the flux of thermal neutrons in water in the absence of the counter, was computed with the aid of the theory of diffusion and transport approximation in the assumption of an infinitely long counter and isotropic distribution of neutron flux in water. Following were the values of the constant quantities for thermal neutrons: macroscopical absorption cross section in water 0.022 cm^{-1} ; diffusion length in water 2.76 cm; B^{10} absorption cross section for a mean velocity of thermal neutrons of 3540 barns; BF_3 scattering cross-section 16.3 barns; absorption cross-section for 1 cm^3 of the BF_3 counter 0.033 cm^{-1}; macroscopical scattering cross-section of filled counter $1.4 \cdot 10^{-4}$ cm^{-1}. The probability of absorption of thermal neutrons during their passage through the BF_3 counter, computed with the aid of the transport approximation, is 0.10. The value of the multiplier F was found to be 0.76. The lowering of neutron flux by duralumin casing constitutes then about 1 percent.

The data corrected for the background and the neutron field distortion are also plotted in Figures 1 and 2 (curve 3). It may be seen from these drawings that a clear transitional effect is observed at all observation points. At Ladoga and Balkhash lakes the maximum is located at a depth of 4.8 ±0.5 cm and its magnitude exceeds by a factor of 3.5 that on water surface.

If we plotted the value of neutron intensity as a function of depth in a semi-logarithmic scale, we would obtain a straight line upon damping of the transient effect. The place of this effect attenuation characterizes the depth, beginning with which one may estimate the rate of neutron formation in water at the expense of the neutron-forming component of cosmic radiation (Fig.3). At 45 cm depth the transient effect is practically fully attenuated, and at greater depths a drop of neutron density is observed according to the relation $n = n_0 e^{-h/L}$, where h is the thickness of the water layer in cm; L is the mean free path of the neutron-forming component in water. Analysis of experimental data by the method of least squares yields the value of L at depths to 4.5 m, which is (152 ±9) cm^{-1}.

It is well known that the cadmium ratio characterizes in the first approximation the energy spectrum of neutrons in the region of low energies. This is why it should be noted that the value of cadmium ratio obtained by us at depths above 30 cm is close to 15 and increases to about 21 in the transient maximum, while in the equilibrium region of the atmosphere this ratio constitutes about 2.2.

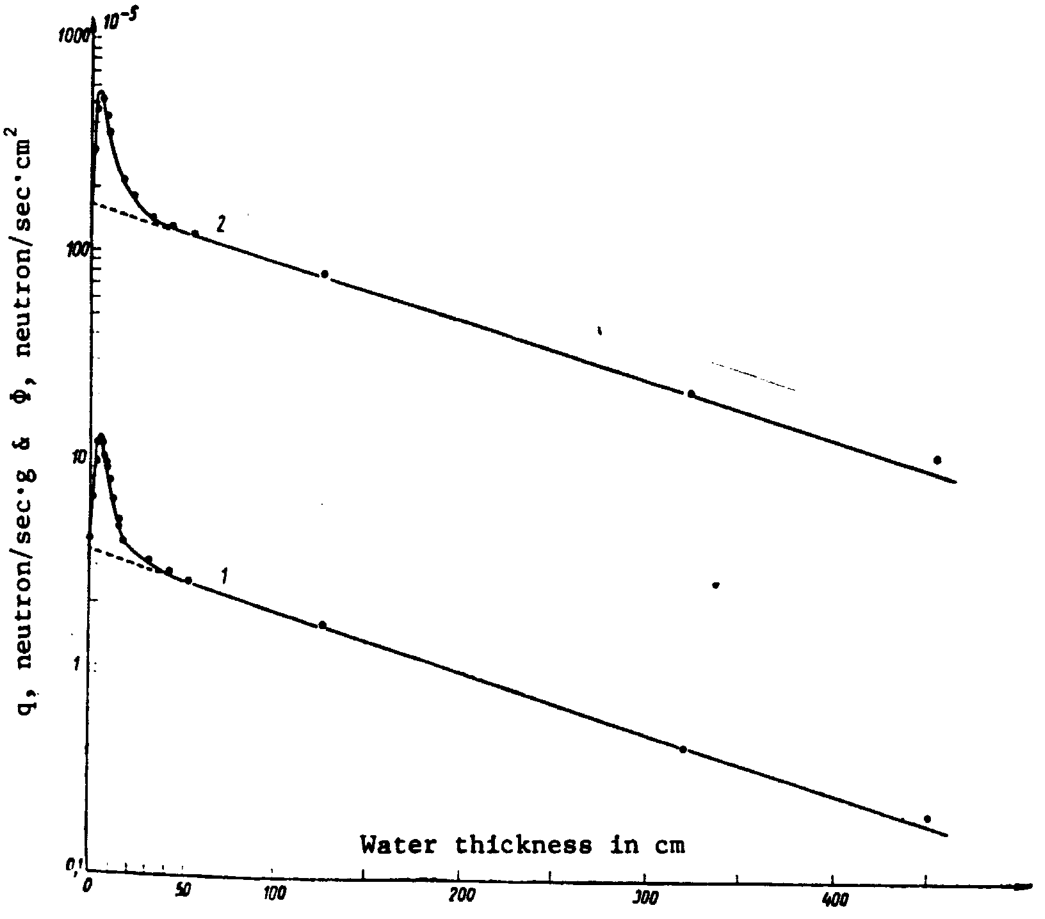

Fig.3. Rate of formation q and flux Φ of thermal neutrons in water at depths from 0 to 4.5 cm (Lake Ladoga, sea level) :
1) $q_0 = 3.67 \cdot 10^{-5} e^{-h/152}$; 2) $\Phi_0 = 1.66 \cdot 10^{-3} e^{-h/152}$.

The rate of neutron formation in water, q_0, under the action of cosmic radiation may be computed by the Korf formula [23]:

.../..

$$q_0 = n_0 \left(\frac{\sigma_{H_2O}}{\sigma_{BF_3}}\right) \frac{22{,}4 \cdot 10^3}{MVP},$$

where n_0 is the counting rate (pulses/min), extrapolated by the method of least squares to zero depth, taking into account the background and the distortion effect of the neutron field, induced by the introduction into the water of the BF_3 counter; σ_{H_2O} is the cross section of capture for an average velocity of thermal neutrons computed for a H_2O molecule, equal to 0.66 barns; σ_{BF_3} is the capture cross section for a mean velocity of thermal neutrons, computed for a BF_3 molecule (enrichment in B^{10} to 85%), equal to 3010 barns; M is the molecular weight of water, which is 18; V is the operational volume of the detector, composed of four BF_3 counters, which is 3420 cm^3; P is the gas pressure inequal to 0.4 atm.

The values of n_0 and the computed rates q_0 of neutron formation in water for the indicated three points of observation are compiled in Table 1.

TABLE 1

RESULTS OF MEASUREMENT OF THE RATE OF NEUTRON FORMATION IN WATER UNDER THE ACTION OF COSMIC RADIATION

Measurement Point geom.lat. λ	Atm.Pr. mm. Hg	Counting rate n_0 puls/m.	Rate of neutron formation neutr/s·g	Flux Φ_0 10^{-3} neutron sec·g	reduced to sea level	
					$q_0 \cdot 10^{-5}$ neutron/s g	$\Phi_0 \cdot 10^{-3}$ neutron/s cm²
Lake Ladoga (56°N lat.)	760	11,0±0,5	3,67±0,16	1,67±0,08	3,67±0,16	1,67±0,08
Lake Balkhash (37° N.lat)	728	12,0±0,4	3,98±0,13	1,8±0,06	3,0±0,2	1,37±0,09
High-mountain lake (33°N.lat.)	582	44,7±1,8	14,9±0,6	6,75±0,27	3,0±0,2	1,37±0,09

The decrease in the rate q of neutron formation with depth h (see Fig.3) is expressed by the same exponent as the measured density of neutrons, that is, $q = q_0 e^{-h/152}$, where q_0 is the rate of formation of neutrons extrapolated to zero depth.

Following is the dependence between the rate of formation of neutrons and the flux Φ of thermal neutrons:

$$q = \Phi \Sigma a,$$

where Σ_a is the macroscopical cross-section of thermal neutron absorption in water. The computed values of fluxes of slow neutrons (Φ_0), corresponding to the formation rate q_0 at points of observation, are also compiled in Table 1.

Inasmuch as the rate of formation of neutrons under the action of cosmic radiation is being determined in conditions ruling out the influence of lateral factors (transient effects, distortion of the neutron field near the ground and so forth), we may, by neglecting the insignificant difference in the latitudes for the lakes Balkhash and high-mountain (37° vs. 33° N.Lat.), compute the mean free path in the air (L_1) for the neutron-forming component. From the data of the Table, one may see that the rate of formation of neutrons in water at the altitude of 2150 m above the sea level (582 mm.Hg) is 3.7 times greater than at 350 m (728 mm.Hg), which corresponds to the path

$$L_1 = 155 \pm 9 \text{ g/cm}^2 \text{ (144} \pm 6 \text{ mm Hg)}.$$

Within the limits of measurement precision, this value coincides with that of the path of the neutron-forming component in water. Therefore, the dependence of intensity J of natural neutron radiation on altitude above the sea level may be also expressed for the indicated geomagnetic latitudes by the relation:

$$J = J_0 e^{h/155},$$

where J_0 is the intensity at sea level.

On the basis of the obtained altitude dependence of the values of q_0 and Φ_0 for Balkhash (p = 728 mm.Hg) and the mountain lake (p = 582 mm. Hg), it is possible to reduce to sea level. These data are represented in the two last columns of Table 1, where compiled also are the values of q_0 and Φ_0 for Lake Ladoga (sea level). Comparison of the obtained data for the Ladoga and Balkhash lakes shows that the latitude effect between 56° N.lat. and 37° N. lat. constitutes correspondingly with the expression

$$\frac{q_{56°} - q_{37°}}{q_{56°}} \cdot 100$$

(18 ± 1) percent.

The value of the mean free path of the neutron-forming component in the air obtained during the study of the altitude dependence in the present work (155 g/cm^2) is close to the mean value obtained by other authors (about 160 g/cm^2)

for the lower layers of the atmosphere and moderate latitudes [9, 24].

The value of the mean free path of the neutron-forming component obtained in water (152 g/cm) coincides within the limits of measurement precision with the data provided by works [4, 5].

The measured value of the latitude effect is free from the influence of lateral factors and, in particular, from the distirtion of the neutron field near the Earth's surface and from the background of atmospheric neutrons.

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