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Abstract

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GEOPHYSICS

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ON THE NEUTRON RADIATION OF ROCKS

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In papers (^{1,2}), studies of the neutron radiation of rocks were published. The insufficient sensitivity of the apparatus that we had at that time, as well as the absence of initial data for calculation, did not allow us to estimate with any reliability the neutron radiation of the rocks of the earth' s crust, and at that time (^{2}) we expressed only the conjecture that the intensity of the neutron radiation of rocks should be tens of times less than the intensity of cosmic neutrons at sea level. Since then, numerous works have been published on the study of the neutron radiation of the atmosphere ($^{3-18}$)* and, very recently, also several contradictory works on the neutron radiation of rocks ($^{19-25}$). In some of these works (^{19,22,25}) and others, a considerable intensity of neutron radiation of rocks was found, of the same order of magnitude as, and even exceeding, the flux of cosmic neutrons at sea level, whereas in others (^{21}) it proved impossible to measure neutron radiation in mine workings, and by estimate it is less than 5% of the flux of cosmic neutrons at sea level.

Having at present more complete initial data for estimating the neutron radiation of rocks, in the present note we have attempted to calculate the rate of neutron production in rocks of the earth' s crust and, on the basis of published data on the rate of neutron production in various materials due to cosmic rays at sea level, to estimate the absolute intensity of neutrons from rocks. Our estimate is more or less valid if only those nuclear processes which we know at present operate in the earth' s crust (the yield of neutrons upon bombardment of nuclei of light elements by α-particles of radioactive substances, photonuclear reactions, and spontaneous fission of heavy nuclei with emission of neutrons).

Near the earth' s surface, thermal neutrons are formed by the following three processes:

1) Formation of thermal neutrons as a result of slowing down in the atmosphere and soil of fast neutrons produced by cosmic rays in the atmosphere.
2) Formation of thermal neutrons as a result of slowing down of fast neutrons, produced by cosmic rays in the materials surrounding the detector, in these materials (most often this material is paraffin).
3) Formation of thermal neutrons as a result of slowing down of fast neutrons produced by nuclear processes in the soil, in the atmosphere, and in the

materials surrounding the detector.

If we surround a thermal-neutron detector with a thick layer of paraffin, and the paraffin on the outside with a thin layer of cadmium, which absorbs thermal neutrons, the detector will register neutrons slowed down in paraffin. But it is also known that at sea level there are almost no fast neutrons produced by cosmic rays in the atmosphere—all of them have time to slow down to very low velocities, close to thermal ones. Consequently, the effect registered in this case by the detector is due to neutrons produced in the paraffin by cosmic rays and slowed down in it (if one neglects the effect of terrestrial neutrons, which, as we shall show below, is very small for rocks with a normal content of radioactive light elements). Experiment shows that the effect observed in a boron detector when it is surrounded by a thick layer of paraffin and a thin layer of cadmium is, in order of magnitude, equal to the effect in the detector in the absence of paraffin and cadmium. The rate of neutron production in various materials by cosmic rays at sea level is known. Thus, for example, Table 1 gives, according to Tobey and Montgomery (26), the rates of neutron production by cosmic rays.

Table 1

Substance	Rate of neutron production, $\frac{\text{g}}{\text{sec}} \cdot 10^{-5}$
Paraffin	2.6
Carbon	3
Aluminum	5.2
Lead	8.7

The absolute intensity of thermal cosmic neutrons at sea level is at present taken to be 230 neutrons/cm^2 • day (27).

In order to estimate the intensity of thermal neutrons of the soil, we must calculate the rate of neutron production due to nuclear processes occurring in the rocks of the earth' s crust. The chief of these processes is the bombardment of nuclei of light elements by α-particles of natural radioactive elements, which are always present in rocks. V. I. Matvienko and one of us published studies of the neutron yield from various materials, including granite, when nuclei were bombarded by α-rays of radon and its decay products (28). In accordance with these studies, the neutron yield from granite is equal to $80.7 \cdot 10^3$ neutrons/sec • curie.

If we take the radium content in granite to be $3 \cdot 10^{-12}$ g of radium/g, then the neutron yield from granite is expressed by the value $80.7 \cdot 10^3 \cdot 3 \cdot 10^{-12} = 2.4 \cdot 10^{-7}$

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* In article (3) a bibliography up to 1947 is given, as well as numerous references to the literature up to 1951.

neutrons/sec • g (here we neglect the yield of neutrons from the α-rays of radium, ionium, polonium, and uranium, thereby somewhat underestimating the yield).

Approximately the same yield should be expected for bombardment of nuclei by the α-rays of the thorium family contained in granite. In all, we shall have about $5 \cdot 10^{-7}$ neutrons/sec • g.

Let us now estimate the neutron yield from spontaneous fission of U^{238} nuclei. We shall take the half-life of U^{238} for spontaneous fission to be $1.1 \cdot 10^{16}$ years and $\lambda_{\text{div}} = 2 \cdot 10^{-24}$ sec^{-1}. We shall assume that 3 neutrons are emitted in each fission. Then in 1 g of granite, in 1 sec., there are formed

$$\frac{6.02 \cdot 10^{23} \cdot 2 \cdot 10^{-24}}{238} \cdot 3 \cdot 1 \cdot 10^{-5} = 1.5 \cdot 10^{-8}$$

neutrons/sec • g (here $1 \cdot 10^{-5}$ is the amount of U^{238} in grams per 1 g of granite).

Thus, the neutron yield in spontaneous fission is approximately 30 times less than in bombardment of the nuclei of the elements contained in granite by the α-rays of radioactive substances. This relative estimate is in agreement with the data of Morrison and Pine (^{30}). Neutron yield under the action of γ-rays of natural radioactive substances can occur only in beryllium and heavy water, and since their content in rocks is in general extremely small, photonuclear reactions may be neglected in estimating the neutron yield from rocks. The estimate we obtained for the neutron radiation of granite is in agreement with the experimental studies of Pine and Morrison, who measured the ob-

neutron production in granite and found it to be equal to 0.5 ± 0.35 neutrons per second per ton of granite (^{8}).

Thus, in granite, under the action of nuclear reactions in the Earth, approximately 50 times fewer neutrons are produced than in paraffin by cosmic rays at sea level. Consequently, from rocks of the granite type one should expect a neutron flux of approximately about 5 neutrons/cm^2·day. This is still beyond the sensitivity of our instruments. However, the calculations given show that neutron fluxes in mine workings with an increased content of radioactive elements are quite accessible for measurement with modern instruments. It is possible that, with an increased content of some light elements (beryllium, lithium), the neutron flux will also be accessible to measurement. In studies of neutron radiation from rocks, it should be taken into account that cosmic rays, even at sea level, produce many times more neutrons than nuclear processes in ordinary rocks. When measurements are made in mountainous regions, cosmic neutrons will create especially large interference in measurements of the neutron radiation of rocks.

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Note: Figure translations are in progress. See original paper for figures.