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Variation of Environmental Neutron Flux with the Depth of Water and Soil

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As a part of interest in the study of the neutron flux in biological environments, variations of slow neutrons with depth of water and soil were measured through the radioactivity induced in gold by $^{197}Au(n,\gamma)^{198}Au$ reaction. The measurements made for 0–100 cm in fresh water and 20–400 cm in sea water showed that the thermal neutron flux had a peak at around 10 cm depth and then gradually decreased with depth in water. The depth profile in seawater was almost the same as freshwater. In the case of soil made for 0–60 cm, thermal neutron flux showed a peak at 5 cm and decreased rapidly to 60 cm accompanying a shoulder-like shape during 10–30 cm range.

1. Introduction

Background neutrons are present throughout the earth's atmosphere from the interaction of primary and secondary cosmic rays with nitrogen and oxygen nuclei in the air. From a few hundred meters above the ground to the top of the atmosphere an equilibrium condition exists in which the intensity of the neutron background remains proportional to the local neutron production. Throughout this region the shape of the neutron energy spectrum remains essentially unchanged. However, near the air/soil or air/water boundary a discontinuity in both neutron production and scattering properties leads to a non-equilibrium situation.[1–3] In particular, neutrons produced in seawater or in air, which diffuse in seawater, are so rapidly thermalised that near the air/seawater boundary, the thermal flux is considerably higher than would be expected in free air.[1] As cosmic rays interact with any material to produce neutrons, the background flux measured over seawater or over soil is made up of neutrons produced in both air and seawater or air and soil. Any massive object serves as a medium for the production of neutrons by secondary cosmic rays and therefore represents an additional source of background neutrons. For this reason, background measurements taken at the soil or at sea level may be higher near a large mass of material such as iron or aluminum.[1]

As a matter of fact, because of the considerable variety of soil compositions, particularly its water content, the thermal neutron energy distribution and the thermal neutron flux in soil should be variable.[1,2] In soil, near the air/soil boundary, the production rates of nuclides derived from low-energy neutrons increase to the maximum and subsequently decrease exponentially with increase in depth.[3] In this paper depth profiles of environmental neutrons in water and soil were measured by a gold activation method coupled with an extremely low background γ-ray spectrometry.

2. Experimental method

The $^{197}Au(n,\gamma)^{198}Au$ reaction was used in the present work to estimate the thermal neutron flux at different depths of water and soil. The 411.8 keV γ-ray from ^{198}Au (2.695 d) was measured using extremely low background Ge-detectors installed in Ogoya Underground Laboratory (OUL)[4] to calculate the number of ^{198}Au atoms produced per unit weight of gold and then converted to the neutron flux using Monte Carlo Code Program.[5]

Two experiments have been made to know the dependence of the thermal neutron flux in the depth of water. The first one was in fresh water at Wake pond, Nomi city. The second one was in seawater at Marine Research Laboratory of Kanazawa University at Ogi, Uchi-ura-Machi in Noto Peninsula of Japan seaside.

In the freshwater experiment targets were distributed from the surface of water to 100 cm depth. Gold grain targets of 50 g set were exposed to the neutron flux. On the other hand, in the sea water experiment, the 20 g targets were affirmed at 20, 100, 200, and 400 cm depth. The targets were exposed during May and June, 1999.

To estimate the variance of thermal neutron flux with the depth of soil, experimental data were taken at different soil depths. One sample at 50 cm over the soil and seven samples inside two holes were used. The first hole was 30 cm depth that contained three samples at 10, 20, and 30 cm depth. Other four samples were placed at 5, 15, 45, and 60 cm depth in the second hole. All samples were 20 g gold grain targets packed in 3 × 2.5 cm^2 polyethylene bags. The targets were exposed to the environmental neutrons during December, 1999. At the start of the experiment, water content in soil was 22%. However this value increased to about 27.5% by rain fall and 34% by snow fall.

After more than three weeks of exposure for every group, the targets were collected carefully and every target was wrapped with a cadmium sheet and transferred to the extremely low background Ge-detectors to measure for more than 4000 min.

3. Results and discussion

3.1. Variation of thermal neutrons with the depth of fresh and seawater. Measured thermal neutron values in fresh water and seawater are summarized in Tables 1 and 2 and are plotted in Figure 1 together. As seen from Figure 1, the depth profile of slow neutrons in seawater is almost the same as that in fresh water.

Thermal neutron flux at about 10 cm depth increases 1.6 times higher than that in free air. Then it decreases rapidly with increasing of water depth until 400 cm.

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TABLE 1: Thermal neutron flux in fresh water

Water depth (cm)	^{198}Au (atoms/g)	flux (10^{-3} n cm^{-2} s^{-1})	Relative flux
Free air	45.2 ± 6.5	8.35 ± 1.17	1.00
0	44.9 ± 10.7	8.29 ± 1.98	0.99
10	71.4 ± 9.6	13.20 ± 1.77	1.58
20	37.4 ± 7.1	6.91 ± 1.30	0.83
37	16.6 ± 3.9	3.07 ± 0.73	0.37
50	15.5 ± 5.1	2.86 ± 0.95	0.34
60	11.5 ± 3.6	2.12 ± 0.86	0.25
75	10.4 ± 2.5	1.91 ± 0.47	0.23
85	13.3 ± 6.0	2.46 ± 1.11	0.29
100	9.2 ± 3.1	1.70 ± 0.57	0.20

TABLE 2: Thermal neutron flux in seawater

Water depth (cm)	^{198}Au (atoms/g)	flux (10^{-3} n cm^{-2} s^{-1})	Relative flux
20	28.5 ± 9.0	5.26 ± 1.66	1.00
100	8.0 ± 5.5	1.48 ± 1.02	0.20
200	7.6 ± 3.7	1.40 ± 0.69	0.27
400	6.7 ± 3.3	1.23 ± 0.61	0.23

The present results at the seawater is higher than that calculated ones.[1,2] However, they showed that the flux reaches its maximum value at 8 cm in the water and decreases slowly with the increase of the water depth until about 40 cm, which is in well agreement with the present results.

Below 30 cm, the thermal neutron intensity decreases exponentially with depth. Edge[6] found a rapid decrease of slow neutron intensity with the depth in the first 20 cm layer and a slower decrease at greater depth.

These results show that the thermal neutron flux at 100 cm in seawater decreased to 28% of the value at 20 cm and to 23% at 400 cm depth. No fundamental difference of depth profile was observed between fresh water and seawater. This may be due to the contribution of dissolved material in seawater (~3.7%) affects only small for absorption of neutron. However, the rapid decreasing of flux within the first 100 cm is of interest for in future study.

3.2. Variation of thermal neutrons with the depth of soil. Table 3 and Figure 2 show the neutron measurement in soil. The thermal neutron flux at 50 cm above soil surface was (6.7 ± 1.1) × 10^{-3} n cm^{-2}s^{-1}, and this value increased to a maximum value (8.6 ± 1.2) × 10^{-3} n cm^{-2}s^{-1} at 5 cm depth. This increase is explained by the thermalization of fast neutrons mainly by the soil water (22%) in humid surface soil. The thermal neutron flux begins to decrease at 10 cm depth showing a shoulder-like decease until about 30 cm. This shoulder-like decease may be explained by thermalization of neurons mainly caused by soil components. The stability of neutron flux between 10 and 30 cm depth was not in agreement with the calculated curves.[1,2] This discrepancy may be caused by snow fall during exposure which increased the water content of soil from 22 to 34%.

TABLE 3: Thermal neutron flux in soil

Soil depth (cm)	^{198}Au (atoms/g)	flux (10^{-3} n cm^{-2} s^{-1})	Relative flux
free air	45.2 ± 7.2	6.72 ± 1.10	1.00
5	57.7 ± 8.3	8.58 ± 1.23	1.28
10	44.4 ± 7.1	6.60 ± 1.05	0.98
15	45.2 ± 9.3	6.72 ± 1.38	1.00
20	43.8 ± 12.1	6.51 ± 1.80	0.97
30	35.8 ± 5.6	5.32 ± 0.83	0.79
45	18.0 ± 6.5	2.68 ± 0.97	0.40
60	12.4 ± 3.6	1.84 ± 0.54	0.37

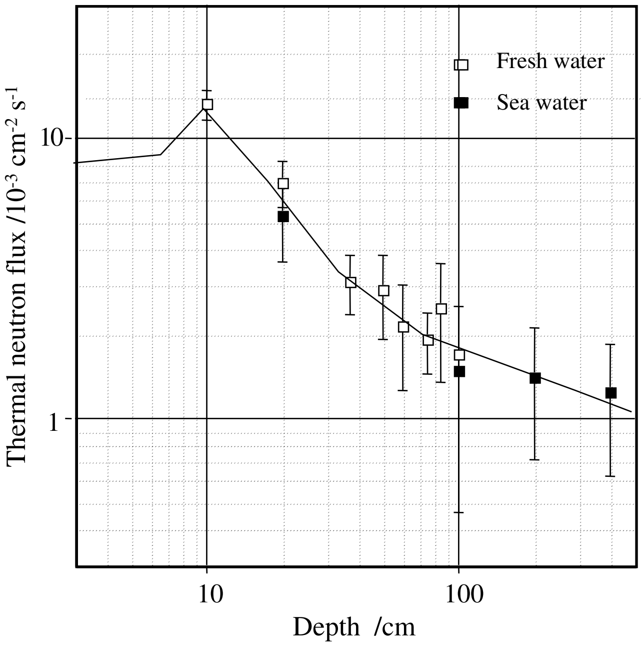

Figure 1. Depth profile of thermal neutron flux in the freshwater and seawater.

Wet earth tends to slow down fast neutrons from the air rapidly. A part of these slow neutrons then diffuse back into the air and subsequently absorbed by the $^{14}N(n,p)^{14}C$ reaction.[7] Thus the energy spectrum of cosmic neutron changes in soil, resulting in more thermal neutrons.

Both the absorption of thermal neutrons by the components of soil and the moderation by the large amount of water content are competed each other. After 30 cm depth, the thermal flux intensity decreased rapidly again to reach about 27% of its surface value at 60 cm depth.

The present results showed that the thermal neutron flux at the surface of the soil is (6.7 ± 1.1) × 10^{-3} n cm^{-2}s^{-1} which is in

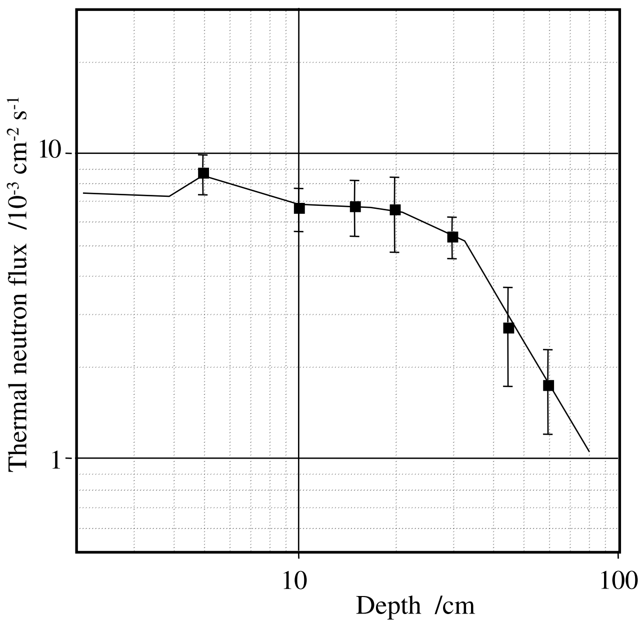

Figure 2. Depth profile of thermal neutron flux in soil.

good agreement with the calculated values (6.6×10^{-3} n $cm^{-2}s^{-1}$) [2] and (6.4×10^{-3} n $cm^{-2}s^{-1}$).[3] However, the decrease pattern with the depth of soil is different from the calculated one[1] which predicts the equilibrium value at about 23–30 cm depth. As mentioned before, the disagreement of the present result with the calculated data is probably due to the effect of snow cover.

4. Conclusion

Depth profiles of environmental neutron at air/water and air/soil boundary were measured by $^{197}Au(n,\gamma)^{198}Au$ reaction using gold grain and/or gold sheet. The depth profiles for freshwater (0–100 cm) and seawater (20–400 cm) showed a similar variation with a small peak at around 10 cm. In the soil experiment a small peak was observed at 5 cm and a shoulder-like region in 10–30 cm and then decreased rapidly.

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