Variation of environmental neutron flux with altitude and depth of both water and soil

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Abstract Applying the extreme low-level γ-ray spectroscopic analysis the environmental neutron flux is measured using different moderator construction and environment through the reaction ^{197}Au (n, γ) ^{198}Au. The contribution of thermal and resonance neutrons is separated using the cadmium difference technique, while fast neutrons are measured by the paraffin moderator. The results of altitude dependence of the neutron flux are discussed. The thermal neutron flux near the surface of sea water is less than its value at 100 cm over ground near sea water, while the value over the surfaces of fresh water is higher than that near the surface of sea water. Also the thermal neutron flux at 5 cm soil depth increases, then decreases to its original value at 10 cm depth and still constant until 25 cm, then decreases rapidly to reach 27% of its original value at 60 cm depth. The soil compositions, corresponding neutron temperatures and effective absorption cross sections of earth are the most effective factors on the equilibrium region of thermal neutrons in the ground.

Keywords Extreme low-level γ-ray spectroscopy, Environmental neutron flux, Gold activation

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1 Introduction

Reactions induced by neutrons have a great importance in both pure and applied nuclear physics where neutrons have proved to be especially effective in producing nuclear transformations. Not only are highly energetic neutrons capable of causing various nuclear reactions, but slowly moving neutrons are also extremely effective particularly in causing capture reactions. Because of these properties of neutrons many more radioactive nuclides have been produced by neutron reactions than by any other particles. Slow and thermal neutrons can be captured by the nucleus to render it unstable. This process is accompanied by the emission of γ-rays. Measurement of secondary process is, therefore, required for their detection. The fast neutrons can be slowed down by allowing them to pass through some hydrogen-containing substance such as water or paraffin.

In view of the uncertainties in the absolute value of neutron flux density integrated over the entire energy spectrum, especially at the altitudes near the ground, it is not surprising that there is no general agreement as to the detailed shape of the neutron differential energy spectrum. One of the major problems in the experimental determination of the cosmic-ray neutron spectrum is that it extends over a wide energy range, from ~ 0.01 eV to at least several tens of GeV. Near the ground the equilibrium condition no longer holds, and some change in the attenuation length is expected because the production, moderation, and absorption of neutrons differ between air and soil or water. The spectral intensity is also relatively low even at high altitudes, and the flux lacks strong directional characteristics. Distribution of cosmic neutrons in the atmosphere is affected by altitude, latitude, air pressure, and solar activity.[1-8]

On the other hand, the interest of such measurements has increased in the exposure of large populations to low levels of ionizing radiation owing to human activities. For example, since the discovery of cosmic rays in 1912, the growth of commercial jet aviation has increased the exposure of passengers and crews to secondary cosmic-ray radiation at high alti-

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tudes. The cosmic radiation environment at these altitudes is very complex and is significantly different from that experienced by workers in the nuclear industry and by the populations in general at ground level.[8] Most international and domestic flight routes involve cruising altitudes between 10 and 17 km where the intensity of ionizing particles becomes significant.[9] The interaction of primary galactic cosmic radiation in the atmosphere produces three main components of the radiation field at aviation altitudes, namely the hadron, the electromagnetic and the muon cascade. The total ionization for a given altitude is a function of the geomagnetic latitude and is dependent also on the level of solar activity.[10]

Near the air / ground or air / seawater interface a discontinuity in both neutron production and scattering properties leads to a non-equilibrium situation. In particular, neutrons produced in seawater or in air, which diffuse in seawater, are so rapidly thermalized. As cosmic rays interacting with any material will produce neutrons, the background flux measured over seawater or over ground is made up of neutrons produced in both air and seawater or air and ground. 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 ground level or at sea near a large mass of material, such as iron or aluminum,[11] may be higher.

As a matter of fact, because of the considerable variety of earth compositions, particularly water content, the thermal neutron energy distribution and the thermal neutron flux in the earth should be variable.[12] In the ground, near the air / ground boundary, the production rates of nuclides produced from low-energy neutrons increase to a maximum and subsequently decrease exponentially with the increase in depth.[13]

2 Procedure and experimental method

The ^{197}Au (n,γ) ^{198}Au interaction with 100% abundance has rather large cross-section for low energy neutrons [(98.5±0.4) barn] and has been used widely to measure neutron flux in nuclear reactors and neutron-related environments. The β-decay of ^{198}Au occurs with the emission of 411.8 keV γ-rays (95.56 %).[14] This interaction was used in the present work to estimate the environmental neutron flux at different environments and altitudes. The 412 keV γ-rays from ^{198}Au (2.695 d) were measured using extremely low background Ge-detectors installed in Ogoya underground laboratory to calculate the number of ^{198}Au atoms produced per unit weight of gold and then converted to the neutron flux.[15]

In the present measurements, the pure gold (99.99%) was used as a neutron target for activation analysis of neutrons. Usually three gold targets of 50g gold grain and / or 20 g gold plate (0.7mm thick sheet), in bare state and covered with 8.5 cm paraffin and 0.5 mm cadmium sheet, were used in each experiment. The targets were separated by at least 100 cm to avoid the interference effect.[1] In every experiment, the gold targets were exposed to the environmental neutrons for from 3 weeks to one month to make ^{198}Au activity nearly in the saturation state. After the exposure to the neutron flux, each sample was wrapped with cadmium sheet and brought back to the laboratory as early as possible. The 412 keV γ-ray was measured for more than 4000 min to determine ^{198}Au activity produced by the neutron capture reaction. To study the altitude dependence of neutron flux, the neutron flux was estimated at low altitude (near sea level), high altitude (mountains, 500 m height and more) and at a flight. The variation of neutron flux between sea level and 500 m altitude was not measured. This is attributed to the fact that within a few hundred meters above the earth's surface, the low-energy cosmogenic secondary neutron production is not proportional to the absorption because of the differences in neutron production, scattering, and absorption between air and ground.[13]

Two experiments have been made to study the dependence of thermal neutron flux on the depth of water. The first one was performed in seawater at Marine Research Laboratory of Kanazawa University at Ogi, Uchiura-Machi in Noto Peninsula of Japan seaside. The second experiment was performed in fresh water at Wake pond, Tatsunokuchi town. Four gold grain targets of 50 g set were exposed to the neutron flux in seawater. The targets were affirmed at 20, 100, 200, and 400 cm depth in seawater. Another experiment using 10 gold targets was performed to study the variation of thermal neutron flux with the depth of fresh water. The targets were distributed from the surface of water to 110 cm depth. The targets were exposed in successive groups at the same point during May and June 1999.

To estimate the variance of thermal neutron flux with the depth of ground, experimental data were taken for the flux inside the ground at different depths, at sea level. One sample with 50 cm over the ground and seven samples inside two holes were used. The first hole contained three samples at 10, 20, and 30 cm depth respectively. 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 cm×2.5 cm polyethylene bags. The targets were exposed to the environmental neutrons during December 1999. The water content of soil was 22 % at the start of the experiment. During the collection of the first two targets at 50 cm over ground surface and 5 cm depth respectively, this ratio increased to about 27.5 %. Because the ground was covered by snow, that ratio increased again to 34 % at the collection of the other six targets. After more than three weeks of exposure for every group, the targets were collected with care. Every target was wrapped with cadmium sheet and transferred to the Ge-detectors to measure the spectrum of γ-rays for more than 4000 min.

A three-dimensional Monte Carlo code, MORSE,[16] was employed to design typical models of the gold targets to calculate the sensitivity of the produced gold atoms to the energy of neutrons. These models showed obviously that the production of ^{198}Au atoms almost resulted from thermal and epithermal neutrons with energy less than 1 eV in the bare targets. The resonance peak between 4 and 8 eV came from the large cross-section of gold for epithermal neutrons. On the contrary, the prevailing neutron flux was shifted to the high-energy region by covering the gold targets with 8.5 cm paraffin layer. This region represents the fast neutrons with energy from 10 eV to 10 MeV. On the other hand, the 0.5 mm cadmium thickness is completely enough to cut all the thermal neutrons and to be reasonable only for the epithermal neutrons. In the following the term “slow neutrons” will represent both thermal and epithermal neutrons with energy less than 10 eV, whereas the term “fast neutrons” will represent neutrons with energy ranging from 10 eV to 10 MeV.

3 Results and discussion

3.1 Low altitude measurements

These measurements were done to assess neutron flux near the sea level. The neutron targets were exposed at the roof of Low Level Radioactivity Laboratory (15m height) during the period from October 1998 to July 1999. The results show an agreement between the measured neutron flux by four groups of targets. The slow neutron flux at roof of LLRL ranged from $(7.8\pm2.2)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ to $(9.0\pm1.6)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$, with an average of $(8.4\pm0.6)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$. On the other hand, the fast neutron flux ranged from $(1.9\pm0.2)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ to $(2.5\pm0.3)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$, with an average of $(2.1\pm0.3)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$. General observation of the low altitude measurements is in very good agreement with the simulation of slow neutron flux at all measurements and the small differences are within the background and measurement error. This is in contrast with most of the previous works, in which existed a wide range of discrepancy. This means that the activation of gold is a convenient method to estimate neutron flux even in very low environmental flux.

3.2 High altitude measurements

These measurements were made at some mountains with different heights to confirm the dependence of environmental neutron flux on altitude. These mountains lie between 36° and 36.5 °N. The environmental neutron flux at Okura skiing field, 500m height, was estimated. The measurements were repeated four times to study the variation of neutron flux with different meteorological conditions. Also from the results it is evident that the neutron flux at some point depends on the surrounding meteorological conditions and its effects. The targets covered with paraffin moderator showed that there was a slight difference of fast neutron flux during the snow and heavy rain seasons, but the flux inside the concrete house was lower than that outside the house. The average of fast neutron flux outside the concrete building is $(2.2\pm0.1)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$. In dry season this value increased to $(2.9\pm0.2)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$. This may be due to the much snow as well as the continuous heavy rain which had the same effect as a moderator of fast neutrons and slowed down them. On the other hand, the reduction of fast neutrons inside the house to 88% of that outside can be attributed to the shielding effect of the concrete ceiling and walls of the building.

The slow neutron flux measured by bare targets showed a slight difference for the corresponding values during snow and rainy seasons. And, the average value of $(12.1\pm0.6)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ increased to $(14.2\pm1.5)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ in dry season. The decreasing of the winter and rainy season values comparing with the dry season value means that the much amount of snow and continuous heavy rain was enough to absorb some of thermal and slow neutrons. Slow neutron flux decreased from $(12.5\pm1.7)\times10^{-3}$ to $(10.0\pm1.5)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ with a ratio of 80 % inside the concrete building.

From the results of snow and rainy seasons we have found that there is a slight difference between fast neutron flux values at the two seasons, although this difference is clearer for slow neutron flux. This effect is due to the fact that slow neutron flux is about 5 times higher than fast neutron flux. On the other hand, the measured neutron fluxes by targets covered with cadmium were $(2.2\pm1.3)\times10^{-3}$ and $(3.8\pm0.7)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ in winter and summer, respectively. The calculated cadmium ratios were 4.6±2.2 and 3.7±0.8, respectively.

The measurements of neutron flux were made also at the summit of Shishiku mountain, 650m height. These measurements showed that slow neutron flux is $(11.8\pm1.9)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ and fast neutron flux is $(2.3\pm0.6)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$, while the measurement with cadmium sheet is $(3.3\pm1.2)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ with cadmium ratio of 3.6±1.5. On the other hand, the measurements of neutron flux at the summit of Sena skiing field were repeated three times to estimate its variation with different conditions at 1000m height. Fast neutron flux decreased from the average value of $(3.0\pm0.3)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ outside the concrete building to $(2.3\pm0.5)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ inside the building, both during winter. This apparent decrease is due to the effect of the concrete ceiling layer as moderator of fast neutrons. The corresponding value in dry summer was $(5.6\pm0.5)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$.

The reduction of fast neutron flux during winter comparing with the summer value may be due to the effect of snow as was explained in Okura skiing field measurements. Slow neutron flux at 1000 m height ranged from $(12\pm1.5)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ inside the concrete building to $(17.1\pm2.3)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ outside the building during winter. On the other hand, the neutron flux obtained by cadmium was $(4.0\pm1.3)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ inside the concrete building during winter with Cd ratio 3.0±1.1. This value increased to $(4.9\pm1.1)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ during summer.

Within the August and September of 1999, only two targets were exposed at Sanpo-iwa parking (1450 m height) to measure the neutron flux. Slow neutron flux was $(25.6\pm2.1)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ during summer, dry season. The corresponding value measured by cadmium was $(8.9\pm2.3)\times10^{-3}$ $cm^{-2}\cdot s^{-1}$ with Cd ratio 2.9±1.0. These measurements show a higher increase of slow neutron flux than in the low altitude measurements on similar meteorological conditions.

3.3 Slow neutron flux at flight altitudes

Most of the previous aviation measurements concentrated on neutron flux in the energy range from 1 eV to tens of MeV. In the current study, density of thermal and epithermal cosmic-ray neutrons was measured in some flights at 8 and 11 km using the gold activation method and extremely low background Ge detectors. The gold targets were carried by a passenger inside the airplane to be exposed to neutron flux.

The results show that the average value of slow neutron flux at 8 km elevation is (1.1 ± 0.2) $cm^{-2}\cdot s^{-1}$ at average geomagnetic latitude of ~ 26 °N. On the other hand, the corresponding value at 11 km ranged from average (1.1 ± 0.2) $cm^{-2}\cdot s^{-1}$ at average geomagnetic latitude ~ 21 °N to (0.9 ± 0.1) $cm^{-2}\cdot s^{-1}$ at average geomagnetic latitude ~ 4.5 °N. The average value at 11 km altitude was (1.0 ± 0.1) $cm^{-2}\cdot s^{-1}$ at average geomagnetic latitude ~ 13 °N. The cadmium ratio was 2.1 at 11 km altitude. These values show that the flux at 8 km is higher than that at 11 km, which is due to the dependence of neutron flux on geomagnetic latitude and altitude in a complex way. Neutron flux increases with flight altitudes for all latitudes but more rapidly at the higher latitudes.[17] The intensity of primary cosmic-ray protons reaching the top of the atmosphere increases at higher latitudes because the shielding effect of the magnetic field is least at the magnetic poles. Hence, the composition of secondary radiation in the atmosphere changes with latitude. The neutron component increases much more than the ionizing components and represents a larger percentage of the total radiation at high latitudes than at the equator.[2] According to this fact, the value of the second 11-km aviation at average geomagnetic latitude 4.5 ºN was expected to be lower than the corresponding value at 21 ºN. However, the slight difference between these two values may come from the neutron fluence rate decreasing with an effective attenuation length from about 220 to 160 g·cm^{-2} going from equatorial latitudes to about 60º geomagnetic latitude. The mean energy of the primaries, which induce cascades in low geomagnetic latitudes, is higher than those in Polar Regions. More neutrons per interaction are produced and the secondaries have a higher mean energy and are able to penetrate deeper into the atmosphere. For these reasons the maximum of the neutron intensity is located at lower altitudes in the equatorial than in the Polar regions. Near the Pole the maximum neutron flux appears at about 18 km, while at the equator at about 15 km.[18] This means that the measured value at 4.5 ºN is in more vicinity to its maximum value, which fades the expected difference with the other value at 21 ºN.

Table 1 shows the summary of the environmental neutron flux measurements at different altitudes and meteorological conditions. Although the cosmic-ray neutron flux density at sea level is very low and difficult to measure, particularly the spectrum in the ther-

Table 1 Summary of neutron flux measurements at different altitudes and meteorological conditions

Height (m)	Metrological conditions	Fast neutron flux (×10^{-3} cm^{-2}·s^{-1})	Slow neutron flux (×10^{-3} cm^{-2}·s^{-1})	Measurements with Cd sheet (×10^{-3} cm^{-2}·s^{-1})	Cd ratio	Fast/thermal neutron ratio
20	Roof of concrete building	2.0 ± 0.3	7.7 ± 1.2	3.2 ± 1.0	2.4 ± 1.3 (a)*	0.26
	Inside the concrete building	1.7 ± 0.3	6.2 ± 1.4	2.3 ± 0.9	2.7 ± 1.6 (b)	0.27
500	Concrete and snow	2.1 ± 0.3	10.0 ± 1.5	2.2 ± 1.3	4.6 ± 2.2 (c)	0.21
	Snow	2.3 ± 0.3	12.5 ± 1.7			0.19
	Rainy season	2.1 ± 0.3	11.6 ± 1.2			0.18
	Summer	2.9 ± 0.2	14.2 ± 1.5	3.8 ± 0.7	3.7 ± 0.8 (d)	0.21
	Average (outside building)	2.5 ± 0.4	12.8 ± 1.3	3.8 ± 0.7		0.19
650	Concrete building	2.3 ± 0.6	11.8 ± 1.9	3.3 ± 1.2	3.6 ± 1.5 (e)	0.19
1000	Concrete and snow	2.3 ± 0.5	12.0 ± 1.5	4.0 ± 1.3	3.0 ± 1.3 (f)	0.20
	Snow	2.9 ± 0.3	17.1 ± 2.3			0.17
	Summer	5.6 ± 0.5		4.9 ± 1.1		
	Average (outside building)	4.3 ± 1.9	17.1 ± 2.3	4.9 ± 1.1		
1450	Free air		25.6 ± 2.1	8.9 ± 2.3	2.9 ± 1.0 (g)	
8000	During air flight at 26° N		1100 ± 150			
11000	During air flight at 21° N		1060 ± 190			
11000	During air flight at 4.5° N		910 ± 50	440 ± 50	2.1 ± 0.5 (h)	
	Average		985 ± 106	440 ± 50	3.0 ± 0.5	0.21

* For dots a, b, c, d, e, f, g, h, see Fig.4

mal and near-thermal energy region may be perturbed by features of the local terrain, slow neutron flux was measured successfully in successive measurements by activation of pure gold near sea level.

Slow neutron flux was estimated at different altitudes and flight aviation as well as different meteorological conditions. Fig.1 shows obviously that slow neutron flux is strongly dependent on the altitude. The increase of the flux values at low altitudes near ground is quite small in comparison with the values at aviation altitudes. This is due to the fact that slow neutron flux near the ground is greatly affected by ground conditions in a complicated way. The temperature near the ground affects the neutron-diffusion properties of the earth rather than of the air. This is supported by the fact that thermal neutrons near the ground come predominantly from the ground.[12] Also in the vicinity of the air-ground boundary, the boundary effect should be governed by the fact that the earth's surface has a smaller absorption cross section for slow neutrons and a larger decelerating power than air. Thus, the lower energy part of the neutron spectrum should be more subject to the boundary effect. The average slow neutron flux near sea level, at 1 km and at 11 km altitude was 8.4×10^{-3}, 17.1×10^{-3} and 0.98 $cm^{-2}\cdot s^{-1}$, respectively. These values show that the flux at 1 km and 11 km height is 2 and 116 times that near sea level, respectively, which agrees well with the expected values.

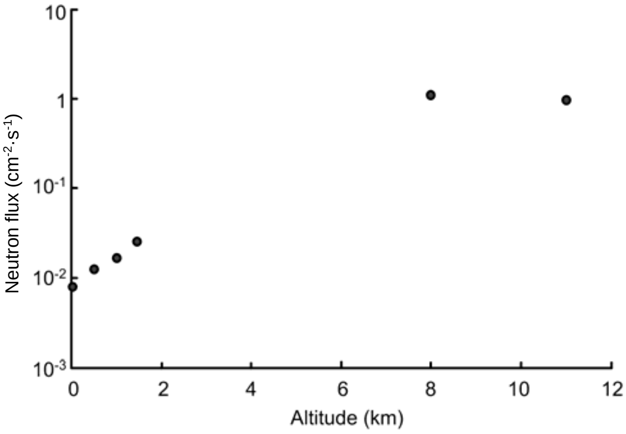

Fig.1 Variation of slow neutron flux with the altitude.

Fig.2 shows obviously that neutron fluxes are strongly dependent on the altitude. For more certainty, the measured neutron fluxes inside concrete buildings at different altitudes were plotted in Fig.3. This figure shows that, although there are some effects of concrete on neutron fluxes, the effect of altitudes is prevailing.

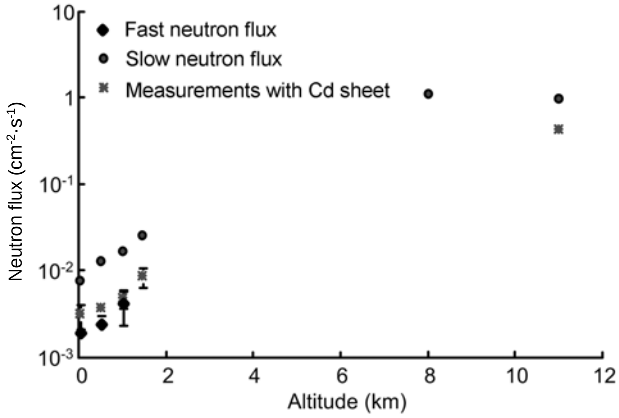

Fig.2 Variation of average neutron fluxes with the altitude.

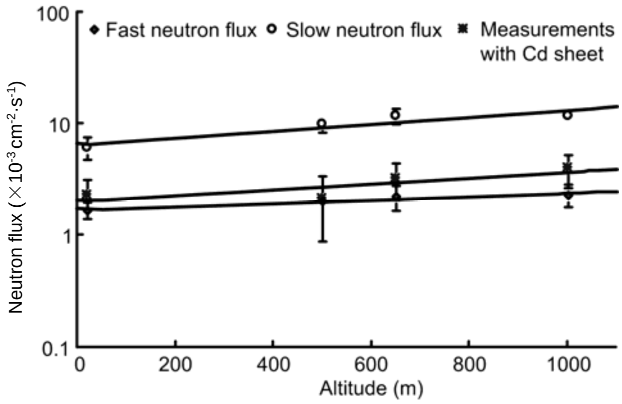

Fig.3 Variation of neutron fluxes inside concrete buildings with the altitude.

The Cd ratio was calculated at different altitudes. Fig.4 shows the variation of Cd ratio with slow neutron flux at different altitudes. This figure clarifies a weak dependence of Cd ratio obtained by using 0.5-mm cadmium sheet on the flux. Most of these values ranged from (2.4±1.3) to (3.7±0.8) with an average value of (3.0±1.3) even at high altitudes and flux. However, this value decreased to 2.1 at 11 km altitude, which may be due to that the neutron energy at high altitude is higher than that at low altitude. This fact gives the chance to epithermal neutrons to be more contributed in the measured flux to the production of ^{198}Au.

On the other hand, the ratio of fast to slow neutrons had been calculated. The range is between 17% and 27% at low altitudes with an average value of 21%. This value gave the information on the fast to slow environmental neutron ratio to be 1/5. Generally, the flux of cosmic-ray neutrons increases as the ground altitude rises. Data acquired from activation of

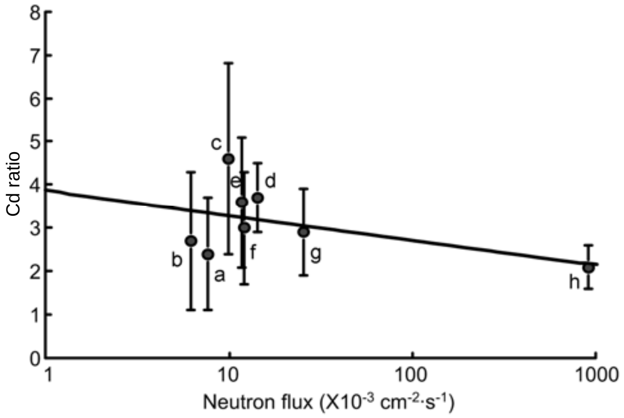

Fig.4 Dependence of cadmium ratio on flux of thermal and epithermal neutrons (see Table 1).

gold by environmental neutrons with ground altitudes up to 1450 m above sea level indicate little variation with respect to those obtained in aviation altitudes where the cosmic neutron intensity increases rapidly. Hence at high ground levels, as the air pressure decreases with the increases of altitude, the effect of shielding and attenuation of cosmic neutrons by thinner layer of air becomes weaker, resulting in more cosmic neutrons penetrating downward.[19]

The present experimental results of neutron fluxes near sea level are higher than the reported values but in good agreement with the calculated values. However, these results are in agreement with most of data at high altitude measurements.[3, 20-22] The higher value of slow neutron flux near sea level in this estimation compared with the others may be partly related to the time variation of cosmic-ray intensity associated with solar activity.

3.4 Variation of thermal neutron flux with the depth of seawater

The first observation of these results shows that the slow neutron flux near the surface of seawater is less than its value at 100 cm over ground near sea level (average 8.4×10^{-3} cm^{-2}·s^{-1}). The reason for this reduction is the neutron absorption in hydrogen with the fact that neutron production per gram is lower in water than in air.[11] Also, these results show that the thermal neutron flux at 100 cm depth decreased to 28% of the value near the surface of seawater and to 23% at 400 cm depth. The decreasing of the thermal flux with the depth of seawater was expected as a result of the interaction and absorption of neutrons with and by the components of water. This explains the rapid decreasing in the first 100 cm, but the slight decreasing from 100 cm to 400 cm may be relative to the fact that the flux becomes proportional to the local neutron production.

3.5 Variation of thermal neutron flux with the depth of fresh water

Fig.5 shows the variation of the thermal environmental neutron flux with the depth of fresh water. The values of the thermal neutrons at the surface of water and 10 cm over the surface are near the average value over the ground. But these values are higher than that near the surface of seawater. This may be due to the fact that the large body of sea surface is more effective as a moderator and absorber for the neutrons in the air near the surface than the body of the pond. The figure shows that the thermal flux increases dramatically near the air / water interface after penetrating the surface. The neutron flux reaches a maximum value at about 10 cm depth in the water to be 1.6 times its value at the surface, then decreases rapidly with the increase of water depth until about 40 cm to be about 35% of its original value. The increase of the thermal flux can be attributed to the effect of hydrogen as a moderator for fast neutrons. In the top 10 cm of water, the production of thermal neutrons by hydrogen is predominant. Equilibrium between the production and absorption of thermal neutrons occurs at 10 cm where the flux reaches its maximum. The decreasing of the flux between 10 cm and 40 cm is rapid because the absorption of thermal neutrons by the components of water becomes dominant. The flux decreased to 83% at 20 cm and to 37% at 37 cm depth, which means that the half-thickness of thermal neutrons in the fresh water is more than 20 cm. At 40 cm, where the flux is proportional to the local neutron production, the decreasing becomes more slowly. The flux value reached to 20% of its original value at 110 cm, although that value was 28% in the seawater at 100 cm depth. The difference between the corresponding values in the sea- and fresh-water may be due to the slight difference between the components of the two types of water.

The present results of seawater surface are higher than those calculated by O'Brein *et al*.[11] However, they showed that the flux reaches its maximum value

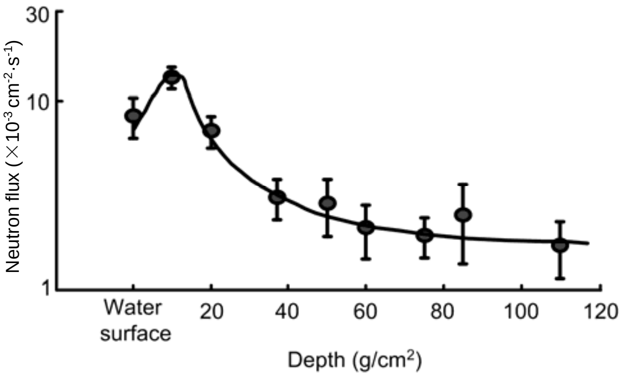

Fig.5 Thermal environmental neutron flux as a function of depth in fresh water.

at 8 cm depth in the water and decreases rapidly with increasing the water depth until about 40 cm, which is in good agreement with the present results. Bethe *et al*[23] showed that immediately above the water surface a larger number of thermal neutrons can be observed than in the free atmosphere. Also, they indicated that there is a marked increase in thermal neutron density in the top 20 cm of water. Swetnick[24] showed that the top 30 cm of water is a transition region where the thermal neutron intensity varies rapidly with the depth; and below 30 cm level, thermal neutron intensity is found to remain almost constant over the next 20 cm of water. Edge[25] found that there is a rapid decrease of slow neutron intensity at the depth of the first 20 cm layer and a slower decrease at greater depth.

3.6 Variation of thermal neutrons with the depth of ground

Fig.6 depicts the experiment results and shows the dependence of thermal neutron flux on the depth of soil. The figure shows that the thermal neutron flux above ground surface was $(6.7 \pm 1.1)\times10^{-3}$ cm^{-2}·s^{-1}. This value increased to a maximum value $(8.6\pm1.2)\times10^{-3}$ cm^{-2}·s^{-1} at 5 cm soil depth. This increasing is due to the thermalization of fast neutrons by the components of soil. The thermal neutron flux decreased again to its original value at 10 cm depth and still constant until about 25 cm. The stability of neutron flux between 10 and 25 cm depth was not in agreement with the calculated curves by Yamashita *et al*[12] and O'Brien *et al.*[11] These results can be attributed to the fact that, before measuring the targets with 15 cm depth and more, the snow covered the ground.

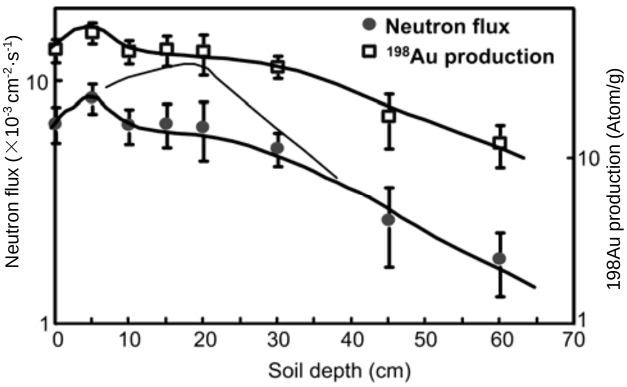

Fig.6 Variation of thermal neutron flux and ^{198}Au production with the depth of ground.

Wet earth tends to soak up fast neutrons from the air and slow them down rapidly. Many of these slow neutrons then diffuse back into the air and are subsequently absorbed by the $^{14}N(n,p)^{14}C$ reaction.[26] Also, the much amount of water content was enough to moderate the high-energy neutrons and change the energy spectrum of cosmic neutrons on the ground, causing more thermal neutrons, instead of fast neutrons to penetrate the ground. It is the dramatic increase of hydrogen in soil compositions that moderates the high-energy cosmic neutrons. These two effects make the absorption of thermal neutrons by the components of soil appearing at ground depth earlier than the normal case. Therefore the absorption of thermal neutrons by the components of soil and the moderation by the large amount of water content are correlated with each other. Below 25 cm depth, thermal neutron flux decreased rapidly again. For example, it reached about 27% of its original value at 60 cm depth. This decreasing is due to the decrease of water content with the increase of depth, subsequently, its effect as a moderator reduces with the depth. So, the absorption effect of soil compositions regains its dominance.

The present results show that thermal neutron flux at the surface of the ground is $(6.72 \pm 1.1)\times10^{-3}$ cm^{-2}·s^{-1}. This value is in a good agreement with the calculated values of 6.4×10^{-3} cm^{-2}·s^{-1} by Yamashita *et al*[12] and of 6.6×10^{3} cm^{-2}·s^{-1} by O'Brien *et al*,[11] although there is a disagreement in the equilibrium point between the present work and those results. The proposed curve with shaded area in Fig.6 is in agreement with the calculated values by Yamashita *et al.*[12] They calculated the equilibrium depth of thermal neutron flux in the ground to be about 15 to 20 cm and then the flux decreases with the depth of ground. O'Brien et al calculated the equilibrium value at about 23~30 cm depth.[11] The discrepancy of the present work with the calculated data is due to the effect of snow cover.

4 Conclusions

1. The slow neutron flux ranges from 7.8×10^{-3} to 9.0×10^{-3} $cm^{-2}\cdot s^{-1}$ at and near sea level, with an average value of 8.4×10^{-3} $cm^{-2}\cdot s^{-1}$.

2. The slow neutron flux is strongly dependent on the altitude. The increase of the flux values at low altitude near ground is quite small comparing with the values at aviation altitude.

3. The slow neutron flux at 1 km and 11 km altitude is 2 and 116 times higher than that near sea level.

4. The slow neutron flux near the surface of sea water is less than its value at 100 cm over ground near sea level. Also the results show that thermal neutron flux increases dramatically near the air/water interface after penetrating the surface.

5. The thermal neutron flux at 5 cm soil depth increases to 1.28 times its original value at the ground surface.

6. In general, the current results give our method the preference to more sensitively measure the thermal and epi-thermal neutron flux in low-level environment.

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