Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 757–760

Measurement of Cosmic Ray Neutron Spectra in the Energy Region of 20-200 MeV at the Summit of Mauna Kea and Several Different Altitudes

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Abstract: Aiming to accurately determine "soft error" rate of computer systems, we measured cosmic ray neutron spectra at the summit of Mount Mauna Kea in Hawaii and at several different altitudes e.g. Hilo city and New York city.

Introduction

Nowadays, information on the flux of cosmic ray neutrons has become important in regards to computer technology. Since the scaling down of LSIs (large scale integrated circuits) proceeds, the effect of cosmic ray neutrons on such LSIs is predicted to become significant. Neutrons hit an LSI running in a computer and generate pseudo-signals and false data [1, 2]. This phenomenon is known as "soft error" of the computer. Soft error is defined as a single event upset (data error) in a memory cell that can be correctly rewritten. The error is termed "soft" because the circuit itself is not permanently damaged and behaves normally after the data state has been restored [3].
The soft error may cause incorrect operation of the computer system, and in the worst case, the computer system will be stopped. The soft error may therefore cause a severe situation especially in regards to "mission-critical" applications. Many efforts thus have been made to reduce the soft error rate. The causes of soft error are α-particles, thermal neutrons, and high-energy neutrons. In regards to the latest semiconductor technologies, the influence of α-particles and thermal neutrons are effectively reduced by using material technology. However, the influence of high-energy neutron still remains. We therefore focus on high-energy neutrons.
For evaluating the reliability of computer systems, accurate estimation of the soft error rate has become essential. Accordingly, accurate observation of the cosmic ray neutron spectrum in the energy range up to several hundreds of MeV has been anticipated.
In this study, we report the energy spectra of neutrons in the energy range of 20 to 200 MeV at various altitudes, including the summit (Subaru Telescope; altitude: 4200 m) and foot (Hilo City; altitude: about 100 m) of Mount Mauna Kea (Hawaii) and near sea level of New York City (altitude: about 100 m). The reason for measuring spectra at Mauna Kea is the wide elevation span at this location. There are many factors that determine the neutron flux (altitude, geomagnetic rigidity etc.), but we can extract the effect of elevation by measuring at the summit (4200 m) and foot (about 100 m) of Mauna Kea. The spectrum measured at sea level in New York City is also important because it is used as a *de facto* standard for a neutron spectrum in the soft error evaluation.

Experimental

Neutron Spectrometer

The neutron spectrometer used in this study consists of two pieces of apparatus; the Bonner multi-sphere spectrometer and a scintillation counter. The Bonner multi-sphere spectrometer covers the low-energy region (≤ 20 MeV), and the scintillation counter covers the higher energy region (40 – 200 MeV).

Figure 1: Experimental apparatus for measuring cosmic ray neutron spectra: (left) Bonner multi-sphere spectrometer; (right) scintillation counter.

Figure 1 shows the spectrometer set up in the building of Subaru Telescope.
The Bonner multi-sphere spectrometer is based on a spectrometer firstly introduced by Bonner *et al*. [4]. In this study, we used four 2-inch ^{3}He proportional counters enclosed by polyethylene moderator balls with various thicknesses of 30, 50, 90 and 200 mm.
The scintillation counter uses 10-cm-thick plastic scintillator as a main detector. The 10-cm scintillator is surrounded by 1-cm-thick plastic scintillators used to generate veto signals. All scintillators are enclosed in a lead box. Scintillation light is detected by photomultiplier. Detection signals are accumulated on a multi-channel analyzer after amplification. The neutrons are detected by taking the anti-coincidence of main detector signal with veto signal.
A 2-cm-thick plastic scintillator is also used as a main detector for the range of 8 – 40 MeV.

Results and Discussion

Spectral change

Figure 2 shows the neutron spectra measured with 10-cm-thick scintillator. The energy range is 40 – 200 MeV. The vertical axis is normalized by duration of accumulation.
The shapes of the three spectra are fairly similar. This observation is consistent with that of formerly reported spectra [2]

Altitude Dependence of Neutron Flux

Figure 3 shows the neutron spectra for the range of 8 – 40 MeV range measured inside and outside of the Subaru Telescope building. Because the shapes of the spectra are quite similar, it can be said that the shielding efficiency of the building seems is nearly constant versus energy in this range. The total flux ratio i.e., inside flux/outside flux, is 0.47. Table 1 summarizes the measured neutron fluxes.
To consider the altitude effect, the following correction equation is proposed.

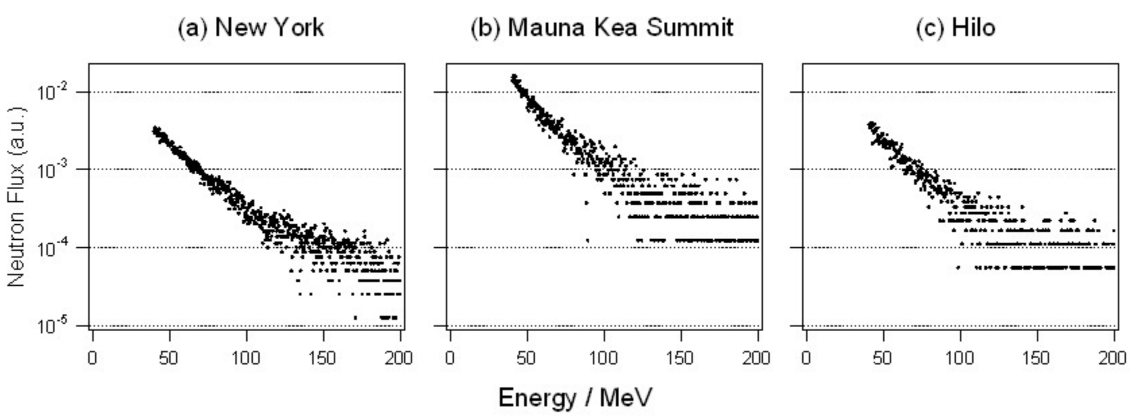

Figure 2: Neutron spectra measured in (a) New York City (altitude about 100 m), (b) Mauna Kea summit (in the building of Subaru Telescope; altitude: 4200 m) and in (c) Hilo (foot of Mauna Kea; altitude: about 100 m)

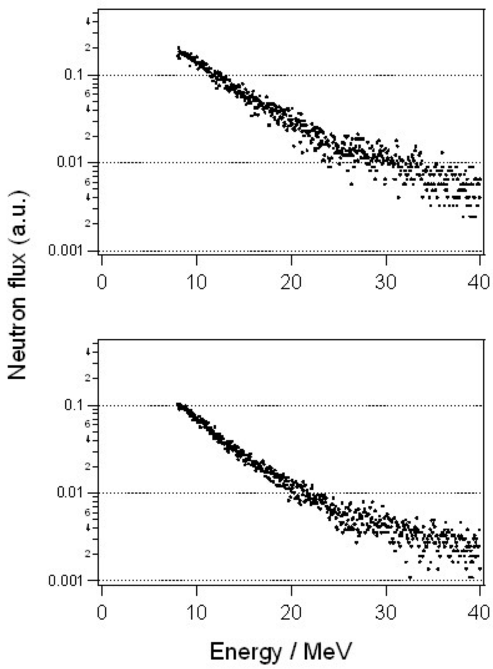

Figure 3: Neutron spectra measured by 2-cm-thick scintillator (8 – 40 MeV): (a) measured outside the Subaru Telescope building and (b) measured at inside the building

$$\gamma = \frac{\Phi_n}{\Phi_0} = \exp\left[-\frac{A - A_0}{L} \right] \qquad (1)$$

where γ is a correction factor, and Φ_n, and Φ_0 are neutron fluxes at the altitude of interest and at a reference altitude, respectively, A and A_0 are air pressures at relevant altitudes (g/cm^2), and L is a flux attenuation factor (L = 148 g/cm^2 for neutrons)

To calculate A and A_0, a NASA-Langley formulation is proposed [3]:

$$A = 1033 \exp[-0.03813 \times (a/300) - 0.00014 \times (a/300)^2 + 6.4 \times 10^{-7} \times (a/300)^3] \qquad (2)$$

where a is altitude in meters above sea level.

According to Equations (1) and (2), the flux ratio i.e., flux value at Mauna Kea summit (open air)/value at foot of Mauna Kea (open air) is calculated as 18.1. On the other hand, from the data of Table 1, this flux ratio is calculated as 8.06. The reason for discrepancy is not clear at present.

Neutron flux in New York City is higher than that at foot the of Mauna Kea. This observation is consistent with the fact that the geomagnetic rigidity in New York (5 GV) is lower than that in Hawaii (13 GV).

Time Dependent Change

Figure 4 shows the time dependence of the neutron flux measured at the Mauna Kea summit. Standard deviations of the neutron flux in the range of 40 – 200 MeV (Figure 4(b)) and about 20 MeV (Figure 4(c)) are 2.8 % and 5.6 % of the average value, respectively. The flux seems to be nearly constant both in the ranges of 40 – 200 MeV and about 20 MeV in the time span of about four months.

Location	Altitude (m)	Geomagnetic rigidity (GV)	Neutron flux (relative)
New York City (open air)	100	5	1.00
Mauna Kea summit (open air)	4200	13	6.77
Mauna Kea summit (building)	4200	13	3.18
Foot of Mauna Kea (open air)	100	13	0.84

Table 1: Measured neutron flux in the energy range of 40 – 200 MeV. The neutron flux is normalized by the New York City value.

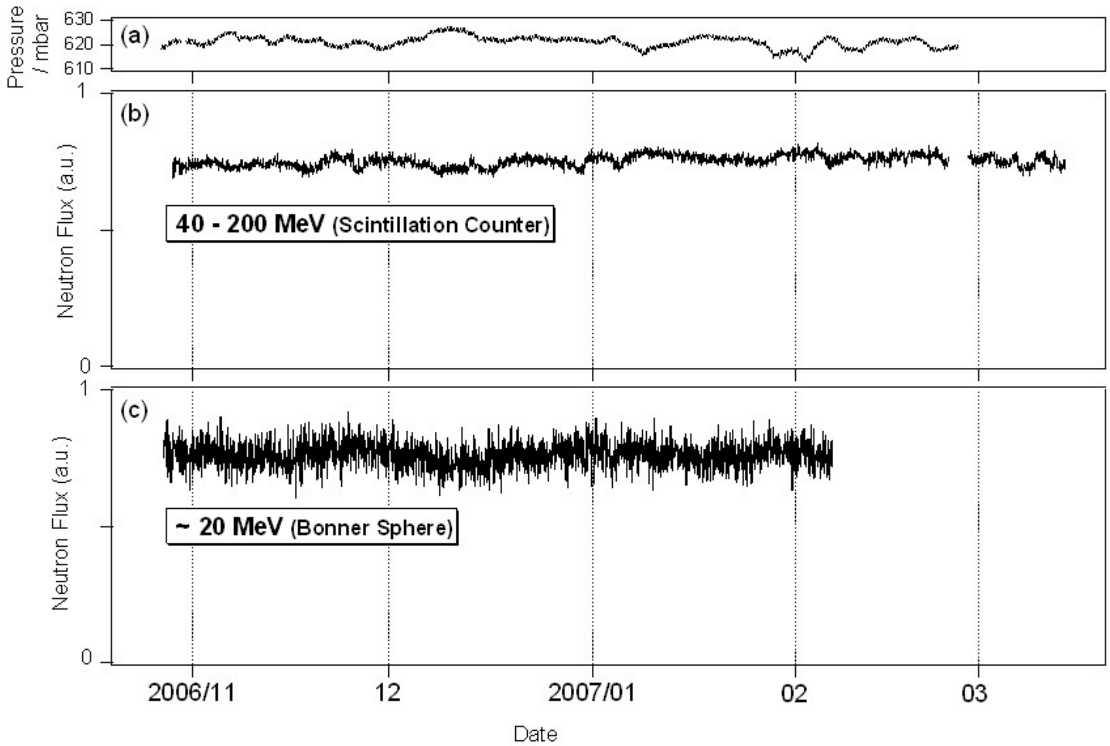

Figure 4: Time dependence of the neutron flux measured at the Mauna Kea summit: (a) atmospheric pressure in the Subaru Telescope building, (b) neutron flux in the range of 40 – 200 MeV measured by scintillation counter, and (c) neutron flux at about 20 MeV measured by the Bonner sphere detector.

Small humps and depressions can be seen simultaneously in both in the 40 – 200 MeV and ~20 MeV curves. In Figure 4(a), the atmospheric pressure measured at the Subaru Telescope is also plotted as a function of time. A weak relationship between the neutron flux and atmospheric pressure is observed: that is, high atmospheric pressure lowers the neutron flux. This indicates that the atmosphere near ground level acts as a neutron shield.

Summary

Aiming to accurately determine soft error rate in computer systems, we measured cosmic ray neutron spectra at the summit and foot of Mount Mauna Kea and near sea level of New York City. Measurement of absolute neutron spectra at various locations in Japan is now undergoing.

Acknowledgement

We thank Prof. Matsubara (Nagoya University) for his kind support. We also thank Dr. Beliolovsky for providing the measurement room in NYC.

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