Sequential monitoring of cosmic-ray neutrons and ionizing components in Japan

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Abstract. A fixed-point measurement of cosmic-ray intensity has being continued at Chiba, near Tokyo in Japan to obtain the time-sequential data. High efficiency neutron rem counter and Multi-sphere neutron Spectrometer (Bonner Sphere: BS) were used for the measurement of cosmic-ray neutron components and for the evaluation of the cosmic-ray ionizing components, NaI(Tl) scintillation spectrometer was employed. A series of measurement of the cosmic-ray intensity (neutron and ionizing components) were compared with the available experimental data obtained by the other cosmic-ray monitoring group. In this study we clarify that cosmic-ray neutrons and ionizing components measured at ground level vary according to an exponential attenuation law with the atmospheric pressure and that the variation due to the solar activity (called Forbush decrease) are observed from the monitoring data of pressure corrected cosmic-ray neutron dose rate and cosmic-ray ionizing component. It is confirmed that the magnitude of the variation of cosmic-ray neutron is rather larger than that of ionizing components.

1. Introduction
Exposure to natural source ionizing radiation is continuous and inescapable. Although the assessment of the exposure to cosmic-ray induced neutron is getting more important [1], the experimental studies on the neutron in the environment in low geographical latitude area are quite few [2]. The authors, therefore, have begun the series of investigation on the cosmic-ray neutron energy spectrum and the neutron dose rate in Japan to assess the natural neutron background at sea level in detail in low geographical latitude area. Cosmic-ray intensity at ground level is affected by environmental factors such as, altitude, geomagnetic latitude and so on, and also by solar activity. More detailed information about the variation of cosmic-ray intensity in particular neutron component in the environment, is therefore indispensable to assess the natural background dose rate in Japan with good accuracy. In this study, a fixed-point measurement of cosmic-ray intensity has being continued at Chiba, near Tokyo in Japan to obtain the time-sequential data from May 2002 to May 2003. High efficiency neutron rem counter and Multi-sphere neutron Spectrometer (Bonner Sphere: BS) were used for the measurement of cosmic ray neutron components and NaI(Tl) scintillation spectrometer was employed for the evaluation of the cosmic-ray ionizing components. A series of measurement of the cosmic-ray intensity (neutron and ionizing components) were compared with the available experimental data obtained by the other cosmic-ray monitoring group.

2. Experimental Setup and Measurement
In this study, a fixed-point measurement of cosmic-ray intensity has being continued at Chiba, near Tokyo in Japan to obtain the time-sequential data. The geomagnetic latitude in Chiba is about 26.6°. We carried out cosmic-ray measurements by using three kinds of apparatus: High efficiency neutron rem counter equipped with 12.7cm diameter spherical He-3 proportional counter [3], Multi-sphere neutron Spectrometer (BS) with 5.07-cm diameter spherical He-3 proportional counter, and 7.62-cm diameter spherical NaI(Tl) scintillation spectrometer. The list of apparatus is shown in Table I. All the our results of the cosmic-ray intensity (neutron dose rate, counting rate by NaI(Tl) spectrometer and neutron counting rate by each He-3 counter of the BS) were averaged from the accumulation of counts measured for 24 hours to decrease the counting error. Duration of the measurement is from May 2002 to May 2003 and now the sequential monitoring of the cosmic-ray has been also continued. All the measurement apparatus are placed in a well air-conditioned room in one-story concrete building with galvanized iron roofing. Before the beginning of the sequential monitoring of cosmic-ray, the
comparison of the cosmic-ray intensity between inside and outside of the building was carried out using neutron rem counter and NaI(Tl) scintillation spectrometer. As the result of this experimental, it was confirmed that there was no influence of shielding by the building materials on the measurement result of cosmic-ray intensity. In parallel with the sequential monitoring of cosmic-ray intensity, ambient temperature and atmospheric pressure were also measured. In order to clarify the relationship between the cosmic-ray intensities and the atmospheric pressure, a series of the result of atmospheric pressure was used. A series of measurement of the cosmic-ray intensity (neutron and ionizing components) were compared with the available experimental data obtained by the other cosmic-ray monitoring group. In this study, our results of the cosmic-ray measurement were compared with the cosmic-ray neutron counting rate at Fort Smith, Canada performed by BARTOL RESEARCH INSTITUTE NEUTRON MONITOR PROGRAMME [4].

**Table I. Measurement Apparatus for the sequential monitoring of cosmic-ray intensity**

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Purpose</th>
<th>Model and Manufacturer</th>
<th>Manufacturer</th>
<th>duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Efficiency Neutron rem counter</td>
<td>monitoring of neutron component of cosmic-ray</td>
<td>He-3 proportional counter</td>
<td>Fuji Electric Co. Ltd.</td>
<td>From May-13-2002 Now under measurement</td>
</tr>
<tr>
<td>Neutron rem counter</td>
<td>monitoring of ionizing component of cosmic-ray</td>
<td>Spherical (7.62 cm diameter)</td>
<td>LND, Inc.</td>
<td>From May-01-2002 Now under measurement</td>
</tr>
<tr>
<td>NaI(Tl) scintillation</td>
<td>monitoring of the shape of neutron component</td>
<td>Multi-sphere Spectrometer</td>
<td>Aloka Co. Ltd.</td>
<td>From May-04-2002 Now under measurement</td>
</tr>
<tr>
<td>Spectrometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bonner Multi-sphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1 Neutron rem counter
Neutron rem counter used for the sequential monitoring was the high efficiency neutron rem counter equipped with 12.7 cm diameter spherical He-3 proportional counter, developed by Nakamura et al. [3]. From the counting rate obtained by neutron rem counter, the ambient dose equivalent rate \((H^*\text{(10)})\) for neutrons was obtained by multiplying the counting rate to ambient dose equivalent rate \((H^*(10))\) coefficient. Counting rate to ambient dose equivalent rate \((H^*(10))\) coefficient was estimated by performing the calibration by Cf-252 source at the Facility of Radiation Standard of the Japan Atomic Energy Research Institute. It was estimated to be about 15.2 \((\text{cps}/(\mu\text{Sv}\cdot\text{h}^{-1}))\).

2.2 NaI(Tl) scintillation spectrometer
The purpose of the measurement of ionizing components is to compare the magnitude of the variation of ionizing components with that of neutron component. As well known, ionizing components of the cosmic-ray consists of various kind of the secondary cosmic-ray, muons, pions, electrons and gamma-rays. Many reliable investigations on the assessment of public dose due to ionizing components are reported [1,5,6]. As shown in Fig.1, the counting rate \((\text{cpm})\) of the above 3 MeV region measured by NaI(Tl) spectrometer agreed with the air equivalent absorbed dose rate \((\text{nGy}\cdot\text{h}^{-1})\) originated to cosmic-ray obtained by pressurized ionization chamber. This result shows that the counting rate \((\text{cpm})\) of the above 3 MeV region measured by NaI(Tl) spectrometer can be used to evaluate the cosmic-ray ionizing components. In addition, it is more reliable than ionization chamber due to its higher counting rate. In this study, NaI(Tl) scintillation spectrometer was employed for the evaluation of the cosmic-ray
ionizing components.

![Graph showing correlation between counting rate and absorbed dose rate](image)

**Fig.1** Correlation between counting rate (above 3MeV) by NaI spectrometer and absorbed dose rate of ionizing component

### 2.3 Neutron spectrometer

The spectrum of the cosmic-ray induced neutrons was determined by using Multi-sphere neutron Spectrometer (Bonner sphere: BS). The BS consists of five 5.07-cm diameter spherical He-3 proportional counters filled with 5 atom He-3 gas, surrounded by spherical polyethylene moderators, with different size together with no moderator (bare He-3 counter). The diameters of the polyethylene moderators are 8.0cm, 11cm, 15cm, and 23cm, respectively. As the response of the BS to neutron with energy from thermal region to 400MeV, the set of response functions determined by Uwamino et al. [7] was used except for the response function of bare He-3 counter. The response function of bare He-3 counter determined by Nunomiya [8] was used in this study. Calibration and tests of the measurement of the BS were performed using monoenergetic neutrons from 250keV to 15MeV in the Dynamitron facility at the Tohoku University [9] and irradiation of thermal neutrons and neutrons from Cf-252 source were performed at the Facility of Radiation Standard of the Japan Atomic Energy Research Institute. Throughout the series of calibration the mean errors between the measured and calculated response were within the range of 20%. From the measured data sets of count rates, the cosmic ray neutron energy spectra were obtained by performing unfolding process using the SAND2 code. The analytical conditions are shown in Table II.

**Table II.** Analytical conditions for estimating neutron fluence rate and neutron dose rate (H*(10)) using SAND2 code

<table>
<thead>
<tr>
<th>Energy region</th>
<th>0.01eV - 400MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Bin</td>
<td>34</td>
</tr>
<tr>
<td>Response function</td>
<td>calculated by Uwamino et al. [7] (except bare) calculated by Nunomiya [8] (bare)</td>
</tr>
<tr>
<td>Initial Guess</td>
<td>Neutron spectrum at ground level obtained by Goldhagen et al. [10]</td>
</tr>
<tr>
<td>Spectrum</td>
<td>Based on ICRP 74 and Sannikov and Savitskaya [11] (more than 200MeV)</td>
</tr>
</tbody>
</table>
After obtaining neutron spectra, the ambient dose equivalent rate $H^*(10)$ were estimated based on ICRP Publication74. In the case of the estimation of ambient dose equivalent rate $H^*(10)$, we used neutron fluence to ambient dose equivalent conversion factor calculated by Sannikov and Savitskaya [11] in the energy range of 200MeV to 400MeV.

3. Results and Discussion

3.1 Relationship between cosmic-ray intensities and atmospheric pressure

Figure 2 shows the relationship between the neutron dose rate and the atmospheric pressure in the monitoring period. The main component of the cosmic-ray measured at ground level is secondary cosmic-ray, and is attenuated by the air above the ground which acts as a shield. In Fig. 2, it is confirmed that the cosmic-ray neutrons and the ionizing components measured at ground level vary according to an exponential attenuation law with the atmospheric pressure in the form of $\sim \exp(-A \cdot P)$.

$$y = 2700e^{-0.0064P}$$

As shown in Table III, the attenuation factor $A$ of ionizing components is lower than that of neutron component. In addition, the attenuation factors of each He-3 counter of BS are slightly different from each other. Using this A-value, normalization to 1 atom (1013.25hPa) of the each component of the cosmic-ray was performed according to the following equation.

$$N' = N \exp[-A(1013.25 - P)]$$

where $N'$ is the pressure corrected value, $N$ is the measured value by each apparatus, $A$ is the attenuation factor, and $P$ is the atmospheric pressure in hPa.
factor in hPa⁻¹, and P is the measured atmospheric pressure. As the case of the normalization of the result of BS, at first the normalization of results of the counting rate of each He-3 counter was performed and then the cosmic-ray neutron energy spectra were obtained by unfolding using the SAND2 code from the pressure normalized data sets of count rates. Figure 3 shows the results of the sequential monitoring of neutron dose rate of the cosmic-ray in the period.

Figure depicted above shows the decrease of the fluctuation of the measured cosmic-ray intensities by performing the pressure normalization. In the rest of the series of sequential monitoring data by other apparatus the same tendency is also confirmed. Using these pressure corrected results of the cosmic-ray intensities, a series of measurement of the cosmic-ray intensities were compared with the available experimental data obtained by the other cosmic-ray monitoring group.

3.2 Variation of the neutron energy spectra
Figure 4 shows the comparison of the neutron energy spectra of day of higher cosmic-ray intensity (July 10th 2002) and that of lower cosmic-ray intensity (August 4th 2002). Neutron energy spectra are represented by the relative neutron fluence rate per lethargy spectra normalized using the highest neutron fluence rate around 3MeV. As the result of the comparison of the neutron energy spectra between the day, which indicates high cosmic-ray intensity and the day show lower intensity, the neutron energy spectrum at higher intensity day shifts to lower neutron energy region. In particular, the ratio of the spallation peak (around 100MeV) at lower intensity day decreases and the ratio of components of lower energy region (10keV to 1MeV) increases. On the other hand, the ratio of near thermal neutron region is almost the same between the two spectra.
3.3 Influence of solar activity on cosmic-ray intensity

Figure 5 shows the comparison of the series of measurement of the cosmic-ray intensities (neutron dose rate, counting rate by NaI(Tl) due to ionizing component and ambient neutron dose equivalent obtained by BS) and the hourly neutron counting rate at Fort Smith, Canada obtained by BARTOL RESEARCH INSTITUTE NEUTRON MONITOR PROGRAMME [4]. From the monitoring data of pressure corrected cosmic-ray neutron dose rate and cosmic-ray ionizing component, the variation due to the solar activity (called Forbush decrease) was observed. Comparing the series of measurement of the cosmic-ray intensities with the neutron counting rates measured by the other experimental group at high geomagnetic latitude (Fort Smith, Canada), the annual variations reflecting the solar activity are found to be almost identical. Comparing the results of the neutron dose rate and counting rate above 3MeV region by NaI(Tl) spectrometer, the sequential data of the neutron dose rate by BS has a large discrepancy in some period of the monitoring duration. Due to the result of the unfolding process, errors of the neutron dose rate by BS could be larger than the rest. In order to evaluate the variation of the neutron component of the cosmic-ray more reliably, measurement using BS with more sensitive counter or much longer measurement might be required. And from the Fig.5, it is confirmed that the magnitude of the variation of the neutron dose rate by neutron rem counter is larger than that of the counting rate by NaI(Tl) spectrometer. In Table IV, the annual variation of each component of cosmic-ray intensity obtained by the sequential monitoring was evaluated.
Fig. 5 Comparison of variation of the cosmic-ray intensities obtained by other cosmic-ray monitoring group

Table IV. Comparison of an annual variation of each component of cosmic-ray intensity

<table>
<thead>
<tr>
<th>Component</th>
<th>Neutron (%)</th>
<th>Ionizing components (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>4.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Solar Activity</td>
<td>2.7</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Duration used for the evaluation of the variations of cosmic-ray intensities is from May 1st 2002 to April 30th 2003. All components of the magnitudes of the variation were evaluated by the calculated standard deviation of the measured values and were represented in the form of the relative standard deviation (1σ). Estimating the standard deviation of the annual variation of the atmospheric pressure, the variations due to atmospheric pressure of each cosmic-ray component were evaluated using attenuation factor A. The annual variation due to solar activity was evaluated using the set of the pressure corrected results. As shown in Table IV, the magnitudes of the variations of the neutron component due to atmospheric pressure and to solar activity were both larger than those of ionizing components. In contrast with the case of neutrons, ionizing components, mainly muons, penetrate deep into the air and are less influenced on nuclides consisting the air [1]. In case of the neutron component, therefore, the variation of the primary cosmic-ray resulting from the solar activity was considered to be much emphasized than that of the ionizing component. In this study, the duration used for the evaluation of the variation of the cosmic ray intensity due to solar activity is 1 year. Since the cycle of the modulation by solar activity is about 11 years, continuous measurement of the cosmic-ray intensity and the evaluation using the results for 11 years are also essential to evaluate the variation due to the solar activity more reliably.
4. Conclusions
A fixed-point measurement of cosmic-ray intensity has been continued at Chiba (geomagnetic latitude of 26.6° degrees), near Tokyo in Japan to obtain the time-sequential data from May 2002 to May 2003. The series of data (neutron and ionizing components) were compared with the available experimental data obtained by the other cosmic-ray monitoring group. The following results were clarified:

1) Cosmic-ray neutrons and ionizing components measured at ground level vary according to an exponential attenuation law with the atmospheric pressure.
2) From the monitoring data of pressure corrected cosmic-ray neutron dose rate and cosmic-ray ionizing component, the variation due to the solar activity (called Forbush decrease) are observed.
3) Comparing the neutron dose rate obtained by a high efficiency neutron rem counter with the neutron counting rates measured by the other experimental group at high geomagnetic latitude, the annual variations reflecting the solar activity are almost identical.
4) As the result of the comparison of the neutron energy spectra between the day which indicates high cosmic-ray intensity and the day show lower intensity, the neutron energy spectrum at higher intensity day shifts to lower neutron energy region. The ratio of the spallation peak (near 100MeV) at lower intensity day especially decreases and the ratio of components of lower energy region (10keV to 1MeV) increases.
5) The annual variations due to the solar activity in the cosmic ray neutron dose rate and cosmic ray ionizing components are almost the same. The magnitude of the variation of cosmic ray neutron is rather larger than that of cosmic ray ionizing components.

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References
4. BARTOL NEUTRON MONITORS (http://www.bartol.udel.edu/~neutronm/)