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LONG-TERM MEASUREMENTS OF COSMIC RAY NEUTRONS BY MEANS OF A BONNER SPECTROMETER AT MOUNTAIN ALTITUDES – FIRST RESULTS

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A Bonner multi-sphere spectrometer has been installed in 2005 at the Environmental Research Station 'Schneefernerhaus' (2660 m above sea level) on the Zugspitze mountain, Germany, to measure the energy spectrum of cosmic-ray neutrons at high altitudes continuously. The system can be used to investigate small temporal variations in the cosmic radiation intensity. For example, measurements were done during periods of 2 Forbush decreases of the cosmic radiation intensity in July and September 2005, respectively. The results were compared with those obtained by using neutron monitors, and neutron fluence spectra measured during these events are presented and discussed.

INTRODUCTION

The Earth is continuously exposed to particles from the intergalactic space (galactic cosmic radiation (GCR)) and from the sun (solar wind). These particles consist predominantly of protons (about 85%) and helium nuclei (about 13%). Because of their electric charge, particles of the GCR are partially shielded by the solar magnetic field, and both the galactic and the solar components are shielded by the geomagnetic field. Interaction of these primary particles with the atoms in the atmosphere finally results in a complex field of secondary cosmic radiation, which includes neutrons, protons, pions, photons, electrons and muons.

Due to the field of cosmic radiation, an effective dose rate of about 0.3 mSv per year is observed (corresponding to about 35 nSv h^{-1}), at sea level and mean geomagnetic latitudes (about 50°N). At typical flight altitudes (10–12 km), the effective dose increases drastically and pilots and cabin crews as well as airline passengers are exposed to a dose rate of about 5 μSv h^{-1}, which is more than a factor 100 higher than that at sea level. Close to the geomagnetic poles the dose rate is even higher, due to low shielding by the geomagnetic field.

In order to monitor the intensity of cosmic radiation on the ground, more than 50 neutron monitors are being used worldwide. These monitors include a combination of heavy and light materials (such as lead and polyethylene) to moderate the incident protons and neutrons, and a detector in the centre to measure the resulting thermal neutrons. Thus, the count rates of these monitors provide accurate information on the relative intensity of the cosmic radiation at their individual locations and as a function of time. However, they do not provide any information on absolute neutron and proton fluxes, nor do they allow us to deduce the energy distribution of the protons and neutrons.

It is interesting to note that the intensity of the cosmic radiation on the Earth is anti-correlated to the sun's activity, and shows a typical variation within an 11-year cycle. Short-term increases of the solar wind and the associated solar magnetic field such as those during a Forbush effect also decrease the intensity of GCR at the top of the atmosphere. These Forbush decreases last for several days and may occur even several times per year. During these decreases the dose is often reduced by more than 20%.

Some years ago, first *short-term* measurements had been performed by the GSF group for several weeks using a Bonner multi-sphere spectrometer (BSS), on the summit of the Zugspitze mountain (2963 m, cut-off 4.4 GV, Germany)(1), and the Chacaltaya mountain (5240 m, cut-off 12.53 GV, Bolivia). These investigations have recently been extended and a BSS was installed on Zugspitze mountain, to perform *continuous* measurements of the neutron spectrum on a routine basis, for at least three years. The spectrometer is operated by remote control from the GSF institute, and the produced data are transferred to the GSF-Institute of Radiation Protection via modem/internet. In this paper, the experimental setup on the Zugspitze mountain is described, and first results obtained with the BSS are discussed.

MATERIALS AND METHODS

Location

All measurements were performed on the Environmental Research Station (UFS) 'Schneefernerhaus'

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(2660 m above sea level) located on the Zugspitze mountain, Germany (latitude: 47°25′N, longitude: 10°59′E). The effective vertical cut-off rigidity corresponds to 4.4 GV. In 2005, the system was first installed inside a laboratory on the fourth floor of the building. The flat roof above the laboratory is made of different materials including wood, iron, heat insulating material and asphalt covering. As a major disadvantage, snow on the roof influenced the shape of the measured neutron spectrum, during eight months of the year. For this reason, a measurement shed was constructed on a terrace of the UFS, specifically dedicated to house the spectrometer.

The major feature of the measurement shed is a roof with a tilt of 64°, covered by aluminium plates to ensure that any snow will not remain on the roof but slide down to the ground. Inside the shed (7.0×3.0 m; height: 3.15 m), continuous heating during winter also prevents the snow to remain on the roof. The infrastructure also includes internet access, power supplies ensuring continuous measurements using spectrometer, and remote control of all major parameters from the GSF institute.

Spectrometer

The system consists of 15 spheres with ^{3}He proportional counters in their centre, covered by polyethylene shells of various thicknesses (2.5–15 inches). Depending on thickness, incident neutrons are moderated and the resulting thermal neutrons are detected through the ^{3}He(n, p)^{3}H reaction. As a specific feature, the spectrometer includes two polyethylene spheres (9 inch in diameter) with lead shells, to increase their response to high-energy neutrons above 10 MeV. Finally, a 16th detector is used without surrounding polyethylene, which is sensitive to thermal neutrons. The response functions of this Bonner sphere spectrometer were calculated by means of the MCNP[2] and LAHET[3] code. Details are given elsewhere [4–8]. It is important to note that the system allows continuous measurements using all 16 detectors at the same time. Thus, in principle, variations of the neutron spectrum can be quantified on a time scale and within a statistical precision that is predominantly determined by the count rate of the detectors.

Typically, the count rates obtained vary between 0.02 and 0.15 cts s^{-1}, respectively, depending on the spheres and time. The count rates are stored every hour and thus hourly neutron spectra can be deduced. To increase the statistical significance, however, data from several hours may be combined and, using the response functions mentioned above, the neutron spectrum is deduced by means of modified version of the SAND unfolding code[9].

Meteorological data

Data on meteorological parameters measured at the UFS are provided by the German Weather Service (DWD). These parameters include air temperature, air pressure, wind velocity and direction, relative humidity, precipitation rates, etc. Data on air pressure are used to correct the count rates measured with the spectrometer, by using equation:

$$N_{\mathrm{cor}} = N \exp[-\beta(P_0 - P)]$$

where N is the observed counting rate at a particular pressure P and N_{cor} is a value it should have had at the standard pressure P_0. The quantity β is a barometric coefficient determined for each neutron monitor from regression curve of the logarithm of hourly counting rates against pressure. The value of 0.712% per mbar of neutron monitor of the University of Kiel[10] was used in this study. As a standard pressure value, 740 mbar was used.

RESULTS AND DISCUSSION

Measured count rates

September 2005

Figure 1 shows, as an example, relative deviations of hourly averaged count rates (sum from all detectors) obtained in September 2005. The data shown are normalised to the first hourly averaged count rate, for the time period investigated. To reduce the statistical uncertainty, the count rates obtained from the various detectors were added, and compared to data from the neutron monitor on the Lomnicky stit mountain (latitude: N 49°20′, longitude: E 20°22′), Slovakia[11]. This neutron monitor was chosen for comparison because the geographic characteristics of its location (cut-off 3.84 GV, altitude 2634 m) are similar to those of UFS.

It is evident from Figure 1 that, except for a short period between 17 and 20th of September, good agreement was obtained between the relative deviations measured during this month, and those from the Lomnicky stit station. In particular, a significant decrease was observed within a few hours in the morning of 11 September, which is attributed to a Forbush decrease, and which was also observed by other neutron monitors. Figure 1 demonstrates that, although our spheres are much smaller than any neutron monitor, the statistics of the combined count rates measured on an hourly basis is sufficient to quantify changes of the cosmic ray intensity of the order of about 5% and more.

July 2005

A similar decrease of the cosmic ray intensity was observed in July 2005, with an additional short-term

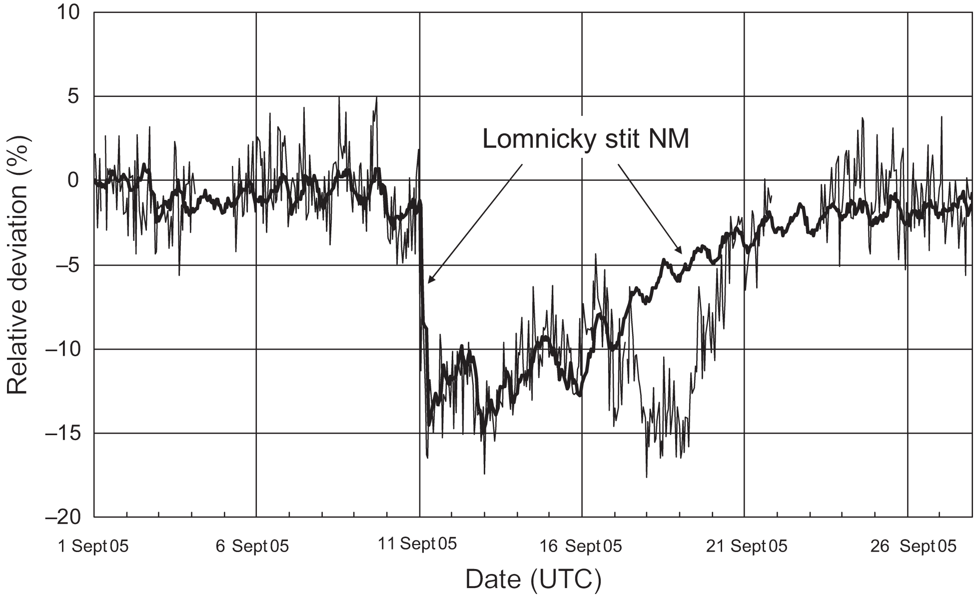

Figure 1. Relative deviations of added count rates from all detectors (hourly averaged) for time period of September 2005 are shown together with neutron monitor data of Lomnicky stit in Slovakia for comparison. The relative deviations are related to the first value of the shown time interval.

increase during the period of lowest intensity. Figure 2 compares the count rates obtained with our detectors, and those obtained by means of the neutron monitors on Lomnicky stit and Jungfraujoch (cut-off 4.49 GV, altitude 3570 m) in Switzerland, respectively. Clearly, a decrease is observed in all cases, on 16 July, followed by a short intermediate peak which started to rise early in the

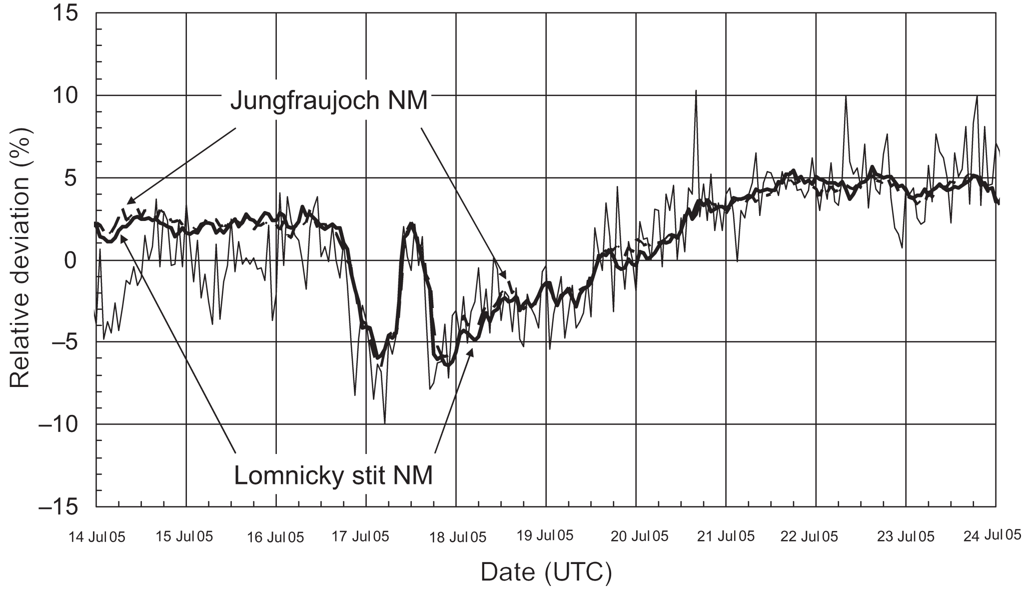

Figure 2. Relative deviations of added count rates are shown for time between 14 and 24 July 2005. For comparison, data obtained by means of neutron monitor on Lomnicky stit (think solid line) in Slovakia and Jungfraujoch (dashed line) in Switzerland, respectively, are also shown. The relative deviations are related to the value of small peak on July 17.

morning of 17 July, with a maximum between 10 and 15 o'clock.

Figure 2 demonstrates that short-term variations such as the small peak that occurred during the Forbush minimum can indeed be observed with our system. This peak has also been observed by other neutron monitors and was investigated in detail by various groups. For example, Papaioannou *et al.*[12] concluded that "The peculiarity of this event owes to the fact that it does not comprise a ground level enhancement of solar cosmic rays neither a geomagnetic effect in cosmic rays. This event appears to be caused by some special structure of interplanetary disturbances in the inner heliosphere at that time period when the Earth crossed a periphery of a giant Forbush effect started in the western part of the heliosphere after the flare on 14 July".

First measured neutron spectra

By means of the SAND program, which was specially modified to unfold neutron spectra from Bonner sphere measurements, the total neutron fluence rate, Φ, was derived. Using the fluence-to-ambient dose equivalent conversion coefficients for neutrons[13,14], the ambient dose equivalent, $H^*(10)$ was also calculated. Figure 3 shows the neutron fluence and ambient dose equivalent derived from neutron spectra measured in September 2005 and averaged over 6 h. It is evident that during the Forbush decrease in September 2005 the dose was reduced by about 13%. The shape of the dose curve is very close to the shape of the neutron fluence, except for a period between the 17 and 20th of September. This was possibly caused by accumulated water concentration in the local environment due to heavy rainfall on September 17. Preliminary calculation by means of various Monte Carlo transport codes indicate that, for example, an increase in hydrogen concentration above the BSS on the roof of the laboratory would change the neutron spectra by moderating fast neutrons and absorbing thermal neutrons. These processes are currently being under investigation, for the site of the BSS.

Figure 4 shows neutron spectra deduced from our Bonner sphere measurements, for the Forbush decrease on 10–11 September 2005. The figure presents the data in the lethargy representation – equal areas below the curve correspond to equal number of neutrons per cm^2, in the corresponding energy intervals. The major components of the spectrum are clearly visible: (a) a first peak that is due to thermal neutrons with energies between 20 and 40 meV, (b) a second peak at about 2 MeV that originates from neutrons evaporating from highly excited residual nuclei, and (c) a third peak at 100 MeV that is due to a broad minimum in the corresponding neutron–air reaction cross-sections at energies of about 100–300 MeV[15]. The neutron spectra in Figure 4 are from 3 o'clock on 10 September to 21 o'clock on 11 September 2005. They were derived from 6 h averaged count rates, to increase the accuracy. Except for a slight height variation of about $\pm 25\%$ of the 100 MeV peak, the shape of the neutron spectra appears to remain almost unchanged, in the whole energy range from thermal energy to several of GeV. This may suggest that any changes during a Forbush decrease might alter all secondary neutrons from cosmic radiation in a similar way, independent of their energy.

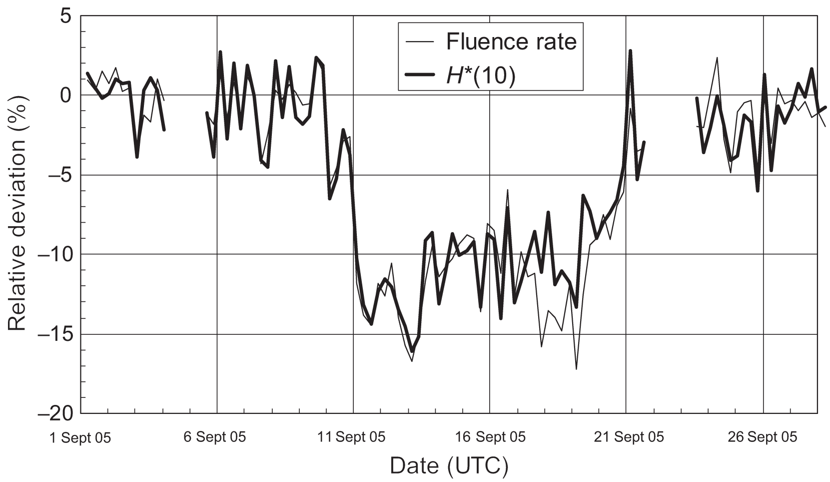

Figure 3. Relative deviations of neutron fluence rate and ambient dose equivalent, $H^*(10)$, derived from 6 h averaged neutron spectra measured in September 2005.

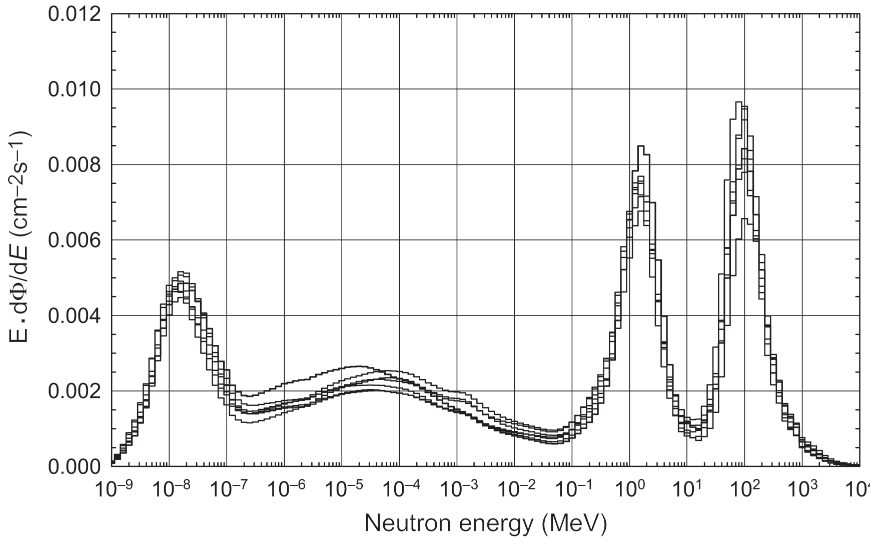

Figure 4. Neutron spectra measured during Forbush decrease on 10–11 September 2005 on Zugspitze mountain 2660 m above sea level.

CONCLUSIONS

A BSS has been installed in 2005 at the Environmental Research Station 'Schneefernerhaus' (2660 m above sea level) on the Zugspitze mountain, Germany, to measure the energy spectrum of cosmic ray neutrons at high altitudes continuously. The spectrometer worked reliably and allowed the quantification of any variations in the secondary neutron component of the cosmic radiation larger than 5%. In addition, detailed information on the energy dependence of the time-dependent neutron spectra was obtained as a function of time. First results indicated that any changes during a Forbush decrease might alter all secondary neutrons from cosmic radiation in a similar way, independent of their energy. In future, time series of neutron spectra would be analysed in terms of parameters that might change the shape of the neutron spectra. These parameters at the BSS site might include, for example, liquid water and water vapour in the atmosphere, water concentration in the local environment, materials of surrounding structures such as concrete, rocks, etc., or any change in the primary cosmic radiation spectra.

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