Continuous Measurement of Secondary Neutrons from Cosmic Radiation at Low Atmospheric and Geomagnetic Shielding by Means of Bonner Sphere Spectrometers

W. Rühm, V. Mares, C. Pioch, E. Weitzenegger, and H.G. Paretzke

Abstract The hadronic component of the secondary cosmic radiation is being measured continuously by the global network of neutron monitors at different geographical locations and altitudes. However, the neutron monitors themselves do not provide any information on the energy distribution of detected particles (mainly neutrons). For some applications like the estimation of doses obtained from secondary neutrons of cosmic radiation, knowledge of the spectral particle fluence rate is essential. To determine the energy distribution of secondary neutrons from cosmic radiation continuously, the Institute of Radiation Protection of the Helmholtz Zentrum München is operating two Bonner sphere spectrometers. These spectrometers are described in detail in the following paper and typical neutron spectra during normal solar activity are discussed. Furthermore, both Bonner spectrometer measurements are compared to neutron monitor data, to show consistency of the different measurements.

1. Introduction

PARTICLES from primary cosmic radiation (mainly protons from the galactic and solar component) that hit the atmosphere of the Earth give rise to a complex field of secondary particles. These particles include – among others – neutrons, protons, electrons, pions, muons, and photons. As a result, pilots, cabin crew members, and passengers on board aircrafts are exposed to ionizing radiation depending on altitude, latitude, longitude and time. At mean latitudes (about 50 ºN), effective dose rates at typical flight altitudes of 10 km are in the order of 5 µSv/h, while it is more than a factor of 100 lower at sea level. Based on recommendations published by the International Commission on Radiological Protection in 1990 [1] that were confirmed recently [2], pilots and cabin crew members should be monitored if their annual effective dose is likely to exceed 1 mSv.

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In fact, in 2005 more than 31,000 air crew members were monitored in Germany, and a mean annual dose due to cosmic radiation of 2.0 mSv was obtained, which is similar that of workers in nuclear industry or radiography [3].

In order to quantify the doses from secondary cosmic radiation for any flight route, the European Program Package for the Calculation of Aviation Route Doses (EPCARD) was developed [4-6]. The code is based on energy spectra for various particles of the secondary cosmic radiation field that were calculated at any location in the atmosphere by means of the FLUKA Monte Carlo code using energy spectra of protons from the primary cosmic radiation as input [6]. These particle fluence spectra were converted into dose quantities related to human health risks such as effective dose using appropriate dose-conversion coefficients, and finally an overall numerical procedure was included that provides doses to pilots and cabin crews on board of aircrafts for any flight route. To give an example, based on the online version of EPCARD that is available on the homepage of the Helmholtz Zentrum München (http://www.helmholtz-muenchen.de/epcard), the effective doses for the flights Munich – Vienna – Kosice on 8th September 2008 and for Kosice – Prague – Munich on 12th September 2008 that were used by two of the authors (W.R. and C.P.) to attend the 21st European Cosmic Ray Symposium were 4 µSv and 5 µSv, respectively. These doses compare to an annual effective dose from cosmic radiation at sea level and mean latitudes of 0.3 mSv, and to a total annual effective dose for the population in Germany of about 4 mSv that includes natural contributions from cosmic, terrestrial, and internal radiation, and exposure to radon, as well as anthropogenic contributions which are dominated by exposures due to medical diagnostics.

Presently, considerable efforts are being made to validate these calculations through measurements of particles from secondary cosmic radiation. Particular attention is being paid on secondary neutrons, as these provide the major contribution to the effective dose, at flight altitudes. For this reason, we have installed two Bonner Spheres Spectrometers (BSS) that allow quantitative measurement of secondary neutrons from secondary cosmic radiation, both in terms of absolute particle fluxes and in terms of their energy spectra. These systems are described in detail below, and first results are given.

2. Materials and Methods

A. Measurement location

The measurement locations were chosen in a way that either the shielding by the atmosphere or by the geomagnetic field is as low as possible. Therefore, one BSS system was installed at mountain altitudes, while another one was installed close to the North Pole.

The first BSS system was installed in 2005 at the environmental research station "Schneefernerhaus" (UFS). It is located close to the summit of the Zugspitze mountain, the highest mountain in Germany, at an altitude of 2,650 m (see Fig. 1, left). Its coordinates are E10º58.9' and N47º25', which corresponds to 4.4 GV vertical geomagnetic cut-off rigitidy [7]. The BSS system is located on a terrace of the station and housed inside a small measurement shed (7.0 x 3.0 m; height: 3.15 m). The roof of this shed has a slope of 64º and is covered by aluminum plates, to minimize the amount of snow that might remain on the roof during periods of snow fall (see Fig. 1, right).

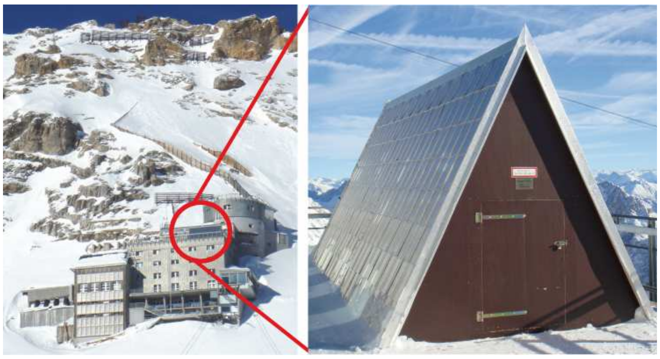

Fig. 1: UFS Schneefernerhaus close to the summit of the Zugspitze mountain (left) and measurement shed on a terrace of the UFS (right)

The second BSS system was installed in 2007 at the French-German Arctic Research Base AWIPEV (inside the Koldewey station of the Alfred Wegener Institute (AWI)) in Ny-Ålesund, Spitsbergen, at sea level. In this case the coordinates are N78º55'24'' and E11º55'15'' (town center), corresponding to a cut-off of about 0.3 GV (including atmospheric cut-off). The spectrometer is operated inside a one-floor extension of the station (3.40 m x 5.65 m; see Fig. 2, left). The infrastructure available at both stations allows remote control of all major parameters of the spectrometers, and continuous data transfer to our home institute [8].

Fig. 2: One-floor extension of the Koldewey station of the AWI (left) in Ny-Ålesund, Spitsbergen, and Bonner sphere spectrometer inside the extension (right).

B. Specification of the BSS systems

Both BSS systems consist of 15 polyethylene (PE) spheres with spherical ^3He proportional counters in their center (see Fig. 2, right). Depending on the thickness of the PE, incident neutrons from secondary cosmic radiation are moderated and the resulting thermal neutrons are detected by the proportional counters through the $^3He(n,p)^3H$ reaction. As a specific feature, both spectrometers include two polyethylene spheres (9 inch in diameter) with lead shells (thickness: 0.5 and 1 cm), to increase the response to high-energy neutrons above 10 MeV. Finally, a 16th proportional counter without any moderating polyethylene is used which is mainly sensitive to thermal neutrons. The detailed response as a function of neutron energy of each moderator/detector configuration was calculated by means of the MCNP code. Details are given elsewhere [9, 10]. Note that both systems allow continuous measurements using all 16 detectors at the same time. Thus, any variations in the energy spectrum of neutrons from secondary cosmic radiation can be quantified on a time scale and within a statistical precision that is determined primarily by the count rate of the detectors.

The detector signals are amplified by pre-amplifiers and amplifiers in multiports which also digitize the signals, and finally analyzed by a multichannel analyzer (MCA) in the computer (Canberra GmbH, Rüsselsheim, Germany). The pulse height spectrum provided by each detector is stored, and the count rate is obtained by integrating over a region of interest that was defined for each detector before installation using an Am/Be neutron source.

The count rates are stored every hour at the UFS, and every 5 minutes at the Koldewey station. To increase the statistical significance of the results, data from 6 hours are usually combined during normal solar activity.

C. Unfolding of the neutron spectra

The count rates obtained by the 16 proportional counters are used, together with the calculated response functions of the various moderator/detector configurations, to unfold the energy spectrum of the neutrons by means of the MSANDB unfolding code [11], which is a modified version of the earlier SAND code [12]. The unfolding procedure requires a-priory knowledge on the rough shape of the neutron spectrum to be measured, which is governed by the physics of the secondary neutron field produced in the atmosphere: very roughly, the differential energy spectrum includes a Maxwell-Boltzmann peak of thermalized neutrons with energies of about 25 meV, an epithermal part which decreases with increasing neutron energy similar to 1/E, an evaporation peak at 1-2 MeV, and a cascade peak at about 100 MeV. A detailed study by Simmer et al. showed that the choice of the start spectrum is not critical, as far as the unfolded neutron spectrum is concerned, if the start spectrum includes these four regions [13].

D. Correction for air pressure

Meteorological data measured at the UFS are provided by the German Weather Service (DWD), while those measured at the Koldewey station are provided by the AWI. Most importantly, the air pressure is measured at both stations continuously. This allows correction of the count rates measured by the BSS systems to the air mass overburden, according to (1) [14].

$$N_{cor} = N \cdot e^{[-\beta(p_0 - p)]} \quad (1)$$

where N is the observed count rate at a particular pressure p and N_{cor} is the corrected value at a reference pressure p_0. For the barometric coefficient β, a value of 0.712% per mbar was used [15].

3. RESULTS AND DISCUSSION

A. UFS "Schneefernerhaus", Zugspitze, Germany

Typically, the count rates obtained vary between 1.2 and 9.6 cts/min at the UFS, and between 0.18 and 1.32 cts/min at the Koldewey station, respectively, depending on the moderator/detector configuration. In the "neutron monitor mode", the count rates of all 16 detectors are simply added to provide a total count rate of the spectrometer, and corrected for the air mass overburden using equation (1). In this way, information on the relative intensity of secondary neutrons from cosmic radiation as a function of time can be obtained. As an example, Fig. 3 shows the relative count rates obtained by the BSS system on the UFS in July 2005 (normalized to a mean air pressure of 740 mbar), compared to those measured by the Neutron Monitor (NM) at Lomnicky Stit [16].
Obviously, a Forbush decrease was observed by the BSS system at the UFS on July 16th, followed by a short intermediate peak which started to rise on July 17th, at about 5 o'clock in the morning, with a maximum between 12 o'clock and 15 o'clock, and a final phase of recovery that lasted several days. This pattern was observed by various neutron monitors including that at Lomnicky Stit (Fig. 3) [16].

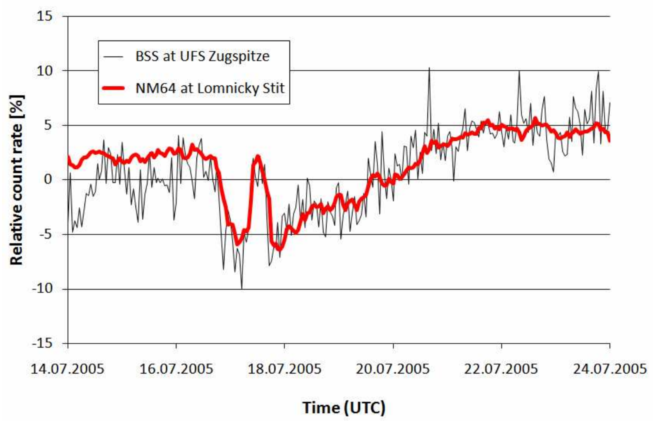

Fig. 3: Total relative hourly count rates obtained by the BSS system on the UFS in July 2005 (thin line) [7] compared to those measured by the NM at Lomicky Stit (thick line) [16].

Figure 4 shows typical unfolded neutron spectra deduced from the BSS measurements ("neutron spectrometer mode") at the UFS on Zugspitze mountain, one for a dry period in summer (16th August 2007), and another for a period with heavy snow fall and about 1.5 m snow cover on the terrace (7th September 2007). The figure presents the data in the lethargy representation – equal areas below the curve correspond to equal numbers of neutrons per cm^2, in the corresponding energy intervals. The major components of the spectrum already mentioned above are clearly visible: a) a first peak that is due to thermal neutrons with energies between 20 and 40 meV b) a plateau in the epithermal region that reflects the 1/E behavior of the spectrum in this representation c) a second peak at about 2 MeV originating from neutrons evaporating from highly excited residual nuclei, and d) a third peak at 100-200 MeV that is due to a broad minimum in the neutron-air reaction cross-sections at energies above 100 MeV [17].

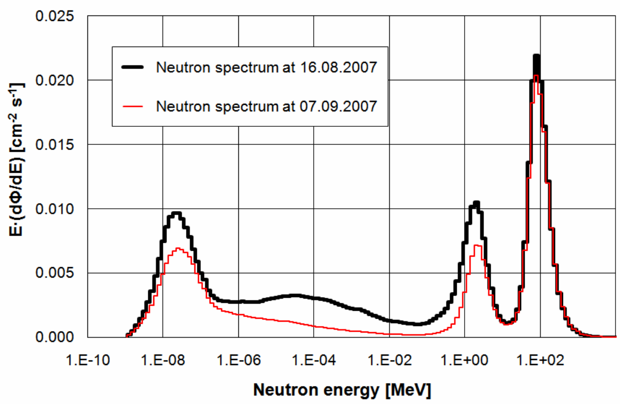

Fig. 4: Unfolded neutron spectra measured at the UFS on 16th August 2007 (dry and sunny weather), and three weeks later on 7th September 2007 with heavy snow fall and about 1.5 m snow cover on the terrace.

Obviously, the measurements with Bonner spheres located 1.75 m above the floor in the measurement shed were strongly influenced by the surrounding snow cover on the terrace, which reached a height up to 1.5 m on 7th September 2007. Interestingly, the surrounding snow cover has markedly reduced the fluence rate of neutrons below 10 MeV, while the cascade peak at 100 MeV stayed almost unchanged. This can be explained as a consequence of the higher moderation/absorption cross sections of hydrogen for neutrons with energies below 10 MeV, compared to the cross sections for higher-energetic neutrons. Furthermore, lower-energetic neutrons (E < 10 MeV) are moving isotropically, whereas high-energy neutrons are mainly coming from above. Hence a significant part of neutrons with energies below 10 MeV has to pass material in the surrounding environment (including snow cover) before reaching the BSS. Therefore, the number of interactions between low-energetic neutrons and nuclei in the surrounding materials is much higher compared to that of high-energy neutrons. This results in an additional reduction of the neutron fluence rate at energies below 10 MeV during periods with a lot of snow in the vicinity of the spectrometer.

At present, detailed Monte Carlo simulations are being performed, to model the energy spectrum of secondary neutrons at the UFS taking the local environment into account. These efforts will also include parameter studies such as variations in snow cover and water content in the surrounding environment.

B. Koldewey station, Ny-Ålesund, Spitsbergen

As an example for typical BSS measurements at the Koldewey station in Ny-Ålesund, Spitsbergen, the total relative count rate of the BSS in the "neutron monitor mode" is shown in figure 5 (black line, hourly corrected data). The data were obtained in February 2008, and normalized to the mean air pressure of 999.7 mb for this period of time using equation (1). A mean total count rate of about 10 cts/min was measured. As can be seen from the figure, the relative count rate of the spectrometer was quite constant, which demonstrates the stability of the system with time. The observed variations are mainly due to counting statistics.

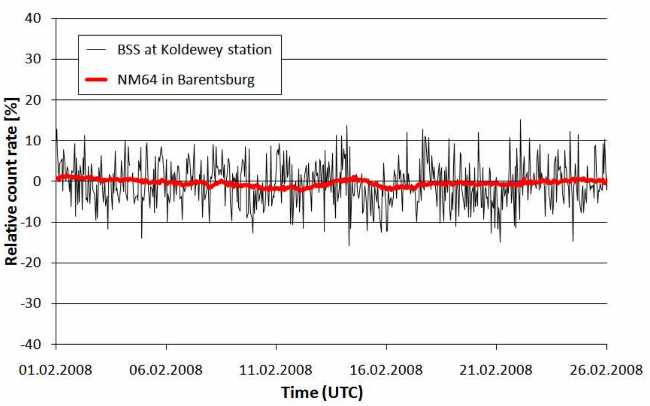

Fig. 5: Total relative hourly count rates of the BSS at the Koldewey station in February 2008 (thin line) and relative count rate of the NM in Barentsburg (thick line) [18]; data are normalized to the corresponding mean values in this period of time.

For comparison, the relative count rate obtained by the 18-NM64 Neutron Monitor operated at Barentsburg [18], Spitsbergen, is also shown for the same period of time. Comparison between both count rates indicates a consistent time behavior. It can also be seen from the figure that the statistical uncertainties involved in the NM measurements are much smaller than those obtained by our BSS system, due to the much larger detectors used in the NM. However, the advantage of the BSS system is – as already discussed above – the possibility to extract information on the energy of the neutrons, which cannot be obtained from the NM measurements.

As an example for a typical neutron energy spectrum in Ny-Ålesund, the mean count rates obtained in January/February 2008 at the Koldewey station for the 16 detectors were used to unfold a neutron spectrum ("neutron spectrometer mode") (see Fig.6). Due to the higher atmospheric shielding at sea level compared to that at the Zugspitze mountain, the integral fluence rate of secondary neutrons from cosmic radiation is roughly a factor of 6.7 lower at the Koldewey station than at the UFS (see equation (1)). The fluence rate of high-energetic neutrons (E > 20 MeV), which is not much influenced by surrounding materials or hydrogen content in the vicinity of the spectrometer, is roughly a factor of 5.5 lower on Spitsbergen than at the Zugspitze mountain.

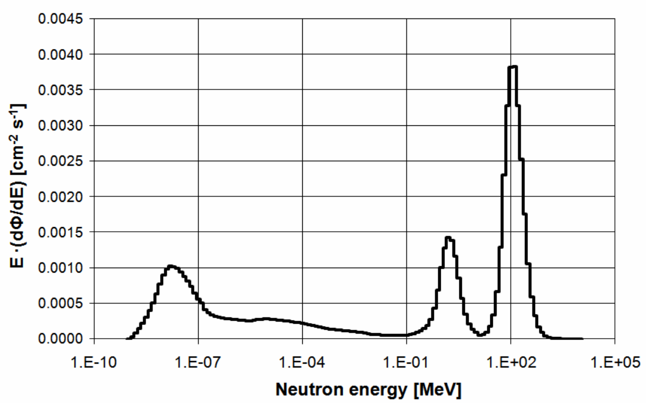

Fig. 6: Unfolded neutron spectrum for January/February 2008 at the Koldewey station in Ny-Ålesund, Spitsbergen.

4. CONCLUSIONS

Two BSS systems have been installed recently, to measure the spectra of secondary neutrons from cosmic radiation at low atmospheric and low geomagnetic shielding. Both systems are operating without major problems, and the neutron spectra obtained after unfolding the detector count rates are consistent and – from the physical point of view – reasonable.

Future efforts will concentrate on the modeling of secondary neutrons from cosmic radiation in the vicinity of both research stations. These efforts will include Monte Carlo simulations of the local environment of the BSS systems by means of the MCNPX and/or GEANT4 [19] codes including the buildings, ground composition and water concentration, in order to understand the influence of these parameters on the neutron spectra. Such calculations are required for a quantitative comparison of the neutron spectra obtained by both BSS systems. They will also allow calculation of effective doses based on the measured neutron spectra, correction for environmental influences such as rain or snow fall, and comparison with doses calculated by the EPCARD code that is used for air crew dosimetry.

To be able to compare the BSS measurements with neutron monitor data in a quantitative way, the response functions for neutrons and protons of the 18-NM64 in Barentsburg [18] were calculated using the GEANT4 simulation toolkit [19]. With the response function for neutrons and the neutron fluence rate obtained from the Bonner spectrometer, the count rate of neutron monitors can be calculated and compared to the actually measured ones. This comparison showed very good agreement for the BSS data at the Koldewey station and the 18-NM64 in Barentsburg [20]. These efforts still require further analyses of the various high energy models used in GEANT4, and of the contribution of charged particles from secondary cosmic radiation such as protons to the count rates measured by the Bonner sphere spectrometers and by Neutron Monitors [21].

5. FUTURE

The Bonner spectrometer systems described in the present paper are ready to measure neutron spectra during normal solar activity. Additionally, the systems are operated continuously to determine the spectral fluence rate of secondary neutrons during ground level enhancements (GLEs) after solar particle events (SPEs). This will allow accurate calculations of air crew doses during such events. Therefore, a detailed statistical analysis of the expected uncertainties in the neutron spectra during potential GLEs of various strengths was performed. Details are given in [8].

6. ACKNOLEDGEMENTS

This work was in part supported by the „Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz". Technical support by staff of the UFS and the French-German Arctic Research Base (AWIPEV) is acknowledged. The current paper makes use of data obtained at the neutron monitor stations "Lomnicky Stit" [16] and "Barentsburg" [18]. The NM at Lomnicky Stit is operated by the Department of Space Physics (Institute of Experimental Physics, Slovak Academy of Sciences in Kosice; K. Kudela). Barentsburg neutron monitor data are kindly provided by the Polar Geophysical Institute (Kola Science Center, Russian Academy of Sciences, E.V. Vashenyuk, Yu.V. Balabin).

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