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SAMADHA neutron spectrum and cosmic ray dose rate measurements at 5200 m in the SAA region

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The aim of the SAMADHA (South Atlantic Magnetic Anomaly Dosimetry at High Altitude) project is to monitor the spectrum of the secondary cosmic ray neutrons and the environmental dose due to cosmic rays at very high altitude in the South Atlantic Anomaly (SAA) region. In the SAA the confinement volume of the inner Van Allen belt, containing magnetically trapped protons with energy up to a few GeV, has its minimum distance from the Earth surface of approximately 200 km. SAMADHA studies the possible variations of the neutron flux and relative dose rate at ground level due to perturbations of the inner Van Allen belt during geomagnetic storms. The measurement site is the Cosmic ray Laboratory at Chacaltaya (5240 m) in Bolivia, where a Bonner sphere neutron spectrometer and dosimetric instruments are in operation since winter 2022-2023, aimed to monitor the neutron flux during the phase of increasing solar activity of cycle 25. The paper reports the first results of the experiment.

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1. Introduction

SAMADHA is a project of the Italian National Institute for Nuclear Physics (INFN) dedicated to the monitoring of the secondary cosmic ray neutron flux and spectrum, and to the assessment of the dose rate due to cosmic rays at very high altitude in the region of the South Atlantic Anomaly.

The SAA is a large area that extends over part of the Atlantic Ocean and South America, in which the geomagnetic field has the lowest values of our planet. This anomaly is due to the inclination of $\sim 10°$ of the geomagnetic field axis with respect to the Earth rotation axis and to the displacement of ~500 km of the dipole center with respect to the Earth's center. This geomagnetic field asymmetry causes the inner Van Allen belt to be closest to the Earth in the SAA region, reaching a minimum distance of $\sim$ 200 km and constituting a reservoir of energetic particles just above the upper layers of the atmosphere.

The aim of SAMADHA is to study the variations of the neutron spectrum and cosmic ray dose rate due to the solar activity in this special region of the Earth from the geomagnetic point of view, in particular during geomagnetic storms, Ground Level Events, Forbush decreases and other possible Sun-related phenomena. SAMADHA can be considered an interdisciplinary activity, addressing both the physics of Sun-Earth interactions, the cosmic ray physics and the environmental dosimetry.

Concerning dosimetry, a special attention must be paid to neutrons. Although the neutron flux at ground level is lower than that of other cosmic ray secondary particles (as gamma rays, electrons and muons), their contribution to the natural environmental radiation to which living organisms are exposed is significant, due to the serious damages neutrons cause to biological tissues. The neutron flux increases with altitude, at 5000 m being about 25-30 times higher than at sea level. At mountain altitude neutrons constitute the major contribution to the dose rate of natural origin.

One of the main aims of SAMADHA is to investigate whether the proximity of the Van Allen belts to the Earth surface in the SAA region can affect the neutron flux during perturbations of the geomagnetic field due to the Sun activity. According to measurements made by the low Earth orbit PAMELA mission, the inner Van Allen belt is predominately populated by protons with energy up to a few GeVs. The flux of the most energetic particles is maximum over South America and in particular above the Bolivian region [1].

It is known that in case of strong solar storms, particle precipitations in atmosphere from the radiation belts can occur, in particular from the outer belt, mainly populated by electrons. The inner belt is much more stable, but in particular cases it can be affected too. In October 2003, observations made by SAMPEX at approximately 600 km of altitude at around L=2, revealed an abrupt dropout of the proton flux, when the belt of trapped protons almost completely disappeared, recovering only after several months [2].

This suggests that in case of protons precipitations, a sudden flux of protons with energy under the geomagnetic rigidity cutoff could enter the atmosphere, and the most energetic ones, interacting with the atmosphere nuclei, could in principle produce secondary particles as neutrons, able to reach the ground, in particular at high altitude. This prompt neutron flux would add up to the standard neutron flux due to galactic cosmic rays. The observation of these phenomena would be favored at high altitudes due to the lower atmospheric absorption.

The chosen location for the measurements in the SAA region is the Chacaltaya Cosmic Ray Station at 5240 m a.s.l. in Bolivia, owned by the Universidad Mayor de San Andrés of La Paz,

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the historical laboratory where the pion particle was discovered in 1947 by Lattes, Occhialini and Powell. A second high altitude station used by SAMADHA to have a term of comparison outside the SAA is the Testa Grigia Laboratory, located on the Italian Alps, at 3480 m a.s.l., owned by the National Research Council (CNR) of Italy.

In both laboratories a set of instruments to monitor the secondary component of cosmic rays and the relative dose rate have been installed and are in continuous operation. Both stations also host a neutron monitor, whose data are useful to study the trend of primary cosmic rays.

SAMADHA data are analyzed and published in quasi real time on the website samadha.to.infn.it.

2. Measurements at Chacaltaya

The Chacaltaya Laboratory is located on Bolivian Andes at 5240 m a.s.l. (16.35° S - 68.13° W, vertical rigidity cutoff Rv = 11.9 GV). It has a unique geographical position thanks to its extreme elevation and location in the core of the SAA region. The SAMADHA instrumental setup (Fig.1), in operation since winter 2022-2023, consists of a Bonner sphere neutron spectrometer and several dosimeters.

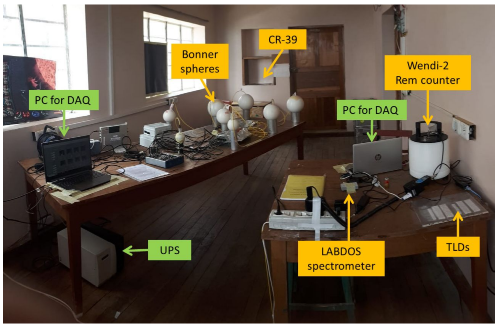

Figure 1: SAMADHA instrumental setup at Chacaltaya.

Figure 2: 12NM-64 Neutron monitor at Chacaltaya.

The SAMADHA extended range Bonner Sphere spectrometer (S-ERBSS) [3] (Fig.3) was specifically designed to operate unattended in remote locations and in a low counting rate scenario. It is composed of: a) six polyethylene spheres with diameter 80, 100, 120, 150, 170 and 200 mm, plus two extended energy range spheres with diameter 200 mm with lead or iron inserts; b) cylindrical 3He proportional counters [4] with effective volume 2.8 cm^3, effective length 40 mm and gas pressure 10 bar; c) real-time data processing system: the waveform from the analog board is digitized in order to eliminate the non-neutron events and special filters are applied in real-time by the software. From the S-ERBSS data, the neutron fluence, the energy distribution, the ambient dose equivalent and the arrival time distribution of the events can be obtained. The system has been successfully tested at the Testa Grigia Laboratory (see Section 3) [5].

The S-ERBSS system is taking data at Chacaltaya continuously since March 2023. Fig.4 shows the variations of the hourly counting rate of the 200 mm sphere in 150 hours from 10 to 16 April 2023, demonstrating the stability of the system.

Fig.5 shows the neutron spectrum reconstructed from the data taken in the same interval. The total measured flux is 0.150 ± 0.015 $cm^{-2}s^{-1}$. It is interesting to compare this spectrum with the

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Figure 3: The S-ERBSS system composed of eight 3He proportional counters inside six polyethylene spheres of diameter 80, 100, 120, 150, 170 and 200 mm, plus two spheres with diameter 200 mm including lead or iron inserts.

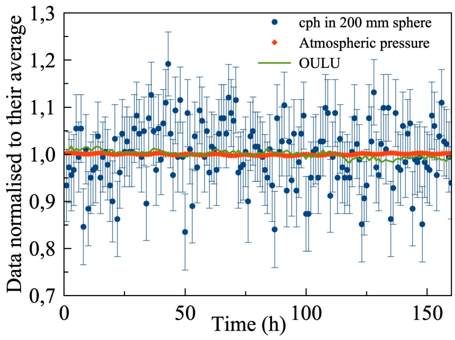

Figure 4: Hourly counting rate variations (with respect to the average) of the S-ERBSS 200 mm sphere from April 10 to 16 2023, together with the variations of the local atmospheric pressure and the Oulu neutron monitor counting rate.

one taken during the S-ERBSS test at the Testa Grigia Laboratory at 3480 m shown in Fig.6. Beside the higher flux at Chacaltaya (by a factor 1.3), it is noticeable the different ratio between the cascade and the evaporation peaks. At Testa Grigia, due to the presence of the snow around the hut, the evaporation peak is significantly reduced.

In the past, a measurement of the neutron spectrum at Chacaltaya have been performed in 1999 with a set of passive detectors [8] and a Bonner sphere system [7].

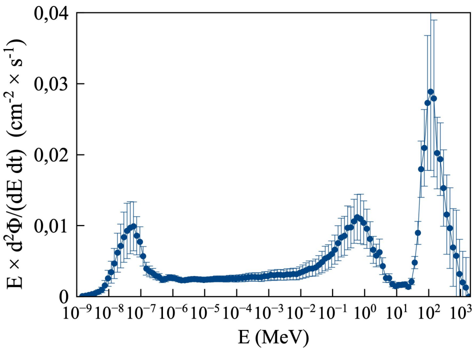

Figure 5: Neutron spectrum measured at Chacaltaya on April 10-16 2023 (multiplied by energy).

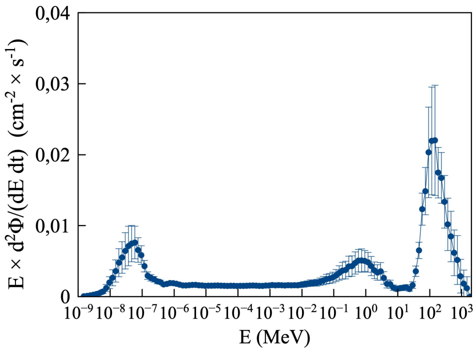

Figure 6: Neutron spectrum measured at Testa Grigia in July 2022 (multiplied by energy).

In addition to the Bonner sphere system, a THERMO WENDI-2 rem counter measures the dose rate due to neutrons of energy from thermal up to ~5 GeV in terms of the ambient dose equivalent H*(10). The average measured dose rate measured from December 2022 to June 2023, is 0.122 μSv/h. The daily pressure-corrected dose rate percent variations observed during six months are shown in Fig.7, together with the data of the South Pole neutron monitor (Rv = 0.10 GV, h = 2820 m). Dose rate fluctuations of order ±5% are observed, mainly due to cosmic ray solar modulations, and partly to local effects. We expect a correlation between the rem counter and the neutron monitor data, but not so strict, given the different geographical position, rigidity cutoff and altitude of South

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Pole and Chacaltaya, and because about half dose rate is due to neutrons of energy < 20 MeV whose flux can be affected by local conditions, as the presence of snow or water in the soil.

The analysis of the Bonner spheres daily data will allow the assessment of the neutron flux variations in different energy ranges.

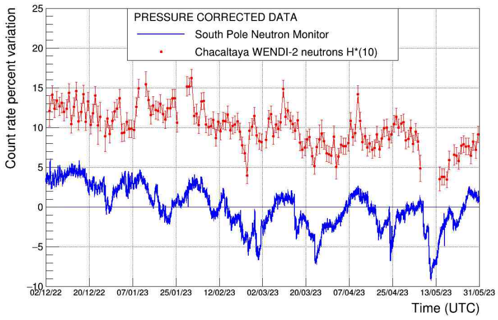

Figure 7: Pressure-corrected counting rate percent variations of WENDI-2 rem counter and South Pole Neutron Monitor during 6 months. The data of the two detectors are shifted by 5 units on the y axis for a better view.

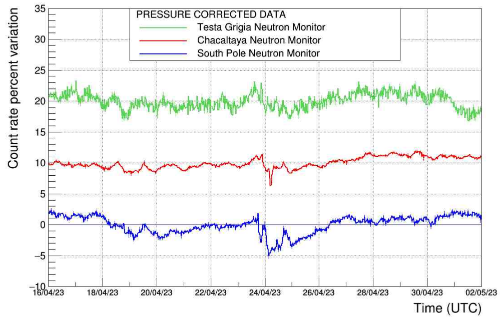

Figure 8: Percent variations of the Chacaltaya neutron monitor counting rates, compared with the data of the South Pole and Testa Grigia neutron monitor during 16 days around the G4 solar storm on 23 April 2023.

A set of passive Thermoluminescence dosimeters [6] and CR-39 detectors are also exposed in the Laboratory. A Boltek EFM-100 electric mill, installed outside the laboratory, monitors the atmospheric electric field, to study possible variations of the neutron flux due to acceleration/deceleration of charged particles during thunderstorms.

Finally, the laboratory hosts since 1966 a standard 12NM-64 neutron monitor (Fig.2), consisting of 12 Boron Trifluoride (BF_3) proportional counter tubes surrounded by polyethylene moderator, lead producer, and polyethylene reflector (total area 13.1 m^2) [9]. The neutron monitor, after a long stop due to technical problems, is operational again since March 2023. Fig. 8 shows the percent variation of the Chacaltaya neutron monitor counting rates, together with the data of the neutron monitors of South Pole and Testa Grigia (the latter is described in the next session) during 16 days around the G4 solar storm on 23 April 2023.

3. Measurements at Testa Grigia

The Testa Grigia Laboratory is located on the Italian Alps (45.95° N, 7.7° E, vertical rigidity cutoff RV = 4.71 GV), on a rocky ridge across the Italy-Swiss border, at 3480 m a.s.l. Built in 1947, the laboratory has a long history of scientific activities and it is one of the highest research stations in Europe [10]. The SAMADHA dosimetric instruments in operation at Testa Grigia monitor the dose rates due to different secondary cosmic ray particles, as neutrons, gamma rays and charged particles.

A Thermo WENDI-2 and a DIGITECH NECH rem counters measure the neutron dose in the energy range from thermal to ∼5 GeV. Beside the standard calibration with a AmBe source, the NECH rem counter has been exposed at the CERF high energy neutron field at CERN, showing a sensitivity a factor ∼2 larger with respect to WENDI-2 (counts-to-dose conversion factor f=0.58

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μSv/h/cps). The average ambient dose equivalent rate measured by both instruments at Testa Grigia is H*(10) ~ 0.075 μSv/h. Their pressure-corrected counting rates show variations of order ±5% due cosmic ray modulations mainly related to the solar activity (see Fig.9).

The Liulin-LET spectrometer [11] measures the energy deposited in a Silicon diode in the energy range from 81.3 keV to 20.8 MeV, corresponding the a LET deposition in the range 0.135–69.4 keV/μm. At Testa Grigia the average absorbed dose in Silicon (0.153 μGy/h) is mainly due to electrons, positrons and muons, with a small contribution from other particles. An approximate value of H*(10) can be obtained from the absorbed dose in Silicon applying the empirical method described in [12], that allows to calculate the separate contribution of low-LET and high-LET particles. The found total value of H*(10) is ~ 0.28 μSv/h, with a high LET particle contribution (at the ground level mainly due to neutrons) of ~0.09 μSv/h, consistent with rem counter data.

The Atomtex BDKG-04 gamma ray dosimeter, sensitive to photons of energy 15 keV- 3 MeV, measures a dose rate H*(10) ~ 0.072 μSv/h, a value that can be considered a lower limit for the gamma ray dose, since the instrument does not cover the entire energy range of cosmic ray photons.

As in Chacaltaya, a Boltek-100 electric mill, located outside, monitors the atmospheric electric field, while a weather station records useful atmospheric parameters as pressure, temperature, humidity, wind direction and velocity.

In addition to SAMADHA instruments, a portable modular neutron monitor is in operation since 2014, owned by the SVIRCO observatory in Rome (INAF-IAPS) [13]. It consists of a single ^{3}He tube of length 191 cm, surrounded by 23 modules, each composed by a polyethylene reflector, a lead ring and an inner polyethylene moderator.

Fig.9 shows the percent variations of the pressure-corrected neutron monitor counting rate during four months, together with the corresponding percent variations of the dose rate measured by the WENDI-2 and NECH rem counters. Modulations related to the 27-day Bartels rotation of the sun are well visible in all instruments count rates.

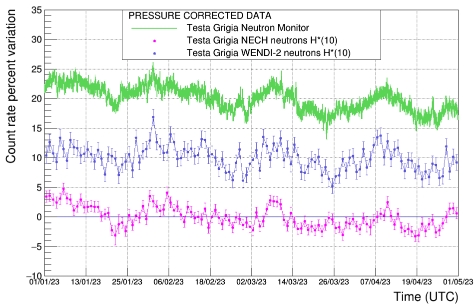

Figure 9: Counting rate percent variations of the neutron monitor and rem counters WENDI-2 and NECH at Testa Grigia. The data of the different detectors are shifted by 5 units on the y axis for a better view.

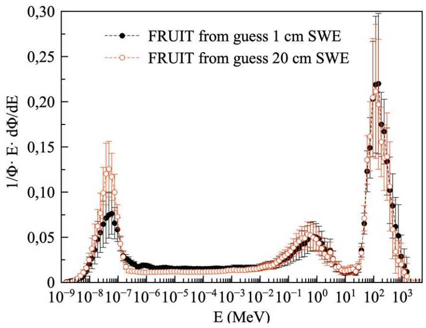

Figure 10: Normalized neutron spectrum at Testa Grigia (multiplied by energy) obtained using two guess spectra corresponding to a different amount of snow.

In July 2022 the Bonner Sphere system S-ERBSS realized for Chacaltaya was exposed at the Testa Grigia station for a test at high altitude [5]. To obtain the neutron spectrum, the spheres count rates measured in 15 hours were unfolded with the FRUIT code (in the special gradient mode

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FRUIT-SGM), using the S-ERBSS response matrix. Since the station is adjacent to a glacier, the presence of snow is the main responsible for the shape of the neutron spectrum. The cascade-to-evaporation peak ratio increases with the snow cover until a saturation value of 15-20 cm of snow water equivalent (SWE). For this reason two unfolding sessions were conducted, using two guess spectra corresponding to "extreme" snow conditions: a) minimal snow cover (1 cm of SWE) with the evaporation peak larger than the cascade peak, b) saturation snow cover (20 cm of SWE), with the evaporation peak attenuated. The obtained unfolded spectrum (normalized to the unit fluence) is shown in Fig.10. The large cascade-to-evaporation peak ratio is consistent with the large snow cover at the measurement site. The measured total neutron flux is 0.113 ± 0.013 $cm^{-2}s^{-1}$, while the flux of cascade neutrons is 0.049 ± 0.010 $cm^{-2}s^{-1}$ in agreement with expectations according to the site altitude and rigidity cutoff. The corresponding ambient dose equivalent rate is 0.077 ± 0.010 μSv/h, consistent with the value measured by rem counters.

4. Conclusions

SAMADHA is a project aimed to monitor the neutron spectrum and cosmic ray dose rate at very high altitude in the South Atlantic Anomaly region during the ascending phase and the maximum activity of the 25th solar cycle. The goal is to investigate whether the proximity of the inner Van Allen Belt to the Earth surface in the SAA region could affect the cosmic ray neutron flux at ground level at high altitude during strong solar phenomena perturbing the geomagnetic field and the Van Allen Belts configuration.

The project has an interdisciplinary character, addressing not only the physics of the Sun-Earth interactions and the cosmic ray research field, but also concerns the dosimetric aspect of cosmic radiation. At high elevations, neutrons are the major contributors to the dose due to radiation of natural origin to which we are exposed. On the Andes, many population centers are located above 4000 m. of altitude.

Since winter 2022-2023, measurements are carried out at the Chacaltaya Laboratory at 5240 m a.s.l. in Bolivia, by means of a Bonner sphere system and dosimetric instruments, taking data continuously. In parallel, the dose rates due to the different components of secondary cosmic rays are monitored at the Testa Grigia Laboratory, on Italian Alps, at 3480 m a.s.l., to have a term of comparison outside the SAA. The data recorded in both sites are analyzed in real time and the relative dose rate are published on the site samadha.to.infn.it.

5. Acknowledgments

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