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Measurement of the neutron spectrum and dose in the SAA region during strong solar activity episodes by the SAMADHA experiment

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The main aim of the SAMADHA (South Atlantic Magnetic Anomaly Dostimetry at High Altitude) project is to monitor the cosmic ray neutron spectrum and dose at very high altitudes in the South Atlantic Anomaly region during the maximum activity of the 25^{th} solar cycle.
The experimental setup for this measurement consists of an Extended Bonner Sphere System and a commercial Rem counter. A linear energy transfer spectrometer to measure the electromagnetic part of the extensive air showers, and a high-precision barometer to correct the effect of the atmospheric pressure variations, complete the system. The experiment is operated at the Chacaltaya Cosmic Ray Laboratory in Bolivia, 5270 m above sea level, and can be remotely controlled via an Internet connection.
The instruments have been collecting data almost continuously since March 2023, together with a 12NM-64 neutron monitor managed by the local research group. This high energy neutron detector monitors the variations in the flux of cosmic rays which can be used to identify the periods of most intense solar activity.
We looked at some important Forbush Decreases that occurred in 2024 and 2025 after strong CMEs from the Sun searching for cross correlations in our data. In this paper, we report on the preliminary comparison between the neutron spectrum and dose measured during two of these episodes with the spectrum and dose measured during the corresponding "quiet sun" periods.

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1. Introduction

SAMADHA is a project that aims to monitor the neutron spectrum and the dose due to secondary cosmic rays in high-altitude areas within the South Atlantic Magnetic Anomaly (SAA) region of South America during the peak of Solar Cycle 25. The project encompasses various fields of research, including Sun-Earth interaction phenomena, cosmic ray physics, and environmental dosimetry.

The main idea is to study variations in the neutron spectrum (shape and intensity) during solar events such as Forbush decreases and GLEs, as well as other phenomena associated with solar activity. Taking measurements in the SAA region allows us to study potential unknown effects on the ground resulting from the interaction between the interplanetary and geomagnetic fields in this region.

The SAA is a large region extending over part of the Atlantic Ocean and South America where the geomagnetic field is weakest due to the tilt and offset of the geomagnetic dipole. Due to this asymmetry, the inner Van Allen radiation belt (populated mainly by protons) approaches the Earth's surface by about 200 km in the SAA, creating a local "reservoir" of energetic particles just above the upper atmosphere. According to data from the Pamela space experiment, the most energetic protons (whose spectrum extends to a few GeV) are trapped in an area above central South America, including Bolivia [1].

Solar activity is known to affect the flux of particles in the Van Allen belts. In some cases, it can cause a sudden release of particles from the trapping region, mainly electrons from the outer belt. The inner belt can be affected only by very strong magnetic perturbations, and it has been observed to nearly disappear during a particularly intense event [2]. In case of "precipitation" from the inner belt, the interactions of the most energetic protons with the atmosphere could, in principle, produce secondary particles capable of reaching the ground. This would sum up the standard flux of secondary particles and increase the cosmic ray induced dose at ground level. These particles, especially neutrons, are more easily detected at high altitudes due to the lower atmospheric depth. In fact, the neutron flux produced by cosmic rays increases by a factor of 25–30 from sea level to 5000 meters. The neutron component is of particular interest because of its high radiation weighting factors and among cosmic ray particles it is responsible for most of the radiological risk to humans.

The main SAMADHA measurements are performed at the Chacaltaya Laboratory (Bolivia, 5270 m a.s.l., 16.35° S, 68.13° W, vertical geomagnetic rigidity cutoff Rv ~11.8 GV), the world's highest experimental site, which is owned by the Instituto de Investigaciones Físicas of the Universidad Mayor de San Andrés in La Paz.

The Testa Grigia Laboratory of the CNR, located on Plateau Rosa in the Alps (Italy, 3480 m a.s.l., 45.95° N, 7.7° E, Rv ~4.71 GV), is used for long-term instrumental tests and to provide data outside the SAA region for comparison. The Testa Grigia Laboratory has a long history of scientific activity [3], and it is one of the highest research stations in Europe.

2. The experimental setup

The SAMADHA instrumental setup consists of several commercially available instruments to measure the dose of neutrons and charged particles, as well as a self-developed Bonner spheres spectrometer (S-ERBSS) to measure the neutron spectrum [4]. This is composed of six polyethylene spheres with diameters of 80, 100, 120, 150, 170, and 200 mm, as well as two extended energy range spheres with diameters of 200 mm with lead or iron inserts. Each sphere contains a cylindrical 3He proportional counter with an effective volume of 2.8 cm^3 [5].

The first instruments were installed in Testa Grigia in 2021: two Rem Counters, a Liulin LET spectrometer [6], a gamma-ray dosimeter, and a meteorological station. The following year, a Rem Counter, a LABDOS LET spectrometer [7], and a set of thermoluminescence detectors were installed in Chacaltaya. In April 2023, the Bonner Sphere system was put into operation in Chacaltaya, and the first neutron spectrum was obtained. This spectrum showed a flux that was 1.3 times higher than that collected in July 2022 by the same detector during commissioning test at Testa Grigia [8] Laboratory.

The SAMADHA experimental setup incorporates local instruments available at both sites, including the 12NM-64 neutron monitor at Chacaltaya and the small, modular NM64 at Testa Grigia, the latter of which is owned by the SVIRCO observatory in Rome (INAF-IAPS) [9].

All the instruments in each laboratory are integrated into a dedicated system for real-time data acquisition. This system is essential for experiments which study space weather effects. One of SAMADHA's key features is that data from all instruments at both stations are automatically backed up on local computers and synchronized every five minutes with our data servers in Turin and La Paz, where online analysis is performed. The results of these preliminary analyses, i.e., the percent dose rate and counting rate variation of our instruments (corrected for pressure variation), are published on an hourly basis in quasi-real time on the SAMADHA website: https://samadha.to.infn.it/.

Since their installation, all instruments in both laboratories have been collecting data continuously, except during brief power outages caused by storms.

We regularly perform offline data analysis by cross-correlating our measurements at both stations with solar events. Some results are discussed in the following sections.

3. Dosimetric monitoring

From 2023 to 2025, we observed a significant modulation in the dose and counting rates of our instruments due to strong solar activity, which is expected to peak in 2025.

The results of the monitoring during 2024 and the first months of 2025 are summarized in Figures 1 and 2, that show the percent variation of the dose and neutron monitor count rates, corrected for the effects of atmospheric pressure, at Chacaltaya and Testa Grigia sites. The modulation amplitude observed by the different instruments varies because the detectors are sensitive to different secondary components of extensive air showers and local radioactivity background. The percent counting rate variation of the Oulu and South Pole neutron monitors are also reported in the same figures for comparison.

Unlike at Chacaltaya, where snowfall is rare, a large amount of snow accumulates on the roof and walls of the Testa Grigia laboratory during the winter and spring. The snow significantly decreases the counting rate of all instruments, especially neutron detectors. The gamma ray detector and Liulin spectrometer show a smaller decrease compared to neutron detectors. Separating the effect of snow from that of solar activity is complicated and requires an in-depth understanding of the entire system.

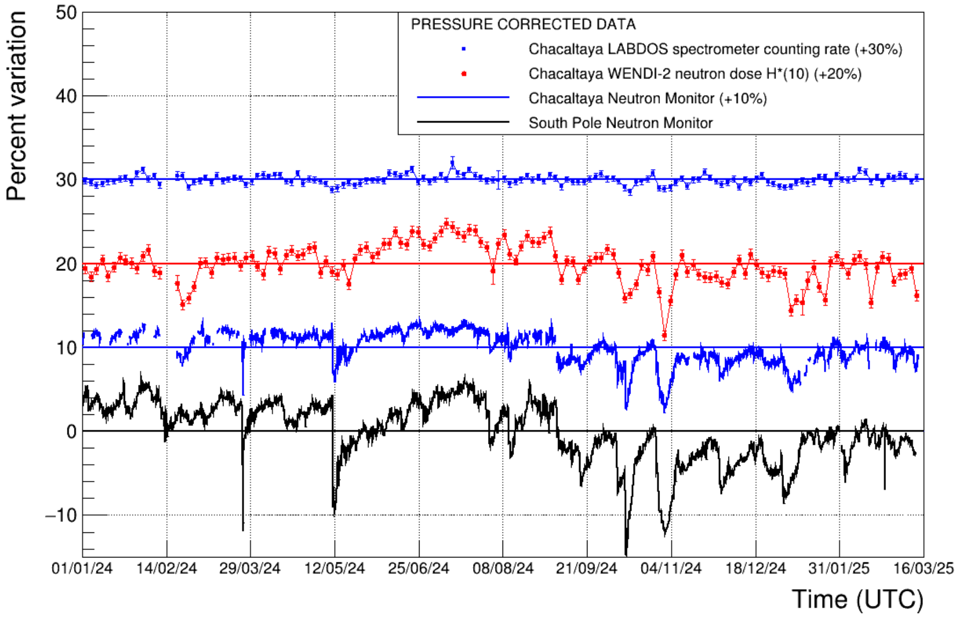

Figure 1: Percent counting rate and dose variations of the SAMADHA detectors at Chacaltaya. The South Pole neutron monitor data are reported. For clarity, the data from the different detectors are shifted by 10%.

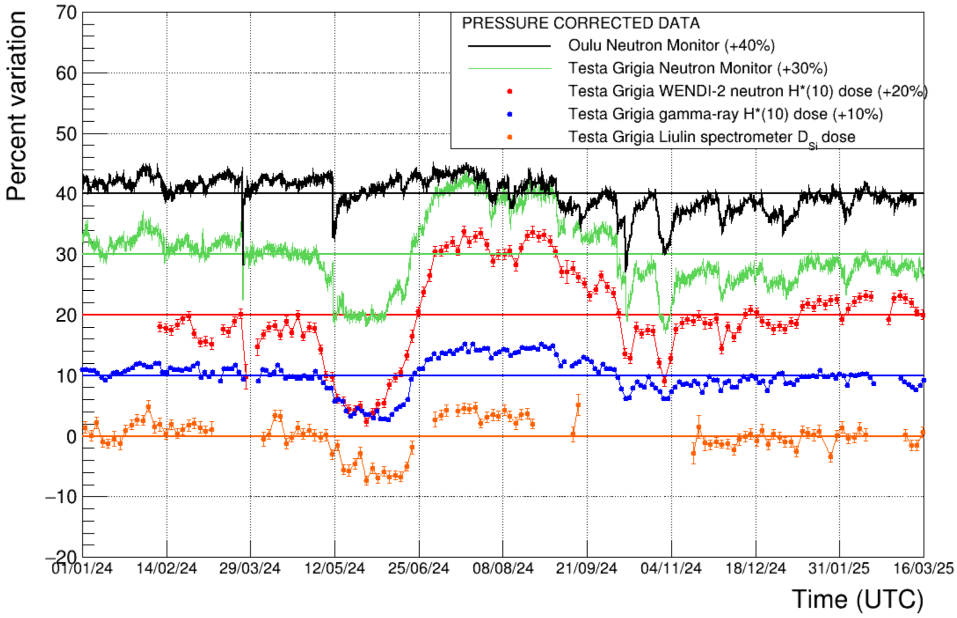

Figure 2: Percent counting rate and dose variations of the SAMADHA detectors at Testa Grigia. The Oulu neutron monitor data are also reported. For clarity, the data from the different detectors are shifted by 10%.

Several FDs following coronal mass ejections (CMEs) have been detected at both sites, particularly by neutron detectors. This is because neutrons at ground level originate from lower-energy cosmic ray primaries, which are most affected by solar activity. A FD is a rapid decrease in galactic cosmic ray flux observed on Earth within a few days after a CME. It generally takes several days for the flux to recover. The depth of a FD observed by neutron monitors is larger at high magnetic latitudes, where the rigidity cutoff is lower, but it also depends on the altitude of the detector and its geographic position with respect to the CME direction. Figures 1 and 2 show that the percent rate decreases measured by the Testa Grigia neutron monitor during FDs are in general approximately 1.2 times larger than the corresponding values measured by the Chacaltaya NM. This difference is due to the higher rigidity cutoff in Chacaltaya, which is only partially compensated for by its extreme altitude. A complete simulation of the neutron propagation in the atmosphere is under development to study how the neutron flux at ground depends on the primary cosmic ray spectrum at both sites.

No anomalous neutron dose/flux enhancement due to the proximity to the inner Van Allen belt has been observed. The modulation of the dose and cosmic ray flux is in agreement with the general modulation observed by the worldwide neutron monitor network.

Table 1 reports the average dose rates measured in both sites. Typically, the neutron dose rate at Chacaltaya is 50% higher than at Testa Grigia, while the dose due to charged particles, as measured by the LET spectrometers, is almost a factor of 2 higher.

Detector (station)	Type of measurement	Average dose rate	Measurement interval	Barometric coeff. (%hP^{-1})
Wendi-2 Rem counter (CH)	Neutron dose H*(10)	125 nSv/h	02-12-2022 to 13-03-2025	0.72
LABDOS Spectrometer (CH)	Absorbed dose in Silicon	294 nGy/h	03-12-2023 to 13-03-2025	0.41
Wendi-2 Rem counter (TG)	Neutron dose H*(10)	81 nSv/h	13-09-2021 to 16-03-2025	0.72
Nech Rem counter (TG)	Neutron dose H*(10)	82 nSv/h	22-10-2022 to 16-03-2025	0.72
Atomtex BDKG (TG)	Gamma-ray dose H*(10)	75 nSv/h	15-12-2021 to 16-03-2025	0.38
Liulin Spectrometer (TG)	Absorbed dose in Silicon	150 nGy/h	13-04-2022 to 16-03-2025	0.41

Table 1: Average dose rates measured by SAMADHA detectors in Chacaltaya (CH) and Testa Grigia (TG).

4. Neutron spectrum studies in the SAA

A detailed analysis of all the data from the Bonner Sphere System is currently underway. Here, we present preliminary results on the neutron spectrum measured during two FDs occurred in October 2024. Figure 3 shows the counting rates of the Chacaltaya and South Pole neutron monitors during the two FDs. The maximum decrease observed by the Chacaltaya neutron monitor is around 8-9% during both events.

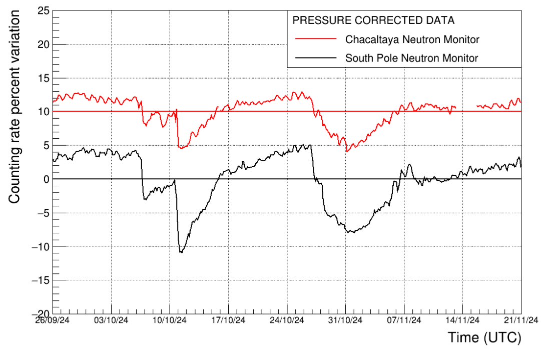

Figure 3: Counting rate percent variation of the Chacaltaya and South Pole NMs around FD-1 and FD-2. For clarity, the data of the Chacaltaya NM are shifted by 10%.

Under normal conditions, the rate of the eight Bonner spheres ranges from about 0.040 to 0.065 Hz, depending on the size of the sphere and the presence or absence of the Fe/Pb insert.

By comparing the average rate of the spheres on the day of minimum flux (in 24 hours) with the average rate in three days of nearly "quiet sun" (QS) conditions immediately preceding the event, we found that all sphere rates exhibit a decrease, whose amplitude depends on the sphere: 4.7-8.3% for the first FD and 13.1-16.7% for the second. The statistical errors on the average rates are approximately 1.4-1.8% in one day and 0.8-1.0% in three days.

The final neutron spectrum for each selected period is provided by an unfolding, self-developed and semi-automated procedure based on the iterative GRAVEL method (see [10]). The algorithm includes the response functions of the spheres to different neutron energies as obtained by a Montecarlo simulation and energy calibration (see [4]).

Figures 4 and 5 show the neutron spectra obtained on the day of the minimum flux for the two FDs, compared to those obtained during the periods of quiet Sun.

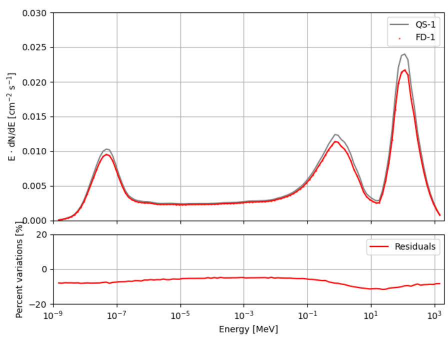

Figure 4: Neutron spectrum during FD-1 and the reference "quiet Sun" period QS-1.

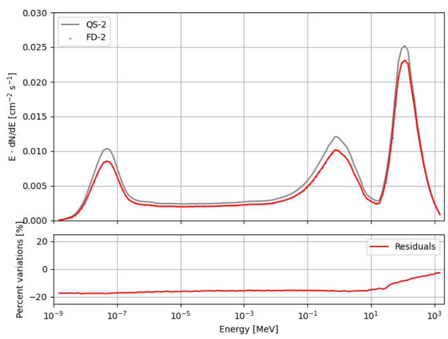

Figure 5: Neutron spectrum during FD-2 and the reference "quiet Sun" period QS-2.

Table 2 reports the selected time intervals and the measured neutron fluences during the FD and QS periods. The fluences are given in four energy ranges: thermal (below 0.4 eV), epithermal

Event	Measurement time interval T_{min} - T_{max}	Thermal fluence (cm^{-2} s^{-1})	Epithermal fluence (cm^{-2} s^{-1})	Evaporation fluence (cm^{-2} s^{-1})	Cascade fluence (cm^{-2} s^{-1})
QS-1	01-10-2024 h00 03-10-2024 h24	0.044 (±10%)	0.019 (±6%)	0.042 (±10%)	0.052 (±36%)
FD-1	11-10-2024 h00 11-10-2024 h24	0.041 (±10%) -4.8%	0.018 (±6%) -5.3%	0.038 (±10%) -8.4%	0.047 (±35%) -10%
QS-2	21-10-2024 h00 23-10-2024 h24	0.044 (±10%)	0.019 (±5%)	0.041 (±10%)	0.055 (±33%)
FD-2	31-10-2024 h00 31-10-2024 h24	0.037 (±10%) -17%	0.016 (±6%) -15%	0.035 (±10%) -16%	0.051 (±30%) -8.0%

Table 2: Neutron fluences measured during the minimum of two FDs, compared to the average fluences measured in three days of "quiet Sun" preceding the events. The errors on the fluences are systematic errors due to uncertainties in the Monte Carlo calculations of the Bonner Spheres response curves and should not affect significantly the measurement of the flux decrease during the FD (reported in percentage under the FD fluences). Time intervals of the measurements are given in UTC.

(0.4 eV to 0.1 MeV), evaporation (0.1 to 15 MeV), and cascade (15 MeV to several GeVs). As can be seen, a decrease is observed in all energy ranges. The decrease in the "cascade" peak is consistent with the local neutron monitor data. Lower energy neutrons are more influenced by local conditions such as absolute humidity, whose effects have been neglected in this initial analysis.

5. Conclusions

Since March 2023, the SAMADHA experiment has been monitoring the neutron spectrum and dose due to cosmic rays at the Chacaltaya laboratory, the world's highest cosmic ray station. A preliminary analysis of the collected data (data acquisition will continue until the end of 2025) reveals significant variations in the dose correlated with space weather events, particularly during Forbush Decrease events. So far, no anomalous dose increase due to proximity to the inner Van Allen belt has been observed. The modulation of the dose is consistent with the general modulation of the cosmic ray flux observed by the global neutron monitor network.

The neutron spectra measured by a Bonner Sphere System on the day of the minimum flux during two Forbush decreases were compared with the spectra obtained in the days immediately preceding the start of the decreases. Analysis of further events is ongoing.

6. Acknowledgments

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