SEVAN PARTICLE DETECTOR NETWORK FOR SOLAR, ATMOSPHERIC PHYSICS, AND SPACE WEATHER RESEARCH

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INTRODUCTION

We examine the energy spectra of secondary particles linked to solar events to identify and research Forbush decreases (FD), ground-level enhancements (GLE), and magnetospheric effects (ME) detected by particle detector networks on Earth's surface. Our findings underscore the role of magnetic reconnection in allowing low-energy galactic cosmic rays (GCR) to penetrate the magneto-sphere, leading to enhanced secondary particle fluxes through reduced cutoff rigidity—a phenomenon known as the magnetospheric effect (ME). In contrast, the Forbush decrease (FD) driven by the scalar magnetic field strength results in significant particle flux reductions. On May 10-11, 2024, the FD, directly linked to the enormous geomagnetic storm (GMS), was complicated by the simultaneous registration of secondary particles from the Solar Energetic Particle (SEP) event, which was energetic enough to generate secondary particles in space and on the ground, leading to increases in detector count rates, known as ground-level enhancements (GLEs). Using new experimental facilities, we reveal that secondary particles during ME events release up to 10 MeV energy (maximum energy of approximately 10 MeV), whereas, during the GLE event, the energy release extends to 200 MeV. These insights contribute to refining event classification schemes and predictive models of space weather.

SEVAN LIGHT SPECTROMETER

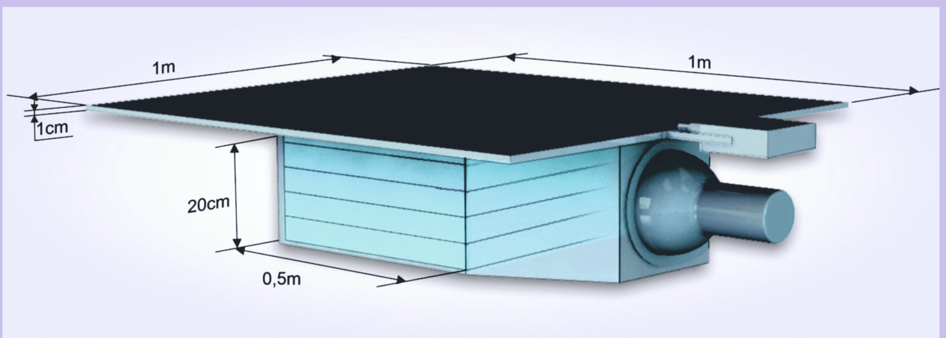

Figure 1. Detector SEVAN-light measuring charged and neutral species of cosmic rays and their energy releases.

SEVAN-light	Neutron (%)	Proton (%)	mu+ (%)	mu- (%)	e- (%)	e+ (%)	gamma ray (%)
Coin. "01" neutral	32,1	0,3	1,0	0,9	1,0	0,9	63,8
Coin."11" charged	1,6	6,4	33,3	29,6	12,1	10,4	6,5

Table 1. The share of cosmic ray species selected by different coincidences of the SEVAN-light detector in percent.

After recognizing that charged fluxes are as sensible to solar modulation as neutrons, we commissioned new SEVAN-light detectors with two layers without lead (see Fig. 1). Also, SEVAN's electronics board was updated with a new capability to measure and store energy-release histograms of charged and neutral particles each minute. The logarithmic ADC provides linearity from 5 to 100 MeV. Using the veto signal from the upper thin scintillator, the detector separates charged and neutral fluxes: "01" coincidence the neutral particles, and "11" - charged particles.

The list of available information from SEVAN-light includes:

- 1-minute count rates of stacked 1 and 20-cm thick scintillators.
- 1-minute count rates of the coincidences "01", signal only in 20 cm scintillator; "10" – signal only in the upper 1-cm thick scintillator, and "11" – signal in both scintillators.
- Histograms of energy releases in the thick scintillator correspond to the abovementioned coincidences.

Table 1 shows the results of the SEVAN-light detector response calculation with the simulated cosmic ray flux on Aragats. As we can see in Table 1, the "01" coincidence (signal only in the bottom scintillator) comprises ≈32% of neutrons and ≈64% of gamma rays. The contamination of charged particles is negligible; thus, with the "01" coincidence, we achieve a large purity of selected neutral particles. The "11" coincidence selects ≈63% of negative and positive muons and ≈23% of electrons and positrons; the share of neutral particles is ≈ 8%. Consequently, by the "11" coincidence, we select charged particles. Thus, using a SEVAN-light detector, we separate neutral and charged fluxes and measure the energy releases of each separately.

RESULTS

In Figure 2, we show the events registered by the Aragats Neutron Monitor (ArNM, red) and the SEVAN light detector located at the same station (blue, neutrons, and green, muons; see details of detector operation in Chilingarian et al., 2024a).

In Fig. 4, we show correlated enhancements (3-4%) count rates at middle latitudes and high altitudes NMs. The time series are measured by NMs across more than 5500 km. The shapes of enhancements are similar, and correlations are obvious. In contrast, monitors located at sea level do not show enhancements due to the attenuation of the neutron flux in the thick air due to atmospheric cutoff (see Figs 5 and 6 of Chilingarian et al., 2024a).

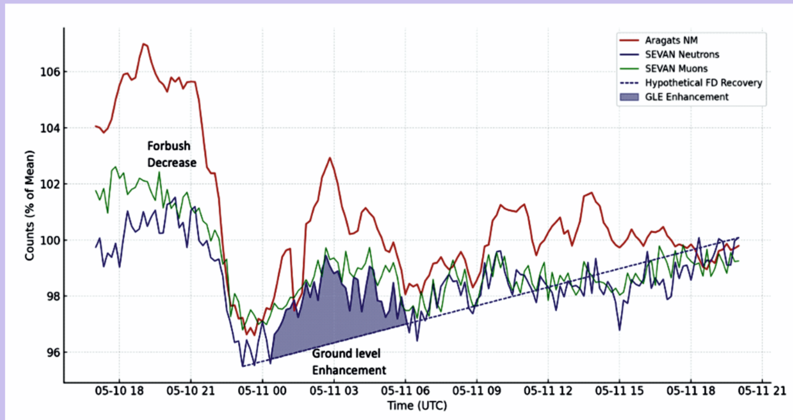

Figure 2. Pronounced enhancement in the count rates of NMs located at middle latitudes and high altitudes.

Figure 4. Pronounced enhancement in the count rates of NMs located at middle latitudes and high altitudes.

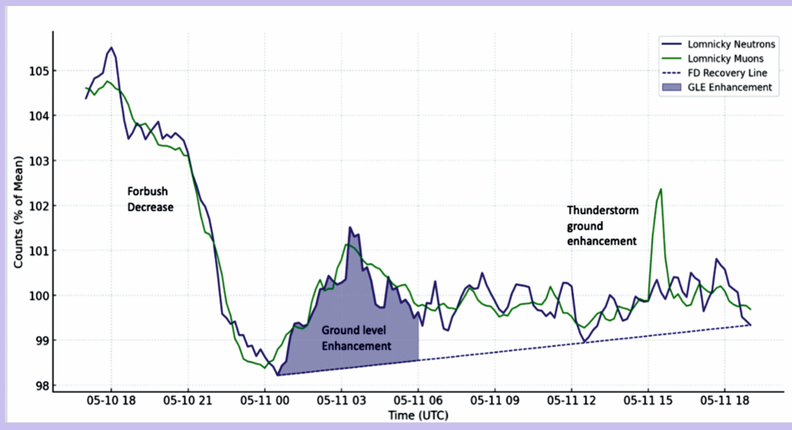

Figure 3. FD and GLE registered by Lomnicky Stit Neutron monitor (blue) and SEVAN detector's upper 5 cm thick scintillator (green).

CONCLUSIONS

The SEVAN light spectrometer enables the recovery of energy spectra of GLEs for neutrons and muons separately (see details in Chilingarian et al., 2024a). Energy spectra were recovered using energy deposit histograms and GEANT4-based detector-response modeling. The recovered spectra were segmented into three energy intervals for separate power-law analysis, as seen in Fig.4. The energy spectra were fitted using three power-law segments: 2–50 MeV, 50–200 MeV, and >200 MeV. Each segment reflects different physics of solar-induced particle cas-cades in the atmosphere:

Segment 1 (2–50 MeV): Soft Secondary Population

- Dominated by low-energy **evaporation neutrons** and **moderated secondaries** from surrounding structures or shallow atmospheric cascades

Segment 2 (50–200 MeV): Core of Solar-Induced Cascade

- Corresponds to the peak in secondary production resulting from pion decay and spallation.
- Neutrons: Moderately attenuated, tracing the depth of cascade development and neutron transport.
- Muons: Reflect direct pion decay at production altitudes (~10–20 km); energy survives transport to 3200 m.
- Solar protons with E>7.1 V are required to penetrate the geomagnetic field and initiate these cascades.

Segment 3 (>200 MeV): High-Energy Solar Proton Tail

Represents the hard tail of the solar spectrum **exceeding the local geomagnetic cutoff.**

- Muons in this range arise from high-energy pions/kaons decaying high in the atmosphere.
- The presence of high-energy neutrons confirms the presence of multi-GeV solar protons, with limited moderation and atmospheric absorption.
- Spectral steepening reflects both the drop-off in the solar proton spectrum and increased atmospheric attenuation.

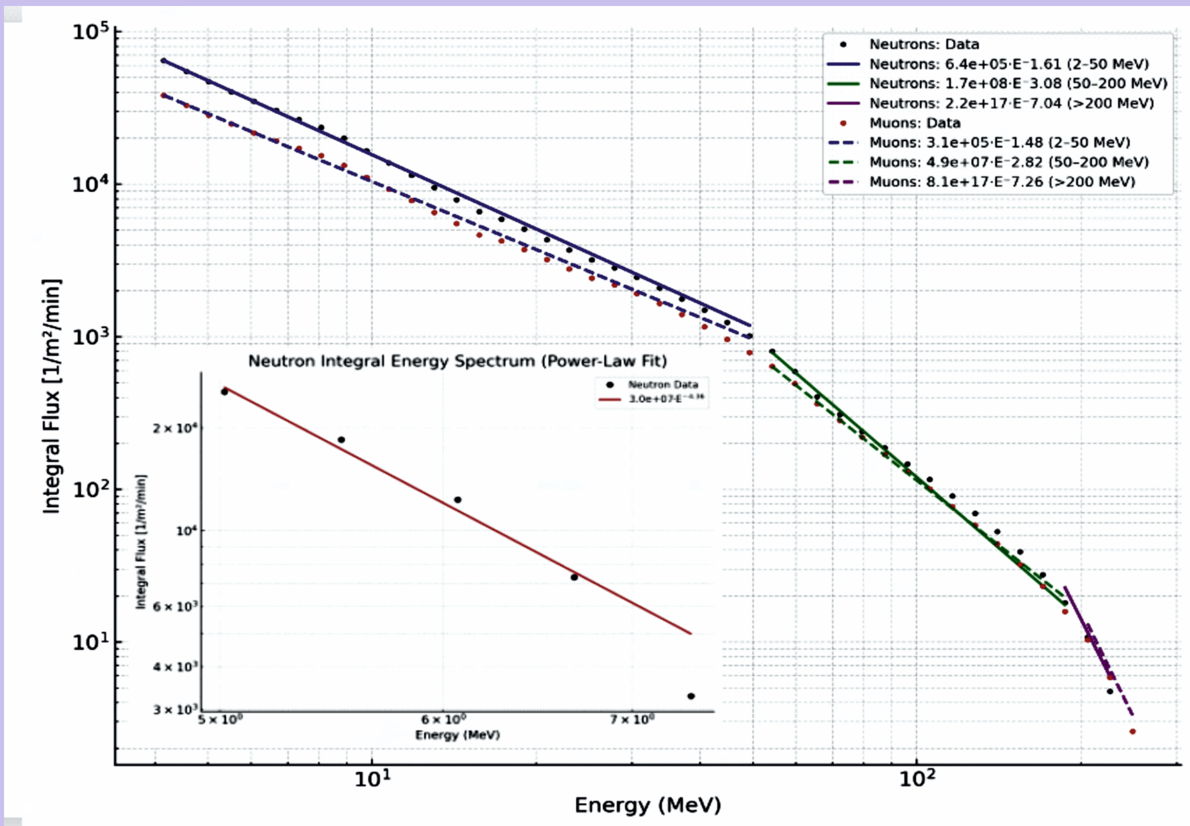

Figure 5. Reconstructed integral energy spectra of GLE from May 11, 2024, for neutrons (solid line) and muons (dashed line) with 3-segment power-law fits, shown in different colors. In the inset, the energy spectra of the magnetospheric effect from November 5, 2023.

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