

Solar Neutron Decay Protons observed on November 7, 2004

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Abstract

We have found an interesting event registered by the solar neutron telescopes installed at high mountains in Bolivia (5250 m a.s.l.) and Mexico (4600 m a.s.l.). The event was observed on November 7th of 2004 in association with a large solar flare of magnitude X2.0. Some features in the registers reveal the presence of solar neutrons, but also possible solar neutron decay protons (SNDP). SNDPs were recorded on board ISEE3 satellite in June 3rd, 1982. On October 19th, 1989, the ground level detectors installed in Goose Bay and Deep River revealed the registration of SNDPs. Therefore this is the second example that such an evidence is registered on the Earth's surface.

1. Introduction

Gamma rays and neutrons propagate freely in the interplanetary medium when emitted as secondary products of solar explosion events. Therefore they may provide information regarding the condition of production site and mechanism of acceleration. Solar neutrons have been observed in space crafts and ground based detectors [1-4]. In order to push forward

*37th International Cosmic Ray Conference (ICRC 2021) July 12th – 23rd, 2021
Online – Berlin, German*

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this study, we have an international solar neutron telescope (SNT) network at high mountains around the world. In this paper we report the registers obtained at two Solar Neutron Telescopes installed at high mountains that could be interpreted as products of solar neutrons and solar neutron decay protons (SNDP) produced at the 7 November 2004 X2 solar flare.

2. The two mountain detectors located on the American continent

Two solar neutron detectors are located at Mt. Sierra Negra (4,600 m, 19.0°N 97.3°W) and Mt. Chacaltaya (5,250 m, 16.3°S 68.1°W). The detector installed at Mt. Chacaltaya in Bolivia has of 4 m² of plastic scintillator with 40 cm thickness. The detector installed at Mt. Sierra Negra, Mexico is composed of 4 m² plastic scintillator with 30 cm thickness. In addition, four layers of proportional counters are installed underneath the scintillator for the identification of the arrival direction of charged particles [5]. At the top of the anti-counter, 5mm thick lead plate was installed. These SNTs were constructed for the detection of solar neutrons. Both instruments distinguish neutral from charged incident particles.

3. Signals recorded in the Solar Neutron Telescopes

Increases of the counting rate were recognized in the 5-minute-value of the solar neutron telescopes (SNT) located in Bolivia from 15:48 to 16:06 UT, and in Mexico from 15:51 to 17:09 UT of November 7th, 2004. The statistical significance of each excesses was 3.7σ and 12σ respectively. Both data are shown in **Figures 1** and **2**. The red lines in the figures show the neutron emission time at the Sun estimated from GOES X-ray data at 15:47:00 UT.

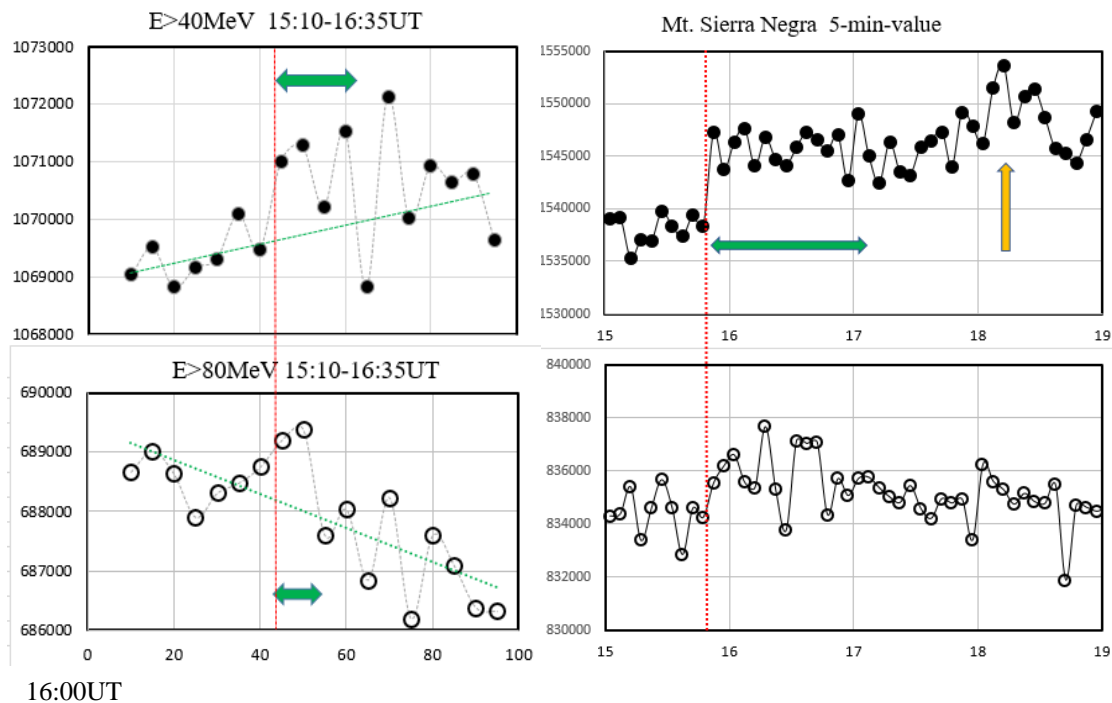


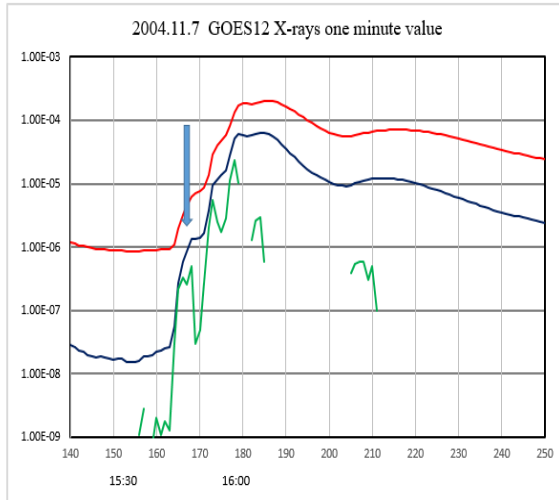
Figure 1. Counting rate of Chacaltaya SNT. Vertical axis presents the 5-minute value of counting rate. The green arrow presents the arrival time of solar neutrons.

Figure 2. (up) Sierra Negra counting rate of anti-counter ($>2\text{MeV}$)/5 min. (down side) charged particles with $E>30\text{MeV}$. Horizontal axis shows the time in UT.

The excesses of signal of the SNTs started almost at the same time, assuming them to be due to the solar flare of X2.0. The increase cannot be explained by fluctuations of the background.

4. Interpretations of the events

We make the following hypotheses in order to explain the observations:



(a) The increase of the 5-minute counting rate registered during 15:48-16:06 UT at Chacaltaya was induced by solar neutrons. These neutrons were produced by the impulsive X2.0 flare. The most probable production time is when the derivative of the GOES X-ray intensity showed the first maximum at 15:47:00 UT as shown by the arrow in Figure 3. There we can see that the flare reached X2.0 via three steps. The tendency is quite similar to the event observed in April 15, 2001 [6].

Figure 3. The GOES X-ray intensity around 15:30 - 16:00 UT. X, M, C represents the class of X-ray intensity.

(b) The increase of the counting rate observed between 15:51 and 17:09 UT at Mt. Sierra Negra was due to solar neutron decay protons (SNDP) produced in the space between the front of the Coronal Mass Ejection (CME) and the Earth. We specify the preceding CME as CME1 (Figure 4). Two large CMEs were produced: one in November 6th at 00:34 UT (CME1) and another in 7th at 16 UT (CME2). Possible acceptable area for the SNDP by each detector is shown in Figure 4. The distance $D1$ in Figure 4 is estimated to be 10^7 km. First, the SNDP produced near the magnetosphere arrived (GOES event), then the SNDP produced near the CME1 transported to the Earth (Sierra Negra event). The CME1 shock front arrived the Earth at 18:30UT [7]. The time is indicated by the yellow arrow in Figure 2.

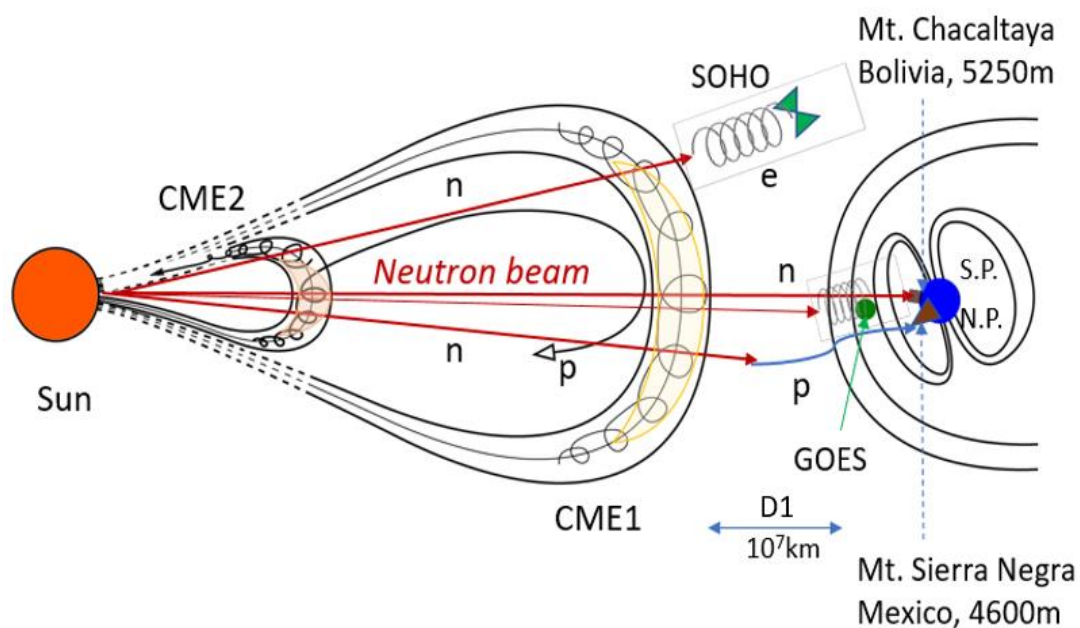


Figure 4. General view of the interplanetary space at the time of the discussed event.

The hypotheses (a) and (b) were introduced based on two reasons. One arises from the difference of the atmospheric thickness of the neutron path length between the two stations. At the flare time, there were 200g/cm² difference of atmospheric thickness between the two observatories for the passage of neutrons [8-10]. Therefore the flux of neutrons at Mt. Sierra Negra should be 7 times less than that of Chacaltaya (~1/7), because both detectors are located at nearly the same altitude. (Let us remind that the Sun was situated above South America.) However, both excesses were detected with nearly the same intensity.

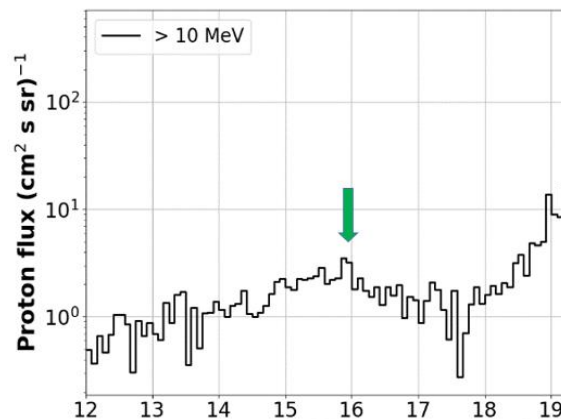
The second reason is based on the difference of the event duration. The signal of Chacaltaya was observed during 18 minutes, while the excess of Sierra Negra continued for 78 minutes (as shown by the horizontal green arrow in Figure 2). Neutrons with an energy of 50 MeV are expected to arrive to the Earth 18 minutes later than the fastest neutron, if neutrons were produced instantaneously. It is possible to detect neutrons with energy 50 MeV by the Chacaltaya detector, since the threshold energy is set at >40 MeV. On the other hand, neutrons with an energy of 30 MeV arrive at the Earth after 22 minutes (1,300 seconds) later than the highest energy neutron. The threshold energy of the S1 channel of the Sierra Negra SNT is set at >30 MeV. However, the increase continued for 78 minutes. Therefore it would be difficult to explain the signals observed at Mt. Sierra Negra by the direct hit of solar neutrons.

The charged particles observed at Mt. Sierra Negra were produced in the interplanetary space and transported toward the Earth being trapped by the magnetic-field. This may be one of the reasons why the excess of Mt. Sierra Negra continued for 78 minutes and was slightly delayed with respect to the fastest neutron arrival time [11]. In comparison with the June 3rd, 1982 event [12], the SNDP of November 7th, 2004 event was short (~1/10). One of the reasons may be due to the difference of the decay space of the SNDP between the events.

The excess of the counting rate at Chacaltaya was ~100 events/(m²·minute) in the >40 MeV channel between 15:48 UT and 16:06 UT. On the other hand, the S1 channel of Sierra Negra (the channel for charged particles with the energy higher than >30 MeV) showed 133 events / (m²·minute) as the excess between 15:51-16:27 UT. The flux was observed with nearly the same intensity as that of Chacaltaya, and the excess start time was nearly the same. However, the excess duration was completely different. Therefore, in order to explain both enhancements consistently, we may introduce the assumption that the excess of Chacaltaya was produced by the direct arrival of solar neutrons, while the excess of Sierra Negra was produced by solar neutron decay protons (SNDP).

c) We also point out that the increase observed by the GOES 11 satellite during 15:50-16:00 UT was produced by neutron decay protons (Solar Geophysical Data 2004) [13]. They were decay products of high energy neutrons in the energy range between 80 and 400 MeV. If these neutrons were produced at 15:47 UT, from the observed time, the parent neutrons had the energy between 80 and 400 MeV.

Figure 5. The GOES11 X-ray intensity curve. A 16 σ enhancement was observed.



(d) We also present the one-minute-value of the Oulu neutron monitor in **Figure 6**. During 16:00-16:03 UT (indicated by the arrow), a 5.3 σ enhancement is recognized. The cut-off rigidity of Oulu is 0.78GV. On the other hand, the neutron monitors located at the South Pole showed minor excesses. All these could be due to SNDP.

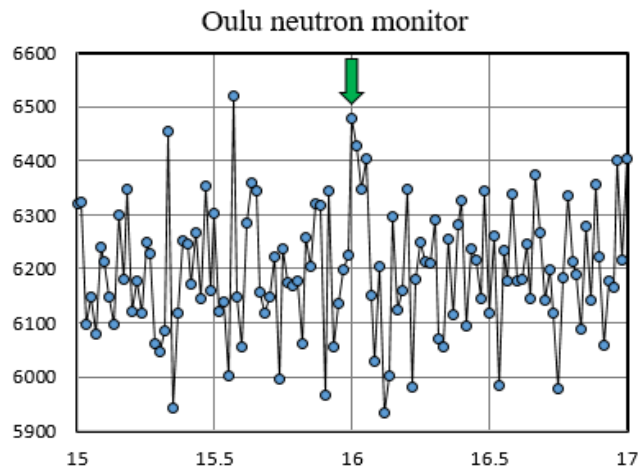


Figure 6. Vertical number presents one-minute-value of Oulu Neutron Monitor.

5. Estimating the flux of SNDP at Mt. Sierra Negra

To estimate the flux of SNDP, we may take into account another effect, since the energy of the SNDP is expected to be around a few GeV. After transportation of SNDP in the magnetosphere, some of them may be trapped by the Earth's magnetic field, but some of them will penetrate and arrive over Mt. Sierra Negra. The characteristic energy is known as the cut-off energy of primary low energy protons or Störmer limit (rigidity). The rigidity of Mt. Sierra Negra for vertical entrance is estimated as 7.5 GV, while for the protons from the west direction it is 5.5 GV.

The “gate energies” were calculated by tracing back the anti-proton trajectories ejected upward from Mt. Sierra Negra; whether these anti-protons can arrive at the magnetosphere boundary or not ($\sim 9.5 R_E$) [14]. On the other hand, the rigidity at Mt. Chacaltaya was estimated as 11~12 GV [15].

The differential energy spectrum of protons near the rigidity has been measured in space by PAMELA [16] and AMS [17] independently. The result is shown in **Figure 7** by the green triangles for the rigidity energy region of 2-8 GV. The expected flux of SNDP near the rigidity at the top of the atmosphere is shown by the open circles (\circ) in Figure 7. They are made by multiplying the PAMELA's observed differential flux of 2-7.5GeV [18, 19] to the expected neutron energy spectrum of $E_n^{-4}dE_n$ (the red diamond in **Figure 7**). The energy spectrum of SNDP beyond the cut-off energy is expected to follow the neutron energy spectrum. However, in the low energy region, less than the rigidity energy, the energy spectrum of SNDP at the top of the atmosphere is predicted to have nearly constant value to the 0.0001 neutron spectrum of $E_n^{-4}dE_n$. The expected flux must also take into account the attenuation of secondaries in the atmosphere. They are shown by the full circles (\bullet) in Fig 7. The effect has been estimated by the GEANT4.

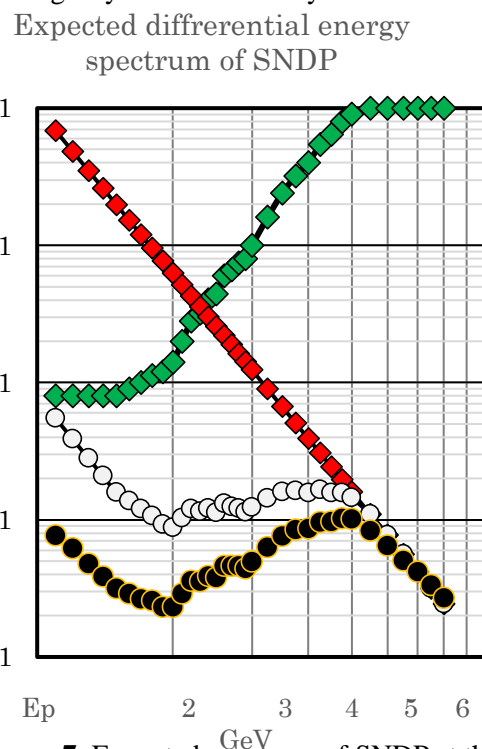


Figure 7. Expected spectrum of SNDP at the top of the atmosphere (\circ) and Mt. Sierra Negra (\bullet).

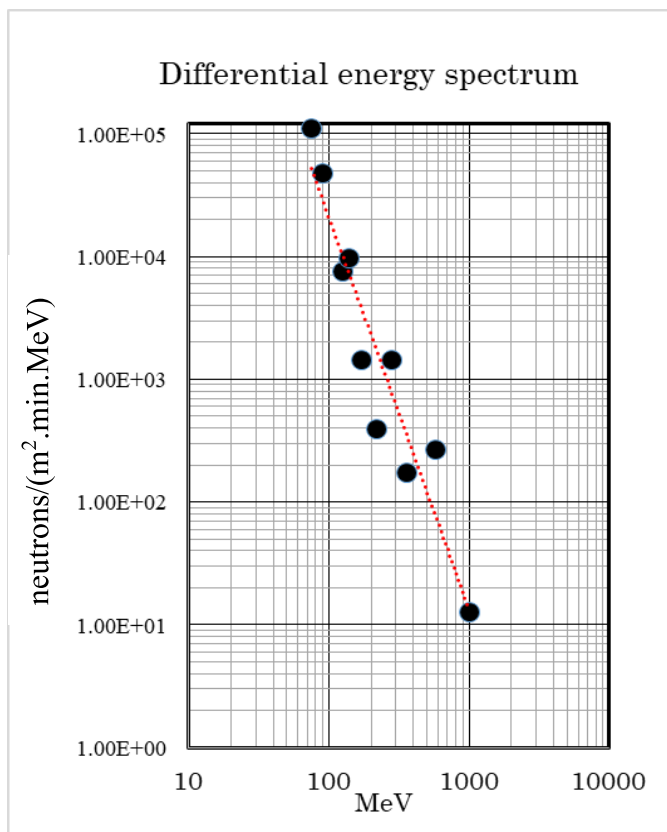


Figure 8. The differential energy spectrum of solar neutrons observed in Bolivia on November 7, 2004.

In order to derive the differential energy spectrum, we introduce the hypothesis that neutrons were produced impulsively at the Sun. The fixed production time is at 15:47:00 UT.

Then the kinetic energy of neutrons is uniquely determined from the flight time. Then the differential flux of solar neutrons is derived as a function of energy after correction of the detection efficiency [20] and the attenuation in the atmosphere [21].

Figure 8 provides the flux at the top of the atmosphere and the flux is normalized to the unit of area ($/m^2$).

6. Comparison with the fluxes

a) Deriving solar neutron flux at the top of atmosphere over Chacaltaya.

At 16 UT (12 Local Time), the atmospheric thickness over Chacaltaya is estimated as 550 g/cm^2 . The differential energy spectrum is presented in Figure 8. Figure 8 is derived based on the one-minute value of the counting rate.

b) Flux of solar neutron decay protons over Mt. Sierra Negra

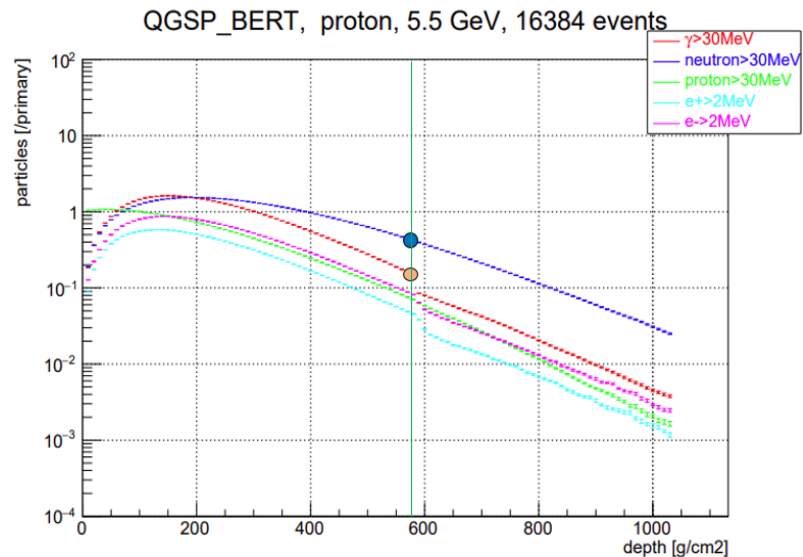
Next we will estimate the flux of SNDP at Mt. Sierra Negra. We use the event rate recorded by the Mt. Sierra Negra SNT in between 15:51 UT and 15:54 UT. They may carry information on the flux near the rigidity energy region of protons around $E_{cut} \sim 5.5 \text{ GeV}$. Such high energy protons make nuclear interactions with air nuclei and produce small size air showers. The process has been simulated by GEANT 4. The results are shown in Figure 9, where it is shown that the flux of secondary particles (gamma-rays (●) and neutrons (●) with the energy higher than $E > 30 \text{ MeV}$) has almost keep the intensity of the incident proton flux of $E_p \sim 5.5 \text{ GeV}$.

Figure 7 suggests that the SNDP between the energy range $E_p = 3.5\text{--}6 \text{ GeV}$ may be observed at Mt. Sierra Negra. Therefore, we choose the width of the energy bin (ΔE) as $2500 \text{ MeV} (=6000\text{--}3500 \text{ MeV})$ and divide the observed intensity by ΔE . Then the differential flux of the SNDP in $3.5\text{--}6 \text{ GeV}$ (at the top of the atmosphere) is estimated as $(0.23 \pm 0.02) / (m^2 \cdot \text{min} \cdot \text{MeV})$. On the other hand the flux of solar neutrons at the top of the atmosphere over Mt. Chacaltaya is estimated as 12.8, 1.8, 0.5, 0.2 and 0.1 events/ $(m^2 \cdot \text{min} \cdot \text{MeV})$ at $E_n = 1, 2, 3, 4$ and 5 GeV respectively. (We extended the red line of Figure 8 up to 5 GeV .) If we compare these fluxes, the estimated flux of SNDP at Mt. Sierra Negra (0.23) was just twice higher than the Chacaltaya neutron flux (0.1) at $\sim 5 \text{ GeV}$. Taking into account the decay probability of $E_n \sim 5 \text{ GeV}$ neutrons of $(\sim 0.0077 (\sim 1/130))$,

the value is too high. We may find out a solution to resolve the difference in a point of acceptance difference between protons and neutrons between protons and neutrons (4m^2).

Protons may enter from various area of the magneto-sheath. If the effective acceptance is wide as $1,040\text{m}^2$ ($=32\times 32\text{m}^2$), we can explain each flux. There seem to be several routes to the Earth for the SNDPs. It is called *cosmic ray penumbra* [22]. Here we assume that $\sim 5\text{GeV}$ neutrons decay in the D1 space of 10^7km of Figure 4.

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Figure 9. The inter-gap at $570\text{g}/\text{cm}^2$ is due to the lead plate.



7. Discussions

The possibility of a chance coincide between the arrival of high energy protons accelerated by the CME2 and solar neutrons exists. However the magnetic field of the CME1 (40nT) may prevent entering the accelerated particles with an energy less than 60GeV into the space between the CME1 and the Earth.

Here we point out a result of GEANT4. The simulation suggests that the ratio between the anti-counter and the S1 channel to be 0.5 at 1 GeV. However the ratio increases from 1.25 to 1.7~2.0 from $E_p=4$ to 5.5 GeV . Furthermore it predicts 2.0 at 7 GeV . The result of the observation is (2.0 ± 0.7) and this is consistent with our assumption that the excess was made by protons with energies around $5\sim 7\text{ GeV}$.

8. Concluding Remarks

We have presented evidences based on two ground based detectors. Taken together, observations admit an interpretation that the excesses would explained by the observation of solar neutrons and SNDP. Solar neutron decay protons were first reported in 1981 by Evenson et al. [23]. Ruffolo and other researchers discussed solar neutron decay electrons and protons [24, 25]. Another possible candidate of SNDP has been found in the GOES-7 proton data of 1990 May 24 (Solar Geophysical Data sgd9006.pdf [26] and in [27, 28].

However, we do not know any report of this kind of events after that. To the best of our knowledge, there are only four early reports on the detection of neutron decay protons and electrons onboard satellites and one report of neutron decay protons by ground level detectors in October 19th, 1989 [27] The event of October 1989, was also discussed by Koi et al. [29]. So, the event presented here may be the second case where neutron decay protons were registered by a ground-based detector. Further study is necessary to understand this phenomenon deeply. However, we report this fact to call community attention in the search of neutron decay protons and electrons in solar events.

Acknowledgments

The authors acknowledge INAOE personnel and authorities for their continued support in providing the services needed to keep the Mt. Sierra Negra SNT functioning. The authors express the acknowledgment to the staffs of physics department of UMSA, who have kept the Solar

Neutron Detector located at Mt. Chacaltaya under good condition for 28 years. This work has been carried out, being based on the international solar neutron telescope (SONTEL) network data reserved in the storage system of ISEE, Nagoya University. The authors acknowledge Prof. Philip Yock of Auckland University to provide useful comments.

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