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Proton penetration efficiency over a high altitude observatory in Mexico

S. Miyake[1], T. Koi[2], Y. Muraki[3⋆], Y. Matsubara[3], S. Masuda[3], P. Miranda[4], T. Naito[5], E. Ortiz[6], A. Oshima[2], T. Sakai[7], T. Sako[8], S. Shibata[2], H. Takamaru[2], M. Tokumaru[3] and J. F. Valdés-Galicia[9]

1 National Institute of Technology (KOSEN), Ibaraki 312-8508, Japan
2 Engineering Science Laboratory, Chubu University, Kasugai, Aichi 487-0027, Japan
3 Institute for Space, Earth and Environment, Nagoya University, Nagoya 464-8601, Japan
4 Instituto de Investigaciones Físicas, UMSA, La Paz, Bolivia
5 Information Science Laboratory, Yamanashi Gakuin University, Kofu 400-8375, Japan
6 Escuela Nacional de Ciencias de la Tierra, UNAM, Ciudad de México 55010, Mexico
7 Physical Science Laboratory, Nihon University, Narashino, Chiba 275-0006, Japan
8 Institute for Cosmic Ray Research, The University of Tokyo, Chiba 277-8582, Japan
9 Instituto de Geofísica, UNAM, 04510, Mexico D.F., Mexico

⋆ muraki@isee.nagoya-u.ac.jp

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Abstract

In association with a large solar flare on November 7, 2004, the solar neutron detectors located at Mt. Chacaltaya (5,250 m) in Bolivia and Mt. Sierra Negra (4,600 m) in Mexico recorded very interesting events. In order to explain these events, we have performed a calculation solving the equation of motion of anti-protons inside the magnetosphere. Based on these results, the Mt. Chacaltaya event may be explained by the detection of solar neutrons, while the Mt. Sierra Negra event may be explained by the first detection of very high energy solar neutron decay protons (SNDPs) around 6 GeV.

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1 Introduction

An interesting event was registered in association with the large solar flare on November 7, 2004 by the high-altitude solar neutron detectors located at Mt. Chacaltaya in Bolivia and Mt. Sierra Negra in Mexico [1]. The data are shown in **Figure** 1 and 2, respectively. Counting

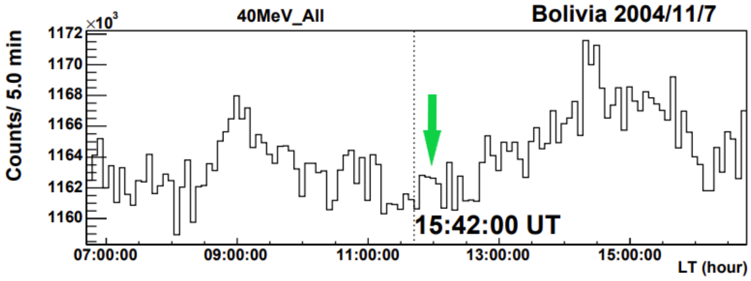

Figure 1: The 5-minute value of the counting rate of the solar neutron detector located at Mt. Chacaltaya (5,250 m). The first peak at the local time 9 am corresponds to the particle current along the IMF line, the second peak at 12 LT (the green arrow) was produced by solar neutrons, and the third peak around 14:30 LT corresponds to the arrival of the CME to the Earth. The threshold of this channel corresponds to the particles with energy higher than 40 MeV. The flare start time (15:42 UT) is shown by the dotted line.

rate excesses in both detectors started at the same time around 15:50 UT, however clear differences were observed in the duration of the respective events. The Chacaltaya event lasted for 20 minutes, while the Sierra Negra event continued for 78 minutes. The signal of the Chacaltaya event may be explained by the detection of solar neutrons. These neutrons were produced at 15:47 UT on the solar surface instantaneously with the increase of X-ray intensity.

If the Sierra Negra event was produced by solar neutrons, the excess should not continue after 25 minutes, since the threshold energy of one of the channels of the detector (S1) was set at > 30 MeV. Therefore, we have assumed that the excess of the Sierra Negra detector may be explained by the detection of Solar Neutron Decay Protons (SNDPs) [2,3].

If the observed excess counts are really produced by protons, we must show how they can arrive at Mt. Sierra Negra, passing through the magnetosphere. The cutoff rigidity of the magnetic latitude of Mexico was originally calculated as 8 GV [4]. However, an early work by Smart, Shea, and Flückiger [5] suggests a possibility that low energy protons less than the rigidity of 8 GV could penetrate into the magnetosphere and arrive over the atmosphere of Mt. Sierra Negra [6,7]. Therefore, we estimate the detection efficiency of low energy protons in the energy range between 4.5 GeV and 20 GeV.

In the next section, we describe details of the calculation and present the results. Then we compare the results of the calculation with the two experimental results. We examine whether both events are reasonably explained by the hypothesis of Solar Neutron Decay Protons.

2 Calculation method and results

Method: We have injected anti-protons from 20 km above Mt. Sierra Negra. Anti-protons were emitted every one degree in the north-south direction and the east-west direction independently. Therefore, for one fixed energy of anti-protons, 32,761 (181 × 181) trajectories were examined. The trajectory of each anti-proton was followed by solving the equation of motion using the Runge-Kutta-Gill method until they arrive at the magnetopause at $8 R_E$ (*allowed*) [8].

Of course, some trajectories do not reach at $8 R_E$. Then they were counted as the forbidden trajectories for proton arrivals. The initial energy of anti-protons was examined in the energy range between 4.5 GeV and 20 GeV. In the present calculation, the distance from the Earth center to the head of the magnetosphere (*i.e.* magnetopause) is approximated by $8 R_E$ and

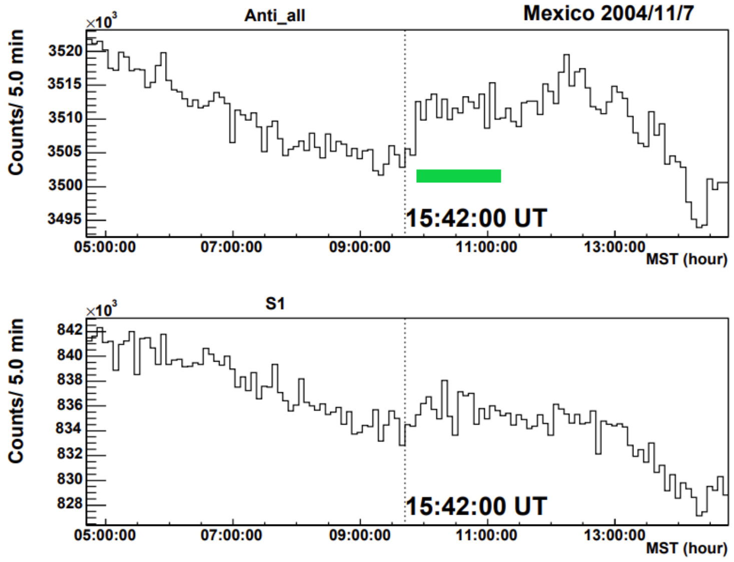

Figure 2: The 5-minute value of the anti-counter and the lowest proton-neutron channel (S1) of the Mt. Sierra Negra solar neutron telescope on November 7th of 2004. The horizontal green line indicates the time span when the excess was observed ($\sim$ 78 minutes).

examined whether or not anti-protons arrived there. The SNDPs are expected to come from the day side, so present approximation may be enough for this study.
Results: We found that quite low energy anti-protons, less than 8 GeV, arrived at the magnetopause as predicted by the earlier work [5]. The proton penetration probability from all directions at 20 km above Mt. Sierra Negra is presented by open boxes in **Figure 3**, while the arrival probability from the day side ($X > 0$) is given by open triangles.

We also consider the crossing angle between $X-$axis of GSE coordinate and the momentum (**P**) of SNDPs. Considering the entrance of charged particles along the IMF direction ($45^\circ \sim 60^\circ$), the anti-protons to satisfy the two conditions of $P_X > 0$ and $\tan^{-1}(P_X/P_Y)$ larger than 45° were finally selected. (In other words, the momentum region of $P_Y < P_X$ is selected.) The results are shown in **Figure 4** on the $P_X - P_Y$ plane and $P_Y - P_Z$ plane of the GSE coordinate respectively. We require further condition; the incident angle to the atmosphere of the incident protons is less than 40°. All points plotted in Figure 4 satisfy these conditions.

Furthermore, we consider another factor; proton attenuation in the atmosphere. When protons enter into the air vertically, the survival probability of proton signal is larger than the arrivals from large zenith angles. The value is estimated as to be approximately 0.4 for neutrons with vertical entrance ($\theta < 20^\circ$) and 0.2 for the entrance with 40° respectively. Those results were obtained by using the GEANT4 simulation. Details are given in Supplementary Information (S1) [11].

3 Boosting factor and reduction factor

Boosting factor: Figure 5 presents the arrival point of the anti-protons at $8\,R_E$. Figure 5 tells us another information. The acceptance area of the interplanetary protons by the magnetopause does not cover all area of the magnetopause (not circle as in Figure 5) but the acceptable area is limited within the rectangular area. Thus, total area of acceptance of the magnetopause for

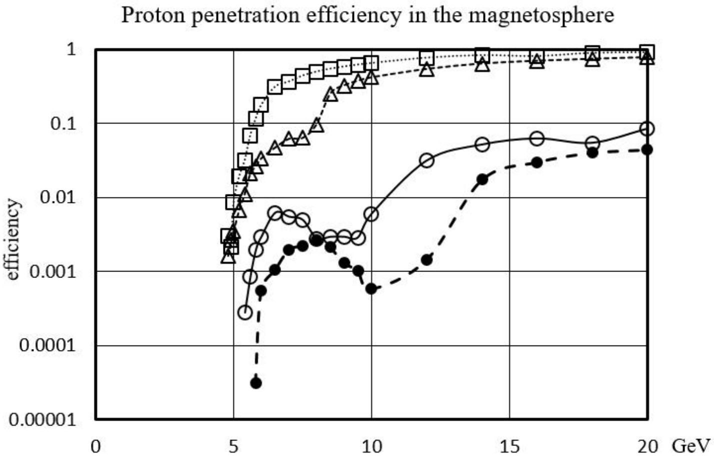

Figure 3: Proton penetration rate is shown as a function of the incident energy. The open box presents the protons coming into the top of the atmosphere of Mt. Sierra Negra from all directions. The open triangles represent protons arriving from the day side. These data are normalized by the shot number, 32,761 examples. On the other hand, the proton rate entering over the top of the atmosphere with the incident angle less than 20 degrees is shown by closed circles. The protons rate coming at the top of the atmosphere with an incident angle between 20-40 degrees are shown by open circles.

receiving the SNDPs is estimated as to be $1 \times 10^{15}\,\mathrm{m}^2$. The decay factor of neutrons with the energy of 6 GeV during the flight in the distance of $l \sim 0.067$ au, is estimated as 0.0047. More details are given in Supplementary Information 2 and 3 (S2, S3) [11].

After we apply the decay factor to the above area, the effective decay area for accepting the SNDP signals around 6 GeV may be evaluated as to be $4.7 \times 10^{12}\,\mathrm{m}^2$. The detector areas at Mt. Chacaltaya and Mt. Sierra Negra are only $4\,\mathrm{m}^2$. Therefore, in comparison with these small detector areas, a huge collecting area will be expected according to our estimation that may intensify very weak signal of high energy neutrons. Here let us call the effect as a *Horn effect*. Details are also described in (S3) [11].

Reduction factor: Assume that one high energy neutron decay proton is produced in a unit long volume in the space ($1\,\mathrm{SNDP}/(\ell \cdot \mathrm{m}^2)$), then enormous number of protons will be produced. (Let us imagine a cylinder space with the base of $1\,\mathrm{m}^2$.) According to the above estimate, the number of protons must be of the order of 4.7×10^{12}. But not all of them can enter into the magnetosphere. The Earth has a capability to protect “cosmic radiation” through the double gates; (a) by the absorption in the air and (b) by the rejection with the magnetic field. By the former process of (a), the flux of incident protons will be reduced by an order of $0.1 \sim 0.4$ depending on the incident angle to the atmosphere (see S1), while by the latter process of (b), incoming protons will be rejected by the condition of, *i.e.*, the incoming proton trajectory must be continuously connected with the trajectory inside the magnetosphere.

As is shown in S1, the reduction factor by the absorption in the air depends on the incident angle. In case protons enter within 40°, the candidates of the well-connected trajectory may be reduced to 46 among the 32,761 simulated trajectories as shown in Figures 4 and 5. Thus, the entrance probability will be reduced to be less than 1.4×10^{-3}. If we require the entrance condition of protons into the air less than 20°, only 10 events are left.

The momentum vector of the anti-protons must match with the momentum vector of protons arriving from the outside of the magnetosphere. As shown in Figure 4, the matching probability of the two tracks is very few and actually no optimum vector is found in the $P_X - P_Y$

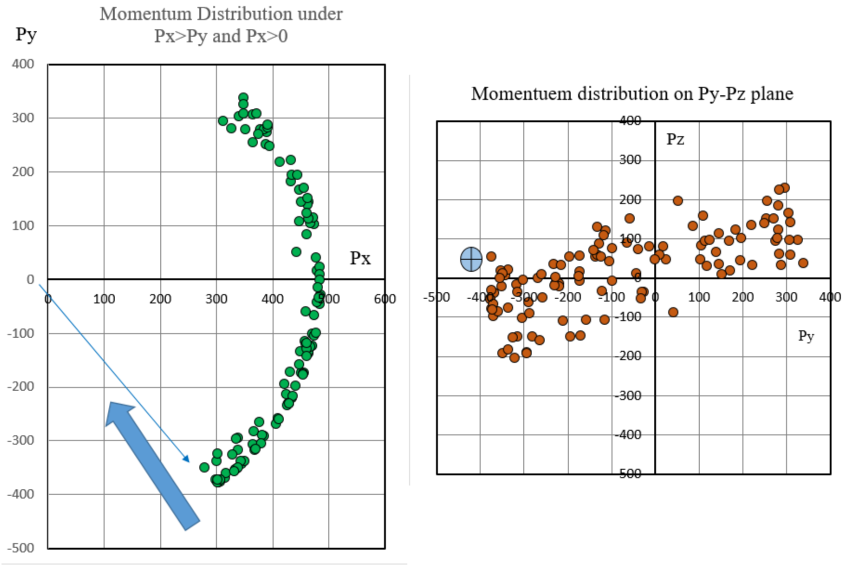

Figure 4: The momentum distribution of anti-protons arrived at $8R_E$ is shown on $P_X - P_Y$ plane (left) and $P_Z - P_Y$ plane (right) respectively. Here the positive P_Y is defined to the eastward, while P_Z positive vector points the northward. The P_X −axis indicates the solar direction. The IMF direction ($56° \sim 60°$) is shown by the arrow and by the ⊕ mark in the plots respectively.

plane of Figure 4 that matches with the IMF direction. Therefore, we postulate here the number of matching trajectories is less than one. Then actual rejection factor by above condition reduces the acceptable flux to be less than 3.1×10^{-5} (= 1/32,761). We should collect more samples of the simulation around the allowed condition region to get a finite number.

In addition, we require another condition of the smooth connection to the momentum vector in the $P_Z - P_Y$ plane, because protons will make gyro-motion along the IMF direction. The momentum vector of the Z-direction varies to the north-south direction. Details are given in Supplementary Information (S4) [11]. As a result, the total reduction factor can be estimated as to be 9.6×10^{-10} ($= 3.1 \times 10^{-5} \times 3.1 \times 10^{-5} \times 1.4 \times 10^{-3}$). Therefore, when we multiply this reduction factor to the boosting factor, we may get the “effective” boosting factor of SNDPs as to be 450 ($= 9.6 \times 10^{-10} \times 4.7 \times 10^{12}$).

In summary, the detection efficiency of SNDPs can be described by the production of the two factors; the entrance probability of the SNDPs into the magnetosphere from the interplanetary space *by* the attenuation of the SNDPs inside the atmosphere.

4 Application of results to actual data

Let us compare our prediction with the observed results. In this chapter, we examine whether current estimation may explain the observed results.

From the observed data of Mt. Chacaltaya, the neutron intensity is estimated as $1.5 \times 10^6/\text{m}^2$ at 100 MeV and $3,000/\text{m}^2$ at 1,000 MeV (1 GeV) respectively. These intensities were already converted into the flux at the top of the atmosphere, considering the attenuation in the atmosphere. However, the Chacaltaya detector did not measure the high energy region beyond 1 GeV. Therefore, we estimate the flux at 6 GeV by extending the Chacaltaya spectrum into high energies. We estimate the flux to the three cases of the spectra beyond 1 GeV, assuming the integral spectrum of the power law as $E_n^{-\gamma}$, with the power index of γ. Case (1) simple

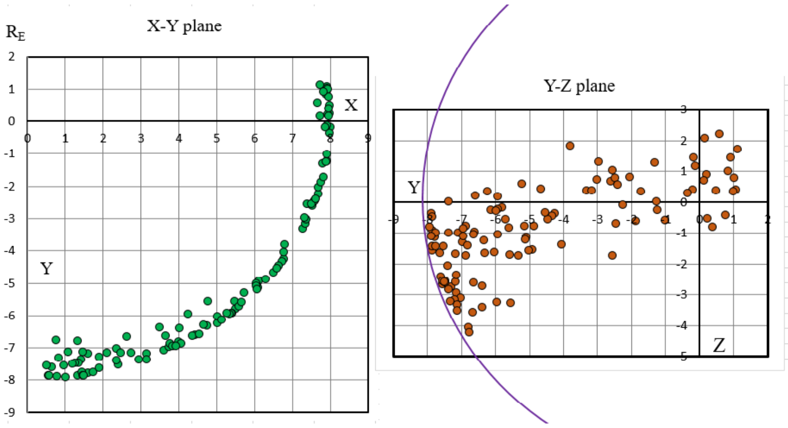

Figure 5: The arrival map of anti-protons of 6 GeV at 8 R_E on the $X-Y$ plane, while the right-side plot shows the distribution on the $Y-Z$ plane. The $Z-$axis corresponds to the north-south direction, while $X-$axis directs toward the Sun. Here the equivalent incident angle of protons to the atmosphere is selected less than 40 degrees. The number of the data points is 126, however, when we require a condition of Vy < 0, this number is reduced to 46.

extension from 1 to 10 GeV with $\gamma = 2.7$, Case (2) moderate case; $\gamma = 3.7$, and Case (3) Soft case; $\gamma = 4.7$. Then we may estimate the probable flux at 6 GeV for Case (1) $= 23.7/\mathrm{m}^2$, Case (2) $= 4.0/\mathrm{m}^2$, and Case (3) $= 0.66/\mathrm{m}^2$ respectively. See also Supplementary Information (S5) [11].

Now we compare the extended flux of neutrons at 6 GeV with the flux of the SNDPs observed at Mt. Sierra Negra. From the actual data of the S1 channel, the total flux of SNDPs may be estimated as $(45,000 \pm 900)/\mathrm{m}^2$ or the first one-minute value may be deduced as $(360 \pm 125)/(\mathrm{m}^2 \cdot \mathrm{min.})$. The latter flux may correspond to the observed events in early time. They were the decay product of neutrons with the energy greater than 6 GeV between 0.934 au and 1.0 au ($\approx$ 0.066 au).

Then we find that the observed one-minute value of Mt. Sierra Negra is 14$\sim$ 1,130 times higher than the extended flux of Chacaltaya. Considering present calculation of the boosting factor intensified by $\sim$450 times, the observed results could fairly well reproduce the experimental result. The expected boosting factor can explain actual observed data.

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