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Proton Penetration Efficiency over Sierra Negra (Mexico) and Oulu (Finland)

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On November 7, 2004, a large solar flare was observed, which had a notable impact on the solar neutron detectors located at Mt. Chacaltaya (5,250 m) in Bolivia and Mt. Sierra Negra (4,600 m) in Mexico. In addition, the neutron monitor at Oulu, Finland, recorded a 5-sigma enhancement. In order to determine the causes of these enhancements, we performed trajectory simulations ejecting anti-protons from 20 km above each location, and checked whether or not these anti-protons could reach the magnetopause ($\sim 8R_{\mathrm{E}}$). Then, we understand that the Chacaltaya enhancement was caused by solar neutrons themselves, while the Mt. Sierra Negra event may have been produced by high-energy solar neutron decay protons (SNDPs) with energies $\geq$ 6 GeV. Based on our anti-proton trajectory analysis, we suggest that the enhancement at Oulu may also have been produced by solar neutron decay protons with energies around $\geq$ 200 MeV. During this flare, protons were accelerated up to 10 GeV within one minute, leading to the production of SNDPs.

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1. Introduction

This paper discusses the observation of solar neutron decay protons (SNDPs) in association with the X2.0 solar flare on November 7, 2004. The signal was detected by three detectors: the solar neutron detector at Mt. Chacaltaya in Bolivia (5,250 m), the solar neutron telescope at Mt. Sierra Negra in Mexico (4,600 m), and the neutron monitor at Oulu in Finland (ground level). Previous analysis suggests that the signal detected at Chacaltaya was produced by solar neutrons, while the enhancement observed at Mt. Sierra Negra may be due to high-energy solar neutron decay protons. The proton acceleration beyond 10 GeV within one minute in the impulsive solar flare has been reported in the previous conference proceedings of ICRC2021 [1] and ISVHECRI2022 [2].

In this paper, we present the result of analysis on the 5.15 σ excess observed by the neutron monitor (9NM64) at Oulu cosmic ray station in Finland (Figure 1) and try to demonstrate whether or not the three signals independently observed can be explained consistently. The rigidity of Oulu is relatively low, 0.78 GV. The signals of the two neutron monitors located at the South Pole were also found to have an increase, however a 1 σ level increase was found in each detector in the 5-minute data, therefore these data were not considered in our study.

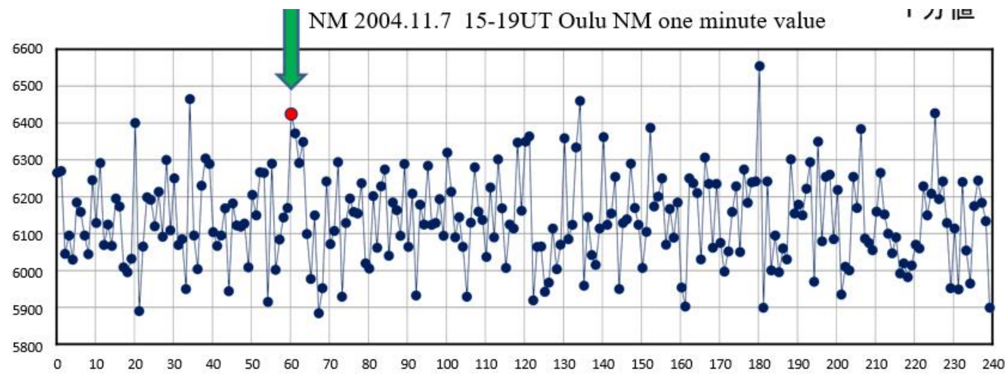

Figure 1: The 9NM64 neutron monitor counting rate of Oulu cosmic ray station. One minute value from 15:00UT to 19:00 UT is shown. The green arrow corresponds when the X2.0 flare reached the maximum intensity in X-rays.

2. The trajectory analysis of antiprotons for Oulu Station

Antiproton trajectories from the top of the atmosphere to the magnetopause are investigated whether or not arrived at $8R_\mathrm{E}$ or $15R_\mathrm{E}$. Antiprotons were injected from 20 km above Oulu, Finland, changing the emission angle by one degree both zenith and azimuthal angles of $0° \sim 90°$ and $0° \sim 360°$ respectively. For each energy, we simulated 32,760 (=91×360 trials) trajectories. We found that a significant number of emitted antiprotons can arrive at $8R_\mathrm{E}$ or $15R_\mathrm{E}$ from Oulu Station. In other words, even protons with energies as low as 0.4 GeV can penetrate the magnetosphere and arrive over Finland, near the polar region.

Figure 2 shows some of the results of our anti-proton orbit calculations. The figure demonstrates that antiprotons of energy 400 MeV launched within 15 degrees (or 30, 45 degrees) from 20 km altitude over Finland are distributed in a narrow cone on the sphere of $15R_\mathrm{E}$. We have investigated the arrived area of antiproton at $8R_{\rm E}$ and $15R_{\rm E}$, One of the case of $15R_{\rm E}$ is presented in Figure 2. In other words, protons that enter this narrow aperture from outside the magnetosphere will reach 20 km above the Earth's surface. The trajectories resemble the shape of a horn or funnel. In Figure 3, we present the arrival area of antiprotons from the Earth for different energies. When the energy of antiproton increases, we notice that the area increases.

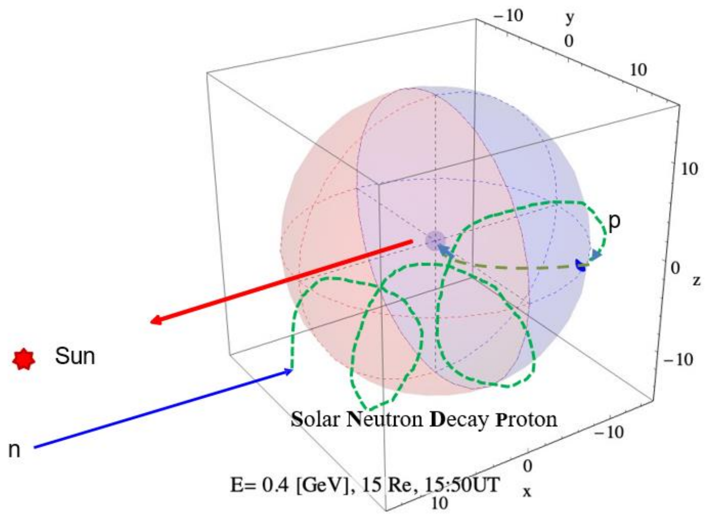

Figure 2: A schematic trajectory of neutron decay protons to Oulu station is presented on the GSE coordinate. The x-direction looks toward the solar direction, while the positive z-direction corresponds to the North-pole. The small blue area represents the allowed region for the solar neutron decay proton at $15R_{\rm E}$. The incident energy of solar neutron decay proton (SNDP) is set at 0.4 GeV. Results of precise calculations are given in Figure 7. At 10:50 UT, the solar direction was just on horizon.

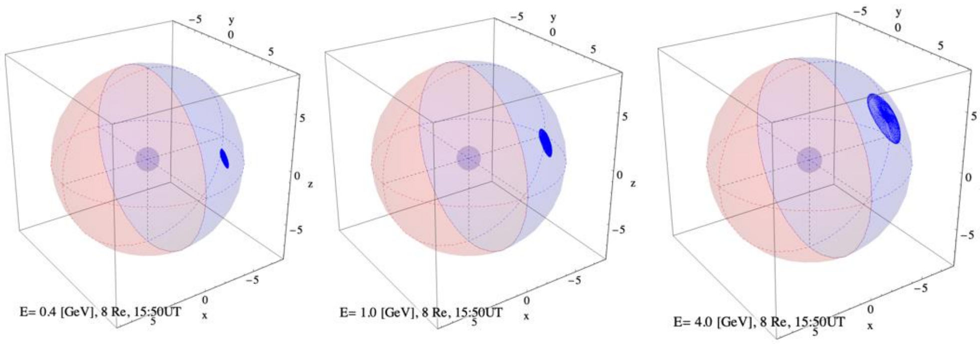

Figure 3: The hitting points of antiprotons at $8R_{\rm E}$ for the primary energy of 0.4 GeV, 1 GeV, and 4 GeV respectively. The accepted area (the blue area) increases with the energy of incident protons.

3. Precise Calculation of the Penetration efficiency

The magnetosphere has a small window for protons through which they can enter the Earth's surface. Furthermore, not all protons that arrived in the open window (on the coordinate space) can reach the Earth's surface. Results of the trajectory analysis of antiprotons clearly indicate that only protons with a specific component in the momentum space can reach the Earth's surface; there double gate for protons, coordinate and momentum. Judging from the allowed phase space in the momentum space for antiprotons, we could say that only one proton in 60,000 has possibility to reach the Earth's surface (1.7×10^{-5}). Detailed results of the study are described below.

Protons produced by neutron decay (SNDP) are captured by the interplanetary magnetic field and transferred to the vicinity of the Earth as shown in Figure 2. The value of the interplanetary magnetic field near the Earth on the day was 10 nT. Since the solar neutron decay protons have approximately the initial momentum of neutrons; the V_x component of the proton must always have negative value (the anti-solar direction) in the GSE coordinate. In other words, when we analyze the results of antiproton trajectories, it is enough to consider the positive component of antiprotons (V_x component toward the solar direction). Therefore, we considered half of the 3-dimensional phase space with a radius of 400 MeV. Why we set the maximum momentum at 400 MeV? This is due to the minimum momentum of protons that can enter over Oulu at 15:50UT. As already mentioned, the rigidity of Oulu is quite low as 780 MeV.

On the other hand, the neutron-decay-protons are trapped in the magnetic field and rotate, so the V_y and V_z components could have a wide range in the momentum space. It would be estimated as $(4\pi/3) \times (400\,\mathrm{km})^3/2$; the number of lattice points per unit volume $(\mathrm{km/s})^3$ of the momentum space. It is estimated to be about 1.3×10^8. From the antiproton trajectory analysis, the momentum range of antiprotons arriving at $8R_E$ at the magnetosphere boundary is limited to the range of 15 $\sim$ 10 km/s in the V_x, V_y, and V_z plane (Figure 4). Therefore, the allowed (accepted) momentum volume ($\Delta V_x \cdot \Delta V_y \cdot \Delta V_z$) in the momentum space (phase space) is estimated to be 2.3×10^3 (2,250). Dividing the allowed volume by half the volume of the total momentum space, we obtain the rate of 1.7×10^{-5} ($\approx$ 1/60,000) protons that enter the magnetopause. This value represents the rate of protons that satisfy a condition to enter the Earth's surface (from the phase space point of view).

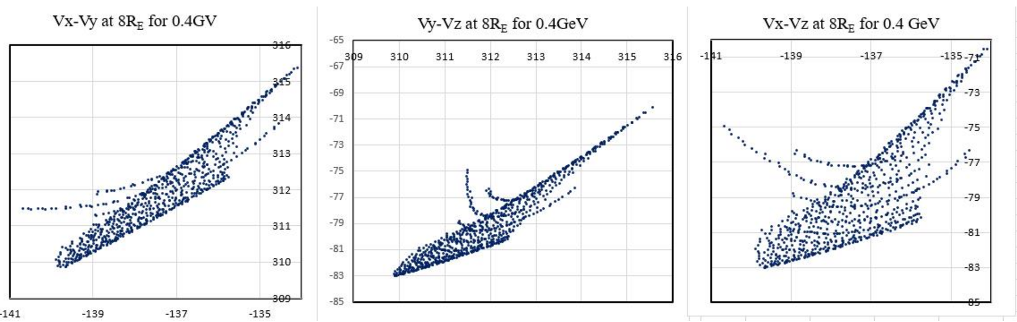

Figure 4: Anti-proton arrival momentum on the surface of $8R_E$ is shown. They are injected every one degree from 20 km above Oulu within 15 degrees of open zenith angle. The three panels represent the velocities of the anti-protons in the $V_x - V_y$, $V_y - V_z$, and $V_x - V_z$ momentum space (phase space). They are presented in unit of km/s.

However, we must take into account another "limiting factor" coming from the space region on the incident window. As shown in Figure 5, not all protons can enter the observation point (Oulu) from outside the magnetosphere. From the calculation of the antiproton orbits, the aperture over the magnetopause at $8R_E$ (estimated from dx, dy, dz based on the spread on the x, y, and z coordinates) is about 0.08, 0.08, and $0.30R_{\mathrm{E}}$, respectively. Then, the area of the incident window in the x-z plane at $8R_{\mathrm{E}}$ is approximately estimated as $0.024R_{\mathrm{E}}^2$, as indicated by the rectangular dotted area in Figure 5. The total surface area of the magnetosphere may be approximated by $4\pi \cdot (8R_{\mathrm{E}})^2$ (the magnetosphere actually extends like a stream towards the minus X direction, but we do not consider this extension effect). Normalizing the area of the incident window by the total area, the damping factor coming from the restriction of the aperture of the magnetosphere is estimated as 3.0×10^{-5}. Therefore, taking into account the product of the two limiting factors (space and momentum limit) we obtain the factor as $(1.7 \times 10^{-5}) \times (3.0 \times 10^{-5}) \approx 5.1 \times 10^{-10}$.

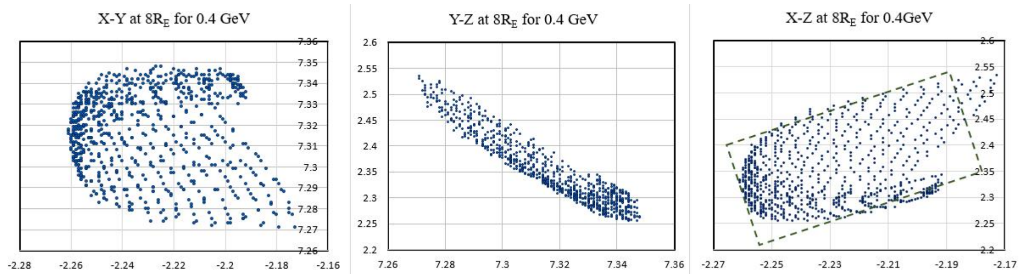

Figure 5: Anti-proton arrival points on the surface of $8R_{\mathrm{E}}$ is shown. They are injected every one degree from 20 km above Oulu within 15 degrees of open zenith angle. Other cases have been tried injecting every one degree within 5, 30 and 45 degree open angles, but they are not shown. The three panels present the allowed region in x-y, y-z, and x-z plane (shown by R_{E} units); the actual size of the open window for SNDPs is estimated by the dotted rectangular area in the x-z plane in the upper right diagram.

However we must take into account "focusing factor" to deduce a correct flux on this event. We must take into account the collection effect, which is caused by the orbit of antiprotons due to geomagnetic field, resulting in an amplification of the flux of solar neutron decay protons (SNDP). The effective acceptance area of the aperture at $8R_{\mathrm{E}}$ is much larger than the launch point, implying that a SNDP flux of 1 m^2 is amplified by a factor of 10^{12} ($0.024R_{\mathrm{E}}^2 = 0.97 \times 10^{12}$ m^2). So the solar neutron decay protons that hit the possible area of acceptance (the blue area in Figures 2 and 3) have a possibility to arrive at the Earth. Multiplying the spread of antiprotons in the surface area at $8R_{\mathrm{E}}$ to the damping factor gives a final amplification factor of $\sim 500 \approx (0.97 \times 10^{12}) \times (5.1 \times 10^{-10})$.

The number of solar neutron decay protons (SNDP) at the top of the atmosphere is estimated from the Oulu neutron monitor observation as $(3.8 \pm 0.7) \times 10^5$ protons/m^2. The value is obtained, dividing the actual observation value by the attenuation in the atmosphere [3], and a correction of 0.3 coming from the detection efficiency of neutron monitor for protons [4]. After correction of the detection efficiency, the number of SNDPs at the top of the atmosphere is estimated as $(1.3 \pm 0.2) \times 10^6$ protons/m^2 over Oulu.

The expected flux of solar neutrons is deduced using the delay time of neutrons from light and turns out to be 2.5×10^5 neutrons/m^2 above 200 MeV over Chacaltaya. Multiplying the decay probability of 0.033 of neutrons with $E_{\mathrm{n}} = 200$ MeV, within the flight distance of 0.067 au gives an expected flux of 8.25×10^3 SNDPs/m^2 near the magnetopause. Multiplying 500 to this value as the amplification factor, the expected value at the top of the atmosphere is estimated to be 4.1×10^6 protons/m^2. When compared with the observed value, it is found that the estimated value is about 3 times larger than the observed value.

4. Comparison with the SNDP event in October 19, 1989

Only four SNDP events have been reported so far, including the present one. The SNDP event occurred on October 19, 1989, was observed by neutron monitors located at Goose Bay and Deep River in northern Canada [5], as well as the GOES-7 satellite in geostationary orbit [6]. The rigidity at these locations was low, and it was expected that a large number of protons could enter even at the cutoff rigidity of 0.64 GV in Goose Bay. Here we presents the expected and observed flux of SNDP over Goose Bay, which was calculated using the integrated flux of the GOES data above 320 MeV. The observed flux over Goose Bay was converted to the flux over the atmosphere, taking into account the attenuation of neutron component in the atmospheric [3] and the detection efficiency of neutrons in the neutron monitor [4]. The count rates at Goose Bay and Oulu were found to be similar, and an increase of 585 /min was observed in the 18NM64, with a statistical significance of 5 σ at 1 minute counting rates. Then , the value is obtained for the upper atmosphere as 5,571,429 /min, which was converted to $0.49/\mathrm{cm}^2$sec for comparison with the flux obtained from the GOES satellite..

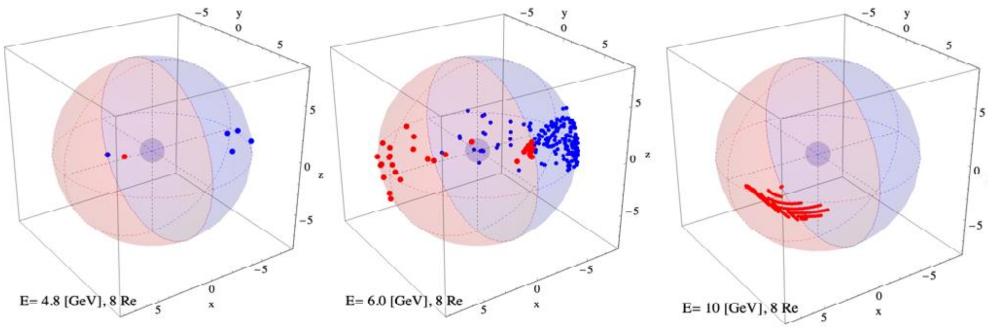

Figure 6: The anti-proton arrival area on the surface of $8R_\mathrm{E}$ over Sierra Negra is shown. For comparison with Oulu event shown in Figure 3, The SNDPs are expected to come from the day side (the red points). Because 15:50 UT corresponds to 09:50 local time of Mexico. It would be interesting to know when the incident energy increases from 4.8 to 6 GeV, the dayside entrance points (red one) are increasing and at 10 GeV, they are almost entering from the dayside. The blue points represent the entrance from night side.

The GOES satellite data provided the solar neutron decay proton fluxes for $E_\mathrm{p} = 320\,\mathrm{MeV}$ (differential value) and $E_\mathrm{p} > 320\,\mathrm{MeV}$ (integral value) as $0.01/\mathrm{cm}^2 \cdot \mathrm{sr} \cdot \mathrm{MeV}$ and $0.06/\mathrm{cm}^2 \cdot \mathrm{sr}$, respectively. Applying the 2π steradian to limit the solid angle over the atmosphere, the expected integral counting rate was found to be $0.38/\mathrm{cm}^2 \cdot \mathrm{s}$. This value is very near to the value obtained from the neutron monitor observations.

A note is added here. The reason for the shorter enhancement duration of the November 7, 2004 event compared to the October 19, 1989 event may be due to the fact that the effective solar neutron decay space for the November 2004 event was limited to the distance of 0.067 au. The CME rope approached the Earth's vicinity, which was created by the M9.7 flare just one day earlier to the X2.0 flare. Details are shown in reference [2].

5. Conclusion

In conclusion, the data from the Oulu neutron monitor station suggests that the 5.15 σ excess may be attributed to solar neutron decay protons, which were likely produced impulsively on the solar surface. The extended 5 minute enhancement supports this assumption, as it matches the estimated delay time of solar neutrons with an energy threshold of $E_n = 200$ MeV. Solar neutron decay protons are rare events, with only three reported events to date, including the October 19, 1989 event [5–8]. This recent event may be the second event where solar neutron decay protons were detected by instruments located near the polar region.

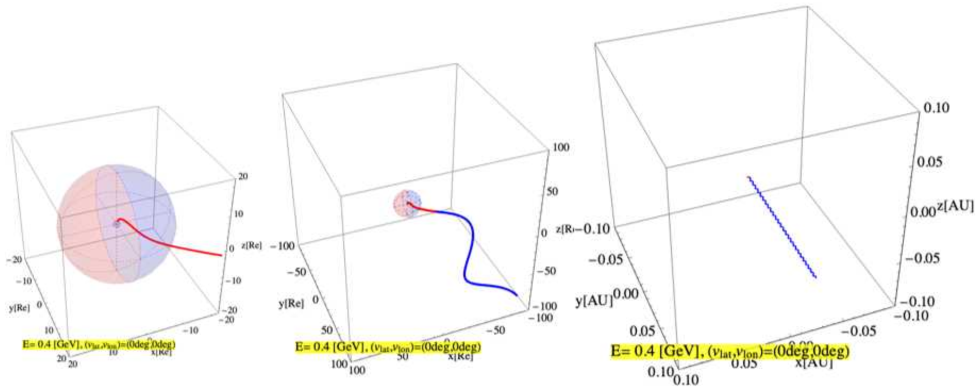

Figure 7: The antiproton trajectories with the energy of 0.4 GeV are shown. They are emitted vertically from 20 km above Oulu station at 15:50 UT. The red points represent the trajectory inside the magnetosphere, while the blue points correspond to the positions outside the magnetosphere. From left to right, the space boxes are zoomed out from 20 R_E, 100 R_E, to 0.1 au, respectively. In this flare, the CME rope was approaching just near 0.067 au from the Earth. Therefore, protons with energy less than 60 GeV cannot take over the CME wall and only SNDPs produced in the region between 0.067 au and the magnetopause had a possibility to arrive at the Earth. The strength of the interplanetary magnetic field was 10 nT.

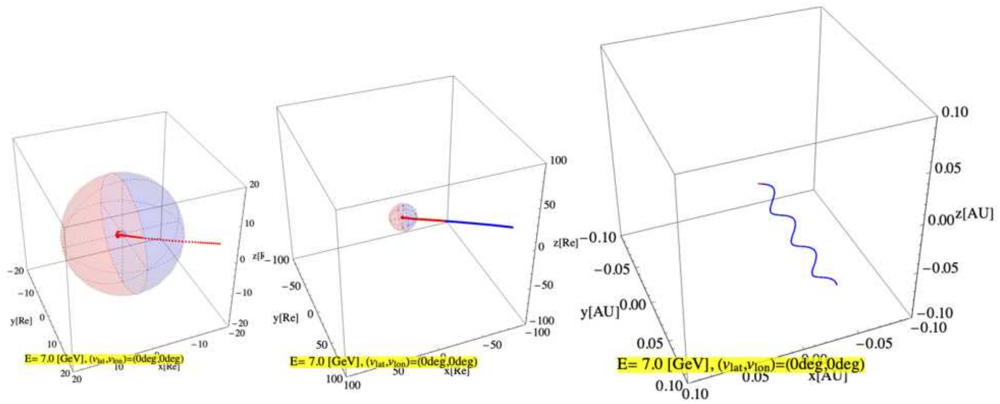

Figure 8: Antiproton trajectories emitted from 20 km above Mt. Sierra Negra at 15:50 UT. The energy of antiprotons are set at 7 GeV. The trajectory has more straight behavior in the magnetosphere and the rotation radius is wide in comparison with the case of 0.4 GeV Figure 7.

6. Acknowledgments

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