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Search for solar neutrons at Mount Chacaltaya associated with M- and X-class flares during the rising period of solar cycle 24

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Abstract

To better understand the acceleration mechanism of high-energy particles that are driven by solar flares, we examined solar neutron signals. We have performed a statistical analysis by reviewing the data collected by a neutron monitor during the period of January 2010 to August 2013. This detector operates at Mount Chacaltaya in Bolivia at 5,200 m above sea level. Our aim is to search for solar neutron events in association with large solar flares observed by the GOES satellite. We report that our analysis did not yield any positive excess due to solar neutrons that are statistically significant. Hence, we calculated the upper limit of the number of solar neutrons for the X2.8-class solar flare which occurred on 13 May 2013. We performed a similar calculation with a solar neutron event that occurred on 7 September 2005. Our upper limit is seven times less than the one produced by the real signal.

Keywords: Solar neutrons; Neutron monitor

Correspondence/Findings

Introduction

Solar flares are a sudden burst and release of energy that take place at the solar surface. They are not isolated events, because they are always associated with other eruptive phenomena, such as filament eruptions, coronal mass ejections, Moreton waves, and sometimes sunquakes. Actually, all of these phenomena are different manifestations of a single energy release. During an X-class solar flare, the bulk energy of released ions is in the order of 10^{32} [erg] (Hudson 2011). The interaction of these ions with the photosphere can produce solar neutrons via nuclear interactions (Lingenfelter et al. 1965). Understanding the acceleration mechanism at the early stage of a solar flare is of primary importance in the study of solar neutrons. Solar neutrons can arrive forthwith from the Sun to the Earth – since they are not affected by the interplanetary magnetic fields – holding key information concerning the original particle acceleration.

Solar neutron observation has been carried out by neutron monitors (NMs) which continuously record the primary cosmic ray intensity and by solar neutron telescopes (SNTs). SNTs are detectors specially designed to discriminate neutral particles from charged particles, to estimate the energy and to determine the arrival direction of neutrons (Tsuchiya et al. 2001 and Watanabe 2005). It is specially important that SNTs can measure the energy of neutrons because they have mass, thus their travel time from the Sun to the Earth depends on their energies, which are of the order of a few gigaelectronvolts. However, when they reach the Earth, they are attenuated in the atmosphere (Shibata 1994). Therefore to diminish the attenuation effect, the detector for solar neutrons must be positioned at very high mountains and also at low latitudes. It is mentioned that a new solar neutron telescope has been completed recently in Mexico (Sasai et al. 2014).

Solar neutrons are sometimes associated with solar flares and/or coronal mass ejections and can be observed both in space (Muraki et al. 2013) and on the ground (Watanabe 2005). During the declining phase of solar cycle 23, we were able to observe six solar neutron events associated with solar flares (Watanabe et al. 2005 and Sako et al. 2006). Proceeding with our effort to collect more solar neutron events, we directed our attention to

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the current solar cycle, which started in October 2009 and reached its first peak in August 2013. In this paper, we show the results of searching for solar neutrons at Mount Chacaltaya associated with a series of M- and X-class solar flares during the rising period of the solar cycle 24. Here, we mention that several authors have discussed about the acceleration of particles in solar cycle 24. More recently Gopalswamy et al. (2014).

Experiments in Chacaltaya

One of the highest cosmic ray observatories in the world is located at Mount Chacaltaya in Bolivia. Its high elevation (5,250 m a.s.l., 540 g/cm^2) and low latitude (16°21′S, 68°08′W) makes it a suitable site to accomplish our aim. At this observatory, there are two detectors for solar neutron monitoring. The first one is the neutron monitor (hereafter NM-64) with an area of 13.1 m^2, and it has been operational since 1966 (Martinic et al. 1985). The second one is the Bolivia SNT, with an area of 4 m^2 and in operation since 1992 (Matsubara et al. 1993). The NM-64 consists of 12 NM64-type tubes (Carmichael 1964). Its components are the polyethylene-made reflector, the lead-made producer, the polyethylene-made moderator, and the BF_3-gas-filled proportional counter. Particles entering the NM-64 are thermalized and captured by ^{10}B nuclei in the BF_3 counter.

One experimental problem with NMs is that the number of neutrons is multiplied in the detector. This effect is significant and should be taken into account when we measure the number of incident neutrons by the neutron monitor. The treatment of this effect measured by the neutron monitor will appear in the sections below.

On the other hand, the Bolivia SNT consists of four 40-cm-thick plastic scintillator and an anti-counter to reject charged particles. This anti-counter consists of 17 scintillators that surround the whole detector (Matsubara et al. 1993). The measurement strategy is as follows. Incoming neutrons are converted into protons by nuclear interactions in the target (plastic scintillator). These recoil protons which undergo a charge exchange process tend to be scattered in the direction of incident neutrons, almost conserving its energy (Flückiger et al. 2005). The ionization energy loss of the protons is measured by photomultipliers (PMTs) located at the top of the plastic counters. Discriminator thresholds of the PMTs are set at four different energy levels, which are $>$40 MeV, $>$80 MeV, $>$160 MeV, and $>$240 MeV, respectively. The SNT is capable of measuring the energy of neutrons, whereas the NM-64 is not. The NM-64, however, is more efficient – because of its larger area – at detecting solar neutron signals. The detection efficiencies of both detectors are expected to be nearly similar compared at the same area (Muraki et al. 2008). Therefore, our criterion to search for solar neutron signals is to first look for a significant excess greater than 3σ with the NM-64 data and then we examine the SNT data.

Actually, we have not detected any significant excess from the NM-64 in the current analysis. Therefore, we have not examined the SNT data at all in this paper.

To examine if the NM-64 is operating properly, we measured counting rates per 5 min when 'no' solar flares occurred (i.e., when the X-ray intensity was lower than a C-class flare). We assumed these days as the cosmic ray intensity that neutron monitors record, and we found that it is stable except for power failure. On the left of Figure 1, we show a typical counting rate per 5 min recorded by the NM-64 for 1 day. This variation occurs daily, and it is explained by the variation of the pressure. On the right, the histogram shows the range of the daily variation.

Analysis

Solar flare sample

We concentrated our analysis examining the data collected between the beginning of the current cycle up to its first peak, which was reached in August 2013. We consulted the GOES (NOAA 2014) catalogue of soft X-rays

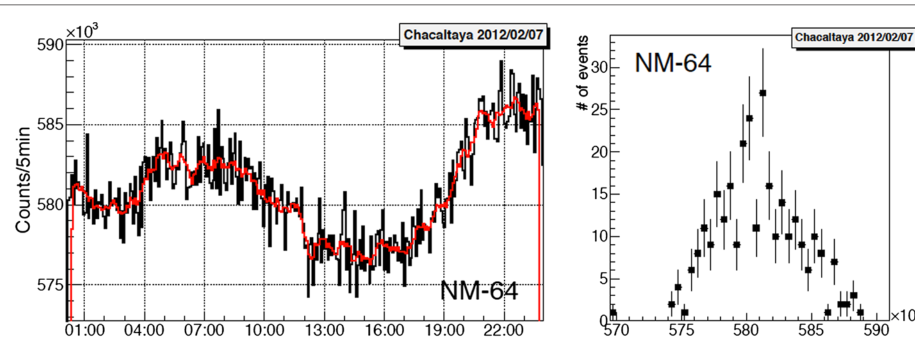

Figure 1 On the left, typical counting rate for 1 day recorded by the NM-64. The red line shows the running average for 30 min. On the right, a 5-min count rate occurrence histogram for the NM-64 on 7 February 2012. Indicated error bars are Poissonian $\pm 1\sigma$.

(SXR). Between January 2010 and August 2013, a number of 300 M-class and 19 X-class solar flares have occurred. Among these 319 solar flares, we selected only those that satisfied the condition that at the onset time (t_0 in local time) of the SXR flux, the solar zenith angle ($\theta_\odot$) at Chacaltaya was lower than 65° yielding a line-of-sight air mass lower than 850 g/cm^2. In Table 1, we list these events and their conditions of observation.

Analysis method

Let us describe how we proceeded with our analysis. First, we set a 'work window' at $t_0 \pm 3$ h. Here, t_0 represents the onset, in local time, of the SXR flux. This first interval includes the backgrounds and the possible excess due to solar neutrons. Then, we define a 'signal window' at $t_0\pm$ 30 min in which we will search for solar neutrons. Even if solar neutrons are emitted at the same time as X-rays, they

Table 1 List of soft X-ray flares observed by GOES (considering initial conditions) and the local time of possible observation in Mt. Chacaltaya

Conditions	Solar flare				Observation site			
Date	Start (UT)	t_P[a] (UT)	Class	Position	t_0[b] (UT-4)	$\theta_\odot$[c] [deg]	Air mass[d] [g/cm^2]	α[e] (NM-64)
2005 Sep 07[f]	17:17	17:40	X17.0	S06E89	13:17	28	612	1.7 ± 0.2
2010 Oct 16	19:07	19:12	M2.9	S20W26	15:07	42	724	1.7 ± 0.3
2010 Nov 06	15:27	15:36	M5.4	S19E58	11:27	12	551	1.8 ± 0.2
2011 Feb 13	17:28	17:38	M6.6	S20E04	13:28	10	541	1.6 ± 0.3
2011 Feb 14	17:20	17:26	M2.2	N56W18	13:20	9	540	1.8 ± 0.2
2011 Aug 03	13:17	13:48	M6.0	N16W30	09:17	60	773	1.9 ± 0.3
2011 Sep 24	12:33	13:20	M7.1	N14E45	08:33	59	792	1.4 ± 0.2
2011 Sep 24	17:19	17:25	M3.1	N15E56	13:19	21	547	1.3 ± 0.2
2011 Sep 24	19:09	19:21	M3.0	N15E54	15:09	43	627	1.6 ± 0.2
2011 Sep 24	20:29	20:36	M5.8	N16E54	16:29	62	786	1.6 ± 0.2
2011 Sep 25	15:26	15:33	M3.7	N16E43	11:26	21	552	1.5 ± 0.1
2011 Sep 25	16:51	16:58	M2.2	S28W75	12:51	17	543	1.7 ± 0.3
2011 Sep 26	14:37	14:46	M2.6	N14E30	10:37	30	580	1.6 ± 0.2
2011 Oct 02	17:19	17:23	M1.3	N09W56	13:19	19	570	1.6 ± 0.2
2011 Nov 03	20:16	20:27	X1.9	N22E63	16:16	58	716	1.5 ± 0.2
2012 Mar 02	17:29	17:46	M3.3	N16E83	13:29	14	543	1.7 ± 0.2
2012 Mar 05	19:10	19:10	M2.1	N14E44	15:10	37	617	1.9 ± 0.2
2012 Mar 10	17:15	17:44	M8.4	N18W34	13:15	15	543	1.9 ± 0.2
2012 Mar 13	17:12	17:41	M7.9	N17W60	13:12	16	543	1.7 ± 0.4
2012 Mar 14	15:08	15:21	M2.8	N14E05	11:08	27	558	1.8 ± 0.2
2012 Jun 03	17:48	17:55	M3.3	N16E38	13:48	43	638	1.8 ± 0.3
2012 Jun 06	19:54	20:06	M2.1	S19W05	15:54	63	824	1.2 ± 0.2
2012 Jul 08	16:23	16:32	M6.9	S17W74	12:23	39	615	1.7 ± 0.2
2012 Jul 12	15:37	16:49	X1.4	S15W01	11:37	41	624	1.6 ± 0.3
2012 Oct 20	18:05	18:14	M9.0	–	14:05	27	554	1.3 ± 0.1
2012 Oct 22	18:38	18:51	M5.0	S12E61	14:38	35	576	1.7 ± 0.2
2012 Nov 21	15:10	15:30	M3.5	N06E05	11:10	17	564	1.7 ± 0.2
2013 Apr 05	17:34	17:48	M2.2	N08E81	13:34	27	565	1.7 ± 0.2
2013 Apr 12	19:52	20:38	M3.3	N20E41	13:52	55	736	1.7 ± 0.2
2013 May 13	15:48	16:05	X2.8	N08E89	11:48	36	602	1.9 ± 0.2
2013 May 22	13:08	13:32	M5.0	N15W70	09:08	62	813	1.8 ± 0.2
2013 Aug 17	18:16	18:24	M3.3	S07W30	14:16	38	615	2.0 ± 0.3

[a]GOES SXR maximum peak time. [b]Flare onset in local time. [c]Solar zenith angle at the onset time. [d]Line-of-sight air mass at the onset time. [e]Normalization factor for the NM-64. [f]The solar neutron event reported by Sako et al. (2006) is also included as a reference for calculations.

will reach the Earth and our detectors delayed from them. We know that neutrons with energy of 1 GeV require about 1.2 min longer than X-rays' travel time to reach the top of the Earth's atmosphere. In contrast, 100-MeV neutrons are delayed by 11 min covering the same distance. This is why we extend the signal window up to 30 min. Neutrons with energies lower than 100 MeV cannot reach the ground. They will be attenuated in the Earth's atmosphere (Shibata 1994). We still cover the case if neutrons are produced for more than 20 min as it occurred in the solar neutron event of 7 September 2005 (Sako et al. 2006). The remaining two time intervals (2.5 h before and after the onset) of the work window are used to estimate the background. This can be done by calculating the running average (N_b) for 20 min with a 3-min counting rate. However, to estimate the background (B_s) at the signal window, we interpolate N_b between $t_0 - 30$ and $t_0 + 30$ min. In Figure 2, we show four of the studied events. It is possible to observe the work and signal windows. In these figures, the whole interval corresponds to the work window. The signal window is enclosed by two horizontal violet lines and a double-direction arrow.

Statistical significances are determined as follows. First, we calculate the deviation of each point of our data from the average background excluding the signal window. Second, we build a background distribution with these data. Then, we fit a Gaussian function to this distribution. The result, however, does not always yield a normal distribution. To obtain a unitary standard deviation (std.dev.), we normalize our data by the standard deviation. We call this parameter 'normalization factor' and symbolize it as 'α' to avoid ambiguity. This factor comes from the multiplicity effect of neutron counts as explained in the previous section. The resulting distribution is fitted again by a Gaussian function. It follows now the behavior of a unit normal distribution. We apply the same α factor to the signal window and calculate a significance distribution. In other words,

$$\xi_b = \frac{N - N_b}{\alpha\sqrt{N_b}} \qquad (t_0 \pm 3\text{ h}) \tag{1}$$

$$\xi_s = \frac{S - B_s}{\alpha\sqrt{B_s}} \qquad (t_0 \pm 30\text{ min}) \tag{2}$$

where N is the observed data from the NM-64, N_b is the averaged background, and α is the factor calculated from the first Gaussian fit. S represents the signal window data and B_s the interpolated background data. In the case that we see an excess of events considerably significant at the signal window, we will regard it as a candidate for a solar neutron event associated with the solar flare.

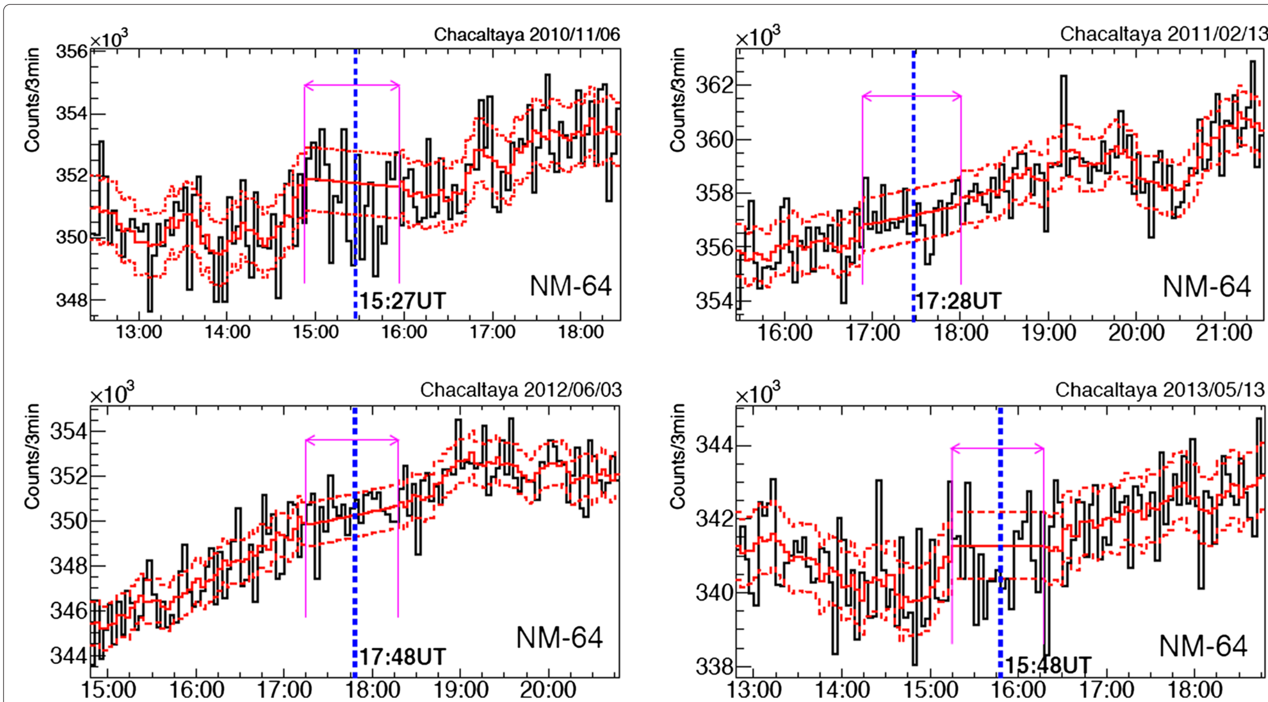

Figure 2 The 3-min counting-rate profiles of the NM-64 for one X-class and three M-class flares. The left- and right-upper panels and the left-lower panel indicate those for the M5.4 (2010/11/06), M6.6 (2011/02/13), and M3.3 (2012/06/03) flares, respectively. The right-lower panel corresponds to the X2.8 (2013/05/13) flare. The interval of the signal window is indicated by horizontal and vertical violet lines. The red thick line represents the average background for 20 min. The red dashed lines which follow the average background are $\pm 1\sigma$ curves. The dashed blue line and the label time show the flare onset (t_0) according to GOES-SXR. The abscissa in all plots represent the time in UT.

Before we proceed with the collected data during the current solar cycle, we applied the analysis method previously described to a solar neutron event that occurred in the past solar cycle. During solar cycle 23, the NMs and SNTs have observed six solar neutron events (Watanabe 2005 and Sako et al. 2006). Here, we will discuss the event which occurred on 7 September 2005 (hereafter the Bolivia-Mexico event). According to the registry of GOES satellite, the onset time of the SXR flux was at 17:17 UT. The maximum intensity reached an X17-class solar flare at 17:40 UT. At the time of the maximum intensity of SXRs, the solar zenith angle and the line-of-sight air mass at Chacaltaya were 28° and 612 g/cm^2 respectively, making it a suitable location to observe solar neutrons associated with this solar flare. On the left of Figure 3, a 3-min count rate of the NM-64 is plotted. The SXR onset time is represented by a dashed vertical line. We can see that at 17:40 UT, the NM-64 started to increase its intensity which lasted for more than 20 min. On the right of this figure, we can observe the resulting distributions after being normalized by the α factor (shown in Table 1). The black-hatched distribution which corresponds to the signal window shows several positive excesses due to this event. The background is represented by a blue line distribution exhibiting a Gaussian behavior.

Results

Having tested our analysis method with the Bolivia-Mexico event, we applied the same procedure to the events listed in Table 1. To do that, we first constructed time profiles per 3 min. Next, we set the working and signal windows and then we calculated the normalization factor for each of the events listed in Table 1. The 'α' factor distribution for the NM-64 exhibits a Gaussian-like behavior with mean equals to 1.73 ± 0.03. This variation comes from the multiplicity effect that the NM provides.

In Figure 4, we show two of the events analyzed by the method described in the previous section. Both distributions show a normal behavior. By observing the black-hatched distribution, we can clearly see that no positive enhancement is observed in the signal window. Including those events shown in Figure 4 and the other events listed in the Table 1, we could not find any statistically significant (and positive) excess. We hence concluded that our data do not contain a solar neutron signal associated with solar flares.

To further validate our not finding solar neutron signals within the period of our analysis, we calculated the probability of obtaining no successful events. We considered the number of solar neutron events detected in the last solar cycle compared with the number of solar flares which exceeded X2.3[a] class. In solar cycle 23, the number of solar neutron events detected in Chacaltaya is four, whereas the number of solar flares greater than X2.3 class is 43. In this analysis, the number of solar flares greater than X2.3 class is six. Therefore, the probability that a solar neutron event will not occur is 0.57, if GOES SXR classification is an indicator of solar neutron events.

Upper limit of the number of solar neutrons

Having not found a statistically significant excess within our selected dataset, we proceeded to calculate the upper limit for solar neutron observation. We can do this if we assume that when a solar flare occurs, solar neutrons will

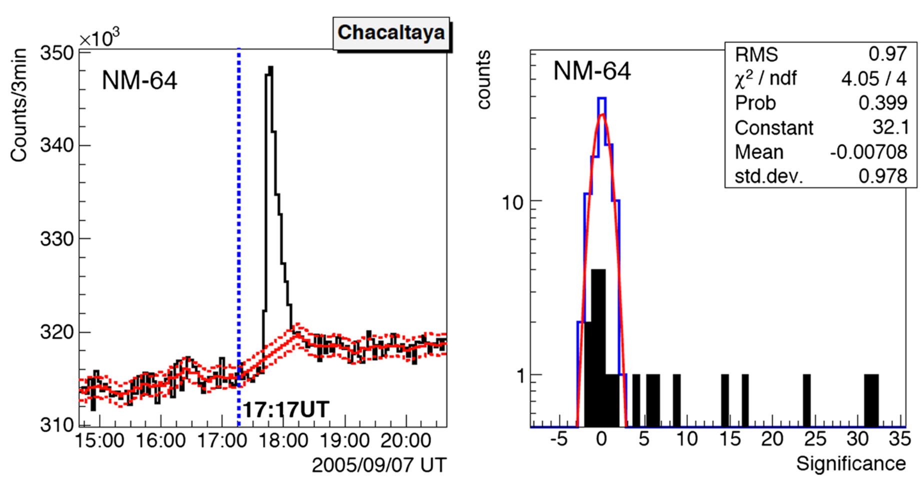

Figure 3 On the left, time profile of neutrons for the Bolivia-Mexico event observed by the NM-64 in Mount Chacaltaya. The blue dashed line at 17:17 UT (13:17 local time) represents the time of the onset for the SXR intensity recorded by GOES. The red thick line corresponds to the running average for 20 min. The red dashed lines are $\pm 1\sigma$ calculated without including the signal window. The abscissa corresponds to the time in UT. On the right, the statistical analysis following the same procedure described in this section. In this case, we obtained a significant excess equivalent to 32σ. More details can be found in Sako et al. (2006).

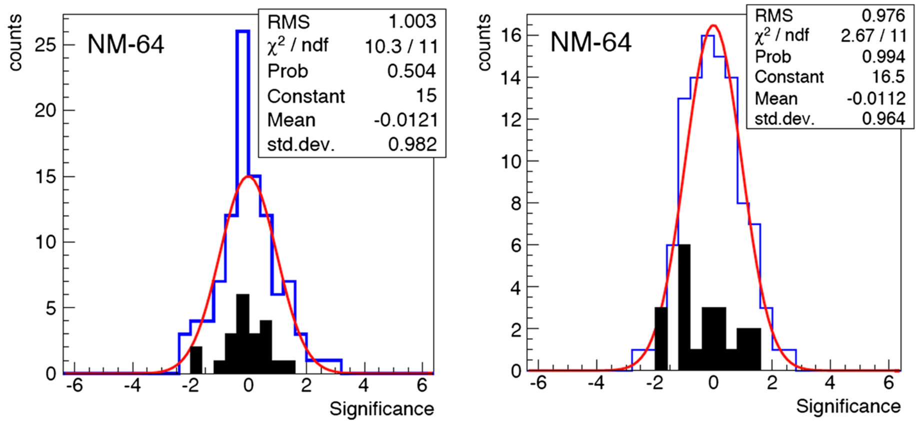

Figure 4 In both figures, the background distribution is well fitted by a Gaussian curve, represented here as a red thick line. The overlapped black-hatched area shows the significance distribution for the signal window. On the left, the results for the event occurred on 13 February 2011. On the right, the results for the event which occurred on 13 May 2013.

be produced at the same time (δ-emission) as SXRs. Let us consider the solar flare that occurred on 13 May 2013. It was recorded and classified by GOES as X2.8. The SXR flux onset was at 15:48 UT. On this day, our analysis method does not give a statistically significant excess in our data from the NM-64.

We perform the calculation of the upper limit of the excess signal, which actually was not detected, as below. First, we define the detection threshold N_{min} of solar neutrons as a 3σ excess over the background. When we consider the upper limit, we take into account the fluctuation of the signal plus background, then our upper limit is the value which gives less than N_{min} within 90% C.L. of signal plus background. We thus obtained $N_U = 11{,}450$ counts as the upper limit for the NM-64.

To estimate the number of neutrons at the Sun, we assume the energy spectrum of neutrons at the Sun as: $f(E) = C \times \left(E/100[\,\mathrm{MeV}]\right)^{-3}$

This spectrum is modified due to the decay of neutrons as:

$$F(E) = \Omega\, P(E)\, C \left(\frac{E}{100[\,\mathrm{MeV}]}\right)^{-3} \qquad (3)$$

Here, Ω is the area factor and P(E) is the neutron decay probability. This spectrum is further modified by the attenuation in the atmosphere and the detector's response. We considered the detection efficiency of the NM which was calculated by Clem and Dorman (2000), and the neutron's attenuation in the Earth's atmosphere which was calculated by Shibata (1994) taking into account the zenith angle of the Sun ($\theta_\odot = 36°$). The area factor is given by (area of the detector)/$(4\pi(1[\,\mathrm{AU}])^2)$.

We consider neutrons exceeding 70 MeV, because lower energy neutrons are extremely attenuated in the atmosphere. By integrating Equation 3 from 70 MeV to 1 GeV taking into account these modifications and compared the result with N_U, we obtained 1.07×10^{27}[/MeV/sr] as C. Finally, our neutron spectrum will be like:

$$f(E) = 1.07 \times 10^{27}[\,/\mathrm{MeV/sr}] \left(\frac{E}{100[\,\mathrm{MeV}]}\right)^{-3}$$

We performed a similar calculation with the Bolivia-Mexico event (the positive signal lasted for about 30 minutes). In this case we considered real signal excess as the one corresponding to N_U and obtained 7.33×10^{27}[/MeV/sr] as the upper limit. This is a factor of seven times larger than the one we calculated when no neutron signal was observed.

Conclusions

To further proceed in our better understanding of the acceleration mechanism of high-energy particles, we searched for solar neutrons during the current solar cycle using the detectors installed at Mount Chacaltaya. Our examination included data in the period of January 2010 to August 2013 where more than 319 X-ray solar flares classified as greater than M1 occurred.

One of our results is that, with our analysis method no statistically significant solar neutron signals were found from our sample which consisted of 28 M-class and 3 X-class flares. The second result is the estimation of the upper limit for solar neutrons to arrive at Chacaltaya and obtained 1.07×10^{27}[/MeV/sr] at the Sun. Applying similar calculation to the Bolivia-Mexico event, the upper limit for this solar neutron event is 7.33×10^{27}[/MeV/sr].

Endnote

[a]In solar cycle 23, the 24 November 2000 (Watanabe et al. 2003) solar neutron event detected by the NM-64 was the

smallest X-class among the six successful detections in this solar cycle.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
DL performed the statistical analysis and upper limit calculation. DL and YM drafted the manuscript. Both authors read and approved the final manuscript.

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