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Sensitivity of the SciBar Cosmic Ray Telescope (SciCRT) to solar neutrons

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The SciBar Cosmic Ray Telescope (SciCRT) is aimed to help elucidate the acceleration mechanism of high-energy ions that may produce neutrons at the Sun. It is a fully active scintillator tracker which consists of 14,848 plastic scintillator bars, originally constructed for accelerator neutrino oscillation experiments. The SciCRT; it has a huge detector volume compared with conventional Solar Neutron Telescopes (SNTs), e.g. 15 times larger than Mexico SNT. Furthermore, the SciCRT can measure the energy deposition of each particle as neutron ADC data which have not been registered before. Neutron ADC data provide us with a precise measurement of energies deposited at the detector. The SciCRT was deployed at the summit of Mt. Sierra Negra (4,600 m) and began to acquire data in September 2013. Then we partially upgraded the DAQ system developed originally for an accelerator experiment, as the readout rate of the DAQ system was significantly limited for our experiment.

This paper highlights sensitivity numerical studies of solar neutrons that the SciCRT is able to register. At first, we focus in the accuracy to determine the spectrum power-law index, assuming an instantaneous emission of solar neutrons. This is required to determine the power-law index within an error of ± 1.0 in order to discuss the efficiency of the acceleration. Then in the case of the fixed power-law index, we discuss the capability of discriminating three different lengths of emission times: 0 min, 5 min, and 8 min. Finally we evaluate whether it is possible to discriminate a different combination of these two parameters simultaneously. Thus, we show that data from the SciCRT will unlock the degeneracy problem amid the emission time and the energy spectrum of solar neutrons.

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1. Particle acceleration by solar flares and observations of solar neutrons

Cosmic rays have thus far been researched over the course of more than 100 years. It is well known that the spectrum has a wide energy band which ranges from 10^8 eV to about 10^{20} eV. Although the maximum energy of cosmic rays accelerated at the Sun reaches to a few tens of GeV at most, it is the most well-known cosmic-ray source and permanently monitored by observatories at various wavelengths. On the other hand, the acceleration mechanism of cosmic rays arriving at the Earth has been an unresolved problem of cosmic-ray physics. In that sense, research on solar cosmic rays is a meaningful task for cosmic-ray physics.

Solar wind and neutrinos are regularly radiated from the Sun. On the other hand, high energy particles are sometimes blown from solar flares. Solar flares release magnetic energy through the magnetic reconnection process [1]. A part of the magnetic energy is subsequently interchanged to accelerate particles, namely electrons and ions. As a matter of fact, magnetic reconnection has been discussed as one of the acceleration processes for cosmic rays in the universe, e.g. blazer flares (e.g., [2]) and pulsar wind nebulae (e.g., [3]). The acceleration of electrons has been studied by observations of hard X-rays and radio waves, whereas that of ions has been researched by observing gamma rays and neutrons. Neutrons are produced only by interaction between accelerated ions and the ambient plasma. The spectrum of solar neutrons is, in many cases, harder than that of accelerated ions. What can we know from observations of solar neutrons? We can have important clues to understand the acceleration mechanism of parent ions from the spectrum shape of solar neutrons [4].

Solar neutrons have been observed at satellite-onboard detectors and ground-based telescopes. Since neutrons are attenuated by the Earth's atmosphere, ground-based telescopes are sensitive to relatively high-energy solar neutrons (>100 MeV) [5]. In contrast, low-energy solar neutrons may be directly detected by satellite-onboard detectors. Actually, solar neutrons have been first detected by Gamma-Ray Spectrometer (GRS) onboard the Solar Maximum Mission (SMM) satellite in 1980 [6]. High-energy solar neutrons have been observed by using Neutron Monitors (NMs) and Solar Neutron Telescopes (SNTs) [7]. NMs are sensitive to high-energy neutrons which are thermalized and changed into alpha particles or protons. Thus, the energy spectrum of solar neutrons can be estimated by time of flight (TOF) method [7] assuming we know the time distribution

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of neutrons emitted at the Sun. On the other hand, SNTs have the capability to directly measure the energy of neutrons roughly. However, the capability has not been sufficiently utilized for almost all the events ever detected, because of low neutron statistics. Alternatively, the TOF method was applied to some events as well as the case of NMs. But the TOF method are followed by the degeneracy problem between the arrival time and energies of solar neutrons. There are only two events that the energy spectrum is directly measured by SNTs. One of them is the most recent event simultaneously detected by Mexico SNT, Bolivia SNT, and the solar neutron detector onboard the International Space Station on July 8, 2014 [8]. The other one is the most significant one occurred in 2005 September 7 [9] [10] [11] [12]. Solar neutrons were observed by two different SNTs in Mexico and Bolivia simultaneously. This enabled us to put a constraint on the emission of solar neutrons. It is necessary to obtain such events more and more.

This paper focuses on the capabilities of ground-based observations of solar neutrons by using a new solar neutron telescope called SciCRT. It is motivated to detect more solar neutron events with its high statistics and resolve the degeneracy problem. In Section 2, we summarize the detector part of the SciCRT and the current status. Section 3 describes our studies on the expected sensitivity of the SciCRT to solar neutrons.

2. SciBar Cosmic Ray Telescope (SciCRT)

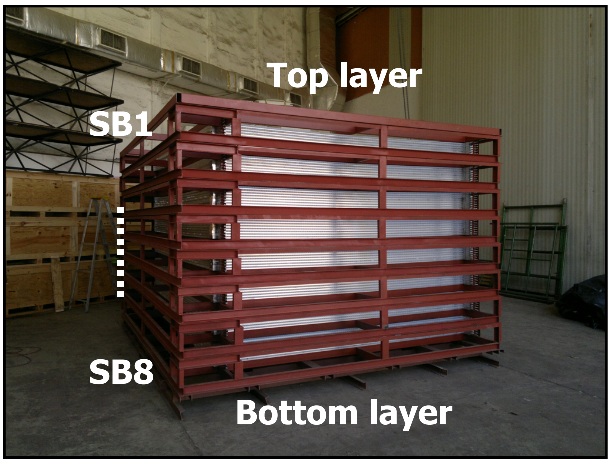

Figure 1: An image of the SciCRT detector. Scintillator bars are contained in an iron-based structure for supporting the weight of all bars. The detector is functionally divided into two operation modes: i) the top and the bottom layers, are employed for muon selection and as charged particles veto counters to the other part. ii) the central tracker, is divided to eight blocks called Super Blocks (SBs). Neutrons are detected using the central tracker.

In 2013, the SciCRT [13] was installed at Mt. Sierra Negra (about 4,600 m) in Mexico. The hut of the SciCRT is neighboring to that of Mexico SNT [14]. The SciCRT aims to observe high-energy solar neutrons to contribute to elucidate the acceleration mechanism of ions by solar flares and muons for studying the transport of galactic cosmic rays in the heliosphere and space weather. It uses the SciBar detector [15] which was constructed for K2K and SciBooNE experimets. Table

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Table 1: Specification of the SciCRT compared with that of Mexico SNT.

	SciCRT	Mexico SNT
Total volume (m^3)	15.3	1.2
Number of scintillators	14,848	4
Thickness of one segment (cm)	1.3	30
Energy threshold for scintillators (MeV)	14	30, 60, 90, 120
Output information	Neutron scaler and ADC	Scaler for 4 scintillators

1 shows the specifications of the SciCRT compared with the Mexico SNT. The detector volume of the SciCRT is about 15 times larger. Therefore, it is clear that the SciCRT is sensitive to low statistical events in comparison with the Mexico SNT. Furthermore, this detector is characterized as a fully active scintillator tracker with fine segmentation. It is to say that we can obtain energies of neutrons particle by particle and a continuous spectrum curve. SNTs always record the counting rate for four different energy threshold levels by scaler. On the other hand, the SciCRT records not only the counting rate by neutron scaler but also the energy deposit as neutron ADC data.

This detector consists of 14,848 plastic scintillator bars, with a dimension of $300\times300\times170$ cm^3. Each scintillator bar has $1.3\times2.5\times300$ cm^3. Sets of 116 scintillator bars are arranged in a plane and two planes are orthogonally attached. This combination of two scintillator bar planes is called a layer. Every scintillator bar has a hole to put a wave-length shifting (WLS) fiber. Scintillation photons from one end of the 64-bundled WLS fibers are read out by a 64-channel Multi-Anode PhotoMultiplier Tube (MAPMT).

Figure 1 shows an image of the SciCRT detector. The SciCRT has two simultaneous operation modes: in one of them, the topmost layer and the bottommost layer (called muon layers), are used as a muon telescope and as active veto counters for charged particles. The central part is divided into eight Super Blocks (SBs). They are arranged from top to bottom as SB1 to SB8 as indicated in Figure 1. Every SB consists of eight layers, each with a dimension of $20.8\times300\times300$ cm^3.

The SciCRT has been under continuous operation using muon layers and three SBs (SB1-3) since September 2013. The sensitivity of the SciCRT to solar neutrons was significantly limited by the dead time of the DAQ system originally developed for the accelerator experiments, because background neutrons are dominant for our observational environment at 4,600 m. Therefore, we developed a fast readout DAQ system for the SciCRT which was installed into muon layers and one SB in July 2016 [16]. We have analyzed data obtained by the SciCRT, but no candidates have been found for any solar neutron events yet. For the simulations performed in this work, we assume that the new DAQ system is implemented on muon layers and four SBs in the following section.

3. Sensitivity of the SciCRT to solar neutrons

We mentioned about the degeneracy problem between the arrival time and energies of solar neutrons in Section 1. Here we demonstrate whether the SciCRT has a capability to discriminate

Table 2: Input parameters used in the MC simulation.

Altitude of Mt. Sierra Negra	4,600 m
Vertical cutoff rigidity	8 GV
Force field potential	750 MV
Zenith angle of the Sun	17°.5

Table 3: Reduced χ^2 to fit each combination of two energy spectra; E_s and E_e. E_s is the assumed energy spectrum and E_e is the background included energy spectrum.

E_s \ E_e	Impulsive	5 min	8 min
Impulsive	1.0230	1.1943	1.9603
5 min	1.1852	1.0149	1.5897
8 min	1.9453	1.5923	1.0173

different types of the neutron emission.

We assumed the same background situation as the solar neutron event occurred in 2005 September 7. Table 2 shows several input parameters we used in the MC simulation. In this simulation, the energy spectrum of solar neutrons at the Sun is followed by a power-law function such as the equation 3.1.

$$dN/dE = k_0(E/E_0)^{\gamma} \tag{3.1}$$

In addition to that, neutrons are emitted impulsively or gradually with some duration time. In this simulation, we used a couple of general simulation packages. The Shibata model [5] is employed to calculate the propagation of solar neutrons in the atmosphere. Particle and Heavy Ion Transport code System (PHITS) [17] is used for background estimation. The response of the detector is calculated by GEANT4 [18] [19].

Figure 2 shows three kinds of energy spectra reconstructed from neutron ADC data. The power-law index of all spectra is fixed to -3.4. The difference between them is the emission duration: 0 min (impulsive), 5 min, and 8 min, respectively. We prepared two different MC sets for each energy spectrum. One is an ideal energy spectrum not including background fluctuation and the other one is an actual energy spectrum including background fluctuation. Then we can compare the ideal energy spectra with the actual energy spectra by using the reduced χ^2 method as shown in Table 3. According to our calculations of the confidence level, it is possible to discriminate between the impulsive emission and the 8 min duration or the 5 min and 8 min durations.

Figure 3 illustrates the time profiles based on neutron ADC simulated data. Each color shows different combinations of the power-law index and duration time of the emission of solar neutrons.

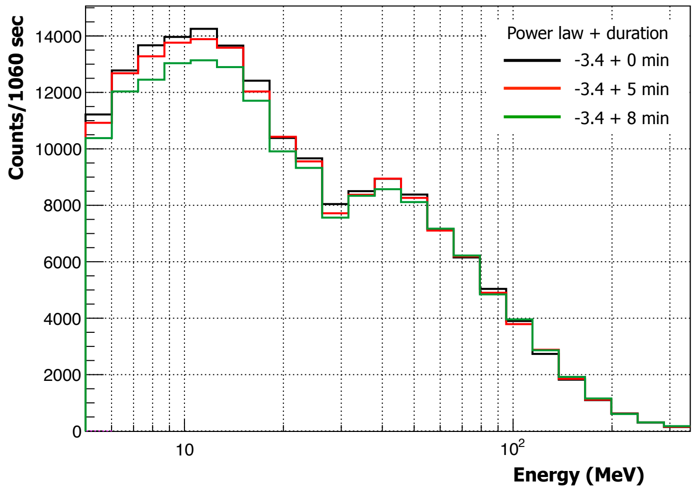

Figure 2: Energy spectra derived from neutron ADC data estimated in the Monte Carlo simulation. The black line is an energy spectrum assuming an impulsive neutron emission. The red and green lines are spectra assuming the neutron emission with durations of 5 and 8 minutes, respectively.

Because the time profile strongly reflects the difference of the emission duration, it is evident that it makes a large difference of the shape in comparison with the energy spectrum. Although the shape of the green line is quite similar to that of the orange line, the difference will be increased as the threshold energy of the time profile is increased. For the sake of identification of the acceleration mechanism of parent ions, the power-law index should be determined with accuracy ± 0.5 at most. Therefore, we can conclude that it is possible to determine the power-law index and the emission duration independently.

4. Summary

The SciCRT is motivated to help elucidate the acceleration mechanism of ions at the Sun by observing solar neutrons. Although the energy spectrum of solar neutrons has been estimated from data of SNTs and NMs, there was a constraint on the assumption of the time generation distribution of solar neutrons at the Sun. Since the SciCRT can record not only the counting rate but also the energy deposit of neutrons directly, it is expected to resolve the degeneracy problem between the arrival time and energies of solar neutrons. In this paper, we have discussed whether the emission of solar neutrons may be resolved by the SciCRT. When we try to find the difference by the energy spectrum of deposited energies, it is possible to discriminate between the impulsive emission and a gradual 8 min emission duration. We found that the time profile calculated from neutron ADC data enables us to clarify the power-law index of the energy spectrum of solar neutrons and the emission duration.

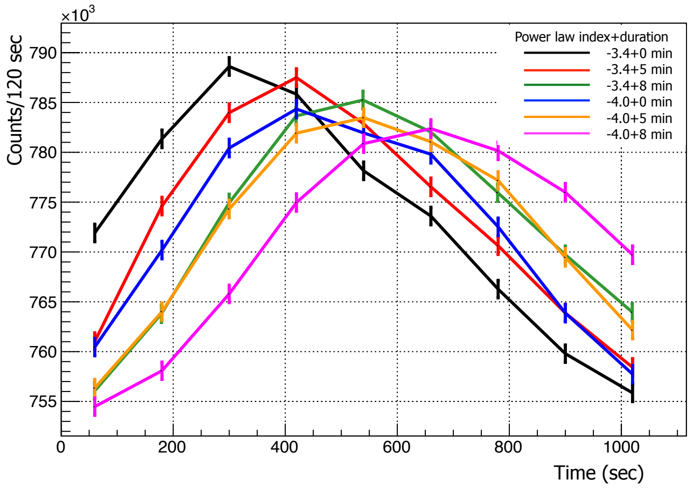

Figure 3: Time profiles derived from neutron ADC data assuming different power-law indices and emission durations. Each broken line has a different combination of the power-law index and the emission duration. Each point shows the count rate for 2 minutes with its statistical error.

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