Emission profile of solar neutrons obtained from the ground-based observations for the 7 September 2005 event

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Abstract: Strong signals of energetic neutrons associated with the solar flare of 7 September 2005 were detected by using the Solar Neutron Telescopes (SNTs) located at Mt. Chacaltaya in Bolivia and Mt. Sierra Negra in Mexico, Neutron Monitors (NMs) located at Mt. Chacartaya and Mexico City. In a previous work, the observed profiles indicate a continuous emission of neutrons. In this paper, we present the results of a unique analysis of the SNT data to obtain energy spectrum of the neutrons. The SNT channels of different response functions in energy enabled us to obtain spectrum without any assumption of the emission time profile. The result is consistent with the previous and independent studies, which indicate a differential power law index of 3. This supports the previous conclusions that the emission of the neutrons and γ-rays started at the same time and neutrons were continuously emitted. A marginal inconsistency about the existence of a spectral cutoff at around 500 MeV may indicates some more complicated scenario.

Introduction

Observations of neutral emission are important keys to understand the nature of ion acceleration near the solar surface. Among various neutral emissions (radio, X-ray, γ-ray continuum, γ-ray line), advantages of the neutron observations are that 1) neutrons are purely emitted from ions, 2) kinetic energy of the neutrons reflects that of ions. On the other hand, there is a diffi culty of the solar neutron observation due to the fact that a neutron has mass and its flight time to the earth is a function of its kinetic energy. Solar neutrons have been mainly observed by Neutron Monitors (NMs) installed over the world. Because the NMs are not capable of measuring the energy of the neutrons, we can not separate energy spectrum and emission duration from its count profi le. In the analyses of the NM data, we usually assume the emission profi le identical to that of high energy radiations and determine the energy spectrum of the neutrons from their time-of-flight ([4], for example). However because the parent particles of the neutrons and radiations are not identical, this assumption is not trivial.

Solar Neutron Telescopes (SNTs) were designed and installed in high altitude mountains to solve this problem. It has the capability of measuring the

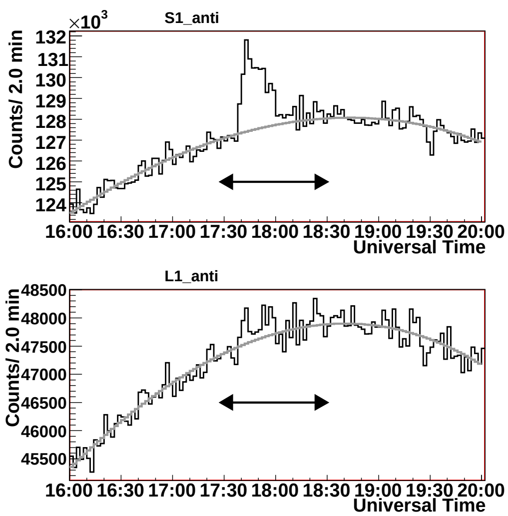

Figure 1: 2 minutes counting rates of the Mexico SNT. Top) Neutral particles measured at the lowest threshold scintillator channel. Bottom) Neutral particles penetrated into the first layer of the PRC below the scintillator. Histograms show the observed count and the smoothed curves indicate the estimated background. Arrows indicate the time window to integrate the total excess count.

energy and is expected to solve the degeneracy of the spectrum and the emission duration. In this paper, we introduce a new kind of analysis based on the data taken by the Mexico SNT in the 7 September 2005 solar neutron event. Here we concentrate on the analysis of the energy spectrum, which is free from any assumption of the emission profile. This is an important step to extract the true emission profile of neutrons.

Observations

Strong neutron signals were detected in association with the solar flare occurred on 7 September 2005 [1]. The X-ray flux peaked at 17:40 UT and was classified as X17.0. The flare occurred in AR 10808, which was located at S06°, E89°. Ground-based observations were made by the SNTs in Mexico (Sierra Negra) and Bolivia (Chacaltaya), NMs in Mexico (Mexico city) and Bolivia (Chacaltaya). Parts of the observed data by the Mexico SNT ([3]) are shown in Figure-1. The Mexico SNT has plastic scintillators of a 4 m^2 area and 30 cm thickness covered by proportional counters (PRCs) as anti-counters. Scintillator signals are discriminated by four different energy thresholds (30 MeV, 60 MeV, 90 MeV and 120 MeV) and they are designated to be *S1*, *S2*, *S3*, *S4*, respectively. Scintillator signals without associated anti-counter signal are regarded as generated by neutral particles and designated like *S1_anti*. Four layers of PRCs are installed below the scintillators and coincident signals with *S1_anti* are named as *L1_anti*, *L2_anti*, *L3_anti and L4_anti*. In Figure-1, 2-minutes counting rates of *S1_anti* and *L1_anti* are presented. We can see a strong excess in the *S1_anti* but only a marginal increase in *L1_anti*.

Analysis

To estimate the primary neutron energy spectrum , we integrated the counts of each channel recorded between 17:30 UT and 18:30 UT as indicated by arrows (N_{tot}). Background counts are estimated from 3-rd order polynomial fit, as plotted in the Figure, excluding 17:30 UT – 18:30 UT. The statistical significances (excess/$\sqrt{N_{tot}}$) of each channel are 16.6, 12.0, 9.9, 6.2, 2.7, 1.7, 1.6 and 1.8 for *S1_anti*, *S2_anti*, *S3_anti*, *S4_anti*. *L1_anti*, *L2_anti*, *L3_anti*, *L4_anti*, respectively. So the detections in the scintillator channels are significant but marginal in the lower PRC channels.

Because the responses of each channel have different energy dependence, the relative count among channels must be sensitive to the energy spectrum of primary neutrons. To have a general idea of this energy dependence, the detection efficiencies of each channel are shown in Figure-2 as functions of neutron kinetic energy at the top of the detector. In this calculation, we used GEANT3 and distributed neutrons uniformly over the detector in the vertical direction.

To simulate the case of the 7 Sep event, we assumed that the neutrons had a power law energy spectrum at the sun. We calculated the β-decay of neutrons in flight and attenuation in the earth's atmosphere [2] including the actual atmospheric depth and the solar angle at Sierra Negra at the flare time. The relative counts normalized to *S1_anti* are

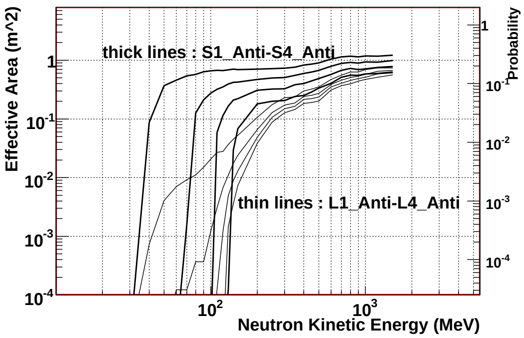

Figure 2: Response function of various channels of the Mexico SNT. Detection efficiencies (right axis) of each channel are plotted as functions of the neutron kinetic energy at the top of the detector. In the calculation, neutrons were uniformly distributed over the detector with a vertical injection angle.

plotted in Figure-3 for some differential power law indexes, 2–5, assumed in the simulation. The plots with error bars are the results of observation. Error bars are calculated based only on the statistical errors as described above.

Results

From Figure-3, we can conclude that the most likely power law index is 3. This is consistent with the results of [1] and [5] where indexes were estimated to be 3.2 and 3.1, respectively, based on the analyses of the Bolivia NM data and γ-ray profile. This is very important that we have obtained the index without any assumption of the emission time and duration that was necessary in the previous studies. The consistent results of two independent analyses with different data sets supports the assumptions and the conclusions in the previous analyses. Those are: 1) emission of the neutrons started at a same time with the γ-ray radiations. 2) The neutrons were emitted continuously.

Here we must note that in the previous works, a single power law model could not fit the observed counting profile very well. They have concluded a truncated spectrum at 400–500 MeV can fit the

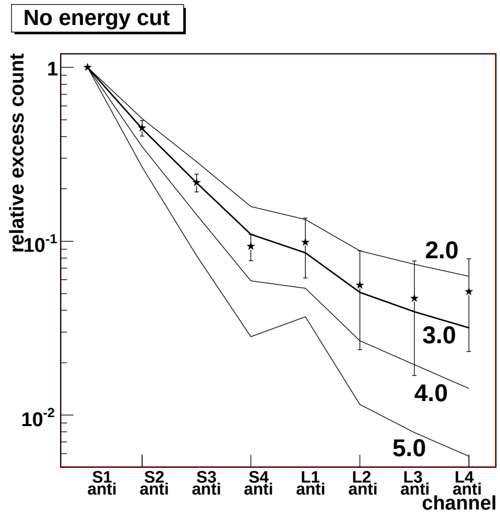

Figure 3: Relative excess counts of various channels. Plots are results of the Sep 7 events with statistical errors. Solid lines show expected counts for different neutron spectra. Neutron spectra are assumed to be power laws with indexes indicated at each line.

data very well. We tested spectra with a cutoff at 500 MeV and results are shown in Figure-4. The result indicates a slightly harder index than 3.0. Of course the difference is within the statistical errors and not significant.

Conclusions

We have analysed the solar neutron data observed by the Mexico SNT on 7 September 2005. The data showed excesses in several channels those have different response functions in energy. We demonstrated the relative excess counts of these channels are sensitive to the spectrum of the primary neutrons. The comparison between the observed data and the MC expectation indicated the differential power law index of the neutron spectrum was likely to be 3, that is consistent with the completely independent analysis from the Bolivia NM data and γ-ray profile. This supports the assumptions and conclusions made in the previous work. However, our analysis preferred a single power law spectrum though the previous work in-

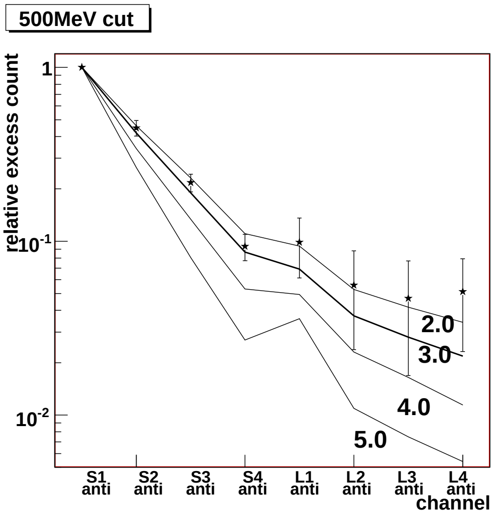

Figure 4: Same as Figure-3, but spectra truncated at 500 MeV.

dicated a cutoff at around 500 MeV. Because the result is marginal and sensitive to the detector calibrations, we must first carefully treat the systematics.

If the discrepancy becomes true, a possible solution is a time evolution of the neutron spectrum that is ignored in the analyses of the previous and current works. High energy cutoff was introduced to explain the slow rise in the NM counting profile. However, if there are high energy component as indicated in this study, they must be emitted not in the fast phase but some later time. If such delayed high energy neutrons exist, it can be found with analyses like this paper but for time interval slices. We can test also this and other kinds of models in further detail with fruitful data of the Mexico SNT, Bolivia SNT, Mexico NM and Bolivia NM. Time dependent analyses of all the available data sets will lead us to the final goal to decide the energy spectrum and emission profile of neutrons at the Sun only from the neutron observations. Consequently, we will understand a behavior of high energy ions near the solar surface.

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References

[1] T. Sako et al. Long-lived Solar Neutron Emission in Comparison with Electron-Produced Radiation in the 2005 September 7 Solar Flare. *ApJ*, 651:L69–L72, 2006.

[2] S. Shibata. Propagation of solar neutrons through the atmosphere of the Earth. *JGR*, 99:6651–6665, 1994.

[3] J. F. Valdés-Galicia et al. An improved solar neutron telescope installed at a very high altitude in México. *NIMA*, 535:656–664, 2004.

[4] K. Watanabe et al. Solar Neutron Events of 2003 October-November. *ApJ*, 636:1135–1144, 2006.

[5] K. Watanabe et al. Ion acceleration and neutral emission mechanisms for 2005 September 7 flare. In *International Cosmic Ray Conference, 30th, Merida, Mexico, July 3-11, 2007, Conference Papers*, 2007.