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Highest Energy Neutrons Detected by a Solar Neutron Telescope in Association with the November 28th 1998, Solar Flare

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A large flare was observed at N17E32 on the solar surface at 5:31 UT with an intensity of X3.3 as measured by the *GOES* satellite. In association with this flare, the solar neutron telescope located in Tibet ($600\,\mathrm{g/cm^2}$) observed an enhancement from the direction of the Sun. In this paper we discuss the possibility that this enhancement was caused by high energy neutrons. If confirmed, this is the first evidence of solar neutrons with energy beyond 10 GeV, and shows that even during winter in the northern hemisphere we can detect solar neutrons under some conditions if we use the telescope function.

1. Neutron event on November 28th, 1998

In the conference proceeding of 26th ICRC, the authors reported the arrival of solar neutrons in association with a large solar flare on November 28th 1998 [1, 2, 3]. In this paper we report further results of the data analysis for this event.

On November 28th 1998, an X3.3/3N solar flare was observed at N17E32 in active region 8395. According to *GOES* spacecraft data, the flare onset time and the maximum time were 4:54 UT and 5:52 UT respectively. A complicated loop structure was observed by the soft X-ray telescope on board *Yohkoh*. The loop started growing at ∼5:30 UT with thermal emission from the loop reaching a maximum intensity at ∼5:50 UT. *Yohkoh* detected hard X-ray emission ($93 - 252$ keV) between 5:39 UT and 5:43 UT (the peak time was ∼5:41 UT). *CGRO*/BATSE also detected hard X-ray emissions ($30 - 58$ keV) with the peak at 5:40:46 UT. Hard X-ray emission started at 5:31:26 UT with a rapid increase beginning at 5:38 UT. The Nobeyama Radio heliograph detected radio emission at a frequency of 17 GHz and 34 GHz with the maximum emission observed at 5:39:51 UT.

We have investigated the time profile obtained from the Tibet solar neutron telescope near the time when the solar flare occurred. There is no noticeable enhancement of the counting rate obtained by the upper scintillators. In this respect, the data from the upper scintillation counters shows the same behavior as the data from the neutron monitor in Tibet [4].

Quite surprisingly, as shown in Figure 1, the higher energy counting rate from the south (the direction of the Sun) clearly shows an enhancement in comparison with the (off-source) data obtained from the north. The neutron telescope detects neutrons higher than 270 MeV and is also sensitive to photons with energy higher than 80 MeV. The difference in the threshold energy comes from the difference in ionization loss between

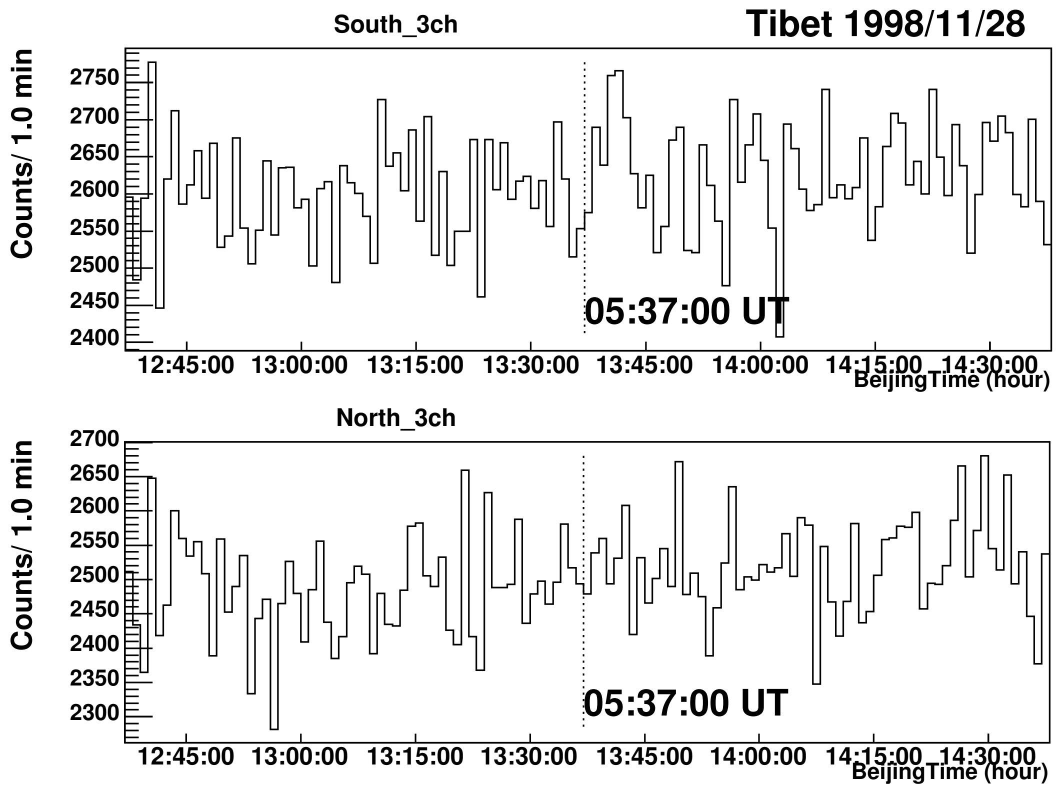

Figure 1. Comparison of the flux of neutrons from the north and the south directions. Three directional data for the north and the south were summed up independently. The vertical dotted line indicates the start time of rapid increase of the hard X-rays. An increase of counting rate can be seen for 5 minutes in the data from the south (solar direction), but no excess has seen in the data from the north.

electrons and protons since low energy protons lose more energy in the scintillator and the wood than electrons. In the first stage of the data analysis, we did not considered a possible contamination of high energy photons in neutron events since photons are much more strongly absorbed in the atmosphere than are neutrons. (This is not true if the energy of the photon is over $10\,\mathrm{GeV}$, at which point a few particles produced by the cascade shower arrive at high altitude.) In Figure 2, the counting rate of secondary particles produced by vertically incident neutrons is shown, based on a Monte Carlo calculation made using GEANT4. In the calculation a power law spectrum of incoming solar neutrons is assumed with $\gamma = -2.5$ in the energy range $E_n = 1$ to $100\,\mathrm{GeV}$. From Figure 2, the number of neutrons over $270\,\mathrm{MeV}$ at Tibet is estimated as to be 0.05 event per high energy neutron (over an area equal to that of the detector) at the top of the detector and 0.045 event for each photon with energy higher than $80\,\mathrm{MeV}$. This implies that the attenuation of electrons and neutrons is the same order of magnitude and we could expect to see an effect due to photons when high energy neutrons interact at the top of the atmosphere.

Taking into account the zenith angle of the Sun at the time of the event, the atmospheric mass between the Sun and the detector was actually $750\,\mathrm{g/cm^2}$. In this case, the number of counts in the detector that simulate neutrons above $270\,\mathrm{MeV}$ is estimated to be more than 0.008 per neutron incident at the top of the atmosphere and more than 0.012 per photon incident at the top of the atmosphere. We estimate the sensitivity by the multiplying the attenuation of each component by the detection efficiency. The result, obtained from the

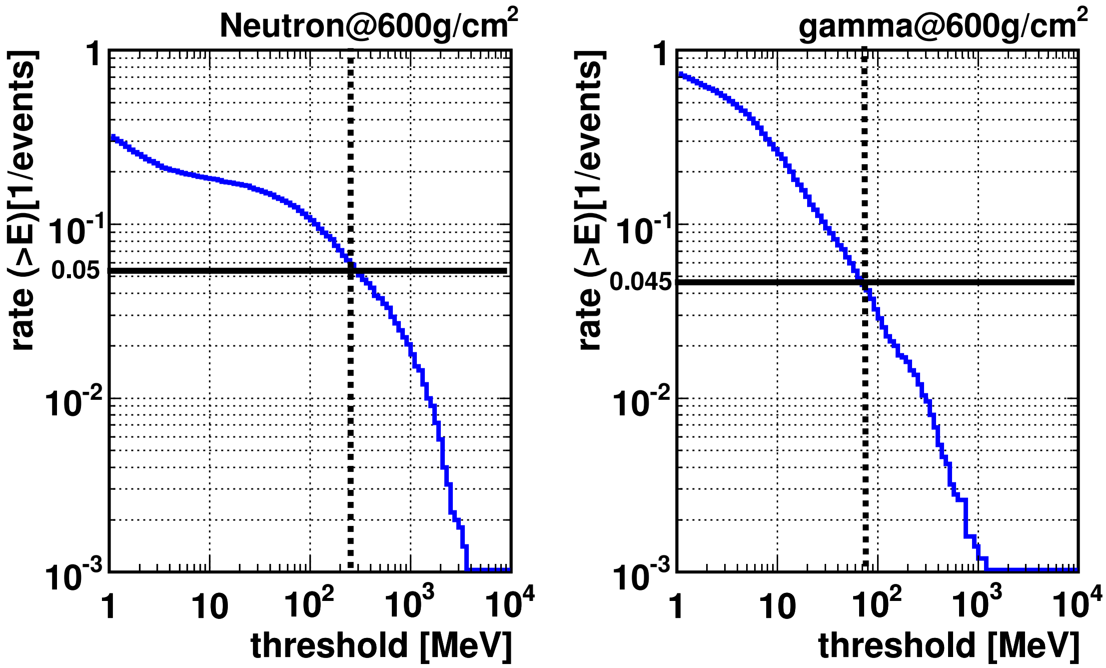

Figure 2. Counting rate of secondary particles produced by neutrons for vertical incidence at the Tibet altitude derived from a Monte Carlo calculation using GEANT4. The vertical dotted line of the left panel corresponds to the threshold energy $E_n > 270$ MeV for neutrons and the vertical dotted line of the right panel represents the energy of photons $E_\gamma > 80$ MeV which can penetrate to the bottom of the detector.

Monte Carlo calculation and analytically based on the data is 0.25% and 0.2% for neutrons (> 270 MeV) and photons (> 72 MeV) respectively. Again we can expect the same order of magnitude number of photons and neutrons at the top of the detector.

2. A new interpretation for the November 28th 1998, event

On February 22nd 1999, Japanese solar physicists who observe the Sun at different wave lengths met at the Solar-Terrestrial Environment Laboratory, Nagoya University to discuss this event.

One of the difficulties in understanding this event is that the number of events detected by channel 3 (E_p or $E_e > 120$ MeV) of the upper scintillators is the same as that in the down side proportional counters ($E_p > 270$ MeV). If the excess of the event were due to neutrons, according to Monte Carlo calculations, the number of events detected by upper scintillator should be greater than the number of penetrating events. Trigger pulses are produced by the coincidence between the upper channels (at least > 40 MeV deposited energy is necessary in the scintillator) and lower four layers of the proportional counters. Inside the four layers of the proportional counters are two layers of wood with a total thickness of 20 cm. According to the Monte Carlo calculation the ratio of the upper channel to coincidence signal is expected as to be a factor of four to ten, depending on the energy of the neutrons in the range $270 - 1000$ MeV [5].

Recently we have concluded that high energy (beyond 5 GeV) neutrons were involved in this event, requiring that photons be included in the calculation. Only the most recent version of GEANT4 can treat neutron cascades in the atmosphere correctly down to a few MeV (Koi et al., private communication). We have determined the best model using a new version of GEANT4 and compared the results to those of Shibata [6]. In this process, we discovered that the intensity of photons is expected as to be the same order as that of neutrons. Hence we have arrived at a new interpretation for this event, namely that the flare must have accelerated protons to beyond $100\,\mathrm{GeV}$ and thereby also produced high energy neutrons. In our simulation we have assumed a power law spectrum of neutrons with index $\gamma = -2.5$. Such high energy neutrons produce not only charged pions in the atmosphere but also neutral pions, which immediately decay into two photons and initiate an electromagnetic cascade. Those photons penetrate the solar neutron telescope through the anti-counter which cannot separate neutrons from photons. The radiation length of upper scintillator is just one radiation length, so most photons are converted into electron positron pairs in the scintillator. These are minimum ionizing particles which can penetrate both layers of wood and all four layers of the proportional counters.

3. Summary and Conclusions

In the solar flare on November 28th, 1998, ions were accelerated up to $100\,\mathrm{GeV}$ with a time profile similar to that of X-rays observed by the *Yohkoh* Hard X-ray Telescope. Those high energy ions collided with the atmosphere of the Sun to produce high energy neutrons. When the neutrons entered the atmosphere of the Earth they produced charged and neutral pions. The neutral pions decayed immediately and started the electromagnetic cascades, with the photon component of the cascade shower able to penetrate the atmosphere to the depth of the solar neutron telescope.

The detector responds to both photons and neutrons and cannot differentiate between them. Electrons and positrons produced in the scintillator can penetrate two layers of the wood and trigger four layers of the proportional counters. This must be the source of the enhancement observed in the solar direction by the neutron telescope since the adjacent neutron monitor, which is insensitive to photons, showed only a weak enhancement in its counting rate. In future versions of the neutron detector will be possible to separate photons from neutrons by installing a thin lead layer over the anticoincidence shield.

We conclude that in this solar flare, particles were accelerated to at least $10\,\mathrm{GeV}$, and probably to over $100\,\mathrm{GeV}$ over a time interval of a few minutes. Confirmation of such high energy solar particles will be one of the most important tasks of the next solar cycle.

4. Acknowledgments

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