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# Observations of neutrons in association with the solar flare of 6 November 1997

**H. Tsuchiya[1], Y. Matsubara[1], Y. Muraki[1], K. Murakami[1], T. Sako[1], F. Kakimoto[2], S. Ogio[2], Y. Tsunesada[2], H. Tokuno[2], H. Yoshii[3], N. Tajima[4], N. Martinic[5], P. Miranda[5], R. Ticona[5], and A. Velarde[5]**

[1]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, 464–8601, Japan
[2]Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo, 152–8551, Japan
[3]Department of Physics, Faculty of Science, Ehime University, Matsuyama, 790–8577, Japan
[4]Institute of Physical and Chemical Research, Wako, 351–0198, Japan
[5]Institute of Physical and Chemical Research, Wako, 351–0198, Japan
[5]Instituto Investigaciones Fisicas, Universidad Mayor de San Andres, La Paz, Bolivia

**Abstract.** Solar neutrons were detected by the Mt. Chacaltaya neutron detector in Bolivia (S16°, E292°, 5250 m above sea level) in association with solar flares on 1997 November 6th. A clear signal was observed in association with a C4.7 solar flare which occurred at about 10 minutes before the X9.4 large solar flare. Previously, there have been no observation of solar neutrons in association with C class solar flares. Moreover, the signal was detected at early in the morning(7:41 Local Time). Therefore, solar neutrons which arrive at the earth must travel through a thick atmosphere to reach the detector because of large incident angle (69°) to the atmosphere. In the thick atmosphere, it has been believed that solar neutrons could not arrive at the detector if we applied the usual attenuation model. However, calculations based on a new attenuation model for solar neutrons in the atmosphere, which takes account of multiple and/or large scattering, gives us a new possibility for us detecting solar neutrons under extreme conditions.

## 1 Introduction

It is well known that solar neutrons can be produced by very large solar flares. Neutrons are produced by interactions between the solar atmosphere and protons accelerated in solar flares. They bring us valuable information on the acceleration mechanism of ions to high energies. High energy solar neutrons are able to penetrate in the earth atmosphere and be detected by detectors installed on high mountains. In order to detect solar neutrons on the ground and elucidate the ion acceleration mechanism, a new type of solar neutron detector has been installed on several high mountains. Moreover, they have been placed at different longitudes in order to realize a continuous observation of solar neutrons in association with solar flares (Tsuchiya et al., 2001).

At 11:49 UT on 1997 November 6th, a X9.4/2B solar flare was observed at S18W63 on the solar surface. In space, several satellites detected phenomena associated with the solar flare. Yohkoh detected strong impulsive hard X-ray and gamma-ray(up to $\sim$ 20 MeV) emissions. The neutron capture line (energy of 2.223 MeV) was also detected by Yohkoh as confirmation of the production of solar neutrons at the solar surface (Yoshimori et al., 1999). Furthermore, other gamma-ray line emissions were also detected, which are due to the de-excitation processes of C(4.443 MeV) and O(6.129 MeV) nucleus. The Compton Gamma Ray Observatory(CGRO) was in South Atlantic Anomaly(SAA) during the peak phase of X9.4 solar flare, therefore no data for the peak phase were available, but BATSE on board CGRO detected hard X ray emissions 10 minutes before X9.4 solar flare. This emission was thought to be due to the C4.7 solar flare which started at 11:31 UT and continued until 11:44 UT. As will be mentioned in the next section, the Bolivian solar neutron detector detected a clear signal in association with this C4.7 solar flare. This event displays a very new feature in comparison with previous solar neutron events. In the past results, solar neutrons have been detected on the ground only in association with $>$ X8 solar flares.

In this paper, a striking feature of this solar neutron event detected by the Bolivian solar neutron detector is discussed in section 2. In section 3, it is shown that the detection of solar neutrons in association with a C4.7 flare is possible, taking account of the attenuation of solar gamma-rays in the solar atmosphere . Our conclusion is given in section 4.

## 2 Observation of solar neutrons at Mt. Chacaltaya

The Bolivian solar neutron detector consists of four scintillation counters, which are surrounded by other anti scintillation counters for rejecting charged particles. Descriptions of the Bolivian solar neutron detector can be found elsewhere (Matsubara, 1993).

At around 7:40 UT on 1997 November 6th, the air mass along to the line of the sight from the sun to the detector

*Correspondence to:* Matsubara(ymatsu@stelab.nagoya-u.ac.jp)

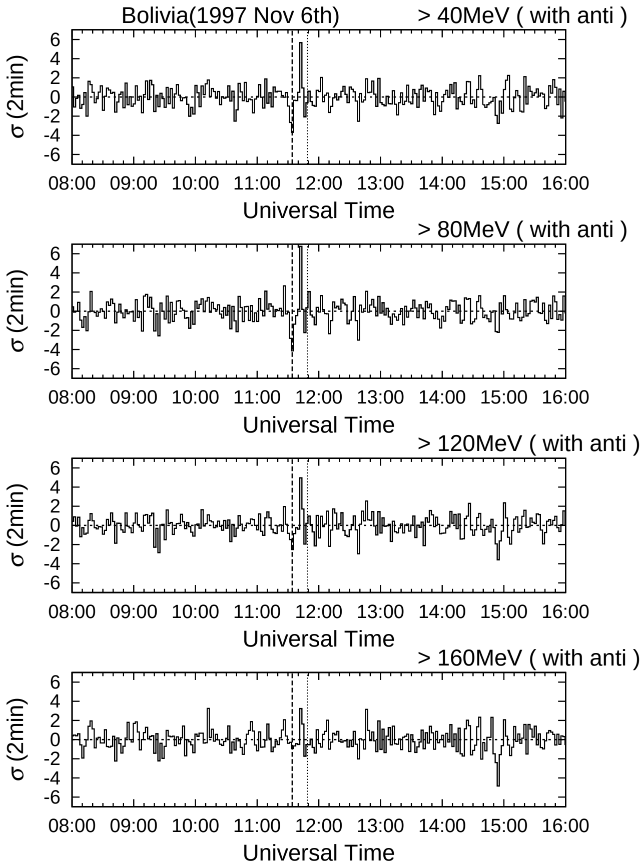


**Fig. 1.** The statistical significance of the 2 minute average counting rate between 8 UT and 16 UT. The vertical dashed line in all graphs indicates the flare onset time determined by BATSE/CGRO, which corresponds to 11:34:02 UT. The second vertical dotted line shows the X9.4 solar flare onset time(11:49 UT).

was $\sim$ 1500 $\mathrm{g/cm^2}(540/\cos 69°)$. It has previously been thought that solar neutrons are absorbed by such a thick atmosphere. However, clear signals were observed in the data of Bolivian solar neutron detector. Figure 1 shows statistical significances for the 2 minute counting rate between 8 UT and 16 UT. After the BATSE flare onset time (11:34:02 UT), a clear signal is seen in all channels with energy thresholds ($>$ 40 MeV, $>$ 80 MeV, $>$ 120 MeV and $>$ 160 MeV) between 11:41 UT and 11:43 UT. The statistical significances from 8 UT to 16 UT for each channel were 5.7$\sigma$, 6.8$\sigma$, 5.0$\sigma$, 3.2$\sigma$ respectively. The distribution of the statistical fluctuations for the $>$ 80 MeV threshold channel is shown in Figure 2.

In order to obtain the neutron spectrum at the top of the atmosphere, 30 second counting rates for $>$ 40 MeV, $>$ 80 MeV and $>$ 120 MeV were used. In Figure 3, the spectrum given has been calculated from the data for $>$ 80 MeV. The attenuation of solar neutrons in the atmosphere and the detection efficiency of the Bolivian solar neutron detector were calculated using a Monte Carlo simulation based on the Shibata model (Shibata, 1994). The spectrum has an index of -3.3$\pm$1.6 if the data is fitted with a power law.

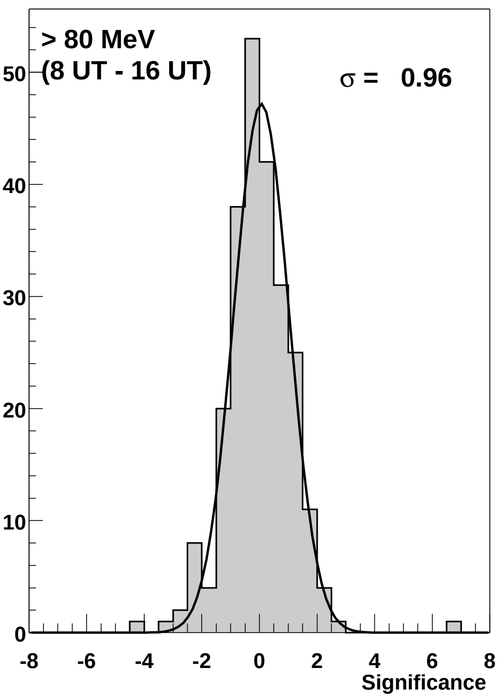


**Fig. 2.** The distribution of statistical significance for $>$80 MeV. Solid curve drawn in the Figure indicates a fit to a gaussian function. The fitted curve has a standard deviation of 0.96 as shown in the Figure.

## 3 Discussion

### 3.1 Attenuation of solar neutrons in the atmosphere of the earth

As mentioned before, there is a problem with the thick air mass associated with this event. Because of the large solar zenith angle of 69°, it was thought that solar neutrons would be attenuated strongly in the earth's atmosphere. On the basis of a simple calculation, the attenuation of solar neutrons at an altitude of 5250 m, with a vertical atmospheric depth 540 $\mathrm{g/cm^2}$, turns out to be about $2.9 \times 10^{-7}$ using the formula $\exp(-1506/100)$, where the value 1506 is calculated from $540/\cos 69°$ and the value 100 represents the attenuation length of solar neutrons in the atmosphere calculated by Shibata (1994). However, if we consider the "refraction effect of solar neutrons in the atmosphere", which was first pointed out by Smart et al.(1995), it becomes possible to detect solar neutrons in such a thick atmosphere. Recently, taking account of the scattering effect, Galicia et al.(2000) explained an increase of counting rate of North America neutron monitors in association with the 1990 May 24th solar flare. They emphasized that it was very important in observations of solar neutrons to consider the atmospheric refraction effect in cases where the solar zenith angle was large, for example, in the early morning, late evening and in winter

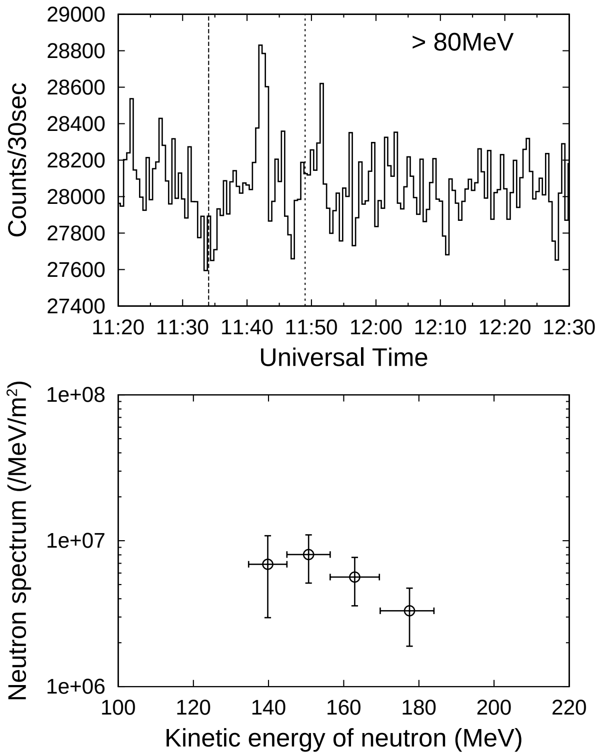


**Fig. 3.** 30 second counting rate for the $> 80$ MeV threshold energy channel is shown in the top panel. The bottom panel shows the spectrum derived for the top of the atmosphere. In the top panel, the dashed and dotted vertical lines indicate the BATSE flare start time(11:34 UT) related to C4.7 solar flare and the X9.4 solar flare onset time respectively. Two spikes can be clearly seen after the occurrence of C4.7 and X9.4 flares.

time.

The refraction effect arises from the diffraction process between solar neutrons and air nuclei by elastic collisions. Due to scattering, the path of solar neutrons in the atmosphere is normally bent from a line connected from the sun to the detector. Therefore, the total path length of solar neutrons becomes shorter than the case of no scattering. A schematic view of the refraction effect is shown in Figure 4. Here the effective total pass length turns out to be 835 $\mathrm{g/cm^2}$ instead of 1506 $\mathrm{g/cm^2}$ provided that solar neutrons are scattered on average 6° after each scattering. Under another assumption that angular distribution of solar neutrons after each scattering is expressed by a Gaussian function with a standard deviation of $6°$, the effective total pass length is predicted to be 887 $\mathrm{g/cm^2}$. Therefore, the effective path length calculated under two conditions become much shorter than with the straight line hypothesis. It has been found that the refraction effect decreases the path length of solar neutrons in the atmosphere. This is especially important for the case in which angle of incidence of solar neutrons is large. According to our Monte Carlo simulations, in the case of an incident zenith angle of less than 30°, no remarkable difference is found. However, a big difference appears in the case when the incident zenith angle of solar neutrons exceeds 30°(Tsuchiya, 2001). There-

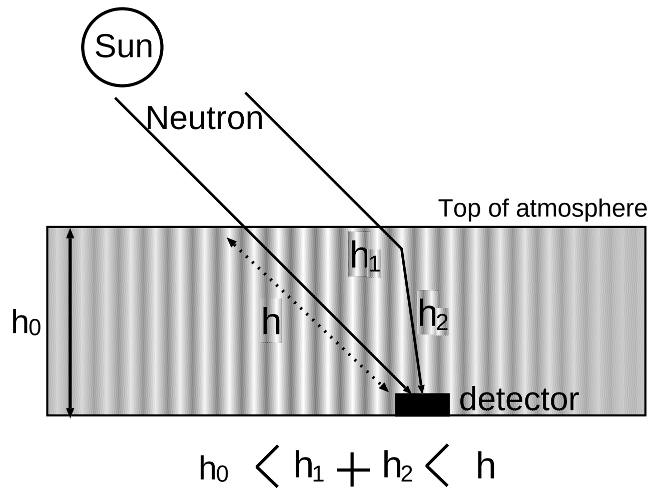


**Fig. 4.** Schematic view of the refraction effect of solar neutrons in the atmosphere. In the Figure, $\mathrm{h_0}$ shows the vertical atmospheric depth. Due to scattering in the atmosphere, the total path length ($\mathrm{h_1 + h_2}$) becomes shorter than the direct path (h).

fore, it is predicted that solar neutrons even with an incident angle of 69° can arrive at the detector.

### 3.2 Attenuation of solar neutrons and 2.223 MeV photons in the solar atmosphere

Neutrons produced at the limb of the sun have higher probability to arrive at the earth than those produced at the center of the sun(Hua and Lingenfelter, 1987). On the other hand, it seems that 2.223 MeV photons (neutron capture line gamma rays) emitted at the limb have a lower probability of arriving at the earth than those produced at the center of the sun. This phenomenon is the result of attenuation of 2.223 MeV photons by Compton scattering in the solar atmosphere. This phenomenon is called "limb darkening" (Wang and Ramaty, 1974). Also, 2.223 MeV photons are produced in deeper regions of the solar surface in comparison with the place where the original low energy neutrons are produced, because these must be decelerated before being captured by ambient protons. The flare which was observed on 1997 November 6th was not located at the limb, but we have assumed here that 2.223 MeV photons are produced deeper in the solar atmosphere and are strongly attenuated by Compton scattering. So, a calculation for escape probability of neutrons and 2.223 MeV photons from the solar atmosphere has been made, the result of which is shown in Figure 5. In this calculation, the standard composition of the solar atmosphere was used (Reams, 1999). From Figure 5, we can understand that there is no big difference between neutrons and 2.223 MeV photons in the case that the production regions of neutrons and 2.223 MeV photons are in the chromosphere. However, once the production of neutrons and 2.223 MeV photons takes place in the photosphere, the escape probability for neutrons and 2.223 MeV photons apparently changes. The probability for 2.223 MeV photon in the solar atmosphere decreases rapidly as the production level becomes deeper. According to

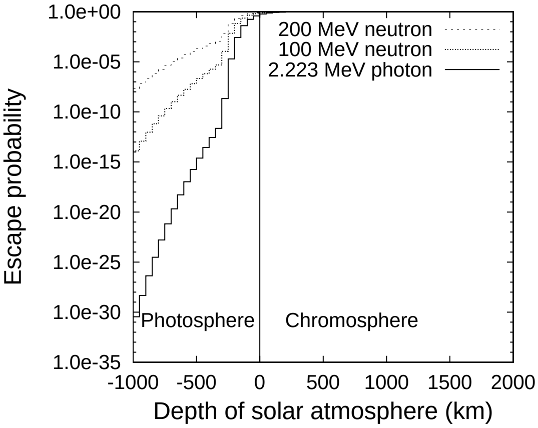


**Fig. 5.** Calculated escape probability of neutrons and 2.223 MeV photons from the solar atmosphere. The horizontal axis represents the depth from the boundary between the photosphere and the chromosphere.

the calculations of Hua and Lingenfelter(1987), the production of 2.223 MeV photons must occur approximately 100 to 200 km deeper in comparison with the neutron production region. Taking account of this effect, the escape probability of the 2.223 MeV photons should be much smaller. For example if the production of neutrons occurs at $z = -300$ km and the 2.223 MeV photons at $z = -400$ km, the ratio of the escape probability of neutrons (100 MeV) and photons(2.223 MeV) is estimated as $4.0 \times 10^8$.

In 1997 November 6th event, the solar flare occurred at the position S16W63 on the solar surface. Moreover, no neutron capture line was detected during C4.7 solar flare (11:31 UT - 11:44 UT) although Yohkoh detected the neutron capture line in the X9.4 solar flare. Therefore, there is a possibility that neutrons were produced in association with C4.7 solar flare and neutron capture line also was emitted, but they might be masked by the thick solar atmosphere because of deep production region of neutrons and 2.223 MeV photons.

## 4 Conclusions

On 1997 November 6th, a solar flare occurred at around 11:50 UT. A C4.7 solar flare first occurred at 11:31 UT and a X9.4 solar flare occurred at 11:49 UT. In association with both flares, the solar neutron detector installed at Mt. Chacaltaya, Bolivia detected solar neutrons. However, it was very strange that a clear signal ($6.8\sigma$ for 2 minute counting rate) was obtained for the C4.7 solar flare, and a weak signal was detected for the X9.4 solar flare. Until now, there has been no report of the detection of solar neutrons in association with C class solar flares. Moreover, there was an apparent problem because of the large incident zenith angle of solar neutrons at the top of the atmosphere.

However, according to Monte Carlo simulations, it is found that solar neutrons can arrive at the detector with no great attenuation, allowing for the refraction of solar neutrons in the atmosphere. Also, in this event, if neutrons were produced in a region at the depth greater than 300 km from boundary between the chromosphere and the photosphere, any 2.223 MeV photons produced would have been attenuated strongly by the solar atmosphere. In the 1997 November 6th event, due to a refraction effect of solar neutrons in the earth's atmosphere and the strong attenuation of 2.223 MeV in the solar atmosphere, it has been concluded that solar neutrons were detected on the ground and 2.223 MeV photons were not detected at space.

At last we would like to thank to Prof. Sir Ian Axford for reading the manuscript. We note that the clock of Chacaltaya CPU has been adjusted to GPS within one minute.

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