Solar Neutron Event in Association with a Large Solar Flare on August 25, 2001

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Abstract

Solar neutrons have been detected using the neutron monitor located at Mt. Chacaltaya, Bolivia, in association with a large solar flare on August 25, 2001. The statistical significance of the detection is $4.7\,\sigma$. In this flare, intense emission of hard X-rays and γ-rays was observed by the *Yohkoh* Hard X-ray Telescope (HXT) and Gamma Ray Spectrometer (GRS), respectively. The time of solar neutron production is better correlated with that of hard X-rays and γ-rays than with the production time of soft X-rays.

1. Introduction

More than 60 X-class flares occurred in solar cycle 23. Among them, solar neutrons were detected by the neutron monitor installed at Mt. Chacaltaya, Bolivia, in association with an X2.3 flare on November 24, 2000 (Watanabe *et al.* [3]), and with an X5.3 flare on August 25, 2001. In this paper, we describe the solar neutron event of August 25, 2001. The neutron monitor data for this solar flare have been analyzed and compared with X-ray and γ-ray data obtained by the *Yohkoh* satellite.

2. Observation

An X5.3 class solar flare occurred at 16:23 UT in NOAA region 9591 on August 25, 2001. The location of the active region was S17°E34° and this flare was a disk flare. The soft X-ray flux observed by the *GOES* satellite was at a maximum at 16:45 UT, which was 22 minutes after the flare onset time. Since it

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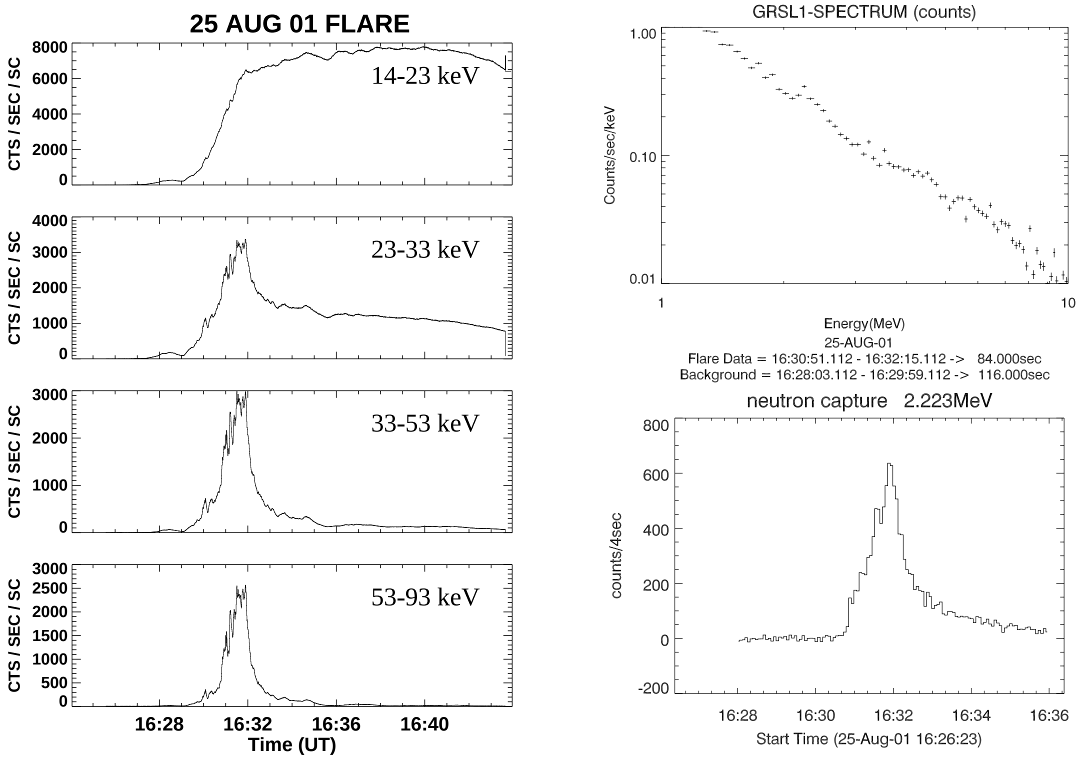

Fig. 1. The hard X-ray and γ-ray data observed by *Yohkoh* on August 25, 2001. The left side shows the time profiles of hard X-rays. The upper figure on the right shows the γ-ray spectrum, and the lower one the time profile of γ-rays around 2.223 MeV.

took a considerable time for the soft X-ray flux to reach the level of X5.3, the neutron production time cannot be determined from the soft X-ray data alone.

Large fluxes of hard X-rays and γ-rays were also observed in this event. Fig. 1 shows the time profile of hard X-rays observed by the *Yohkoh*/HXT, the γ-ray spectrum and the time profile of γ-rays around 2.223 MeV observed by the *Yohkoh*/GRS on August 25, 2001.

At the start time of an X5.3 flare on August 25, 2001, the Sun was directly over Bolivia and the neutron monitor installed at Mt. Chacaltaya, Bolivia, was the most suitable place for observing solar neutrons. This station is located at 292.0°E, 16.2°S, 5250 m above sea level, and the vertical air mass is 540 g/cm^2. At this time, the zenith angle of the Sun was 26.5° and the air mass for the line of sight to the Sun was 603 g/cm^2.

The neutron monitor installed at Mt. Chacaltaya is 13.1 m^2 in area and of the NM64 type. The counting rate is recorded every 1 minute. The time profile of neutrons observed by the neutron monitor is shown in Fig. 2. A clear excess was found between 16:34 UT and 16:49 UT. The statistical significance of these excesses are 4.7 σ at 16:34−16:39 UT, 1.4 σ at 16:39 − 16:44 UT, and 2.5 σ at 16:44−16:49 UT. The total significance for the period of 15 minutes, between 16:34 UT and 16:49 UT, is 4.7 σ.

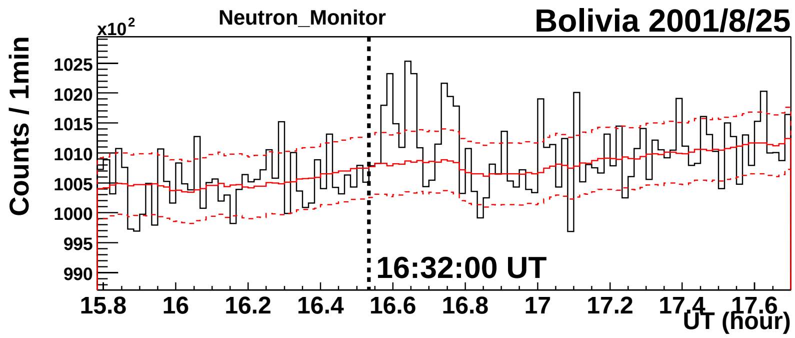

Fig. 2. The time profile of neutrons detected by the Bolivia neutron monitor on August 25, 2001. The solid smooth line is the averaged background, and dashed lines are $\pm 1\,\sigma$ from the background.

There is a possibility that these excesses came from energetic ions which can also be detected by the neutron monitor. However, there is no evidence that this was the case since measurements by other stations in the worldwide neutron monitor network showed no enhancement. Accordingly, these signals must have come from solar neutrons.

3. Analysis result and Discussion

In the γ-ray spectrum in Fig. 1, a weak signal of 2.223 MeV neutron capture line γ-rays is seen in the bremsstrahlung component. However, the γ-ray lines produced by de-excited ions are not seen because this solar flare was electron rich. Solar neutrons are produced simultaneously with line γ-rays of de-excited ions by interactions of accelerated ions with the solar atmosphere. In this event, the γ-ray lines of de-excited ions were not observed, however, large fluxes of hard X-rays and γ-rays are evident in Fig. 1. The time profiles of the high energy channel of hard X-rays and γ-rays are similar, and the fluxes of the hard X-rays and γ-rays were largest at 16:32 UT. From these data, we deduce that solar neutrons were produced at 16:32 UT. On this basis, the energy of neutrons which cause the increases recorded by the neutron monitor are estimated to be 612.2 MeV at 16:34 UT, and 54.6 MeV at 16:49 UT.

From the time profile of the neutrons, we calculated the energy spectrum of solar neutrons at the solar surface. We use the detection efficiency of the neutron monitor calculated by Clem & Dorman [1], and the attenuation of solar neutrons in the Earth's atmosphere as calculated by Shibata [2] by Monte Carlo simulations. To derive the energy spectrum of neutrons at the solar surface from the flux at the top of the Earth's atmosphere, the survival probability of neutrons between the Sun and the Earth must also be taken into account. The result is shown in Fig. 3. This spectrum was derived from the 3 minutes counting rate. These data points fitted with a power law of the form $C \times (E_n/100[\mathrm{MeV}])^{\alpha}$, to obtain the energy spectrum of the solar neutrons. Here C is the flux of neutrons at 100 MeV, and α is the power law index. The fitting region is chosen to be above 100 MeV, where the errors resulting from the uncertainty of neutron attenuation in the Earth's atmosphere are small. The values obtained were as follows:

$$(1.1 \pm 0.9) \times 10^{27}\,[/\mathrm{MeV/sr}] \times \left(\frac{E_n}{100\,[\mathrm{MeV}]}\right)^{-3.9\,\pm\,0.7} . \quad (1)$$

For this fit, the value of $\chi^2/\mathrm{dof} = 0.007/1$. The total energy flux of solar neutrons which were emitted from the Sun in the energy range between $50 - 600$ MeV was calculated as 3.4×10^{25} erg/sr. This is obtained by simply integrating Equation (1). We did not assume any turnover of the energy spectrum of neutrons in this energy region.

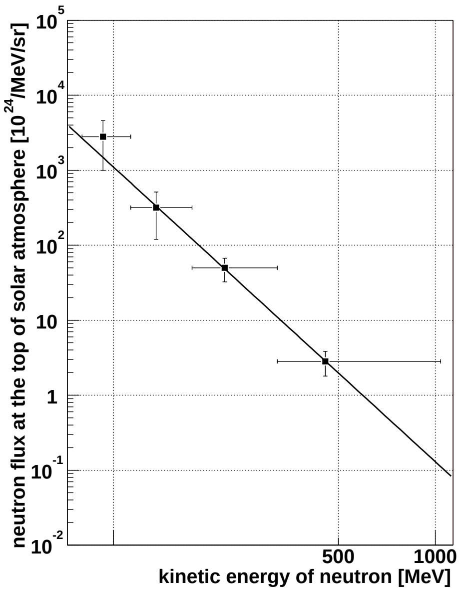

Fig. 3. The spectrum of solar neutrons at the solar surface produced in association with the solar flare that occurred on August 25, 2001. The vertical error bars represent only statistical errors.

4. Conclusion

We have detected solar neutrons in association with the solar flare that occurred on August 25, 2001. This detection was made by the neutron monitor at Mt. Chacaltaya, which was a very suitable site to observe solar neutrons from this flare. In order to determine the production time of neutrons, we compared the solar neutron data with the X-ray and γ-ray data obtained by the *Yohkoh* satellite. From the data of *Yohkoh*/HXT and *Yohkoh*/GRS, hard X-rays and γ-rays were observed with high intensity. The observability of solar neutrons is possibly correlated with the intensity of hard X-rays and γ-rays in a solar flare.

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References

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