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SOLAR NEUTRON EVENT IN ASSOCIATION WITH A LARGE SOLAR FLARE ON 2000 NOVEMBER 24

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ABSTRACT

Solar neutrons have been detected using the neutron monitor located at Mount Chacaltaya, Bolivia, in association with a large solar flare on 2000 November 24. This is the first detection of solar neutrons by a neutron monitor that has been reported so far in solar cycle 23. The statistical significance of the detection is 5.5 σ. In this flare, the intense emission of hard X-rays and γ-rays has been observed by the *Yohkoh* Hard X-ray Telescope (HXT) and Gamma Ray Spectrometer (GRS), respectively. The production time of solar neutrons is better correlated with those of hard X-rays and γ-rays than with the production time of soft X-rays. The observations of the solar neutrons on the ground have been limited to solar flares with soft X-ray class greater than X8 in former solar cycles. In this cycle, however, neutrons were detected associated with an X2.3 solar flare on 2000 November 24. This is the first report of the detection of solar neutrons on the ground associated with a solar flare with an X-ray class smaller than X8.

Subject headings: Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

Since the discovery of cosmic rays, their acceleration mechanism has been one of the most important themes in cosmic-ray research. Most cosmic rays are ions, such as protons. Charged particles are reflected by magnetic fields at the acceleration site and by interstellar and interplanetary magnetic fields. When they arrive at the Earth, exact information on the acceleration place and acceleration time have already been lost. On the other hand, neutral particles such as γ-rays, neutrons, and neutrinos that arrive at the Earth retain information on the acceleration, because they are not affected by any magnetic field. Therefore, neutral particles are useful for investigating the acceleration mechanism. However, it is difficult to observe neutrinos, and it is difficult to distinguish whether γ-rays have originated from ions or electrons. Therefore, it is valuable to use neutrons to solve the acceleration mechanism of ions. We note, however, that the survival probability of decay should be taken into account for neutrons of nonrelativistic energy.

The Sun is the nearest source of particle acceleration to the Earth. The Sun, which is a typical star, causes the explosive release of energy known as a solar flare. The energy release in a flare amounts to 10^{29}–10^{33} ergs during a few to a few tens of minutes. The flare energy is released as electromagnetic radiation, plasma heating, and particle acceleration. The information on ion acceleration is transferred to neutrons, line γ-rays, and neutrinos that are produced by the interaction of accelerated particles with the solar atmosphere.

So far, γ-rays have been observed in association with the solar flares by the Gamma Ray Spectrometer (GRS) on board the *Solar Maximum Mission* (*SMM*) in the 1980s. In the 1990s, solar γ-rays were observed by detectors onboard the *Compton Gamma Ray Observatory* (*CGRO*) satellite, Oriented Scintillation Spectrometer Experiment (OSSE), Burst and Transient Source Experiment (BATSE), Energetic Gamma Ray Experiment Telescope (EGRET), and the Compton Telescope (COMPTEL). Also since 1991 August, the Gamma Ray Spectrometer (GRS) onboard the *Yohkoh* satellite has continued measurements. The *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*) started observations in 2002 February.

Many of γ-ray events associated with solar flares have been detected by these detectors (Murphy et al. 1997). In some of these events, line γ-rays, which originate from deexcited nuclei (1–8 MeV), electron-positron annihilation (0.511 MeV), and neutron capture (2.223 MeV) processes, are observed with a continuous bremsstrahlung component. The deexcited nuclei γ-rays indicate the occurrence of ion acceleration, and 2.223 MeV γ-rays are produced by neutrons. However line γ-rays cannot be clearly observed in many events because they are buried in the bremsstrahlung component.

The importance of observing solar neutrons produced by accelerated particles was pointed out by Biermann et al. (1951) and by Lingenfelter et al. (1965a, 1965b). Lower energy neutrons (kinetic energy below 100 MeV) are observed only in space because they are attenuated in the Earth's atmosphere, and high-energy neutrons with kinetic energies higher than 100 MeV are observed on the ground. By simultaneous observations in space and on the ground, an energy spectrum of solar neutrons, or accelerated particles, can be obtained in a wide energy range. Moreover, by acquiring knowledge of the acceleration time, we can know whether particle acceleration has taken place impulsively or gradually.

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Solar flares that produce neutrons occur frequently when solar activity is the maximum in a solar cycle, and they have been X-class solar flares in most cases. Solar neutrons were observed for the first time by *SMM*/GRS at the flare on 1980 June 21 (Chupp et al. 1982). On 1982 June 3, solar neutrons were detected for the first time by the ground-level neutron monitor installed at Jungfraujoch, Switzerland, as well as by *SMM*/GRS (Chupp et al. 1987). In this event, high-energy solar neutrons were observed by the IGY-type neutron monitor, and low-energy neutrons and high-energy γ-rays were observed by the *SMM*/GRS satellite at the same time. Since a long tail of signals was observed by the neutron monitor, this event was interpreted using impulsive and gradual particle acceleration models, and the neutron energy spectrum of this event was described as a power law with index $= -2.4$. But the time-extended neutron signals were interpreted using only the impulsive model (Shibata 1993). This distinction came from the difference of the neutron propagation model in the Earth's atmosphere.

After the solar neutron event on 1982 June 3, four solar neutron events were observed with ground-based detectors. The second event was observed by the IGY-type neutron monitor located at Climax and a several stations in North America on 1990 May 24 (Shea et al. 1991; Debrunner et al. 1997; Muraki & Shibata 1996). The third event was on 1991 March 22 (Pyle & Simpson 1991). This event was observed by the NM64-type neutron monitor at Haleakala, Hawaii. The fourth and fifth events were on 1991 June 4 and 6 (Muraki et al. 1992; Struminsky et al. 1994). On June 4, solar neutron signals were recorded by three different detectors (neutron monitor, neutron telescope, and muon telescope) located at Mount Norikura. On June 6, solar neutrons were detected at Haleakala and Mount Norikura at the same time. Until the present time, solar neutrons have been observed only in association with solar flares larger than the X8 class (Shibata et al. 1993).

In this paper we report detection of solar neutrons by the neutron monitor installed at Mount Chacaltaya, Bolivia. Solar neutrons were produced in association with a solar flare that occurred at 14:51 UT on 2000 November 24. The soft X-ray class was X2.3. Therefore, this event is not only the first report of the detection of solar neutrons by a neutron monitor in solar cycle 23, but also the first ground-level event recorded with a soft X-ray class smaller than X8. The analysis result of the neutron monitor data for this solar flare is described. It is compared with X-ray and γ-ray data obtained by the *Yohkoh* satellite.

2. OBSERVATION OF SOLAR NEUTRONS

Three X-class solar flares occurred successively in NOAA active region 9236 on 2000 November 24. At 14:51 UT, an X2.3 class flare was observed which was the largest among these three. The location of the active region was N22°, W7° at the time of the flare, and the flare was a disk flare.

The time profile of the soft X-ray flux in this flare observed by the *GOES* satellite is shown in Figure 1. Although the start time of this flare defined by the *GOES* satellite was 14:51 UT, the time when the soft X-ray flux became a maximum was 15:13 UT, which was more than 20 minutes after the start time. In Figure 1 we can distinguish three bumps starting at 14:51, 15:00, and 15:07 UT, respectively. Each of them arrives at C, M, and X class at its maximum. In order to understand this stepwise increase of the soft X-ray flux, we examined the soft X-ray images obtained by the Soft X-ray Telescope (SXT) on board the *Yohkoh* satellite.

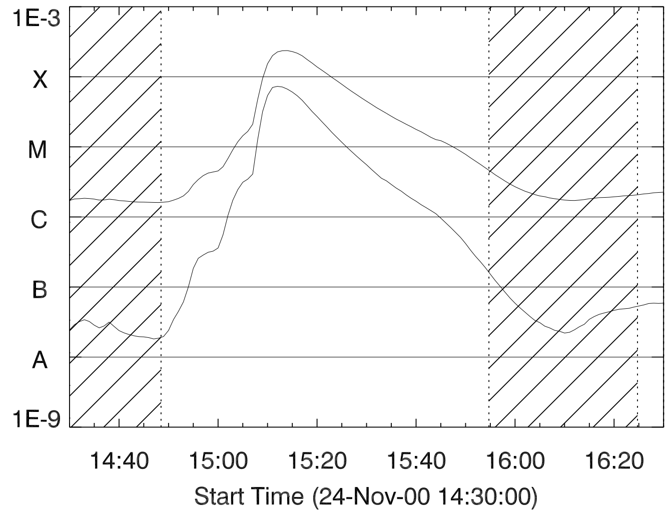


FIG. 1.—Time profile of the soft X-ray flux observed by the *GOES* satellite at the solar flare that occurred on 2000 November 24 (14:30–16:30 UT). The start time of this X2.3 flare was 14:51 UT. Oblique lines mean night for the *Yohkoh* satellite. The upper profile expresses the X-ray flux in the wavelength range 1.0–8.0 Å, and the lower one is for 0.5–4.0 Å.

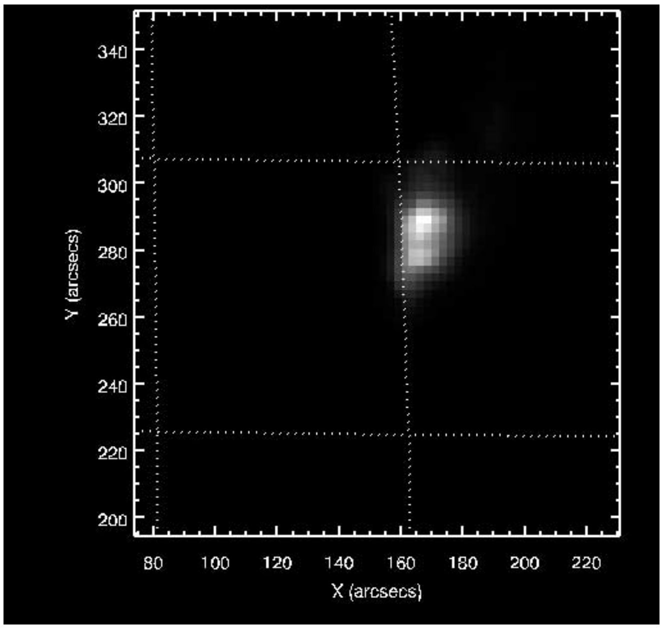
Soft X-ray images observed by *Yohkoh*/SXT at 15:06:23 and 15:07:55 UT on 2000 November 24 are shown in Figure 2. At 15:06:23 UT, the soft X-ray flux reached M-class level, and at 15:07:55 UT, it was at X-class level by the *GOES* satellite. A bright point appears on the 15:07:55 UT image, which did not exist on the 15:06:23 UT image. From these images, we can say that distinct energy release phenomena occurred at around 15:07 UT, and the soft X-ray flux observed by the *GOES* satellite was superposed stepwise.

Around 15:08 UT, when the energy release phenomenon occurred, a large amount of hard X-rays was observed. The time profile of the hard X-rays observed by *Yohkoh*/HXT is shown in Figure 3. The hard X-ray flux suddenly increased from 15:07:30 UT, when the new bright spot appeared in the soft X-ray image in Figure 2.

The hard X-ray image observed by *Yohkoh*/HXT is shown in Figure 4 on the soft X-ray image observed by *Yohkoh*/SXT. At the time when the new soft X-ray source appeared, the hard X-ray source turned up at the footpoint of the soft X-ray flare loop. Therefore, hard X-rays were produced in parallel with soft X-rays around 15:08 UT. Moreover, the energy spectrum of the hard X-rays was very hard between 15:07:30 and 15:09:30 UT.

High-energy electrons can emit hard X-rays by bremsstrahlung. Therefore, the onset time of hard X-rays can indicate the time when the particle acceleration took place. But hard X-rays are produced by high-energy electrons, not by ions. Therefore, we cannot assert that at the time when a large amount of hard X-rays are produced, ions are accelerated and solar neutrons are produced.

It is more useful to examine information on γ-rays to estimate the acceleration time of ions. Around 15:08 UT, a large amount of γ-rays was observed by *Yohkoh*/GRS. Figure 5 shows the energy spectrum of γ-rays at that time. In this figure, a clear signal of 2.223 MeV neutron capture



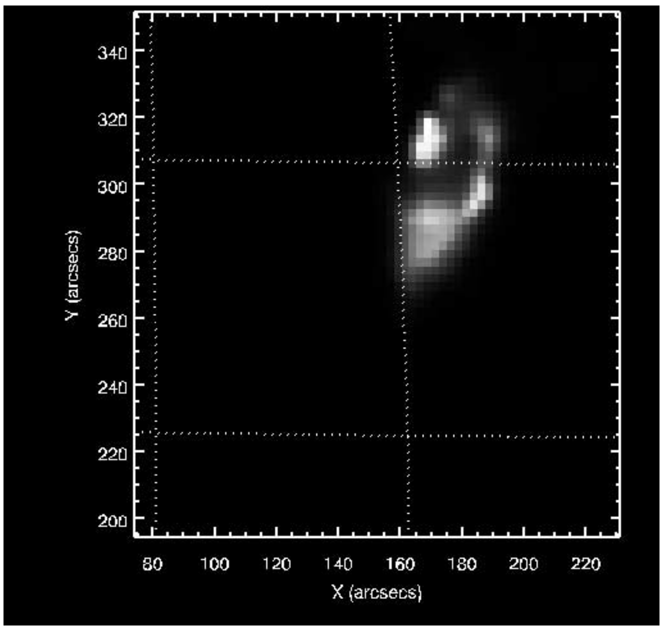


FIG. 2.—Soft X-ray images observed by *Yohkoh*/SXT at 15:06:23 and 15:07:55 UT on 2000 November 24. The *X*-axis is in the east-west (*west is at the left*) direction and the *Y*-axis is north-south (*north is at the top*). At 15:06:23 UT, the soft X-ray flux reached M-class level, and at 15:07:55 UT, it was determined to be X-class level by the *GOES* satellite. In the bottom image there appears an isolated bright point that does not exist in the top image.

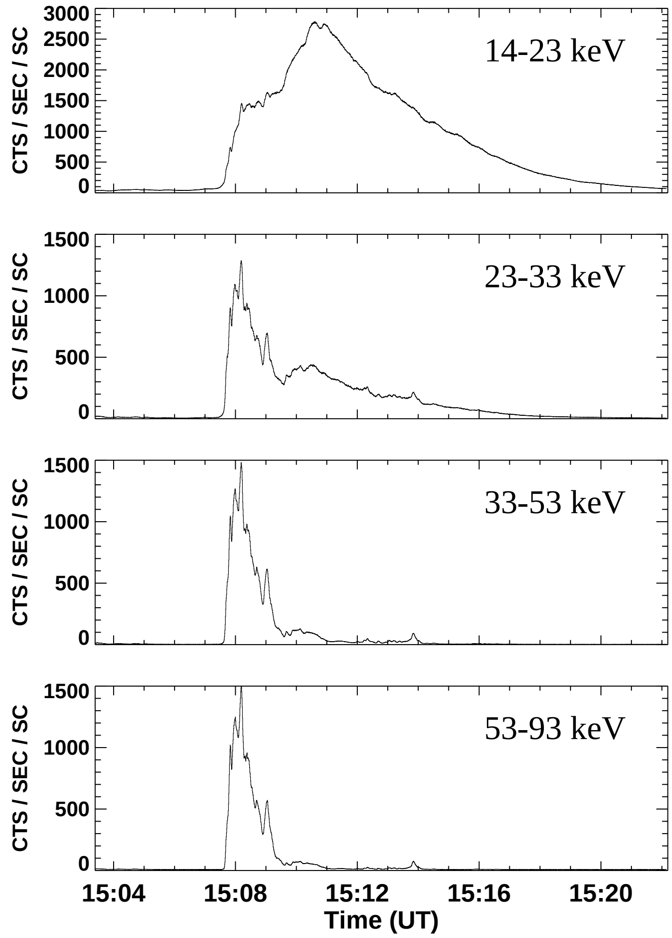


FIG. 3.—Time profile of hard X-rays observed by *Yohkoh*/HXT on 2000 November 24. The vertical axis is the count rate per subcollimator. Hard X-rays were suddenly emitted from 15:07:30 UT.

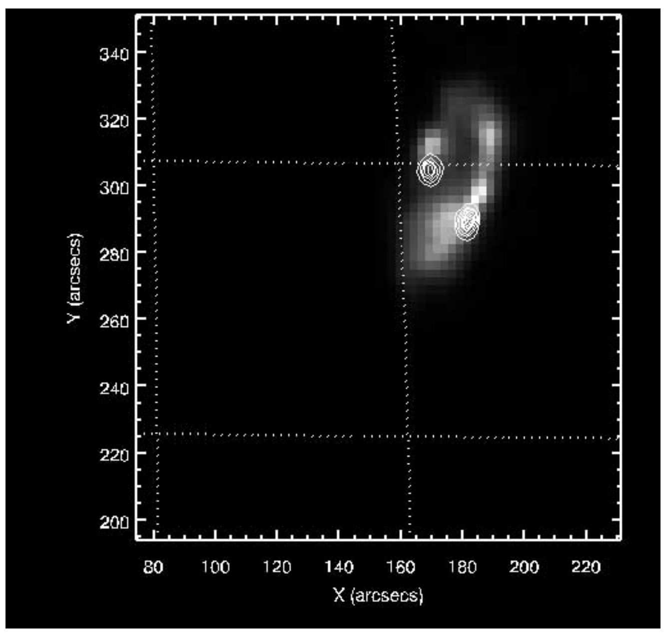


FIG. 4.—Soft X-ray and hard X-ray images observed by *Yohkoh*/SXT and *Yohkoh*/HXT at 15:07:53 UT on 2000 November 24. The hard X-ray image is drawn by contours on the soft X-ray image. The hard X-ray source is at the footpoint of the soft X-ray flare loop.

line γ-rays is seen on the bremsstrahlung component. Therefore, it is evident that neutrons were produced around 15:08 UT on 2000 November 24. Furthermore, between 4 and 7 MeV, weak signals of line γ-rays produced by deexcited ions, C (4.443 MeV) and O (6.129 MeV), for example, are seen too. Consequently, it is certain that ions were accelerated at that time.

In principle, from these line γ-ray data, we can calculate the amount of produced neutrons and the energy spectra of the accelerated ions independently of the neutron measurements (Ramaty et al. 1996). But at this event the flux of line

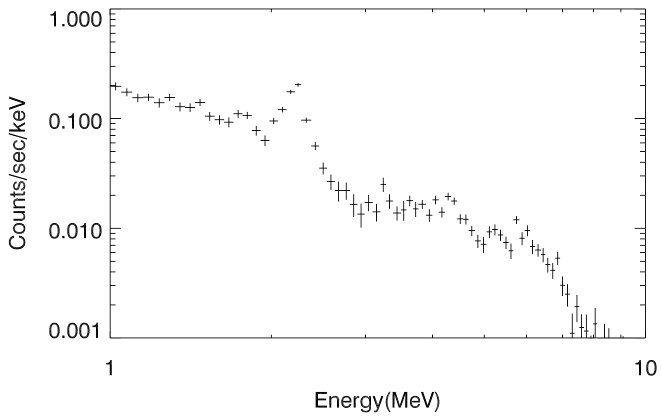


FIG. 5.—Background-subtracted γ-ray spectrum observed by the *Yohkoh*/GRS on 2000 November 24. There is a clear signal of 2.223 MeV γ-rays and weak signals of deexcited nuclei line γ-rays between 4 and 7 MeV on the bremsstrahlung component.

γ-rays produced by deexcited ions was weak. It is difficult to estimate the amount of γ-rays produced by each deexcitation process because of a contamination of electron bremsstrahlung. For this reason, the neutron spectrum was not derived from the line γ-ray data to compare it with that determined by the neutron monitor data.

The time profiles of 2.223 MeV neutron capture line γ-rays and 4–7 MeV γ-rays observed by the *Yohkoh*/GRS around 15:08 UT on 2000 November 24 are shown in Figure 6. The bremsstrahlung component is not subtracted. The 4–7 MeV γ-ray time profile included line γ-rays produced by deexcited ions, C (4.443 MeV) and O (6.129 MeV). Therefore, the 4–7 MeV γ-ray time profile is approximately equal to the C+O line and bremsstrahlung γ-ray time profile. In these figures, the duration of 2.223 MeV γ-ray emission is longer than that of 4–7 MeV γ-rays. The 2.223 MeV γ-rays are produced when thermal neutrons are captured by hydrogen. High-energy neutrons are produced simultaneously with line γ-rays of deexcited ions by the interaction of accelerated ions and the solar atmosphere. On the other hand, the 2.223 MeV γ-rays are produced about 100 s after the production of the high-energy neutrons, because of the time required for neutrons to slow down and be captured. Therefore, the time profile of 2.223 MeV γ-rays is dilated compared with that of 4–7 MeV γ-rays. Hence, we can consider that the high-energy neutrons were produced at the same time as deexcited nuclei γ-rays rather than 2.223 MeV γ-rays.

At 15:08 UT on 2000 November 24, the Sun was over Bolivia. The neutron monitor installed at Mount Chacaltaya, Bolivia, was at the most suitable place for observing solar neutrons. This station is located at E292°.0, S16°.2, 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 17°.47 and the air mass for the line of sight to the Sun was 566 g cm^{-2}.

The neutron monitor installed at Mount Chacaltaya is 13.1 m^2 in area and of the NM64 type. The count rate is recorded every 10 s. The time profile of neutrons observed by the neutron monitor is shown in Figure 7. A clear excess was found between 15:10 and 15:25 UT. The statistical significance of each bin is 4.7 σ at 15:10–15:15 UT, 2.4 σ at 15:15–15:20 UT, and 2.4 σ at 15:20–15:25 UT. The total significance for 15 minutes, between 15:10 and 15:25 UT, turned out to be 5.5 σ.

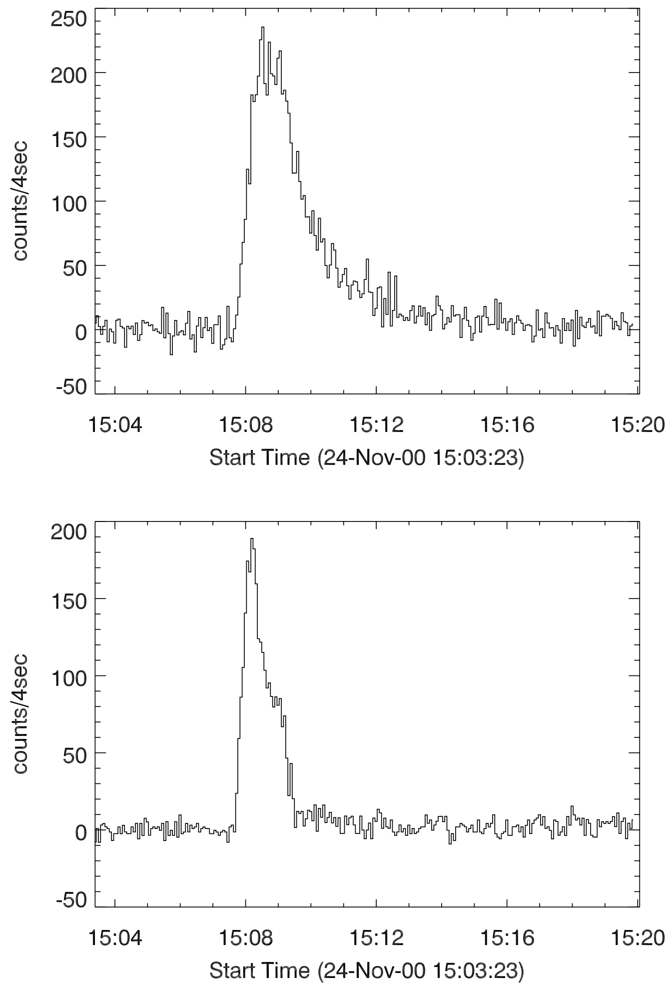


FIG. 6.—Time profiles of 2.223 MeV neutron capture line γ-rays and 4–7 MeV γ-rays on 2000 November 24. The upper figure is the 2.223 MeV time profile, and the lower one is the 4–7 MeV time profile. The bremsstrahlung component is not subtracted. The 4–7 MeV γ-ray time profile includes line γ-rays produced by deexcited ions, C (4.443 MeV) and O (6.129 MeV). In both of them, the vertical axis is the count rate per 4 s. The time profile of neutron capture γ-rays is more expanded than that of 4–7 MeV γ-rays.

There is a possibility that these excesses came from energetic ions because the neutron monitor can observe energetic ions. But there is no evidence that the enhancement was produced by energetic ions since the measurements by the other stations in the worldwide network of neutron monitors showed no enhancement. In addition, the cutoff rigidity at Mount Chacaltaya is high, that is, 12.53 GV, so it is difficult for ions to reach ground level. There are many neutron monitor stations located at places where the cutoff rigidity is lower. If these excesses came from energetic ions, some enhancement should have been detected by other stations. Furthermore, protons with kinetic energy greater than 100 MeV were observed by the *GOES* satellite in association with the X2.3 solar flare, which was observed 1 hr later. Therefore, these signals must have come from solar neutrons.

Neutron monitors cannot measure the energy of neutrons. Therefore, we cannot directly derive the energy spectrum of solar neutrons. But using the time-of-flight (TOF)

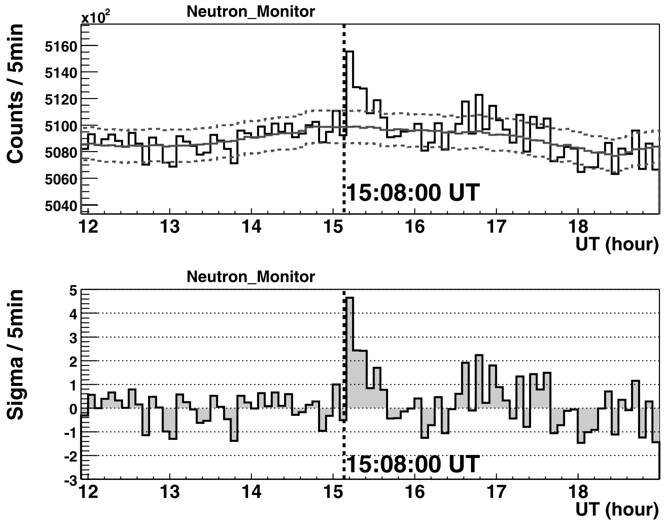


FIG. 7.—Five-minute count rate observed by the Bolivia neutron monitor on 2000 November 24. This is the pressure-corrected data. The top panel is the time profile observed by the neutron monitor and background. The solid smooth line is the averaged background, and dashed lines are $\pm 1\ \sigma$ from the background. The bottom panel is the statistical significance. From 15:10 to 15:25 UT, a clear excess made by solar neutrons was observed. The total statistical significance for 15 minutes is $5.5\ \sigma$.

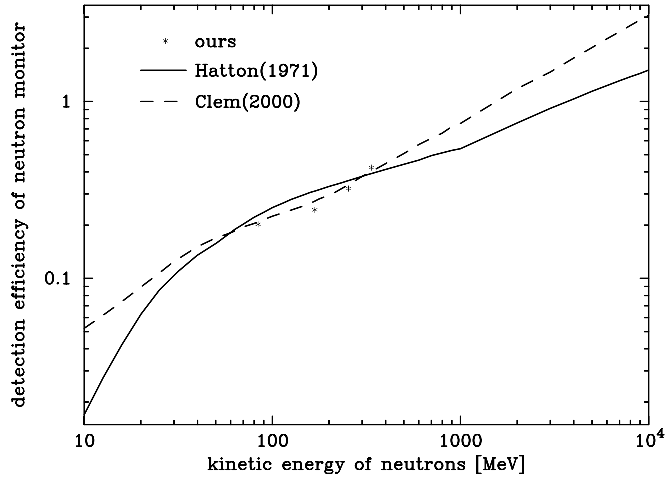


FIG. 8.—Detection efficiency of the neutron monitor (Shibata et al. 2001). In this diagram " ours " is the result of the accelerator experiments by Shibata et al. (2001). The solid line is the Monte Carlo prediction of Clem & Dorman (2000), and the dashed line is the value of Hatton (1971).

method by assuming the emission time of solar neutrons, this can be derived. To this end, we must postulate the production time of solar neutrons. As shown above, the production time of deexcited nuclei line γ-rays is taken to be that of solar neutrons. Unfortunately, the excess obtained in this event is not strong enough to examine the time profile of the signals in detail. Therefore we do not touch on the possibility of an extended production of neutrons in this paper and simply assume that neutrons were produced instantaneously in this event.

If solar neutrons were produced at 14:51 UT, which was the start time of soft X-rays, then the energy of the neutrons detected between 15:10 and 15:25 UT is calculated to be 47–19 MeV. Since neutrons suffer violent attenuation in the Earth's atmosphere, such low-energy neutrons cannot arrive at the ground. On the other hand, the assumption of the production time as 15:08 UT, which is the time hard X-ray and γ-ray emissions were seen, gives 772–57 MeV, which is much more reasonable. Consequently, the production time of solar neutrons is set at 15:08 UT hereafter.

From the time profile obtained by the neutron monitor, the flux of solar neutrons at the top of the Earth's atmosphere was calculated by the formula

$$\frac{\Delta N}{\epsilon \times S \times \Delta E_n} , \tag{1}$$

where ΔN is the excess count contributed by solar neutrons and ϵ is the detection efficiency of the neutron monitor. Here ϵ includes the attenuation of solar neutrons through the Earth's atmosphere, S is the area of the neutron monitor, and ΔE_n is the energy range corresponding to one time bin.

The detection efficiency of the neutron monitor and the attenuation of solar neutrons depend on the energy of the neutrons. The detection efficiency of the neutron monitor was calculated by Hatton (1971) and recently by Clem & Dorman (2000). Experimentally, that has been measured directly by the accelerator experiment (Shibata et al. 2001). The results are shown in Figure 8, together with calculations by Hatton (1971) and by Clem & Dorman (2000). Although the two calculations are consistent with the experimental result in the energy range 100–400 MeV, there is a big discrepancy between the calculations of Hatton (1971) and Clem & Dorman (2000) outside this experimental range. The deviation of the calculation by Clem & Dorman (2000) from the experimental result is $\pm 5\%$, whereas that by Hatton (1971) is $\pm 10\%$. Consequently, in equation (1) we adopted the efficiency calculated by Clem & Dorman (2000) because it was closer to the result of Shibata et al. (2001) than the calculation by Hatton (1971).

The attenuation of solar neutrons in the Earth's atmosphere was calculated by Debrunner et al. (1989) and Shibata (1994) by Monte Carlo simulations. Hereafter they are called the Debrunner model and the Shibata model, respectively. There is a big discrepancy between the two models. In order to examine which model is correct, an accelerator experiment was conducted at the Research Center for Nuclear Physics, Osaka University (RCNP). The Shibata model can explain the experimental result (Koi et al. 2001). Consequently, we adopted the Shibata model in calculating the propagation of neutrons in the air.

The attenuation of solar neutrons in the Earth's atmosphere at the ground level of Mount Chacaltaya at 15:08 UT on 2000 November 24 is shown in Figure 9. This is obtained by using the Shibata model. Solar neutrons whose kinetic energy are below 100 MeV are strongly attenuated by the Earth's atmosphere.

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 is taken into account. The result is shown in Figure 10. The vertical errors come only from statistical ones. This spectrum was derived from 2 minutes' count rate. By fitting these data points with a power law of the form $C \times (E_n/100\ [\mathrm{MeV}])^{\alpha}$, the energy spectrum of solar neutrons was obtained. where C is the flux of neutrons at 100 MeV, and α means the power-law index. The fitting region is chosen above 100 MeV, because there the errors from neutron attenuation in the Earth's atmosphere are small.

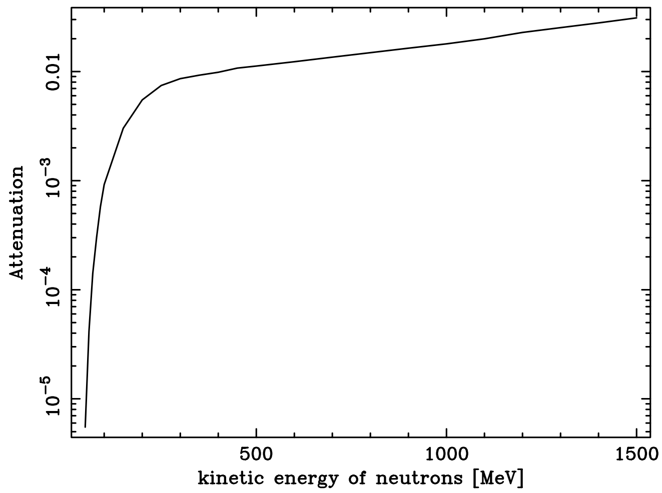


FIG. 9.—Attenuation of solar neutrons through the Earth's atmosphere at Mount Chacaltaya at 15:08 UT on 2000 November 24. This was obtained using the Shibata model. The horizontal axis is the kinetic energy of the neutrons at the top of the Earth's atmosphere.

These values were obtained as follows:

$$(1.8 \pm 0.8) \times 10^{27}\ [\mathrm{MeV}^{-1}\ \mathrm{sr}^{-1}]\left(\frac{E_n}{100\ [\mathrm{MeV}]}\right)^{-4.9\pm0.7}. \quad (2)$$

For this fit, the value of $\chi^2/\mathrm{dof} = 0.307/3$. The total energy flux of solar neutrons that were emitted from the Sun with energy range between 50 and 800 MeV was calculated as 7.4×10^{25} ergs sr^{-1}. This is obtained by simply integrating equation (2). We did not assume any turnover of the energy spectrum of neutrons in this energy region.

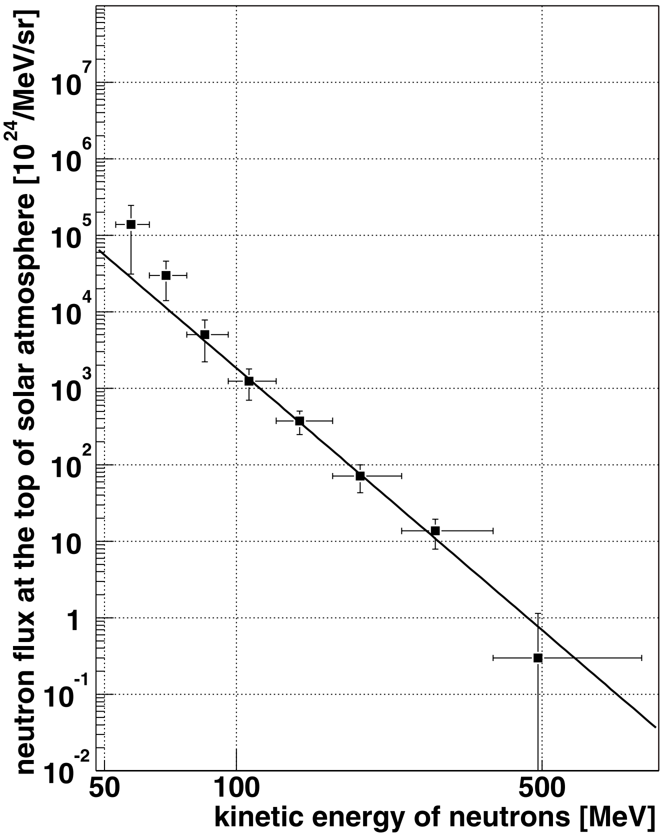


FIG. 10.—Energy spectrum of solar neutrons on the solar surface for the flare that occurred on 2000 November 24.

3. DISCUSSION

Energy spectra of solar neutron events at the top of the Earth's atmosphere were provided by Shibata et al. (1993). They used the attenuation of solar neutrons in the atmosphere calculated by Shibata (1993) and the neutron monitor detection efficiency calculated by Hatton (1971). Using the Shibata et al. (1993) values, neutron energy spectra at the solar surface of these solar neutron events can be calculated. Calculated values are shown in Table 1 together with the results of the 2000 November 24 event discussed in this paper. The solar neutron event on 1991 June 4 was observed by three different detectors, but only the neutron monitor value is shown in Table 1. The data for the solar neutron event on 1991 June 6 do not exist in Shibata et al. (1993). The solar neutron event on 1991 March 22 is the weakest event in Table 1. Because the Haleakala neutron monitor has a large area, this event was detected. Comparing the solar neutron events observed in former cycles with that observed on 2000 November 24, the latter event is fainter than previous events. Because of the thin air mass at Mount Chacaltaya (540 g cm^{-2} for vertical air mass), even faint signals can be detected.

Table 1 shows most solar neutron events observed in former solar cycles come from limb flares. But, the 2000 November 24 event came from disk flare. Solar neutrons are released tangentially to the solar surface (Hua & Lingenfelter 1987a, 1987b; Hua et al. 2002). Therefore, solar

TABLE 1
SOLAR NEUTRON EVENTS

Date	1982 June 3	1990 May 24	1991 March 22	1991 June 4	2000 November 24
Time (UT)	11:43	20:48	22:44	3:37	14:51
Observatory	Jungfraujoch (Switzerland)	Climax (USA)	Haleakala (Hawaii)	Mount Norikura (Japan)	Mount Chacaltaya (Bolivia)
Height (m)	3475	3400	3030	2770	5250
X-ray class	X8.0	X9.3	X9.4	X12.0	X2.3
Sunspot location	S09° E72°	N36° W76°	S26° E28°	N30° E70°	N22° W07°
Detector	12IGY	12IGY	18NM64	12NM64	12NM64
Flux at 100 MeV ($\times 10^{28}$ neutrons MeV^{-1} sr^{-1})	2.6 ± 0.7	4.3 ± 0.4	0.06 ± 0.01	1.8 ± 0.2	0.18 ± 0.08
Power index	-4.0 ± 0.2	-2.9 ± 0.1	-2.7 ± 0.1	-7.3 ± 0.2	-4.9 ± 0.7

neutrons are thought to be detected easily from limb flares. The result in the solar neutron event in solar cycle 23, however, is not explained by this argument. The production direction of solar neutrons in the solar atmosphere has to be treated in more detail, taking into account the position of the solar flare at the solar surface and the loop structure of each event.

The spectrum of accelerated ions can be calculated from the neutron spectrum using the spectrum of escaping neutrons produced by the accelerated ions (Hua & Lingenfelter 1987a, 1987b). From the neutron spectra shown in Table 1, the number of protons above 30 MeV would be larger than 10^{33} in all events, under the assumption that there is no turnover of the spectrum. This is larger than the number of protons accelerated in the very large flare on 1991 June 4 (Murphy et al. 1997). Estimating the number of solar neutrons below 100 MeV accurately, however, is impossible because these low-energy neutrons suffer from high attenuation through the Earth's atmosphere. Possibly the turnover of the spectrum in the low-energy range results in a smaller estimate of the number of accelerated protons. The observation of solar neutrons below 100 MeV by satellite experiments is indispensable in order to determine the total number of protons accelerated in a solar flare.

4. CONCLUSIONS

We detected solar neutrons in association with the solar flare occurred on 2000 November 24. This detection was made by the neutron monitor at Mount Chacaltaya, where was a very suitable site to observe solar neutrons in this flare.

Assuming that neutrons were produced impulsively at 15:08 UT, the energy spectrum of solar neutrons at the solar surface was obtained as

$$(1.8 \pm 0.8) \times 10^{27}\ \left[\mathrm{MeV}^{-1}\ \mathrm{sr}^{-1}\right]\left(\frac{E_n}{100\ [\mathrm{MeV}]}\right)^{-4.9\pm0.7},$$

and the total integrated energy of solar neutrons in the energy range 50–800 MeV emitted from the Sun was calculated to be 7.4×10^{25} ergs sr^{-1}.

We assumed neutrons were produced at 15:08 UT because a large amount of hard X-rays and γ-rays were observed. If neutrons were produced at the start time of the solar flare defined by the *GOES* satellite (14:51 UT), the energy of neutrons was estimated to be too low to be detected on the ground because of the extreme attenuation in the Earth's atmosphere. Therefore, it can be said that neutrons are not necessarily produced following the time profile of soft X-rays.

In order to investigate 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 strong intensity. The observability of solar neutrons is possibly correlated with the intensity of hard X-rays and γ-rays in a solar flare.

Most solar neutron events observed before solar cycle 23 were limb flares, and theoretically solar neutrons were thought to be detectable only from limb flares. But the flare discussed in this paper was a disk flare, and by combining our result with former events, the detectability of solar neutrons seems to be independent of the position of the flare on the Sun. The number of solar neutron events is, however, still too small. For a statistical argument, it is necessary to increase the number of solar neutron events. At the same time, further study of the acceleration of particles and the production and propagation of neutrons at the solar surface for each event is necessary, for example, by Monte Carlo simulation, including real loop construction of each solar flare.

All the solar neutron events observed in solar cycles 21 and 22 were associated with solar flares beyond X8. However, the X-ray class was X2.3 on 2000 November 24, when solar neutrons were observed. This is the first report of the detection on the ground of solar neutrons associated with a solar flare whose X-ray class is smaller than X8.

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