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Positron Annihilation radiation and > 10 MeV gamma rays from the 1997 November 6 flare

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Abstract. Yohkoh observed the positron annihilation ra diation at 511 keV and high-energy γ rays at 10-100 MeV from a X9.4/3B flare at 11:52 UT on November 6, 1997. A lower limit for line fluence is 64 ± 13 photons$/cm^2$ and the line width (FWHM) was <16 keV. The Yohkoh data places restrictions on the temperature of <2.1 MK and the density of $>10^{14} cm^{-3}$ at the positron annihilation site. The spectrum above 10 MeV suggests a mixture of primary electron bremsstrahlung and broad-band γ rays resulting from the π^0 decay. It implies that protons were efficiently accelerated to energies above a few hundreds of MeV and streamed down to the chromosphere. We discuss high-energy particle production based on the Yohkoh and solar energetic particle (SEP) observations.

1 Introduction

Positrons in solar flares mostly results from the β^+ decay nuclei (e.g., ^{11}C, ^{13}N, ^{15}O) and π^+ decay, all of which are produced by interactions of accelerated protons and heavy nuclei with the ambient solar atmosphere (Ramaty and Murphy, 1987). The first process results from low energy interactions at ∼10 MeV and the resultant positrons have typical energies of ∼1 MeV. On the other hand, the second one from high-energy proton interactions above 300 MeV and the positron energies are ∼30 MeV. In a thick target, the positrons are slowed down to ∼10 eV where they either annihilate directly or form positronium atom after thermalization. Direct annihilation and singlet state positronium emit two 511 keV photons, while triplet state positronium produces three γ rays (positronium continuum below 511 keV). Triplet positronium is broken up by collision if the ambient density is above $10^{14} cm^{-3}$. Since a time profile of the 511 keV line depends on the density and lifetimes of β^+-decay nuclei, its temporal variation is complex, depending on solar flares. A ratio of 3γ to 2γ depends on the ambient density. The line width is a function ot the temperature of the annihilation site (Crannel et al., 1976; Bussard et al., 1979). The first measurement of the 511 keV line was reported from the OSO observation (Chupp et al., 1973). Share et al.(1983) observed the positron annihilation line with the Solar Maximum Mission (SMM). Further, Share et al. (1996) analyzed the 511 keV line and positronium continuum from seven flares and discussed the temperature and denisty at the positron annihilation sites.

High-energy γ rays above 10 MeV are produced from interactions of high-energy flare-accelerated particles with the solar atmosphere. Several high-energy γ-ray flares were observed with SMM (Forrest et al., 1985), Gamma-1(Akimov et al., 1991) and CGRO (Kanbach et al., 1993). Particle acceleration and γ-ray production processes were discussed based on the observations. γ rays above 10 MeV are produced from (1) bremsstrahlung of >10 MeV primary electrons, (2) π^0 decay, (3) bremsstrahlung of positrons from π^+ decay and (4) annihilation in flight of positrons from π^+ decay (Ramaty et al.,1987, Murphy et al., 1987). γ rays from the π^0 decay result in the broad-band spectrum which peaks at 70 MeV and extends to energies greater than 100 MeV. These radiations are signatures of the highest-energy processes taking place on the Sun.

In this paper we report the Yohkoh observation of the 511 keV line and >10 MeV γ rays from a flare on Novemebr 6, 1997 and discuss γ-ray production and particle acceleration processes.

2 Observation

Yohkoh observed a X9.4/3B intense flare at 11:52 UT on November 6 and strong X- and γ rays were measured with the hard X- and γ-ray spectrometers (Yoshimori et al., 2000; Yoshimori et al., 2001). The count-rate time profiles at 25-826 keV and 1 MeV are shown in Fig. 1. The hard X-ray count rate was much higher than 10^4 counts/s during the peak phase of the flare (11:52:40-11:55:30 UT). It is difi-

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cult to make deadtime corrections at the count rate above 10^4 counts/s because a model of deadtime behavior of the HXS counting system is paralyzable(deadtime is 40μs). We do not analyze the hard X-ray data of which count rate is $>10^4$ counts/s. The count-rate time profile at 1 MeV, however, does not need the deadtime correction because of the low count rate. For inflight energy-calibration, we use three lines at 60 keV (^{241}Am), 191 keV (^{123}I) and 511 keV (Earth's atmospheric origin). The background-subtracted hard X-ray count spectrum between 11:55:30-12:00 UT is given in Fig. 2. We see a line feature at 511 keV. In order to analyze the 511 keV line feature, we plot the continuum-subtracted spectrum in Fig. 3. Using the response function of the spectrometer, we derive the 511 keV line fluence of 64 ± 13 photons$/cm^2$. The observed width (FWHM) of the flare 511 keV line is 50 ± 14 keV. However, this width is mostly due to the instrumental resolution of the NaI scintillation detector because the instrumental energy resolution is 48 keV (FWHM) at 511 keV.

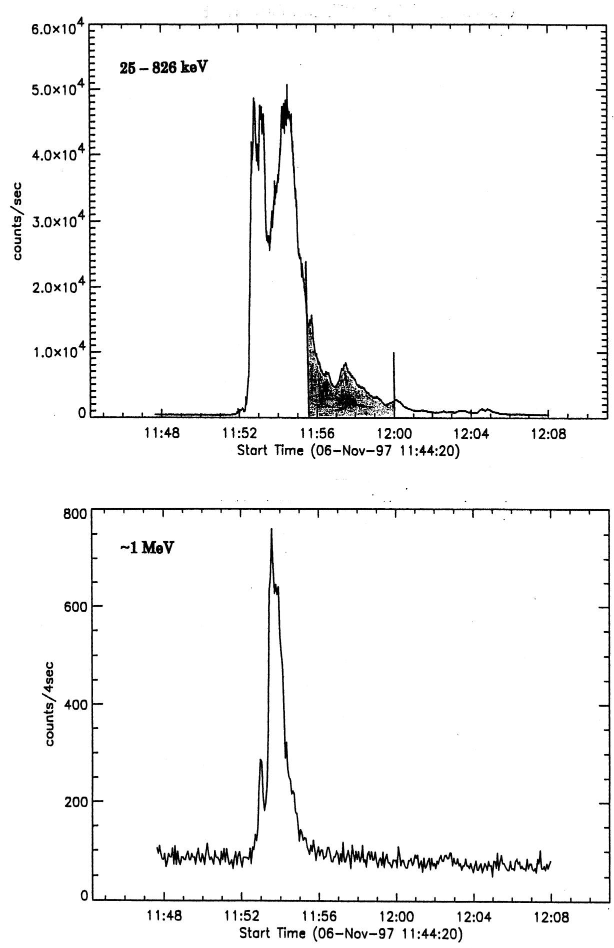

Fig. 1. Count-rate time profiles at 25-826 keV and 1 MeV. A shaded part of the upper data is a spectral measurement time.

It indicates that the intrinsic width of the flare 511 keV line is less than 16 keV. Moreover, the Yohkoh result does not exhibit the positronium continuum resulting from the triplet state of posi- tronium (three γ-ray emission).

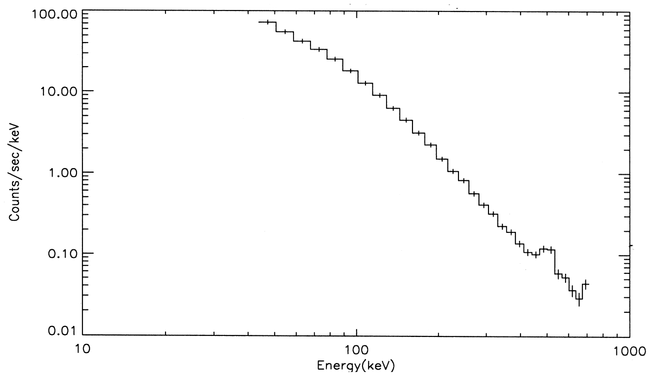

Fig. 2. Background-subtracted hard X-ray count spectrum between 11:55:30-12:00UT.

The γ-ray spectrometer detected photons above 10 MeV in the peak phase. The count-rate time profiles at 20-33, 33-53 and 53-72 MeV are shown in Fig. 4. The arrows in Fig. 4 show the time when the hard X-ray count rate reaches the maximum. The time of the maximum count rate of hard X rays is nearly coincides with that of the >10 MeV γ rays. The background levels at these energies gradually increase with time. The background-subtracted wide range γ-ray count spectrum in the peak phase is given in Fig. 5. The γ-ray spectrum above 10 MeV is not well fitted by a single power law function. It shows a broad excess above 40 MeV which is likely due to the π^0 decay.

3 Discussion

The intrinsic width of the 511 keV line is related to a temperature of the positron annihilation site. The FWHM of the line is approximated by $1.1\text{x}(T/10^4)^{1/2}$ keV, where T is the temperature. The observed width of <16 keV indicates that the temperature is less than 2.1 MT. Share et al. (1996) obtained the temperatures ranging from 0.2 to 10 MT from the width of the 511 keV line observed from seven SMM γ-ray flares. It is difficult to determine the accurate plasma temperature with the NaI scintillation detector. A Germanium spectrometer aboard HESSI will determine the temperature

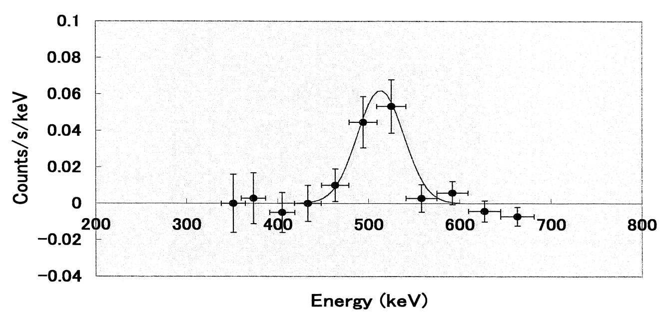

Fig. 3. Continuum-subtracted 511 keV line observed between 11:55:30-12:00UT.

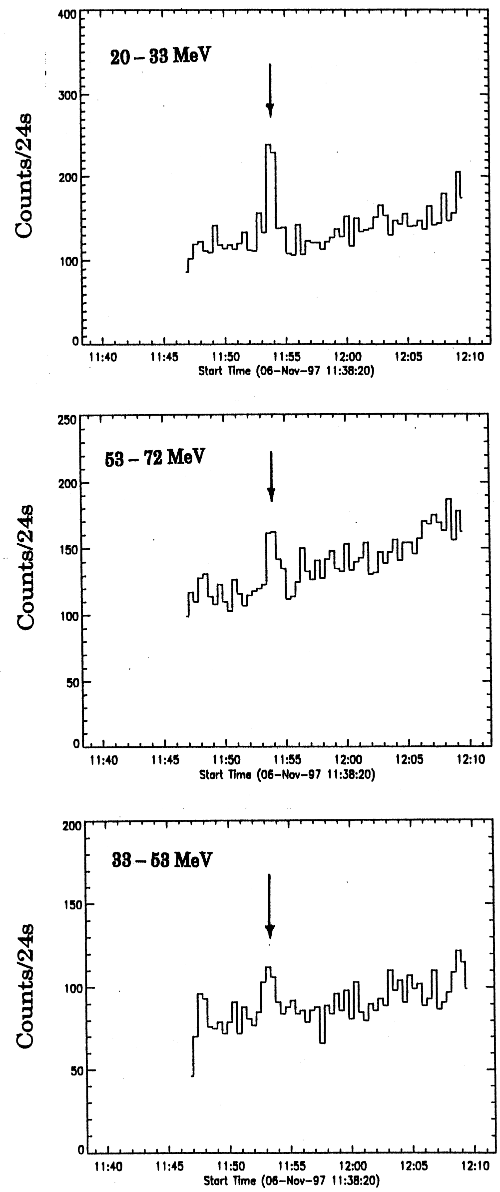

Fig. 4. Count-rate time profiles at 20-33, 33-53 and 53-72 MeV for the 1997 November 6 flare.

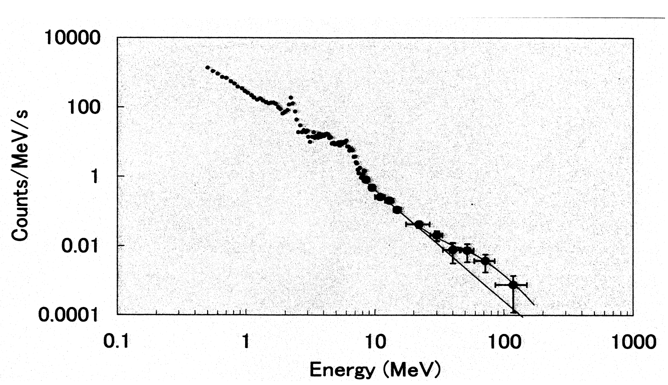

Fig. 5. Background-subtracted wide band γ-ray count-spectrum of the 1997 November 6 flare.

much accurate.

The present Yohkoh observation does not give evidence for the positronium continuum, suggesting that triplet positronium was quenched by collisional breakup at the annihilation site of density of $>10^{14}cm^{-3}$ (Ramaty and Murphy, 1987). The SMM γ-ray flares reveal that a ratio of 3γ to 2γ fluences ranges from 0 to 2.5, depending on the flares (Share et al., 1996). The Yohkoh observation of the 1997 November 6 flare indicates that positron annihilation took place at the site of the temperature of <1.6 MK and density of $>10^{14}cm^{-3}$. It implies the possibility that positron annihilation occurred low in the chromosphere.

The temporal characteristic of the 511 keV emission provides essential information on the interaction history of the accelerated ions. The count-rate time profiles of the 511 keV line and 4-7 MeV γ-rays are shown in Fig. 6. The solid circles and the dotted curve express the 4-7 MeV γ-ray data and the Ramaty et al.'s calculation (1983). The calculation assumed that the interactions take place instantaneously at the ambient denisty of $>10^{14}cm^{-3}$. The 511 keV line exhibits a longer decay constant compared with the prompt 4-7 MeV γ-rays. If the density of the positron annihilation site is $>10^{14}cm^{-3}$, the positrons should annihilate on a very short time scale. The time profile of the observed 511 kev line fits the Ramaty et al's calculation, suggesting the possibility that the positrons were produced from the long life β^+ radiaoactive nuclei of ^{11}C, ^{13}N and ^{15}O of which lives are are 20.5, 10 and 2 min, respectively.

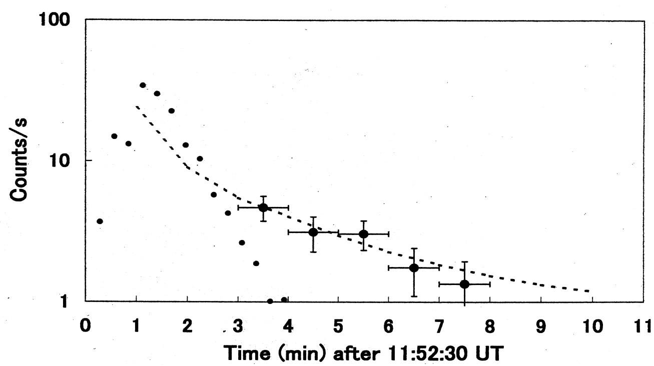

Fig. 6. Comparison between count-rate time profile of the 511 keV line and the 4-7 MeV γ-rays. The solid circles and the dotted curve express the 4-7 MeV γ ray data and the Ramaty et al.'s calculation, respectively.

The γ-ray count spectrum above 10 MeV is shown in Fig. 7. Although the spectrum below 30 MeV is approximated by the power law continuum of E^{-3}, there is the broad excess above 40 MeV. Three processes contribute to >10 MeV γ-ray production : (1) primary >10 MeV electron bremsstrahlung, (2) π^0 decay and (3) bremsstrahlung of positrons from π^+ decay (Murphy et al., 1987). Further, there is a small contribution from annihilation in flight of positrons from π^+ decay. In Fig. 7 we plot the three

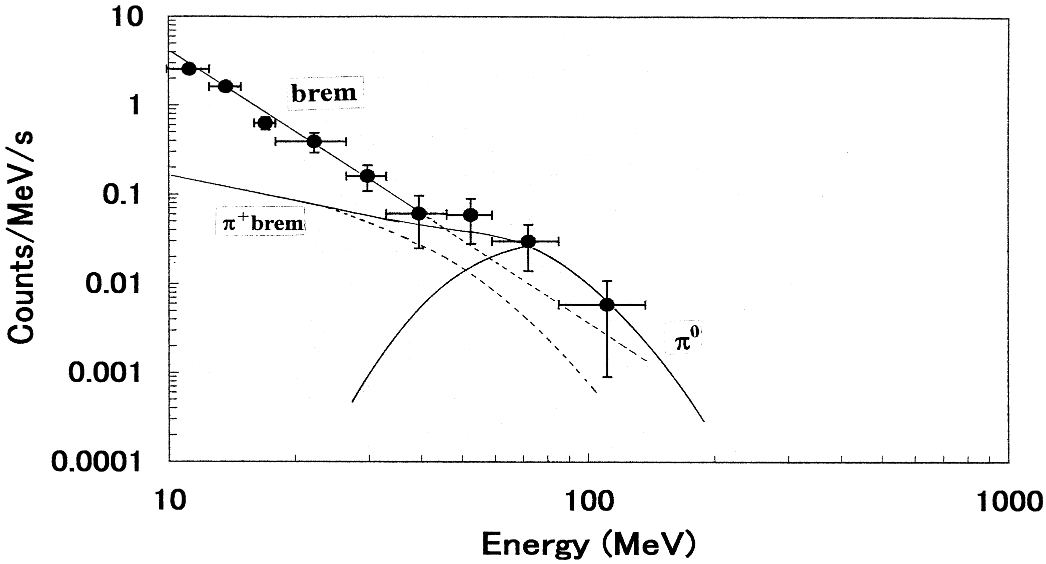

Fig. 7. High-energy γ-ray count spectrum above 10 MeV in the peak phase of the 1997 November 6 flare."brem", "π^+ brem" and "π^0 stand for the primary electron bremsstrahlung, π^+-decay positron bremsstrahlung and π^0-decay broad spectrum, respectively.

components which were calculated by Ramaty and Murphy (1987). Fig. 7 indicates that the continuum below 30 MeV is dominated by the primary electron bremsstrahlung, while the broad excess above 40 MeV are likely due to the π^0 decay γ-rays. The broad excess peaks at 70 MeV and its broadness depends on the accelerated-proton spectrum. The broadness increases as the proton spectrum hardens (Murphy et al., 1987). The Yohkoh observation implies that both electrons and protons were efficiently accelerated to energies above 10 and 300 MeV in the peak phase of the flare.

The Yohkoh X-ray image exhibits two hard X-ray sources which are located at both footpoints of the flaring magnetic loop. The temporal variation in the hard X-ray sources shows that a distance between the two sources increases with time during the peak phase (Yoshimori et al., 2001). Separation of the two hard X-ray sources suggests the possibility that a magnetic reconnection site moves up with time (Sakao et al.,1998). Particle acceleration is thought to take place in association with the magnetic reconnection. The magnetic energy released by magnetic reconnection is converted to kinetic energy of plasma particles in a nonthermal manner. One possible scenario is that both electrons and ions were accelerated to high energies on a short time scale by stochastic scattering with fast shock waves or Alfven waves generated at the magnetic reconnection site (Tsuneta and Naito, 1998). Part of the accelerated particles precipitates to the chromosphere and produce hard X rays, γ rays and neutrons.

SEPs exceeding 10 GeV associated with this event were reported from the groundbased water Cherenkov detector experiment (Falcone et al., 2001). Strong coromal mass ejection(CME) was simulatneously measured with the flare (Mason et al., 1999). These very high-energy SEPs could be accelerated by not the magnetic reconnection but the CME-driven shock in the higher corona.

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