NEUTRAL PION PRODUCTION IN SOLAR FLARES

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ABSTRACT

The Gamma-Ray Spectrometer (GRS) on SMM has detected more than 130 flares with emission >300 keV. More than 10 of these flares were detected at photon energies >10 MeV (1). Although the majority of the emission at 10 MeV must be from electron bremsstrahlung, at least two of the flares have spectral properties >40 MeV that require gamma rays from the decay of neutral pions. We find that pion production can occur early in the impulsive phase as defined by hard X-rays near 100 keV. We also find in one of these flares that a significant portion of this high-energy emission is produced well after the impulsive phase. This extended production phase, most clearly observed at high energies, may be a signature of the acceleration process which produces solar energetic particles (SEP's) in space.

1. Introduction. Gamma-ray production in solar flares at energies >10 MeV is only expected from a few mechanisms. These are bremsstrahlung by primary accelerated electrons, bremsstrahlung by positrons and electrons from the decay of charged pions, and directly from the decay of neutral pions. Each process has secondary characteristics other than it's spectrum at energies >10 MeV. These include intense low-energy X-ray emission from any continuous spectrum of primary electrons, emission of the 0.511 MeV gamma-ray line for charged pions, and the emission of high-energy neutrons for neutral pions. These secondary signatures can be used to confirm a spectral interpretation and they can also be used to extract more information concerning the primary particle spectra at the Sun. In particular we note that while the spectral shape of the pionic gamma rays does not depend strongly on the details of the accelerated particle spectrum, it's intensity is a strong indicator of the nuclear reaction rate which must produce both neutrons and pions (2, 3). Hence, combined measurements of both pions and neutrons will yield information on both the directivity and spectra of the very high-energy accelerated ions.

2. The High-Energy Monitor on GRS. The high-energy monitor on the SMM GRS (4) consists of 2 separate sensors. The top or sunward sensor consists of seven 7.6 cm X 7.6 cm NaI detectors and the bottom sensor consists of a 24 cm X 7.5 cm CsI back detector. Neutral events producing energy losses between (10-100) MeV are recorded in 4 energy bands in each of the sensors for three different cases. These are events which occur only in the NaI, only in the CsI, and events which occur in both (called "mixed" events). By appropriately summing these energy-loss bands we can define a five-channel energy-loss spectrum. The nominal energy edges of these channels are 10,25,40,65,100 and 140 MeV. The effective area for both gamma rays and neutrons have been calculated by Cooper et al. (5). These calculations have also shown that only gamma rays are effective in producing "mixed" events. Hence, the ratio of the "mixed" to the NaI only and/or CsI only events is an effective separator of neutrons and gamma rays. We note that events in the (100-140) MeV band, which only uses "mixed" events, requires gamma rays with energies greater than 100 MeV.

3. Flare Observations. The high-energy neutron observations from the flare at 01:18:20 UT on 21 June 1980 have been presented earlier (6,7) and have been reanalyzed with improved neutron efficiencies in a companion paper (8). The basic high-energy observations shows strong emission >10 MeV in the 65 s impulsive phase, followed by a low-intensity excess lasting to the end of the orbit (see Figure 1; ref. 8). Figure 1 shows the photon spectrum measured during the impulsive phase of this flare. The solid curves in this figure are the best-fit photon spectrum, determined by combining both power-law and pion gamma-ray spectra. The power-law spectrum is (5.0±0.1) $(E/10\ \mathrm{MeV})^{(2.7\pm0.1)}$ photons $\mathrm{MeV}^{-1}\ \mathrm{cm}^{-2}$ and the integral of the neutral pion spectrum is 0.6 photons cm^{-2}. The statistical test used to determine these values shows that while the overall fit is better with the pion spectra, the improvement is not sufficiently large to require it. Hence, the above pion flux must be considered an upper limit. The only way to get a larger pion flux would be to introduce a spectral break in the power law near 40 MeV. Note however, that the data do require photons >100 MeV. In the extended emission phase we find that neither the spectral properties nor the observed ratio of "mixed" to CsI counts (8) is consistent with gamma rays. We find that only 13±6% of the observed counts in this phase can be due to photons with a resulting upper limit neutral pion photon flux of 0.5±0.2 cm^{-2}.

The time history in several energy bands for the flare of 3 June 1982 is shown in Figure 3 by Chupp et al. (8). Again the high-energy observations show strong emission in a 65 s impulsive phase. However, in this event the impulsive phase is followed by a stronger extended emission phase. Figure 2 shows the photon spectrum observed during the 65 s impulsive phases. Again, these data indicate an intense power-law continuum but in this case the data show a strong hardening at energies >40 MeV which is described by a neutral pion photon spectrum with a integrated flux of 12 photons cm^{-2}. Figure 3 shows a 65 s spectrum from the beginning of the extended phase. As can be seen all of the data in this interval can be fit with a combined charged and neutral pion photon spectra. We have used these data to experimentally determine the charged-to-neutral pion ratio and find it to be 3.1±0.2.

Finally, in Figure 4 we show a 65 s spectrum further into the extended phase. In this case an attempt was made to fit the data, under the assumption that all the counts are due to photons. The data in Figure 4 show that a pion-photon spectrum is a good fit in the lowest and the highest channel but the observations exceed the pion-photon model in the three middle channels. Both the spectral shape and the time dependence of this mid-energy excess is what is expected from the high energy neutrons which must accompany any pion emission. It is just this process which allows us to separate the gamma-ray and neutron components versus time within the GRS data. Chupp et al. (8) have used these separated data to study the high-energy neutron production from this flare.

As a confirmation of the pion intensities deduced from gamma-ray spectral shape arguments, we note that these intensities are a predictor of the 0.511 MeV line flux from charged pions. As an example we use the spectrum shown in Figure 3, which requires an integrated neutral pion-photon flux of 7.8 ± 0.4 cm^{-2}. With our observed charged-to-neutral pion ratio of 3.1 ± 1, and a positive-to-total charged pion ratio of 0.70, our predicted 0.511 MeV flux, during this interval, from charged pions is 0.12 ± 0.02 [f(0.511)] photons cm^{-2} s^{-1}. Here, f(0.511) is the 0.511-to-positron ratio (3). Share et al. (9) found that the total flux at this time 0.35 ± 0.05 photons cm^{-2} s^{-1}. Murphy et al. (3) found that only 0.15 photons cm^{-2} s^{-1} could be accounted for by the radioactive positron emitters produced mainly in the impulsive phase. The difference between the measured value and Murphy's values is 0.20 photons cm^{-2} s^{-1}, which is in agreement with our predictions for charged pions produced well after the impulsive phase for a $f(0.511) = 1.6\pm0.2$.

Our analysis shows a integrated flux of 45 cm^{-2} neutral pion photons measured after 11:46:00 UT. When compared to the 12 cm^{-2} measured in the impulsive phase, we find that >80% of the pion emission was observed in the extended phase.

4. Discussion. We have presented spectral evidence for pion production in 2 flares. During the impulsive phase this emission is always accompanied by intense primary electron bremsstrahlung. In the larger of these two flares, 3 June 1982, the pion production continued well after the impulsive phase. The properties of this extended phase are distinctly different from the impulsive phase. Specifically, the extended phase seems to be ion enriched and spectrally hardened.

It is interesting to speculate that this newly discovered phase is associated with the acceleration process that generates SEP's in space. Surprisingly, there is poor correlation between the nuclear gamma-ray intensity and the size of the well-connected SEP's (10). This argues against a close link between impulsive phase acceleration and SEP acceleration. McDonald et al. (11) have shown that the cosmic-ray event associated with the 3 June 1982 flare had an unusually hard spectrum. It is intriguing that the spectrum associated with the extended gamma-ray phase is also unusually hard.

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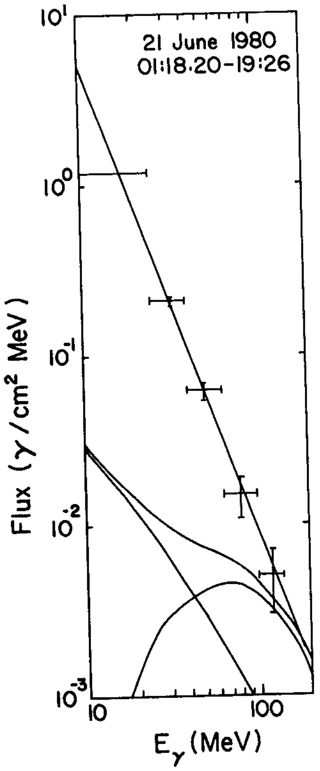

Fig. 1. The (10-140) MeV photon spectrum for the impulsive phase of the 21 June 1980 flare

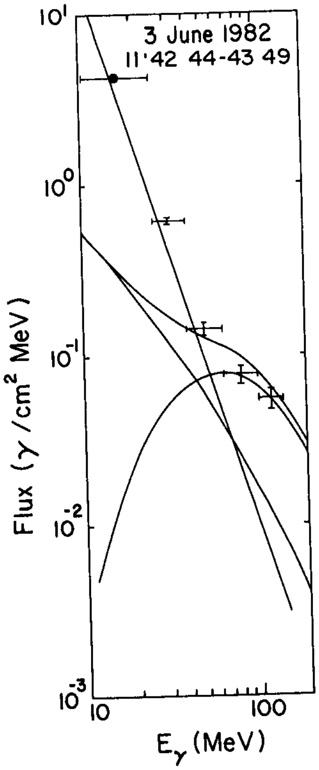

Fig. 2. The (10-140) MeV photon spectrum for the impulsive phase of the 3 June 1982 flare.

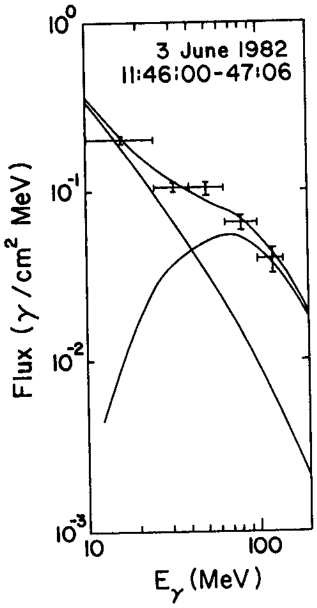

Fig. 3. The (10-140) MeV photon spectrum early in the extended phase of the 3 June 1982 flare.

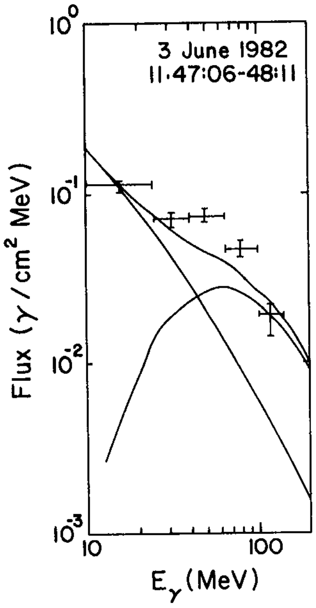

Fig. 4. The (10-140) MeV spectrum showing the photon spectrum and the effects of the high-energy neutrons in the extended phase of the 3 June 1982 flare