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A DIRECT OBSERVATION OF SOLAR NEUTRONS FOLLOWING THE 0118 UT FLARE ON 1980 JUNE 21

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ABSTRACT

Energetic solar neutrons (> 50 MeV) have been detected at the Earth following a solar flare which occurred on the west limb on 1980 June 21 at 01:18:20 UT. Impulsive photon emission from 10 keV to greater than 65 MeV lasting over a period of ~ 66 s was followed by a transient flux of ~ 50–600 MeV neutrons incident over a ~ 17 minute period. The peak counting rate corresponds to an average flux at the Earth of $(3.8 \pm 0.6) \times 10^{-2}$ neutrons $cm^{-2}s^{-1}$ at ~ 130 MeV. These observations indicate the emission of $\sim 3 \times 10^{28}$ neutrons sr^{-1} with energies $\gtrsim 50$ MeV requiring the rapid acceleration ($\ll 60$ s) of protons to ~ GeV energies during the impulsive phase of the flare.

Subject headings: nuclear reactions — particle acceleration — Sun: flares

I. INTRODUCTION

In this *Letter* we report the first observation of a transient flux of solar neutrons at the Earth with a greater than 13 σ statistical significance, using the Gamma Ray Spectrometer (GRS) on the *Solar Maximum Mission* satellite (*SMM*). The possibility that high-energy neutrons produced by solar-flare–accelerated protons at the Sun could reach the Earth was first suggested by Biermann, Haxel, and Schülter (1951) to explain ground-level increases in the cosmic-ray intensity after major solar flares. Later, Simpson (1963) suggested that anomalous, continuous fluxes of low-energy protons (> 200 MeV) observed in space were a result of the decay of free neutrons emitted by the Sun. More recently, Lingenfelter and Ramaty (1967) calculated the expected yield of neutrons from solar surface reactions and found that a detectable flux should be present at the Earth following a large solar flare and that such an observation would give valuable information on high-energy processes. Until now, there has been no confirmation of these latter predictions.

The present observation was made with the *SMM* GRS (Forrest *et al.* 1980). The spectrometer consists of seven (7.6 cm × 7.6 cm) NaI(Tl) detectors recording γ-rays from 0.3 to 9 MeV. These detectors, used in conjunction with a 25 cm diameter times 7.5 cm thick CsI(Na) crystal, act as a high-energy detector for neutral events producing energy losses greater than 10 MeV with a time resolution of ~ 2.05 s. A 4π anticoincidence shield rejects direct incident charged particles as well as any secondary leakage charged particles produced in the high-energy detector by neutral events, the latter being defined as self-gated events. The combined NaI and CsI detectors provide an effective thickness of 50 g cm^{-2}, or ~ 0.3 interaction length, for neutrons (> 200 MeV) and ~ 4 interaction lengths for γ-rays (> 10 MeV). Inflight calibration at high energies (> 10 MeV) is carried out by placing independent front and back plastic shield elements in coincidence with the high-energy detector, forming a crude charged particle telescope for cosmic rays.

II. OBSERVATIONS AND ANALYSIS

The type 1B/X2.5 flare at 0118:20 UT on 1980 June 21 gave rise to intense, impulsive X-ray and γ-ray emission, lasting for ~ 66 s, with a photon spectrum extending from less than 10 keV to 65 MeV. The location of the optical Hα flare is shown by McCabe (1982) to be on the visible disk but within 5° of the optical west limb at N20 in the active region 2502 (NOAA designation). Although energetic charged particles associated with this flare have been detected on space probes, (von Rosenvinge, Ramaty, and Reames 1981; Evenson, Meyer, and Yamagita 1981), no enhancement of terrestrial neutron monitor rates has been reported (Kondo, Fenton, and Pomerantz 1981). A preliminary analysis (Reppin *et al.* 1980; Share *et al.* 1980, 1982) of our GRS data indicates that nuclear reactions occurred during the

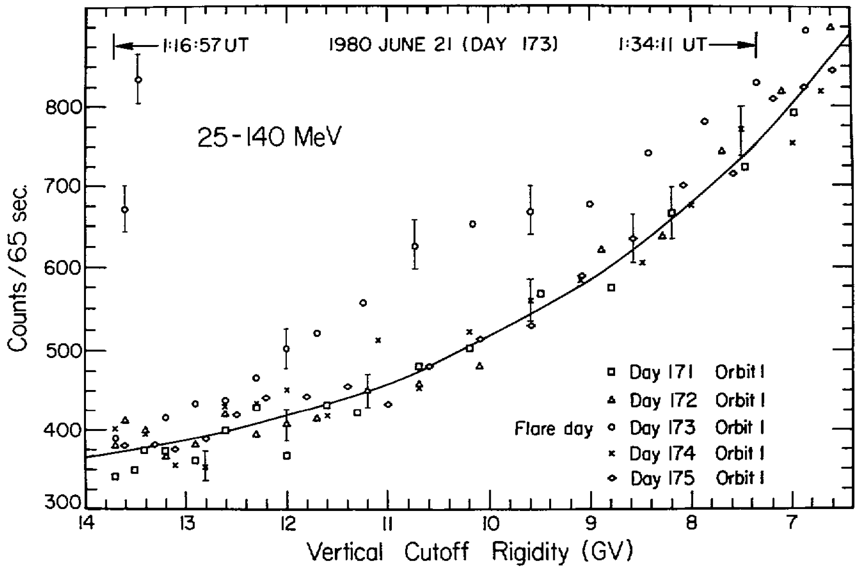

FIG. 1.—The count rate in the high-energy detector is shown for electron equivalent energy loss events between 25 and 140 MeV vs. the cutoff rigidity at the satellite for the initial *SMM* orbit on 5 successive days. The flare occurred in orbit 1 on 1980 June 21 at 0118:20 UT, when the satellite was at a cutoff of 13.6 GV. An orbital period is 96 minutes.

impulsive phase producing neutrons, positrons, and excitation of nuclear levels in ^{12}C and ^{16}O. We demonstrate here that neutrons, in addition to producing the well-established 2.223 MeV line at the Sun, have also been detected directly at 1 AU.

In order to determine the time-dependent high-energy background during and after the impulsive phase of the flare, we studied the effect of changes in geomagnetic cutoff rigidity and detector aspect (relative to the Earth) for the same satellite orbits on days before and after the flare. This analysis has shown that the variation with rigidity is the dominant effect for this event. Figure 1 shows the cutoff variation of the rate of high-energy events as a function of cutoff rigidity for corresponding orbits on two days preceding and two days following the flare, and for the flare day, 1980 June 21. The solid curve shown is the best fit exponential to nonflare orbit count rates and is used for the flare orbit background. The two high points shown in Figure 1 at ~ 13.6 GV occurred during the impulsive phase of the flare, and since they are in near coincidence (± 1 s) with γ-ray and X-ray emissions extending down to less than 10 keV, they must be due to high-energy γ-rays from the decay of π^0 mesons or relativistic electron bremsstrahlung, or both. The *anomalous* extended emission observed on 1980 June 21 after the impulsive phase was only observed in the energy loss band greater than 25 MeV and continued for 17 minutes. The evidence shown in Figure 1, together with a study of all other known experimental conditions, leads us to conclude that the excess radiation observed following the impulsive phase is also associated with the flare.

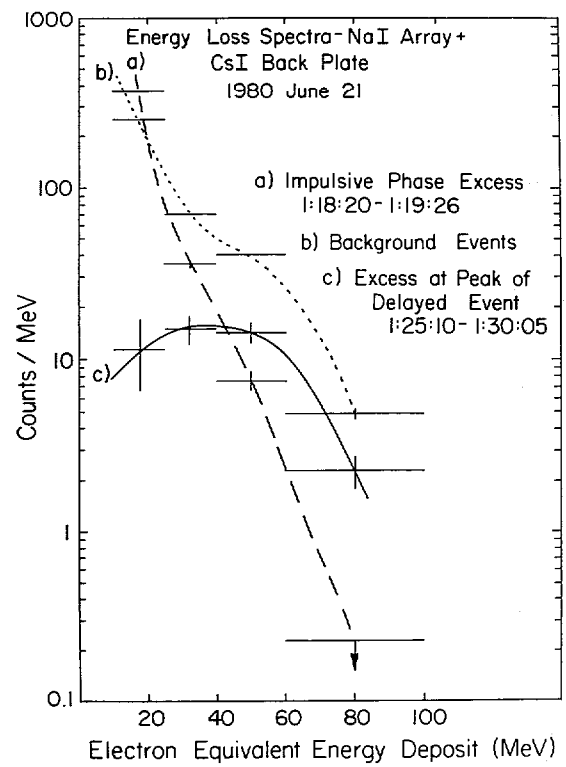

FIG. 2.—The differential number of events in the combined NaI(Tl) and CsI(Na) high-energy detector elements is shown for each electron equivalent energy loss window. See text for explanation of curves. (Note: nuclear fragments do not produce the same light output as an electron of the same energy.)

We now describe the evidence that leads to the conclusion that the delayed excess radiation is due to solar neutrons. In Figure 2 are plotted the energy-loss spectra in the high-energy detector elements for the (*a*) impulsive phase excess, (*b*) solar quiet background for the delayed event, and (*c*) postimpulsive phase excess. The first two spectra are similar and appear to decrease monotonically with increasing energy as expected for energetic γ-rays. On the other hand, the postimpulsive phase excess spectrum has a different shape, consistent with that expected for the nuclear fragment energy-loss distribution resulting from energetic neutrons interacting in alkali halide scintillators (Forrest 1969).

Other forms of high-energy radiation cannot produce the postimpulsive phase emission for the following reasons. First, there is no increased rate in any portion of the 4π charged particle shield. For example, if the front plastic charged particle shield had an efficiency of 96% (the lowest possible), then an increase of the local charged particle rate of $\sim 10\%$ would be required to account for the high-energy detector enhancement. On the other hand, the shield rate did not show any enhancement and, in fact, indicated a 0.1% decrease (1 σ) during the anomalous event. We, therefore, rule out as a source any excess high-energy charged particles. Second, there is no unexplained increase in the count rate of neutral events in the energy range 300 keV $< E <$ 20 MeV. This rules out both electron-produced high-energy bremsstrahlung and proton-produced π^0 decay photons since these would be accompanied by an intense flux of γ-rays in the 4–7 MeV range during the postimpulsive phase.

Based on the above discussion, we conclude that the excess high-energy flare radiation observed is due to a direct flux of solar neutrons. The excess count rate versus time, in a broad energy channel, 25–140 MeV, is plotted in Figure 3. Shown in the inset is the detailed time structure of the γ-radiation during the impulsive phase in the 10–140 MeV energy band. Also shown is a neutron energy scale obtained from time of flight where we have assumed a δ-function emission of neutrons on the Sun occurring a light travel time (i.e., 507 s) before

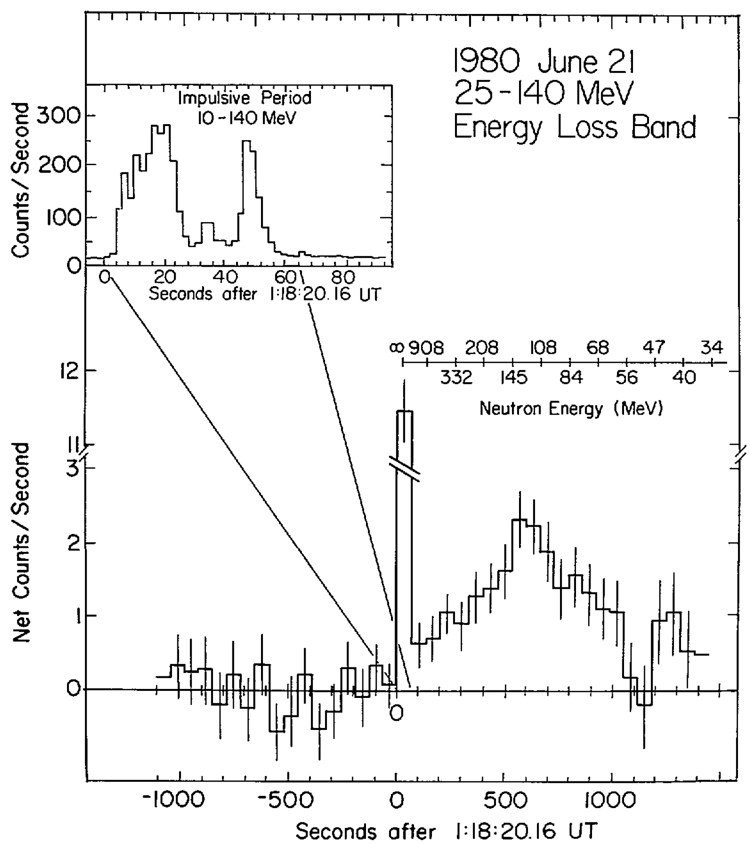

FIG. 3.—(*lower*) Excess count rate vs. time is shown for electron equivalent energy loss events between 25 and 140 MeV before and after the start of the impulsive flare at 0118:20 UT. The neutron energy scale, center, assumes the neutrons left the Sun at the light travel time (507 s) before 0118:36 UT. (*inset*) The total count rate vs. time after 0118:20 UT for electron equivalent energy loss events between 10 and 140 MeV during impulsive phase only.

0118:36 UT. The figure demonstrates that solar neutrons from ~ 50–600 MeV have been detected.

III. DISCUSSION

In principle, direct measurements at 1 AU of both the neutron energy and intensity as a function of time allow a direct inference of both the spectrum and production interval at the Sun, since both the travel time and survival probability as a function of neutron energy are known. However, in this case, statistical limitations and the lack of an experimental neutron energy response function for the *SMM* instrument preclude this type of direct unfolding. To interpret the observed data, we must use our best knowledge of the energy-dependent neutron detection efficiency and assume either a neutron production interval or spectral shape at the Sun. The detection efficiency uses the measured cross sections on CsI for neutrons at 14, 100, and 150 MeV of 13 ± 6 mb per atom, 330 ± 100 mb per atom, and 660 ± 150 mb per atom, respectively (Forrest 1969), together with the assumption that the cross section approaches the geometrical value of ~ 1.5 barns at very high neutron energies. The total (NaI and CsI) effective areas for neutron detection (without self-gating) at 50, 100, 200, 400, and 600 MeV are 11, 40, 103, 150, and 153 cm^2 respectively. Correction for self-gating can significantly reduce the above values of effective area for neutron energies above 300 MeV; for example, by a factor of 6 at 600 MeV.

To estimate the neutron spectrum at the Sun, we use an energy-dependent effective area, uncorrected for self-gating, an assumed production time, a power-law energy spectrum, and the known velocity dispersion and decay probability over 1 AU to calculate neutron spectral shapes for comparison with the observations shown in Figure 3. If we assume that all the neutrons were released in a short interval of time centered at the first peak of the impulsive high-energy photon emission as shown in Figure 3 (*inset*), we find that, an inverse power-law exponent between 3 and 4 gives a reasonable fit. However, independent of the specific spectral shape, the total number of neutrons emitted from the Sun is $\sim 3 \times 10^{28}$ neutrons sr^{-1} above 50 MeV. This result is not changed significantly if the emission is uniform over the entire ~ 66 s photon production interval or if corrections are made for self-gating above 300 MeV. Further detailed calculations are in progress to relate these neutron observations to a primary flare particle spectrum.

Since neutrons with energies at least as high as 600 MeV were recorded, their production requires that ~ GeV or higher energy protons were accelerated in the impulsive phase and probably within a 20 s time interval corresponding to the first impulsive phase burst shown in the inset in Figure 3. This fact alone imposes a strong constraint on the properties of the solar flare particle accelerator operating in this event. Current theories of solar flare particle acceleration for the most energetic ions and electrons rely solely on a "second phase" (Heyvaerts 1981) or "second step" (Bai and Ramaty 1979; Bai 1982) Fermi processes; however, the rapidity with which GeV protons had to be accelerated in this event forces us to consider that a single primary accelerator could be operative. (See also Forrest *et al.* 1983.)

The detection of solar neutrons in this event was possible because of two factors. (1) The impulsive γ-ray line emission was extremely intense, lasting only 1 minute, indicating a maximum time scale for neutron production. (2) The flare occurred early enough in the orbit so that about 20 minutes of observing time was available for the detection of the neutrons before eclipse by the Earth. Solar neutrons would be more difficult to detect in a slower rising, less intense event, such as the 1972 August 4 event, since their production would have lasted at least 10 minutes and the terrestrial flux would be less intense. A preliminary search was made for solar neutrons in other less intense γ-ray line events through 1981 with no success; however, observing conditions were not as optimum as in the fortuitous 1980 June 21 event. More solar neutron events will be detected with instruments of greater sensitivity. High-energy neutron observations give a direct measure of the accelerated particle spectrum at the highest energies (~ GeV) while γ-ray line observations, only give the spectrum in the low-energy range, ~ 1–100 MeV. Future studies of solar flare neutron emission could help advance our understanding of flares as much as electromagnetic observations have.

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Note added in manuscript, 1982 September.—On 1982 June 3 shortly before this *Letter* was submitted for publication, the most intense γ-ray line event yet observed occurred at 1143 UT. Although data analysis of this event is not complete, a clear signal, characteristic of solar neutrons, is evident in the high-energy detector of the *SMM* GRS. In addition, the ground-level IGY neutron monitor at Jungfraujoch at the atmospheric depth of 660 g cm^{-2} and with a time resolution of 1 minute recorded an increase of the count rate of about 4%, lasting for several minutes in time coincidence with the neutron signal at the satellite (Debrunner *et al.* 1982).

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