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SOLAR NEUTRON DECAY PROTON OBSERVATIONS IN CYCLE 21

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ABSTRACT

Measurement of the flux and energy spectrum of the protons resulting from the decay of solar flare neutrons gives unique information on the spectrum of neutrons from 5 to 200 MeV. Neutrons from three flares have been observed in this manner during solar cycle 21. We review the use of the decay protons to determine neutron energy spectra and present new and definitive energy spectra for the two large flares on 1982 June 3 and 1984 April 25.

Subject headings: Sun: flares — Sun: particle emission

I. INTRODUCTION

Like gamma rays, solar flare neutrons have no electric charge and propagate freely through the solar and interplanetary magnetic fields which make the study of charged energetic solar particles difficult (Forman, Ramaty, and Zweibel 1986). Neutrons are produced in the same nuclear reactions which produce gamma-rays but the cross sections for neutron production have a different energy dependence from those for gamma ray production. The time of production, spectral shape, and anisotropy of the neutrons should provide information regarding the energetic particle population and the target which cannot be inferred from gamma-ray observations alone (Murphy 1985). Neutrons, however, are produced much less copiously than gamma-rays. To date only a few flares have yielded measurable neutron fluxes. Whereas the anisotropy of production of gamma rays (Rieger *et al.* 1983) is under detailed study (Dermer and Ramaty 1986) only crude limits exist on the degree of neutron isotropy (Evenson, Kroeger, and Meyer 1985). Because of velocity dispersion, little is directly known about the time structure of neutron production. (Murphy and Ramaty 1984).

Solar neutrons have been observed directly at high energy (Chupp *et al.* 1982; Debrunner *et al.* 1983) and indirectly at low energy via the 2.2 MeV gamma-ray line from the capture of neutrons by hydrogen in the solar photosphere (Prince *et al.* 1982). Evenson, Meyer, and Pyle (1983) reported the discovery of interplanetary protons produced by the decay of solar flare neutrons. By observing the protons produced as the neutrons decay in flight, very accurate energy spectra can be obtained in the important energy range 10–300 MeV. Coordinated observations among interplanetary spacecraft or between interplanetary and near Earth spacecraft can increase the coverage of the solar disk and can make a determination of the anisotropy of the escaping neutrons possible. The decay proton method has, by itself, poor time resolution. However the determination of accurate time averaged spectra will allow removal of ambiguities due to velocity dispersion in the analysis of data from neutron detectors with less than perfect absorption efficiency.

In this paper we briefly review the determination of neutron energy spectra from measurements of decay protons. We then present a compilation of previously published and newly analyzed data that taken together provide definitive neutron spectra for the events on 1982 June 3 and 1984 April 25. We note that the neutron spectrum from the 1984 event is significantly harder than that of the 1982 event. Also, we report indications that the flux of neutrons below 10 MeV may be lower than would be expected from theoretical calculations of neutron production and escape.

II. INITIAL OBSERVATIONS

Figure 1, after Evenson, Meyer and Pyle (1983), shows the first reported detection of interplanetary protons produced by decaying solar flare neutrons. The observations were made near 1 AU by the University of Chicago instrument on the *International Cometary Explorer* (*ICE*) spacecraft. Prior to the arrival of the neutrons, interplanetary proton fluxes were low and nearly constant. An intense pulse of gamma rays passed the spacecraft at 11:42 UT (*dashed line*) followed by expanding shells of neutrons which arrived at later times according to the lower velocities corresponding to their different energies. As each shell of neutrons passed the spacecraft a small fraction of them decayed, and the decay protons immediately became trapped by the interplanetary magnetic field. As shown in Figure 1, a flux of protons suddenly appeared.

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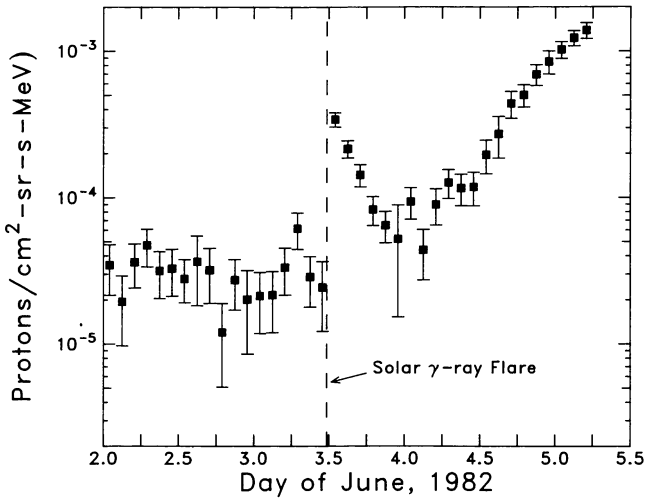

FIG. 1.—Flux of 25–45 MeV protons observed at *ISEE-3*. Two hour averages are plotted. Arrival of gamma rays from an intense solar flare is indicated by a dashed line. After Evenson, Meyer, and Pyle (1983).

These protons then began to diffuse away through the magnetic field in the solar wind. The proton flux declined until protons accelerated directly by the flare began to arrive. Because these protons had to diffuse through the interplanetary magnetic field all the way from the Sun their arrival was slowed sufficiently to allow the observation of the smaller flux resulting from the decaying neutrons.

III. PRINCIPLES OF DETECTION

Even though only a tiny fraction of the neutrons decay at one location, the decay protons are observable if they are held captive by an appropriate magnetic field (Evenson 1987). Moving in approximately circular orbits, each proton has many chances to strike a fixed detector whereas the freely propagating neutron had but one. A simple calculation allows this process to be expressed as an equivalent detector efficiency for comparison to conventional neutron detectors. Assume that an impulsive neutron fluence, J_n (neutrons cm^{-2}), passes a detector of area A oriented normal to the beam. By definition, the efficiency, η, relates the number of neutrons detected, N_n, to the fluence.

$$N_n = \eta J_n A . \tag{1}$$

Some passing neutrons decay in flight to yield a local proton density, n (protons cm^{-3}), where

$$n = \frac{J_n}{\beta\gamma c\tau} , \tag{2}$$

with β and γ being the Lorentz parameters of the neutron, c the speed of light, and τ the mean neutron lifetime (914 s). Were it not for the magnetic field, these protons would simply continue along with the neutrons. However, the magnetic field immediately traps the protons with the result that a steady flux of protons, j_p (protons cm^{-2} s^{-1} sr^{-1}), appears with an intensity given by

$$j_p = \left(\frac{\beta c}{4\pi}\right) n = \frac{J_n}{4\pi\gamma\tau} . \tag{3}$$

Assume that the proton detector is a flat surface of area A (with arbitrary orientation) and thereby has a geometry factor of πA cm^2 sr. If the magnetic field is able to hold the particles for some residence time, t_r, then the total number of protons detected, N_p, is

$$N_p = (\pi A)(j_p)(t_r) = \frac{t_r J_n A}{4\gamma\tau} . \tag{4}$$

An equivalent efficiency, $\eta_{\rm eq}$, is then easily identified by comparison with equation (1)

$$\eta_{\rm eq} = \frac{t_r}{4\gamma\tau} . \tag{5}$$

Thus, if the protons are detained for about an hour, as they were in the event shown in Figure 1, the equivalent efficiency of the system is nearly unity and can in principle be larger than unity. Compared to a direct neutron detector, where efficiencies of a few percent might be considered good, the decay proton method permits use of a detector having a far smaller sensitive area (Frye *et al.* 1988).

In addition to having high detection efficiency, the decay proton method also has extremely good energy resolution. In most neutron detectors, the first interaction almost never deposits the entire energy of the neutron in the detector. Either a second scattering or a large absorptive mass must be used to determine the energy. By contrast, nearly the entire kinetic energy of the decaying neutron is transferred to the proton. In the energy range of interest, this proton is nonrelativistic, hence its energy can be accurately determined by relatively small, charged particle detectors using standard techniques.

IV. MEASUREMENTS IN THE INTERPLANETARY MAGNETIC FIELD

To interpret decay proton observations, details of the external magnetic field must be considered. In the interplanetary magnetic field (IMF) uncertainties in knowledge of the exact structure of the IMF translate to uncertainties in the neutron flux determination. The simple calculation of the previous section assumed a homogeneous neutron source. In reality the neutrons propagate in a pattern of expanding spherical shells upon which is superposed an exponential radial decay. Further, the local solar horizon at the flare site casts a shadow over one-half of the heliosphere.

The solar system geometry at the time of the 1982 June 3 event is displayed in Figure 2, where the Sun is represented by a small dot. Two schematic field lines of the IMF in the Parker model are shown originating from the Sun and extending into interplanetary space. One of these lines originates from the flare site and curves away from Earth (the

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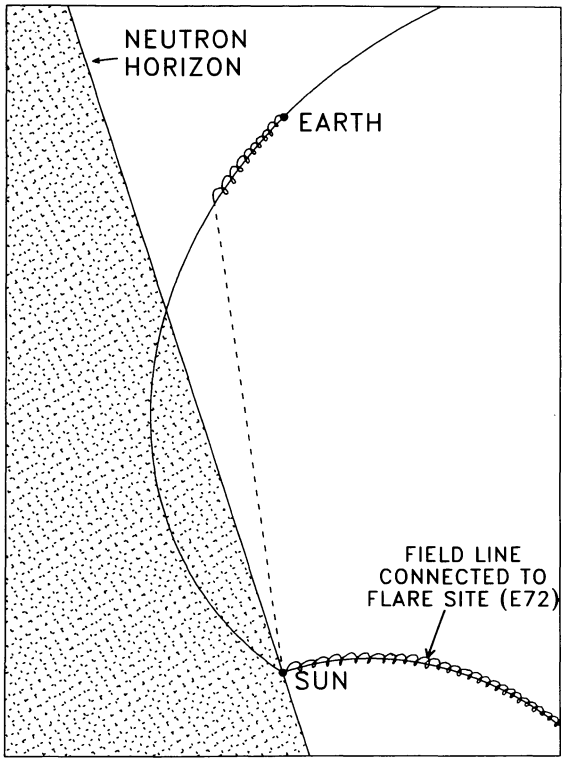

FIG. 2.—Solar system geometry at the time of the 1982 June 3 solar flare. The view is looking down on the ecliptic plane. Protons from the flare are intially confined to field lines far from Earth, while neutrons cross the field lines freely until they decay. (Evenson, Meyer, and Pyle 1983).

spacecraft was close to the Earth at the time). A proton from the flare site is shown propagating outward from the Sun in a helical path along this field line. Such protons must diffuse across many field lines in order to reach an observer at Earth —a process which requires a long time. The dashed line represents the trajectory of a neutron which is destined to reach the observer as a decay proton. While propagating as a neutron it travels in a straight line, unaffected by the IMF. As soon as it decays, the resulting proton is bound to the field. The most readily observed decay protons are those which are created on the field line connecting to the observer. Note also that the solar horizon shields a significant fraction of this critical field line from population by the decaying neutrons.

A close look at Figure 2 shows that the angular distribution of emitted neutrons can be determined in principle from a single location using the decay proton method. Each location on the observer's field line corresponds to a particular angle of emission; hence, the resulting proton deposition can be exactly calculated from the assumed angular dependence of the neutron production. If subsequent diffusion along the field line was modeled accurately the resulting flux versus time curve measured by the observer could be deconvolved to give the injection distribution. To do this would require a knowledge of particle propagation in the interplanetary medium which is beyond the present state of the art but which is not inconceivable for the future (Bieber, Evenson, and Pomerantz 1986).

V. PROTON DATA

During solar cycle 21 a total of four gamma-ray producing solar flares are known to have occurred at times when interplanetary proton fluxes were at levels low enough to permit meaningful searches for decay protons. Decay protons were detected in retrospective analysis of data on the 1980 June 21 flare following the direct neutron detection by Chupp *et al.* (1982) Although the decay protons were clearly seen (Evenson, Kroeger, and Meyer 1985) the statistical accuracy of the measurements was poor, and the results were consistent with any reasonable extrapolation of the higher energy direct measurements. On 1983 May 7 at 22:17 UT the cesium iodide detector in the *ICE*/MEH instrument (Kane, Evenson, and Meyer 1985) recorded a gamma-ray event comparable to that of 1980 June 21. At this time the *SMM* spacecraft was not observing the Sun. Evenson, Kroeger, and Meyer (1985) were able to set upper limits on neutron production from this flare that indicate that neutrons were not produced more copiously than they were in the 1980 June 21 event.

In contrast, highly significant measurements were made for the flares of 1982 June 3 at 11:42 UT and 1984 April 25 at 0:00 UT. Figure 3 summarizes the decay proton data available for the 1982 June 3 event. Data from the *IMP-8* spacecraft were fully calibrated at the time of publication by Evenson, Meyer, and Pyle (1983), therefore they are simply reproduced in this summary. The calibration of the

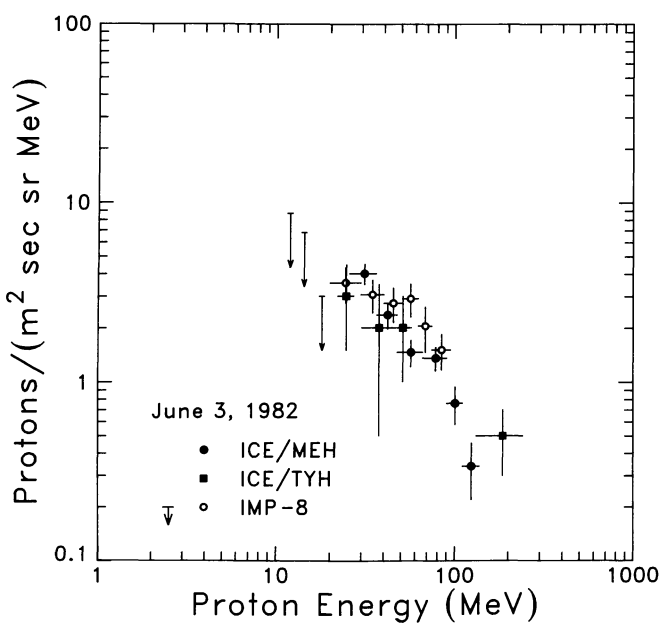

FIG. 3.—Decay proton spectrum constructed for the 1982 June 3 neutron flare using data from the *ISEE-3* and *IMP-8* spacecraft. Flare was located at E72 with respect to the spacecraft. *IMP-8* data are from Evenson, Meyer, and Pyle (1983).

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ICE/MEH instrument was later worked out in detail by Kroeger (1986), and the data presented in Figure 3 from this instrument are based on that calibration. In addition, we have added data from the *ICE*/TYH instrument (von Rosenvinge *et al.* 1978) that agree with the other instruments at lower energy and improve the statistical confidence of the highest energy measurement. The data shown were all taken during the time interval 12:00 to 14:30 UT on 1982 June 3, and have had background subtracted based on flux levels during the 12 hr preceding the flare. Indicated errors at at the one standard deviation level, considering both the error on the measured flux and the subtracted background. The upper limits below 20 MeV are the result of interplanetary proton background—for clarity only *IMP-8* limits are shown although similar limits are obtained from the *ICE*/TYH data.

In Figure 4 we show the available data for the flare of 1984 April 25. Unfortunately, at this time the *IMP-8* spacecraft was inside the magnetosphere and unable to contribute data useful to this study. The *ICE* spacecraft, on its way to a rendezvous with comet Giocobini-Zinner, was located at 0.93 AU, ~ 10° ahead of Earth in solar orbit. Therefore, from the spacecraft, the flare appeared at a longitude of E54. Proton fluxes from the *ICE*/MEH and *ICE*/TYH sensors obtained during the interval 0:15 UT through 2:45 UT on 1984 April 25 are displayed in the figure. Note that the proton fluxes in this event are much higher than those in the previous event. As discussed in the following section, this is almost certainly due to the illumination of a greater length of the interplanetary field line connected to the spacecraft due to the smaller difference in heliolongitude. Because of the lower background and higher flux the energy spectrum can be determined to significantly lower energies in this event.

VI. NEUTRON SPECTRA

In order to convert the observed proton spectra to solar neutron production spectra it is necessary to use a model for the interplanetary propagation of the resulting protons. We use the simple diffusion model discussed by Evenson, Meyer, and Pyle (1983) assuming that the neutron deposition on the unshaded portion of a nominal Parker magnetic field line connected to the observer results from isotropic emission at the Sun. Use of this simple model is roughly equivalent to use of the time of maximum method to estimate solar flare particle production spectra. Clearly a much more elaborate approach would be necessary in order to discuss possible information contained on the anisotropy of the neutron emission. Our work on such a model is currently in a stage too preliminary to warrant discussion at this time.

Using this model, we show the deduced neutron production spectrum for the 1982 June 3 flare in Figure 5 and the spectrum for the 1984 April 25 flare in Figure 6. Error estimates shown are scaled from the error estimates in Figure 3 and Figure 4 with the proportionality constants used for flux determination. In the simple model used, the only free parameter is the interplanetary diffusion mean free path. We have used 0.3 AU in both cases; a value that is consistent with the time profile of both events. Choosing a value of 0.15 AU would lower our deduced neutron production by 25%, whereas a value of 0.6 AU would raise the deduced spectrum by 50%. For reference, we show calculations of neutron production in a thick target model from the work of Lingenfelter and Ramaty (1967). These calculations assume that the particles interacting to produce the neutrons have spectra that are exponentials in rigidity. Curves shown are calculated for characteristic rigidities of 125 and 200 MV. The curves are shown with the same normalization in both

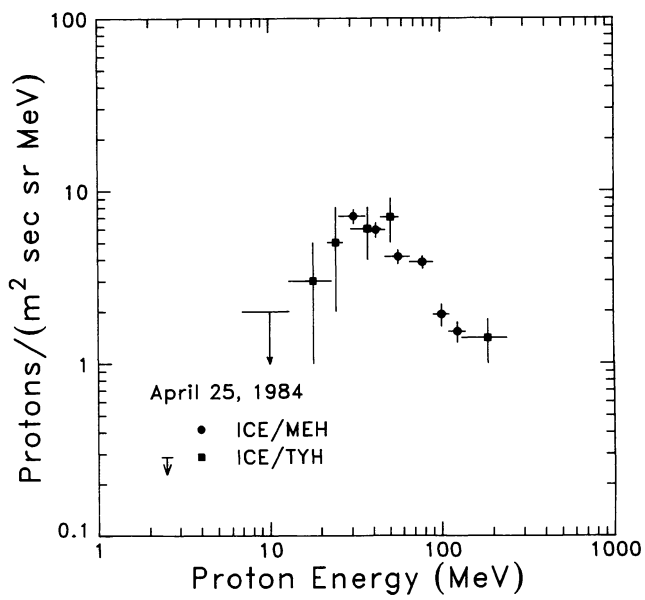

FIG. 4.—Decay proton spectrum constructed for 1984 April 25 neutron flare using data from the *ICE* spacecraft. Optical flare was located at E54 with respect to the spacecraft.

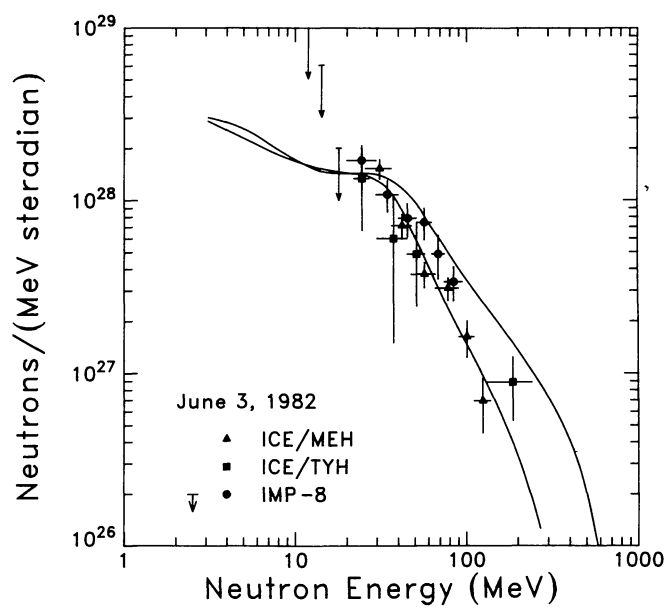

FIG. 5.—Emitted neutron spectrum derived from the decay proton data from the 1982 June 3 event. High upper limits at low energies are caused by interplanetary proton background. Curves are from Lingenfelter and Ramaty (1967).

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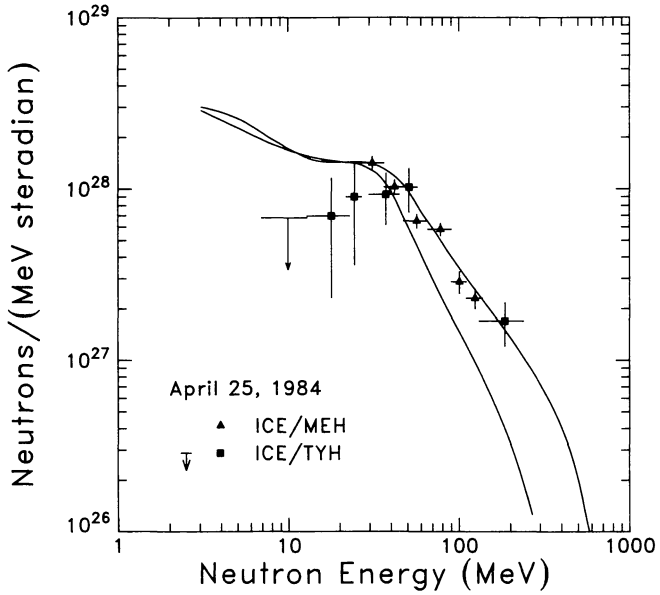

FIG. 6.—Emitted neutron spectrum derived for the 1984 April 25 event is harder than that of the 1982 June 3 event. Suppressed fluxes at low energies are also implied by these data.

figures, which is also the normalization selected by Evenson, Meyer, and Pyle (1983).

In comparing the figures, two features stand out. First, although the number of neutrons produced at energies around 30 MeV is similar in the two events, and perhaps higher in the 1982 June 3 event, the 1984 April 25 event has a spectrum that is much harder. The June 3 spectrum is reasonably well fitted by the curve corresponding to 125 MV characteristic rigidity, while the 200 MV characteristic rigidity provides a better description for the April 25 flare. Second, there is every indication that the flux of neutrons at lower energy (below 20 MeV) in the 1984 April 25 event is significantly lower than would be expected on the basis of the calculation.

At the present we regard the lower fluxes at lower energies as unexplained. More modern calculations, such as those by Hua and Lingenfelter (1987) do not result naturally in spectra that fall off at lower energies. Indeed, consideration of effects such as production of the neutrons deeper in the solar atmosphere tend to produce spectra that are enhanced rather than depleted at lower energies (except for limb flares). The April 25 flare, at E54 with respect to the spacecraft, was not at all a limb event. Unfortunately the background at lower energy in the June 3 event makes it impossible to determine whether or not there was similar spectral behavior.

VII. CONCLUSIONS

During solar cycle 21 it was possible to construct accurate neutron spectra in the energy range 10–200 MeV for the solar flares of 1982 June 3 and 1984 April 25 by using a simple model of interplanetary charged particle propagation. At energies of 20–30 MeV, the neutron emission from both flares was comparable, but the extension of the spectrum to higher energies was considerably harder in the April 25 event. Below 20 MeV, fewer neutrons were emitted into interplanetary space from the April 25 event than might have been expected from calculations normalized to the higher energy production. The source of this discrepancy is not understood at present. Background prevented significant measurements below 20 MeV in the June 3 event, so no statement can be made regarding the generality of this effect.

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