# SOLAR NEUTRON OBSERVATIONS AND THEIR RELATION TO SOLAR FLARE ACCELERATION PROBLEMS

E. L. CHUPP

*Physics Department, University of New Hampshire, Durham, NH 03824, U.S.A.*

(Received 16 February, 1988)

**Abstract.** We review the current observational knowledge on the production of neutrons in association with solar flares. From a study of the observations it is shown that unique information can be obtained on the spectral properties of accelerated ions produced during the flare. Also, the abundance of $^3$He/H in the photosphere can be directly determined. We also review the current interpretations of all available neutron observations and in particular highlight the uncertainties, and provide guide posts for future experiments.

## 1. Introduction

The interest in the emission of $\gamma$-ray and neutrons from the Sun has been closely coupled, almost from the time that it was realized that the Sun could produce particles with cosmic-ray energies. Indeed, the proper study of the solar flare acceleration process, required observations of both the neutrons and $\gamma$-ray energy spectra. It was first realized by Biermann, Haxel, and Schlüter (1951) that GeV protons accelerated at the Sun could produce a sufficient flux of neutrons to be observable at the Earth. These neutron radiations could, therefore, be a powerful direct probe of solar flare particle acceleration processes, since they are not affected by solar and interplanetary magnetic fields. The expected neutrons were first observed in 1980 by an instrument on the Solar Maximum Mission (SMM) satellite Chupp *et al.* (1982). In addition, the spectra of neutrons remaining at the Sun can be studied by observing the properties of the $n - p$ capture $\gamma$-ray line at 2.223 MeV, first observed in solar flares by Chupp *et al.* (1973). Following this observation Wang (1975), and Wang and Ramaty (1974) carried out detailed calculations on the propagation of neutrons and their capture in the photosphere, leading to the 2.223 MeV line. Further detections of this line was made by Hudson *et al.* (1980) and Prince *et al.* (1982).

In this paper we will review the status of solar neutron observations and the current interpretations. The most thorough early studies of neutron production at the Sun were made by Lingenfelter and Ramaty (1967). This work has been recently updated by Murphy and Ramaty (1984), Murphy, Dermer, and Ramaty (1987) and Hua and Lingenfelter (1987a, b, c). See also recent reviews on the high-energy aspects of solar flares by Chupp (1984, 1987) and Ramaty and Murphy (1987).

*Solar Physics* **118** (1988) 137–154.

## 2. Current Observations

Solar neutron observations are primarily used as a probe to learn the properties of the ions accelerated in solar flares. In addition, as will be shown below, a measure of the $^3$He/H abundance ratio in the photosphere may be obtained. Current information on the spectra of neutrons at the Sun is obtained from:

(1) Capture $\gamma$-rays from neutrons absorbed by photospheric nuclei, predominately those of hydrogen.

(2) The measurement of the spectra of protons in space which arise from the inflight decay of energetic neutrons emitted from the Sun.

(3) The direct detection of solar neutrons by spacecraft detectors and ground level neutron monitors on the Earth.

| (a) Neutron capture gamma rays | (b) Neutron-decay protons | (c) Direct spectrum observations |
|---|---|---|
| $np \rightarrow 2.223$ MeV<br><br>Measures flux of neutrons interacting in the photosphere<br><br>$E_n < 20$ MeV | $n \rightarrow p + e^- + \bar{\nu}_e$<br><br>Measures spectrum of neutrons decaying in interplanetary field<br><br>$20 \text{ MeV} < E_n < 100$ MeV | Satellites $E_n > 50$ MeV<br><br>Ground level neutron monitors<br><br>$E_n > 300$ MeV |

Fig. 1. The approximate neutron energy range which is probed by observations using (a) neutron capture $\gamma$-rays, (b) neutron decay protons, and (c) direct observation of neutrons in space or at ground level.

Figure 1 shows the approximate range of neutron energies which are investigated by these three techniques, which will now be discussed in detail. The most important sources of neutrons from solar flares have been summarized by Murphy, Dermer, and Ramaty (1987). The cross-sections for the various reactions are shown in Figure 2. The resulting neutron spectra for the different reactions were originally presented by Lingenfelter and Ramaty (1967).

### 2.1. Neutron capture gamma rays

Neutrons emitted from the interactions of charged particles with the atmospheric constituents, and traveling into the photosphere are thermalized by elastic collisions with protons in a time $< 0.1$ s, for neutrons of initial energy $\sim 1$ MeV. In turn, the radiative capture cross-sections of thermalized neutrons for most elements is inversely proportional to the neutron velocity and ranges for solar constituents from $\sim 0.05$ barns to 0.5 barns for capture by protons and iron nuclei, respectively, for the most probable

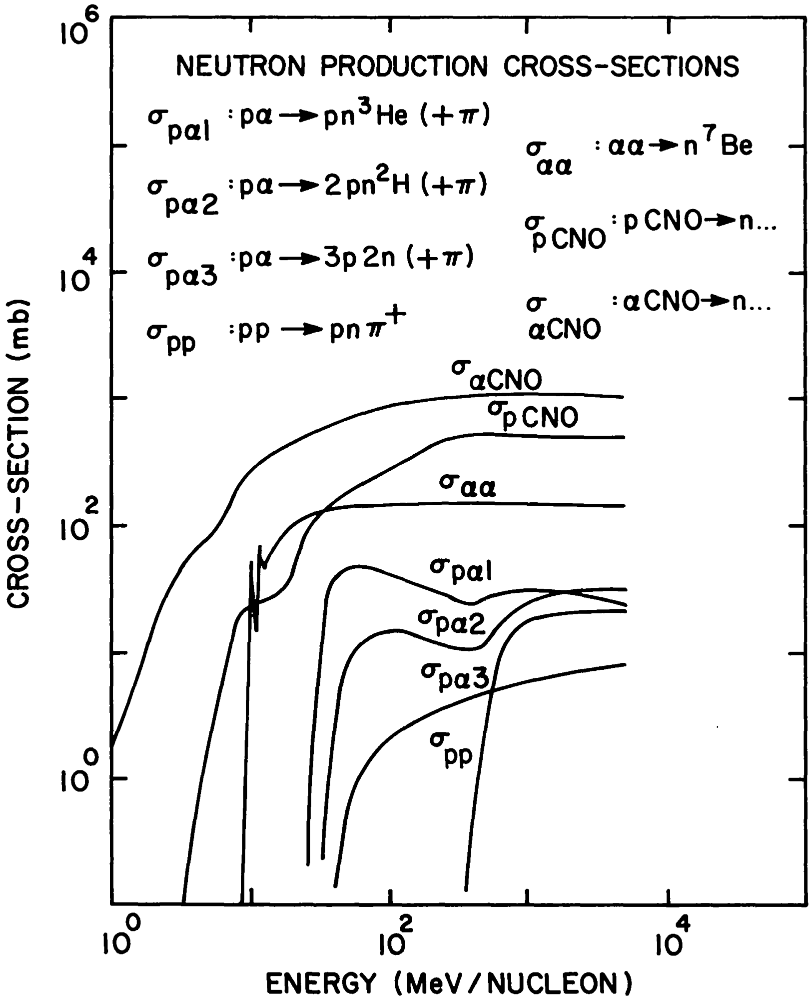


Fig. 2. The cross-section for neutron production on the ambient solar constituents versus proton or $\alpha$ particle energy (MeV nucleon)$^{-1}$. After Murphy, Dermer, and Ramaty (1987).

thermal velocity at a photospheric temperature of 10000 K. Since the hydrogen abundance far exceeds (by $10^4$) that for any photospheric elements which have significant neutron capture cross-sections, the primary source of $\gamma$-rays from neutron capture in the photosphere is from $^1H(n, \gamma)^2H$. Since there are no bound states of the deuteron a single $\gamma$-ray of energy 2.223 MeV is emitted for each capture reaction and the line width ($\sim$100 eV) is characteristic of the photosphere temperature ($\sim 10^4$ K). The mean neutron proton capture time is $t_{c\gamma} \simeq 1.4 \times 10^{19}/n_H$ s, where $n_H$ (cm$^{-3}$) is the number density of protons, so for a typical photospheric density of $\sim 10^{17}$ cm$^{-3}$ the characteristic mean radiative capture time is $\sim$100 s. The simple form for the capture time results because the capture cross section is inversely proportional to neutron velocity.

It is also important to note that neutrons may be lost by the non-radiative capture reaction $^3He(n, p)^3H$, Wang and Ramaty (1974) and by decay according to $np + e^- + \bar{\nu}_e$. In the former case the typical photospheric thermal capture cross-section is $\sim 952$ barns, which leads to a mean non-radiative capture time $\tau_{cn} \simeq 8.6 \times 10^{14}/n_{^3\text{He}}$ s, where $n_{^3\text{He}}$ cm$^{-3}$ is the number density of $^3$He nuclei. Actually the abundance of $^3$He relative to hydrogen, $^3$He/H, is unknown in the photosphere and $n_{^3\text{He}}$ may be related to the hydrogen (proton) density according to $n_{^3\text{He}} = (^3\text{He/H})n_\text{H}$ giving $\tau_{cn} \simeq 8.6 \times 10^{14}/(^3\text{He/H})n_\text{H}$. For example, if the photospheric $^3$He/$^4$He abundance ratio were the same as observed in a solar prominence by Hall (1975) as $^3\text{He}/^4\text{He} = (4 \pm 2) \times 10^{-4}$, and if the photospheric $^4$He/H abundance ratio were equal to $\sim 0.07$ (Cameron, 1982), then $^3\text{He/H} \simeq 2.8 \times 10^{-5}$ giving $\tau_{cn} \simeq 3.1 \times 10^{19}/n_\text{H}$ s. This is about twice as long as the mean radiative capture time on protons. Finally, the mean life for free neutron decay is $\tau_d = 918$ s (Hua and Lingenfelter, 1987b). The total loss time for all processes, along with the neutron production time history, determines the time dependent intensity of the 2.223 MeV line, as described in more detail below.

The first observations of the $n - p$ capture $\gamma$-ray at 2.223 MeV were made from OSO-7 during the large flares in August 1972 (Chupp *et al.*, 1973) and later from HEAO-1 (Hudson *et al.*, 1980) and HEAO-3 (Prince *et al.*, 1982). These measurements served primarily to verify that nuclear reactions producing neutrons took place in solar flares. The most comprehensive observations of the 2.223 MeV $\gamma$-ray line have been made by the $\gamma$-ray spectrometers on the SMM spacecraft, launched in 1980 (Forrest *et al.*, 1980) and the Hinotori spacecraft, launched in 1981 (Yoshimori *et al.*, 1983a, b). It is the interpretation of these recent observations we will discuss here.

Prince *et al.* (1983) using SMM GRS data have observed the time history of the 2.223 MeV line emission for over $10^3$ s following the large solar flare on 1982, June 3. In Figure 3 is shown the time history of several emissions from this flare. Of particular interest here is a time history of the photon in the 4.1–6.4 MeV energy band, indicated as MCW in the figure. This energy band reflects the time-history of nuclear reactions producing both $\gamma$-ray lines and neutrons (cf. Ramaty, Kozlovsky, and Lingenfelter, 1979). The time history of $\gamma$-ray line production from the reaction H($n$, $\gamma$)$^2$H is delayed with respect to that of the actual neutron production, because of the relatively long mean time for radiative capture given above (typically, $\sim 100$ s for $n_\text{H} \sim 10^{17}$ cm$^{-3}$). Thus, if neutrons were injected into the photosphere in a time short compared to the *loss-time* (see above), the 2.223 MeV line intensity will fall off with time approximately exponentially with a time constant equal to the *loss-time*. On the other hand, in the case of the 1982, June 3 flare it is clear from the MCW curve, in Figure 3, that neutron production is taking place for several minutes after the initial strong impulsive production shown at approximately 11:43 UT. As an example we show in Figure 4 the time-integrated $\gamma$-ray spectrum around 2.223 MeV over about 6 min, during the decay of the event. As can be readily seen, the line is sufficiently intense in this event that a detailed time history of the intensity can be constructed as done by Prince *et al.* (1983). The shape of this curve depends on the injection time history of neutrons into the photosphere and the total probability of their loss due to all processes (radiative capture, nonradiative capture, decay, and scattering into space). Neglecting scattering out of the photosphere as a loss process, the total mean *loss time* $\tau$ can be expressed as

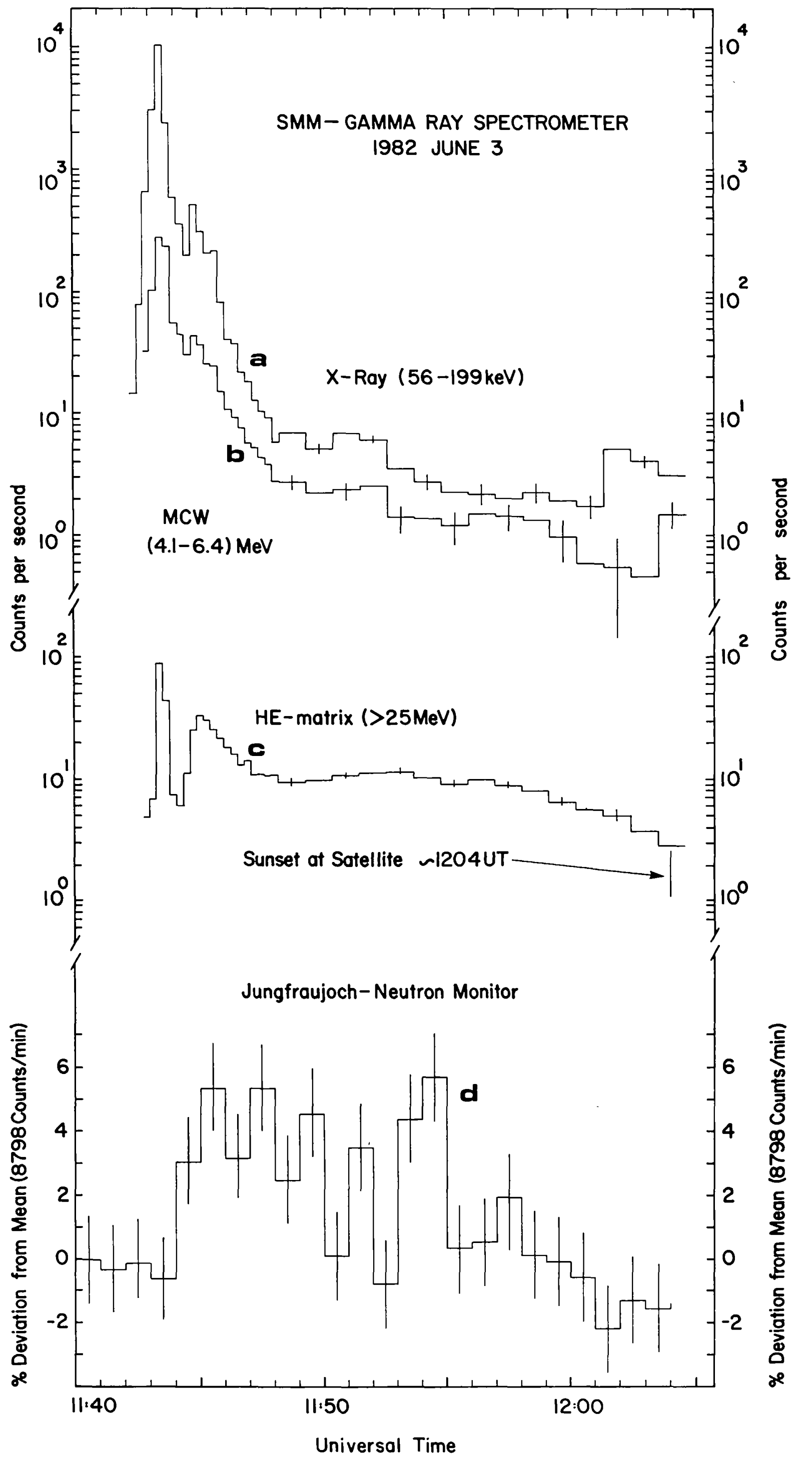


Fig. 3. The time history of several emissions observed during the 3 June, 1982 flare by the SMM GRS, curves a, b, c, and the Jungfraujoch (Ch) IGY Neutron Monitor, curve d. (After Chupp *et al.*, 1987.)

$\tau = (\tau_{c\gamma}^{-1} + \tau_{cn}^{-1} + \tau_d^{-1})^{-1}$ which of course depends on $n_H$ and the unknown $n_{^3He}$ as previously discussed. (Note that for neutrons with energies below 2 keV, gravitational trapping will keep a neutron population near the photosphere until decay or capture occurs, thereby increasing $\tau$.) Prince *et al.* (1983) have analyzed the time history of the

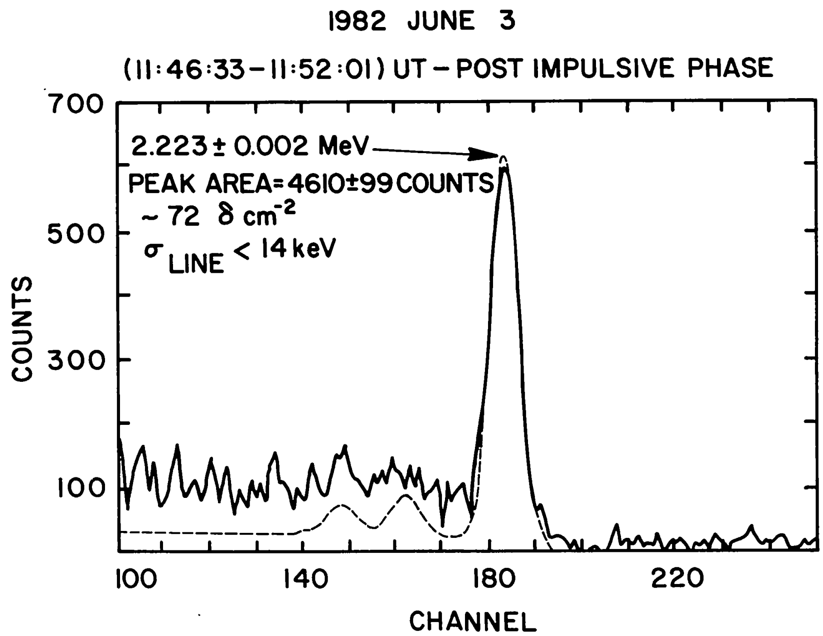


Fig. 4. The SMM GRS $\gamma$-ray spectrum near the energy of the neutron-proton capture line during the post-impulsive phase of the 1982, June 3 flare. The solid curve is the total observed counts observed in each GRS channel over the time period from 11:46:33–11:52:01 UT. The dotted curve shows the best fit to the line using the measured SMM GRS response function to a Gaussian primary line, single and double escape peaks, and the Compton continuum. (After Chupp, 1983.)

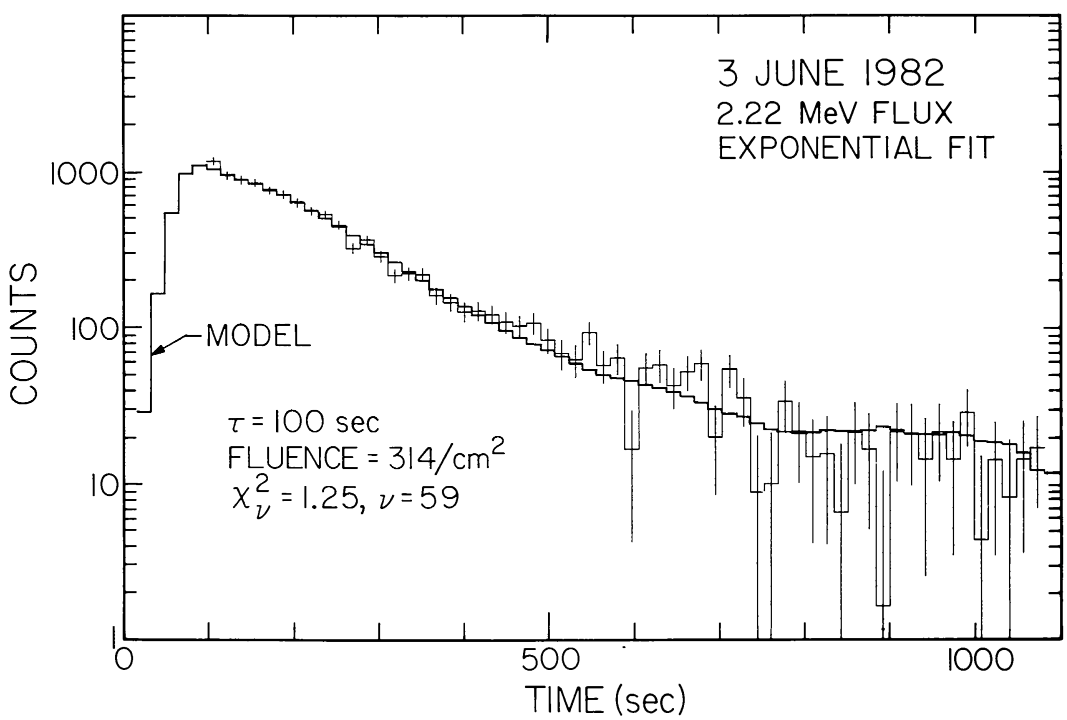


Fig. 5. Time history of the 2.223 MeV $\gamma$-ray line flux during the 1982 June 3 flare. The histogram, with $1\sigma$ error bars, shows the observed counts in the line in 16 s time bins of the SMM (GRS). The darkened histogram shows the best fit predicted time history for a single exponential decay with a model of neutron production which is proportional to the observed flux of prompt nuclear $\gamma$-rays in the 4.1–6.4 MeV GRS energy band. (After Prince *et al.*, 1983.)

capture line shown in Figure 5 by relating the 2.223 MeV flux $F_{2.2}(t)$, at a time $t$, to an assumed model of time-dependent neutron production according to:

$$F_{2.2}(t) = \int_{\infty}^{t} S(t_s) R(t - d/c, t_s)\, \mathrm{d}t_s \,,$$

where $S(t_s)$ is the neutron production time history and $R$ is a function relating the neutron production at time $t_s$ to the production of the 2.223 MeV capture gamma-ray which reaches the Earth at time $t$. Prince *et al.* (1983) have used for $S(t_s)$ the MCW time history shown in Figure 3 and for $R$ an exponential with a single time constant $\tau$. The best fit model was obtained with a time constant of 100 s and a total fluence for the line of 314 (photons cm$^{-2}$) as illustrated by the model curve in Figure 5. Using the above relation for the mean loss time, $\tau$, the $^3$He/H ratio can be determined if an average capture density $n_{\mathrm{H}}$ is known. Using Monte Carlo results of Kanbach *et al.* (1981), Prince *et al.* (1983) derive a value $^3\mathrm{He/H} = 0.4^{+3.4}_{-0.4} \times 10^{-5}$.

Recently, Hua and Lingenfelter (1987a, b) have done more elaborate calculations on the production and transport of neutrons from a range of assumed flare accelerated ion energy spectra, angular distributions and elemental abundances. These results were used to determine the rate of emission of 2.223 MeV $\gamma$-rays from the Sun, toward the Earth, considering the effects of neutron transport, scattering, decay and nonradiative capture on $^3$He and the scattering of the escaping $\gamma$-rays for different flare locations. These new calculations show that the total capture time dependence of neutrons is greatly different from a single exponential such as used by Prince *et al.* (1983). This is primarily a consequence of capture occurring over a range of photospheric depths. Therefore, Hua and Lingenfelter (1987b) have performed new calculations appropriate for 2.223 MeV emission from the flare of 1982, June 3 (see Figure 5) at a heliocentric longitude of $\sim 72°$ E. In particular they studied the time dependence of the emission line flux as a function of the $^3$He/H ratio, the accelerated ion spectra, and its angular distribution. For the neutron production function they also used the MCW curve shown in Figure 3.

Finally, for reasons cited mainly by Ramaty and co-workers (cf. Murphy and Ramaty, 1984, and below), Hua and Lingenfelter (1987b) have performed model calculations using, primarily, a Bessel function spectrum in their study of the $^3$He/H ratio as compared to the experimentally determined time history as shown in Figure 5. Their analysis involves making best fit comparisons of calculations and observations and results in basically two parameters: (1) a value of $\alpha T = 0.035 \pm 0.007$ which determines the shape of the Bessel function spectrum and (2) a ratio $^3\mathrm{He/H} = (2.3 \pm 1.2) \times 10^{-5}$, both values at the 90% confidence level. The former value agrees closely with other independent determinations of $\alpha T$ ranging from $0.03 < \alpha T < 0.04$ by Hua and Lingenfelter (1986b) and Murphy, Dermer, and Ramaty (1987). The $^3$He/H ratio above falls within the range found by Prince *et al.* (1983) which assumed the 2.223 MeV time history could be fit by an experimental curve with a single time constant. It appears safe to conclude that the value of $^3$He/H found by Hua and Lingenfelter (1983a) is finite and quite well determined, at least within the constraints provided by their model. A more precise determination of this ratio must await analysis of observations of the 2.223 MeV line from flares at other solar longitudes and also a more comprehensive analysis of all emissions to be sure self consistent models are used.

The shape of the ion accelerated spectra can also be estimated by using the measured fluence ratio for the 2.223 MeV line to the 4.1–6.4 MeV $\gamma$-rays, the latter predominately due to nuclear de-excitation (Ramaty, Kozlovsky, and Suri, 1977; Ibragimov and Kocharov, 1977). This is so because the bulk of the prompt MeV $\gamma$-ray emission comes from the two strongest nuclear de-excitation lines from $^{12}$C and $^{16}$O (Ramaty *et al.*, 1979; Ibragimov and Kocharov, 1977), produced by accelerated ions with energies below $\sim 50$ MeV, the same energy ions which probably produce the neutrons leading to the 2.223 MeV line. Since the time histories of the emissions in the two $\gamma$-ray energy bands are so different (see Figures 3 and 5) it is necessary to use total time-integrated fluxes to account for all the production. Then if one assumes some ion spectrum, whose shape is given by some parameter, such as $\alpha T$ for the Bessel function form or the exponent in a power-law form, one can calculate the ratio of fluences $\phi_{2.223}/\phi_{4-7}$ for different spectral parameters for a given assumed flare location. These values also depend on an assumed $^3$He/H ratio and are different for thin or thick target interaction geometries as recently discussed by Ramaty and Murphy (1987) and Hua and Lingenfelter (1987a). (The observed fluence, $\phi_{2.223}$, must be corrected for eclipse of the flare emissions by the Earth.) Comparison of a model value with the observed value then gives a specific spectrum if the spectral form is assumed; e.g., for the 1982, June 3 flare Prince *et al.* (1983) give a value of $1.03 \pm 0.10$ for $\phi_{2.223}/\phi_{4.1-6.4}$ from which Hua and Lingenfelter (1987a) infer a value of $\alpha T \simeq 0.04$ for a thick target model. It is interesting that $\alpha T$ values obtained, in the same way for all flares for which $\gamma$-ray data is available, range between $\sim 0.01$–$0.04$. Hua and Lingenfelter (1987a) have also found that the fluence ratio $\phi_{2.23}/\phi_{4-7}$, gives for an assumed ion power-law spectrum, an exponent range of $\sim 3.1$ to 4.0 for all known $\gamma$-ray emitting flares since August 1972.

While considerable progress has been made in understanding the behavior of neutron transport in the photosphere, once they are produced, and how factors such as $^3$He/H abundance and primary particle spectral shapes can be estimated from observations it should be noted that primarily only the properties of the narrow 2.223 MeV line (and the prompt nuclear emission) have been used for this determination. Therefore, in a given flare this information only comes from those neutrons captured at a column depth in the photosphere corresponding to approximately one optical thickness to the observer, $\sim 12$ g cm$^{-2}$ (cf. Vestrand *et al.*, 1988).

### 2.2. Neutron-decay protons

Due to the relatively long mean life ($\sim 918$ s) for the free neutron, those which have an energy greater than $\sim 130$ MeV will have a high probability, ($> e^{-1}$), of reaching the Earth before decay. Figure 6 shows a plot of the survival and decay probabilities for neutrons at 1 AU taking into account the relativistic time dilation versus neutron energy. For those neutrons which do decay according to $n \to p + e^- + \bar{\nu}_e$, the resulting electrons

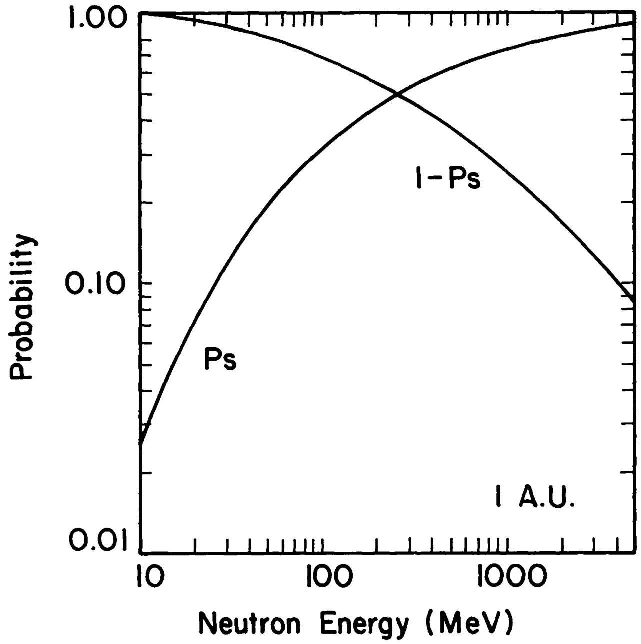


Fig. 6. The survival and decay probabilities are shown for neutrons at 1 AU versus their kinetic energy $E_n$.

and protons are trapped in the interplanetary magnetic field and in principle may be detected at any point in space magnetically connected to the location where the neutron decayed. The characteristic energies of neutrons produced in solar flares range from a few MeV to > GeV so the resulting decay protons preserve the direction and most of the energy of the neutron.

Roelof (1966) studied in detail the expected signature of the neutron decay protons assuming an isotropic diffusion model for these particles in the interplanetary field. While this work indicated that these secondary protons could not be detected above the primary protons emitted from the flare, Evenson, Meyer, and Pyle (1983) were able to detect the decay protons in space, near the Earth, following the intense $\gamma$-ray flare on 1982, June 3. The detection was possible because the flare was on the Eastern side of the Sun's disk so the primary protons were greatly delayed in arrival time at the Earth because of the poor magnetic connection. Figure 7 shows the observed flux of 25–45 MeV protons at the ISEE-3 spacecraft versus time during early June 1982 as measured by Evenson, Meyer, and Pyle (1983). The dotted line indicates the arrival time of $\gamma$-ray photons at the Earth at $\sim$11:43 UT. The decaying proton flux after this time and until $\sim$24:00 UT on June 3 is due to the arrival of neutron decay protons followed by the arrival of primary protons which have diffused through the coronal magnetic fields until they reach the field lines connected to the spacecraft. Of course, the earliest arriving protons are from the highest energy neutrons which decay on field lines between ISEE-3 and the Sun while the later arriving protons are of lower energy due to neutrons which decay both within and beyond 1 AU. Since the decay protons are trapped on field lines passing through the satellite, a diffusion model must be used in order to determine

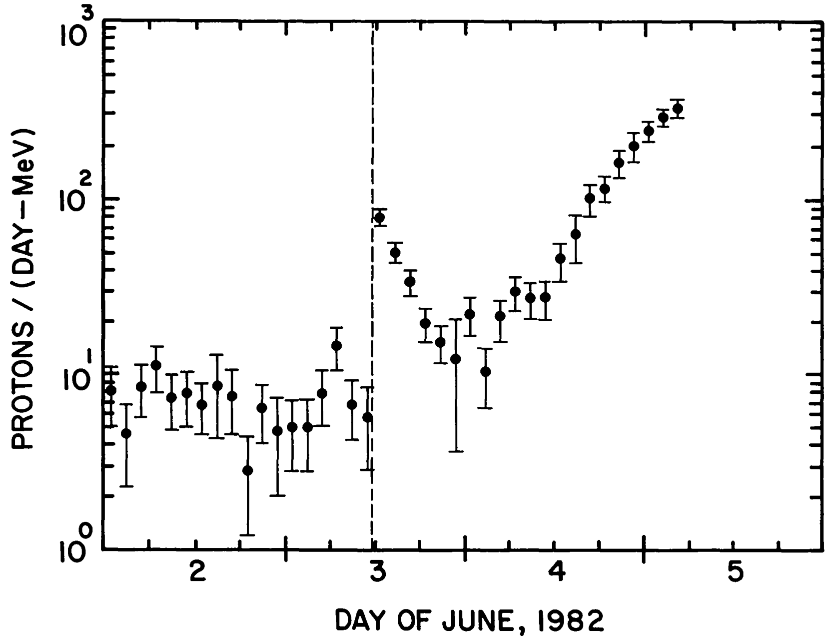


Fig. 7. The flux of 25–45 MeV protons observed on ISEE-3, near the Earth, during the 1982, June 3 flare. (After Evenson, Meyer, and Pyle, 1983.)

the actual neutron fluence at the Sun in a given energy band which give the decay protons of corresponding energy. Evenson, Meyer, and Pyle (1983) have found that a diffusion mean free for the protons of 0.3–0.5 AU gives the best fit to the observed proton flux shown in Figure 7. This model then gives the time integrated solar neutron spectrum at the Sun at energies below ~ 100 MeV. These results are discussed in more detail below in the context of the solar neutron spectrum deduced from neutrons directly detected at the Earth and on the SMM satellite. Solar neutron decay protons have also been observed during two other events; after the 1980, June 21, 01:18 UT flare and following the 1984, April 24, 23:59 UT flare; Evenson, Meyer, and Pyle (1983) and Evenson, Kroeger, and Meyer (1985), respectively.

### 2.3. Direct neutron observations

The first detection of ~ 400 MeV solar neutrons near the Earth following an impulsive solare flare on 1980, June 21 (Chupp *et al.*, 1982) initiated an opportunity to study the highest energy particles accelerated in solar flares. The observation was made with the Gamma-Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) satellite which is sensitive to energy loss events from high-energy neutrons (> 10 MeV) interacting in the scintillators (Forrest *et al.*, 1980). In general, a flux of $\gamma$-rays (> 10 MeV) may be simultaneously incident on the detector with the neutrons and in this case the differing response of the instrument to the two radiations may be used to separate the fluxes (Cooper *et al.*, 1985; Forrest *et al.*, 1985; Chupp *et al.*, 1985). However, in the case of the flare mentioned above, the impulsive $\gamma$-ray emission had ended before the neutrons reached the Earth. Further, the neutrons were most likely produced in a time-scale of ≤ 1 min at the Sun which is short compared with the time of travel to the Earth of the earliest arriving neutrons. Neutrons with an energy of 400 MeV arrive at the Earth approximately 3 min after the photons and 50 MeV neutrons arrive about 15 min later, so a solar neutron burst occurs over a large fraction of a satellite orbit. In this case the arrival time of the neutron at the Earth directly determines its energy if one assumes the neutrons were emitted at a single instant at the Sun (the $\delta$-function approximation).

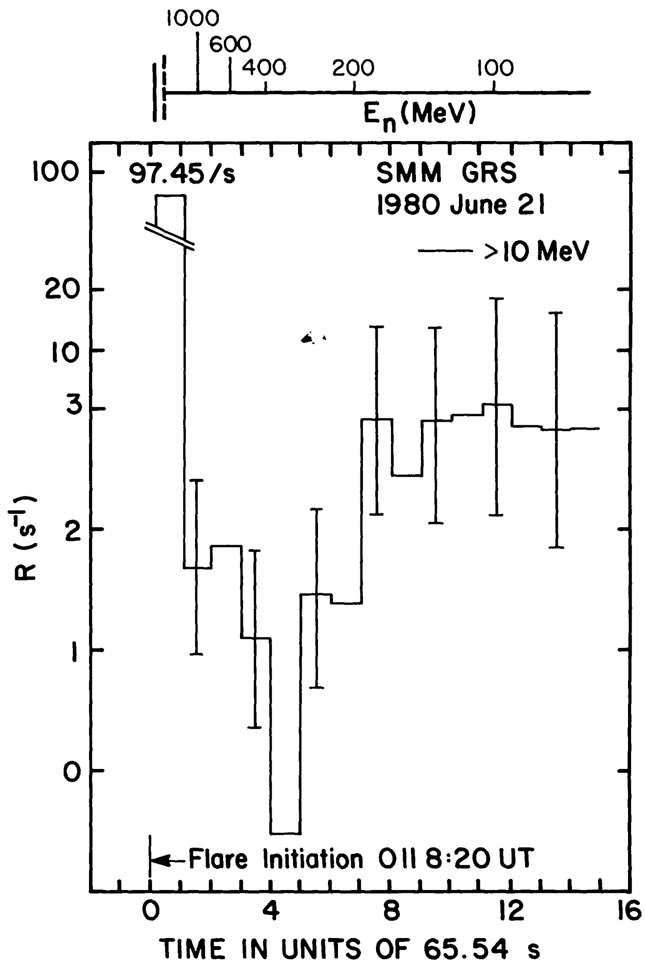


Fig. 8. The count rate of SMM GRS for energy-loss events (> 10 MeV) during and after the flare at 01:18:20 UT on 1980, June 21. The counts during the first four time bins are due to high-energy photons and thereafter are due to high-energy neutrons starting at about 400 MeV and decreasing to about 50 MeV. (After Chupp *et al.*, 1985.)

In Figure 8 we show the time history of the excess count rate (above background) for the high-energy-loss events in the SMM GRS during and after the start of the impulsive flare at 01:18:20 UT on 1980, June 21 averaged over 65.54 s. Assuming the $\delta$-function model, there is a one to one correspondence between neutron energy and arrival time at the Earth if the time zero fiducial is taken at the peak of the high-energy $\gamma$-ray flux which occurred at ~ 01:18:36 (cf. Chupp *et al.*, 1982). Based on the GRS response, the count rate after 4 time units is due to neutrons. The highest energy neutrons observed in this event had an energy of $\sim 400$ MeV.

The emissivity of the neutrons emitted from the Sun, in a given energy interval, may then be found from the observed count rate versus time, $C(t)$, in the GRS detector according to

$$C(t) = S(E_n) D^{-2} Q(E_n) (\mathrm{d}E_n/\mathrm{d}t) P_s(E_n) \text{ counts s}^{-1}, \qquad (1)$$

where $Q(E_n)$ is the total neutron emissivity in the direction to the Earth, at energy $E_n$ in units of (neutrons MeV$^{-1}$ sr$^{-1}$), $\mathrm{d}E_n/\mathrm{d}t$ is the relativistic neutron-energy time dispersion factor given by Lingenfelter and Ramaty (1967) and $P_s(E_n)$ is the survival probability for a neutron to reach the Earth before decay, the latter two quantities dependent only on the neutron kinetic energy. The quantity $S(E_n)$ is the effective area (cm$^2$) or sensitivity of the GRS as shown in Figure 9 based on recent Monte-Carlo calculations of Cooper *et al.* (1985). Using these latest instrument parameters, Chupp *et al.* (1985) have given the total neutron emissivity spectrum for this flare over the energy range $\sim 50$ MeV to 400 MeV. They find that, over this limited energy range, a power-law spectrum for $Q(E_n) \sim E_n^{-\alpha}$ with an exponent, $\alpha = 3$, gives a reasonable fit to the data although there is no model of neutron production at the Sun that predicts a strictly power-law spectrum shape for neutron production. In fact, Ramaty *et al.* (1983) have pointed out that the neutron spectrum below 50 MeV must flatten considerably.

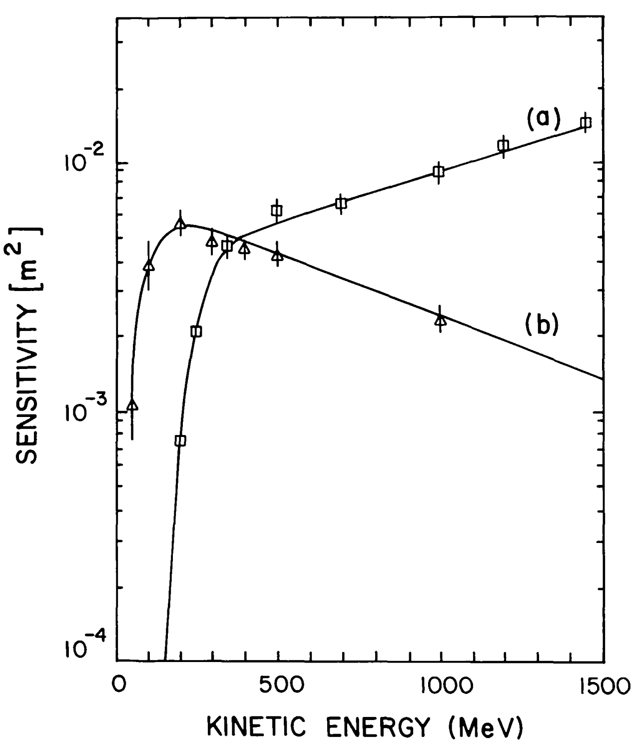


Fig. 9. Nominal sensitivity functions for a standard IGY neutron monitor at 498.0 mm Hg atmospheric pressure for primry neutrons incident at the top of the atmosphere with a zenith angle of 25° (a) and for the SMM GRS (b). (After Chupp *et al.*, 1987.)

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 for the 1980, June 21 flare.

The large flare on 1982, June 3 was sufficiently intense and energetic that direct solar neutrons were detected at the SMM (Chupp *et al.*, 1987) and by ground based neutron monitors (Debrunner *et al.*, 1983; Efimov, Kocharov, and Kudela, 1983). In this event, it is clear from reference to Figure 3 that at later times in the event, the GRS count rate ($> 25$ MeV), observed by the SMM GRS remains anomalously high until 12:04 UT (satellite sunset) and with a time structure not matching that at lower energies. Further from the analysis of the GRS energy-loss data (Forrest *et al.*, 1985) it is evident that high-energy neutron production continued throughout the event as evidenced by the long term presence of meson decay $\gamma$-rays in the GRS spectrum ($> 10$ MeV) (cf. Chupp *et al.*, 1987). In this event then the so-called $\delta$-function approximation used in Equation (1) must be modified to account for the fact that $Q(E_n)$ is also a function of time at the Sun. Therefore, the neutron flux at anytime $t$ at the Earth will include a band of energies, each produced at the Sun at a different time. Therefore, the GRS detector was exposed, at any instant, to a combined flux of high-energy $\gamma$-rays and neutrons which must be separated, on a time averaged basis, using the Monte-Carlo results of Cooper *et al.* (1985). Furthermore, the ground level neutron observations by the Jungfraujoch neutron monitor shown in Figure 3 must be taken in account in order to deduce the neutron spectrum at the Sun. Because the energy dependent responses of the neutron monitor and the GRS are considerably different, a combined analysis of both data sets leads to a more accurate estimate of the time dependent neutron emissivity spectrum from the Sun. In this regard it should be noted that the Jungfraujoch neutron monitor has a relatively higher sensitivity to neutrons with energies $> 300$ MeV as compared to the SMM GRS which is relatively more sensitive to neutrons with energies $< 300$ MeV as shown in Figure 9.

The combined analysis is described by Chupp *et al.* (1987) and is based on a time history of neutron production at the Sun that follows the instantaneous emission of $\pi^0$ $\gamma$-rays from the Sun deduced by Forrest *et al.* (1985) and Forrest (1988). Besides a production time history, a neutron energy spectral form, which also may be time dependent, must be assumed and for this event the standard mathematical forms, power law, Bessel function and exponential (McGuire, 1983) were used to model the data. Initially, it was assumed that the spectrum shape was constant in time but varied in intensity. Thus for a given spectral form, the unnormalized time dependent flux of neutrons at the Earth is calculated. By using the two detector sensitivities shown in Figure 9 the best fit absolute solar neutron emissivity spectrum, for a given spectral form, was found by using the two observed detector neutron count rates and $\chi^2$ tests. Best fits to the combined data sets are provided by neutron emissivity spectra with spectral forms $E_n^{-2.4}$ and $E_n^{3/8} \exp[-(E_n/0.016)^{1/4}]$. The power-law form requires a truncation at an energy $E_c$, where 2 GeV $< E_c <$ 4 GeV. In both cases, the integrated neutron emissivity for energies $> 100$ MeV is $\sim 8 \times 10^{28}$ neutrons $sr^{-1}$. While there is evidence for an evolution of the high-energy neutron spectral shape with time during this event

(Murphy and Ramaty, 1985), a constant spectral shape adequately describes the data. This is so in this case because most of the *high-energy* neutrons were produced in the extended phase of the event after the initial impulsive phase. Murphy, Dermer, and Ramaty (1987) have suggested that the initial impulsive phase was produced by a softer proton spectrum thereby producing a softer neutron spectrum than deduced by Chupp *et al.* (1987).

The observations in this event also require that the first GeV protons producing the GeV neutrons interacted at the Sun within a time span of at most 16 s implying neutron production at densities $n > 10^{14}\ \mathrm{cm}^{-3}$. Figure 10 shows the resulting time integrated solar neutron emissivity for the two spectral forms mentioned above. Also shown are data points from the neutron decay proton observations (Evenson, Meyer, and Pyle, 1983).

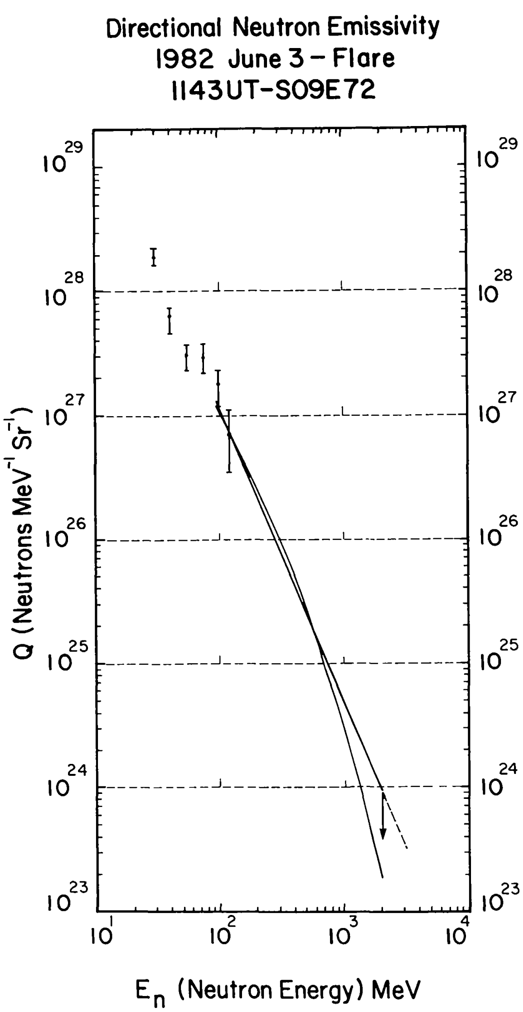


Fig. 10. The time-integrated directional solar neutron emissivity spectrum is shown for the best-fit power law and Bessel function neutron spectral forms with parameters $s = 2.4$ and $\phi = 0.07$, respectively. Data points from the neutron decay proton observations (Evenson, Meyer, and Pyle, 1983) are also shown. (After Chupp *et al.*, 1983.)

### 2.4. Interpretation

We have mentioned earlier that knowledge about the neutron spectrum at the Sun comes from direct and indirect means. The total number of flares for which we have data from thermal neutron energies to several hundred MeV currently numbers three and the data for these are limited by time resolution and intensity. Of course, our goal is to determine what we can about the flare acceleration process from the neutron observations themselves. In general, however, the full range of $\gamma$-ray, X-ray, and neutron (and SEP) observations must be used for a complete description and interpretation of the high-energy flare as recently done by Murphy, Dermer, and Ramaty (1987). On the other hand, the direct observation of the highest energy neutrons gives directly the highest energy ions accelerated in the flare, essentially independent of an acceleration model, as well as the time-scale of the interactions producing these neutrons. This latter constraint in turn limits the acceleration time for any impulsive flare model. Ramaty *et al.* (1983) have also argued that the ambient density of the interaction region where the energetic neutrons are produced cannot be greater than $n \sim 5 \times 10^{15}$ cm$^{-3}$, otherwise the $\sim 50$ MeV neutrons observed in the 1980, June 21 (limb) event would be greatly scattered by elastic neutron-proton collisions and lead to a much softer neutron spectrum than observed. This argument is actually based on the 'assumption' that the neutrons once produced do not undergo further scattering so the observed and calculated (model dependent) neutron spectra should agree. In principle, however, the neutron production region could extend to greater depths but we only see the neutrons produced in the upper photosphere either directly or through the 2.223 MeV line (Vestrand *et al.*, 1988).

In order to see how well the calculations of $\gamma$-ray and neutron yields, by Ramaty and co-workers can explain the observations, Murphy, Dermer, and Ramaty (1987) have assumed a very specific model for the 1987, June 3 flare – a two-phase model in which it was arbitrarily assumed that a stochastic acceleration process operated in the initial phase of the 1982, June 3 flare and produced a Bessel function form for the proton spectrum. It also was assumed that the flare produced a second acceleration process which was probably due to coronal shocks. By using the observational data from the SMM GRS by Chupp *et al.* (1987) and Forrest *et al.* (1985), Ramaty, Murphy, and Dermer (1987) have found that a Bessel function spectral parameter $\alpha T = 0.043$ describes the initial accelerated particle population. It is of interest to recall that Ramaty and collaborators have consistently used a Bessel function spectral form for the accelerated particles for essentially all $\gamma$-ray impulsive flares observed from satellites with the exception of a few flares which appear to have an extended emission phase. Even though the nonrelativistic stochastic acceleration model (Forman, Ramaty, and Zweibel, 1986) predicts a Bessel function spectral form for the accelerated particles it should not be assumed, at this point, that this in fact is the acceleration process.

Later in the 1982, June 3 flare there is clearly evidence for a time evolution of the spectrum of emitted radiations as can be seen by reference to Figure 3 and the discussion above (cf. also Murphy, Dermer, and Ramaty, 1987). Murphy and Ramaty

(1984) have also suggested that the ion spectrum shape becomes harder with time in this flare. Ramaty, Murphy, and Dermer (1987) have (implicitly) assumed that the particles seen in space after this flare by Helios (McDonald and van Hollebeke, 1985) were produced after the impulsive phase of the flare and that the protons which produced the delayed high-energy emission seen by the SMM GRS had the same spectrum as the Helios protons. The protons observed in interplanetary space had a power-law spectrum between ~100–400 MeV with exponent $s = 2.4$.

With this model for primary ions, a soft 'impulsive phase' component and a hard 'second phase' component, Ramaty, Murphy, and Dermer (1987) have calculated the neutron spectra in the two phases using the observed (SMM GRS) ratios of $\gamma$-ray fluences $\phi_{2.223}/\phi_{4-7}$, $\phi(100\ \text{MeV})/\phi_{4.1-6.4}$ and the observed GRS and Jungfraujoch neutron monitor results. Their basic conclusion is that most of the neutrons, and the bulk of the 2.223 MeV emission is produced by the first phase particles (Ramaty and Murphy, 1988). While their second-phase particles produce a harder neutron spectrum, the fraction of high-energy neutrons (> 100 MeV) from this phase compared to those from the first phase is much smaller than the 80% value deduced by Chupp *et al.* (1987). This is a problem to be resolved by future analysis of all available data.

In summary, the neutron (and $\gamma$-ray) observations give us the following information: (1) the spectrum shape and absolute number of ions producing the neutrons, (2) the highest energy ions produced in the flare, and (3) the relative abundance of $^3$He/H in the photosphere at the mean capture depth.

## 3. Conclusions

We have reviewed the observations which allow us to deduce the spectrum of neutrons at the Sun. In order to use this type of information to learn more about the particle acceleration properties in solar flares, considerable improvements are necessary in space borne neutron detecting systems. Of most importance is the development of detectors which can separate, on an event by event basis, a signal from a high-energy photon and a neutron. A companion paper in this issue, Frye *et al.* (1988) describes several new techniques which can lead to further advances in solar neutron observations. Improvements in ground level neutron monitors used for solar neutron observations are described in the proceedings of a solar neutron workshop held in Moscow after the *20th International Cosmic Ray Conference* (cf. Kocharov, 1988).

## Acknowledgements

Preparation of this review was aided by discussions with several colleagues, D. J. Forrest, R. Lingenfelter, R. Ramaty, and W. T. Vestrand. We thank Mary M. Chupp for editing and Sally Cote for typing the manuscript. The work was partially supported by NASA Grants NAG5–720 and NAGW-534.

## References


Biermann, L., Haxel, O., and Schlüter, A.: 1951, *Z. Naturforsch.* **6a**, 47.

Cameron, A. G. W.: 1982, in C. A. Barnes, D. D. Clayton, and D. N. Schramm (eds.), *Essays in Nuclear Astrophysics*, Cambridge Univ. Press, Cambridge, p. 23.

Chupp, E. L.: 1984, *Ann. Rev. Astron. Astrophys.* **22**, 359.

Chupp, E. L.: 1987, *Phys. Scripta* **T18**, 5.

Chupp, E. L., Forrest, D. J., and Suri, A. N.: 1975, in S. R. Kane (ed.), *Solar Gamma, X-, and EUV-Radiation*, D. Reidel Publ. Co., Dordrecht, Holland, p. 341.

Chupp, E. L., Forrest, D. J., Vestrand, W. T., Debrunner, H., Flückiger, E., Cooper, J. F., Kanbach, G., Reppin, C., and Share, G. H.: 1985, *19th Int. Cosmic Ray Conf. Papers* **4**, 126.

Chupp, E. L., Debrunner, H., Flückiger, E., Forrest, D. J., Golliez, F., Kanbach, G., Vestrand, W. T., Cooper, J., and Share, G.: 1987, *Astrophys. J.* **318**, 913.

Chupp, E. L., Forrest, D. J., Higbie, P. R., Suri, A. N., Tsai, C., and Dunphy, P. P.: 1973, *Nature* **241**, 333.

Chupp, E. L., Forrest, D. J., Ryan, J. M., Heslin, J., Reppin, C., Pinkau, K., Kanbach, G., Rieger, E., and Share, G. H.: 1981, *Astrophys. J.* **263**, L95.

Chupp, E. L., Forrest, D. J., Kanbach, G., Share, G. H., Debrunner, H., and Flückiger, E.: 1983, *18th Int. Cosmic Ray Conf. Papers* **10**, 334.

Cooper, J. F., Reppin, C., Forrest, D. J., Chupp, E. L., Share, G. H., and Kinzer, R. L.: 1985, *19th Int. Cosmic Ray Conf. Papers* **5**, 474.

Debrunner, H., Flückiger, E., Chupp, E. L., and Forrest, D. J.: 1983, *18th Int. Cosmic Ray Conf. Papers* **4**, 75.

Debrunner, H., Flückiger, E., Lockwood, J. A., and McGuire, R. E.: 1984, *J. Geophys. Res.* **89d**, 769.

Efimov, Yu. E., Kocharov, G. E., and Kudela, K.: 1983, *18th Int. Cosmic Ray Conf. Papers* **10**, 276.

Efimov, Yu. E., Kocharov, G. E., and Kudela, K.: 1985, *19th Int. Cosmic Ray Conf. Papers* **4**, 154.

Evenson, P., Meyer, P., and Pyle, K. R.: 1983, *Astrophys. J.* **274**, 875.

Evenson, P., Kroeger, R., and Meyer, P.: 1985, *19th Int. Cosmic Ray Conf.* **4**, 130.

Forman, M. A., Ramaty, R., and Zweibel, E. G.: 1986, in P. A. Sturrock, T. E., Holzer, D. Mihalas, and R. K. Ulrich (eds.), *The Physics of the Sun*, Vol. II, Ch. 13, D. Reidel Publ. Co., Dordrecht, Holland, p. 249 (FRZ).

Forrest, D. J.: 1988, in preparation.

Forrest, D. J., Chupp, E. L., Ryan, J. M., Cherry, M. L., Gleske, I. U., Reppin, C., Pinkau, K., Rieger, E., Kanbach, G., Kinzer, R. L., Share, G., Johnson, W. N., and Kurfess, J. D.: 1980, *Solar Phys.* **65**, 15.

Forrest, D. J., Vestrand, W. T., Chupp, E. L., Rieger, E., Cooper, J., and Share, G.: 1985, *19th Int. Cosmic Ray Conf. Papers* **4**, 146.

Forrest, D. J., Vestrand, W. T., Chupp, E. L., Rieger, E., Cooper, J., and Share, G.: 1986, *Adv. Space Res.* **6**, No. 6, 115.

Frye, G. M., Dunphy, P. P., Chupp, E. L., and Evenson, P.: 1988, *Solar Phys.* **118**, 321 (this issue).

Hall, D. N. B.: 1975, *Astrophys. J.* **197**, 509.

Hua, X-M. and Lingenfelter, R. E.: 1987a, *Solar Phys.* **107**, 351 (HLa).

Hua, X-M. and Lingenfelter, R. E.: 1987b, *Astrophys. J.* **319**, 555 (HLb).

Hua, X-M. and Lingenfelter, R. E.: 1987c, *Astrophys. J.* **323**, 779 (HLc).

Hudson, H. S., Bai, T., Gruber, D. E., Matteson, J. L., Nolan, P. L., and Peterson, L. E.: 1980, *Astrophys. J.* **236**, L91.

Ibragimov, I. A., and Kocharov, G. E.: 1977, *Soviet Astron. Letters* **3**(5), 221.

Iucci, N., Parisi, M., Signorini, C., Storini, M., and Villoresi, G.: 1984, *Nuovo Cimento* **7C**, 732.

Kanbach, G., Pinkau, K., Reppin, C., Rieger, E., Chupp, E., Forrest, D., Ryan, J., Share, G., and Kinzer, R.: 1981, *17th Int. Cosmic Ray Conf. Papers* **10**, 9.

Kocharov, G. E. (ed.): 1988, *Proc. Moscow Solar Neutron Workshop*, Ioffe Institute, Leningrad.

Lingenfelter, R. E. and Ramaty, R.: 1967, in B.S.P. Shen (ed.), *High Energy Reactions in Astrophysics*, Benjamin, New York, p. 99.

McDonald, F. B. and Van Hollebeke, M. A. I.: 1985, *Astrophys. J.* **290**, L67.

McGuire, R. E.: 1983, *Rev. Geophys. Space Phys.* **305**, 18.

McGuire, R. E. and von Rosenvinge, T. T.: 1984, *Adv. Space Res.* **4**, No. 2–3, 117.

Murphy, R. J.: 1985, 'Gamma Rays and Neutrons from Solar Flares', Ph.D. Dissertation, University of Maryland.

Murphy, R. J. and Ramaty, R.: 1984, *Adv. Space Res.* **4**(7), 127.
Murphy, R. J., Dermer, C. D., and Ramaty, R.: 1987, *Astrophys. J. Suppl.* **63**, 721 (MDR).
Prince, T. A., Ling, J. C., Mahoney, W. A., Riegler, G. R., and Jacobson, A. S.: 1982, *Astrophys. J.* **255**, L81.
Prince, T. A., Forrest, D. J., Chupp, E. L., Kanbach, G., and Share, G. H.: 1983, *18th Int. Cosmic Ray Conf. Papers* **4**, 79.
Ramaty, R.: 1986, in P. A. Sturrock, T. E., Holzer, D. Mihalas, and R. K. Ulrich (eds.), *The Physics of the Sun*, Vol. II, D. Reidel Publ. Co., Dordrecht, Holland, p. 291.
Ramaty, R. and Murphy, R.: 1987, *Space Sci. Rev.* **45**, 213.
Ramaty, R., Kozlovsky, B., and Lingenfelter, R. E.: 1975, *Space Sci. Rev.* **18**, 341 (RKLa).
Ramaty, R., Kozlovsky, B., and Suri, A. N.: 1977, *Astrophys. J.* **214**, 617.
Ramaty, R., Kozlovsky, B., and Lingenfelter, R. E.: 1979, *Astrophys. J. Suppl.* **40**, 487 (RKLb).
Ramaty, R., Murphy, R. J., and Dermer, C. D.: 1987, *Astrophys. J.* **316**, L41.
Ramaty, R., Colgate, S. A., Dulk, G. A., Hoyng, P., and Knight, G. W.: 1980, in P. A. Sturrock (ed.), *Solar Flares*, Colorado Assoc. Univ. Press, Boulder, p. 117.
Ramaty, R., Murphy, R. J., Kozlovsky, B., and Lingenfelter, R. E.: 1983, *Astrophys. J.* **273**, L41.
Roelof, E.: 1966, *J. Geophys. Res.* **71**, 5.
Share, G. H., Chupp, E. L., Forrest, D. J., and Rieger, E.: 1982, *Bull. Am. Astron. Soc.* **18**, 875.
Share, G. H., Chupp, E. L., Forrest, D. J., and Rieger, E.: 1983, in M. L. Burns, A. K. Harding, and R. Ramaty (eds.), *Positron and Electron Pairs in Astrophysics*, AIP, New York, p. 15.
Vestrand, W. T.: 1988, in N. Gehrels and G. Share (eds.), *Nuclear Spectroscopy of Astrophysical Sources*, AIP, New York, p. 234.
Wang, H. T.: 1975, Ph.D. Dissertation, Univ. of Maryland, 94 pp.
Wang, H. T. and Ramaty, R.: 1974, *Solar Phys.* **36**, 129.
Yoshimori, M., Okudaira, K., Harasima, Y., and Kondo, I.: 1983a, *Solar Phys.* **86**, 375.
Yoshimori, M., Okudaira, K., Harasima, Y., and Kondo, I.: 1983b, *18th Int. Cosmic Ray Conf. Papers* **4**, 85.