Adv. Space Res. Vol.4, No.7, pp.127-136, 1984
Printed in Great Britain.
0273-1177/84 $0.00 + .50

SOLAR-FLARE NEUTRONS AND GAMMA RAYS

R. J. Murphy*,** and R. Ramaty*

**Laboratory for High-Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*
***Physics Department, University of Maryland, College Park, MD 20742, U.S.A.*

ABSTRACT

Calculations of neutron and gamma-ray production in solar flares are reviewed and compared with neutron and gamma-ray data from the 21 June 1980 and 3 June 1982 flares, as well as gamma-ray data from other flares. The implied charged-particle numbers and spectra are compared with interplanetary observations.

I. INTRODUCTION

Nuclear reactions of flare-accelerated particles in the solar atmosphere produce detectable fluxes of neutrons and gamma rays. Neutrons have been observed directly at Earth /1,2,3,4/ and in the 2.223 MeV gamma-ray line from neutron capture on hydrogen in the photosphere /5,6/. In addition, neutron production in flares has been inferred from observations /7/ of protons resulting from neutron decay in interplanetary space. A variety of nuclear deexcitation lines and the 0.511 MeV positron annihilation line have also been seen /2,8/. Gamma-ray continuum, probably from relativistic electron bremsstrahlung and π° meson decay, has been observed /9/ as well. The theory of neutron and gamma-ray production in flares has been reviewed recently /5,10/.

In the present paper we derive the numbers and spectra of the accelerated protons and nuclei that produce the observed neutrons and gamma rays and we compare the results with interplanetary observations of flare protons. For a discussion of the implications of the continuum observations on relativistic electrons we refer the reader to the review /10/. In Section II we discuss the two most widely studied flare acceleration mechanisms, stochastic and diffusive shock acceleration, and we briefly review the arguments favoring the thick-target interaction model for neutron and gamma-ray production at the Sun. In Section III we present the pertinent results of the theory of neutron and gamma-ray production, in Section IV we derive the number and spectrum of the accelerated particles from observations of nuclear deexcitation lines and the 2.223 MeV line from several flares, and in Section V we discuss the 21 June 1980 and 3 June 1982 flares from which a wealth of neutron, gamma-ray and energetic-particle data has recently become available.

II. ACCELERATION AND INTERACTION MODELS

The acceleration mechanisms that have been investigated in greatest detail for solar flares are stochastic acceleration and shock acceleration /11/. The spectrum of nonrelativistic particles produced by stochastic acceleration with a constant diffusion mean-free-path and energy-independent escape from the acceleration region is

$$N(E) \propto K_2\,[2(3p/(mc\alpha T))^{1/2}]\ , \tag{1}$$

where N(E) is the differential particle number, E and p are particle kinetic energy and momentum per nucleon, respectively, m is the mass of the proton, α is the acceleration efficiency proportional to the ratio of the square of the velocity of the scattering centers to the diffusion mean-free-path, T is the escape time from the acceleration region, and K_2 is a modified Bessel function. The combination of parameters αT characterizes the spectrum, such that a larger αT corresponds to a harder spectrum. It has been shown /12/ that Bessel function spectra with values of αT in the range $0.014 \lesssim \alpha T \lesssim 0.036$ provide good fits to solar flare energetic particle spectra observed in interplanetary space.

The spectrum of particles resulting from diffusive acceleration by a large-scale planar shock is given by /11/

$$N(E) \propto p^{-(r+2)/(r-1)}/v, \tag{2}$$

where r is the compression ratio and v is particle velocity. In the nonrelativistic limit, $N(E) \propto E^{-s}$, where $s=(r+1/2)/(r-1)$. For a strong shock in a nonrelativistic fluid, r=4, hence s=3/2. This is the hardest spectrum that can be expected from shock acceleration in solar flares. But power laws generally do not provide good fits to energetic particle spectra observed in interplanetary space over a broad energy range /12/. An exception is the recently reported /13/ proton spectrum of the 3 June 1982 flare, which could be fit from about 1 to 200 MeV by a power law with $s \approx 1.7$. This value is close to the maximum expected value for a strong shock. However, the fact that solar flare particle spectra are generally not power laws is not an argument against shock acceleration, because for finite shock sizes and finite acceleration times the power laws produced by shock acceleration are expected to cut off exponentially at high energies /11/. Such spectra could provide fits to the interplanetary data that are as good as those provided by the Bessel-function spectra.

Neutron and gamma-ray production in solar flares most likely takes place in thick-target interactions. In the thick-target model /5/ nuclear reactions occur during the slowing down of the accelerated particles rather than during their acceleration or escape from the Sun. The following findings support the validity of this model: (1) The bulk of the gamma-ray-producing ions remain trapped at the Sun; this result is obtained /14/ from the comparisons of the number of particles required to produce the gamma rays with the number observed in interplanetary space. (2) The particles that escape from the Sun do not produce many nuclear reactions; this follows from the low upper limits on ^2H, ^3H, Li, Be and B in these escaping particles /15/. (3) The bulk of the positrons also remain trapped at the Sun; we demonstrate this result below. (4) In thin-target interactions, not enough neutrons are produced relative to the observed deexcitation lines to account for the observed 2.223 MeV line /5/; on the other hand, as we show below, the observed ratio of deexcitation lines to the 2.223 MeV line is consistent with thick-target interactons of energetic particles with spectra similar to those observed in interplanetary space.

The thick-target interaction region appears to be located in the chromosphere. The observed rapid slowing down and annihilation of the positrons requires a high ambient density which rules out annihilation in the corona /10/, while observations of high-energy neutrons from a limb flare imply that the bulk of the neutrons should be produced above the photosphere /16/. This implies that, with the exception of the 2.223 MeV line photons, gamma rays escape from the solar atmosphere essentially unattenuated.

We assume that the spectrum of the accelerated particles that impinge on the interaction region is either the Bessel function given by eq.(1) or a power law E^{-s} and that in the interaction region these particles are isotropic. Since this region is the chromosphere, the slowing down of the particles is due to Coulomb losses in a neutral medium. We also assume that the composition of both the accelerated particles and the ambient medium is the same as that of the photosphere /17/.

III. NEUTRON, DEEXCITATION-LINE, POSITRON AND π-MESON PRODUCTION

Neutron production in solar flares has been studied previously /5,18/. Here we have reexamined the thick-target calculations and we give the resultant neutron yields, Q_n, in Figure 1.

Neutron spectra and time-dependent neutron fluxes at Earth, resulting from instantaneous neutron production at the Sun, were also calculated previously /16,19,20/. In the present paper we calculate time-dependent neutron fluxes for finite-duration neutron production at the Sun and apply these calculations to the 21 June 1980 and the 3 June 1982 flares.

The propagation of neutrons in the photosphere and the production of the 2.223 MeV line were treated previously /21,22/. The 2.223 MeV photon yield per neutron was calculated /21/ as a function of neutron energy for isotropic neutron production above the photosphere and for several values of the angle θ between the normal to an assumed planar photosphere and the direction of observation. In Figure 2 we present spectrally-averaged neutron-to-photon conversion factors, $f_{2.223}$, such that the 2.223 MeV fluence is $\phi_{2.223} = Q_n \cdot f_{2.223}/(4\pi R^2)$, where R=1 AU. The assumption of planar geometry is valid for all the values of θ shown; there are no published calculations of $f_{2.223}$ for $\theta > 85°$.

Nuclear deexcitation lines can make a significant contribution to the total gamma-ray emission, particularly in the 4 to 7 MeV range /2,5/. Calculations of the 4-7 MeV gamma-ray production have been made previously /5/. We have reexamined these calculations and we present in Figure 1 the thick-target yields, Q_{4-7}. Also shown are total positron yields, Q_+, and positive and neutral pion yields, Q_{π^+} and Q_{π^0}. As can be seen, for hard spectra the contribution of π^+ decay dominates the total positron production.

The time dependence of the positron production for instantaneous pion and radioactive-nuclei production was calculated previously /10,23/. In the present paper we calculate time-dependent positron production for finite-duration pion and radioactive-nuclei production and we apply these calculations to the 21 June 1980 and 3 June 1982 flares. The time profile of the 0.511 MeV line flux depends, in addition, on the slowing-down and annihilation time of the positrons, which, in turn, is a function of the positron energy and the density, temperature and degree of ionization of the ambient medium /5,24,25/. Depending on the density and temperature of the ambient medium, positrons annihilate either directly or via positronium. For densities less than about 10^{15} cm^{-3} and temperatures less than a few hundred thousand degrees, the bulk of the positrons annihilate via positronium, leading to ~ 0.65 annihilation-line photons per positron /25/.

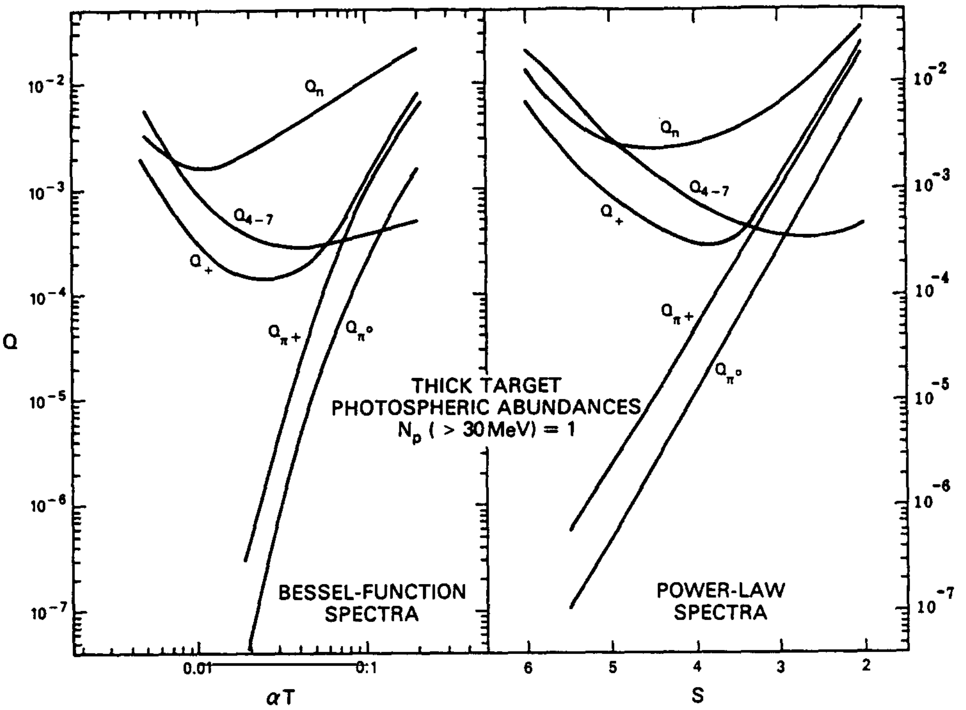

Fig. 1. Neutron, 4-7 MeV nuclear gamma-ray, positron, π^+ and π^0 production.

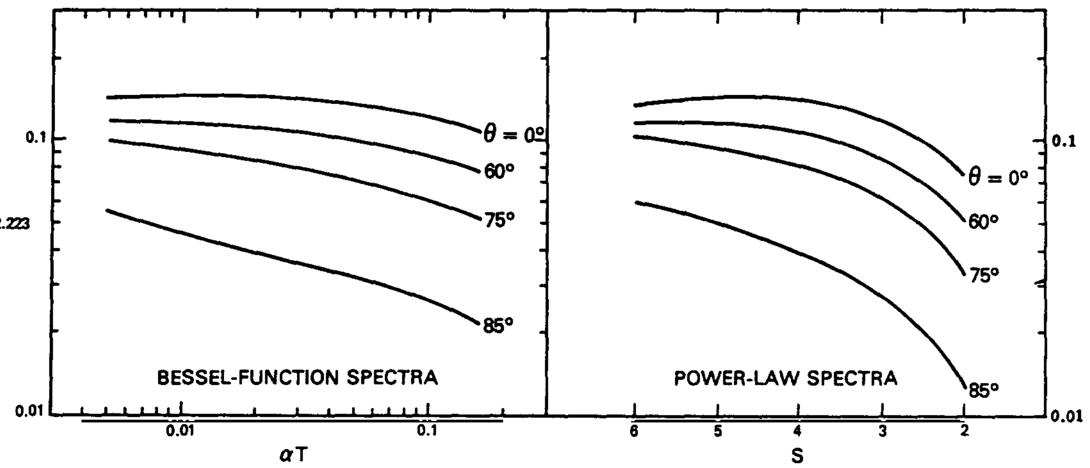

Fig. 2. Spectrally-averaged neutron-to-2.223 MeV photon conversion factors; θ is the angle between the normal to the photosphere and the line of sight.

IV. ENERGETIC PARTICLE NUMBERS AND SPECTRA AND COMPARISONS WITH INTERPLANETARY OBSERVATIONS

The number and spectrum of accelerated particles in a flare can be determined /5/ from the value of ϕ_{4-7} and the ratio $\phi_{4-7}/\phi_{2.223}$. This calculated $\phi_{4-7}/\phi_{2.223}$ equals $Q_{4-7}/(Q_n \cdot f_{2.223})$, where Q_{4-7} and Q_n are given in Figure 1 and $f_{2.223}$ is given in Figure 2. The results are given in Figure 3. We have compared these calculations with data for the flares listed in Table 1. The observed $\phi_{4-7}/\phi_{2.223}$ ratios, shown in Figure 3, are from the review /5/, except for the 21 June 1980 and the 3 June 1982 flares, for which they are from refs. /9,16,26/ and /6,9/, respectivly. For the disk flares, events 1 though 8, each of these ratios determines a value of αT or s. For the 21 June 1980 limb flare, however, αT is deduced from the neutron time profile as discussed in Section V. These values of αT and s are listed in Table 1, together with the associated values of N_p(>30MeV), the number of protons with energy greater than 30 MeV. We note that these values of αT are slightly larger than those obtained in ref. /5/, where it was assumed that the neutrons were produced anisotropically, giving larger values of $f_{2.223}$. The determination of the angular distribution of neutrons produced in solar flares awaits further neutron observations from flares at a variety of locations on the Sun.

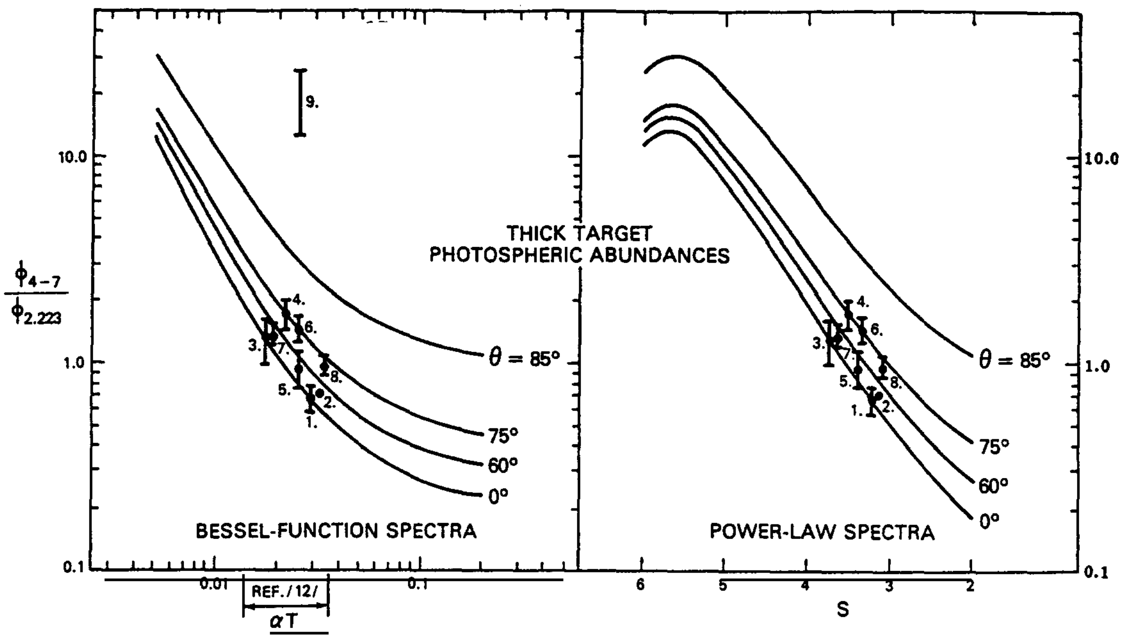

Fig. 3. Ratios of the fluence in 4-7 MeV nuclear gamma rays to the fluence in the 2.223 MeV line. The numbered points are data for the flares listed in Table 1. The 21 June 1980 data clearly shows the strong limb darkening of the 2.223 MeV line.

TABLE 1 Energetic Particle Parameters

	Bessel Function		Power Law		Interplanetary Observations	
Flare	αT	N_p(>30MeV)	s	N_p(>30MeV)	Spectral Index	$N_{p,esc}$(>30MeV)
1. Aug. 4, 1972	0.029±0.004	1.0×10^{33}	3.3±0.2	7.2×10^{32}	-	4.3×10^{34}
2. July 11, 1978	~0.032	1.6×10^{33}	~3.1	1.3×10^{33}	-	-
3. Nov. 9, 1979	0.018±0.003	3.6×10^{32}	3.7±0.2	2.6×10^{32}	-	-
4. June 7, 1980	0.021±0.003	9.3×10^{31}	3.5±0.2	6.6×10^{31}	αT=0.015	8×10^{29}
5. July 1, 1980	0.025±0.006	2.8×10^{31}	3.4±0.2	1.9×10^{31}	-	$<4\times10^{28}$
6. Nov. 6, 1980	0.025±0.003	1.3×10^{32}	3.3±0.2	1.0×10^{32}	-	3×10^{29}
7. April 10, 1981	0.019±0.003	1.4×10^{32}	3.6±0.2	1.0×10^{32}	-	-
8. June 3, 1982	0.034±0.005	2.9×10^{33}	3.1±0.1	2.2×10^{33}	s=1.7	3.6×10^{32}
9. June 21, 1980	~0.025	7.2×10^{32}	-	-	αT=0.025	1.5×10^{31}

Also listed in Table 1 are spectral indices and values of $N_{p,esc}$(>30MeV), the number of escaping protons above 30 MeV, deduced /5,13,27/ from interplanetary observations. As can be seen, the number of particles escaping from gamma-ray flares is generally much lower than the number needed to produce the gamma rays. As mentioned in Section II, this is an argument for the validity of the thick-target model. On the other hand, no firm conclusions can be drawn from the comparison of the spectral indices, but the fact that the range $0.015 \lesssim \alpha T \lesssim 0.040$, deduced from the gamma rays, is in reasonable agreement with the range $0.014 \lesssim \alpha T \lesssim 0.036$, obtained /12/ from the interplanetary observations, suggests that, for most flares, a common mechanism could accelerate both particle populations. This conclusion, however, is weakened by the fact that the two sets contain only one common flare, that on 7 June 1980. For this flare, the αT obtained from the gamma rays, assuming isotropic neutron production, is slightly larger than that measured in interplanetary space.

V. THE 21 JUNE 1980 AND 3 JUNE 1982 FLARES

Nuclear gamma rays in the 4-7 MeV region, neutrons released into interplanetary space, lines at 2.223 and 0.511 MeV, and continuum above 10 MeV have been observed from the 21 June 1980 and the 3 June 1982 flares. For the June 21 flare, ϕ_{4-7} is ~ 76 photons/cm^2 /9/, the time-dependent neutron flux /2/ is shown in Figure 4, $\phi_{2.223}$ is about 3 to 6 photons/cm^2 /16,26/ and ϕ(>10 MeV) is ~ 18 photons/cm^2 /9/. For the June 3 flare, ϕ_{4-7} is ~ 305 photons/cm^2 /9/, the time-dependent neutron flux is shown in Figure 5, $\phi_{2.223}$ is ~ 314 photons/cm^2 /6/ and ϕ(>10 MeV) is ~ 51 photons/cm^2 /9/. The time-dependent 0.511 MeV flux for both the June 21 /8/ and June 3 /8/ flares is shown in Figure 6. We constructed the June 3 neutron time profile by combining the direct ground-based /3/ and spacecraft /4/ neutron observations with the inferred time dependence obtained from observations /7/ of the energy spectrum of the neutron-decay protons. This energy spectrum implies a neutron energy spectrum, from which we deduced a time dependence by assuming that these low energy (< 100 MeV) neutrons were produced instantaneously at the peak of the 4-7 MeV fluence (11:43.4 UT /4/). Based on our calculations of time-dependent neutron fluxes from finite-duration nuclear interaction rates, we find that this assumption of instantaneous production for the June 3 flare introduces a negligible error.

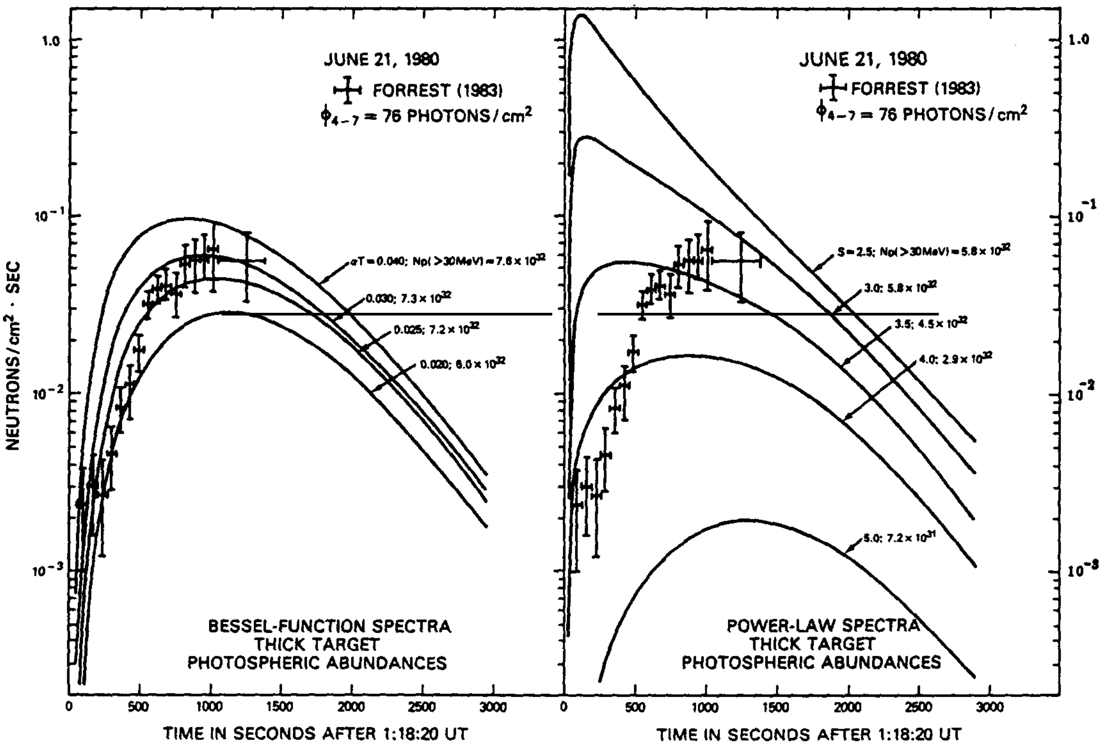

Fig. 4. Neutron time profiles for the 21 June 1980 flare.

We first compare the June 21 neutron observations with calculations. In Figure 4, in addition to the data, we show calculated time-dependent neutron fluxes, normalized to the observed ϕ_{4-7}. For the time dependence of the neutron production, we assumed the profile of the observed /2/ 4-7 MeV flux. As can be seen, the curve corresponding to $\alpha T = 0.025$ and $N_p(>30MeV) = 7.2x10^{32}$ fits both the shape and the absolute value of the data. Curves corresponding to larger values of αT rise faster and contain more neutrons than the observations; conversely, curves with smaller values of αT do not rise fast enough and do not contain enough neutrons. In the previous analysis of this flare /16/, the approach was to deduce αT by establishing which calculated neutron time profile best fit the data and then use the implied normalization to calculate ϕ_{4-7}. It was found that $\alpha T = 0.02$ provided the best shape. But the implied ϕ_{4-7} of 150 photons/cm^2, while consistent with the preliminarily reported value, exceeds the recently published value (~76 photons/cm^2). The αT that we deduce now is consistent with both the shape of the neutron time profile and the absolute normalization of both the neutrons and the 4-7 MeV nuclear gamma rays. We have compared a Bessel-function spectrum with $\alpha T = 0.025$ with the interplanetary observations /13/ of particles from the June 21 flare and find reasonable agreement.

We repeated this analysis for power-law spectra and we find that a single power law cannot simultaneously fit both the observed neutron time profile and ϕ_{4-7}. This is illustrated in Figure 4. Here, the spectrum which would provide an adequate normalization (s = 3.5) would imply a time profile which is totally inconsistent with the observations, and, vice versa, the spectrum which would provide an acceptable fit to the time profile (s = 5.5) would give an unacceptable normalization.

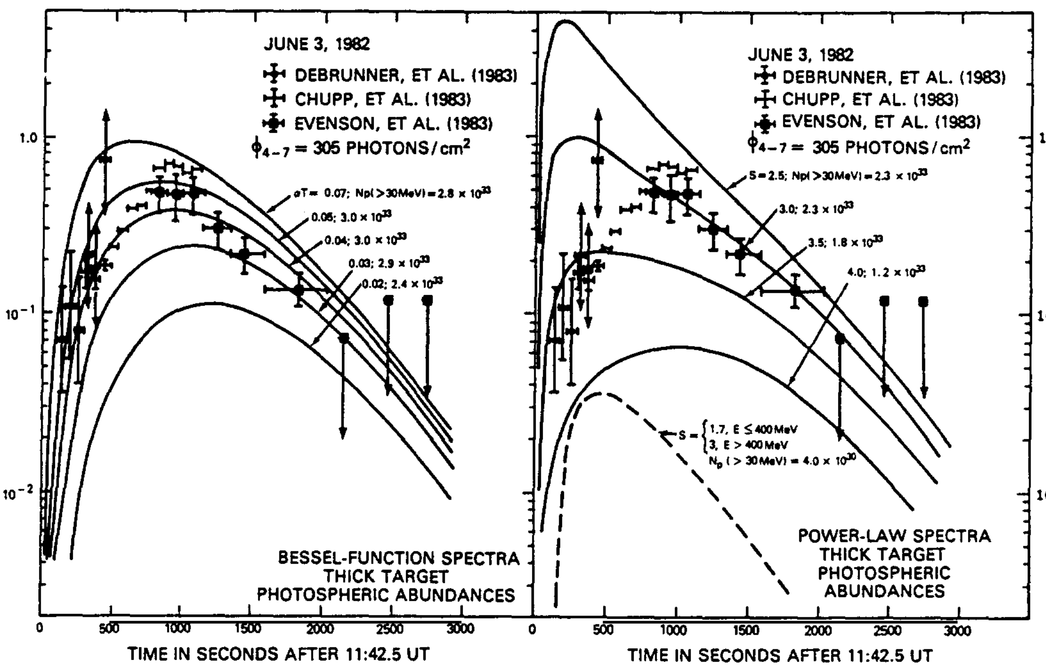

Fig. 5. Neutron time profiles for the 3 June 1982 flare.

Next we consider the June 3 neutron observations. In Figure 5, in addition to the data, we show calculated time-dependent neutron fluxes, normalized to the observed ϕ_{4-7}. For the time dependence of the neutron production, we assumed the profile of the observed /4/ 4-7 MeV flux. As can be seen, the curve corresponding to $\alpha T = 0.04$ and $N_p(>30MeV) = 3x10^{33}$ fits both the shape and the absolute value of the data. In addition, this αT (0.04) is quite close to that deduced from the comparison of the calculated and observed $\phi_{4-7}/\phi_{2.223}$ for this flare ($\alpha T \approx 0.034$, Table 1). As can be seen in Figure 5, we find that, as for the June 21 flare, no single power law can fit both the observed neutron time profile and ϕ_{4-7}. But, independent of spectral shape, no more than about 15% of the particles which produce the neutrons escape (see Table 1). We have compared a Bessel-function spectrum with $\alpha T = 0.04$ with the interplanetary observations /13/ of particles from the June 3 flare and we find that the power-law spectrum with s = 1.7 for $1 \lesssim E \lesssim 400$ MeV suggested in ref. /13/ provides a better fit. But this proton spectrum would be inconsistent with the neutron time profile and therefore would require a separate acceleration for the interplanetary particles.

We have derived the 2.223 MeV fluence for the June 3 flare using the accelerated-particle parameters ($\alpha T = 0.04$ and $N_p(>30MeV) = 3x10^{33}$) obtained from the neutron observations and the results of Figures 1 and 2. We obtain $\phi_{2.223} \approx 360$ photons/cm^2, in good agreement with the observed /6/ value of ~ 314 photons/cm^2. This implies that the directional neutron flux sampled by the interplanetary neutron observations (50° ≲ θ ≲ 90°) agrees with that sampled by the 2.223 MeV line observations (90° ≲ θ ≲ 180°), suggesting a considerable degree of isotropy of neutron angular distribution in this flare.

We next consider the 0.511 MeV line. We have calculated the production rate of positrons for αT = 0.025 and N_p(>30 MeV) = 7.2x10^{32} for the June 21 flare, and for αT = 0.04 and N_p(>30MeV) = 3x10^{33} for the June 3 flare. As for the neutrons, we assumed that the production time-profile of the radioactive nuclei and the pions is the same as the respective 4-7 MeV time-profile for each flare. Provided that the slowing-down and annihilation times of the positrons are shorter than the detector resolution time (~ 16 sec for the SMM detector /8/), the time dependence of the 0.511 MeV flux is indistinguishable from that of the positron production rate. The curves in Figure 6 show these time dependences for $f_{0.511}$=0.65 (the positron-to-0.511 MeV photon conversion factor with no positronium destruction). As can be seen, there is good agreement between the calculations and observations for the June 21 flare, but for the June 3 flare, the calculated curve falls short of the observations by about 30 photons/cm^2 at t ≳ 100 sec. No 0.511 MeV data is available at earlier times during the intense portions of the impulsive phase.

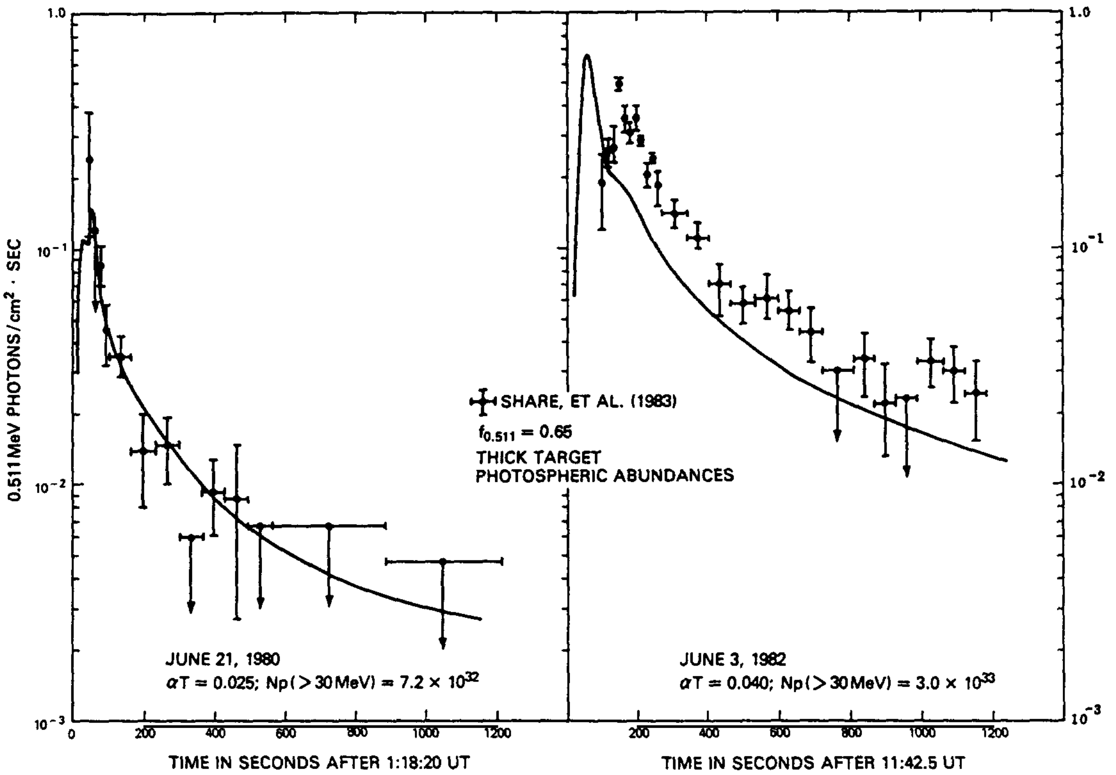

Fig. 6. 0.511 MeV line time profiles for the 21 June 1980 and 3 June 1982 flares.

The agreement between the calculations and the data for the June 21 flare implies that the slowing-down and annihilation times should be less than about 16 sec and therefore that the ambient density should exceed about 10^{11} cm^{-3}. Furthermore, the fact that essentially all the positrons annihilate promptly provides strong support for the thick-target model.

The difference between the observed and the calculated 0.511 MeV-line fluxes in Figure 6 for the June 3 flare could be due to the annihilation of additional positrons from the decay of pions produced by a separate proton population having a harder spectrum than that given by αT = 0.04. This possibility has been suggested /28/ based on the observed flattening of the high-energy continuum, which could be caused by photons from π^0 decay, and the coincidence between the peaks of the time profiles of the high-energy continuum and the 0.511 MeV line /4,8/. We study this possibility quantitatively below, but first we evaluate the high-energy continuum resulting from the proton number and spectrum already established from the neutron observations.

The calculated (from Figure 1 and ref./23/) > 10 MeV fluence from π° decay and bremsstrahlung of positrons from π^+ decay is ~ 0.2 photons/cm^2 for the June 21 flare (αT = 0.025 and N_p = 7.2 x10^{32}) and ~ 15 photons/cm^2 for the June 3 flare (αT = 0.04 and N_p = 3x10^{33}). Thus, for both flares, the calculated fluences obtained for the parameters deduced from the neutron observations are less than those observed (18 photons/cm^2 for the June 21 flare and 51 photons/cm^2 for the June 3 flare). As suggested /16,23/ previously, for the June 21 flare the bulk of the radiation above 10 MeV is probably bremsstrahlung from directly-accelerated electrons. On the other hand, for the June 3 flare, the observed emission > 10 MeV could contain an important contribution from pions produced by energetic particles with a much harder spectrum than that of the particles which produce the bulk of the neutrons, the 4-7 MeV emission and the 2.223 MeV line. A possible spectrum is the observed /13/ power law with s = 1.7, steepening to s = 3 above 400 MeV, as suggested in ref./13/. For this spectrum, we find that N_p(>30MeV) = 4x10^{30} if all of the >10 MeV excess of 36 photons/cm^2 is attributed to pions. This number is only about 1% of the particles observed /13/ in interplanetary space (see Table 1). The 0.511 MeV , 4-7 MeV and 2.223 MeV fluences that would result from these particles are ~ 30, ~ 2 and ~ 5 photons/cm^2, respectively. Thus, while this spectrum produces sufficient 0.511 MeV photons to account for the difference between the observed and calculated time profiles shown in Figure 6, it predicts only a negligible addition to the 4-7 MeV and 2.223 MeV fluences. We have also calculated the time-dependent neutron flux that would result from this spectrum, assuming that the neutron production time-profile is given by the difference between the observed and calculated 0.511 MeV time-profiles shown in Figure 6. The result is shown by the dashed curve in Figure 5. As can be seen, the contribution of these neutrons is small.

Thus, in the June 3 flare, as in most gamma-ray flares, the majority of the particles that produce the neutrons and the 4-7 MeV and 2.223 MeV photons remain trapped at the Sun. But, for the June 3 flare, unlike for the other gamma-ray flares studied so far, the spectrum of the interplanetary particles appears to be substantially harder than that of the trapped particles. As suggested by their spectrum, these interplanetary particles could be accelerated by a shock in the corona /29/. The precipitation of a small fraction of these shock-accelerated particles into the chromosphere produces additional nuclear reactions whose signatures are high-energy photons from π° decay and annihilation radiation following π^+ decay.

VI. SUMMARY

We have calculated the production of neutrons, 4-7 MeV nuclear gamma rays, positrons and pions resulting from the interaction of flare accelerated particles with the solar atmosphere. For the energy spectra of these particles we have used the Bessel function predicted by stochastic acceleration and power laws which could result from acceleration at large-scale planar shocks. We have performed the calculations in the thick-target model and we have summarized the best arguments for the validity of this model. We have assumed that in the interaction region the accelerated particles are isotropic. The processes responsible for isotropizing the particles are probably magnetic mirroring and pitch-angle scattering /16,30/.

We have calculated the energy spectra of the neutrons and we have derived the neutron-to-2.223 MeV photon conversion factors for various flare locations on the Sun by averaging the previously calculated conversion factors over these spectra. By comparing the calculations with data, we confirm that for most gamma-ray flares the bulk of the accelerated particles remain trapped at the Sun and that these particles have spectra similar to the spectra of flare particles observed in interplanetary space. These spectra can be fit by the Bessel functions resulting from stochastic acceleration or by spectra resulting from acceleration at shocks of finite size.

We have also derived the time-dependent neutron and 0.511 MeV line fluxes at the Earth using finite-duration nuclear reaction rates at the Sun and we have compared the results with observations of the 21 June 1980 and 3 June 1982 flares. For the June 21 flare, a Bessel-function spectrum can account for both the neutron and 0.511 MeV line observations and is consistent with the particle spectrum observed in interplanetary space from this flare. For the June 3 flare, while a Bessel-function spectrum can explain the neutron, 2.223 MeV line and 4-7 MeV nuclear gamma-ray observations, we find that an additional charged-particle component is needed to account for all the observed 0.511 MeV line and high-energy continuum. This component can be associated with the precipitation of a small fraction of the protons seen in interplanetary space, whose very hard spectrum can be better fit by a power law than by a Bessel function. These interplanetary protons, therefore, are probably due to shock acceleration. In addition, for the June 3 flare, for which the observations sample the neutron angular distribution in both the sunward and anti-sunward hemispheres (by 2.223 MeV line and neutron observations, respectively), we find that an isotropic charged-particle distribution is consistent with all the observations.

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