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GAMMA-RAY LINES AND NEUTRONS FROM SOLAR FLARES

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these observations, solar gamma-ray lines were seen with the NaI spectrometer on HEAO-1 (Hudson et al., 1980), the NaI spectrometer on SMM (Chupp et al., 1981; Chupp, 1982), the high-resolution Ge spectrometer on HEAO-3 (Prince et al., 1982), and the CsI spectrometer on HINOTORI (Yoshimori et al., 1983). Gamma rays of energies >10 MeV and high-energy solar neutrons near Earth were detected with the gamma-ray spectrometer on SMM (Chupp et al., 1982; Chupp, 1983).

Theoretical investigations of solar neutron and gamma-ray production in flares were carried out in considerable detail by Lingenfelter et al. (1965), Dolan and Fazio (1965), Lingenfelter and Ramaty (1967) and Cheng (1972), prior to the discovery of gamma-ray lines from flares. A number of theoretical studies (e.g., Wang and Ramatv, 1974; Kozlovsky and Ramaty 1974; Ramaty, Kozlovsky and Lingenfelter, 1975, 1979; Crannell et al., 1976, 1979; Ramaty, Kozlovsky and Suri, 1977; Ibragimov and Kocharov, 1977; Ramaty, 1979), performed after the OSO-7 observations, provided consistent interpretations for these observations, developed the details of the basic gamma-ray and neutron production processes and made predictions for further observations. Recent theoretical investigations (Ramaty, Lingenfelter and Kozlovsky, 1982; Ramaty, 1983), using the much more extensive SMM and HEAO data, showed that gamma-ray production in flares takes place predominantly in thick-target interactions by accelerated particles whose energy spectra do not vary much from flare to flare. The short acceleration time of nuclei in flares implied by these data was investigated by Bai (1982), and the problem of magnetic mirroring and its effect on gamma-ray production was studied by Zweibel and Haber (1983).

In the present paper we briefly review the theory of gamma-ray and neutron production in solar flares and present a theoretical analysis of the recent neutron and >10 MeV gamma-ray observations. In the discussion that follows we consider only thick-target interactions.

2. NEUTRONS

The 2.223 MeV line was expected (Lingenfelter and Ramaty, 1967) theoretically to be the strongest line from flares and this prediction was confirmed by observations (Chupp et al., 1973; Hudson et al., 1980; Chupp, 1982). The limb darkening of the 2.223 MeV line caused by Compton scattering in the photosphere, predicted by Wang and Ramaty (1974), has also been recently observed (Chupp, 1982; Yoshimori et al., 1983). This effect, together with the observed time delay of the line flux (Chupp et al., 1981; Prince et al., 1982) and the precisely determined line energy (Prince et al., 1982; Chupp, 1983), provides clear evidence that the observed emission at 2.223 MeV is indeed due to neutron capture and that this capture takes place in the photosphere.

For solar flares whose duration is much shorter than the typical neutron transit time from the Sun to the Earth, the time dependence these observations, solar gamma-ray lines were seen with the NaI spectrometer on HEAO-1 (Hudson et al., 1980), the NaI spectrometer on SMM (Chupp et al., 1981; Chupp, 1982), the high-resolution Ge spectrometer on HEAO-3 (Prince et al., 1982), and the CsI spectrometer on HINOTORI (Yoshimori et al., 1983). Gamma rays of energies >10 MeV and high-energy solar neutrons near Earth were detected with the gamma-ray spectrometer on SMM (Chupp et al., 1982; Chupp, 1983).

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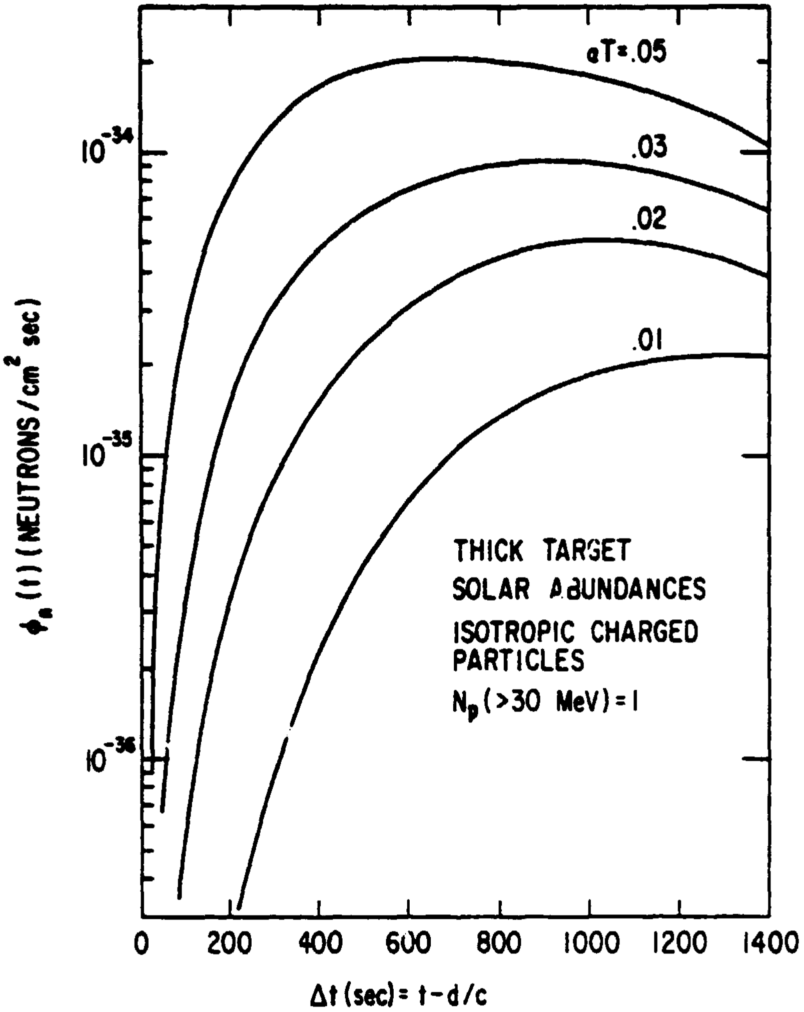

Figure 1. Time-dependent neutron fluxes at Earth from neutron production at the Sun.

of the high-energy neutron flux at Earth is a direct measure of the energy spectrum of the neutrons released from the Sun. The recent high-energy solar neutron observations (Chupp et al., 1982) confirm the time dependence of the neutron flux at Earth predicted earlier (Lingenfelter et al., 1965; Lingenfelter and Ramaty, 1967). Extending these previous studies, we have carried out a detailed investigation of the energy and angular distribution of neutron production in flares. We show in Figure 1 calculated time-dependent neutron fluxes at Earth resulting from various energetic particle spectra at the Sun.

For these calculations we have assumed an isotropic distribution of energetic particles incident on the solar atmosphere, producing a burst of neutrons at $t = 0$ in a thick-target model. We have normalized the number of energetic particles to 1 proton above 30 MeV and we have assumed that the composition of these particles is the same as that of the photosphere. We have further assumed that for all particle species, the energy spectrum incident on the atmosphere is given by the Bessel function appropriate for stochastic Fermi acceleration to nonrelativistic energies, $N(E) \propto K_2[2(3p/(mc\alpha T))^{1/2}]$ (Ramaty, 1979; Forman, Ramaty and Zweibel, 1983), where K_2 is the modified Bessel function of order 2, E and p are particle energy and momentum per nucleon, m is the proton mass, and α and T are, respectively, the stochastic acceleration efficiency and the particle residence time in the acceleration region. We have also assumed that after their production, the neutrons escape freely from the Sun. But because the neutrons have mean free paths comparable to the stopping range of the protons which produce them, this assumption requires that the charged particles be trapped magnetically in the thick-target interaction region at column depths significantly less than their ranges.

As can be seen from Figure 1, the rise time to maximum of the neutron flux becomes shorter as αT increases. This follows because larger values of αT imply more high-energy particles, which in turn produce more high-energy neutrons. We have compared the time-dependent neutron fluxes of Figure 1 with observations of the June 21, 1980 limb flare (Chupp et al., 1982; D. Forrest, private communication, 1982). We find that the calculated curve for αT = 0.02 fits the observed time-dependent neutron flux very well. Larger values of αT produce curves which rise to maximum too fast, while for αT less than about 0.02 the rise is slower than observed. As we shall see in Section 4, this value of αT, deduced from neutron observations of a limb flare, is essentially the same as the αT deduced from deexcitation-to-neutron capture line ratios for 7 disk flares.

By normalizing the $\alpha T = 0.02$ curve in Figure 1 to the absolute value of the time-dependent neutron flux from the June 21, 1980 flare (D. Forrest, private communication, 1982), we find that the number of protons above 30 MeV was 1.0×10^{33} and that the total neutron production was 2.3×10^{30}. For a disk-centered flare, this neutron production would imply a 2.223 MeV fluence of ~190 photons/cm^2, based on a neutron-to-2.223 MeV photon conversion factor of 0.23 (Ramaty, 1983). The observed (Chupp, 1982; D. Forest, private communication, 1982) 2.223 MeV fluence of ~6 photons/cm^2 for the June 21, 1980 limb flare provides clear evidence for the limb darkening of this line.

3. NUCLEAR DEEXCITATION LINES

A variety of gamma-ray lines are produced in solar flares from the deexcitation of nuclear levels. These levels are populated by inelastic collisions (e.g., $^{12}C(p,p')^{12}C^{*4.44}$), spallation reactions (e.g. $^{20}Ne(p,p\alpha)^{16}O^{*6.13}$), nonthermal fusion reactions (e.g., $^{4}He(\alpha,p)^{7}Li^{*0.478}$) and the decay of radionuclei produced by spallation reactions (e.g., $^{16}O(p,p2n)^{14}O(e^{+})^{14}N^{*2.31}$). Using laboratory measurements of the excitation functions of a large number of such reactions, calculations have been made (Ramaty, Kozlovsky and Lingenfelter, 1979) of the resultant gamma-ray spectra. An example is shown in Figure 2. Here the energies of 1.5×10^5 photons were derived from a Monte-Carlo calculation for thick-target interactions of isotropic energetic particles having solar abundances and αT = 0.02. These photons were then binned in 100 keV intervals, appropriate for a NaI detector such as that flown on SMM. The upper

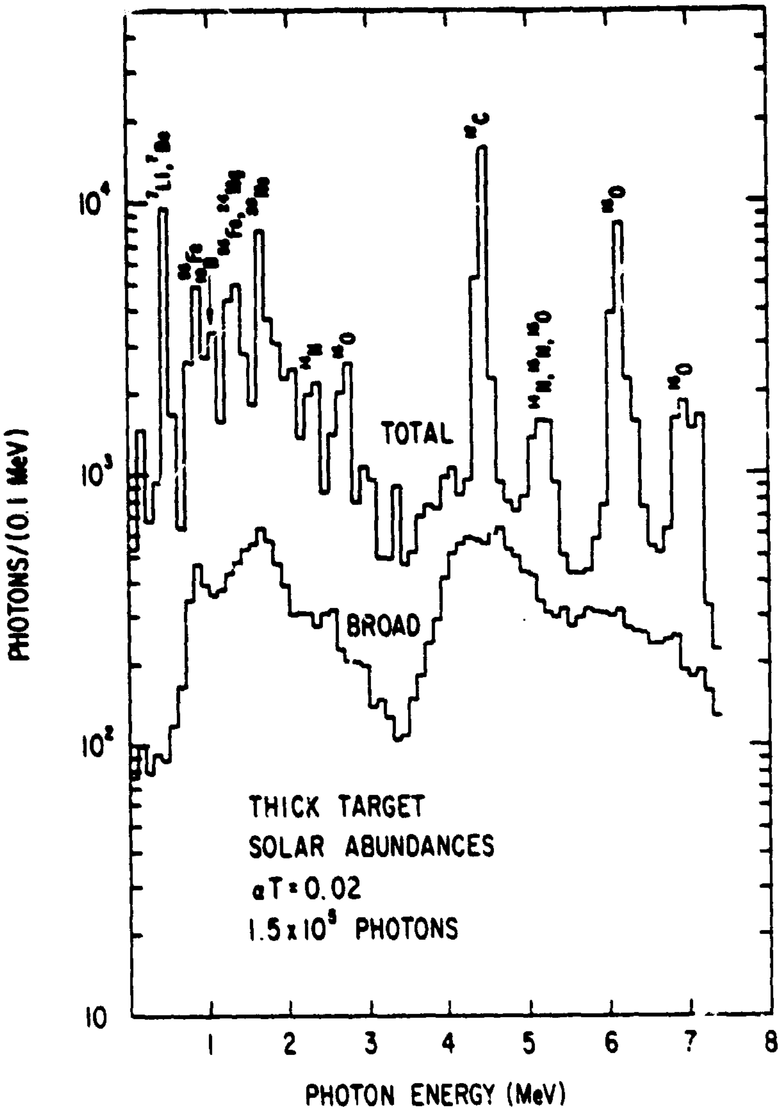

Figure 2. Energy spectrum of prompt nuclear deexcitation radiation.

histogram shows the total gamma-ray spectrum, while the lower one shows the broad component, i.e., gamma rays from the interactions of energetic nuclei heavier than He.

The total spectrum in Figure 2 contains a variety of narrow lines which result mostly from the deexcitation of ambient nuclei excited by fast protons and alpha particles. As can be seen, the strongest such lines are at 6.129 MeV from ^{16}O, at 4.438 MeV from ^{12}C, at 1.634 MeV from ^{20}Ne, at 0.847 MeV from ^{56}Fe, at ~1.3 MeV from ^{24}Mg and ^{56}Fe, and at ~ 0.45 MeV from ^{7}Li and ^{7}Be. The excited states $^{7}Li^{*0.478}$ and $^{7}Be^{*0.431}$ are formed in flares by nonthermal fusion reactions between alpha particles (Kozlovsky and Ramaty, 1974).

While the relative widths of these narrow lines, broadened by the recoil velocities of the heavy target nuclei, are only on the order of 1 to 2 percent, the widths of the broad lines, reflecting the velocities of the projectiles themselves, are much larger. Consequently, only a few discrete features can be discerned in the broad component. As can be seen, there is a broad feature between 4 and 5 MeV, mostly from ^{12}C, another one between 1 and 2 MeV from ^{20}Ne, ^{24}Mg, ^{28}Si and ^{56}Fe, and a broad line at ~ 0.85 MeV from ^{56}Fe.

But the contribution of the broad component to the total emission in Figure 2 is quite small. In thick-target interactions, this is caused by suppression of the contribution of heavy nuclei in comparison with that of protons and alpha particles resulting from their larger energy loss rates. However, the contribution of the broad component can be much larger if the abundance of accelerated heavy nuclei relative to accelerated protons significantly exceeds that in the photosphere. In particular, a higher Fe abundance in the accelerated particles could produce a more intense 0.847 MeV line of FWHM less than 200 keV.

The 4.438 MeV and 6.129 MeV lines have been observed from several flares (e.g. Chupp, 1982). These two lines, as well as several of the other strong lines shown in Figure 2, including the ^{7}Li-^{7}Be feature at ~0.45 MeV, have been seen from the April 27, 1981 limb flare (Chupp, 1983; Yoshimori et al., 1983).

In addition to the nuclear lines shown in Figure 2, gamma-ray emission from flares should also contain a significant contribution from electron bremsstrahlung (see also Section 6). In the 4-7MeV band, however, most of the emission appears to be nuclear (Ramaty, Kozlovsky and Suri, 1977; Ibragimov and Kocharov, 1977). This result is supported by recent data (Chupp, 1982) which indicate that for all disk flares from which gamma-ray lines were seen, the ratio of the observed fluence in the 4-7MeV band to the fluence in the 2.223 MeV line does not vary much from one flare to another. This approximate constancy indicates that both radiations are produced by the same population of energetic particles. If one of them were produced by electrons and the other by nuclei, one would expect a much more variable ratio than observed. Indeed, the ratio of the continuum fluence at ~ 1 MeV (which is mostly electron bremsstrahlung) to the 4-7MeV fluence varies significantly from flare to flare (Chupp, 1982).

4. COMPARISONS OF THE NEUTRON AND NUCLEAR DEEXCITATION LINE CALCULATIONS WITH DATA

Ratios of photon production in the 4-7MeV band to the total neutron production as functions of αT, in both the thick and thin-target models, are shown in Figure 3 (from Ramaty, 1983). These calculations are based on our detailed studies of nuclear deexcitation lines and neutron production in energetic particle reactions. The curves labelled EP1 are for a set of energetic particles enhanced in He and heavier nuclei (see Ramaty, 1983), while those labelled EP2 are for energetic particles with solar abundances.

From the comparison of the curves of Figure 3 with the observed 4-7MeV-to-2.223 MeV fluence ratio for the June 7, 1980 flare, and from the assumption that the αT of the particles from this flare observed (R. McGuire, private communication, 1981; see also Ramaty, 1983) in interplanetary space is similar to the αT of the particles interacting at the Sun, it was shown (Ramaty, Lingenfelter and Kozlovsky, 1982; Ramaty, 1983) that gamma-ray production in the June

7 flare proceeded predominently via thick-target interactions. This conclusion also followed from the comparison of the total number of protons seen in interplanetary space with the number required to produce the gamma rays at the Sun (Von Rosenvinge, Ramaty and Reames, 1981), and from the general absence of spallation products (e.g. ^{2}H, Li, Be, B) in the observed (McGuire, Von Rosenvinge and McDonald, 1979) interplanetary particle fluxes (see also Ramaty, 1983).

By comparing the observed 4-7MeV-to-2.223 MeV fluence ratios for other flares with the thick-target calculations (Figure 3), and by taking into account the flare positions on the solar disk, values of αT were deduced (Ramaty, 1983) for the flares listed in Table 1. As can be seen, the implied αT varies little from flare to flare. This result also applies to limb flares for which αT cannot be easily deduced from observations of the 4-7MeV-to-2.223 MeV fluence ratios because of the strong attenuation of the 2.223 MeV line in the photosphere. But as we have seen in Section 2, αT can be obtained for such flares from high-energy neutron observations. For the June 21, 1980 limb flare, we found that αT≈0.02, in excellent agreement with the disk flare results given in Table 1. This finding demonstrates, first of all, the consistency of the gamma-ray line and neutron production theory in flares since the two determinations of the energetic-particle spectrum rely on different physical proceses and utilize essentially independent sets of nuclear data. In addition, the small variability of αT implies that energetic protons and nuclei are probably accelerated in all gamma-ray flares by the same mechanism and under rather similar conditions.

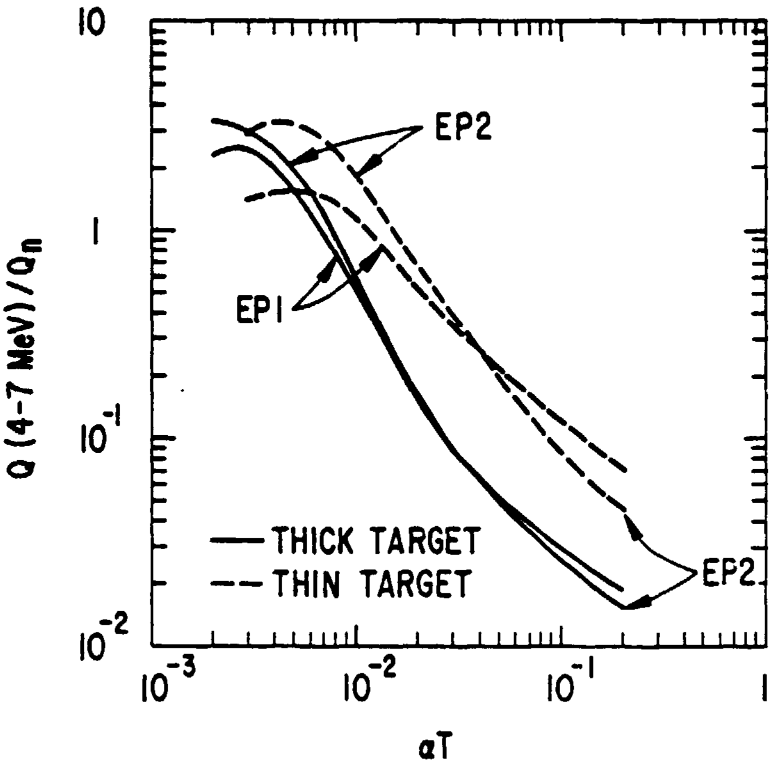

Figure 3. Ratios of the nuclear 4-7MeV photon to neutron production.

The range of αT deduced from both gamma-ray and neutron observations is very similar to the αT range of 0.014 to 0.036 obtained from fitting Bessel function spectra to energetic proton measurements in interplanetary space (McGuire, Von Rosenvinge and McDonald, 1981). Therefore, the same mechanism probably accelerates both the energetic particles which produce gamma rays at the Sun and those observed in interplanetary space.

The last column in Table 1 gives the number of protons greater than 30 MeV required to produce the observed gamma-ray emission by thick-target interactions. These numbers were obtained from our calculation of the total 4-7MeV photon production, the observed

TABLE 1. Energetic particle parameters deduced from gamma ray data of disk flares.

Flare	Location	4-7MeV-to-2.223 MeV Fluence Ratios	αT	N_p(>30 MeV)
1972, Aug. 4	E08N14	0.68±0.09	0.019	1.6×10^{33}
1978, July 11	E43N18	~ 0.71	0.020	1.3×10^{33}
1979, Nov. 9	E00N16	1.32±0.33	0.014	2.6×10^{32}
1980, June 7	W74N12	1.74±0.27	0.015	6.6×10^{31}
1980, July 1	W37S12	0.94±0.19	0.016	1.9×10^{31}
1980, Nov 6	E74S12	1.44±0.2	0.017	1.0×10^{32}
1981, Apr. 10	W37N09	1.38±0.16	0.014	9.7×10^{31}

4-7MeV photon fluences and the deduced αT's (see Ramaty, 1983, for more details). The total number of $\sim 10^{33}$ protons >30 MeV required in the large flares of August 4, 1972 and July 11, 1978 is quite comparable to the total number inferred above from high-energy neutron observations of the June 21, 1980 flare.

Using a >30 MeV proton number of 10^{33} and an $\alpha T = 0.02$ for the June 21, 1980 flare, we predict that the 4-7MeV fluence from nuclear deexcitation to be ~ 130 photons/cm^2 for this flare. This value constitutes about 2/3 of the observed (D. Forest, private communication, 1982) 4-7MeV fluence of ~200 photons/cm^2, a result which confirms the finding that this energy band is predominantly nuclear.

5. POSITRONS

The 0.511 MeV line due to positron annihilation has been observed from several solar flares (Chupp et al., 1973; Share et al., 1980; Chupp, 1982). Calculations of positron production from the decay of π^+ mesons and radioactive nuclei were carried out previously (e.g., Ramaty, Kozlovsky and Lingenfelter, 1975). Here we give results of new calculations of positron production based on a large number of positron emitters produced in nuclear reactions involving all reasonably abundant isotopes up to those of Ni. In Figure 4 we show the ratio of the total, time-integrated positron production to the 4-7MeV nuclear gamma-ray production as a function of αT for thick-target interactions and solar composition for the energetic particles.

The initial energies of positrons from radioactive nuclei are of the order of several hundred keV while those from π^+ decay are from about 10 to 100 MeV. Because only about 10^{-3} of the total positron production is from π^+ decay for an $\alpha T = 0.02$, the initial energies of the bulk of the positrons are expected to be less than an MeV.

The slowing down of positrons from the energies at which they are produced to energies comparable with those of the ambient electrons where they annihilate, and the subsequent annihilation process have been studied in considerable detail (Crannell et al., 1976; Ramaty, 1983). Positrons with an initial energy of ~ 0.5 MeV slow down and annihilate in about($2 \times 10^{12}/n_H$) sec, where n_H is the density of the ambient hydrogen (Ramaty, 1983). If n_H is high enough so that the slowing down and annihilation time is much shorter than the half-lives of the dominant positron emitters, the time dependence of the 0.511 MeV line flux is determined only by the decay rates of the positron emitters and their relative contributions to the total positron production.

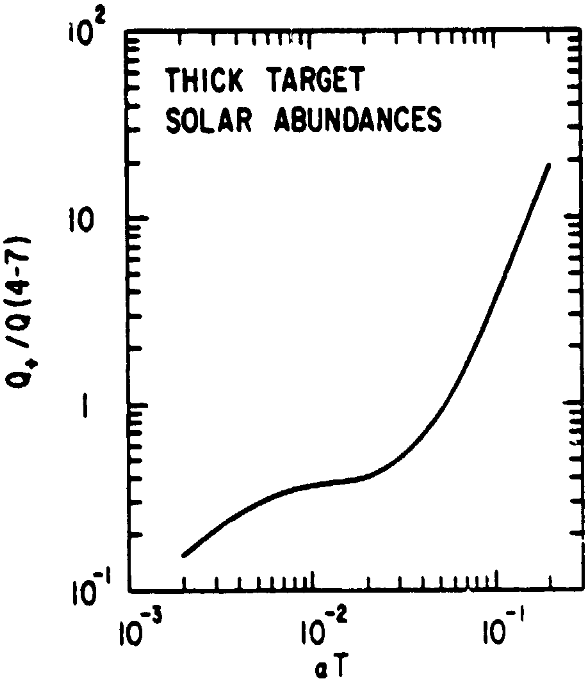

Figure 4. Ratios of the total positron to nuclear 4-7MeV production.

In Figure 5 we show the time-dependent 0.511 MeV line flux at Earth for t>1 sec from a burst of positron-emitter production at t = 0 for thick-target interactions, $\alpha T = 0.02$ and solar abundances for the energetic particles. The quantity $\bar{f}_{0.511}$, which takes into account the formation and breakup of positronium, is the average number of 0.511 MeV photons produced per annihilating positron. In a low density medium ($n_H < 10^{14} cm^{-3}$) where triplet positronium annihilates before it can be broken up, $\bar{f}_{0.511} = 0.65$ (Bussard, Ramaty and Drachman, 1979). For higher density solar plasmas, however, we expect that $\bar{f}_{0.511} = 1$.

The 0.511 MeV annihilation line has so far been detected from only a few flares. For the August 4, 1972 disk flare (Chupp et al., 1973), the ratio of the 0.511 MeV line fluence to the 4-7MeV fluence, measured during the first 500 seconds of the flare, was 0.33±0.11 (Chupp et al., 1973; see also Ramaty, 1983). As shown in Table 1, the energetic particle spectrum of this flare had an αT close to 0.02. From the time dependence calculated for such an αT (Figure 5), we expect that 60 percent of all the positron emitters should have decayed in 500 seconds. Therefore, the ratio of the total positron production to the 4-7MeV production, for $\bar{\tau}_{0.511} = 1$, should have been 0.55±0.17. This value is in good agreement with the expected value of ~0.4 (Figure 4) for that αT.

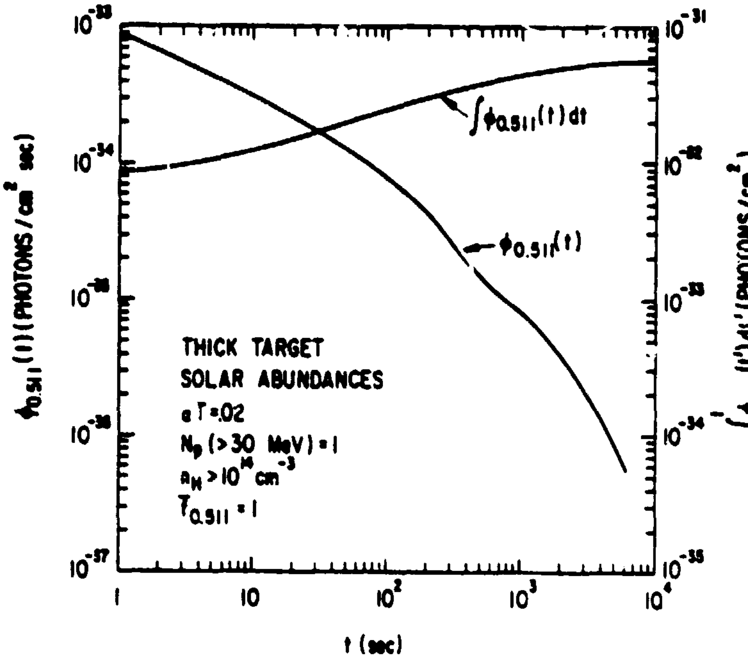

Figure 5. Time dependent 0.511 MeV line.

For the June 21, 1980 limb flare the time-integrated 0.511 MeV fluence for a period of 700 seconds was ~ 20 photons/cm² (G. Share, private communication, 1982) and the nuclear 4-7MeV fluence was estimated to be ~ 130 photons/cm². Using αT = 0.02, deduced from the high-energy neutron time dependence, we expect that about 70 percent of all the positron emitters should have decayed in 700 seconds (Figure 5), implying a positron emitter-to-4-7MeV production ratio of ~ 0.22. This value is smaller than the calculated ratio of ~ 0.4 for αT = 0.02. This suggests that the 0.511 MeV line from limb flares could be attenuated by Compton scattering in the solar atmosphere.

6. HIGH-ENERGY GAMMA-RAY EMISSION

At energies greater than ~ 10 MeV, most of the gamma rays in solar flares are expected to be produced by electron bremsstrahlung and π° decay (Ramaty, Kozlovsky and Lingenfelter, 1975; Crannell et al., 1979). The possibility of producing nuclear line emission in this energy region was studied by Crannell, Crannell and Ramaty (1979) who found only one important line at 15.1 MeV. However, the contribution of this line to the total >10 MeV emission is negligible.

In Figure 6 we present results of calculations of ratios of the

π^+-to-π^0 meson production and the π^0meson-to-4-7MeV nuclear photon production for thick-target interactions and isotropic energetic particles with solar abundances. Using these ratios, we have evaluated the >10 MeV photon production from pion decay, by combining the contributions of the gamma rays from π^0 decay with the bremsstrahlung of positrons and electrons from $\pi^\pm$ decay. We also show in Figure 6 the ratio of this >10 MeV photon production to the 4-7MeV nuclear radiation production.

In addition, we have evaluated the >10 MeV photon production from directly-accelerated electron bremsstrahlung. We find that if the ratio of electrons-to-protons at energies greater than 30 MeV is ~10^{-3}, then at photon energies >10 MeV electron bremsstrahlung exceeds photon production from pion decay by factors of ~10^3 for αT=0.02, ~70 for αT=0.03 and ~5 for αT=0.05. These ratios are only weakly dependent on the spectrum of the electrons.

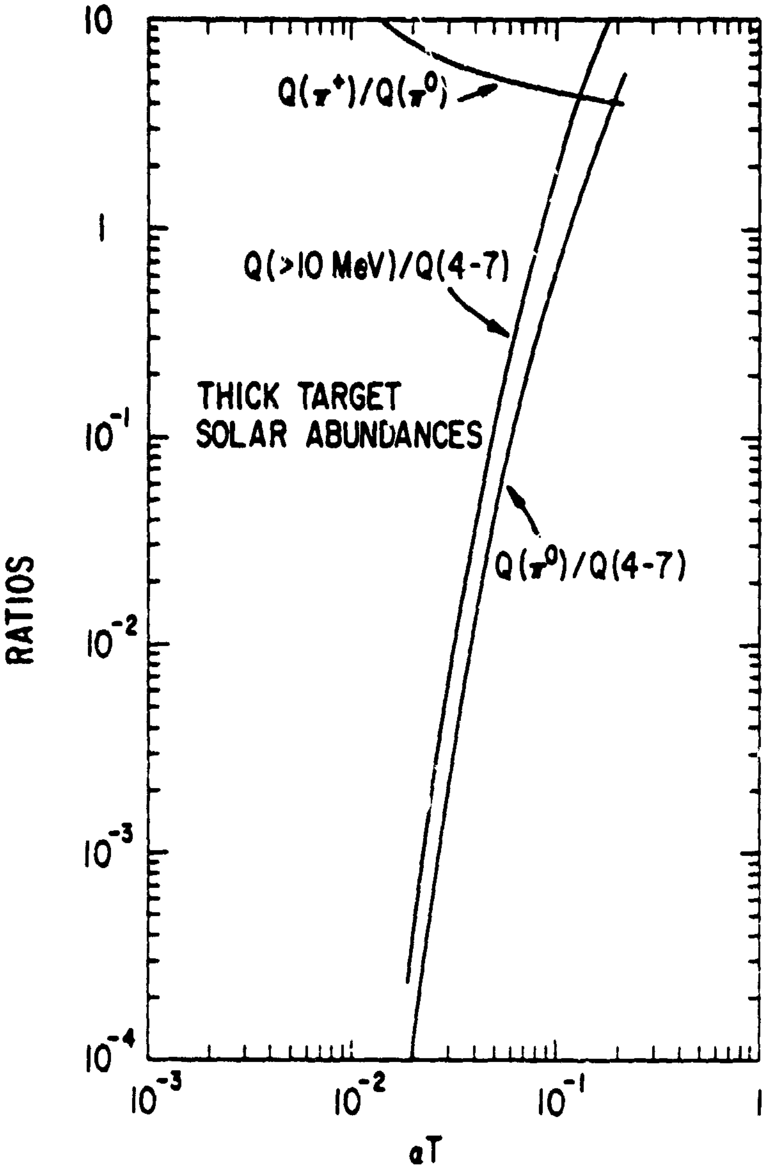

Figure 6. π meson and >10 Mev photon production from π^0 decay and $e^\pm$ bremmsstrahlung from $\pi^\pm$ decay.

The >10 MeV fluence observed (Chupp et al., 1982; D. Forrest, private communication, 1982) from the June 21, 1980 flare was ~ 30 photons/cm^2. This fluence could not have resulted from pion decay if $\alpha T = 0.02$, because with a nuclear 4-7MeV fluence of ~130 photons/cm^2 for this flare (Section 4), the resultant >10 MeV fluence from πions would be only ~0.06 photons/cm^2 (Figure 6). Bremsstrahlung of directly-accelerated electrons, on the other hand, could have produced the observed >10 MeV gamma rays if the number of electrons of energies >30 MeV was ~ 5 x 10^{29}, i.e. about 5 x 10^{-4} of the number of protons of similar energies. This interpretation of the >10 MeV continuum is quite consistent with a simple extrapolation of the continuum measured (Chupp, 1982) between 0.29 and 1MeV. The extrapolation would also imply a bremsstrahlung contribution in the 4-7MeV band of about ½ of the estimated nuclear contribution.

7. SUMMARY AND CONCLUSIONS

We have reviewed the theory of gamma-ray and neutron production in solar flares. We have discussed the production of neutrons, the attenuation of the 2.223 MeV line by Compton scattering in the photosphere, the production of a variety of observable prompt nuclear deexcitation lines, methods for determining the number and energy-spectrum of the charged particles accelerated in flares, the production of positrons and the time dependence of the 0.511 MeV line, and photon production at energies >10 MeV.

We have presented new calculations of time-dependent high-energy neutron fluxes at Earth resulting from energetic-particle reactions at the Sun. These calculations provide a new technique for determining the accelerated-particle energy spectrum at the Sun by comparing the time profiles at the Earth, calculated for isotropic charged-particle distributions incident on the solar atmosphere, with the time-dependent high-energy neutron flux observed from the June 21, 1980 flare. We found that the energy spectrum of the accelerated charged particles in this limb flare was essentially the same as in the 7 disk flares for which the spectrum was determined from the 4-7MeV-to-2.223 MeV fluence ratios. This result strongly suggests that a single mechanism, operating under similar conditions, accelerates the protons and nuclei in all gamma-ray producing flares.

We have also calculated the production of neutral and charged π mesons and the gamma-ray production >10 MeV resulting from their decay. We find that for accelerated-particle spectra with $\alpha T = 0.02$, deduced from observations of both the high-energy neutron time profile for a limb flare and 4-7MeV-to-2.223 MeV fluence ratios for disk flares, the >10 MeV photon fluences from pion decay are <10^{-3} of the 4-7MeV fluences of these flares. This is much less than the >10 MeV emission observed from the June 21, 1980 limb flare. This emission, however, could have been bremsstrahlung of directly-accelerated electrons provided that the electron-to-proton ratio at energies >30 MeV was ~5 x 10^{-4}.

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