NEUTRONS AND GAMMA RAYS FROM THE SUN*

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INTRODUCTION :

The experimental discovery of neutrons and gamma rays from the Sun made during the last few years by the group from University of New Hampshire, U.S.A. (Chupp et al. 1973) has opened up new possibilities in this field and has given some very useful information on problems in solar physics. In this paper, I wish to describe the importance of this area and also to present the new results obtained on the discovery of solar gamma ray lines and discuss some of their implications.

Ever since the discovery of cosmic rays by Hess in 1912, cosmic ray physicists have concerned themselves with the origin of these energetic particles coming from outer space. The first extra-terrestrial object with which they tried to associate the origin of these radiations was of course the Sun. Experiments were carried out during day and night to associate with the Sun, the intensity of these strange radiations. Unfortunately, the cosmic ray physicists were disappointed and had to conclude from these preliminary experiments that the Sun was not responsible for these strange radiations. Subsequent careful work, however, did show that the cosmic ray intensity was in some way related to the changes on the Sun, both on short-term and long-term scale; we refer here to cosmic ray variations observed over the 27 day period and also during the 11 year cycle. (Pomerantz and Duggal 1974). These short-term and long-term variations in the cosmic ray intensity had to be understood in relation to variations of the observed solar activity. In spite of numerous attempts, cosmic ray physicists have not been able to fully understand the complexities of these variations though several model calculations have been proposed.

The major finding in 1956, which demonstrated that energetic particles could be produced by the Sun during the intense Solar flare of February 23, 1956 suggested that it may be useful to consider Sun as an example of a unique astrophysical object producing energetic particles. Naturally, the questions which were asked, related to the mechanisms by which particles could be accelerated to very high energies, extending up to several hundreds of MeV. These particles had to be accelerated during intense solar flare activity on the Sun and were then to be propogated to Earth in a very complex manner, since it involved their passage through electro-magnetic fields present between the Earth and the Sun. As a result of their long tortuous travel from the Sun, not only do they lose their original identity but even the direction and time of arrival are modified considerably. The processes by which these charged particles are produced on the Sun have to be, therefore, inferred from complicated assumptions made in the theoretical models formulated for explaining their acceleration.

The fact that the charged particles are accelerated in the solar atmosphere suggests that secondary particles like neutrons and gamma rays must also be produced as a result of nuclear reactions of accelerated charged particles with the solar atmosphere (see below). These particles being neutral in nature can, in principle, travel directly to Earth and carry information which, when unfolded, can give insight into the acceleration and production mechanisms taking place on the Sun.

PRODUCTION OF SECONDARY PARTICLES IN SOLAR FLARES :

(a) General Considerations :

We will assume that charged particles are accelerated during a solar flare. These particles, mainly protons and alpha particles, accelerated to energies very much greater than several MeVs, interact with the nuclei in the solar atmosphere and produce secondary neutrons and gamma rays which we hope to study here. However, since we do not know the exact location and the geometry under which the production takes place, we will have to make certain assumptions regarding the location and propogation of these particles. Fig. 1 taken from a review by Chupp (1971), shows a few selected geometries where these particles are accelerated. As a simple case, in geometry A one assumes that particles are accelerated in the rarefied region of particle density and then impinge on the solar atmosphere in one of the two ways either tangentially or radially; the models B and C require that particles are accelerated isotropically

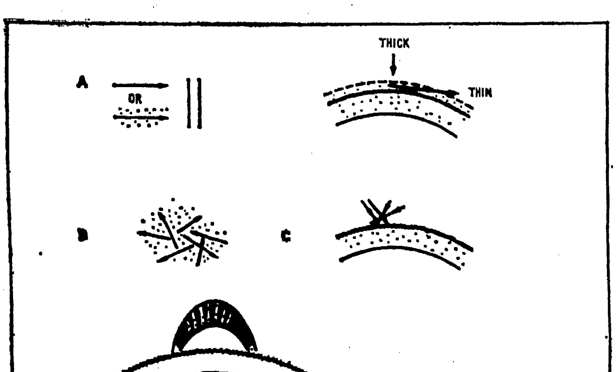

Fig. 1 Accelerated particle—solar atmosphere geometries (Chupp 1971)

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** (Present Address : Department of Electronics, Vigyan Bhawan Annexe, New Delhi-110011) and while some enter the dense regions of the Sun, others escape. In geometry D one considers an extreme case where particles are accelerated in trapped regions for a very long time and by some mechanism they are ejected at the time of the solar flare. I would mainly consider those calculations which have used a combination of models A, B and C. Most of these models can be broadly categorized into two types (a) Thin target geometry and (b) Thick target geometry. The particles may be accelerted in such a way that some would escape from their production region while some may penetrate deep into the photosphere. In either case there will be nuclear reaction which will generate secondary particles.

(b) Nuclear Reaction Yields :

The different products (mainly neutrons and gamma rays) have different origin and are therefore expected to give us different types of information regarding the solar flare phenomenon. I will first consider the production of neutrons. Table 1 taken from Ramaty et al. (1974) shows the various nuclear reactions which would take place in the solar atmosphere, depending upon the energy threshold of the reaction and the ambient target nuclei available. Most of the reactions taking place in the solar atmosphere are caused by proton and alpha particles, which are accelerated during solar flares. Each reaction has a specific cross-section and the yield of neutrons will depend upon the abundance of the target nuclei and the relevant cross-section.

The production of gamma rays, which was first predicted by Morrison (1958), takes place through several processess. In Table 2 we have shown processes which produce gamma ray lines, continuum emission of gamma rays through electron bremsstrahlung and through decay of π° mesons. We will briefly describe the kind of information which is derived from observations on each types of these gamma rays.

The positron annihilation line at 0.51 MeV results from the recombination of the positron with an electron. The origin of the positron may be either through the positron emitting radioactive nuclei or through the decay processes of the π^+ mesons. Some properties of the region, where the annihilation occurs, can be estimated by studying the line-width of the 0.51 MeV line since the thermal velocity of the electrons determines this line-width. On the other hand, the 2.2 MeV gamma ray line determines the region where the neutrons are thermalized and captured by protons. The emission of the 2.2 MeV line also gives an indication of the presence of He^3 in the solar atmosphere since an over abundance of He^3 could result in the non-radioactive capture of neutron, thus the presence of the 2.2 MeV can therefore give an estimate about the upper limit on the presence of He^3. Estimates obtained from the new observations will be given later.

The nuclear de-excitation lines, shown in Table 2 are produced more promptly and give information about the chemical abundance of various nuclei and also about the flux of energetic charged particles which are responsible for their production.

TABLE 1

Neutron Producing Reactions (Ramaty et al. 1974)

Reaction	Threshold Energy Mev
Proton-initiated reactions	
He^4 $(p, pn)He^3$	25.7
He^4 $(p, 2pn)H^2$	32.6
He^4 $(p, 2p2n)H^1$	35.4
He^4 $(p, pn\pi$ ...	197.5
He^4 $(p, p2n\pi$ ...	207.0
H^1 $(p, n\pi^+)H^1$	287.0
H^1 $(p, n\pi^+\pi$ ...	557.0
C^{12} $(p, n$ ...	19.8
N^{14} $(p, n$ ...	6.3
O^{16} $(p, pn$ ...	16.5
Ne^{20} $(p, pn$ ...	17.7
α particle-initiated reactions	
H^1 $(\alpha, np)He^3$	102.8
H^1 $(\alpha, 2pn)H^2$	130.3
H^1 $(\alpha, 2p2n)H^1$	141.5
He^4 $(\alpha, n)Be^7$	38.0
He^4 $(\alpha, \alpha n)He^3$	41.1
He^4 $(\alpha, np)Li^6$	49.2

TABLE 2

Some Prominent Gamma Ray Lines "Expected" In Solar Flares

Photon Energy (MeV)	Origin	Remarks
0.51	Positron Annihilation. Source of Positrons?	Observed
2.2	$n+p \rightarrow \alpha + \gamma$	Observed
0.431	$^4He(\alpha, n)^7Be^*$	Not yet observed
0.478	$^4He(\alpha, p)^7Li^*$	Resolution not enough
4.43	$^{12}C^*$ (Through p and α Interactions	Observed
6.14	$^{16}O^* \rightarrow$ Through p and α Interactions	Observed
6·33	$^{15}N^* \rightarrow$	?

Also Gamma Rays from $\pi^\circ \rightarrow 2\gamma$ and Continuum emission through electron bremsstrahlung.

THE EXPECTED FLUX OF NEUTRONS AND GAMMA RAYS :

The expected production rate depends upon various conditions existing in the solar atmosphere and also depends upon the assumption relating to the number of accelerated particles and their energy spectra. The cross-sections for various nuclear reactions are fairly well-known but other parameters have to be estimated and to be fitted in with the observed parameter. Typical

TABLE 3

Some typical parameters used for production in Solar flares.

(1)	Energy Spectra of Accelerated Particles		(a) $\propto E^{-S}$ (b) $\propto \exp(-P/Po)$
(2)	No. Density of Target Nuclei	$\sim$	10^{10} cm^{-3}
(3)	Total No. of Particles Accelerated >30 MeV	$\sim$	10^{34}
(4)	Acceleration Time	$\sim$	10^{2} sec.

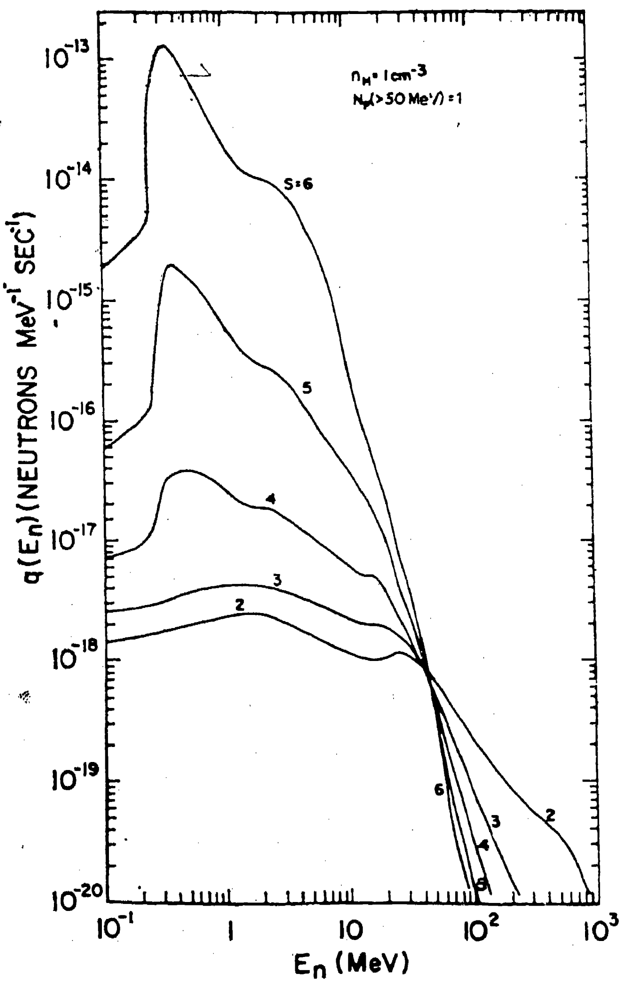

Fig. 2 : Neutron production energy spectra in the thin-target model with power-law spectra (Ramaty et al. 1974)

parameters (though by no means unique) used for such calculations are shown in Table 3. I do not wish to go into the details regarding the basis of such assumptions but would rather discuss the question in a more qualitative manner for the purpose of this paper. Using such calculations and under certain assumptions of interacting geometry, it has been estimated that the flux of neutrons as observed near the Earth would have a characteristic dependence shown in fig. 2 (Lingenfelter and Ramaty 1967). We can see from this figure that the low energy end of the neutron spectrum shows a bend over, because of the preferential decay of low energy neutrons during their passage from Sun to Earth. As a result, the neutrons which reach the Earth have maximum intensity in the energy range of about 50 to 100 MeV depending upon the nature of the primary spectrum utilized. Considering the typical parameters for the expected number of charged particles produced in solar flares, one estimated that a flux of the order of about 1 neutron/cm^2/sec of high energy neutrons is expected near the Earth. Most of the early day detector systems did not have the capability of detecting these high energy neutrons particularly when they have to be detected in the presence of other neutral particles. Hence special design features had to be introduced in fabricating solar neutron detectors. Some of the attempts made in this direction will be discussed a little later.

The flux of gamma rays expected to be produced in solar flares is about 1 photon/cm^2 sec and is fairly large compared to the present day detector limits (fig. 3). However, experiments had to be specially designed to look at the gamma ray lines from the Sun and the observations had to be correlated with the solar flare activity. The experiment which was carried out by the group at University of New Hampshire, U.S.A. was indeed one such experiment which was flown in the OSO-7 satellite during August 1972 and it is the only experiment, so far, which has detected the presence of gamma ray lines during solar flares. I will describe these results a little later.

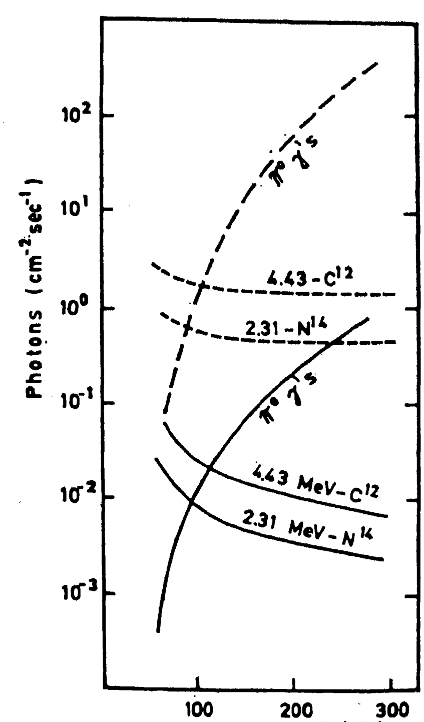

Fig. 3 : Gamma ray fluxes at Earth—isotropic model acceleration phase (solid line) and slowing down phase (dotted line) (Chupp 1971)

EXPERIMENTAL STATUS :

Before describing the various attempts made in detecting solar neutrons and gamma rays, it may be worthwhile to mention here, in brief, the principle behind the detection of these neutral particles. The neutron could either interact in an elastic manner with an hydrogeneous target producing a recoil proton or, if the energy of the neutron is high (say greater than about 50 MeV) it may prefer to interact in a heavy target, resulting in a nuclear collission with the emission of many charged particles. Similarly the gamma ray could either undergo Compton scattering or could produce an electron-positron pair, if it is sufficiently energetic. These basic principles of detection are used in designing various experimental set-ups. In the set-up used by Frye et al. (1969), a spark chamber is completely surrounded by a charged particle shield and thus only neutral radiations are selected. Interactions due to neutrons and gamma rays could be separated from their characteristic ionization produced in the spark chamber. A different kind of experimental set up was used by the Tata Institute of Fundmental Research in designing its experiment for the first Indian Satellite (Damle et al. 1976). The main detector system, also surrounded by a charged particle shield, consisted of a CsI(Tl) crystal in which the neutrons are expected to interact, producing low energy charged particles with high ionization while the gamma rays which interact in the crystal will produce relativistic electrons with low ionization. By using the Pulse Shape Discrimination technique, it is possible to separate neutron and gamma ray pulses produced in the same detector (Joseph 1970). This detector was flown in the first Indian Satellite but unfortunately after successfully obtaining data for a short period of about two days, the experiment was turned off due to power supply problems and could not be reactivated afterwards.

The experimental arragement used by the University of New Hampshire in their experiment in the OSO Satellite consisted of a 3″ × 3″ NaI (Tl) crystal which was surrounded by a charged particle shield and is located in the wheel of the OSO Satellite. The detector periodically looks in the direction of the Sun and away from it during the rotation of the wheel. During August 1972, on two occassion, namely August 4 and 7, this detector clearly recorded gamma ray lines during the period of two flares, each of importance 3B. They were able to measure the intensities of the 0.51 MeV, 2.2 MeV, 4.4 MeV and 6.1 MeV gamma ray lines during these flares. The observed increase in the flux of some of these lines is shown in fig. 4. This was the first evidence for the production of nuclear gamma rays lines in solar flares.

RESULTS & DISCUSSIONS :

The results of the University of New Hampshire Group have clearly given the evidence for the presence of gamma rays resulting from nuclear reactions taking place on the solar surface. So far there have been a few attempts to measure the flux of high energy solar neutrons but no conclusive evidence has been given, though possible evidences have been reported (Chupp 1971). Using these results, Ramaty & Lingenfelter (1974), Ramaty (1975) and Forrest et al. (1974) have given some useful information relating to solar flares which is summarized below:

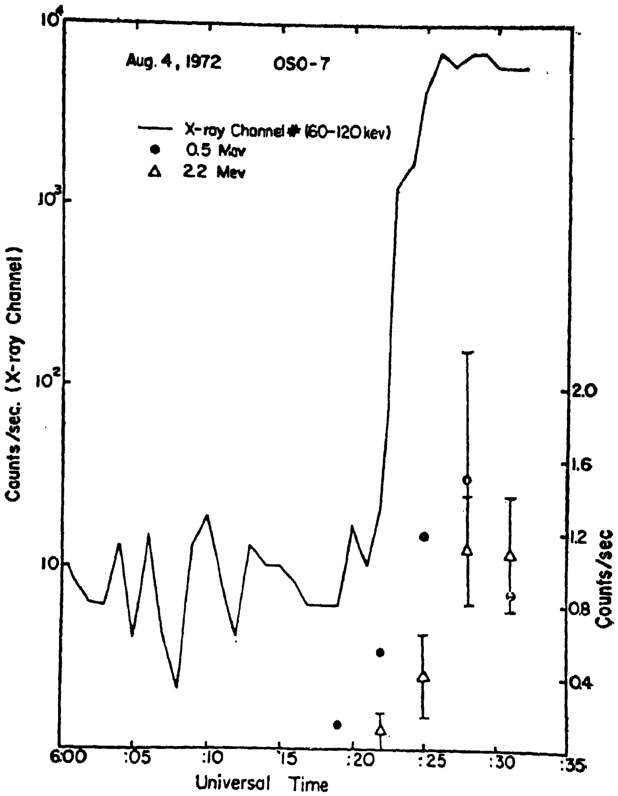

Fig. 4 : Enhanced counting rates of Gamma rays and X-rays for the OSO detector (Chupp et al. 1974)

1. There is convincing evidence that nuclear reactions are indeed taking place on the surface of the Sun.
2. The intensity measurements of the solar gamma rays have yielded information about the energy spectrum, particularly giving some limits on the index, defining the charged particle spectrum (Please see figure 5 and Table 3).
3. The absolute intensities of the gamma ray lines have been utilized to place an upper limit of 10^{34} particles, with $E > 5$ MeV, generated during the 3B solar flares. This estimate is lower than the one obtained earlier by indirect methods.
4. Based on the observation of the He^3 flux at high energies, it has been estimated that energetic He^3 is produced as a secondary product during the interaction of charged particles in regions of density of about $10^{10}/cm^3$. This is in contrast to the estimated density of $10^{12}/cm^3$ obtained from the the observed flux of 0.51 MeV gamma rays.
5. The acceleration time for charged particles produced in flares has been estimated to be about 10^2-10^3 sec.
6. A study of the line-width of gamma rays is expected to give more valuable information relating to the regions of production of gamma rays, e.g., the line-width of 2.2 MeV is expected to be only 100 eV since is is produced as a result of the slow process

of neutron thermalization and capture by ambient protons in the photosphere, while the nuclear de-excitation gamma rays are expected to have line-widths of the order of 100 keV since they are produced by de-excitation of energetic charged particle nuclei. The OSO experiment was not able to measure these line widths accurately and detailed information from these studies could not be given though it was estimated that the regions where the 0.51 MeV line is produced should have temperatures less than 10^7 °K.

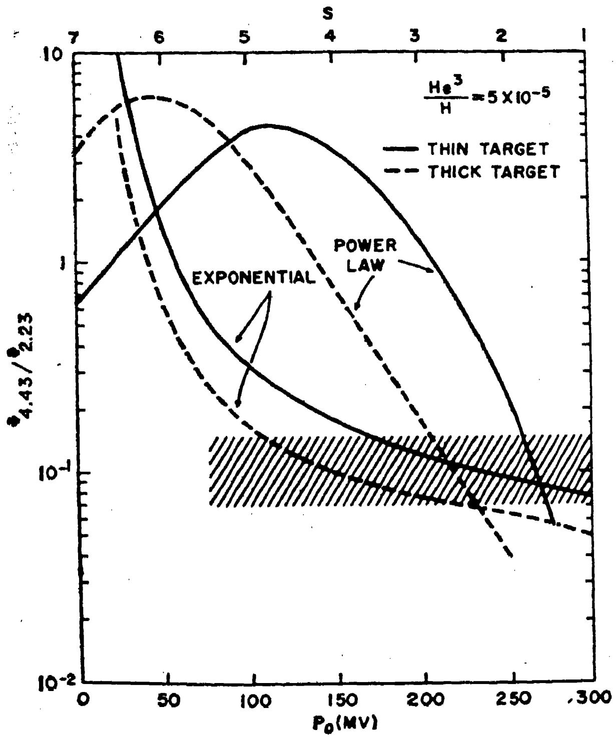

Fig. 5 : Ratios of the 4.4 MeV line, intensity to the 2.2 MeV line intensity in the thin and thick-target models, with power-law and exponential spectra. The shaded area is the data of Chupp et. al.

FUTURE SCOPE :

It will be necessary to fly high resolution solid-state type gamma ray detectors which can measure narrow line-widths due to their intrinsic high resolution and hence can give detailed information regarding the region of production. Also this technique would help in identifying gamma rays of lower intensity than measured so far since the gamma ray lines would clearly stand out over the continuum.

Time history and intensities of gamma rays will have to be studied and correlated with H α profiles and also at other wavelengths. It would help understanding the energetics of the solar flares and the relation of optical flares with the acceleration of the charged particles.

High energy neutrons have yet to be detected and a planned programme will have to be worked out by which regular balloon flights could be made based on the predictions regarding the occurrence of the solar flares. It is perhaps possible that the Solar Udaipur Observatory would develop this technique of forecasting solar flares and balloon flights could then be conducted by using neutron and gamma ray detectors flown by TIFR. I certainly hope that this forecasting technique can be perfected before the approach of the next solar maximum.

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