Gamma astronomy of the Sun and study of solar cosmic rays

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A detailed discussion is given of the various nuclear reactions proceeding in the Sun's atmosphere under the influence of flare-accelerated particles. The role of such reactions in formation of the line spectrum and continuum of gamma-rays from the disturbed and quiet Sun is discussed. The gamma-ray fluxes in individual lines and in the continuum are estimated. The possibility of applying data on gamma-ray emission from the Sun to analysis of particle acceleration in solar flares and the conditions of their ejection into interplanetary space is analyzed.

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CONTENTS

INTRODUCTION

It is now well known that, after a flare of the chromosphere, particles with a wide range of energy and charge are observed in interplanetary space and frequently also on the Earth, so-called solar cosmic rays (SCR). The total number and the spectral distribution of these particles are correlated with the strength of the flare, but there are frequent cases in which energetic particles are observed in interplanetary space, while no substantial manifestations of activity are observed on the Sun. Therefore in what follows, in accordance with the terminology accepted at the present time, we shall use the expression "solar flare" if solar cosmic rays are observed near the Earth and shall not concern ourselves with the question of whether any chromospheric flare can be associated with this event.

Since the purpose of the present article is to analyze various sources of solar gamma radiation and to set forth new methods of studying solar cosmic rays on the basis of data on gamma astronomy of solar flares, we shall dwell only briefly on the contemporary information on solar cosmic rays obtained from direct detection near the Earth. We note at once that information on solar cosmic rays obtained from gamma astronomy (for example, the particle generation spectrum, the duration of particle generation, the time pattern of generation, the density, temperature, and nuclear composition of the material in the region of the flare, and the depth of penetration of the accelerated particles into the solar atmosphere) cannot in principle be obtained by other methods available at the present time.

a) Experimental data on generation of high-energy particles during solar flares

A large amount of data on solar cosmic rays for various solar flares, obtained at surface stations and in the stratosphere, have been analyzed in the book by Dorman and Miroshnichenko.[1] This analysis permits determination of the spectrum of particles with energy *60–100 MeV* and above. *However, in this energy region*

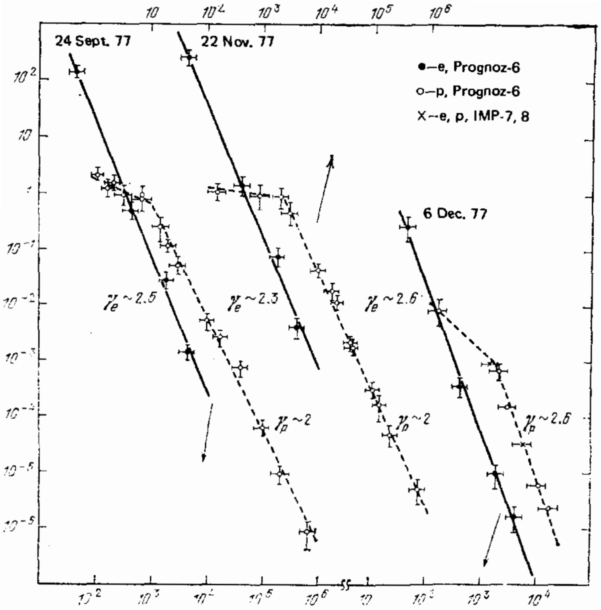

FIG. 1. Differential energy spectra of solar cosmic rays ($cm^{-2}sec^{-1}sr^{-1}keV^{-1}$) of flares.[4] The dates of the flares are shown near the curves. γ_p and γ_e are the exponents of the power representation of the spectrum for protons and electrons. The arrows indicate the energy scale for the corresponding flares (keV).

only a small fraction of the solar cosmic-ray particles accelerated during flares are included. As studies carried out in satellites and space ships have shown, the low-energy limit of the SCR spectrum begins at hundreds or possibly tens of keV. The maximum energy sometimes reaches 10 GeV.

In spite of the considerable period of time over which solar cosmic rays have been studied, complete information is not available at the present time on the shape of the SCR spectrum and the reason for its evolution with time (see for example Refs. 1–5 and work cited therein). For approximation of the SCR spectrum extensive use is made of power and exponential functions, both in the particle energy E and in their rigidity $R = \sqrt{(E^2 - mc^2)}/Z$.

As can be seen from Fig. 1, the energy spectrum of accelerated protons frequently possesses a feature which is important for the subsequent discussion—a change of slope of the spectrum in the energy region below 1 MeV. For particles of higher energy (up to several hundred MeV) the spectrum of energetic photons can be fitted satisfactorily by a power function.

The main flux of nuclei accelerated during flares consists of protons. The concentration of heavier nuclei in solar cosmic rays is determined by their relative concentration in the Sun's atmosphere, the features of the acceleration mechanism (for example, the possibility of preferential acceleration of heavy nuclei[6,7]), and the condition of emission of the particles into the interplanetary medium.[9] At the present time it is known that in SCR there are nuclei from helium (see for example Refs. 10–12) up to iron. An example of an event for which energy spectra have been obtained for

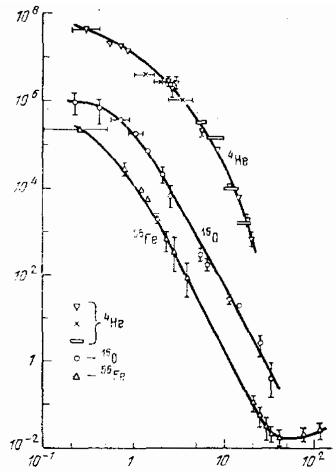

FIG. 2. Example[8] of spectral energy distribution for various nuclei in solar cosmic rays. The abscissa is the energy in MeV/nucleon, and the ordinate is the flux in $cm^{-2}sr^{-1}$ (MeV/nucleon)$^{-1}$.

various nuclei is given in Fig. 2.

The energy spectra of the nuclear component of solar cosmic rays in many events are similar. However, there are flares for which similarity of the spectra does not exist for all nuclei,[13] and in addition the spectrum for the nuclear component frequently differs from the spectrum for the proton component of solar cosmic rays.[1,14,15]

b) Are the nuclear reactions occurring in the solar atmosphere efficient?

The energetic particles arising in a flare enter into interaction with the material of the solar atmosphere. However, the efficiency of this interaction from the point of view of its influence on the observed nuclear and isotopic composition of solar cosmic rays and on the chemical composition of the solar atmosphere is not obvious.

The importance of the nuclear reactions is determined, actually, by the concentration of energetic particles, the density of the material in the region to which the energetic particles penetrate, the time passed by the particles of the solar cosmic rays in the Sun's atmosphere, and the cross section for the various nuclear processes. Therefore it is not difficult to investigate the role of these processes in various models of solar flares and conditions of propagation of solar cosmic rays in the Sun's atmosphere.[16-18] In addition, at the present time there are direct experimental data which indicate that the nuclear reactions in the Sun's atmosphere are efficient. This is indicated by the observation in solar cosmic rays of the isotopes D and ^3He in quantities which are clearly greater than those which follow from the possible concentration of these elements in the Sun.[13,19,20] It is also indicated by the fact that gamma rays have been observed during a number of flares.[21-24] The gamma rays observed here have been not only those arising in the direct interaction of accelerated particles with the atoms of the solar atmosphere, but also gamma rays of, so to speak, secondary origin: the annihilation line $E_\gamma = 0.511$ MeV and the radiation from radiative capture of neutrons by hydrogen, $E_\gamma = 2.2$ MeV, which indicates the efficiency of production of positrons and neutrons in the region of the flare.

As soon as it is clear that in the region of a solar flare the nuclear reactions produced by accelerated particles can occur with sufficient efficiency that their products are experimentally observed, it becomes understandable that we are presented with new possibilities for studying the processes of generation of energetic particles in flares and the conditions of their propagation.

In addition, the gamma radiation from the Sun provides new possibilities for studying the solar atmosphere, and in particular its composition.[25]

1. ACTIVE PROCESSES IN THE SUN AND THE GAMMA RADIATION OF SOLAR FLARES. THE LINE SPECTRUM

Let the concentration of atoms of type i in the region of a flare be n_i, and the concentration of accelerated nuclei $n_j(E)$. Then the number of interactions per unit volume per unit time leading to gamma radiation is determined by the following expression:

$$W = \sum_{i,j} n_i \int_0^\infty n_j(E)\, \sigma_{ij}^{\gamma}(E)\, v\, dE, \qquad (1.1)$$

where v is the relative velocity and $\sigma_{ij}^{\gamma}(E)$ is the cross section for interaction of nuclei i and j with generation of a γ ray. The velocities of the particles which do not take part in the acceleration process are negligible in comparison with those of the particles accelerated in the flare. Therefore in reality we can assume that the interaction occurs between fast and stationary particles. In this case Eq. (1.1) is written as follows:

$$W = 4\pi \sum_{i,j} n_i \int_0^\infty I_j(E)\, \sigma_{ij}^{\gamma}(E)\, dE, \qquad (1.2)$$

where $I_j(E)$ is the intensity of nuclei j.

If the volume is V and the intensity of particles changes with time and over the volume of the flare, then the total number of gamma rays emitted by the flare is

$$N_\gamma(t) = 4\pi \sum_{i,j} \int_V d\mathbf{r}\, n_i(\mathbf{r}) \int_0^\infty I_j(E,\ t,\ \mathbf{r})\, \sigma_{ij}^{\gamma}(E)\, dE. \qquad (1.3)$$

Even large flares on the Sun do not exceed in area a few thousand millionths of the Sun's surface. Therefore, in determining the gamma-ray flux F_γ at large distances such as at the Earth's orbit, we can assume that the radiation is generated by a point source,

$$F_\gamma(t) = \frac{N_\gamma(t)}{4\pi R^2}. \qquad (1.4)$$

Using these expressions, let us consider the role of various reactions as sources of gamma radiation.

Here we note that in propagation of gamma rays in the solar atmosphere and interplanetary space they will absorbed. The main absorption process for gamma rays of the energy considered ($E_\gamma \gtrsim 1$ MeV) will be pair production and the Compton effect.

Therefore in traversing a thickness of material x in g/cm^2 the flux F_γ will be related to the initial flux F_{γ_0} as follows:

$$\frac{F_\gamma}{F_{\gamma_0}} = e^{-\mu x}, \qquad (1.5)$$

where μ is the absorption coefficient in cm^2/g.

For $E_\gamma \gtrsim 1$ MeV $\mu \lesssim 0.01$; hence it is clear that the flux of gamma rays will arrive practically unchanged even from depths of several tens of g/cm^2.

We note that the nuclear processes which lead to gamma radiation are well known. The astrophysical applications of these processes have been discussed in a large number of papers. In one recent review[26] the necessary references are given quite completely. However, the detection of gamma rays during solar flares leads to the need of a detailed discussion of these processes for the purpose of obtaining new information in the future.

a) Inelastic scattering of protons—the main source of the line gamma spectrum

In discussing various processes of gamma-ray generation during solar flares it is necessary to mention as one of the most powerful sources the radiation of gamma rays in inelastic scattering of accelerated protons by various nuclei of the Sun's atmosphere.[17,18,25]

This mechanism is distinguished by the fact that it involves, on the one hand, the most abundant of the accelerated nuclei—protons, and on the other hand the most abundant isotopes of the Sun's atmosphere.

Here the cross sections for this reaction are quite large even for protons with energies of several MeV (Table I). Inelastic scattering of protons by nuclei is important not only as a source of some of the most intense lines in the gamma spectrum, but also as a source of a large number of lines in the gamma-ray spectrum from flares.

Therefore this process is fundamental in generation of the line spectrum of gamma rays during flares.

We shall consider the process of gamma-ray production in which the main flux arises in the region of a flare of dimensions h.

For a given specific mechanism of gamma-ray production, Eq. (1.4) is written in a form which already takes into account the probability of transitions between energy levels of the excited nucleus:

$$F_\gamma = \frac{P(E_k,\ E_l)}{4\pi r^2} n_i h \int_{E_1}^{E_2} dE N_p(E)\, \sigma_{pi}^{\gamma}(E); \qquad (1.6)$$

here $N_p(E)$ is the number of protons with energy E present at a given moment of time in the entire volume of the flare; F_γ is the flux of gamma rays with energy $E_\gamma = E_k - E_e$ at a distance r from the flare, $P(E_k, E_e)$ is the probability of transition of the nucleus from an excited level E_k to a level E_e, and $\sigma_{pi}^{\gamma}(E)$ is the cross section for excitation of the level E_k by a proton with energy E.

For most of the levels given in Table I, direct decays

TABLE I.

Isotope	Energy of level (MeV)	Energy of proton (MeV) and cross section (mb)
^{12}C	4.43	6.6 9 12 15 16 17 18 19 20 22 24 26 28 96 59 260 246 200 175 155 150 130 120 100 95 80 70 4 185 6
	12.7	14 18 20 28 30 0 10 30 4 4
	15.1	17 18 19 20 22 26 30 34 42 48 0 1 2 6 7 2 2 1.8 1.5 1
^{14}N	2.31	3.7 3.9 4 4.6 4.8 5 5.4 6.4 8 10 14 3 70 60 3 40 60 10 60 24 32 34
	3.95	8 10 14 14.6 58 77 22 18.5
	4.91	8.6 10.2 12.6 14.6 7.9 5.6 5.4 4.8
	5.1	8.6 10.2 12.6 14.6 23.2 34 25.7 19
	5.69	8.6 10.2 10.6 12.6 14.6 11.7 16.3 17.9 12 8.7
	5.83	8.6 10.2 10.6 12.6 14.6 17.5 25 40 28.3 19.2
	6.21	10.2 10.6 12.6 14.6 7.6 6.7 6.6 4.7
	6.44	10.2 10.6 12.6 14.6 12.7 19 9 5.9
	7.03	10.2 10.6 12.6 14.6 27.2 28.9 25.9 27.9
^{16}O	6.14	8 13 14 15 16 17 18 19 150 185 10^3 $3\cdot10^3$ 260 130 110 130 100 90 85 80 4 4 7 8.5
	6.92÷7.12	13 14 15 16 17 18 19 150 185 10^3 80 70 65 55 50 45 40 1 4 <1
	8.87	15 16 17 18 19 25 40 40 30 30
^{24}Mg	1.37	17.5 25 30 35 40 45 48 44 42 41 40 39 38 37
^{28}Si	1.78	8 14 320 150
^{32}S	2.14	5 8 11 14 250 120 100 60
^{56}Fe	0.845	1.4 2 3 4 5 6 7 17 $2\cdot10^{-4}$ $2\cdot10^{-2}$ 1 20 100 200 100 40

The information on the cross section is taken from Refs. 28–32 and from works cited in Ref. 25.

to the ground state occur. The levels considered are easily distinguished under laboratory conditions. However, for solar flares there will be a broadening of the lines as the result of the thermal motion of the nuclei.

Using the well known expressions for the Doppler effect, we can estimate the magnitude of this broadening of the lines. Even for temperatures in the region of the flare of 10^8–10^9 K the broadening of the lines will not

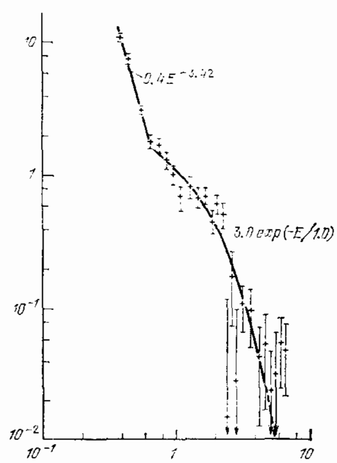

FIG. 3. Gamma-ray spectrum observed for the event of 4 August 1972.[27] The abscissa is the gamma-ray energy in MeV and the ordinate is the flux in ($cm^{-2}sec^{-1}MeV^{-1}$).

TABLE II. Fluxes ($cm^{-2}sec^{-1}$) of gamma rays in individual lines.

E_γ (MeV)	F_γ, theory	Experimental data on flare		
		4 Aug. 1972[21]	7 Aug. 1972[22]	11 Aug. 1978[23]
0.85	$1{,}5\cdot10^{-3}$			
1.37	$2\cdot10^{-4}$			
1.78	10^{-3}			
2.14	$7\cdot10^{-4}$			
2.31	$7\cdot10^{-4}$			
3.95	$2\cdot10^{-5}$			
4.43	$2\cdot10^{-2}$	$(3\pm1)\cdot10^{-2}$	$\leqslant 2\cdot10^{-2}$	0.18 ± 0.07
4.91	10^{-5}			
6.14	$2\cdot10^{-2}$	$(3\pm1)\cdot10^{-2}$	$\leqslant 2\cdot10^{-2}$	
6.92 7.12	$3\cdot10^{-3}$			
8.87	$7\cdot10^{-6}$			
12.7	$3\cdot10^{-4}$			
15.1	$4\cdot10^{-5}$			
20.1	10^{-3}			

In the calculation it was assumed that $n_H = 10^{13}$ cm^{-3} and $h = 10^9$ cm; $N_p(E) = 5\cdot10^{32}E^{-2}$ MeV^{-1} sec^{-1} for $E \geqslant 3$ MeV. These values are characteristic of large solar flares.[25,33,34]

exceed 10–20 keV, so that the individual lines will not overlap.

The time of containment of the accelerated particles in the region of the flare or the duration of their production is given by various estimates as 100–1000 sec. This follows also from data on the radio and x-ray radiation of flares and from data on the nature of the increase in the intensity of particles of solar cosmic rays.

Since at the present time gamma radiation from flares has been observed experimentally[21-24] (Fig. 3), we have given in Table II for comparison the theoretical[25] and experimental results. We note that the possibility of anisotropic motion of the accelerated particles from the region of acceleration may substantially affect the magnitude of the gamma-ray flux. Thus, if the accelerated particles hit the Sun, then F_γ will be increased by several times.[25]

b) Generation of neutrons in flares and their role in radiation of gamma rays from flares

Moving in the Sun's atmosphere neutrons produced in nuclear reactions[35-38] will not only be slowed down in scattering by hydrogen and then absorbed by hydrogen atoms, but also will excite energy levels in various nuclei.

The cross section for interaction of neutrons of energy 0.1–10 MeV with nuclei of various elements can be found, for example, in Refs. 39 and 40. For the nuclei of interest to us (carbon, nitrogen, oxygen, neon, iron, and several others) the cross sections for excitation of low-lying levels by such neutrons reach hundreds of millibarns.

The number of gamma rays emitted in this process can be determined as follows. If $N_n(E)$ is the total number of neutrons of a given energy produced in a flare, then the total number of gamma rays N^γ_{ni} arising in interaction of a neutron with a nucleus of type i is

$$N^\gamma_{ni} = n_i \int_{E_1}^{E_2} N_n(E)\,\sigma^\gamma_{ni}(E)\,\lambda_n(E)\,dE; \tag{1.7}$$

here n_i is the concentration of nuclei i in the flare (or in the region of generation of γ rays) and λ_n is the range of the neutron in centimeters.

The quantity N_n itself is determined from the expression

$$N_n(E) = \sum_i n_i \int_{\geqslant \mathscr{E}_{\text{thresh}}} N_p(\mathscr{E})\, \sigma^n_{pi}(\mathscr{E}, E)\, \lambda_p(\mathscr{E})\, d\mathscr{E} + n_H \int_{\geqslant \mathscr{E}_{\text{thresh}}} N_i(\mathscr{E})\, \sigma^n_{iH}(\mathscr{E}, E)\, \lambda_i(\mathscr{E})\, d\mathscr{E}, \quad (1.8)$$

where $N_p(\mathscr{E})$ is the spectrum of accelerated protons, $N_i(\mathscr{E})$ is the spectrum of accelerated nuclei, $\sigma^n_{pi}(\mathscr{E}, E)$ and $\sigma^n_{iH}(\mathscr{E}, E)$ are the cross sections for production of neutrons with energy E in interaction of a proton of energy $\mathscr{E}$ with a nucleus i and in interaction of a nucleus i of energy per nucleon $\mathscr{E}$ with hydrogen, and $\lambda_p(\mathscr{E})$ and $\lambda_i(\mathscr{E})$ are the ranges of the respective energetic particles.

Using Eqs. (1.7) and (1.8), we can calculate the total number of generated gamma rays of a specified energy.

On the other hand, the accelerated protons will excite similar levels in interaction with the same nuclei, and therefore it is desirable to compare these two sources of gamma radiation in lines.

The ratio of the quantities of gamma radiation for a given line generated by neutrons to the quantity generated by protons we shall write as

$$\frac{N^\gamma_{ni}}{N^\gamma_{pi}} = \frac{\int_{E_1}^{E_2} N_n(E)\, \sigma^\gamma_{ni}(E)\, \lambda_n(E)\, dE}{\int_{\mathscr{E}_1}^{\mathscr{E}_2} N_p(\mathscr{E})\, \sigma^\gamma_{pi}(\mathscr{E})\, \lambda_p(\mathscr{E})\, d\mathscr{E}}. \quad (1.9)$$

Using Eq. (1.9), we can make the comparison $N^\gamma_{ni}/N^\gamma_{pi}$ when the principal generation of gamma rays by protons occurs in the region of flares with parameters similar to those given in Table II. Then for all gamma lines considered the ratio $N^\gamma_{ni}/N^\gamma_{pi}$ will not exceed 30%. Here the greatest value of this ratio is reached for the line at 0.845 MeV—the lowest level of the ^{56}Fe nucleus.

Note that in the case in which a thin-target model can be used for the protons, the role of neutrons in generation of the gamma line spectrum increases substantially, becoming comparable with the role of protons in this process.

c) Radiative capture and gamma radiation of the Sun

In contrast to the gamma-ray production mechanism discussed above, the reaction of radiative capture is attractive in that it occurs at substantially lower energies of the interacting particles.

Although the cross sections for this reaction are small in this case, the significant increase in the number of particles taking part in it can lead to the result that radiative capture becomes important as a source of gamma rays.

The significance of this process is determined in addition by the fact that it is one of the sources of gamma rays with energy 20 MeV, and therefore the possibility arises of estimating a lower limit of the flux of such gamma rays from the Sun. In addition, the flux of gamma rays arising in radiative capture will depend substantially on the form of the low-energy part (less than 1 MeV) of the spectrum of particles accelerated in a flare, which provides the possibility of practical use of the radiation for studying the production spectrum in the low-energy region.

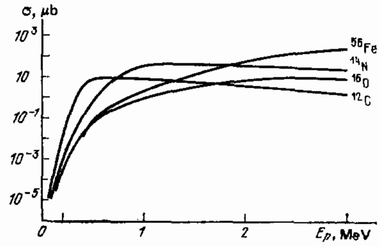

FIG. 4. Energy dependence of averaged cross section for radiative capture of a proton by nuclei.[41-46]

In Fig. 4 we show values of the cross section for this process for the nuclei which are the most abundant in the solar atmosphere. Using these data, we can determine from Eq. (1.3) the number of gamma rays arising in the region of a flare on radiative capture of accelerated protons by the nuclei of the solar atmosphere.

What is the range of energies covered by the emitted gamma rays? The necessary information can be found, for example, in Ref. 47. As a rule, on excitation of a higher level of a nucleus, the decay occurs in a cascade. Therefore the main flux of gamma rays from radiative capture will be in the range from 0.5 MeV up to 5–6 MeV. Here the distribution of the gamma rays over this energy range is not uniform. On the contrary, the gamma-ray flux will drop rapidly in the transition to higher energies. Thus, the flux of gamma rays with energy 3.1 MeV will be 6 times less than the flux of gamma rays with energy 2.6 MeV.[43] In the region of gamma-ray energy less than 2.5 MeV the steepness of the spectrum will decrease somewhat.[46]

Thus, the possible spectrum of gamma radiation of solar flares arising from radiative capture of fast protons by nuclei will have a maximum near 1 MeV with a weak falloff in the low-energy region and a steep drop in the high-energy region.

Without calculating the absolute flux of gamma rays in this energy range, we shall compare it with the actually observed flux arising in inelastic scattering. For a power-law spectrum of particles the ratio of the gamma ray flux radiative capture $F_{r.c.}$ to the flux of gamma rays from inelastic scattering $F_{i.s.}$ is

$$\frac{F_{r.c.}}{F_{i.s.}} = \frac{\int_{\geqslant E_1} E^{-S} \sigma_{r.c.}(E)\, \lambda_p(E)\, dE}{\int_{\geqslant E'_1} E^{-S} \sigma_{i.s.}(E)\, \lambda_p(E)\, dE}, \quad (1.10)$$

where the lower integration limit is determined by the reaction threshold.

In Fig. 5 we have given these ratios (for power spectra as a function of the exponent of the spectrum under the condition that γ-ray production occurs in the same volume of the flare for the entire spectrum of accelerated particles) obtained with the following lower lim-

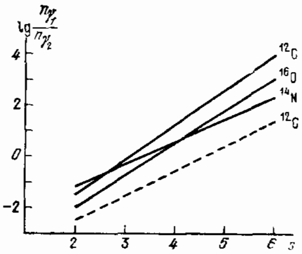

FIG. 5. Logarithm of the ratio of concentrations of gamma rays emitted on radiative capture of protons by various nuclei and in inelastic scattering of protons by the same nuclei, as a function of the value of the spectral exponent of the accelerated particles S.

its for the radiative-capture reaction and the inelastic scattering reaction:

for the nucleus ^{16}O: $E_1 = 0.5$ MeV, $E_1' = 8$ MeV;

for the nucleus ^{12}C: $E_1 = 0.3$ MeV, $E_1' = 8$ MeV;

for the nucleus ^{14}N: $E_1 = 1$ MeV, $E_1' = 8$ MeV.

It is evident that beginning with $S \approx 3.5$ for the differential spectrum, the radiative-capture reaction will provide the main contribution to the gamma-ray flux of the energy considered.

We have already mentioned that the spectrum of solar cosmic rays in the energy region below 1 MeV may differ from a power spectrum. This affects the efficiency of the radiation capture process as a source of the Sun's gamma radiation. This situation may change appreciably if the accelerated-particle spectrum has a maximum. In this case, depending on the location of the maximum, the contribution to the gamma ray flux of radiation capture processes will change.

In Fig. 5 we have shown by the dashed line for the case of carbon how the role of radiative capture changes in the case when a sharp maximum is observed in the accelerated particle spectrum at an energy ≈1–1.5 MeV.

Note that the role of the existence of a maximum in the spectrum of solar cosmic rays for determination of the contribution of radiative capture processes to the gamma ray flux from solar flares is not the same for different nuclei.

For carbon nuclei it may turn out to be important, while for oxygen and nitrogen nuclei the existence of a maximum in the accelerated-particle spectrum will not lead to a negligible contribution of the radiative capture process, as follows from the dependence of the cross section for proton radiative capture by these nuclei on the energy (see Fig. 4).

The radiative capture of protons occurs much more efficiently in heavier isotopes. For example, according to Refs. 48–50 the capture of a proton by ^{13}C is about 10^3 times more efficient than by ^{12}C for a proton energy ≈1–3 MeV, and capture of a proton by ^{15}N is 10–10^2 times more efficient than capture by ^{14}N at a proton energy 1–10 MeV.

Using data on the relative abundance of the elements,[51-53] we have

$$\frac{n_{^{14}N}}{n_{^{15}N}}\frac{\sigma^{\gamma}_{^{14}Np}}{\sigma^{\gamma}_{^{15}Np}} = 10^{1.4} - 3, \quad \frac{n_{^{12}C}}{n_{^{13}C}}\frac{\sigma^{\gamma}_{^{12}Cp}}{\sigma^{\gamma}_{^{13}Cp}} = 10^{-2} - 10.$$

Thus, it turns out that in spite of the fact that the isotopes ^{13}C and ^{15}N have a relatively low abundance, the gamma radiation arising as a result of this reaction is rather intense.

d) Radiative capture of neutrons and the high-energy tail of electromagnetic radiation

Since during solar flares there are nuclear reactions, some of the products of which are neutrons, gamma rays from radiative capture of neutrons will be present in the gamma radiation from a flare.

The most intense radiation will be from capture of neutrons by hydrogen with emission of a 2.2-MeV gamma ray.[54,55]

Radiative capture of neutrons by other nuclei of the solar atmosphere will be substantially less efficient in view of the lower abundance of these nuclei. However, the radiation generated here may turn out to be interesting as a source of gamma rays with energy above 10 MeV and also a source of the quasicontinuous spectrum of gamma rays of solar flares in the energy region from 0.3 to 10 MeV.

From data on the concentration of elements in the solar atmosphere and on the cross sections for neutron radiative capture by nuclei it follows that the flux of gamma rays of various energies arising as the result of radiative capture of neutrons by various elements is 4–6 orders of magnitude less than the flux of gamma rays with $E_\gamma = 2.2$ MeV generated in capture of neutrons by hydrogen.

The actual value of the flux of gamma rays with energy 4–8 MeV measured, for example, during the flare of 4 August 1972,[27] is about three orders of magnitude higher than that which follows from data on neutron radiative capture.

Recently[56,57] it has been possible to measure the cross section for radiative capture of neutrons by ^{3}He nuclei. This reaction is interesting in that it is a source of gamma rays with energy 20.58 MeV and permits estimation of the lower limit of the gamma-ray flux from solar flares in the energy region where no experimental value has yet been obtained. The abundance of the isotope ^{3}He in the solar atmosphere is $(4 \pm 2)\cdot 10^{-5}$ that of hydrogen. It follows from this that the flux of gamma rays with $E_\gamma \approx 20$ MeV due to radiative capture of neutrons by ^{3}He is $\sim 10^{-9}$ of the flux of gamma rays with energy $E_\gamma = 2.2$ MeV if we take into account only thermal neutrons. For the events of 4 August 1972 and 7 August 1972 this gives a gamma-ray flux with $E_\gamma = 20.5$ MeV equal to 10^{-10} cm$^{-2}\cdot$sec^{-1}, and for the flare of 11 July 1978 it gives 10^{-9} cm$^{-2}\cdot$sec^{-1}. Gamma rays of such high energy from solar flares, as we have already mentioned, have not yet been observed. An estimate of the possible flux, obtained from extrapolation of the spectrum from the low energy region, gives a value of the relative flux for the 4 August 1972 event

10^{-7}, which is higher than the value obtained from radiative capture. This comparison, however, does not mean that radiative capture of neutrons by ^3He is not important as a source of gamma rays with energy of the order of 20 MeV. Since the actual flux of such gamma rays is still unknown, this reaction at least gives us a lower limit of the expected flux.

On the other hand, in many flare events an anomalously large number of ^3He nuclei have been observed.[19,58] It is most likely that this is due to conditions of acceleration in which the ^3He isotope experiences preferential acceleration.[59-61] Nevertheless a substantial fraction of the accelerated ^3He nuclei may remain in the solar atmosphere. For example, in the model of spherical emission of the accelerated particles this fraction will amount to half of the total number of energetic particles.

*In view of this the active region in which the flare oc*curred may turn out to be anomalously enriched in this isotope.

Frequently in the active regions there are several flares in succession. In this case in subsequent events this anomaly may appear, which will lead first of all to a substantial increase of the flux of gamma rays with $E_\gamma \approx 20$ MeV, and second to a time dependence of the flux of such gamma rays.

e) Synthesis of elements in a flare and multiple production of gamma rays

Among the processes for gamma-ray generation during flares which we are considering we must mention also nuclear reactions of heavy elements with each other (beginning with ^4He), in the course of which other isotopes are produced, as a rule in an excited state. Such reactions have been studied already for several years by means of heavy-ion accelerators.[62-68] They occur quite efficiently already at energy of the order 1–2 MeV/nucleon. At these energies protons have very low cross sections for excitation of levels; and then only of those levels whose energy does not exceed 1 MeV. At the same time, in interaction of such nuclei as ^{12}C and ^{16}O the newly produced nuclei can become sources of gamma rays with energies up to 8 MeV, and the cross sections for many of these reactions reach hundreds of millibarns already at an energy ≈1 MeV/nucleon in the center-of-mass system.

Element-synthesis reactions are also a source of radioactive nuclei which subsequently maintain the flux of gamma rays from the quiet Sun. This process is discussed below in subsection d of Sec. 2.

Let us estimate the contribution of element-synthesis reactions to the gamma radiation from solar flares. Here we shall consider only synthesis reactions between the most abundant elements of the solar atmosphere.[69]

For example, in production of ^{24}Mg from interaction[62] of the nuclei ^{12}C and ^{16}O the gamma-ray flux F_γ according to Eq. (1.3) is proportional to the intensity of energetic ^{12}C nuclei and the concentration of ^{16}O nuclei and can be written as

$$F_\gamma \sim I_{^{12}C} n_{^{16}O} \sigma^\gamma_{jk},$$

where σ^γ_{jk} is the cross section for this reaction. Since the reaction considered will not depend on whether energetic ^{12}C nuclei are interacting with stationary ^{16}O nuclei or, on the other hand, energetic ^{16}O nuclei are interacting with stationary ^{12}C nuclei, the possible flux of gamma rays must actually be doubled, because the concentrations of these nuclei in the Sun's atmosphere are comparable, and the mechanism of acceleration is equally efficient for them. Thus, the flux of gamma rays, for example, with energy 1.368 and 2.754 MeV will be

$$F_\gamma \sim 2 I_{^{12}C} n_{^{16}O} \sigma^\gamma_{jk}.$$

At the same time gamma rays of these energies will be generated by energetic protons in excitation of levels *directly in ^{24}Mg nuclei, which can be represented in the* following way: $F'_\gamma \sim I_p n_{^{24}Mg} \sigma^\gamma_{pi}$, where I_p is the intensity of protons with energy at least 3 MeV.

Using these expressions, we find

$$\frac{F_\gamma}{F'_\gamma} = \frac{2 I_{^{12}C} n_{^{16}O} \sigma^\gamma_{jk}}{I_p n_{^{24}Mg} \sigma^\gamma_{pi}}. \quad (1.11)$$

For the solar atmosphere,[51,52] we have $n_{^{16}O}/n_{^{24}Mg} \approx 40$. If we take into account for protons and nuclei only the same energy range, then $I_{^{12}C}/I_p \approx 10^{-3}$. In flares with preferential acceleration of heavy nuclei, this ratio may become higher. For particle energies below 5 MeV/nucleon, we have a ratio $\sigma^\gamma_{jk}/\sigma^\gamma_{pi} \approx 100$, since at energies from 2 MeV/nucleon up to 5 MeV/nucleon for ^{12}C nuclei we have $\sigma^\gamma_{jk} \approx 100$ mb,[62,63] whereas for protons of this energy σ^γ_{pi} does not exceed 1 mb. It follows from this that $F_\gamma/F'_\gamma \approx 8$. With increase of the energy the ratio $\sigma^\gamma_{jk}/\sigma^\gamma_{pi}$ decreases. Thus, $\sigma^\gamma_{pi} \approx 40$ mb for protons with $E > 17$ MeV (see Table II), while σ^γ_{jk} for energies above 10 MeV/nucleon apparently does not increase.[62-68] However, in this case the ratio $I_{^{12}C}/I_p$ increases, since it is determined by different energy regions and, depending on the power of the spectrum, will be $\approx 4 \cdot 10^{-2}$ (for an integral-spectrum exponent 2) or higher. Then $F_\gamma/F'_\gamma \approx 3$. Thus, the γ-ray production process at these energies in synthesis of ^{24}Mg is more efficient than the production of γ rays of the same energy as the result of inelastic scattering of protons by "primary" ^{24}Mg nuclei.

This conclusion can be extended to practically all elements whose abundance in the Sun amounts to 0.1 or less of the abundance of carbon or oxygen.[69] What is the possible flux of such γ rays? The ratio of the flux of γ rays with energy 1.37 MeV from ^{24}Mg, generated in its synthesis in the reactions discussed above, to the flux of gamma rays with energy 4.43 MeV determined from Eq. (1.1) or Eq. (1.3) is $(4-10)\cdot 10^{-2}$, that is, the absolute fluxes of gamma rays from synthesized nuclei amount to no more than 10% of the gamma ray flux observed experimentally from solar flares. Here one must keep in mind that this value may rise significantly for two reasons: first—if in the flare there is preferential acceleration of heavy nuclei and, second, if the exponent of the differential spectrum of particles in the flare is higher than 3. It is easy to see that it is sufficient that the relative abundance of nuclei in solar cosmic rays differ from that in the solar atmosphere by several times; then the gamma ray fluxes from the reactions considered will become comparable. In interaction of accelerated He nuclei with He nuclei of the solar atmosphere, such light elements as Li and Be can also arise. Here these nuclei can be a source of gamma rays with energy 0.433 MeV and 0.478 MeV. This process has been considered in Ref. 70. In this case also the synthesis of elements is dominant as a source of gamma rays in the region of energies of the gamma rays arising in excitation of light elements. In addition to the fact that these nuclei will be produced in the region of a flare as the result of reactions between helium nuclei, they can arise also as the result of reactions between nuclei of intermediate atomic weight and reactions produced by energetic protons interacting with the most abundant atoms of the solar atmosphere.

During a flare as the result of nuclear reactions there is formed such a large quantity of light nuclei that it is comparable with the natural concentration of these elements in the Sun.[71] Here the secondary nuclei turn out in great part to be excited and are a source of gamma rays with $E_\gamma = 0.433$ and 0.478 MeV.

f) Annihilation of positrons and gamma radiation

In nuclear reactions in the region of a flare there are numerous possibilities for production of positrons of various energies.[72,73] This may occur as the result of interaction of energetic protons with hydrogen of the solar atmosphere, when positrons with energies of tens of MeV arise, or as a result of nuclear reactions of energetic protons with heavier nuclei of the solar atmosphere, in which radioactive nuclei with positron decay will be produced. It may occur also in synthesis of elements as the result of interaction of the most abundant nuclei of the solar atmosphere with the nuclei of solar cosmic rays. In Table III we give the reactions of these types which are most important as sources of positrons in solar flares.

Since the experimentally observed spectrum of accelerated particles in a flare extends from tens of keV to hundreds of MeV, and sometimes even to tens of GeV, the role of the various nuclear reactions in positron production will be different for different flares. For example, for very low energies the main source of positrons will be radiative capture of protons and element-synthesis reactions. With increase of the energy up to 300 MeV, reactions such as pn, ppn, and others become more and more important. At energies above 300 MeV the production and subsequent decay of π^+ mesons also begins to become important.

TABLE III.

Reaction	Half-life T, sec	Maximum energy of positrons, MeV	Reaction	Half-life T, sec	Maximum energy of positrons, MeV
$^{12}C\,(p,\gamma)\,^{13}N$	600	1.2	$^{12}C\,(ppn)\,^{11}C$	1242	0.968
$^{14}N\,(p,\gamma)\,^{15}O$	123	1.73	$^{14}N\,(ppn)\,^{13}N$	600	1.2
$^{16}O\,(p,\gamma)\,^{17}F$	66	1.747	$^{16}O\,(ppn)\,^{15}O$	123	1.73
$^{20}Ne\,(p,\gamma)\,^{21}Na$	23	2.51	$^{20}Ne\,(ppn)\,^{19}Ne$	16.72	2.24
$^{24}Mg\,(p,\gamma)\,^{25}Al$	7.24	3.24	$^{24}Mg\,(ppn)\,^{23}Mg$	12.1	3.1
$^{28}Si\,(p,\gamma)\,^{29}P$	4.2	3.945	$^{28}Si\,(p, pn)\,^{27}Si$	4.33	3.85
$^{32}S\,(p,\gamma)\,^{33}Cl$	2.5	4.51	$^{32}S\,(ppn)\,^{31}S$	2.61	4.39
$^{12}C\,(pn)\,^{12}N$	10^{-2}	16.38	$^{12}C\,(px)\,^{10}C$	19.48	1.865
$^{14}N\,(pn)\,^{14}O$	71	4.08	$^{14}N\,(px)\,^{10}C$		
$^{20}Ne\,(pn)\,^{20}Na$	0.39	12.7	$^{16}O\,(px)\,^{10}C$		
$^{24}Mg\,(pn)\,^{24}Al$	2.1	8.74	$^{16}O\,(^{16}Ox)\,^{29}S$	0.2	
$^{28}Si\,(pn)\,^{28}P$	0.28	10.6	$^{16}O\,(^{12}Cx)\,^{27}Si$	4	3.76
$^{32}S\,(pn)\,^{32}Cl$	0.31	9.46			

Taking into account the reactions considered, we can write an expression for the concentration of positrons in the region of a flare:

$$n_{e^+}(t) = 4\pi\Big[n_H \int I_p(E,t)\,\sigma_{pH}(E)\,dE + \sum_k \frac{1}{2T_k} \sum_{j,i} n_i \int I_j(E,t)\,\sigma_{ji}(E)\,dE\Big], \quad (1.12)$$

where $n_{e^+}(t)$ is the concentration of positrons, n_H and n_i are the concentrations of nuclei of various types in the solar atmosphere, $I_p(E,t)$ is the intensity of protons in the flare $I_j(E,t)$ is the intensity of nuclei of type j accelerated in the flare, and T_k is the half-life of the radioactive nucleus which arises.

It is known that the annihilation of positrons is unlikely as long as they have appreciable energy. In view of this we can assume that positrons produced during a solar flare will be annihilated after they reach thermal equilibrium with the medium. Then the annihilation process is a source of gamma rays with energy 0.511 MeV.

Comparison of the first and second terms of Eq. (1.12) shows that, depending on the depth to which energetic protons penetrate in the solar atmosphere, the main source of the positrons can be either the pp reaction or the synthesis of nuclei with production of positron-active nuclei.[74]

For example, in Table IV we compare the role of these two positron sources as a function of the exponent of the integral spectrum of accelerated particles.

The results shown in Table IV are suitable for the thin-source model and for the model in which interaction with solar matter occurs in the same volume and during the same time for all solar cosmic ray nuclei.[74] This can occur if the accelerated particles are retained in a closed volume and the energy loss for the low-energy part of the spectrum is compensated by an acceleration process which continues during this time.

We emphasize that the total thickness of matter traversed by fast particles in this model can be large.

As can be seen from Table IV, in these models the role of nucleus-nucleus interactions in positron production is important up to spectral exponent values $S = 2$. In the case in which energetic protons penetrate to great depths of the solar atmosphere, the main source of protons will be the pp interaction.

As will be seen in Sec. 3, this permits one to determine, on the basis of the value of the spectral exponent, the concentration of matter at the depth of the ef-

TABLE IV.

S	1	2	2.2	2.5	3	4	5
$\frac{n_{e^+}(i,j)}{n_{e^+}(pp)}$	10^{-3}	0.32	$\geqslant 1$	6.4	128	$5\cdot 10^4$	$2\cdot 10^7$

ficient nuclear interaction of protons of solar cosmic rays with the material of the solar atmosphere. We note here further that, depending on which nuclear processes in a given flare are the suppliers of positrons, the magnitude of the flux of annihilation radiation will be different. If the main role is played by pp interactions, this means that the interaction occurs at depths to which the low-energy component of solar cosmic rays does not penetrate, and the flux of gamma rays with $E_\gamma = 0.511$ MeV may be one of the highest fluxes. In the opposite case the flux of annihilation gamma rays may be comparable with the fluxes of gamma rays of other energies (for example, with $E_\gamma = 4.43$ MeV), or it may be significantly less. This may explain the fact that gamma fluxes with $E_\gamma = 0.511$ MeV are not recorded in all flares for which gamma rays have been observed.

2. GAMMA RADIATION OF SOLAR FLARES. CONTINUOUS SPECTRUM

The continuous spectrum of gamma rays of the Sun and solar flares can be produced by a number of factors.

First, it can be due to the radiation of energetic electrons and protons in their motion in the solar atmosphere.

Second, it can be due to generation of a line spectrum by accelerated nuclei on interaction with atoms of the solar atmosphere.[75] Since the radiating nuclei are themselves in motion with comparatively high velocities, the line spectrum of the radiation will be substantially smeared. The broadening of the lines may turn out to be so significant that the gamma lines will overlap; this also leads to the observation in practice of a continuous spectrum.

Third, the continuous spectrum of gamma rays can arise as a result of the fact that in excitation of the nuclei of the atoms of the solar atmosphere the number of lines will be so large and they will be placed so closely that it is not possible in practice to resolve these lines.

a) Role of electrons in production of the continuous gamma ray spectrum

The mechanisms of generation of a continuous spectrum of electromagnetic radiation by electrons have been discussed by Ginzburg and Syrovatskiĭ.[76] In the motion of electrons in the Sun's atmosphere the decrease of their energy is due to ionization loss, bremsstrahlung, synchrotron radiation, and Compton scattering. At the present time it is known that the magnetic fields in the Sun may reach 100–1000 Oe.[77] However, even in such strong fields the radiation of energetic electrons will lie in the radio region of wavelengths.

In motion of energetic electrons in the Sun's atmosphere, where the photon density is $1.6\cdot 10^{12}$ cm^{-3}, for a magnetic field strength $H \leqslant 4-5$ Oe the synchrotron radiation loss becomes less than the loss by inverse Compton effect.

The average energy transferred to a photon in the Compton effect is $\Delta E = \overline{\mathscr{E}}(E/mc^2)^2$, where $\overline{\mathscr{E}}$ is the average energy of the thermal photons. For the Sun $\overline{\mathscr{E}} \approx 1$ eV; therefore even at an electron energy $E = 100$ MeV the average energy of the photon which arises is 40 keV. Photons of this energy are assigned to the nonthermal x radiation of the Sun.

Thus, the only mechanism in which energetic electrons can produce gamma rays with energy $E_\gamma \geqslant 0.5-1$ MeV is bremsstahlung. The probability of this process in solar flares for an electron energy $\geqslant 1$ MeV is of the order of 10^{-5}.

b) The role of protons in production of the continuous gamma ray spectrum

Bremsstrahlung from protons of solar cosmic rays will arise both in interaction of the protons with electrons[78,79] and in interaction with the nuclei of the solar atmosphere, mainly with hydrogen. The efficiency of the first process is determined by the fact that protons with energy $E \geqslant 1$ MeV in solar cosmic rays are more abundant than electrons of the same energy by about one hundred times. However, as a result of the rapid decrease of the cross section with increase of energy, this process is mainly a source of protons in the x-ray region.[78,79]

In contrast to this process, proton-proton bremsstrahlung will be a source of gamma rays over a wide range of energies. The spectrum of bremsstrahlung will be determined by the expression

$$n_\gamma(E_\gamma) = 4\pi n_{\rm H} \int_{E_1}^{E_2} I_{\rm p}(E)\,\sigma(E,\ E_\gamma)\,{\rm d}E, \tag{2.1}$$

where $n_\gamma(E_\gamma)$ and $I_p(E)$ are the differential concentration and intensity of gamma rays and protons, respectively, and $\sigma(E, E_\gamma)$ is the cross section for interaction of a proton of energy E with production of a photon of energy E_γ. If the hydrogen concentration $n_{\rm H}$ and I_p are constant over the entire volume considered, then the total number of gamma rays will be determined by multiplication by the volume. Otherwise it is necessary to use an expression similar to Eq. (1.3).

Of course, bremsstrahlung from fast protons arises also in interaction with heavier nuclei. However, the concentration of heavy nuclei in the Sun's atmosphere is small, so that in practice it is necessary to take into account in addition to hydrogen only helium nuclei.

It is feasible to take into account proton bremsstrahlung only for photon energies above 20 MeV, since in the lower energy region the bremsstrahlung of electrons accelerated in solar flares will be more efficient.

On the other hand, gamma rays in the region $E_\gamma > 20$ MeV are provided not only by proton-proton bremsstrahlung if, of course, the spectrum of accelerated particles extends to sufficiently high energies.

Proton-proton interactions are a source of continuous gamma rays in the photon energy region above 20 MeV also as the result of production in such reactions of π^0 mesons. In fact, for protons with $E > 300$ MeV the cross section for production of π^0 mesons becomes appreciable and one cannot neglect proton-proton bremsstrahlung as a source of high-energy gamma rays.

Thus, while the bremsstrahlung cross section for photons with $E_\gamma > 30$ MeV is 0.5 mb for a proton energy 200 MeV and does not exceed a few millibarns at higher energies,[80] the cross section for production of π^0 mesons rises rapidly and is actually comparable with the total cross section for inelastic interaction, which reaches 30 mb.

Thus, in the γ-ray energy region above 20–30 MeV an important source is the inelastic interaction with production of π^0 mesons and their subsequent decay.

In principle this process can be distinguished on the basis of the characteristic spectrum of the gamma radiation. Thus, it follows from the kinematics of decay of the π^0 meson that the gamma ray spectrum will have a maximum in the energy region ≈70 MeV with a steep drop in the low energy region and a slower falloff on the high energy side.

The flux of such gamma rays can be determined from a formula similar to Eq. (1.3) for various spectra of accelerated protons and for various models of a flare, that is, for various conditions of emission of the energetic particles from the region of acceleration. Here in the case of emission of accelerated particles in the direction of the Sun the production of π^0 mesons is the main source of gamma rays with $E_\gamma > 20$ MeV.[81]

Using the formulas which determine the gamma radiation of various energies, we can compare the possible gamma fluxes from flares. Thus, the relative magnitude of the gamma ray flux due to π^0-meson decay F_γ^π in comparison with such an intense source as the line radiation F_γ' in excitation of the most abundant elements of the solar atmosphere is

$$\frac{F_\gamma^\pi}{F_\gamma'} = \frac{n_{\mathrm{H}}}{\sum_i n_i} \frac{\int_{E_1}^{\infty} I_{\mathrm{p}}(E)\, \sigma_{\mathrm{pH}}^{\pi}(E)\, \mathrm{d}E}{\int_{E_2}^{\infty} I_{\mathrm{p}}(E)\, \sigma_{\mathrm{p}i}^{\gamma}(E)\, \mathrm{d}E} \qquad (2.2)$$

in the case when the processes considered occur in the same region.

If the average thicknesses of matter traversed by particles of different energy is different, then the relative fraction of high-energy gamma rays increases.

This is due to the fact that the main contribution to the gamma ray line spectrum is from protons with energy from the threshold of excitation of the level, E_2, to the threshold for production of π^0 mesons, E_1. (Actually even the contribution of protons with $E > 100$ MeV to production of the line spectrum is already small.) Thus, the ranges of the protons which efficiently produce different reactions are different.

Using the necessary information on the concentration of the elements and also on the cross sections, we find that F_γ^π / F_γ' is no less than 10^{-3} for an integral-spectrum exponent of the generated particles $S = 2$.

This is an important number, since it tells us that for large events such as the flares of February 1956 or those of August 1972 the flux of gamma rays with $E_\gamma > 20$ MeV should be definitely observable with presently possible experimental arrangements.

c) Excitation of nuclei and appearance of the quasicontinuous gamma ray spectrum of a flare

The nuclear processes discussed above are sources of the continuous gamma ray spectrum. However, in the case of solar flares a situation can arise in which an essentially continuous spectrum can be observed although the gamma ray source will be excited nuclei.

The charge spectrum of accelerated particles from a flare includes a tremendous range, up to nuclei of the iron group. The interaction of these fast nuclei with the hydrogen of the solar atmosphere also leads to their excitation. As a result of the fact that the gamma ray sources now are moving with relativistic velocities, the Doppler effect will lead to a change of the gamma ray energy by an amount $\Delta E_\gamma / E_{\gamma 0} = 0.7-1.4$, depending on the direction of motion of the radiating nucleus, if its energy is of the order of tens of MeV/nucleon. Then the individual lines will be substantially broadened and one can have overlapping of lines and the appearance of an apparently continuous spectrum. In Ref. 75 it was shown that this process can explain the continuous gamma radiation from the flare of 4 August 1972 in the region of several MeV. The overlapping of individual lines in the radiation of excited fast nuclei and excited nuclei of the solar atmosphere was utilized in Ref. 82 to explain the intensity of gamma radiation in the region $E_\gamma = 4-8$ MeV observed for this same flare.

d) Background of solar gamma rays and general remarks on the gamma ray spectrum of the Sun

In connection with the study of gamma radiation from flares of various sizes, the question naturally arises of the background gamma radiation of the Sun, that is, the radiation which is observed with a quiet Sun.

The Sun, as is thought at present, can be a continuous source of protons with energy of several MeV and electrons with energy not exceeding tens of keV (see for example Refs. 83 and 84 and references cited therein).

Electrons of this energy cannot contribute to the Sun's gamma radiation. Protons with energy of a few MeV produce a gamma-ray flux from the quiet Sun as the result of the radiative-capture reaction and the possibility of exciting low-energy levels in the nuclei of the solar atmosphere.

These reactions do not provide a gamma-ray background flux in the photon energy range of the order of several MeV to an extent larger than 10^{-10} cm$^{-2}\cdot$sec^{-1}.

Here we must keep in mind that if in the course of the cyclical variations of the solar activity the particle fluxes from the quiet Sun increase (both in magnitude and in their maximum energy), the role of the reactions mentioned as sources of background fluxes and radiation naturally increases. An analysis of this type was carried out in Refs. 85 and 86, which discussed the generation of gamma rays by electrons and by nuclei excited in inelastic scattering of protons in weak solar flares and in the quiet Sun.

In addition to the possibilities discussed above for the gamma radiation of the quiet Sun, there is another source of background gamma rays which is sufficiently intense to be observed in contemporary experiments but which is again due to flares.[87] It is clear that during a flare as the result of nuclear reactions there will be produced not only stable nuclei, but also radioactive ones. These can occur both in the composition of solar cosmic rays and in the solar atmosphere.[16,88] Among the radioactive nuclei we shall be interested in those in which electromagnetic transitions occur. Since the half-life of the nuclei can be substantial, an equilibrium content of radioactive nuclei should be established in the Sun, which in turn will be responsible for the existence of some background gamma radiation from the Sun.

Let $N_i(t)$ be the number of nuclei of type i in the Sun. Then the change in these nuclei will be determined by the following equation:

$$\frac{dN_i}{dt} + \Lambda_i(t) N_i = A_i(t), \tag{2.3}$$

where $\Lambda_i(t)$ characterizes the rate of decrease of nuclei of type i.

If the half-life of the nuclei does not exceed a few years, the decrease of the concentration of radioactive nuclei in the Sun will be determined by their rate of decay and $A_i(t)$ is the rate of production of particles of type i. If ψ flares arise simultaneously, then $A_i = \sum_\psi a_i/T$, where

$$a_i = \sum_{k,\,j} \frac{n_j}{n_H} \int N_k(E) \frac{\sigma_{kj}^i(E)}{\sigma_{kj}(E)} \frac{x_k(E)}{\lambda_k(E)} \, dE \tag{2.4}$$

is the total number of particles produced in one flare in interaction of nuclei of types k and j, and T is the duration of the flare. Taking the average rate of formation of particles in various flares to be identical, we obtain $A_i = (a_i/T)\psi$. Then the asymptotic behavior of the solution of Eq. (2.4) has the form $N_i(t) \to a_i\psi/\Lambda_i T$.

Taking into account all these quantities from the asymptotic behavior of the solution, we find that the production and subsequent decay of radioactive elements can provide a background flux of gamma radiation from the Sun in the energy range from 0.5 to 3 MeV in the range $10^{-7} \leq F_\gamma < 10^{-5}$ cm$^{-2}\cdot$sec^{-1}.[87]

In Table V below we have given the results of calculation of the background flux from individual radioactive nuclei.

Attempts at experimental determination of the background gamma radiation of the Sun have been carried out repeatedly over a number of years. A review of the data for $0.1 \leq E_\gamma \leq 10$ MeV obtained up to 1973 can be found in Ref. 91. From these data it is possible, unfortunately, to determine only an upper limit, which, depending on the gamma-ray energy, is at the level of 10^{-2}–10^{-5} cm$^{-2}\cdot$sec^{-1}. At the present time no new results are being reported in the literature on measurement of the background flux of solar gamma rays in this energy range.

The possible background of the Sun in the high-energy region should be determined primarily by interaction of Galactic cosmic rays with the Sun's atmosphere.

TABLE V. Possible background flux at the Earth of solar gamma radiation produced by individual nuclei.

Nucleus	Half-life	γ-ray energy, MeV	Flux at Earth, cm^{-2} sec^{-1}	Nucleus	Half-life	γ-ray energy, Mev	Flux at Earth, cm^{-2} sec^{-1}
^{22}Na	2.58 years	0.511 1.28	10^{-6}—10^{-8}	^{56}Co	71.3 days	0.511 0.845 1.24	10^{-5}—10^{-8}
^{24}Na	14.9 hours	1.37 2.75	10^{-8}—10^{-10}	^{60}Co	5.27 years	1.17 1.33	10^{-12}—10^{-14}
^{26}Al	10^6 years	0.51 1.83	10^{-7}—10^{-9}				

The range of values of the flux is determined mainly by the spread of the data on the concentration of the elements in the Sun, on the total number of accelerated particles, and on the duration of the flare. For a specific calculation we considered flares of magnitude ≥1. Then $\psi = 10^{-4}$, $N_p = 10^{33}$–10^{34} for $E_p \geq 1$ MeV.[89] In Ref. 90 an estimate was made of the possible flux of gamma rays from the Sun with $E_\gamma = 1.28$ MeV. For various spectra of accelerated particles values $F_\gamma = 10^{-2}$–10^{-5} cm$^{-2}\cdot$sec^{-1} were obtained. However, the total number of particles accelerated in the flares was overestimated in Ref. 90.

Determination of the background gamma-ray flux in the region $E_\gamma > 70$ MeV would permit one to obtain the intensity of Galactic cosmic rays near the Sun. Unfortunately, there is so far only an upper limit for the gamma-ray flux with $E_\gamma > 100$ MeV. According to a number of studies[92] it amounts to $(1$–$4)\cdot 10^{-5}$ cm$^{-2}\cdot$sec^{-1}.

In the preceding sections we have discussed various processes which lead to generation of gamma rays during solar flares. It is clear that in various gamma-ray energy ranges the efficiencies of different mechanisms are different. This leads to the following important conclusion: in experimental study of the gamma-ray spectrum from the Sun it is necessary to expect numerous irregularities. Description of the gamma-ray spectrum by a single analytic function will be impossible.

In addition to this common type of irregularities, in the gamma ray energy region below 20 MeV one must expect strong irregularities as the consequence of the different intensities of the radiation in the individual lines. Since the relative intensity of the gamma-ray lines depends on the relative concentration of the different elements in the region of the flare, we must expect arbitrary differences in the relative intensity of individual lines for various flares.

3. INVESTIGATION OF THE GENERATION OF SOLAR COSMIC RAYS BY THE METHODS OF GAMMA SPECTROSCOPY

Observation of the gamma radiation of solar flares opens new possibilities to investigators of solar cosmic rays and the various physical processes occurring in the Sun's atmosphere, since the gamma radiation is associated with the generation and propagation in the Sun's atmosphere of just the nuclear component, which does not appear in other forms of electromagnetic radiation of the Sun.

Analysis of these possibilities is the subject of the present chapter.

a) Determination of the moment and duration of the generation of particles in flares

The nature of the initial period of detection of gamma radiation will depend substantially on the rate of acceleration of the particles and on the nature of evolution of the spectrum of accelerated particles in the initial stage of acceleration.

In Section 1 we showed that excitation of gamma lines occurs with sufficient intensity in nucleus-nucleus interactions. It must be taken into account that while the cross section for excitation of levels in proton-nucleus interactions in the most abundant nuclei of the solar atmosphere has a maximum of ~100–200 mb at $E_p \approx 10$ MeV, the nuclei themselves enter into the interaction already at an energy of the order of 1 MeV/nucleon, which leads to the synthesis of new nuclei and to the radiation of gamma rays. Here the cross section for this interaction frequently exceeds 100 mb.

In view of this, the initial phase of gamma radiation can proceed as follows: if the particle acceleration process occupies a short time, the most intense lines of the gamma radiation will be the excitation lines of the most abundant elements in the Sun, such as oxygen and carbon; if the rate of acceleration is sufficiently small, then initially the greatest flux will be observed for gamma rays with energy less than 2.5 MeV (here nucleus-nucleus interactions provide a large contribution), and subsequently a flux will be observed for gamma rays with energy 4.4 and 6.14 MeV, i.e., with passage of time one will observe not only an increase of the intensity of gamma radiation but also a transition of the maximum intensity of radiation from photons with lower energy to photons with higher energy.

A similar phenomenon can be associated with the change of the spectral exponent in the particle acceleration process in the particle energy region less than 100 MeV. Thus, depending on the increase or decrease of the spectral exponent of the particles, the gamma intensity will decrease or increase. This is important to keep in mind in view of the fact that according to the experimental data the spectra of solar cosmic rays observed on the Earth in the region $E < 10$ MeV differ from flare to flare. On the other hand, evolution of the spectrum in the energy region greater than 100 MeV has practically no effect on the intensity of the line spectrum of gamma radiation, as the result of the rapid decrease of the inelastic scattering cross section and the falling shape of the spectrum.

Since gamma radiation in lines as the result of inelastic scattering occurs in practice instantaneously, it is natural to expect that the duration of this observation will indicate the time for which the energetic particles are present in the rather dense layers of the Sun's atmosphere. However, the time determined in this way cannot be considered to be the particle-generation time. This would be the case if the emission of the particles into the interplanetary medium occurred in a comparatively short time. The duration of the retention of the particles in the Sun is not accurately known. Various estimates show that this time may be several minutes.[1] In principle we can hope to determine the duration of particle generation during a flare with this accuracy.

b) Annihilation of positrons and determination of the parameters of the flare region

Positrons arising in the nuclear reactions discussed above will eventually annihilate with electrons of the solar plasma. Here the annihilation process will occur essentially after the positrons reach thermal equilibrium with the surrounding medium.

For this reason the observation of annihilation gamma rays provides the possibility of estimating the density and temperature of the region of the flare. The broadening of a line as the result of the Doppler effect is $\Delta\gamma/\gamma = \sqrt{2E/mc^2}$. It can be seen from this that for an annihilation-region temperature of 10^4–10^7 °K the amount of broadening is 0.1–3%, i.e., it is quite sufficient to permit determination of the temperature of the annihilation region.

The density of the medium in which the annihilation of the positrons occurs can be determined from the time pattern of change of intensity of the annihilation line. The lifetime against annihilation of a positron of thermal energy is $\tau = (n_e \sigma v)^{-1}$, where $\sigma = \pi r_0^2 c/v$ is the annihilation cross section[93] and r_0 is the classical electron radius. For thermal positrons $\tau = 1.3 \cdot 10^{14} n_e^{-1}$. If the time between the beginning of nuclear interactions (defined, for example, as the moment of observation of gamma radiation from excited nuclei) and the observation of the annihilation is t, then it is clear that it is greater than τ, from which we also obtain an estimate of the density of the medium in which the annihilation occurs.

For the flare of 4 August 1972 the time t did not exceed 100 sec.[21,27] It follows from this that the concentration of electrons in the region where annihilation occurred was at least $n_e = 10^{12}$ cm^{-3}, and this means that the concentration of material is definitely greater than 10^{12} cm^{-3}. On the basis of the experimentally observed line for this flare it was possible to determine the temperature of the flare region, which did not exceed 10^7 °K.[73,94]

Above (in subsection f of Sec. 1) we stated that the average density of matter in the region where the pp reaction occurs efficiently can be determined from comparison of the flux of annihilation radiation and the flux of gamma rays with energy, for example, of 4.43 MeV. In fact, for the flare of 4 August 1972 the spectral exponent of the acceleration particles was $S = 2$–2.5.[2,82] In order to understand the observed flux of gamma rays with $E_\gamma = 0.511$ MeV, which is about twice the flux of gamma rays with $E_\gamma = 4.43$ MeV, it is necessary to assume [according to Table IV and Eq. (1.12)] that the main source of positrons in this event was interaction of energetic protons with hydrogen of the solar atmosphere, and the average concentration of matter in the region of this interaction was approximately two orders of magnitude higher than the average concentration of matter in the region of emission of the gamma rays with $E_\gamma = 4.43$ MeV. According to Eq. (1.5) n_H in the region of generation of the 4.43-MeV gamma rays was $5\cdot 10^{12}$ cm^{-3}, from which the average value of n_H for the region of generation of annihilation radiation will be $5\cdot 10^{14}$ cm^{-3}. For these estimates we made use of the value obtained in Ref. 89 of the total number of protons accelerated in the flare under discussion.

c) Analysis of the energy spectrum of accelerated particles on the basis of the gamma radiation from a flare

The gamma-ray intensity in the lines permits us to determine a number of facts regarding the energy spectrum of particles in flares. Let us rewrite Eq. (1.5) in the following form:

$$N_p(\geqslant E_1) = \int_{E_1}^{\infty} N_p(E)\,dE = \frac{4\pi r^2}{P(E_h, E_1)\,n_i}\,\frac{F_\gamma}{\langle\sigma_{pi}^\gamma\lambda_p\rangle}, \qquad (3.1)$$

where $\langle\sigma_{pi}^\gamma\lambda_p\rangle$ is the average value of the product of the cross section and range of the proton before interaction and $N_p(\geqslant E_1)$ is the total number of protons with energy $\geqslant E_1$ which have been accelerated in the flare. It must be noted that the greatest uncertainty in Eq. (3.1) is in the value of n_i (it can vary by several times). In this way the gamma-ray line spectrum permits us already at the present time to determine with high accuracy the total number of particles in the region of gamma-ray generation.

How important this is can be illustrated by the following example, which has considerable value for understanding also the nature of the emission of particles into the interplanetary medium and their propagation in it.

Usually detection of the particles of solar cosmic rays occurs in a single cosmic-ray apparatus, and more rarely in several, located close together around the Sun. In this case the problem of determining the total number of accelerated particles always involves some kind of assumptions regarding the isotropy of the particle distribution in interplanetary space. For example, it is necessary to assume that in some specific event considered the particles occupy a spherical volume with a radius of an astronomical unit or, on the other hand, to assume that the volume filled by solar cosmic rays consists of a cone or a tube.

In any case there are very few indications of the justification of this or that assumption. Accordingly the accuracy of the estimates obtained is as a rule an order of magnitude and sometimes perhaps even worse. For this reason it is difficult to determine with better accuracy, for example, such an important parameter of a flare as its total energy.

Determination of $N_p(\geqslant E_1)$ according to Eq. (3.1) permits independent evaluation of this quantity and provides the possibility of comparing the two methods.

In addition it is clear that an independent determination of $N_p(\geqslant E_1)$, possibly on the basis of gamma radiation, will permit also a more complete elucidation of questions related to the distribution of solar cosmic rays in interplanetary space.

Then, in addition to determination of the integral number of accelerated particles, the gamma radiation will permit determination also of the spectral characteristics of these particles. Thus, $N_p(E)dE$ is the differential spectrum of protons, which according to current ideas can be represented in the form either of a power function or of an exponential.

The parameters of this distribution can be evaluated from data on gamma lines.

For example, if $N_p(E)dE = AE^{-S}dE$, then we have for determination of the two parameters A and S the following equations, obtained in detection, for example, of the 4.43 MeV and 6.14 MeV lines:

$$F_\gamma(4.43) = \frac{n_{^{12}C}}{4\pi r^2} A \int E^{-S}\sigma^\gamma_{p\,^{12}C}(E)\,\lambda_p(E)\,dE, \qquad (3.2)$$

$$F_\gamma(6.14) = \frac{n_{^{16}O}}{4\pi r^2} A \int E^{-S}\sigma^\gamma_{p\,^{16}O}(E)\,\lambda_p(E)\,dE. \qquad (3.3)$$

It is clear that the parameter S can be determined with an accuracy no worse than the accuracy of determination of the ratio of the gamma-ray fluxes, since the remaining quantities which enter into these expressions are known sufficiently well. Similar discussions are applicable also for another form of functional dependence of the differential spectrum.

In addition, observation of gamma radiation in a sufficiently large number of lines will permit one to learn, possibly, the most important aspect of the acceleration process, related to the acceleration mechanism. The point is that in observation of several individual lines spread over a broad energy interval it will be possible to discover the functional form of the spectral distribution of the generated particles and consequently also the acceleration mechanism which produces this form of spectrum.

Studies of the gamma radiation of flares can provide a variety of information also on the high-energy part of the accelerated-particle spectrum. Gamma radiation with $\gamma \geqslant 20$ MeV has not been observed in solar flares up to this time. However, as follows from Eq. (2.2), we have $F_\gamma^\pi/F_\gamma' \approx 10^{-3}$ if F_γ' is the flux of gamma rays with $E_\gamma = 4.43$ MeV. (The threshold for excitation of this level has been taken as 5 MeV/nucleon.) This quantity is rather large and can be observed in present-day experiments.[95] We note that this ratio is hardly overestimated, since in a number of flares the differential spectrum of particles has a bend in the 10-MeV energy region, so that $N_p(>E)$ may turn out to be less than the value assumed.

In connection with the value obtained for the ratio F_γ^π/F_γ' we must note two consequences which are important for the physics of solar cosmic rays. The failure to observe gamma rays with $E_\gamma \geqslant 20$ MeV or the decrease of the above ratio would mean the following. Either the spectrum of accelerated particles at energies of several hundred MeV is cut off or undergoes an appreciable bend, or the generation of low-energy particles and high-energy particles occurs with substantially different concentrations of matter and substantially different conditions of emission from the exploration region. Thus, according to the data of Refs. 96 and 97 the moment of generation of relativistic protons in flares, determined from detection of the first arrival of these particles at the Earth, does not coincide with the moment of generation of the gamma rays in these flares, but is delayed with respect to it by 8–10 minutes. In these studies this fact is interpreted as proof of capture of particles of this energy and retainment of them in a trap in the Sun for a definite time. On the other hand, however, there are experimental facts and theoretical reasons[98,99] which indicate that the relatistic protons arise later than the nonrelativistic ones and at a point which is high in the corona or even in interplanetary space.

If this is the case, then the moment of detection of high-energy gamma radiation should be delayed relative to the moment of detection of the gamma radiation, for example, in individual lines. Furthermore, if relativistic particles arise under other conditions than those under which nonrelativistic particles appear, it is very likely that also the conditions of their ejection from the acceleration region are different. For example, they easily depart into interplanetary space and do not penetrate to great depths of the solar atmosphere. Measurement of F_γ^π/F_γ^l simultaneously with measurement of the accelerated-particle spectrum will help to solve this question.

We note that annihilation gamma radiation was observed during the time of the flares of 4 and 7 August 1972. Here, as we mentioned above, the source of positrons for the event of August 4 (and possibly also for the event of August 7) was most likely the pp reaction. Then the efficiency of production of π^0 mesons (and consequently also of high-energy gamma rays) should be no less than the efficiency of production of π^+ mesons. Unfortunately there are no experimental data on high-energy gamma rays for these events.

d) Gamma radiation of a flare in synthesis of elements and existence of preferential acceleration of heavy nuclei in solar cosmic rays

In subsection e of Sec. 1 we showed that for a number of lines in the gamma radiation of a flare the most important source will be the formation of excited nuclei in synthesis of these nuclei from other nuclei which, as a rule, are more abundant in the Sun's atmosphere.

This result permits one to hope that the corresponding gamma radiation can be used to determine the subsequent characteristics of the region of the flare and of the processes occurring there.

Since the gamma-ray flux of a given energy at the Earth is $F_\gamma = n_i^\gamma V/4\pi r^2$, where V is the radiating volume and n_i^γ is the concentration of synthesized excited nuclei, it is clear that from data on F_γ one can determine the quantity $n_i^\gamma V$ and also the relative efficiency of synthesis of various nuclei in flares if several gamma lines are observed.

By analogy with the formulas of subsection c of Sec. 1 we can write down as exact expression for the ratio of the concentration of gamma rays generated per second in synthesis of nuclei of type i from nuclei of types j and k to the concentration of gamma rays generated per second in inelastic interaction of protons with nuclei, as follows:

$$\frac{n_{jk}^\gamma}{n_{\mathrm{p}i}^\gamma} = \frac{\sum\limits_{j,k} n_k \int I_j(E)\,\sigma_{jk}^\gamma(E)\,\mathrm{d}E}{n_i \int I_\mathrm{p}(E)\,\sigma_{\mathrm{p}i}^\gamma(E)\,\mathrm{d}E}. \tag{3.4}$$

It is evident from this that from data on the intensity of gamma lines, one of which is emitted by the synthesized nucleus and the other in excitation of the primary nucleus by the proton, one can find the ratio I_j/I_p in the region of generation of the gamma rays, i.e., one can determine whether or not there is preferential acceleration of heavy nuclei of type j during the flare.[69]

e) Gamma radiation and the conditions of emission of solar cosmic rays into interplanetary space

In subsection c of this section we have shown that on the basis of the gamma radiation it is possible to determine the spectrum of accelerated particles and the total number of particles left in the Sun. This information in turn permits elucidation of the following question: What fraction of the total number of accelerated particles is represented by the energetic particles observed in interplanetary space after a flare, i.e., what are the conditions of emission of the accelerated particles into the interplanetary medium? These conditions are undoubtedly determined by the geometry of the magnetic fields of the active region in which the flare occurred,[9] and for the electron component according to Ref. 100 the fraction of electrons ejected into interplanetary space does not exceed a few percent of the total number in the flare. There are indications, however, that the fraction of electrons emitted into interplanetary space may amount to several tens of percent.[101] This is indicated also by the analysis carried out in Ref. 102 of the relation between the value of the x-ray flux of a flare and its total energy. It follows from this analysis that the fraction of electrons emitted into interplanetary space apparently has a regular dependence on the total energy of the flare.

For the proton component a similar analysis was carried out on the basis of information on gamma rays with $E_\gamma = 2.2$ MeV in the flare of 4 August 1972.[89] It was found that the number of protons left in the Sun with energy more than 1 MeV in flares of this class is $\approx 10^{36}$.

The number of protons ejected during a flare into interplanetary space can be determined as $N_\mathrm{p} = \int F_\mathrm{p} dS$, where F_p is the total flux of protons through an area of 1 cm^2 during the entire time of the flare. For the August event the total flux of protons with energy 1–5 MeV at the Earth's orbit was $2\cdot 10^9$ particles.[103] Then $N_\mathrm{p}(E \geqslant 1\ \mathrm{MeV}) \approx 10^{37}$ particles if we assume that F_p depends only weakly on angle. The actual number of particles ejected into interplanetary space should be reduced, since in the 4 August 1972 event the particles occupied only a part of the sphere with radius one astronomical unit. Consequently the number of particles emitted into interplanetary space is comparable in order of magnitude with the number of particles which remain in the Sun.

f) Determination of the nuclear composition of the solar atmosphere from the gamma-ray spectrum

The gamma-ray line spectrum of flares carries information on the nuclear composition of the flare region.[25] In fact, since the intensity of gamma rays in a given line is

$$I_\gamma(E_2)=\frac{P(E_1,E_2)}{4\pi r^2}n_i\int N_p(E)\,\sigma^{\gamma}_{pi}(E)\,\lambda_p(E)\,dE, \qquad (3.5)$$

by observing, for example, the strongest lines arising in inelastic scattering by various elements, we obtain

$$\frac{I_\gamma(E_2)}{I_\gamma(E_2')}=\alpha\frac{n_i}{n_i'}, \qquad (3.6)$$

where the coefficient

$$\alpha=\frac{P(E_1E_2)}{P(E_1'E_2')}\,\frac{\int N_p(E)\,\sigma^{\gamma}_{pi}(E)\,\lambda_p(E)\,dE}{\int N_p(E)\,\sigma^{\gamma}_{ph}(E)\,\lambda_p(E)\,dE} \qquad (3.7)$$

can be calculated since all the quantities and functions entering into it are known.

In this way we can determine the relative nuclear composition of that part of the Sun's atmosphere in which nuclear reactions play a role. It is important in this case to emphasize that gamma spectroscopy can provide information on deeper layers of the solar atmosphere than are accessible to optical spectroscopy.

Absolute values of the concentrations of the various nuclei can be determined from their gamma radiation with an accuracy limited by the information on the accelerated-particle spectrum or, at least, by the accuracy of the total number of particles accelerated in the flare, since the expression for I_γ can be represented in the form

$$I_\gamma(E_2)=\frac{P(E_1E_2)}{4\pi r^2}n_iN_p(>E)\,\langle\sigma^{\gamma}_{pi}\lambda_p\rangle,$$

where $\langle\sigma^{\gamma}_{pi}\lambda_p\rangle$ is the average value of this product.

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