Influence of the temperature of the photosphere and deeper layers of the Sun on the spectra of gamma quanta with energies above 511 keV during solar flares.

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Abstract. Gamma-ray quanta, which occur during solar flares due to the interaction of accelerated protons with the photosphere and deeper layers of the sun, enter interplanetary space from a thickness of several tens of g/cm^2. In the presented work, gamma quanta with energies of more than 511 keV are considered. This makes it possible to exclude from consideration the dependence of the probability of ortho- and parapositronium formation on the temperature and density of the solar matter. And also do not consider the probability of annihilation by two or 3 gamma quanta. Thus, the reactions of thermal neutrons remain dependent on the temperature. As the ambient temperature increases, the average number of elastic neutron scattering before capture increases. This leads to a more likely penetration of neutrons to a greater depth or their departure into the interplanetary space. The high temperature of the Sun below the photosphere may be one of the reasons for the absence of the 2.223 MeV line in solar flares with registered protons in the PAMELA and AMS2 experiments. Using the GEANT4 package, the spectra of gamma-quanta arising in nuclear interactions are calculated. The temperature-dependent features of the gamma-ray spectra are discussed.

1. Introduction

Part of the nuclei accelerated in solar flares (mainly protons) return to the direction of the Sun and interact with the environment. In some nuclear reactions, nuclei are formed in excited states. The excitation is removed by the emission of gamma rays. The annihilation of positrons after beta decay, the decay of neural pions also lead to the appearance of gamma quanta. In the spectra of solar flares, the most intense lines are 511 keV and 2.223 MeV. Less intense lines against the background of a continuous spectrum are observed with the help of devices with high energy resolution. The probability of annihilation of the positron and electron by 2, not 3, gamma quanta depends on the temperature and density. The study of this process requires separate consideration. In this paper, we consider gamma-ray quanta with energies above 511 keV. Temperature can affect the thermalization time of neutrons and the depth of their capture by protons and other nuclei. The depth of formation of gamma quanta affects the number of Compton scattering and thus the rigidity of their spectrum in interplanetary space.

During the period from July 2006 to September 2014, protons with energies above $\sim$80 MeV from 35 solar flares were observed in interplanetary space in the PAMELA and AMS2 experiments [1, 2] . The 2.223 MeV line was detected by instruments that recorded gamma-ray radiation in space during that time period only in one flare [3, 4, 5]. Although there were gamma rays with higher and lower energies including the 511 keV line. In some of these flares, neutrons, isotopes ^{2}H, ^{3}He were detected in the PAMELA experiment. The spectrum of gamma quanta is mainly determined by the spectrum of accelerated ions due to the fact that the cross sections of nuclear reactions depend on the energy. The appearance and interaction of neurons at a depth with an increased ambient temperature, together with other reasons (for example, an increase in the concentration of ^{3}He), may explain the absence of this line in the experimental spectra.

2. Simulation the arise and propagation of gamma-ray radiation during solar flares

Modeling of the occurrence and propagation of gamma-rays during solar flares was carried out using the GEANT4 package [6]. The chemical and isotopic composition is taken from article [7]. The small relative number of atomic nuclei of CNO and heavier ones does not give clearly defined lines. The density distribution over depth for a calm photosphere [8] was used. For deeper layers, we used a model from [9]. Inaccuracy in determining the density-depth relationship may lead to inaccuracy in determining the time of neutron deceleration and capture and the time of their possible decay. In turn, the time shifts of the 2.223 MeV line measured in experiments can provide information about the density and temperature within the framework of a theoretical model. The thickness of the photosphere is much smaller than the average nuclear interaction length of protons, so the time of neutron termalisation is influenced by the parameters of deeper layers. Fig. 1 shows the obtained dependence of the probability of photons with energies of 511 keV and 2.223 MeV entering interplanetary space, depending on the depth of origin. The small kinetic energies of protons and neutrons during the formation of deuterons and the energies of electrons and positrons during annihilation allow us to consider the angular distributions of gamma quanta in the simulation as isotropic. The difference in the Compton scattering cross sections at 511 keV and 2.223 MeV leads to the fact that gamma quanta with the second energy value can come from greater depths, and consequently from layers with a higher temperature.

Fig. 2 shows the change in the neutron energy after elastic scattering before the formation of ^{2}H at the ambient temperature of 6000 K. The number of elastic scattering is determined by the ratio of the elastic scattering and capture cross-sections.

Fig. 3 shows the temperature dependence of the probability of gamma quanta with an energy of 2.223 MeV entering interplanetary space per incident proton. Under the simplifying assumption that the temperature of the solar layers is constant, where the neutrons produced in solar flares and propagate, the probability of gamma-ray quanta with an energy of 2.223 MeV entering interplanetary space is obtained. The anisotropic fall of protons with energies of 8 MeV–10 GeV with a power spectrum and a spectrum index of 3 was assumed.

Fig. 4 shows the time distributions of gamma-ray quanta with an energy of 2.223 MeV per proton falling at a temperature of $4{\cdot}10^3$ and 10^5 K. With increasing time, the probability of neutron decay increases, as does the probability of their exit into the interplanetary space or penetration into the deep layers after repeated scattering.

3. Conclusion

In [3], the probability of the formation and release of gamma-rays into interplanetary space during the interaction of protons with a set of energies from 8 MeV to 10 GeV is obtained. It is found that when protons interact with proton energies of ∼8–40 MeV and more than ∼2 GeV, the probability of a photon with an energy of 511 keV entering interplanetary space is several times higher than with 2.223 MeV. The interaction of protons from the second range can occur at depths significantly greater than those of protons from the first range. In the intermediate range, the intensity ratio is reversed. As shown in this paper (see Fig. 1) the probability of a photon with an energy of 511 keV entering interplanetary space is significantly lower than with

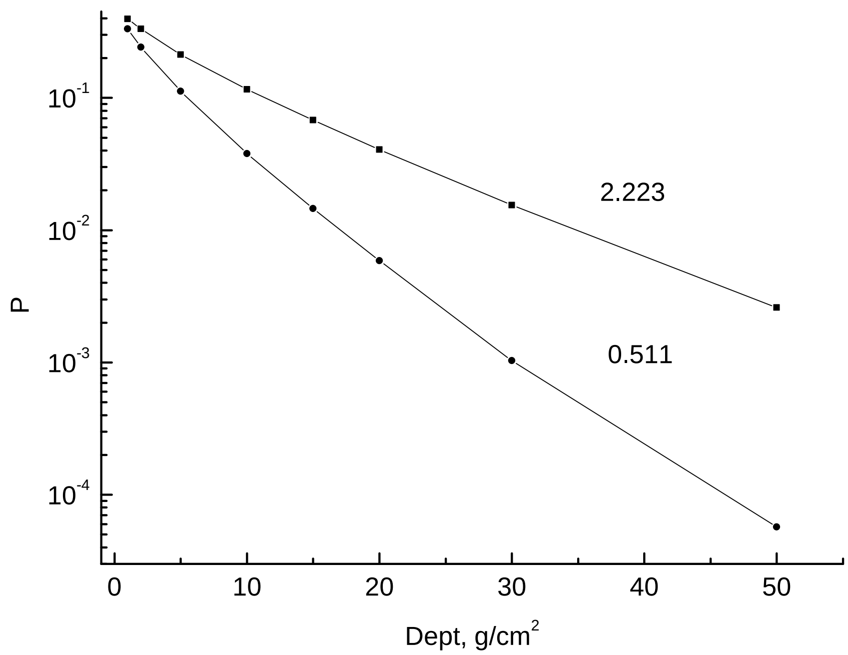

Figure 1. Probability of gamma-quanta release into interplanetary space, depending on the depth of arise.

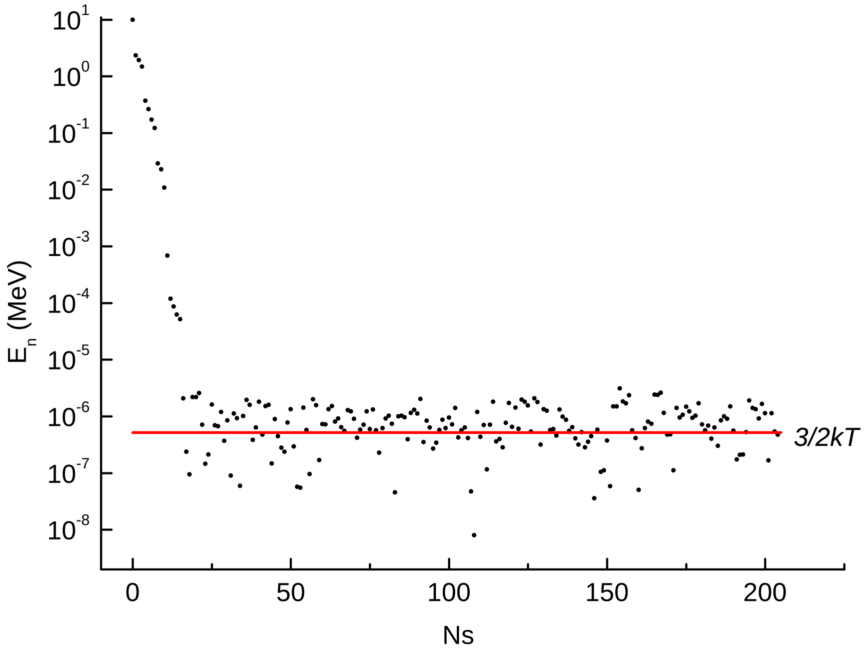

Figure 2. The change in the neutron energy after elastic scattering before the formation of deuterium.

2.223 MeV. The absence of the 2.223 MeV line in a number of solar flares may indicate that a soft spectrum of protons falls on the photosphere. In these cases, the temperature increase may be an additional factor that reduces the intensity of the line against the background of a continuous spectrum. It is also possible to increase the concentration of ^{3}He, which leads to a decrease in the intensity of the line. The registration of protons with energies greater than 80 MeV allows us to make an assumption about the additional acceleration of protons exiting into interplanetary space in these flares.

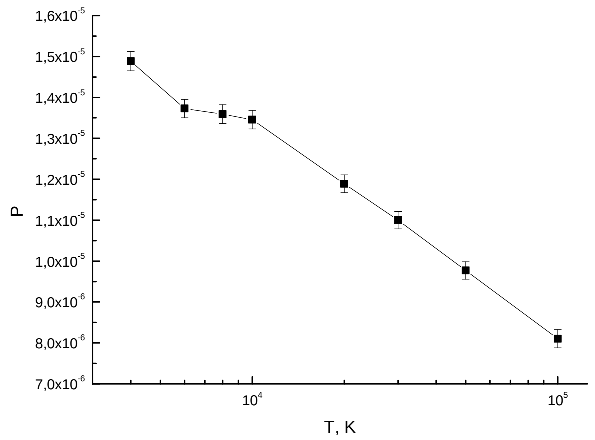

Figure 3. The probability of exit to the interplanetary gamma quantum with an energy of 2.223 MeV depending on temperature.

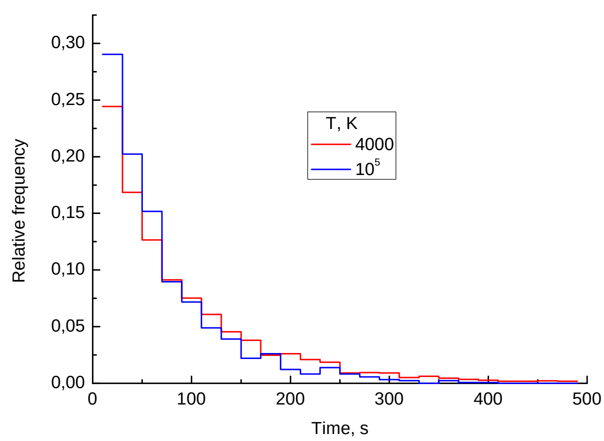

Figure 4. The probability of the exit of gamma quanta with an energy of 2.223 MeV into interplanetary space, depending on the time.

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