The angular and energy distributions of neutrons, gamma- and x-rays produced in solar flares. Related changes in the isotopic composition of the photosphere and the solar wind

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Abstract. Nuclear interactions of protons and helium ions accelerated in solar flares with solar atmosphere are simulated using Geant4 toolkit. The long term average spectrum of solar cosmic rays is taken from measurements of cosmogenic isotopes production in lunar soil. Solar atmospheric profiles of $^6$Li, $^7$Li and $^{14}$C generation are calculated. These isotopes outflow into interplanetary space with coronal mass ejections and following implantation into lunar rocks are considered to explain anomaly isotopic composition of thin lunar surface layer. Also, generated energy spectra and angular distributions of neutrons, gamma- and x-rays in space are presented for different spectra of solar flares.

1. Introduction

Accelerated during solar flares, protons and helium isotopes enter the photosphere and interact with the ambient material. In nuclear reactions stable and radioactive nuclides appear and excited nuclei emit characteristic gamma lines. With a time delay, there emerge lines formed by the decay of radionuclides. Part of the gamma-rays (scattered and noninteracting) leaves the solar atmosphere. These rays and gamma- and x-rays from the electron bremsstrahlung form a continuous spectrum with characteristic lines. Intensity of these lines depends both on flare power, and on the thickness of solar atmosphere, passed by gamma quanta. The greater the thickness traversed by the particle, the more likely it is to be scattered or absorbed. In its turn, the distance, penetrated by the registered particle, depends on the angle of observation and the depth of its generation. Investigation of neutron characteristics provides an additional tool for understanding the processes which take place during solar flares.

2. Method

Using the Geant4 software toolkit, designed for simulating the passage of particles through matter with Monte Carlo approach, we have performed modeling of interaction of protons and helium isotopes accelerated in solar flares with solar atmosphere. The initial chemical and isotopic composition of the photosphere are taken from [1]. The energy spectra of the accelerated particles are power laws in kinetic energy per nucleon with spectral index $\gamma$. The
depth of isotopes formation, the energy and angles of particles leaving the photosphere were fixed in the simulation.

![Graph](image1)

**Figure 1.** Gamma- and x-rays spectra.

![Graph](image2)

**Figure 2.** Temporal distribution of gamma-rays and x-rays resulting from radioactive decays.

![Graph](image3)

**Figure 3.** The depth distribution of Li yield.

![Graph](image4)

**Figure 4.** The depth distribution of $^{14}$C yield.

3. Results
Figure 1 reports spectra of prompt gamma and x-rays, which arise in direct nuclear reactions of $6.6 \cdot 10^8$ protons ($\gamma = 3, E > 30$ MeV) with the photospheric substance (blue curve), and of the gamma quanta which are formed as a result of disintegration of short-lived radionuclides
with decay times less then 10 minutes (green) and in the interaction of $1.8 \cdot 10^8$ alpha particles ($\gamma = 3$, $E > 30$ MeV/nucleon) with $^4\text{He}$ which produces $^7\text{Be}$ and $^7\text{Li}$ in the excited state (red).

We have paid special attention to $^7\text{Be}$, $^6\text{Li}$, $^7\text{Li}$ and $^{14}\text{C}$ isotopes formation with their subsequent involvement into solar wind outflow. The abnormal ratios (relative to solar prevalence) of the implanted isotopes of solar wind, which were observed in samples of lunar soil at depths of several tens of nm [2,3], can be accounted for changes in isotopic composition of solar atmosphere. There are two possible exit mechanisms which draw isotopes into interplanetary space along with solar wind. In the first case isotopes produced in a thin layer ($0.01–1$ g cm$^{-2}$) of photosphere are rapidly released with coronal mass ejections. In the second case, long-living isotopes are stored in the solar convection zone and escape later on with the solar wind. The depth distribution of $^6\text{Li}$ yield in the interaction of accelerated nuclei $^3\text{He}$ with $^4\text{He}$ at a kinetic energy of more than 7.14 MeV (threshold) and $^7\text{Li}$ in the interaction of accelerated alpha-particles with $^4\text{He}$ at a kinetic energy of more than 35 MeV for spectral index $\gamma = 3$ are shown in figure 3. Yield of isotopes in a layer with thickness of $0.1$ g cm$^{-2}$ per one primary particle is $0.5 \cdot 10^{-3}$, $1.2 \cdot 10^{-3}$ and $0.2 \cdot 10^{-3}$ respectively. The depth distribution of $^{14}\text{C}$ yield in the interactions of accelerated protons is shown in figure 4. The yield of isotopes per one primary proton is $4.6 \cdot 10^{-8}$.

The angular distribution (relative to the vertical) of gamma-, x-rays and neutrons leaving the photosphere are shown in the figures 5 and 6. Figures show that as the spectral index $\gamma$ increases, the angular distribution of gamma rays leaving the photosphere depends less on proton’s angles of incidence. It indicates that protons interact in a thin layer of matter, where they do not have enough time to be stopped by electromagnetic interactions. The obtained angular distributions for individual gamma lines are similar to the distributions for gamma particles of all energies.

The analysis of depth distributions of cosmogenic isotopes in the lunar soil makes it possible to determine the average spectrum of solar cosmic rays at very long time intervals [2]. After recalculation of the flux of solar cosmic rays on the Earth’s orbit and assuming that only about 1% of the accelerated ions in the solar flare flow out into interplanetary space, it is possible to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Angular distribution of gamma- and x-rays with energy exceeding 10 keV.}
\end{figure}
obtain an average particle flux into the photosphere. Assuming that the number of accelerated alpha-particles is about 2% of the number of protons, we can determine the lithium production rate. The resulting value shows good agreement with the data obtained in the lunar soil studies.

4. Conclusion
It may be concluded that during solar flares with comparable numbers of accelerated ions of helium and protons observations of lines from excited isotopes $^7$Be and $^7$Li are possible, which is confirmed by the experiment [4].

The results of our simulation show that observed enrichment of $^{14}$C and $^6$Li in lunar soil can be explained by generation of these isotopes in solar flares and their subsequent release into interplanetary space with coronal mass ejections. The accompanying gamma radiation can be used for experimental verification of validity of the model.

The involvement of experimental data on neutrons and protons produced in decay of neutrons in Earth’s orbit gives an additional survey method not only for the processes at the Sun’s surface, but in the solar magnetosphere as well.

References
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Figure 6. Angular distribution of neutrons with energies exceeding 1 MeV.