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Changes in the Solar Wind's Isotope Component, Due to Interaction between Solar Flare Particles and the Photosphere

G. I. Vasilyev[a, *], V. M. Ostryakov[b], A. K. Pavlov[a, b], and M. E. Chakchurina[b]

[a] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*

[b] *St. Petersburg State Polytechnic University, St. Petersburg, 195251 Russia*

**e-mail: Gennadyivas@gmail.com*

Abstract—Possible mechanisms responsible for changes in the solar wind's isotope component caused by interaction between solar flare protons and helium isotopes with photospheric nuclei are considered. Depth profiles of the rates of ^{6}Li, ^{7}Li, ^{7}Be, ^{14}C production in the solar atmosphere are simulated using the GEANT4 software package. It is concluded that anomalous isotopic compositions of the solar wind relative to the average values can form during the coronal mass ejections.

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INTRODUCTION

The concentration of various isotopes (^{6}Li, ^{7}Li, ^{7}Be, ^{3}H, ^{3}He, ^{2}H, and ^{14}C) varies as a result of nuclear interactions between particles accelerated in solar flares and the solar photosphere and chromosphere. The anomalous ratios (relative to the solar abundance) of embedded isotopes of solar wind particles observed in lunar soil samples at depths of several hundredths of microns [1, 2] can be explained by such variations in the isotopic composition of solar atmosphere. In this work, we considered two limiting cases of the ejection of formed isotopes into interplanetary space with the solar wind. In the first case, the isotopes form directly in a thin layer of matter (0.01–0.1 g cm^{-2}) with subsequent rapid plasma expiration during a coronal ejection after a flare. This scenario is most likely for ^{6}Li, since the reactions of its formation occur mainly during the interaction between helium atoms (with energies of tens MeV/n) in a thin layer. For other isotopes that form at higher energies (hundreds of MeV/n), the enrichment of coronal ejections is possible only for a certain topology of magnetic fields that results in the oblique incidence of accelerated particles on the photosphere. In the second case, enrichment occurs during the continuous accumulation of isotopes in deep atmospheric layers with intense convective mixing.

ANALYTICAL APPROACH

Using the GEANT4 software package, we simulated the interaction between protons and helium nuclei accelerated in solar flares and the solar atmosphere (the initial chemical and isotope composition were taken from [3]). The formation of isotopes across the depth (in g cm^{-2}) was determined in nuclear reactions. In our calculations, the spectrum of incident particles was approximated by a power dependence, and the fall onto the layer was modeled for different fixed directions. The maximum depth of isotope formation was estimated for a vertical fall. The depth of primary particle penetration (and thus the depth of isotope formation) grew for harder spectra. The development of a cascade in the solar matter was simulated using the GEANT4 program and the cross-sections for ^{6}Li, ^{7}Li and ^{7}Be isotope formation in direct reactions between ^{3}He and ^{4}He with ^{4}He [4]. The program allows for elastic scattering, electromagnetic interactions, intranuclear cascades, the absence of nucleus excitation, and the emergence of backscattered particles leaving the solar atmosphere. As for the magnetic field effect in the region of a flare, it reduces the geometric depth of isotope formation, due to Larmor rotation. The degree of this effect depends on the initial relation between the particle velocities along and across the field, a model parameter.

RESULTS AND DISCUSSION

Let us consider the results from calculations for a vertical fall of particles accelerated during a solar flare. Figure 1 shows the relative ^{6}Li yield, depending on depth upon interaction between accelerated ^{3}He and ^{4}He nuclei with kinetic energies exceeding 7.14 MeV (the reaction threshold) and particle spectral indexes of 2, 3, 4. Total yields Q of isotopes per one particle are thus 5.1×10^{-4}, 2.5×10^{-4}, and 0.92×10^{-4}. Q falls as the spectral index rises, but the relative proportion of particle formation increases in the thin top layers.

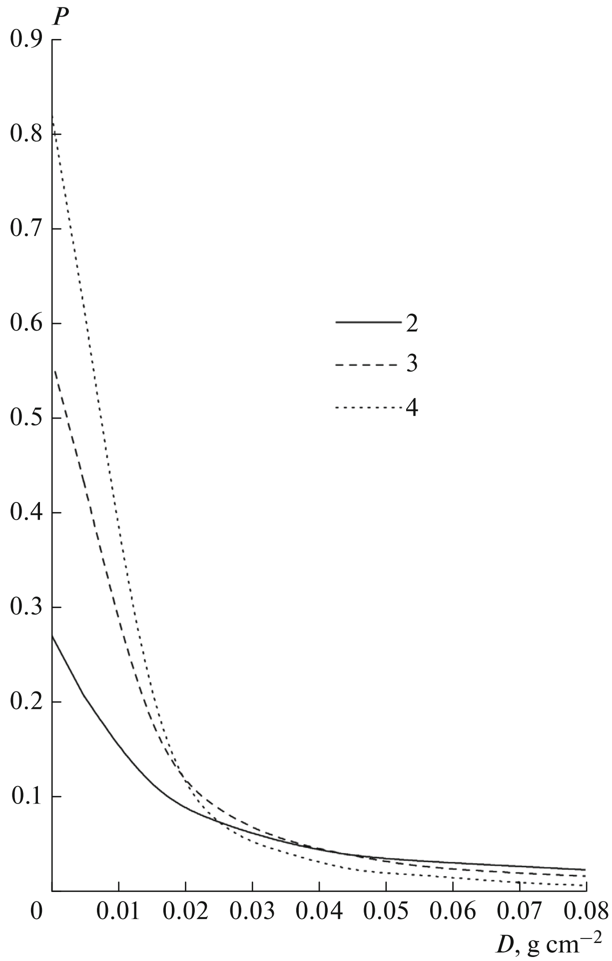

Fig. 1. Relative yield (P) of ^{6}Li formation upon interaction between ^{3}He and ^{4}He, depending on depth (D) with particle spectral indexes of 2, 3, 4.

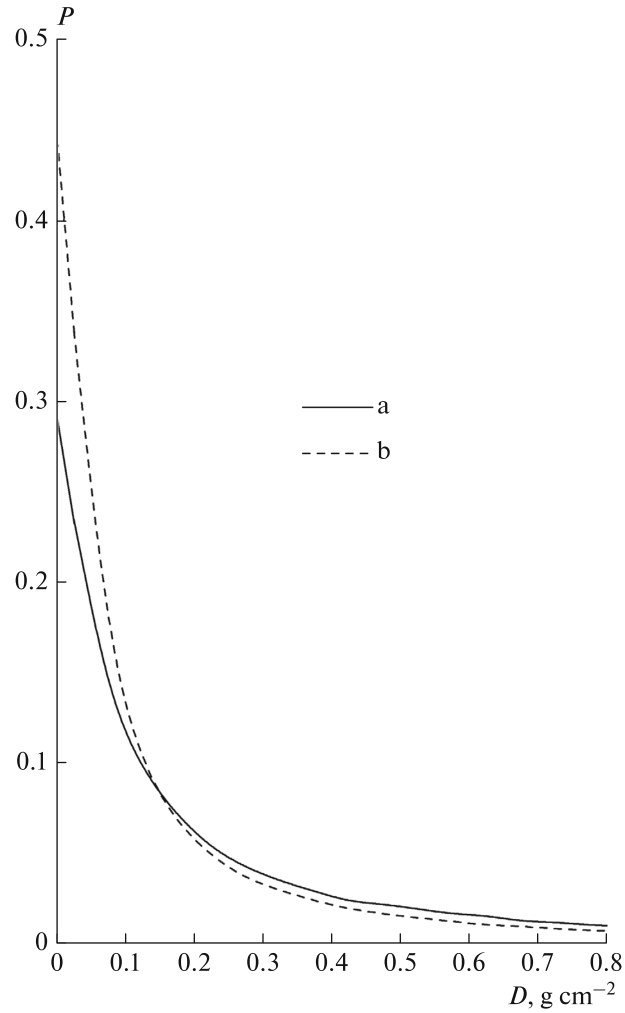

Fig. 2. (a) Relative yield (P) of ^{6}Li formation and (b) the total yield of ^{7}Li and ^{7}Be formation (^{7}Be transforms into ^{7}Li after electron capture) upon interaction between accelerated ^{4}He nuclei and ^{4}He nuclei in the solar photosphere, depending on depth (D) with a spectral index of 3.

Figure 2 shows the relative yield of ^{6}Li and the total yield of ^{7}Li and ^{7}Be (^{7}Be transforms into ^{7}Li after electron capture). These data correspond to the interaction between ^{4}He isotopes accelerated to more than 35 MeV (the reaction threshold) with a spectral index of 3 and ^{4}He in the solar atmosphere. The values of Q are thus 0.69×10^{-3} and 1.9×10^{-3}. The formation of lithium and beryllium isotopes upon interaction between protons occurs at considerably greater depths than with helium isotopes. For radioactive ^{14}C isotopes formed upon interaction between protons with energies above 30 MeV and a spectral index of 3, we obtained $Q = 4.6 \times 10^{-8}$.

As our calculations show, many isotopes form at depths exceeding 1 g cm^{-2}. Because of this, they are involved in the process of fast convective mixing. For long-lived isotopes, this generally results in their accumulation in the convective region. In addition, the concentrations of radioactive isotopes are determined by the ratio of the rates of generation and decay for each one. For stable isotopes, the concentrations are determined by the time of accumulation, and by the average intensity and spectrum of accelerated particles during this time. The experimental data for ^{14}C embedded in the lunar soil by the solar wind [2] in particular can only be explained by part of the formed isotopes (~1%) escaping directly into the solar wind from depths of less than 0.1 g cm^{-2} . This also applies to the anomalous ^{6}Li/^{7}Li ratio in the solar wind [1].

CONCLUSIONS

Our calculations show that nonthermal processes can be important from the viewpoint of changes in the ratios of isotopes in stellar atmospheres (particularly the solar atmosphere). This general conclusion was arrived at earlier for Li isotopes in works by Kotov et al. [5] and Ramaty et al. [4]. However, no depth profiles of isotope formation were obtained in these works. At the same time, such profiles prove to be important in determining the specific mechanism of solar wind enrichment by radionuclides and rare elements. Modeling shows experimental data on lunar soils can be explained only by assuming that some formed isotopes escape directly into the solar wind along with a coronal ejection.

Direct measurements of the formation of isotope ratios in interplanetary space using spacecraft could explain the processes behind the formation and propagation of coronal ejections from the solar surface (the magnitude and place of capturing ejected material, the magnetic field's topology, and so on).

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