# Nuclear Interactions in the Flare Sites

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**Abstract:** We consider the production of energetic light isotopes due to nuclear interactions and acceleration in flare regions. The Monte-Carlo method allows us to take into account several steps of particle interactions with ambient plasma. In our model the high abundance ratios of $^{3}$He/$^{4}$He are obtained at certain simulation parameters. Subsequent interplanetary propagation effects could result in the energy spectra of $^{3}$He, $^{4}$He nuclei similar to the observed ones. The supression of D and T in the outgoing particle flux is likely due to the angular distribution of these isotopes in flare regions.

## Introduction

The problem of elemental anomalies in solar cosmic rays (SCRs) is known since the early 70$^{th}$. It is especially pronounced in small impulsive solar energetic particle (SEP) events. Indeed, the ratio of $^{3}$He/$^{4}$He measured in the interplanetary space turns out to be $10^4$ times of that in the solar plasma ($5\times10^{-4}$) (see, e.g., [1-3]). Later it was found that the enrichment factor for heavier particles for the same class of events is somewhat smaller and lies within a factor of 10 [4]. As to the more powerful gradual SEP events, the chemical composition of CRs for them approximately corresponds to that of the solar corona.

First attempts to account for these anomalies were based on the analysis of nuclear interactions of accelerated particles with the solar photospheric (chromospheric) matter. For the galactic cosmic rays similar approach was applied to simulate light isotope production. Those models for SCRs really yield the great flux of $^{3}$He isotope along with comparable fluxes of deuterium (D) and tritium (T) which were not observed in the interplanetary space. This circumstance seems to be a reason for dropping this idea though certain angular properties of a primary particle beam could suppress interplanetary leakage of D and T. The lack of nuclear data for differential cross sections of various reactions also made this modeling uncertain. Nowadays the most popular models for heavy element enrichment in SEP events are those of selective acceleration operating in background turbulent plasma [5].

In the present paper we reanalyze the nuclear aspect of the problem by adding some improvements to previous consideration in some ways. First of all, we include multiplicity of particle nuclear interactions with the solar plasma, make simultaneous account of acceleration processes as well as subsequent particle propagation in the interplanetary space (adiabatic losses). The latter effect can modify the energy spectra of released species on the way to the Earth along with the other above mentioned effects which are more evident.

## Description of the Model

The simulation model is elaborated to take into account cascading processes of particle interactions with the solar matter. It includes not only nuclear transformation of primary chemical composition of SCRs (inelastic processes) but also elastic collisions resulting in the energy losses. Early papers considered only secondary particles (after first nuclear interaction) to obtain the released particle fluxes and, hence, the corresponding solar flare isotopic composition. To our mind the Monte Carlo method is the best way to realize the idea of multiple nuclear interactions. At the same time, certain kind of turbulence in the flaring region may lead to the particle acceleration inside. Such an energy gain can also be quite easily taken into account within the framework of the Monte Carlo approach along with the particle interplanetary propagation.

Let us consider the production of light isotopes ($^3$He, T, D) which are generated in the interactions of accelerated α*p* particles with the solar plasma (also consisting of α*p* nuclei), see [2,3]. The contribution of heavier elements such as CNO nuclei can be omitted [2].

*1. Nuclear interactions*

We accept the plane geometry of the system of some thickness $x=L_0$ (in cm) or $\bar{x}$ (in g/cm$^2$) which is infinite in two other directions. As a rule, the incident primary nuclei (at $x=0$) are distributed on energy $E$ by a power law. Inside this 'volume' the nuclear cascading processes and particle acceleration can change their energy (i.e., their spectra) and chemical composition. If the particle escapes this region (its current coordinate $x>L_0$) we count it as a released particle. After that the interplanetary propagation takes place which strongly depends on the perturbation level of this medium.

We successively calculate the following particle parameters after its injection at the boundary $x=0$:

(1) free path $l = -\ln\eta / \sum_i n_i \sigma_i^{total}$, where $\eta$ is a random number uniformly distributed inside [0,1] interval; $n_i$ is a reactant number density; $\sigma_i^{total}$ is a total cross section (elastic+inelastic) of the process $i$, and $\sigma_i$ denotes any of them;

(2) displacement $\Delta x = l \cos\theta \cos\varphi$, θ and φ being an angle between particle velocity $\bar{v}$ and layer normal ($x$ direction) and azimuthal angle, respectively;

(3) probability of different nuclear processes according to the relationship $P_i / \sum_i P_i$, where $P_i = 1 - exp(-n_i l \sigma_i)$ is a probability of the $i$-th process to occur (both elastic or inelastic).

After the collision the particle momentum is calculated according to the kinematics of reaction, and the angles are supposed to be uniformly distributed in 4π in a C.M. coordinate system. Notice that all the above parameters are energy dependent, therefore initial particle spectra respectively changed. For each new species appearing in this code we repeat the steps (1)-(3). The outgoing particle is counted independently on the number of coordinate (or time) steps. This implies obtaining the time integrated particle spectra and/or composition.

*2. Nuclear interactions and acceleration*

If, apart of nuclear interactions, we consider acceleration one should inject monoenergetic particle population instead of their initial energy distribution. It was assumed to be conserved in past models to compensate energy losses [2]. This practically means instant acceleration inside *l*.

During their propagation the particles can gain energy due to the (say) stochastic acceleration mechanism which is described by the well-known Fokker-Planck equation for isotropic distribution function $f$:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial E}(A_1 f) + \frac{\partial^2}{\partial E^2}(A_2 f),$$

where $A_1$ and $A_2$ are the kinetic coefficients responsible for the convection and diffusion in a momentum (energy) space, respectively. They are expressed through the turbulent energy level of a definite spectrum and type. At each time step $\Delta t = \alpha l / v$ one should calculate the energy gain $\Delta E = -A_1 \Delta t + \sqrt{2 A_2 \Delta t}\, W$, $W$ being the random number with the Gaussian-like distribution; α is a some numerical coefficient (< 1) . Thus, there are 1/α subintervals inside the 'nuclear' interval *l*, where the particle may be underwent both the acceleration and nuclear interaction of the corresponding probabilities:

$$P_{acc} = exp(-\sum_i n_i \alpha l \sigma_i),$$

$$P_{nuc} = 1 - exp(-\sum_i n_i \alpha l \sigma_i).$$

If nuclear interaction takes place inside the subinterval α*l*, the probability of the *i*-th process is simulated according to the step (3) of the above subsection. So, within the 'nuclear' interval *l* the energy of the particle can change dramatically due to the stochastic acceleration mechanism. It is especially important for energies in the vicinity of the reaction thresholds. Note that secondary particles produced in the collisions have sufficiently high energy to be immediately injected to the acceleration process. So, no primary threshold (injection) energy is necessary in this case.

*3. Interplanetary propagation*

After the particle leaves the interaction region it is supposed to be involved into the interplanetary propagation. Since the energy spectra are measured near the Earth's orbit, the main effect important for our modeling is the adiabatic energy losses in the expanding solar wind. It strongly depends on the mean free path $L$, i.e. on the spatial diffusion coefficient ($\chi$) of this medium, $\chi$=(1/3)$Lv$. In the Monte Carlo approach the energy decrease and particle displacement at each collision with the scattering center should be simulated according to the formulae:

$$\Delta E = -\frac{4w}{3r} E\,\Delta t \ ,$$

$$\Delta r = \left(\frac{2\chi}{r} + \frac{\partial \chi}{\partial r} + w\right)\Delta t + \sqrt{-4\chi \ln \delta_1 \Delta t}\ \sin(2\pi\delta_2)\ .$$

Here $r$ is the heliocentric distance, $w$ is the solar wind speed, and $\chi$ is defined in the interplanetary space (same as in the 'nuclear' interaction region for the momentum diffusion coefficient) by the Alfven wave turbulence of the power law index $S$=1.5; $\chi=\chi^0(r/R_0)(E/E_0)(Q/A)^{(3-S)/2}$, $Q$ and $A$ being the particle nuclear charge and atomic mass, respectively; $R_0$ is the solar radius, $E_0$ is the normalizing energy; $\delta_1$, $\delta_2$ are the random numbers uniformly distributed inside [0,1].

## Results

First of all we represent light isotope energy spectra in the 'nuclear' interaction layer without any energy gain inside. In this case we inject protons and α particles (with the abundance ratio 1:0.1) at $x$=0 with the spectrum $\propto E^{-\gamma}$ which is modified as the particles reach the boundary $x$=$L$. The resulting differential fluxes are depicted in Fig.1 (γ=3, $\bar{x}$=5 g/cm$^2$). Fig.2 shows the effect of additional acceleration ($\bar{x}$=5 g/cm$^2$, characteristic acceleration time is around 0.1 s).

In Figs.3,4, calculated for different values of the interplanetary diffusion coefficients, one can clearly see the shift of the crossing point for $^3$He, $^4$He spectra (from ~4 to ~1.6 MeV/nucleon). The latter value is much closer to the observations while for primary spectra at the Sun it was evaluated to be at ~7.3 MeV/nucleon.

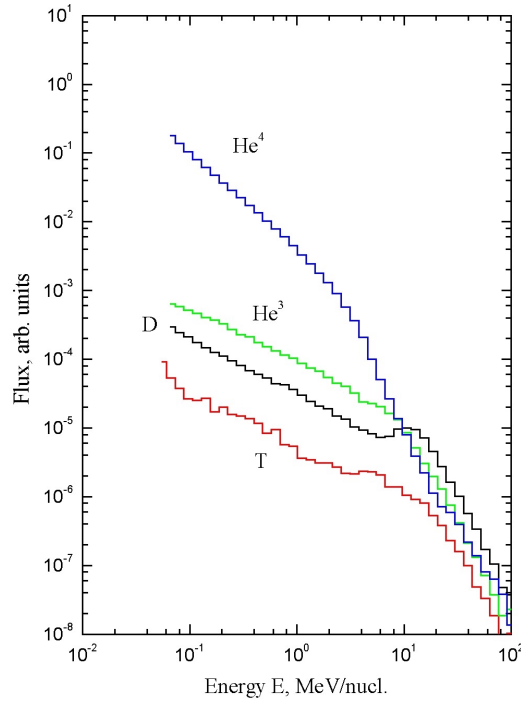


Fig. 1. Spectra of isotopes at the Sun.

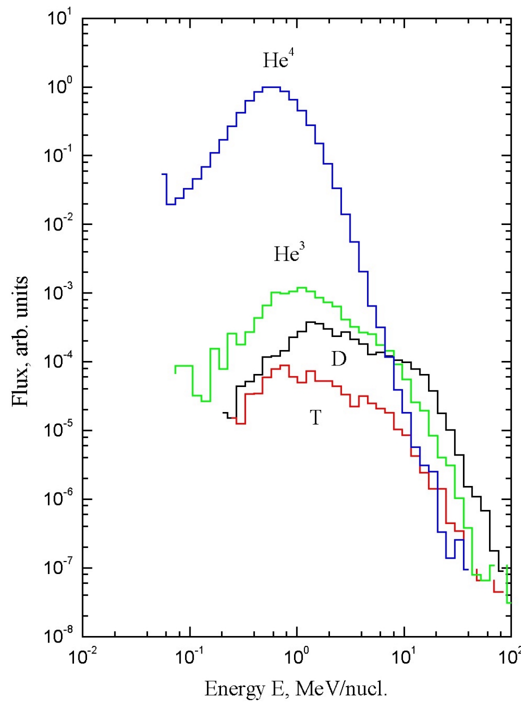


Fig. 2. Spectra of isotopes at the Sun (nuclear interactions+acceleration).

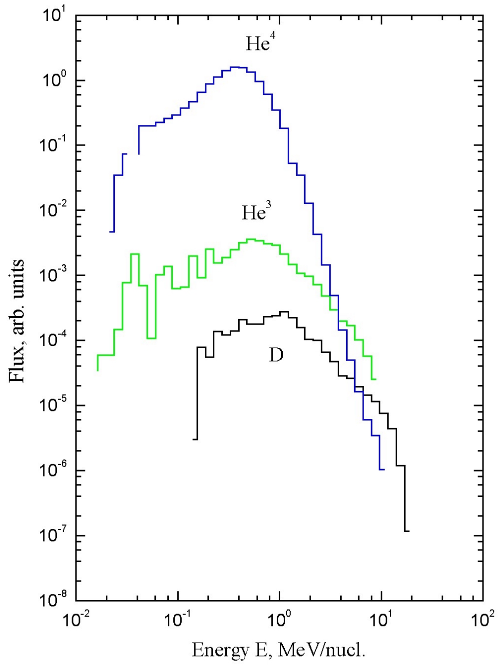


Fig. 3. Spectra of isotopes after their interplanetary propagation for $\chi^0=10^{19}$ cm²/s.

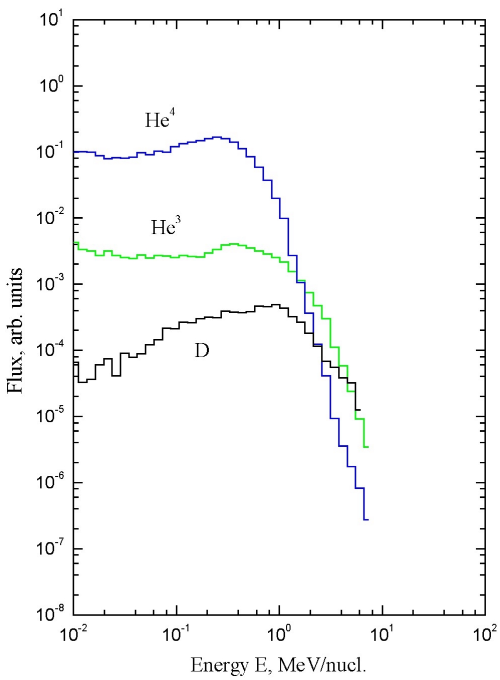


Fig. 4. Same as in Fig.3 for $\chi^0=10^{18}$ cm²/s.

## Conclusion

In the present paper we tried to reanalyze the problem of the light isotope ($^3$He, D, T) production in solar flares. In addition to the previous studies we consider the multiplicity of particle nuclear interactions in the flare sites, include the opportunity of their acceleration due to the stochastic mechanism and also subsequent propagation effects in the interplanetary space. Within this modeling it is quite easy to explain the over-abundance of $^3$He isotopes observed in impulsive SEP events. At the same time, the comparable fluxes of D and T obtained theoretically are not measured in experiments. This property is likely connected with their destruction and/or angular distribution of primary beams, i.e., with the differential cross sections for the production of these isotopes [2,3]. As to the interplanetary propagation, it seems to play an important role in accounting for the observed spectra from ACE. Particularly, this effect (due to adiabatic losses) shift the particle energy to lower values (Figs.3,4) qualitatively making the theoretically obtained spectra closer to the observed ones. However, the detailed fitting of the experimental data on $^4$He, $^3$He, D and T is out of the scope of the present paper. We hope to make this study in our subsequent work.

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## References

[1] Anglin J.D., W.F.Dietrich, J.A.Simpson, Deuterium and tritium from solar flares at ~10 MeV per nucleon, *Ap. J.*, *186*, *L*41, 1973.
[2] Ramaty R., B.Kozlovsky, D, T and He-3 production in solar flares, *Ap.J.*, *193*, 729, 1974.
[3] Colgate SA., J.Audouse, W.A.Fowler, Possible interpretation of the isotopic composition of hydrogen and helium in solar cosmic rays, *Ap.J.*, *213*, 849, 1977.
[4] Reames D.V., J.P.Meyer, T.T.von Rosenvinge, Energetic-particle abundance in impulsive solar flare events, *Ap. J. Suppl.*, *90*, 649, 1994.
[5] Kocharov L.G., G.E.Kocharov, $^3$He-rich events, *Space Sci. Rev.*, *38*, 89, 1984.