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THE DEFORMATION OF THE ENERGY SPECTRA OF THE ^{3}He AND ^{4}He IONS IN THE ENERGY REGION OF ~1 MeV/nucl

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In this paper calculations of energy spectra of particles deformation were made, during their traverse through the solar plasma, due to Coulomb losses, for cases of direct and diffuse propagation of these particles. Calculated ^{3}He/^{4}He ratios were compared with experimentally measured ones, in the energy region of $E \sim 1$ MeV/nucl in ^{3}He — rich solar particle events. Further, it was shown that calculated parameters of the solar plasma correspond to the solar corona.

ИСКАЖЕНИЕ ЭНЕРГЕТИЧЕСКИХ СПЕКТРОВ ИОНОВ ^{3}He И ^{4}He В ОБЛАСТИ ЭНЕРГИИ ~1 МэВ/н.

В работе были сделаны расчёты искажения энергетических спектров ионов, проходящих через солнечную плазму, в следствие кулоновских потерь, для случаев их прямого и диффузного распространения. Проведено сравнение результатов этих расчётов с наблюдательными данными в области энергии ~1 МэВ/н. в богатых гелием-3 событиях. Далее показано, что вычисленные параметры солнечной плазмы соответствуют корональным.

I. INTRODUCTION

The problem of solar flares enriched in ^{3}He has been intensively discussed during the last ten years. A catalogue containing 50 flares enriched in helium-3 has already been compiled [1]. The analysis of ^{3}He-rich solar flares recorded by a number of scientific groups using different experimental instruments and satellites clearly shows that solar cosmic rays enriched in helium-3 are a reliably established experimental fact.

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These events are characterized by an anomalous high flow of ^{3}He, compared to protons and alpha-particle flows, in a relatively wide energetic interval from a few to a few tens MeV per nucl. The ratio of ^{3}He and ^{4}He ions ^{3}He/^{4}He is about two to four orders higher than that in the solar wind.

A high enrichment of ^{3}He relative to alpha-particles and protons considerably restricts the number of possible hypotheses. Nowadays the possibility based on plasma effects in the solar atmosphere is being developed intensively. Two possible mechanisms of helium isotope separation, due to plasma effects during solar flare acceleration, have been proposed and developed [2—5]. The first mechanism, proposed by L. G. Kocharov [4], is based on the induced scattering of plasmons by ions. In the other mechanism, proposed by L. A. Fisk [3], ^{3}He heating at cyclotron frequency occurs.

The present-day knowledge of ^{3}He-rich solar flares shows that it is necessary to investigate these flares completely in connection with other phenomena in the solar atmosphere. In paper [6] there has been proposed the geometry of the acceleration region in ^{3}He-rich solar flares owing to the interaction between particles and ion-sound turbulence, based on the Kocharov model [4]. One of the facts that can prove or disprove the above model is the ^{3}He/^{4}He ratio to the energy of the ions behaviour in the energy region of ~ 1 MeV/nucl.

In papers [7—8] it was pointed out that the energy spectrum of the ion deformation depends on the ion charge Z and the mass number A as $Z/\sqrt{A}$. It follows that the energy spectrum of helium-3 will be deformed in the region of higher energies in comparison with the spectrum of helium-4 and then the ratio of these ions ^{3}He/^{4}He will decrease at an energy about ~ 1 MeV/nucl with the decrease of energy. If, owing to the character of propagation and owing to the geometry of the acceleration region, the thickness of matter, through which the ^{3}He ions pass, is greater than that through which the ^{4}He ions pass, the increase of ^{3}He/^{4}He with energy will be greater. According to the present-day notion the fold in the energy spectra of individual ions may be caused either due to the ionization losses during the transition of these ions across the solar plasma [8] or due to the adiabatic cooling of solar energy particles in their course from Sun to Earth [9]. It is clear that both these mechanisms work independently of each other. In the next calculations we took into consideration only the first mechanism. Our aim was to calculate the energetic spectra of ^{3}He and ^{4}He ions after their transition through the solar atmosphere provided that the energy spectrum of these ions at the source is a power law with the power spectral index γ. In the following we will discuss two cases of spectrum deformation of ions which had traversed through the solar plasma [8]:

a) The case of directly escaped particles from the region with $n_e \geq 10^{17}$ m^{-3}.

b) The case of the diffuse propagation of particles in the region with $n_e \sim 10^{15}$ m^{-3}.

II. DEFORMATION OF THE ENERGY SPECTRA OF IONS IN CASE OF THEIR DIRECTLY ESCAPE DUE TO COULOMB LOSSES IN THE SOLAR PLASMA

In paper [8] there was discussed the deformation of the energy spectra of ions which had traversed the solar plasma, for a various regime of their propagation. In the case of directly escape we assume that the deformation of initial power spectra of particles, described by the expression:

$$\varphi(x_i, y_i = 0) = B x_i^{-2\gamma+1} \tag{1}$$

where x_i is the velocity of particles divided by $\sqrt{2T_e/m_e}$ (T_e and m_e are electron temperature and mass, respectively, T_e is in energy units), y_i is the way traversed by particles through the solar plasma, and B is a constant, occurs in the energy region of ~ 1 MeV/nucl, because of their propagation through the solar plasma. The flux of particles, having the velocity x_i, after traversing the way y_i has the form

$$\varphi(x_i, y_i) = \frac{x_i F(x_0)}{F(x_i) x_0} B x_0^{-2\gamma+1} \tag{2}$$

where x_0 is the velocity of these particles, which traversing the way y_i will have the velocity x_i, i.e. we have

$$y_i = \int_{x_i}^{x_0} \frac{x}{F(x)} \, \mathrm{d}x \tag{3}$$

$F(x_i)$ is the strength of friction acting on the mass unit in the form

$$F(x_i) = \frac{Z^2}{A} K G(x_i) \tag{4}$$

where K is a constant, $K = 4\pi n_e e^4 / m_p T_e \Lambda^{-1}$ (m_p is the mass of the proton, e is the charge of the electron, n_e is electron density, Λ is the Coulomb logarithm), which we will take equal to one in the following calculations [8], A, Z are the mass number and the charge of ions and $G(x_i)$ is the function defined by the relationship

$$G(x_i) = \frac{\mathrm{erf}(x_i) - x_i \dfrac{\mathrm{d}}{\mathrm{d}x_i} \mathrm{erf}(x_i)}{2x_i^2}. \tag{5}$$

Expression (2) describes the energy spectrum of particles having the velocity x_i, initial spectra in the form of (1), after their having traversed the thickness of the solar plasma y_i. The initial power spectrum is then deformed because of Coulomb losses. From the distance y_i we can calculate the real thickness of the solar plasma traversed by particles with the help of the relation

$$N \sim 2.5 \times 10^{-20}\, x_e^4 y_i \quad (6)$$

where $x_e = \sqrt{T_e/m_e}$ is the thermal velocity of electrons.

With the help of the program MARYS for computer EC 1040 there will be calculated energy spectra of the ions of helium-3 and helium-4 for power spectral indices $\gamma \in \langle 2.0, 6.0 \rangle$, for various velocities of x_i. In Fig. 1 energy spectra of ^3He ions are shown, which arise from the initial power spectrum with power spectral index $\gamma = 3.0$, for various thicknesses of the solar atmosphere y_i. The energy of the ions E is in units $E_1 = 6.3\, m_p x_e^2$, where m_p is the mass of protons. A similar energy spectrum is in Fig. 2 for ^4He ions.

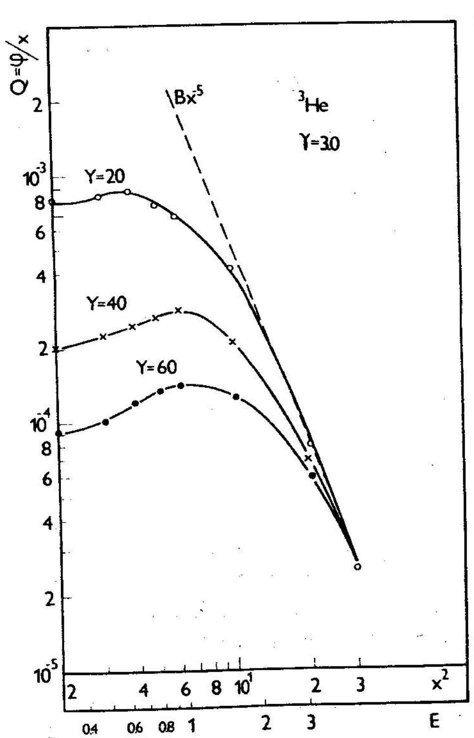

Fig. 1. The deformation of the initial power law energy spectrum of ^3He ions after its traversing various thicknesses of the solar atmosphere $Y \equiv y_i$, for the case of the direct escape of particles on the solar plasma (x is velocity and E is energy of ions in units of $E_1 = 6.3\, m_p x_e^2$, where m_p is mass of protons and x_e is thermal electron velocity).

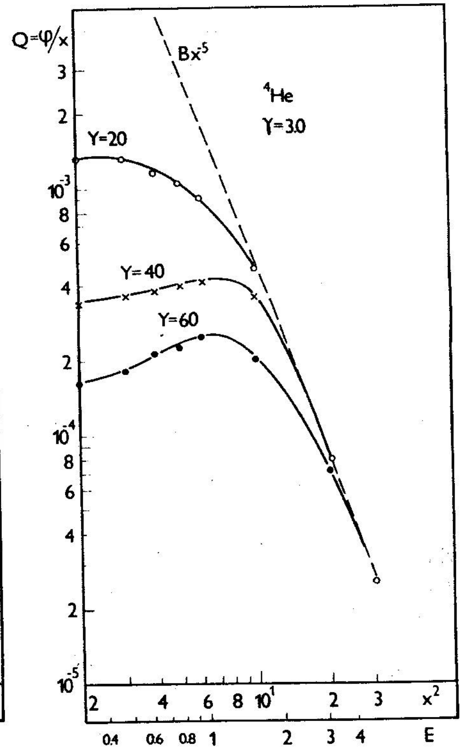

Fig. 2. The deformation of the initial power law energy spectrum of ^4He ions after its traversing various thicknesses of the solar atmosphere $Y \equiv y_i$, for the case of the direct escape of particles in the solar plasma (x is velocity and E is energy of ions in units of $E_1 = 6.3\, m_p x_e^2$, where m_p is mass of protons and x_e is thermal electron velocity).

In Fig. 3 energy spectra of ^3He and ^4He ions for $\gamma = 3.0$ are compared. In this figure also the energy dependence of ^3He and ^4He fluxes $^3He/^4He$ is presented. For each of these spectra the critical thickness of the solar plasma N^{krit} were determined, as like as the way, after traversing which the flux of particles increases

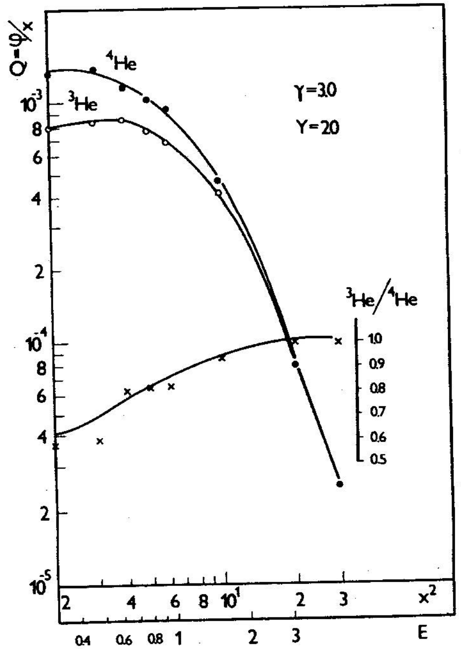

Fig. 3. The comparison of energy spectra of ^3He (○) and ^4He (●) ions, for $\gamma = 3$ and $Y = 20$. The energy dependence of $^3He/^4He$ ratio (×) for the case of direct escape of particles in the solar plasma (Energy E is in units of E_1).

twice with the charge of their energy from unit energy E_1 to $0.8\, E_1$. Values of these critical thicknesses are presented in Table 1 for individual power spectral indices of the initial power law spectra and for ^3He and ^4He ions.

Table 1

Critical thickness of ^3He and ^4He ions $N^{krit}_{He_3}$ and $N^{krit}_{He_4}$ (in units $x_e^4\, m^{-2}$, where x_e is the thermal velocity of electrons) as the function of the power spectral index γ, for the case of direct escape of ions in the solar plasma.

γ	$N^{krit}_{He_3}$ $[x_e^4\, m^{-2}]$	$N^{krit}_{He_4}$ $[x_e^4\, m^{-2}]$
2	6.25×10^{-19}	7.50×10^{-19}
3	4.50×10^{-19}	6.25×10^{-19}
4	5.00×10^{-19}	6.25×10^{-19}
5	5.00×10^{-19}	6.75×10^{-19}
6	4.50×10^{-19}	6.25×10^{-19}

In Fig. 4 there are drawn experimental measured energy spectra of ^{3}He and ^{4}He ions and the pertinent energy dependence of ^{3}He/^{4}He ratio for the ^{3}He-rich event of 5th—10th May 1974, measured on the satellite IMP-8 [10]. For all power indices of initial energy spectra $N^{krit}_{He_3}$ is always smaller than $N^{krit}_{He_4}$.

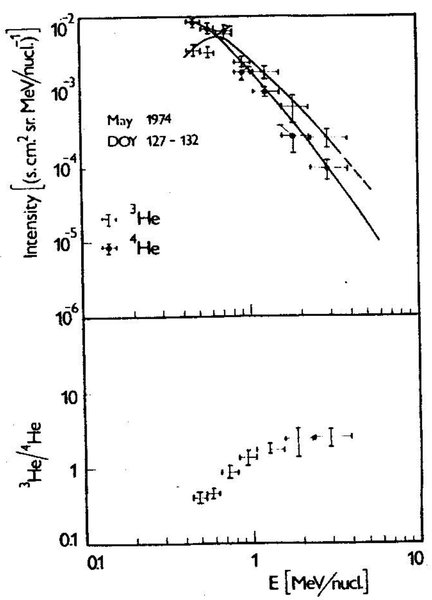

Fig. 4. Energy spectra of ^{3}He and ^{4}He ions measured on the satellite IMP-8, for the ^{3}He-rich solar event of 5th to 10th May, 1974. In the lower tail of this figure the energy dependence of the ^{3}He/^{4}He ratio is shown [10].

If the energy near which is the distorted energy spectrum half the size in comparison to undistorted one, is denoted by E_2, then the effect of deformation on the energy spectrum of ^{3}He ions can be presented by the graphic dependence $E_2 = f(\gamma)$, for various thicknesses of the solar atmosphere $y_i \equiv Y$, which is presented in Fig. 5.

On the basis of these calculations we can make the following conclusions:

A. The deformation of energy spectra of particles after their traversing the same thickness of the solar atmosphere, is for the ^{3}He ions greater than for the ^{4}He ions, which is in agreement with the experimental data [10].

B. For $T_e = 10^6$ K the ^{3}He/^{4}He ratio decreases with the decrease of energy, beginning with the energy 0.3 MeV/nucl, in the region ~2 MeV/nucl this ratio approaches one and in the region >2 MeV/nucl its constant, equal to one. A similar dependence of this ratio was obtained by Möbius et al. [10] for the same ^{3}He-rich solar flares (see Fig. 4).

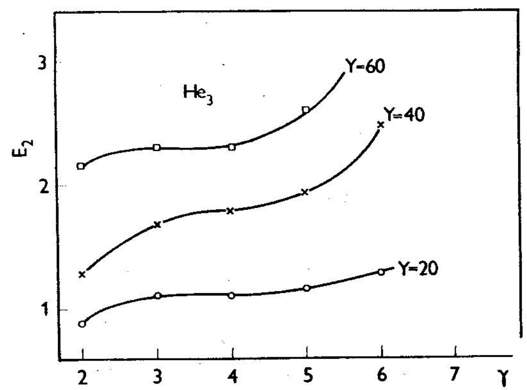

Fig. 5. The effect of spectrum deformation for the case of direct escape of particles as a function of the power spectral index of the initial power law spectrum γ, after traversing various thicknesses of the solar atmosphere Y. E_2 is the energy for which distorted energy spectrum is half as small in comparison to the undistorted one. (Energy E_2 is in units of E_1).

III. DEFORMATION OF THE ENERGY SPECTRA OF IONS THROUGH DIFFUSE PROPAGATION DUE TO COULOMB LOSSES IN THE SOLAR PLASMA

In addition to the direct propagation of ions in the plasma, in which the resulting effect of deformation of their energy spectra depends on their charge and mass number like Z^2/A there exist two other possible alternatives. If the deformation of energy spectrum is connected with the acceleration of particles in their interaction with magneto-hydrodynamic turbulence [11], the resulting effect of their spectra deformation depends on the Z/A ratio. When the turbulence magnifies the distance traversed by particles and changes in these particles are caused only by Coulomb losses, all the deformation effect is dependent on $(Z^2/A)\,(Z/A)^{2-\nu}$, where ν is a turbulence spectral index [8]. For this case it was shown in [8] that initial power law spectrum will have the following form after its deformation

$$\bar{\varphi}(x_i, y_i) = \int \frac{D(x_i)}{F(x_i)} \frac{1}{\sqrt{\pi l^2}} \frac{y_i}{4l^2} \exp - \left[\frac{y_i^2}{4l^2}\right] x_0^{-2\gamma+1}\, dx_0 \qquad (7)$$

where x_i is the relative velocity of ions, y_i is the space coordinate, x_0 is the velocity of ions at the point with the coordinate $y_0 = 0$ (at the time $t = 0$), γ is the power spectral index of the initial power law spectra, according to expression (1),

$$l^2 = \int_{x_i}^{x_0} D(x)/F(x)\, dx,$$

$D(x_i)$ is the diffusion coefficient along the magnetic field, which may be expressed by [12]

$$D(x_i) = (Z/A)^{\nu-2} x_i^{3-\nu} d_r \qquad (8)$$

where d_r is the diffusion coefficient for $x_i = 1$ and $Z = A = 1$, which in the following calculations is taken equal to one.

The real thickness of the solar plasma N is connected with the parameter y_i by the following relation

$$N = y_i \sqrt{\frac{d_r m_e m_p x_e^3 \sqrt{2}\, n_e}{4\pi e^4 \Lambda}} \qquad (9)$$

where m_e, m_p are masses of electrons and protons, $\Lambda \doteq 20$, n_e is the electron density, which is constant throughout the region.

With the help of the program DUBLEMAR for the computer EC 1040 there will be calculated energy spectra of the ions of helium-3 and helium-4 for power spectral indices of the initial power law energy spectra $\gamma \in \langle 2, 6 \rangle$, for four various values of turbulence spectral indices ($\nu_1 = 1.5$, $\nu_2 = 2.0$, $\nu_3 = 2.5$, $\nu_4 = 3.0$) and various thicknesses of the solar atmosphere y_i. In Fig. 6 energy spectra of ^3He and ^4He ions are compared, which arose by the deformation of the initial power law spectrum with the power index $\gamma = 3.0$, for the turbulence spectral index $\nu = 1.5$, after their traversing the thickness of the solar atmosphere $y_i = 14$. This figure

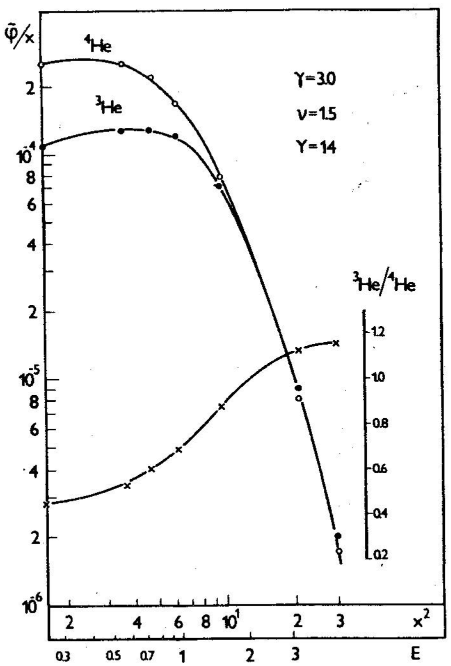

Fig. 6. The comparison of energy spectra of ^3He (●) and ^4He (○) ions for $\gamma = 3.0$, $\nu = 1.5$ and $Y \equiv y_i = 14$. The energy dependence of the $^3He/^4He$ ratio (×) for the case of diffuse propagation of particles in the solar plasma (x is velocity of ions, E is energy of ions in units of E_1).

presents also the energy dependence of the $^3He/^4He$ ratio. Fig. 7 shows energy dependence of the $^3He/^4He$ ratio for various values of the index ν. Values of critical thickness $Y^{krit}_{He_3}$ and $Y^{krit}_{He_4}$ of ^3He and ^4He ions are presented in Table 2 for various values of γ and ν.

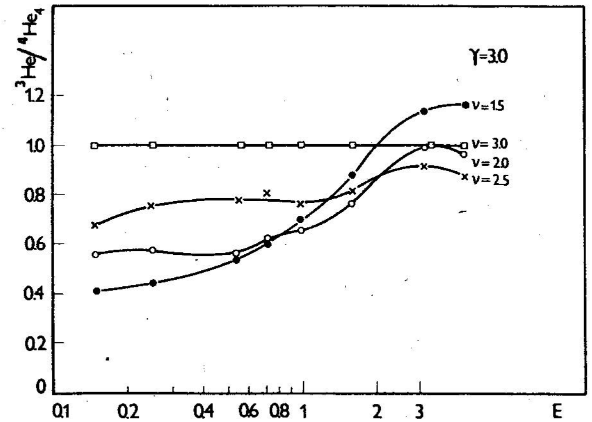

Fig. 7. The energy dependence of the $^3He/^4He$ ratio for $\gamma = 3$ and $\nu = 1.5$ (●), $\nu = 2.0$ (○), $\nu = 2.5$ (×) and for $\nu = 3.0$ (□) (Energy E is in units of E_1).

Another picture of this deformation of energy spectra can be obtained on the basis of values of E_{n_i} as the function traversed thickness of the solar atmosphere y_i dependence, for various values of the power spectral index of the initial energy spectra γ. E_{n_i} indicates the energy near which the distorted energy spectrum is n_i-times smaller in comparison with the undistorted one. These dependences are for ^4He ions shown in Fig. 8 for $n_i = 2$, 5, 10 and 20 and for the turbulence spectral index $\nu = 2$. It shows that these dependences have a universal character, because in the case of ^4He ions ($Z = 2$, $A = 4$) the deformation of the energy spectrum is independent of the charge Z and the mass number A and because for these ions we

Table 2

Critical thickness of ^3He and ^4He ions $Y^{krit}_{He_3}$ and $Y^{krit}_{He_4}$ as the function of the power spectral index for various turbulence spectral indices ν and for the case of diffuse propagation of ions in the solar plasma.

γ	$\nu = 1.5$		$\nu = 2.0$		$\nu = 2.5$		$\nu = 3.0$	
	$Y^{krit}_{He_3}$	$Y^{krit}_{He_4}$	$Y^{krit}_{He_3}$	$Y^{krit}_{He_4}$	$Y^{krit}_{He_3}$	$Y^{krit}_{He_4}$	$Y^{krit}_{He_3}$	$Y^{krit}_{He_4}$
2	16	20	12	12	10	11	10	10
3	15	18	12	14	8	10	8	8
4	15	18	11	12	8	10	8	8
5	15	18	11	12	8	10	6	6

have $(Z^2/A)\,(Z/A)^{2-\nu}=1$. Then for the arbitrary ion with charge Z and mass number A we can for the arbitrary choice of the turbulence spectral index to calculate the thickness of the solar atmosphere y_i, which traversed this ion, for the same distortion as helium-4 one, by the following expression

$$y_i = y_{He_4}\sqrt{(Z^2/A)\,(Z/A)^{2-\nu}} \tag{10}$$

where y_{He_4} is the thickness of the solar atmosphere traversed by ^{4}He ions. From Fig. 8 we can for certain y_{He_4} and power spectral index γ, determine values of E_2, E_5, E_{10} and E_{20} and construct the deformed energy spectrum of an arbitrary ion used in expression (10).

On the basis of these calculations we can make the following conclusions:

A. The deformation of initial energy spectra of ions decrease with the decrease of the traversed thickness of the solar atmosphere by these ions. At the same time the energy spectra of ^{3}He ions are, in agreement with the experimental data, deformed more than the energy spectra of ^{4}He ions.

B. For the turbulence spectral index $\nu<2$ the ^{3}He/^{4}He ratio decreases with the decrease of energy more than in the case of direct escape ($\nu=2$).

C. For $\nu>2$ the ^{3}He/^{4}He ratio decreases with the decrease of energy less than in the case of direct escape.

D. The critical thickness of ^{3}He and ^{4}He ions $Y^{krit}_{He_3}$ and $Y^{krit}_{He_4}$ increases with the

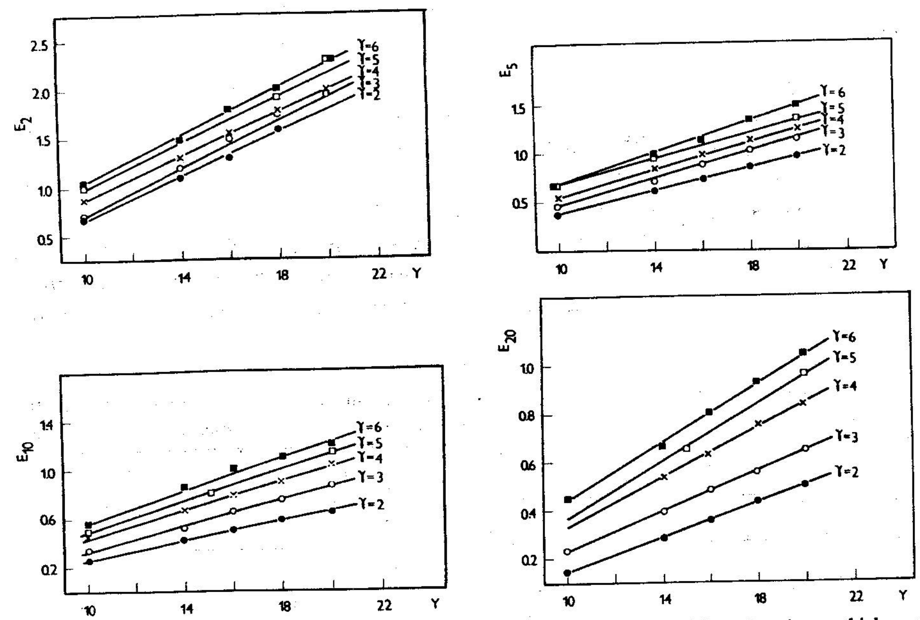

Fig. 8. The dependence of quantities E_{n_i} ($n_i=2, 5, 10, 20$) as the function of the solar plasma thickness Y, traversed by ^{4}He ions, for $\nu=2$ and various values of γ. (Energies E_{n_i} are in units of E_1).

decrease of turbulence spectral index ν, simultaneously for $\nu<3$ there is $Y^{krit}_{He_3}\leqslant Y^{krit}_{He_4}$.

IV. CONCLUSION

According to the comparison of the deformation energy spectra of ions which traversed through the solar plasma, calculations for cases of direct and diffuse propagation of these ions with the experimental data [10], [11], [13] it follows that part of this solar energy particles spectra, registered at the time of ^{3}He-rich solar particle events, we can explain with the help of this deformation mechanism. According to calculations of ^{4}He ions·spectra deformation we can very simply determine the deformation of energy spectra for other ions, which traversed through arbitrary thickness of the solar plasma.

Finally we can study the problem if the parameters of the solar plasma calculated here correspond to their real values in the solar corona. In paper [10] Möbius et al. found that the time of particles injection to the interplanetary space is $\tau_\nu \leqslant 900$ s. In the case of coronal diffuse propagation we can express τ_ν by the formula

$$\tau_\nu \sim L^2/4d, \tag{11}$$

where L is the characteristic dimension of solar flares.

Comparing the spectra calculated here with the experimental ones we obtain the minimal energy E_{min} at which we can, in the acceleration region on the Sun, consider the spectrum of certain ions, it is the power law and also the pertinent temperature of this region T_e. According to values of these quantities we calculate with the help of expressions (9) and (11) that the electron density in this region is $n_e \sim 10^{15}$ m^{-3}. This corresponds to the real concentration of plasma of the corona.

In future it will be interesting to compare calculated energy spectra of heavier ions with the results of experimental measurements.

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