The secondary deuterium spectrum at small atmospheric depths

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Abstract

During the propagation of primary cosmic ray nuclei through the atmosphere, besides protons, light nuclei are produced from both the fragmentation of the air nuclei and the spallation of incident nuclei. In order to study the spectra of light fragments in the atmosphere, a new parameterization of the distribution of protons in the energy range from 10 MeV to 1 GeV from the fragmentation of air nuclei has been developed. This new parameterization is then scaled according to the coalescence model, and it was used to determine the differential energy spectra of secondary deuterium from 100 MeV/n to 100 GeV/n in the atmosphere, as a function of depth and zenith angle.

1. Introduction

Most experiments measuring the composition of cosmic rays are carried out with balloon-borne instruments. Data are collected under a residual atmosphere of few g/cm^2 and to determine the primary abundances, it is necessary to take into account the attenuation and the secondary particle production due to interaction with the air nuclei. At low energies a significant production of light fragments results from the fragmentation of air target nuclei.

An estimate of the atmospheric deuterium flux was described in a previous work[6]. However the parameterization of the inclusive cross-section for the production of deuterons from the fragmentation of air target nuclei during inelastic collisions was based on a limited set of experimental data[5]. We modified now the production term for this process, by using some new accelerator data[2,3,4]. Since the coalescence model[8] allows us to scale the energy and angular distribution of protons from nucleus-nucleus collisions to that of light fragments by a power law, we are able to make use of the available cross-sections for secondary production of protons in such interactions in this investigation.

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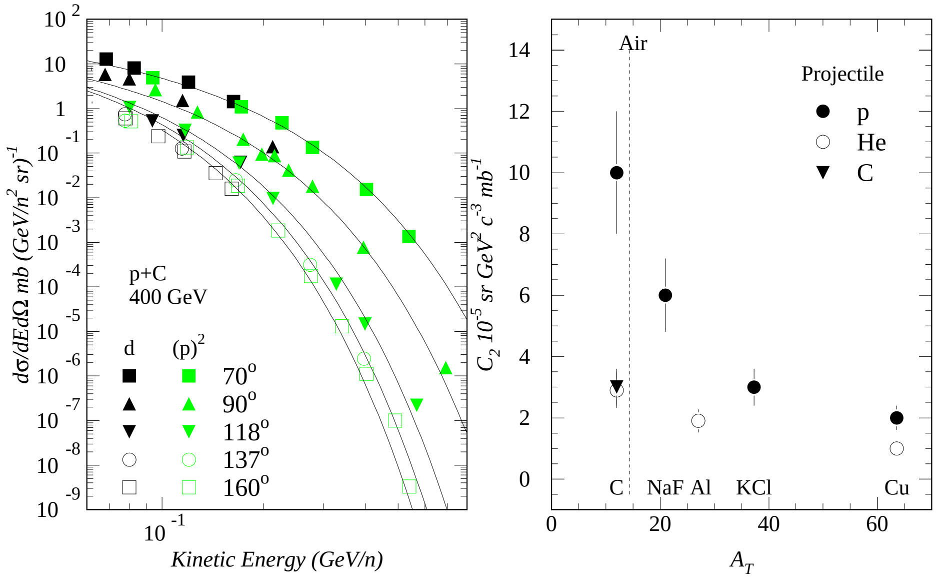

Fig. 1. Left: inclusive cross-section for the production of deuterons in p+C collisions; filled symbols indicate deuteron data[2], gray symbols indicate proton data[1] from the same experiment scaled according to the coalescence model. Right: deuteron coalescence constant as a function of the projectile and the target masses[3,4]

2. Parameterization of the differential cross-section for the production of recoil deuterons

In order to parameterize the differential cross-section for the production of deuterons from the fragmentation of the target we made use of the coalescence model[8]. According to this model, the invariant production cross-section for fragments of mass number A is related to the proton production cross-section by a power law:

$$\epsilon_A \left(\frac{d^3\sigma}{dp^3}\right)_{A,PT} = C_A^{PT} \left[\epsilon_p \left(\frac{d^3\sigma}{dp^3}\right)_{p,PT}\right]^A , \tag{1}$$

where the fragment momentum is $p_A = Ap_p$. In eq. 1, ϵ denotes the total energy and C_A^{PT} is the coalescence constant for a fragment of mass number A.

The accelerator data[1] on the production of protons used to parameterize recoil proton cross-sections[7] include results on light ions[2]. The left plot in fig. 1. shows the differential cross-section for the production of deuterons in the reaction p+C, together with that for the production of protons scaled according to eq. 1 with a deuteron coalescence constant $C_2^{pC} = 0.8\,10^{-4}$ mb^{-1} sr c^{-3} GeV^2. The solid curves represent the parameterization of the proton production cross-section scaled in the same way. The value of C_2^{pC} that fit the Frankel[2] data is consistent with other published results (see for example experimental data shown

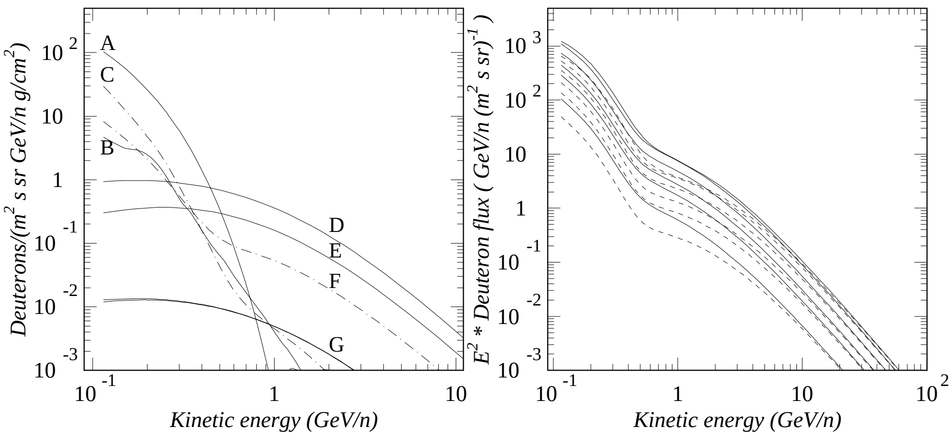

Fig. 2. Left: deuterium production (solid curves) and attenuation (dot-dashed curves) as a function of the kinetic energy, at 5 g/cm^2 of residual atmosphere during minimum solar modulation. The processes included are: fragmentation of air target nuclei (A), production from $p, n + p, n \rightarrow d + \pi$ (B), spallation of ^{4}He (D), heavier nuclei (E) and ^{3}He (G), and loss by ionization (C) and interaction (F). Right: flux of secondary deuterium at (from bottom to top) 1, 3, 5, 10, 20 and 80 g/cm^2, at minimum (solid curves) and maximum (dashed curves) solar modulation levels.

in the right plot of fig. 1.). In order to scale the differential cross-section for the production of deuterons to different projectile and target mass numbers, the proper value of the coalescence constant C_2^{PT} must be taken into account. The right plot in fig. 1. shows measured values of C_2^{PT} for p, He and C projectiles as a function of the target mass number [3,4].

3. Results

The parameterization of the deuteron production process described above was used to estimate the secondary deuterium produced during the propagation of cosmic rays in the atmosphere. The calculation was carried out by using the method described in ref.[6] and included deuteron production both from spallation of cosmic rays and from the fragmentation of air target nuclei. The left plot in fig. 3. shows the production and attenuation terms in the deuteron transport equation at 5 g/cm^2 of residual atmosphere. The deuterium production is dominated by the fragmentation of the air nuclei up to several tens of MeV/n. Beyond this energy ^{4}He spallation dominates; heavier nuclei also play a significant role. The right plot in fig. 3. shows the resulting secondary deuterium flux, as a function of the energy, down to a depth of 80 g/cm^2, at minimum and maximum solar modulation levels.

Fig. 3. shows the deuterium flux as a function of the zenith angle, normal-

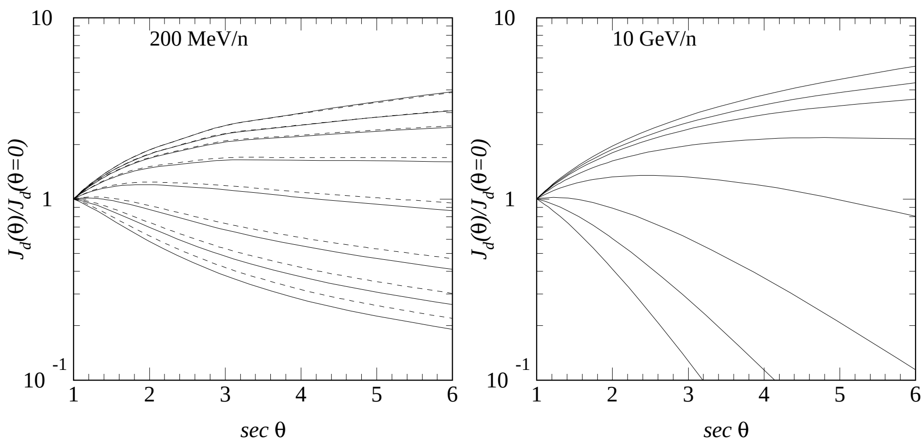

Fig. 3. Deuterium flux, normalized to the flux in the vertical direction, as a function of the zenith angle, at minimum (solid curves) and maximum (dashed curves) solar modulation levels, at 1, 3, 5, 10, 20, 40, 60 and 80 g/cm^2 (from top to bottom).

ized to the flux in the vertical direction for two different values of the fragment energy: 200 MeV/n and 10 GeV/n. The differences between the low and high energy domains are related to the attenuation length of deuterium and to the dominant production mechanism. At high energy deuterium is produced in the forward direction from the spallation of cosmic-ray nuclei and the attenuation is determined by inelastic interactions. At low energy a fraction of deuterons, from target fragmentation, are produced in all directions. Moreover the attenuation length is shorter due to the effect of ionization energy loss.

4. References

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