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An estimate of the secondary ^{2}H spectrum produced by cosmic rays in the atmosphere

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Abstract. A detailed study of the secondary production of ^{2}H in the atmosphere as a function of energy, zenith angle and atmospheric depth was carried out. We present the results at high latitude at minimum and maximum solar modulation level.

1 Introduction

Most experiments measuring the composition and energy spectra of cosmic rays are carried out with balloon-borne instruments. These experiments fly under a few g/cm^2 of residual atmosphere therefore, to determine primary fluxes, it is needed to take into account the attenuation and the secondary particle production processes due to interactions with air nuclei.

In this paper we report results of a calculation of the secondary deuterium production spectrum in the atmosphere. This calculation provides both the spectrum and the angular distribution of the secondary deuterium. The latter information can be used to properly take into account the instrument acceptance, in order to correctly estimate the secondary measured deuterium component.

2 Deuterium production in the atmosphere

Deuterium is produced in the atmosphere from the interaction of cosmic rays with air nuclei. Different processes contribute to deuton production. For each process the production energy spectrum, per second per gram of atmosphere, as a function of the vertical depth x (g/cm^2) and in a given direction θ, has the following general expression:

$$P(E,\theta,x) = \int dE' \int d\Omega^* \Phi(E',E,\theta^*) \frac{J(E',\theta',x)}{\lambda(E')} , \quad (1)$$

where E and θ (here and in the following, if not differently specified, E denotes the kinetic energy per nucleon and θ the zenith angle) are the energy and the direction of the outgoing deuterium, E' and θ' are those of the projectile and θ^* is the emission angle of the deuterium referred to the incidence direction of the incoming particle.

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In eq.1 the last term indicates the number of interactions per unit energy per second per gram of atmosphere for the incident particle flux $J(E',\theta',x)$ at the depth x, where $\lambda(E')$ is the corresponding interaction length for the considered process expressed in g/cm^2 ($\lambda(E') \propto A_{air}/\sigma(E')$ being $\sigma(E')$ the cross-section and $A_{air} = 14.4$). The quantity $\Phi(E',E,\theta^*)$ is the mean number of deutons of energy E produced per single interaction, per unit energy and solid angle by an incident particle of energy E' with a scattering angle θ^*. The production term is integrated over all energies E' and over the emission angles θ^*,ϕ^*.

The production processes that we have considered can be grouped in three categories:

- production from air target nuclei;
- production from incident nucleons through the reaction (p,n)+(p,n)$\rightarrow$ D+π;
- production from the breakup of incident nuclei.

Distinct equations for protons, neutrons, ^{4}He, ^{3}He, ^{3}H and HN (Heavy Nuclei) have been used. The equations for the isotopes ^{3}He and ^{3}H have been separately considered because they are products of ^{4}He breakup that can lead to further D production. Nuclei heavier than ^{4}He have been considered in the calculation in terms of an equivalent number of ^{12}C nuclei and included in only one equation (for a nucleus of atomic number A, we assumed the same behavior of $(A/12)^{2/3}$ ^{12}C nuclei).

2.1 Deuterium production from air nuclei

For the deuterium production from air target breakup we followed the same approach described by Papini *et al.* (1996). The energy and angular distributions are those obtained from data reported by Powell *et al.* (1959) for cosmic-ray proton interactions in nuclear emulsions.

The angular and energy distribution of the produced deutons have been parametrized in the following form:

$$\Phi(E', E, \theta^*) = 0.85 T(E) F(\theta^*) \omega(E')\,. \tag{2}$$

The function $T(E)$ is the number of deutons produced per single interaction and unit energy; the scale factor 0.85 makes this function proper for air targets. By fitting the experimental data we obtained for $T(E)$ the expression:

$$T(E) = \begin{cases} 0.14\,[E(GeV/n)^{-1.6}] & \text{if } E < 0.5 \text{ GeV/n} \\ 2.07\,\exp[-3.2\;E(GeV/n)] & \text{otherwise.} \end{cases} \tag{3}$$

The function $F(\theta^*)$ represents the angular distribution of the emitted D normalized to the solid angle. The weighting function $\omega(E')$ has been introduced to reproduce the observed increase in the number of emitted fragments for projectile energies up to $\sim\ 1$ GeV/n. Beyond this value the fragment distribution is approximately energy independent. Because of the lack of data for deuterium, both $F(\theta^*)$ and $\omega(E')$ are assumed to be those used for recoil nucleons by Papini *et al.* (1996).

To the production of deuterium from the breakup of air target nuclei contribute both incoming nucleons and nuclei. As a consequence, referring to equation 1, we have for this process:

$$\frac{J(E', \theta', x)}{\lambda(E')} \equiv \frac{J_p(E', \theta', x) + J_n(E', \theta', x)}{\lambda'_p(E')} + \sum_i \langle N \rangle_i \frac{J_i(E', \theta', x)}{\lambda'_i(E')}\,, \tag{4}$$

where the summation is carried out over all considered nuclear species. The scale factor $\langle N \rangle_i$ is introduced when projectiles are nuclei and represents the mean number of participating nucleons during an interaction of a nucleus of species i with an air nucleus. $\langle N \rangle_i$ was estimated on the basis of the work reported by Dar *et al.* (1979): $\langle N \rangle_{^3H,^3He} \sim 1.5$, $\langle N \rangle_{^4He} \sim 1.9$ and $\langle N \rangle_{^{12}C} \sim 3.8$.

In eq.4 $\lambda'_{p(i)}(E')$ denotes the total interaction length of nucleons (nuclei) in air.

2.1.1 Deuterium production from incident nucleons

Nucleons contribute to deuterium production through the reaction (p,n)+(p,n)→ D+π, which occurs between incident nucleons and nucleons inside air nuclei. The cross-section for this process is well measured and shows a pronounced peak at 0.6 GeV (Meyer *et al.* , 1972). This process should be included in the deuterium production from target fragmentation. However, the parameterization described in section 2.1 has been obtained from data on nuclear emulsions averaged over the projectile energy. As a consequence any structure in the D spectrum due to the resonant reaction (p,n)+(p,n)→ D+π is lost. We have included this reaction as a separate production process.

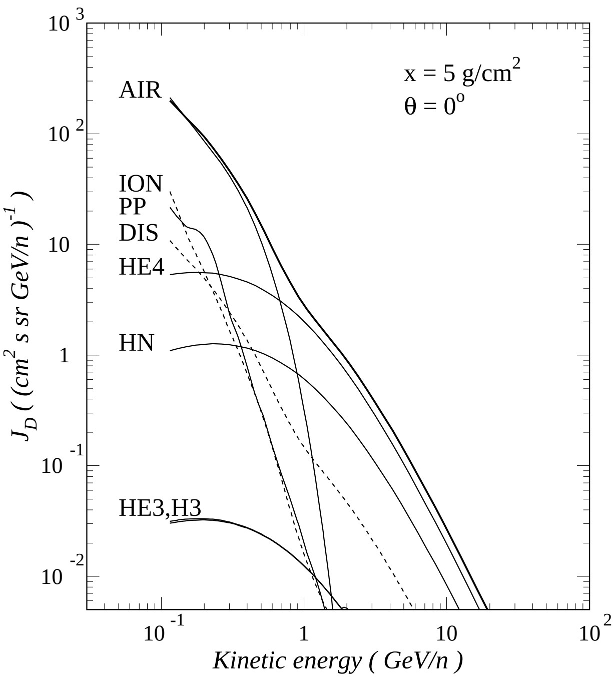

Fig. 1. Contributions to the total flux of deuterium (solid thick line) at the atmospheric depth of 5 g/cm^2 in the vertical direction at solar minimum. The solid lines refer to D production from air target nuclei (AIR), incident nucleons (PP) and nuclei (H3, HE3, HE4 and HN). Dashed lines represent energy losses for D such as ionization (ION) and interactions (DIS).

The deuterium angular and energy distribution for this process is:

$$\Phi(E', E, \theta^*) = \frac{2\,F(\theta^*_{cm})}{M\beta\gamma\beta_\circ\gamma_\circ}\,\delta(cos\theta^* - cos\theta^*_\circ)\,, \tag{5}$$

where $\beta_\circ$ and $\gamma_\circ$ are the velocity and the Lorentz factor of the deuterium in the center-of-mass system, β and γ are those of the center-of-mass in the laboratory system and M is the deuterium mass. The function $F(\theta^*_{cm})$ is the angular distribution normalized to the solid angle and is approximately given by (Meyer *et al.* , 1972):

$$F(\theta^*_{cm}) = \frac{0.22 + \cos^2\theta^*_{cm}}{6.95}\,. \tag{6}$$

The delta function in eq.5 takes into account that, when E', E and θ^* are given, the scattering angle in the laboratory system is fixed.

2.2 Deuterium production from incident nuclei

Since these processes hold at high energy (above ~ 1 GeV/n) we assumed that the energy per nucleon was conserved, therefore equation 1 reduces to

$$P_{i\to j}(E, \theta, x) = \frac{J_i(E, \theta, x)}{\lambda_{i\to j}(E)}\,, \tag{7}$$

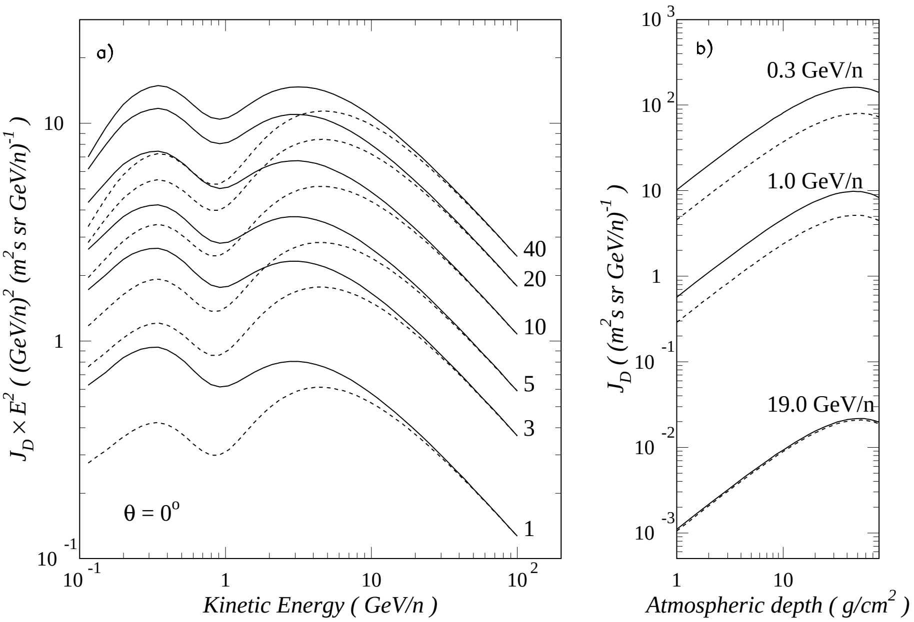

Fig. 2. a) Calculated deuterium energy spectrum (vertical direction) at minimum (solid line) and maximum (dashed line) solar modulation level at various atmospheric depths (g/cm^2). b) Deuterium atmospheric growth curves at different energies at minimum (solid line) and maximum (dashed line) solar modulation.

Table 1. Partial spallation cross-sections (in mb) scaled to air target used in the calculation.

Reaction	Fragment		
	^{4}He	^{3}He,^{3}H	D
^{12}C+air	404±38	132±9	323±29
^{4}He+air	-	57±10	95±30
^{3}He,^{3}H+air	-	-	83.5±14

where i denotes the incident nucleus and j the produced fragment. For the spallation process we used the cross-sections quoted in table 1; these values have been obtained from ^{12}C+^{12}C (Olson *et al.* , 1983), ^{4}He+^{12}C (Abdurakhimov *et al.* , 1981) and ^{3}He+^{1}H (Glagolev *et al.* , 1993) data scaled to air target.

3 Deuterium transport equation

The deuterium production processes discussed in the previous section involve both nucleons and nuclei, we thus need to know their fluxes as a function of the atmospheric depth and of the zenith angle in order to determine the deuterium flux. The equations that describe the evolution of nucleon and nucleus fluxes are essentially those reported by Papini *et al.* (1996) modified to include the nuclear species considered in the calculation.

When all processes are considered at once the transport equation for the deuterium assumes the following expression:

$$\begin{aligned}\frac{\partial J_D(E,\theta,x)}{\partial l} &= \frac{\partial}{\partial E}\left[J_D(E,\theta,x)\left(\frac{dE}{dl}\right)_D\right] + \\ &-\frac{J_D(E,\theta,x)}{\lambda'_D(E)} + \\ &+P_{air}(E,\theta,x) + P_{pp\to D\pi}(E,\theta,x) + \\ &+\sum_i \frac{J_i(E,\theta,x)}{\lambda_{i\to D}(E)}\end{aligned} \qquad (8)$$

The term on the l.h.s. of eq.8 represents the deuterium flux variation per unit length in the θ direction (dl). The first two terms on the r.h.s. of eq.8 take care of ionization energy losses and loss of particles due to interactions. The following terms include of the deuterium production through the processes described in section 2.

4 The calculation

We solved the set of coupled transport equations simultaneously, by assuming a flat atmosphere (so that $l = x/cos(\theta)$) and using a 1th-order Runge-Kutta technique with step size $\Delta x = 0.003$ g/cm^2. The calculation was carried out, starting from the top of the atmosphere, to an atmospheric depth of 80 g/cm^2 and up to $\theta = 85°$. The step size was chosen in order to make the energy losses for low energy carbon nuclei at large zenith angles negligible compared to their energy.

Input primary energy fluxes for protons, ^{4}He and HN have been parametrized from experimental data at both minimum and maximum solar modulation. We estimated the primary HN flux to be equivalent to ~ 3.80 times the carbon flux.

5 Results and discussion

Fig.1 shows how different production processes contribute to the overall deuterium energy flux at the atmospheric depth of 5 g/cm^2 in the vertical direction and at solar minimum. At low energy the deuterium production is dominated by the breakup of the air target nuclei; the shape of the spectrum reflects that of the emitted fragments (eq.3). This process dominates up to about ~ 1 GeV/n. Deuterium production from

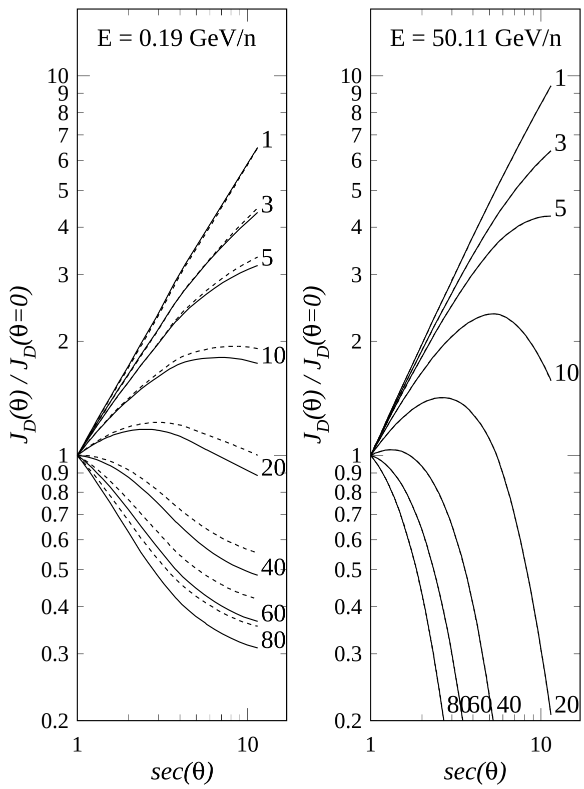

Fig. 3. Deuterium flux, normalized to the flux in the vertical direction, as a function of the zenith angle at minimum (solid line) and maximum (dashed line) solar modulation level at different atmospheric depths (g/cm^2).

incident nucleons gives a non-negligible contribution at very low energy only (up to about ~ 300 MeV/n). The structures present in the spectrum resulting from this process are due to kinematic effects; in particular the peak at ~ 200 MeV/n corresponds to deuterium production in the forward direction in the center of mass system (see eq.6). At higher energy the incident nuclei spallation process dominates. Deuterium is mainly produced by ^{4}He, even if HN play a significant role. Production from ^{3}H and ^{3}He is negligible at small atmospheric depths.

Fig.2a shows the resulting deuterium energy spectrum in the vertical direction at different atmospheric depths and in fig.2b we have reported the growth curves. It can be noted that the deuterium flux begins to attenuate at about ~ 50 g/cm^2.

Fig.3 finally shows the deuterium flux as a function of the zenith angle, normalized to the flux in the vertical direction. At higher energies (right figure), where the spallation dominates, the deuterium is essentially produced in the forward direction. It follows that, at a given depth in a given direction, the produced deuterium is approximately proportional to the path l traversed by nuclei through the atmosphere. This proportionality holds up to $l \sim \lambda$, where λ is the deuterium attenuation length that, at high energies, is given by the interaction length (~ 50 g/cm^2). As an example, at a depth of 5 g/cm^2 the flux increases up to $sec(\theta) \sim 10$ and then it begins to decrease because of primary fluxattenuation. For increasing depths the maximum moves toward lower zenith angle, down to a depth $x \sim \lambda$. Starting from this depth the flux decreases for increasing zenith angles.

At lower energies (left figure) the production from air target nuclei dominates. Deuterium is still mainly produced in the forward direction (Papini *et al.* , 1996), therefore the same arguments used for the high energy flux can approximately be applied. Please note that the position of the maximum is determined by the attenuation length which is now affected by ionization losses. For increasing angle the flux doesn't decrease but flattens. This is a consequence of the isotropic component in the production term (Papini *et al.* , 1996).

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