The Secondary Proton Spectrum at Small Atmospheric Depths

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Abstract

Secondary protons are produced during the propagation of primary cosmic ray nuclei through the atmosphere and the fragmentation of air nuclei dominates this production below 1 GeV/n. By analyzing the available experimental data on light fragments produced in nucleus-nucleus collisions, a new parameterization has been developed for the energy and angular distributions of these fragments from 10 MeV/n to 1 GeV/n. Using this parameterization, we have determined the energy spectra of secondary protons from 100 MeV to 100 GeV, as a function of the depth and zenith angle in the atmosphere.

1. Introduction

When cosmic rays enter the atmosphere, they interact with air nuclei producing secondary protons, both from the spallation of the projectiles and the fragmentation of the target nuclei. The latter component dominates below ~ 1 GeV. The most extensive work of this component is that of Papini et al. [1]. Based on this work and using a larger set of measured cross-sections[2-4], we developed a new parameterization for the production of recoil protons and the fragmentation of the target nuclei. Most of the available accelerator data refer to the production of protons and light nuclei at large emission angles. In order to parameterize the production of fragments in the forward direction, we used nuclear emulsion data, which cover interaction products in all the directions. In particular, we based our parameterization on the compilation by Powell et al [5]. These data were obtained from nuclear emulsions exposed to the cosmic rays by balloons at larger atmospheric depths. This feature is important for this work, since the results are wighted over the cosmic-ray energy spectrum.

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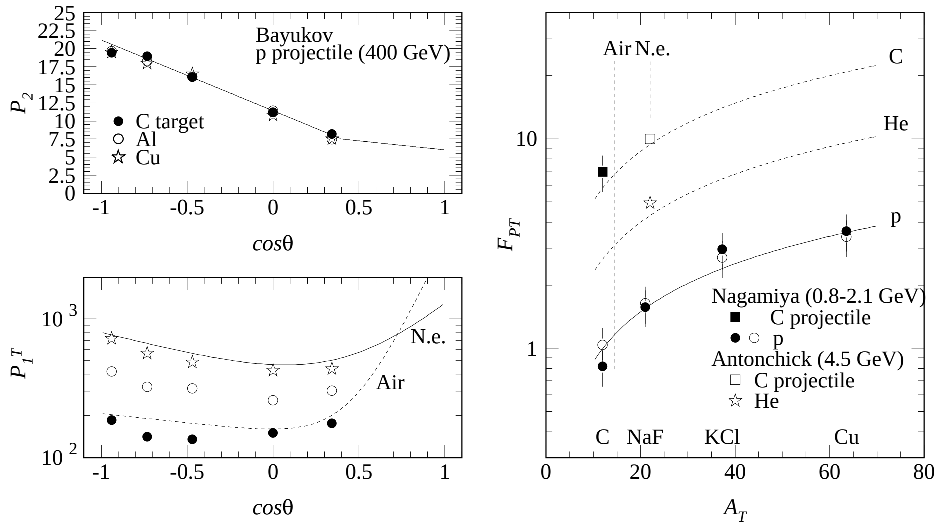

Fig. 1. Value of the parameters for the process of proton recoil from target nuclei as a function of emission angle, target and projectile masses. See text for explanation.

2. Differential cross-section for the production of recoil protons

The differential cross-section for the production of recoil protons was parameterized using the expression:

$$\left(\frac{d^3\sigma}{dEd\Omega}\right) = F_{PT}\,\omega(E')\,P_1^T(\theta)\exp\left[-P_2(\theta)E\right] \ , \qquad (1)$$

where E' is the kinetic energy of the projectile, E is that of the recoil protons and θ is the emission angle. The spectrum of recoil protons is described by exponential functions, in which both the parameters P_1^T and P_2 are functions of the emission angle θ. P_1^T is also dependent on the target (T) mass. The factor F_{PT} depends on both the projectile (P) and the target mass, and is defined in such a way to include the dependence of the total inclusive cross-section on the target. The function $\omega(E')$ takes into account the dependence of the recoil-proton number on the projectile energy.

The factor F_{PT} was first derived for p-nucleus collisions by fitting data from ref. [4] (solid curve in the left plot of fig. 1.), then scaled to heavier projectiles according to the mean number of participating nucleons in the target nucleus. The resulting values are shown by the dotted curves in fig. 1. for carbon and helium projectiles, along with some experimental data[2,4].

P_1^T and P_2 were parameterized at large emission angles using data from Bayukov *et al.* [3], who measured the differential cross-section for the production of protons in p-nucleus collisions for θ ranging from 70° to 160°. The measured differential cross-section, divided by F_{pT}, was fitted with exponential functions.

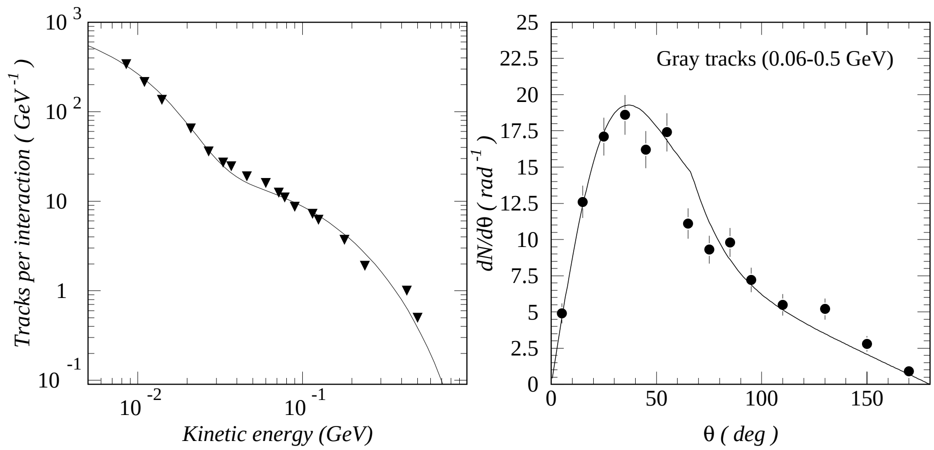

Fig. 2. Experimental data on nuclear emulsion target from Powell et al.[5]. Left figure: energy spectrum of emitted singly charged particles per interaction. Right figure: angular distribution of gray tracks. Data are compared with the parameterization.

The resulting values for the parameters are shown in fig. 1. (left plots) for C, Al and Cu targets.

To extend this parameterization to the forward emission angles, we used the nuclear emulsion data [5]. We adjusted the parameters $P_1^T(\theta)$ and $P_2(\theta)$ in the range $0.4 < cos\theta \leq 1$ to match the energy distribution of singly charged tracks per interaction and the angular distribution of gray tracks. Since the angular distribution is very sensitive to $P_1^{N.e.}(\theta)$, this parameter was first determined at large angles using the accelerator data [3] and then extrapolated in the forward direction in order to reproduce the gray-track angular distribution (fig. 2.). The derived expression is shown by solid line in the lower left plot of fig. 1.. On the other hand, the recoil proton spectrum is very sensitive to $P_2(\theta)$. The Powell spectrum set the minimum value of ~ 6 for this parameter in the forward direction and the solid line in the upper plot of fig. 1. shows the behavior of $P_2(\theta)$. A comparison between the parameterization and data[5] is shown in fig. 2.. In order to calculate the number of track per interaction as a function of the energy, the evaporation process[4] was added to the recoil proton distribution.

In order to describe the production of recoil protons during the propagation of cosmic rays in the atmosphere, these parameters were scaled to air target nuclei. Since the projectile and target mass dependence are included in F_{PT}, $P_1^{Air}(\theta)$ was scaled by first interpolating the data at large emission angle to the proper target mass. It was then extrapolated to the forward direction in such a way to conserve the total inclusive cross-section divided by F_{PT} integrated over the angle and energy. The resultant $P_1^{Air}(\theta)$ is shown by dashed curve in the lower left plot of fig. 1., which falls close to the carbon data.

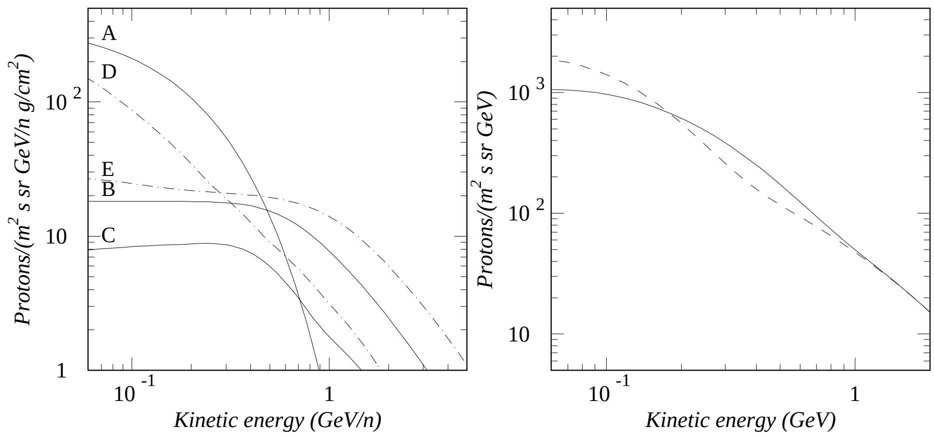

Fig. 3. Left: production (solid curves) and attenuation (dot-dashed curves) of protons, as a function of energy, at an atmospheric depth of 5 g/cm^2 for minimum solar modulation. The processes included are recoil from air target nuclei (A), cosmic-ray inelastic interactions (B) and spallation (C), and loss by ionization (D) and interactions (E). Right: spectrum of secondary protons at 5 g/cm^2 (solid curve) compared with that obtained with the earlier parameterization (dashed curve).

3. Results

A set of atmospheric transport equations described in ref.[6] was solved using the new parameterization to estimate the recoil nucleon production term. The left plot in fig. 3. shows all the production and attenuation terms in the proton transport equation, at 5 g/cm^2 for the period of minimum solar modulation. The right plot shows the absolute spectrum of secondary protons, compared with that obtained using the previous parameterization of the recoil process.

4. References

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