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Nuclear Cosmic Rays propagation in the Atmosphere

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Abstract: The transport of the nuclear cosmic ray flux in the atmosphere is studied and the atmospheric corrections to be applied to the measurements are calculated. The contribution of the calculated corrections to the accuracy of the experimental results are discussed and evaluated over the kinetic energy range 10-10^3 GeV/n. The Boron (B) and Carbon (C) elements system is used as a test case. It is shown that the required corrections become largely dominant at the highest energies investigated. The results are discussed.

Introduction

The direct measurement of nuclear cosmic rays (CR) by balloon borne experiments like CREAM [1] is a precious tool to understand the cosmic rays propagation process in the Galaxy. Among the different observables, the secondary-to-primary ratios of nuclear CR like B/C play a predominant role because they measure directly the thickness of matter crossed by CR and therefore tell us about their confinement in the Galaxy. In addition, the CR flux entering the atmosphere undergoes nuclear fragmentation by interaction with the atmospheric nuclei, producing more secondaries and therefore enhancing the measured secondary-to-primary ratios.

At high energy, the confinement of cosmic rays in the Galaxy becomes less and less efficient. The thickness of matter crossed in the Galaxy is therefore decreasing with energy whereas the thickness of matter crossed in the atmosphere overhead the detector remains constant with energy. The production of secondaries in the atmosphere is then becoming dominant at high energy.

The purpose of this work is to propose a framework to compute the evolution of the nuclear cosmic ray composition in the atmosphere, taking into account the absorption and fragmentation processes. It can be used to reconstruct the top of atmosphere (TOA) flux from the value measured by a detector in the atmosphere. The effects of statistical and systematic errors on this reconstruction are also carefully studied.

Transport model

The weighted slab model (WSM) provides a particularly appropriate framework for the calculations since in this approach, the variable of the transport equation is the amount of matter crossed by the particles (grammage), see Ref. [2] and references of this paper for details on the WSM. In this model the transport equation can be written at a given kinetic energy per nucleon E_k, as:

$$\frac{\mathrm{d}N_i(x,E_k)}{\mathrm{d}x} = \sum_T \frac{R_T(x)}{m_T} \times \left\{ -\sigma_{iT}(E_k)N_i(x,E_k) + \sum_{j>i} \sigma^j_{iT} N_j(x,E_k) \right\}, \quad (1)$$

where N_i is the abundance of nuclear element i at atmospheric depth x, m_T being the target mass, σ_{iR} the total reaction cross section and σ^j_i the fragmentation cross section from a nucleus j to a (lighter, $i < j$) nucleus i. The TOA flux from ref [3] were solar modulated and used for the initial conditions $N_i(0)$. The sum over T corresponds to the various components of the atmosphere, with mass m_T and fraction $R_T(x) = \frac{\rho_T(x)}{\rho_{\mathrm{tot}}(x)}$, which does not change significantly for the altitudes between ground and 200 km for the three main constituents [4]. The numerical approach of the problem has to be handled with care. The inversion of equation 2 where the TOA flux has to be computed from the measured values leads to numerical difficulties and lengthy calculations if the direct integration method is used. In this work, the numerical calculations were instead, performed using the simpler, easier to handle, matrix formulation of the problem, in which the inversion is easy to achieve.

In this framework, the transport equation 2 can be expressed as:

$$\frac{\mathrm{d}\tilde{N}(x,E_k)}{\mathrm{d}x} = S(x,E_k)\tilde{N}(x,E_k) \qquad (2)$$

where $\tilde{N}(x,E_k)$ is the vector containing all the elemental abundances $N_i(x,E_k)$ of the considered CR flux for a traversed grammage of x g/cm^2 in the atmosphere. S is the transformation matrix. It is a triangular matrix, with the diagonal elements of S corresponding to the nuclear absorption and the other elements to the production of secondary nuclei. The solution of 2 is given by:

$$\tilde{N}(x,E_k) = R(x,E_k)\tilde{N}(0,E_k) \qquad (3)$$

where $R(x,E_k) = \exp\left(S(x,E_k)\right)$ is the transfer (transport) matrix.

To compute the S and R matrix, the parametrization from [5] was used for the total reaction cross sections σ_{iT}, while the fit formula from [6] was used for the fragmentation cross sections σ^j_{iT}. In this latter case however, the formula applied mainly to H and He targets. Its application was extended here to larger masses using a factorization approximation [7].

The atmosphere model from [4] was used in these calculations.

Results

Figure 1 shows the non-propagated and propagated cosmic ray fluxes from a calculation for a spectral index of the diffusion coefficient $\delta = 0.3$, versus the energy per nucleon and the correspondant B/C ratio for different values of the spectral index of the diffusion coefficient δ = 0.3, 0.46, 0.6, 0.7, and 0.85. It can be seen that at the highest energy considered, the flux values at TOA (solid lines) and at the balloon detection altitude after crossing 5 g/cm^2 of atmosphere (dashed lines), differ by approximately a factor of two for small values of δ, and by more than one order of magnitude for the largest values. This is easy to understand since for larger δ the alactic contribution at high energy becomes dominated by the atmospheric contribution. The asymptotic limit of this behavior can be observed with the propagated ratio tending to flatten out at high energy above 1 TeV/n for large values of δ where the galactic secondaries production becomes negligible.

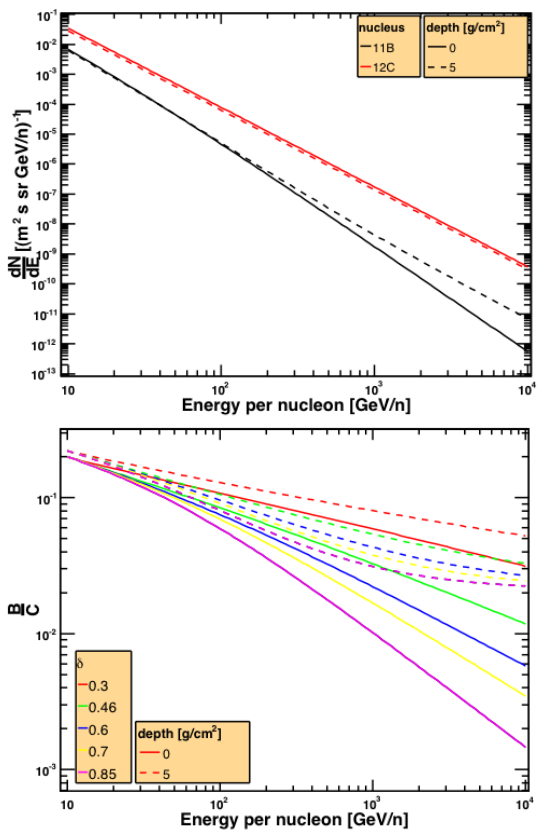

Figure 1: Results of the transport calculations for C and B nuclei. Top: Differential fluxes with $\delta = 0.3$ at TOA (solid lines) and for a crossed matter thickness of 5 g/cm^2 (dashed lines) for ^{12}C (upper curves) and ^{11}B (lower curves). Bottom: B/C ratio at TOA (solid lines) and after propagation (dashed lines) for δ: 0.3, 0.46, 0.6, 0.7, 0.85, from top to bottom respectively. All curves as a function of the kinetic energy per nucleon.

This illustrative example shows how critical are the corrections to be applied to the measured flux values in balloon experiments, and thus how important is a careful study of CR transport in the atmosphere for a reliable results in TOA flux evaluations from atmospheric measurements. In the high energy region, the measured raw B/C value appears to be about one order of magnitude larger than the TOA flux value to be extracted from it.

The flux at TOA can be reconstructed from the flux measured at a given thickness x by inverting the equation 3:

$$\tilde{N}(0, E_k) = R(x, E_k)^{-1}\tilde{N}(x, E_k)$$

But in the inversion process, distortions may be generated by the random (statistical) fluctuations of the experimentally measured fluxes $\tilde{N}(x, E_k)$. Correcting for these distortions is equivalent to the unfolding [8] of a measured spectrum from the detector response, the role of the latter being played here by the transfer function (inverted matrix). This effect has been shown to be negligible for the grammage (5 g/cm^2) considered in this study [9].

The uncertainties induced on the flux calculations by the experimental uncertainties on the nuclear cross-sections have been estimated by the following way for three values of the spectral index of the diffusion coefficient δ=0.3, 0.6 and 0.85, covering the range of realistic values [10, 11]:

A sample of one hundred transfer matrix $R^{err}(x, E_k)$ was generated by adding randomly a $\pm 5\%$ systematic error to the total reaction cross sections (diagonal elements), and $\pm 10\%$ to the fragmentation cross sections (off diagonal elements) in $R(x, E_k)$. The measured fluxes were calculated using the error added matrix

$$\tilde{N}^{\rm err}(x, E_k) = R^{\rm err}(x, E_k)\tilde{N}(0, E_k),$$

and the TOA fluxes were reconstructed by the inversion procedure using the nominal matrix $R(x)$:

$$\tilde{N}^{\rm err}(0, E_k) = R^{-1}(x, E_k)\tilde{N}^{\rm err}(x, E_k),$$

Then the B/C ratios were calculated for each energy E_k, and the minimal and maximal values of B/C were searched in the 100 values calculated with the error-added matrices, and used as an estimate of the upper and lower limits of the uncertainties induced by the systematic errors on cross sections. Figure 2 shows the results from these calculations for three values of the spectral index of the diffusion coefficient δ=0.3, 0.6 and 0.85, covering the range of realistic values [10, 11]. The values obtained from the inversion of $R(x)$ are taken as central values. These results show that as expected from fig 1, for $\delta = 0.3$ the systematic error is increasing with energy, but remains relatively small over the whole energy range, in contrast with the $\delta = 0.85$ result, where it becomes large, extending over almost a factor 2 at high energy. As already mentioned, this can be easily understood since for $\delta = 0.85$ more secondaries are produced in the Earth's atmosphere compared to the secondary galactic flux compared with the $\delta = 0.3$ productions (see figure 1).

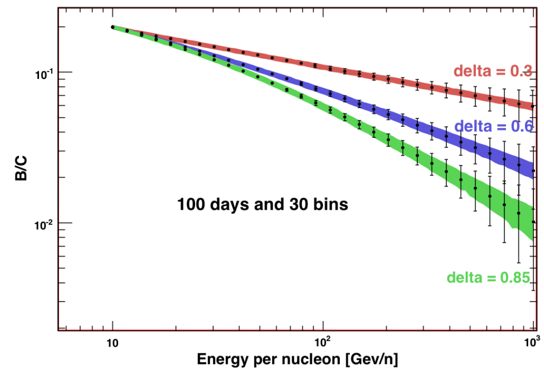

Figure 2: The filled areas show the systematic error region obtained by the method described in the text, for the three different values of δ = 0.3, 0.6, 0.85. The statistical error appear as the error bars on the figure. They were calculated for 100 days of effective counting and for 15 energy bins per decade of energy.

Another question to be addressed is what counting statistics is needed for the measurements to be dominated by systematics errors. A simple evaluation was made by assuming a detector acceptance of 1 $m^2\,sr$, and taking 30 bins over the energy range 10-1000 GeV/n, and 100 days of measurement time. The obtained values are shown as error bars on the B/C ratios on Fig. 2 for the three values of spectral indices δ. It can be seen on the figure that the statistical error is dominant for high energies ($E_k > 200$ GeV/n) for the assumed experimental condition. A more quantitative study comparable to that reported in [11] remains to be performed. In this reference, a χ^2 minimization procedure on the simulated B/C data was performed, to evaluate the accuracy in the determination of δ due to statistical errors, with all the propagation parameters left free. The estimated statistical uncertainty on the determination of δ was 10-15% for experiments like CREAM.

Summary and conclusion

The raw CR flux of nuclear elements measured in balloon experiments must undergo significant corrections for the effects of propagation in the atmosphere, to provide a reliable measurement of the TOA fluxes. These corrections become larger with the increasing energy and with increasing diffusion spectral index. Due to the uncertainties on the absorption and fragmentation cross sections, they dramatically affect the accuracy of the experimental values at high energy, but the measurements keep a good part of their capacity to discriminate between the values of δ predicted by the various models.

Since the same fragmentation process takes place in the detectors, similar results can be expected, and the measured raw flux would have to be corrected by a similar procedure as reported in this paper to account for the flux propagation inside the detector material. The correction will of course depend on the architecture of the apparatus of the experiment and of the amount of matter upstream of the charge measurement detector(s).

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