The Production of Antiprotons in the Upper Atmosphere by Interacting Primary Cosmic Rays

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Abstract

We calculate the $\bar{p}$ -background in the upper atmosphere which results when primary cosmic rays interact with air-nuclei. Since the $\bar{p}$ -yield from p -nucleus and nucleus-nucleus interactions are not directly known from experiments we derive these quantities by using a Monte Carlo simulation which is theoretically based on the Dual Parton Model and which had been successfully applied to the description of hadron production in high energy collisions. Results on the calculated atmospheric $\bar{p}$ -background indicate a larger $\bar{p}$ -background than earlier estimates predicted, particularly at low energies.

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I. INTRODUCTION

Antiprotons are a rare component of the cosmic radiation and all the available data on the antiproton flux have been measured by balloon borne instruments primarily by means of magnetic spectrometers [1,2,3,4,5,6,7,8]. Thus the measured flux at balloon flight altitudes behind typically 5-10 g/cm² residual atmosphere is a superposition of the primary galactic antiprotons and those secondarily produced in the atmosphere by other primary cosmic ray particles which interact with oxygen and nitrogen in the air. Corrections for these secondarily produced antiprotons in air are required in order to deduce the primary galactic antiprotons. An important input into such a calculation are the $\bar{p}$ production cross sections from interactions like proton-nucleus and nucleus-nucleus. But unfortunately, this information is not well known. There are no experimental data available from experiments at accelerators for these complex interactions. This is different for pure pp -collisions which are well studied and reliable inclusive differential p -production cross sections exist. Thus earlier estimates on atmospheric $\bar{p}$ predictions used this information and approximated the most important p -nucleus collision (protons are the most abundant primary component in the cosmic radiation) by a pp -collision [9] and for the even more complex nucleus-nucleus interactions one made use of scaling factors [10,11].

The situation can be improved by applying Monte Carlo models for high energy particle production to the estimation of the atmospheric $\bar{p}$ -yield. In the present paper we use the Monte Carlo code DTUNUC [12] which is based on the Dual Parton Model (DPM) (a review is given in [13]) and it provides a framework for the study of high energy hadron-hadron, hadron-nucleus and nucleus-nucleus interactions and it describes successfully main features of soft hadronic particle production.

II. RESULTS FROM THE MONTE CARLO SIMULATION

The Monte Carlo Model DTUNUC [12] for hadron-nucleus and nucleus-nucleus interactions incorporates various modern aspects of high energy physics.

The Glauber's multiple scattering formalism [14] accounts for the number of elementary interactions between the target and projectile nucleons and the Dual Parton Model [13] describes the particle production in each nucleon-nucleon interaction. The chains which connect the partons of the nucleons involved in the interaction finally hadronize applying the model JETSET [15]. It is also allowed that the hadrons cause intranuclear cascade processes which are treated by a formation zone intranuclear cascade model [16]. This Monte Carlo Model has been successfully applied to the description of hadron production in high energy collisions [12,17].

With the existing code we studied on an event by event basis for various projectiles of different energies the $\bar{p}$ yield from collisions with oxygen and nitrogen targets. Characteristic details can be taken from the sequence of the following figures. In Fig. 1 we show the differential $\bar{p}$ -yield per interaction for a p -oxygen and a pp -collision where the incoming proton had an energy of 40 GeV. The abscissa displays the energy of the $\bar{p}$ and the ordinate the relative $\bar{p}$ -yield per interaction. The error bars represent the statistical uncertainties of the Monte Carlo simulation. The curve through the data points which refer to the p -oxygen interaction is just a mathematical fit to these simulated data and they finally serve as inputs into our transport calculation, which will be described in the next chapter. The curve through the points which refer to the pp -interaction is actually not a mathematical fit to these simulated data. This curve results from an analytic formula developed by Tan and Ng [18] which is constructed in such a way that it fits the experimental data from colliding beam experiments at accelerators. The agreement between the results of DTUNUC and the fit of Tan and Ng [18] is an indication that the Monte Carlo model successfully describes main aspects of antiproton production in hadron-hadron interactions. Fig. 1 further demonstrates very clearly that a pp -interaction differs in its $\bar{p}$ -yield quite distinctively from a p -oxygen

interaction and these differences depend also on the energy of the incoming proton. These results reflect the fact that more than just one target nucleon is involved in the interaction. As a basic result: antiprotons at low energies emerge much more frequently from a p -oxygen interaction than from a pp -interaction and the overall $\bar{p}$ -yield increases at all energies when the energy of the projectile increases.

In Figs. 2, 3 and 4 we present results from different incident nuclei (helium, oxygen and iron) which hit an oxygen target with an energy of 40 GeV/nucleon. Again, it follows from the model that the $\bar{p}$ -yield is increasing with the number of interacting nucleons and therefore with the mass number and energy of the projectile nucleus. As an example, a helium-oxygen interaction would produce 3 times more antiprotons with an energy of 2 GeV than one would predict it for a pp -interaction and for an oxygen-oxygen interaction it is 6 times more and for an iron-oxygen interaction even 9 times.

We used fits through many of these simulated $\bar{p}$ -yields and for the oxygen target we constructed a three dimensional net which allowed us to derive the $\bar{p}$ -yield at all $\bar{p}$ -energies and for different energies of the projectile. Since oxygen and nitrogen are close in mass number we treated both nuclei the same way.

III. THE ATMOSPHERIC CALCULATION

The transport equation which describes the production and the propagation of antiprotons in the atmosphere is given by

$$\begin{aligned} & \frac{\partial N_{\bar{p}}(x, E_{\bar{p}})}{\partial x} + \frac{\partial}{\partial E_{\bar{p}}} \left\{ \left\langle \frac{\partial E_{\bar{p}}}{\partial x} \right\rangle \cdot N_{\bar{p}}(x, E_{\bar{p}}) \right\} + \frac{N_{\bar{p}}(x, E_{\bar{p}})}{\lambda_{int}(E_{\bar{p}})} \\ & - \sum_A \frac{1}{\langle m_{air} \rangle} \int_{E_{th}}^{\cdot} N_A(E_A) \cdot \frac{d\sigma}{dE_{\bar{p}}}(E_{\bar{p}}, E_A) dE_A - \int_{E_{\bar{p}}}^{\infty} \frac{1}{E'_{\bar{p}}} \cdot \frac{N_{\bar{p}}(x, E'_{\bar{p}})}{\lambda_{\bar{p},air}^{non}(E'_{\bar{p}})} dE'_{\bar{p}} = 0 \end{aligned} \quad (1)$$

This differential equation has production terms, loss terms and energy changing terms and carries various total and partial cross sections. $N_{\bar{p}}(x, E_{\bar{p}})$ is the differential intensity of antiprotons with kinetic energy $E_{\bar{p}}$ behind a slab of matter x (g/cm²). The second term describes energy losses due to ionization which we calculated by using a computer code

developed by Salamon and Ahlen [19]. The third term represents $\bar{p}$ losses due to interactions in air and in Fig. 5 we show experimental data on total inelastic cross section for p -carbon and $\bar{p}$ -carbon interactions [20,21,22,23]. For the $\bar{p}$ losses we need the upper curve and we scaled it to air-targets with an $A^{2/3}$ dependence. The fourth term actually accounts for the $\bar{p}$ production. The quantity $\langle m_{air} \rangle$ in front of the integral stands for the mean mass of the target air and in our calculation it had a value of $\langle m_{air} \rangle = 14.58$ amu (78.5% nitrogen, 21.5% oxygen). $N_A(E_A)$ means the differential flux of primary particles of mass A and energy E_A which produce antiprotons of energy $E_{\bar{p}}$ according to the inclusive differential cross section $\frac{d\sigma}{dE_{\bar{p}}}(E_{\bar{p}}, E_A)$ which we derive from the Monte Carlo simulation by multiplying the $\bar{p}$ -yields as given in the previous chapter by the total inelastic cross section of the incoming particle interacting in air. For protons this total inelastic cross section was taken from a formula developed by Letaw et al. [24].

$$\sigma_{inel}^{tot}(E_p, A) = \sigma_0 \cdot \left[1 - 0.62 \exp\left(-\frac{E_p}{200}\right) \cdot \sin(10.9 E_p^{-0.28}) \right] (mb) \quad (2)$$

with

$$\sigma_0 = 45 \cdot A^{0.7} [1 + 0.016 \sin(5.3 - 2.63 \ln A)] (mb) \quad (3)$$

E_p means the energy of the incoming proton in units of MeV and A means the mass of the target in amu. This energy dependent parametrization describes the various experimental data quite well and in Fig. 5 we show as an example how this formula fits the data derived from a measurement with a carbon target (lower curve). For our calculation we only need the high energy limit of this formula since the kinematic threshold, E_{th} , for producing a $\bar{p}$ is 6 times the rest mass of the nucleon [25]. Protons above this energy then encounter a constant mean free path in air of $\lambda_{p,air} = 76.6$ g/cm².

For the more heavy projectiles we used the following parametrization [26]

$$\sigma_{inel}^{tot} = 10 \cdot \pi \cdot r_0^2 [A_p^{1/3} + A_t^{1/3} - \delta]^2 (mb) \quad (4)$$

$$r_0 = 1.47$$

$$\delta = 1.12$$

where A_p and A_t stands for the mass number of the projectile and the target, respectively. The use of this formula leads for helium to a mean free path in air of $\lambda_{He,air} = 42.3 \text{ g/cm}^2$. The integral over this $\bar{p}$ production term in equation (1) then stretches over the differential energy spectrum of the interacting primary particles for energies above the kinematic threshold E_{th} and the sum runs over the different primary components.

The last term in the transport equation (1) accounts for the fact that antiprotons which itself interact in air do not necessarily disappear by annihilation. There is a probability that again an antiproton emerges from such an interaction with an energy lower than that of the incoming antiproton. In this term it is assumed that the emerging $\bar{p}$ has a flat distribution in energy between zero and the energy E'_p of the incoming antiproton. This effect spills high energy interacting antiprotons down to lower energies. $N_{\bar{p}}(x, E'_p)$ means the differential $\bar{p}$ flux at energy E'_p and at atmospheric depth $x \text{ (g/cm}^2\text{)}$ and the integral stretches over all $\bar{p}$ energies which are above the energy $E_{\bar{p}}$ considered. The $\lambda_{\bar{p},air}^{non}(E'_p)$ is the mean free path for nonannihilation. Since this quantity is not directly measured on air targets we scaled it from the known $\bar{p}p$ interaction:

$$\sigma_{\bar{p},air}^{non}(E_{\bar{p}}) = \sigma_{\bar{p}p}^{non}(E_{\bar{p}}) \cdot \frac{[\sigma_{\bar{p},air}(E_{\bar{p}})]_{inel}^{tot}}{[\sigma_{\bar{p}p}(E_{\bar{p}})]_{inel}^{tot}} \quad (5)$$

where $\sigma_{\bar{p}p}^{non}(E_{\bar{p}})$ and $[\sigma_{\bar{p}p}(E_{\bar{p}})]_{inel}^{tot}$ where taken from Tan and Ng [27] and $[\sigma_{\bar{p},air}(E_{\bar{p}})]_{inel}^{tot}$ is known from Fig. 5.

IV. RESULTS

We solved the differential transport equation (1) numerically for different path lengths $x \text{ (g/cm}^2\text{)}$ using the implicit method by Crank and Nicholson [28] see also Heinbach and Simon [29]. Beside the cross sections the primary spectra of cosmic ray particles which impinge upon the atmosphere, and their relative abundances play an important role as inputs into this calculation. This is particularly true for protons and helium, since they provide more than 99% of the total flux of primary cosmic rays nuclei. Unfortunately,

the situation in the literature on measured proton and helium spectra is controversy, since published data obtained from different instruments differ by almost up to a factor of two.

In Fig. 6 we show two published proton spectra which differ almost by that factor. The lower curve refers to a measurement performed with the LEAP-experiment, E.S. Seo et al. [30], and the upper curve is a publication from Webber et al. [31] which uses the former New Mexico State University magnetic spectrometer. Since these two spectra reflect roughly the upper and lower limit of other published primary flux data, see also Gaisser and Schaefer [31], we used these two proton spectra as inputs into our calculation. This will determine the absolute atmospheric $\bar{p}$ -flux within these limits. The helium spectra which we used are also those from these two authors (Seo et al. [30], Webber et al. [31]) while the spectra on the cosmic ray nuclei were taken from a compilation of Wiebel [33]. In Fig. 7 we present the calculated $\bar{p}$ -flux behind an air layer of 5 g/cm^2 . In this calculation the proton and helium flux from the LEAP-experiment [30] served as an input. The different curves then illustrate how the different primary components contribute to the production of secondary atmospheric antiprotons. The primary protons provide by far the biggest contribution to the flux of atmospheric antiprotons and that is true at all $\bar{p}$ energies. The helium contributes roughly 15% to the atmospheric antiprotons which is roughly twice that of their primary abundance at the top of the atmosphere relative to the protons. It reflects the enhanced $\bar{p}$ yield from a helium-oxygen interaction compared to a p -oxygen interaction as illustrated in Fig. 1 and Fig. 2. The contribution from all the heavy nuclei sums up to roughly 6% indicating that the higher $\bar{p}$ -yield from their interactions, see figures in chapter 2, does not compensate their low abundance.

In Fig. 8 we show the calculated total atmospheric $\bar{p}$ -flux in an atmospheric depth of 5 g/cm^2 . There are three curves. Two curves stem from our calculation. It is the full line and the dashed line. Both differ by their inputs concerning the primary proton and helium flux. The upper curve uses the upper proton and helium flux values as published by Webber et al. [31] and the lower curve uses those given by the LEAP-experiment [30]. Solely based on these uncertainties in the inputs the absolute $\bar{p}$ -flux remains uncertain within

these two curves. The third curve (dotted curve) is an earlier and the only other existing calculation on the atmospheric $\bar{p}$ background published by Stephens [10]. This curve was taken from a figure of his publication. Despite the problem in comparing calculated results which are based on different inputs (cross sections, spectra etc.) we used this earlier result from Stephens for comparison. The overall agreement between all these curves in Fig. 8 is not bad. All curves peak around some GeVs which results from a combination of kinematic, energy dependent cross sections and the steep falling incident primary cosmic ray spectra. Then all three curves fall off to higher and lower energies. But there are also systematic differences visible in the shapes of these curves. Our results are broader around the peak and show a much smoother fall off to lower energies. This enhances the number of atmospheric antiprotons at low energies quite considerably and it may be as much as 3 times compared to earlier estimates.

We attribute this enhanced $\bar{p}$ flux at low energies to the new $\bar{p}$ production cross sections for p -nucleus and nucleus-nucleus interactions which we use here and which we derived by means of the Monte Carlo simulation and it is not due to the inelastic $\bar{p}$ scattering term (last term in the transport equation (1)). A calculation without this term only lowered the $\bar{p}$ flux at low energies by about 30%.

In Fig. 9 we present results on calculated $\bar{p}$ fluxes for different atmospheric depths. These results are presented as ratios relative to the secondary $\bar{p}$ flux behind 1 g/cm^2 of atmosphere. As one can see at energies above roughly 400 MeV the secondary atmospheric $\bar{p}$ flux increases almost linearly with depth. At low energies, however, one observes a much stronger increase. This is partially due to the ionization energy loss but predominantly determined by the inelastic scatter of antiprotons in the atmosphere (last term in the transport equation).

V. CONCLUSIONS

In this paper we calculated the $\bar{p}$ flux in the atmosphere which results from the interaction of primary cosmic rays with air nuclei. We derived the $\bar{p}$ yield from these complex nucleus-nucleus interactions from a Monte Carlo simulation code which is designed to study hadron-hadron and nucleus-nucleus collisions since directly measured $\bar{p}$ cross sections are not available. The result on the $\bar{p}$ yield from these interactions are presented and discussed. From these results we conclude that a p -oxygen interaction differs in its $\bar{p}$ yield considerably from a pure pp collision. One obtains an enhanced $\bar{p}$ yield and this enhancement depends on the energy of the emerging $\bar{p}$ and also on the energy of the incoming projectile. Similar dependences could also be seen in nucleus-nucleus interactions. With these new inputs the calculations on the atmospheric $\bar{p}$ background are presented and discussed. As a main result we conclude that particularly at low energy the atmospheric $\bar{p}$ background seems to be considerably higher than earlier estimates predict. This would lead to a larger $\bar{p}$ correction factor to measurements from balloon flight experiments resulting in a reduced primary $\bar{p}$ flux. Since the kinematic threshold for producing antiprotons is 6 GeV/nucleon the results presented above are pretty much immune against solar modulation.

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FIGURE CAPTIONS

1. The differential $\bar{p}$ -yield per interaction from a p -oxygen and a pp -collision as obtained from the Monte Carlo Model DTUNUC [12]. The incoming proton had a kinetic energy of 40 GeV. The enhanced $\bar{p}$ -yield from a p -oxygen interaction compared to the pp -interaction reflects the fact that more than just one target nucleon is involved in the interaction.
2. The differential $\bar{p}$ -yield per interaction from a helium-oxygen interaction as obtained from the Monte Carlo Model DTUNUC [12]. The incoming helium had a kinetic energy of 40 GeV/nucleon. The lower curve is the $\bar{p}$ -yield from a pp -interaction where the incoming proton had a kinetic energy of 40 GeV.
3. The differential $\bar{p}$ -yield per interaction from an oxygen-oxygen interaction as obtained from the Monte Carlo Model DTUNUC [12]. The incoming oxygen had a kinetic energy of 40 GeV/nucleon. The lower curve is the pp -yield from a pp -interaction where the incoming proton had a kinetic energy of 40 GeV.
4. The differential $\bar{p}$ -yield per interaction from an iron-oxygen interaction as obtained from the Monte Carlo Model DTUNUC [12]. The incoming iron had a kinetic energy of 40 GeV/nucleon. The lower curve is the pp -yield from a pp -interaction where the incoming proton had a kinetic energy of 40 GeV.
5. The total inelastic cross sections for p -carbon and $\bar{p}$ -carbon interactions as a function of the kinetic energy E of the incoming hadron [20,21,22,23].
6. The absolute values of primary proton fluxes are not well known. These two spectra [30,31] reflect roughly the upper and lower limit of published data, see also [32]. Both were used as inputs into the calculation.
7. The calculated $\bar{p}$ -flux behind an atmospheric layer of 5 g/cm². The different curves refer to the different primary cosmic ray components. As inputs we used the proton

and helium spectra as measured by the LEAP-experiment [30] and for the more heavy nuclei we used the data compiled by Wiebel [33].

8. The total atmospheric $\bar{p}$ -flux behind an atmospheric layer of 5 g/cm^2 . The full line (upper curve) uses the upper primary proton flux of Fig. 6 [31] as an input and the lower curve (dashed line) the lower primary flux of Fig. 6 [30]. The third curve (dotted line) is a result of an earlier estimate on atmospheric antiprotons [10].
9. The calculated atmospheric $\bar{p}$ flux behind different atmospheric layers relative to the $\bar{p}$ flux behind 1 g/cm^2 of atmosphere.

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