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Atmospheric antiprotons

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Abstract. The atmospheric antiproton flux is evaluated at several altitudes by means of a simulation procedure proven on other particle data. The calculated flux is found significantly larger than in previous studies for the analysis of balloon data. The consequences on the antiproton galactic flux are evaluated. Future satellite measurements are discussed in this context. The expected antiproton flux at terrestrial altitudes is mentioned.

1 INTRODUCTION

The study of cosmic ray (CR) antiprotons ($\overline{p}$) is a topic of current interest in Astroparticle Physics. The major part of the $\overline{p}$ flux is expected to originate from the interaction between the nuclear CR flux with the interstellar matter in the galaxy (ISM). The $\overline{p}$ flux measurements then provide a sensitive test of the production source and mechanism, and propagation conditions in the galaxy (Gaisser and Shaefer, 1992; Gaisser et al., 1999; Chardonnet et al., 1997; Simon et al., 1998; Bieber et al., 1999; Ullio, 99; Donato et al., 2000). In addition to the secondary $\overline{p}$ component, other contributions of primary origin and of major astrophysical interest, have been considered. Contributions from the annihilation of dark matter constituents (Stecker and Rudaz, 1988; Bottino et al., 1999; Bergström et al., 1999), and from the existence of primordial black holes (Carr, 1976; Barrau, 1999) to the CR $\overline{p}$ flux have been discussed recently.

CR antiprotons have been experimentally studied for several decades by satellite or balloon borne experiments (see references in Boezio et al. (2001)). Several recent balloon experiments, like BESS (Orito et al., 2000), and CAPRICE (Boezio et al., 1997; Boezio et al., 2001) have collected some new data whose analysis have provided determinations of the galactic $\overline{p}$ flux over an energy range extending from about 0.2 GeV up to 49 GeV. In these works, the value of this antiproton galactic flux was obtained by subtracting the atmospheric $\overline{p}$ flux obtained from a calculation, from the values of the measured total flux.

Both secondary galactic and atmospheric antiprotons are produced in hadronic collisions by the same elementary reaction mechanism involving nucleon-nucleon collisions, between the incident CR flux and either ISM nuclei (mainly Hydrogen) in the galaxy, or atmospheric nuclei (mainly Nitrogen) in the atmosphere. The basic $\overline{p}$ production reaction is the inclusive $NN \rightarrow \bar{p}X$, N standing for nucleon and X for any final hadronic state allowed in the process. The ratio of $\overline{p}$ production in the galaxy and in the atmosphere scales with the ratio of matter thickness (in units of interaction length) crossed by protons in the two media. These are roughly 5 g/cm^2 of Hydrogen in the galaxy (Engelmann et al., 1990; Webber et al., 1996; Webber et al., 1998), and 5 g/cm^2 of Nitrogen in the atmosphere for 38 km altitude balloon experiments (Orito et al., 2000; Boezio et al., 2001), for protons with momentum above the $\overline{p}$ production threshold (>6.5 GeV). Therefore the contribution of the atmospheric antiproton production to the total flux measured is not expected to be small with respect to the galactic component. The correction of the total flux from the atmospheric contribution therefore needs the latter to be calculated very carefully since the accuracy on the evaluation of this component sets the limit of accuracy on the galactic flux.

This contribution reports on the preliminary results of a calculation of the atmospheric $\overline{p}$ component by Monte-Carlo simulation. Not all effects due to particle interactions have been included yet, neither all contributions of the CR flux. The results are believed to be already significant however.

2 Simulation conditions

The flux of secondary atmospheric antiprotons has been investigated using the same simulation program which has permitted to successfully account for the proton (Derome et al., 2000), electron/positron (Derome et al., 2001), and light nuclei (Derome and Buénerd, 2001) experimental flux below

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the Geomagnetic Cutoff (GC) measured by the AMS experiment, as well as the muon flux measured by other experiments (Liu at al., 2001). CR proton and helium particles are generated and propagated inside the earth magnetic field, and allowed to interact with atmospheric nuclei and to produce secondary nucleons p, n, and antinucleons $\overline{p}$, $\overline{n}$, with cross sections and multiplicities as discussed below. Each secondary particle is then propagated and allowed to interact as in the previous step. A reaction cascade can thus develop through the atmosphere. Only the annihilation reaction channel is taken into account for antinucleons. Non annihilating inelastic $\overline{N}\ A \rightarrow \overline{N}\ X$ ($\overline{N}$ antinucleon) interactions have been ignored at this stage. The reaction products are counted whenever they cross, upward or downward, the virtual sphere at the altitude of the detector: 370 km for the AMS spectrometer, 36 km for balloon experiments (BESS, CAPRICE), or ground level. All charged particles undergo energy loss by ionisation. Each event is propagated until the particle disappears by nuclear collision (annihilation), stopping in the atmosphere by energy loss, or escaping to outer space beyond twice the production altitude. See refs (Derome et al., 2000, 2001; Derome and Buénerd, 2001) for details.

The CR proton flux used in the calculations was measured recently by AMS (AMS, 2000a,c). The contribution of the CR ^4He flux was not taken into account at this stage. This implies that the calculated cross sections are roughly underestimated by about 10% at least. The values of the proton total reaction cross section used were obtained from the parametrization of Letaw et al. (1983), and checked on the carbon data from Jaros et al. (1978). The $\overline{p}$ total reaction cross section was taken from Carroll et al (1979), with the energy dependence from the data compilation of Baldini et al. (1988).

The inclusive $pA \rightarrow \overline{p}X$ production differential cross section was obtained from a fitting procedure. A set of data available over the 12 to 24 GeV energy range, could be consistently and accuratley reproduced (Huang and Buénerd, 2001) by means of an analytical parametrization based on Regge phenomenology and quark counting rules (Kalinovski et al., 1989). This cross section has been implemented in the event generator. The same production cross section has been assumed for $\overline{n}$ production as for $\overline{p}$.

3 Results

The simulation has been run for 3 detection altitudes: The BESS/CAPRICE balloon altitude (38 km), the AMS orbit altitude (370 km), and ground level. The latter was done with the idea of investigating the prospects for ground level or low altitude detection of atmospheric antiprotons and possible measurements with existing devices.

3.1 High altitude balloon data

Figure 3 shows the data points obtained from the BESS and CAPRICE measurements respectively, for the galactic $\overline{p}$ flux,

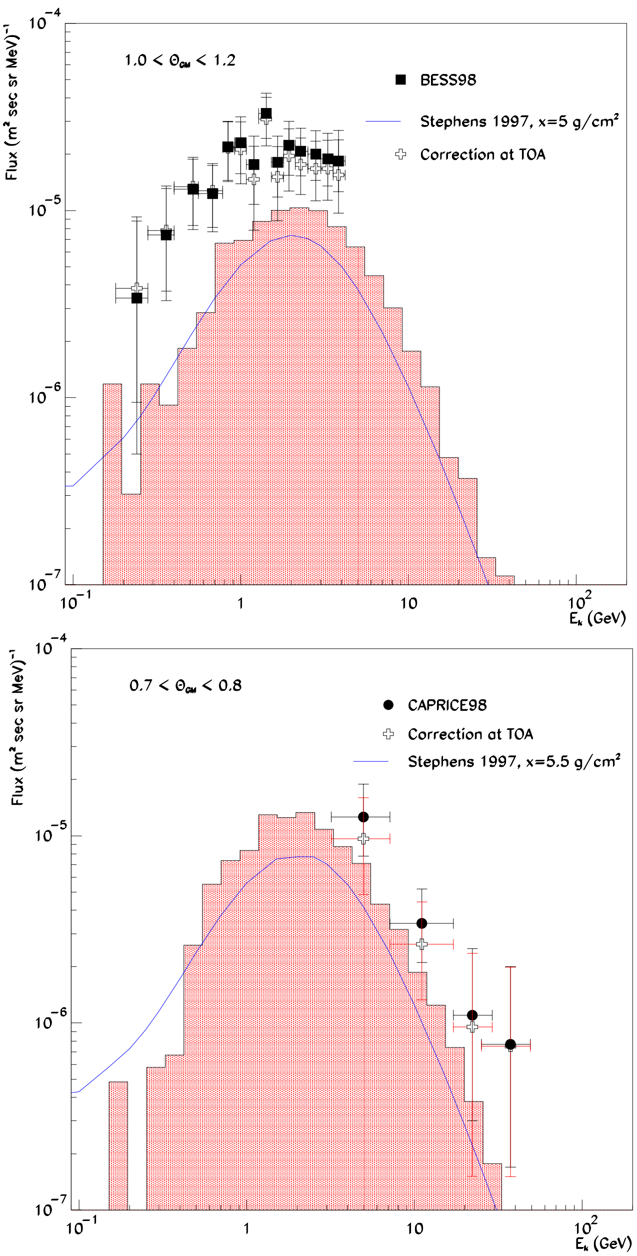

Fig. 1. Top: Galactic antiproton distributions deduced from the BESS experiments (full squares) and atmospheric antiproton flux used to correct the raw flux measurement, evaluated in the original works (curve) and from the present work (histogram). The open cross symbols correspond to the galactic flux obtained using the present results for correction of the raw measurements (see text). Bottom: Same as above for the CAPRICE experiment.

deduced and the contributions of the atmospheric $\overline{p}$ flux as evaluated in the same works on the basis of the calculations of Stephens (1997), compared with the results from the present work for the atmospheric component (see also Pfeifer et al. (1996)). In both cases it appears that the atmospheric antiproton flux obtained in the present calculations are significantly larger than those obtained from the transport equation calculations. On both figures, the deduced CR $\overline{p}$ flux obtained by adding back the original atmospheric $\overline{p}$ correction and subtracting the values obtained here are showm by crosses. They are seen to be below the originally deduced values by about 25-30% on the average for kinetic energies above 1-2 GeV. It must be kept in mind that the present calculations do not include the CR ^4He contribution to the $\overline{p}$ yield, which implies that the atmospheric component is somewhat underestimated here.

It must also be pointed out that, although the $\overline{p}$ production cross section is rather accurately known for antiproton energies above about 1 GeV over the incident energy domain mentioned above, it is much less well known for low antiproton energies, below about 0.5 GeV. The values calculated for the flux should then be taken with care for low energy antiprotons. Note that forthcoming experimental programs aiming at systematic measurements of cross sections of astrophysical interest should fill this void in a near future (HARP , 2001).

3.2 AMS altitude

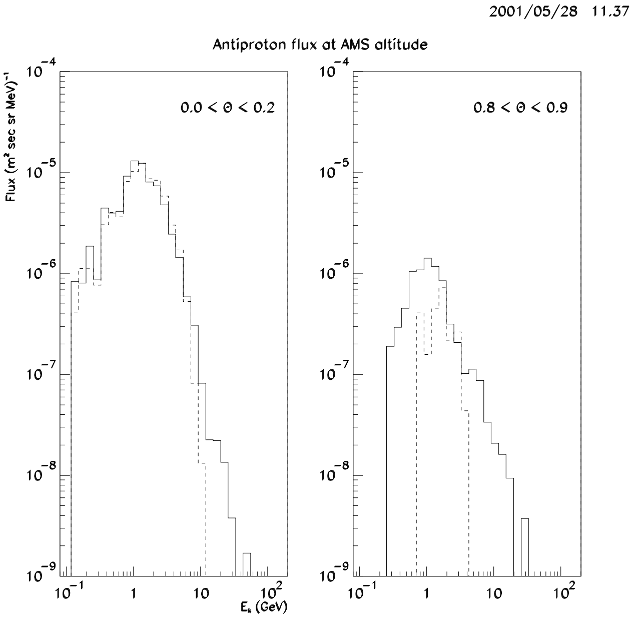

Fig. 2. Atmospheric antiproton spectra expected for the AMS experiment running on the ISS at 380 km altitude, from the present work. Full line: Downward flux; Dashed line: Upward flux.

Figure 3.2 shows the expected flux of atmospheric antiprotons at the altitude of AMS for two regions of geomagnetic latitude, equatorial ($0 < \theta_M < 0.2$ rad), and subpolar (0.8$< \theta_M < 0.9$ rad), and for downwards (secondaries and reentrant Albedo) and upwards (splash Albedo) particles. It is clearly seen that, unexpectedly, the predicted flux is also at this altitude of the same order of magnitude as the galactic flux. Note that the simulated flux is surprisingly predicted larger downward than upward. This is in fact an effect of the spectrometer acceptance (assumed to be 30 deg. with respect to zenith), the mean angle for upward particle trajectories being 2 radians. The overall upward flux is larger than downward by a factor of about 2.5.

This shows that the future satellite (AMS, PAMELA) measurements of antiproton flux will then have to be corrected from the atmospheric contributions and will then suffer more uncertainties than previously thought. The appropriate optimum procedure for extracting the galactic component from the measurements should consist of processing simultaneously and consistently both satellite and balloon altitude data in order to constrain as much as possible the calculations, using the same type of approach as presented here.

3.3 Ground level

The flux of atmospheric antiprotons at ground level has been calculated with the same simulation program and found to be of the order of 0.6 10^{-3} $\overline{p}\ s^{-1}m^{-2}sr^{-1}$ at all latitudes. At 4000 m, the flux raises to about 16 10^{-3} $\overline{p}\ s^{-1}m^{-2}sr^{-1}$. These values are small but large enough for this flux to be measured by currently existing large acceptance detectors (BESS, CAPRICE), or in a near future by new detectors under construction like AMS. More work is in progress on these issues.

3.4 Summary and conclusion

In summary, the secondary antiproton flux produced by cosmic ray protons on the atmosphere has been calculated by Monte-Carlo simulation, and found significantly larger than evaluated in previous works. The flux at satellite altitudes (380 km) appears to be of the same order of magnitude as at high balloon altitude, indicating that it will have to be taken into account in future measurements of the galactic antiproton flux at this altitude. The flux at terrestrial altitudes expected from these calculations is small but measurable and could provide good grounds for testing the identification capability of existing or future devices.

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