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Dependence of Simulated Atmospheric Antiproton Flux on the Microscopic Models of Particle Interactions

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Abstract: Influence of the microscopic particle interaction models on the simulations of atmospheric antiproton fluxes at various altitudes is examined by comparing the Monte Carlo simulated results with those obtained from the BESS observations. Some discrepancies between the simulated results and those obtained by the BESS experiments have been noticed, particularly at high altitudes and at the low energy end of the spectrum. More importantly, the predictions of different interaction models also differ from each other. An estimate of the magnitude of uncertainty in the predictions of atmospheric antiproton fluxes in the energy range of about 0.2-100 GeV at balloon altitude due to the uncertainties in the particle interaction characteristics has been made. The present findings may have some implications in the interpretation of precise galactic antiproton flux as observed recently by the PAMELA experiment.

Keywords: Antiprotons, BESS-balloon measurement, Interaction models, PAMELA experiment.

1 Introduction

Antiprotons ($\bar{p}$) in cosmic rays provide information regarding the sources of cosmic rays and their propagation in the Galaxy as well as the matter-antimatter asymmetry of the local universe [1]. Observations of $\bar{p}$ flux above the Earth's atmosphere may also be considered for probing into the possible signatures of primordial black holes (PBH) [2, 3]. Recently, a precise measurement of the galactic $\bar{p}$ spectrum in an energy range from 60 MeV to 180 GeV has been made by the PAMELA experiment [4, 5]. Comparison of such PAMELA spectrum with several theoretical estimates tends to support the scenario of pure secondary production of $\bar{p}$ due to the interactions of primary cosmic rays with the interstellar medium (ISM) [4, 5]. Such theoretical estimates may, however, be uncertain due to our incomplete knowledge of the detailed features of cosmic ray propagation in the Galaxy as well as the characteristics of high energy particle interactions.

Over the past few years, the BESS experiments have performed precise measurements of atmospheric $\bar{p}$ spectra in the energy range $0.2-3.4$ GeV at balloon altitude, at mountain altitude and at the sea level [6, 7]. Measurement of $\bar{p}$ flux at balloon altitude, at the location of Ft. Sumner, USA [7], is of particular importance as the average atmospheric depth $10.7\ \mathrm{gm\ cm^{-2}}$ in this experiment was comparable to the depth ($5-6\ \mathrm{gm\ cm^{-2}}$) of matter traversed by the cosmic rays in the Galaxy. As the $\bar{p}$ production mechanism in the atmosphere is likely to be similar to that in the Galaxy, a simulation study of such atmospheric $\bar{p}$ at balloon altitude, by employing a number of high-energy particle interaction models, may provide us with an opportunity to quantify the uncertainty in the theoretical estimates of galactic $\bar{p}$ flux that may be caused by our limited knowledge of particle interaction characteristics.

In the present work, we study the influence of high energy particle interaction models on the atmospheric $\bar{p}$ spectra by using the Monte-Carlo simulation code CORSIKA (version 6.735) [8]. For such a purpose, we first simulate the atmospheric $\bar{p}$ spectra at different observation levels by using FLUKA (version 2008.3b) [9, 10] and UrQMD (version 1.3) [11, 12] models and then compare such simulated spectra with the BESS observations. The BESS-measured $\bar{p}$ spectra are, however, limited to 3.4 GeV that corresponds to the mean vertical geomagnetic rigidity cutoff at the location of Ft. Sumner. The simulation study of atmospheric $\bar{p}$ at balloon altitude, that corresponds to the BESS observations at Ft. Sumner, is, therefore, relevant only for the low energy end of the galactic $\bar{p}$ spectrum measured by the PAMELA experiment. To simulate the atmospheric $\bar{p}$ flux up to 100 GeV, a good understanding of particle interactions up to at least a few hundred GeV is necessary. In the absence of experimental data, we here compare the predictions of the well known microscopic high energy particle interaction models QGSJET01c [13], VENUS 4.12 [14], NEXUS 3.97 [15] and EPOS 1.6 [16], each in combination with FLUKA for the description of hadronic interactions below 80 GeV/n, to get some idea about the theoretical

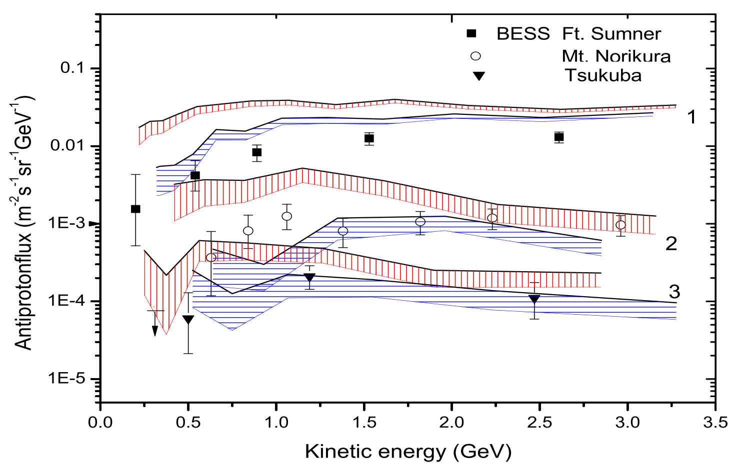

Figure 1: Diagram depicting the simulated differential spectra of vertical atmospheric antiprotons at three locations. In this figure, the red (vertically striped) bands and the blue (horizontally striped) bands represent the results simulated by FLUKA and UrQMD models, respectively; whereas, the uppermost (marked by the numeral 1), middle (marked by the numeral 2) and the lowermost (marked by the numeral 3) pair of bands represent the $\bar{p}$ fluxes at a very high (balloon) altitude (at the location of Ft. Sumner, USA), at mountain altitude (Mt. Norikura, Japan) and at the sea-level (Tsukuba, Japan), respectively. Results of the BESS-2001 [7], BESS-1999 [6] and the BESS-1997 [7] observations are also given for comparison.

uncertainties in the predicted $\bar{p}$ flux at energies beyond the upper cutoff for the BESS-2001 balloon experiment [7].

2 Adapted Simulation Procedure

Apart from the uncertainties due to the hadronic interaction models, a dominant systematic error in simulating the flux of atmospheric particles arises from the uncertainties in the estimation of input fluxes of the primary cosmic rays. To minimize such uncertainties, while considering the fact that we would compare our results with the BESS-observations, we choose the spectra of different primary cosmic ray particles (except $\bar{p}$) precisely measured by the BESS-98 experiment [17] as the inputs in our simulations. For reproducing such BESS-observed primary spectra in CORSIKA, the effect of solar modulation on the spectra is handled by using the force field approximation [18, 19] in which the primary particle flux is expressed in terms of a time dependent *solar modulation potential* that takes on different values at different epochs of solar activity [20]. The energy of the primary particle in the simulation of each event is randomly chosen from a range between the minimum of the geomagnetic rigidity cutoff at the observational location and a maximum energy of 1 PeV/n. The geomagnetic rigidity cutoff calculations have been performed here by using the (back) trajectory-tracing technique [21], while the quiescent International Geomagnetic Reference Field (IGRF) model of 1995 [22] for the Earth's magnetic field has been used for such cutoff calculations. The values of such geomagnetic rigidity cutoffs have been used in the simulations to modify the primary cosmic ray spectra obtained from CORSIKA. The US standard atmospheric model [23] with a planer approximation has been chosen in the present work by considering the fact that the latitudinal and the seasonal variations of such atmospheric models are likely to have small effects on the atmospheric cosmic ray spectra, particularly at very high (balloon) altitude. Contribution of the residual galactic $\bar{p}$ flux to the atmospheric $\bar{p}$, that may be important at a very high altitude, has been taken here into account by combining the BESS-obtained primary proton flux with the precise measurement of antiproton to proton flux ratio obtained from the PAMELA experiment. Such a secondary antiproton spectrum, adjusted for the location and time of the BESS-2001 balloon experiment [7], is taken as the input galactic $\bar{p}$ spectrum in our simulations. The integrated interstellar $\bar{p}$ flux thus obtained is found to be only about $1.4 - 1.5 \times 10^{-4}$ times the integrated primary proton flux in our simulations. We checked that such interstellar $\bar{p}$ flux, in fact, have negligible effects on the generated atmospheric antiprotons within the energy range considered by the BESS experiments and even beyond. Nearly $4 - 20 \times 10^{7}$ events have been generated in each of our simulations for the estimation of atmospheric shower particles to reduce statistical fluctuations to a certain extent. Further details on the techniques adapted in the present simulations may be found in References [24, 25, 26]

3 Simulated Results and Comparison with Observations

Figure 1 displays the simulated atmospheric $\bar{p}$ fluxes obtained by FLUKA and UrQMD models (each in combination with QGSJET01c for simulation above 80 GeV/n) in comparison with the BESS measurements at multiple atmospheric depths as indicated in the diagram. In this figure, the band width of each of the bands represents the statistical error of the simulations. At mountain altitude and at the sea-level, the $\bar{p}$ fluxes generated by UrQMD are found to be consistent with the BESS measurements within error bars; whereas, the UrQMD-derived spectrum is higher than the measured values at very high altitude. The FLUKA-generated fluxes are, however, found to be consistently higher than the experimental fluxes with such disagreement being maximum at very high altitude and minimum at the sea-level.

In Fig. 2, we extend the energy range of our study of the simulated atmospheric $\bar{p}$ at 10.7 gm cm^{-2} up to 100 GeV. At such higher energies, the hadronic models that are suitable to describe particle interactions above 80 GeV/n start to influence the simulation results. As a consequence, we can compare the predictions from a number of microscopic particle interaction models, namely the QGSJET 01c, VENUS 4.12, NEXUS 3.97 and EPOS 1.6 models, with each other at energies at which direct measurements are not available. Fig. 2 shows that the model-predictions deviate significantly from each other at energies below about 3 GeV mainly due to the difference between the FLUKA and the UrQMD results. Such a difference may even be about 80% at energies around 300 MeV. The $\bar{p}$ fluxes predicted by various models are somewhat similar in the energy range of about $5-10$ GeV. Above about 10 GeV, where different microscopic high-energy particle interaction models start to influence the results, the $\bar{p}$ fluxes predicted by different model combinations again show large variations from each other that may even be more than 60% at about 100 GeV; see Ref. [26] for more details. There are, of course, the possibilities of statistical fluctuations, but the fact that the QGSJET model always predicts lower fluxes than those obtained from the VENUS or the NEXUS models with the EPOS model following a trend similar to the one followed by VENUS above about 10 GeV cannot be accommodated in terms of statistical fluctuations alone.

As all the interaction models used here are appropriately tuned to the results of the known collider and other experiments, the difference between the predictions from such models are mainly due to our limited understanding of the high energy particle interactions.

4 Summary and Discussion

Antiproton fluxes at different atmospheric levels are calculated in this article by using CORSIKA simulations with different hadronic interaction models. Such simulated results are then compared with the BESS-measurements. For spectra below about 10 GeV, corresponding to the experimental measurements, only the interaction models FLUKA and UrQMD are relevant. For an atmospheric depth, that is equivalent to the one traversed by the primary cosmic rays during their propagation in the Galaxy, the simulation study is extended up to 100 GeV where the high-energy interaction models QGSJET, VENUS, NEXUS and EPOS start to influence the results. The study leads to the following observations.

- The predictions of $\bar{p}$ flux obtained by FLUKA and UrQMD show significant deviations from each other, particularly at energies below about 3 GeV. While presenting a reasonable description of BESS $\bar{p}$ data at lower altitudes, UrQMD overestimates the $\bar{p}$ flux at very high altitude thus possibly indicating that there is an enhanced production of $\bar{p}$ followed by an enhanced annihilation in this model. The fact that FLUKA yields a higher $\bar{p}$ flux at all the atmospheric depths possibly indicates a strongly enhanced $\bar{p}$ production in this model. The atmospheric $\bar{p}$ annihilation also appears to be slightly enhanced in FLUKA as the disagreement between the FLUKA-derived results and the BESS measurements is found to decrease with increasing atmospheric depth.

- The recent findings of the PAMELA experiment on the positron excess [5, 27] but no antiproton excess [4] in the energy range from sub-GeV to about 180 GeV lead non-trivial constraints on the dark matter models that try to account for the positron excess [28, 29, 30]. Such excess is determined by comparing with the background predictions of the interstellar $\bar{p}$ flux coming from the interaction of primary cosmic rays with the ISM. Such background is usually obtained from the GALPROP propagation code either by applying the parametrization of invariant $\bar{p}$ production cross-section [31] or by implementing the DTUNUC MC [32] code which is based on the DPM [33] class of models.

  The present study shows that at energies below about 3 GeV, the BESS-observed $\bar{p}$ fluxes at balloon altitude are substantially less than those obtained from FLUKA that may be regarded as the one belonging to the DPM class of models. At energies above about 10 GeV, the model predictions cannot be tested experimentally but, interestingly, the predictions from different popular hadronic interaction models tend to differ appreciably. In view of such results, a detailed study of the galactic $\bar{p}$ flux by exploiting different microscopic particle interaction models seems to be necessary in the context of the PAMELA observation and its interpretation in terms of the standard/non-standard (dark matter etc.) sources.

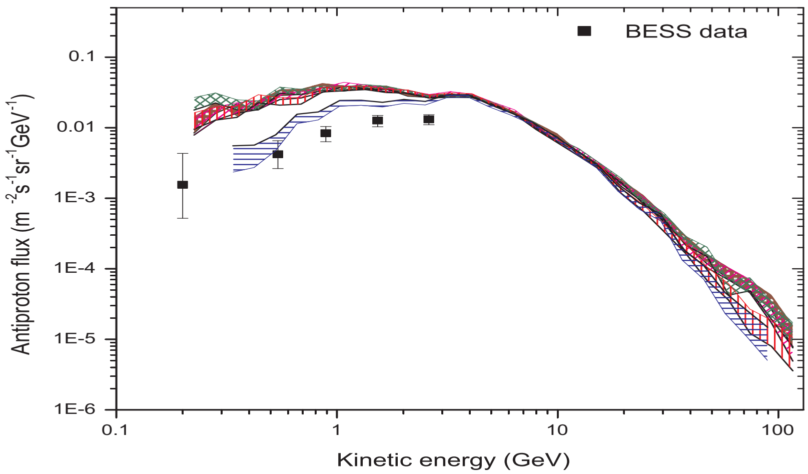

Figure 2: Atmospheric vertical antiproton flux simulated with various combinations of high-energy particle interaction models at an atmospheric depth $10.7\ \mathrm{g\,cm^{-2}}$ at the location of Ft. Sumner, USA for a wide range of kinetic energy of the antiprotons. Here, the blue (horizontally striped) band depicts the simulated results with UrQMD + QGSJET combination. Similarly, the red (vertically striped) band depicts the FLUKA + QGSJET combination, the magenta (shaded by right-tilted lines) band represents the FLUKA + NEXUS combination, the green (cross-hatched) band represents the FLUKA + VENUS combination and the brown (square-hatched) band represents the FLUKA + EPOS combination. Fluxes obtained from the BESS-2001 balloon observation at Ft. Sumner are also given for comparison.

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