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The cosmic-ray antiproton to proton ratio from 4.5 to 50 GV

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Abstract. We present a new measurement of the cosmic-ray $\overline{p}/p$ abundance ratio as a function of energy. The data were obtained from a balloon flight of the HEAT-pbar instrument in the Spring of 2000 from Ft. Sumner, NM. Our results for the energy-dependent antiproton fraction are compared with other measurements and recent predictions based on the observed abundance of secondary light elements in the cosmic rays. Our data appear to be consistent with a purely secondary production of antiprotons.

1 Introduction

Measurements of the $\overline{p}/p$ ratio place strong contraints on models of the confinement history and source distribution of cosmic rays, particularly when combined with measurements of the flux of other secondary interaction products, such as light nuclei, positrons, or diffuse gamma radiation. In addition, an observed excess in the $\overline{p}/p$ ratio over that expected from secondary production would signal the presence of more exotic production processes, such as WIMP annihilation. Used together with measurements of the intensities of positrons and gamma rays, also resulting primarily from proton interactions, one should be able to develop a self-consistent picture of the propagation of cosmic ray protons. This can be compared with the conclusions derived from observations of the intensities of secondary nuclei, such as Li, Be, and B, relative to those of their heavier primary parents. The abundances and energy spectra of heavier cosmic-ray nuclei are commonly interpreted with a propagation pathlength that decreases with energy as $E^{-0.6}$. If this behavior is also valid for protons one would expect a $\overline{p}/p$ ratio of about 10^{-4} at a few GeV, decreasing at higher energies approximately as $E^{-0.6}$. Deviations from this expectation would reveal unusual origins for the antiprotons, or could point to entirely different propagation histories for protons and heavier nuclei.

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Since the first report of a cosmic-ray antiproton flux by Golden et al. (Golden *et al.*, 1979), measurements have been made by a number of groups (for a review see Tarlé and Schubnell (2001) and references therein). Most of these measurements were limited to energies below a few GeV by the particle identification techniques used. Through repeated balloon flights at low geomagnetic cutoff rigidity, the BESS collaboration has been able to precisely define the antiproton spectrum below $\sim$ 3 GeV (Orito *et al.*, 2000; Maeno *et al.*, 2000). Their results are in good agreement with secondary production models within the uncertainties resulting from the effect of solar modulation and the normalization of the interstellar proton reference spectra. After the initial work of Golden, only three antiproton measurements have been reported above 5 GeV (Mitchell *et al.*, 1996; Hof *et al.*, 1998; Boezio *et al.*, 1994; Bergstrom *et al.*, 1998). Recent measurements (Boezio *et al.*, 1994; Bergstrom *et al.*, 1998) of the high energy $\overline{p}/p$ ratio suggest that the ratio increases with energy from energies of a few GeV up to the highest energies explored. This would require a revision of the present 'standard model' of cosmic ray production and confinement. Within a pure secondary production model, a large $\overline{p}/p$ ratio at high energies can be attributed to an energy spectrum of primary cosmic ray protons that is much harder in more distant regions of the Galaxy than that measured locally. This behavior has been proposed to explain the unexpectedly high intensity of diffuse galactic gamma rays above $\sim$ 1 GeV measured by EGRET (Hunter *et al.*, 1997). Alternative explanations of a rising high energy $\overline{p}/p$ ratio suffer from substantial difficulties. For example, extragalactic models which predict a $\overline{p}/p$ ratio rising as $E^{0.6}$ are not favored, due to constraints on the intergalactic transport of cosmic rays (Adams *et al.*, 1997). Closed Galaxy models, while boosting the $\overline{p}/p$ ratio at high energy, would lead to an overproduction of ^{3}He, in disagreement with observation. (Beatty *et al.*, 1993; Mitchell *et al.*, 1996) The precise measurement of the antiproton fraction

Table 1. Event selection results and $\overline{p}/p$ ratios (in 10^{-4}). N_p and $N_{\overline{p}}$ are the number of observed protons and antiprotons for each energy bin, respectively. Values for these quantities corrected for the atmospheric production of antiprotons and interaction and annihilation losses are shown.

R_{meas} (GV)	E_k (GeV)	N_p	$N_{\overline{p}}$	N_p (corr)	$N_{\overline{p}}$ (corr)	$\overline{p}/p$ ratio ($\times 10^{-4}$)
4.5 – 6.0	3.7 – 5.1	119361	18	119621	13.3	$1.11^{+0.48}_{-0.37}$
6.0 – 10.0	5.1 – 9.1	141447	23	142659	16.3	$1.14^{+0.46}_{-0.38}$
10.0 – 15.0	9.1 – 14.1	60727	21	62134	17.6	$2.83^{+1.00}_{-0.82}$
15.0 – 25.0	14.1 – 24.1	37742	15	38409	12.3	$3.2^{+1.40}_{-1.04}$
25.0 – 50.0	24.1 – 49.1	8773	1	8928	0	$<$2.0 (1 σ)
						$<$2.6 (90%)

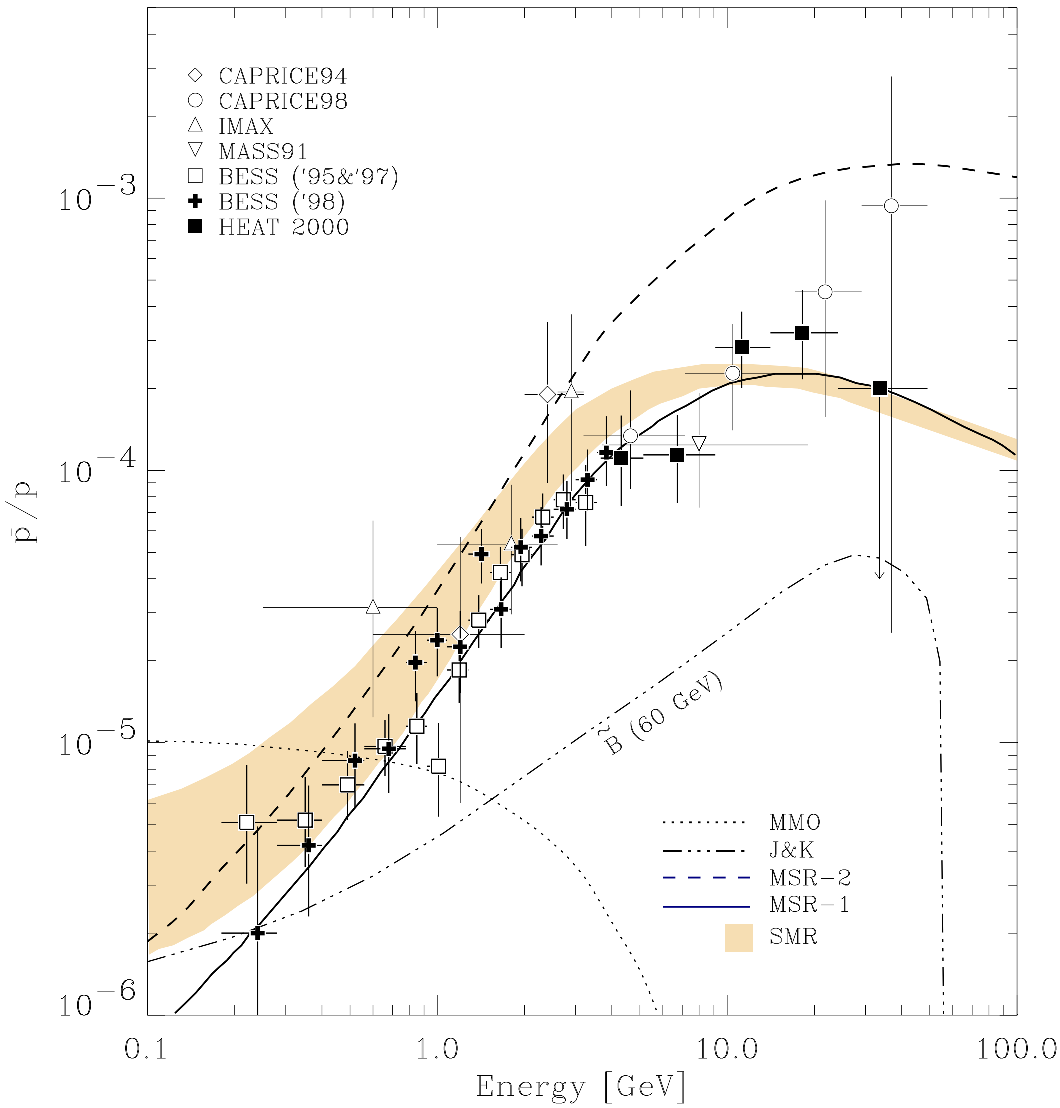

Fig. 1. Compilation of observed $\overline{p}/p$ flux ratios at the top of the atmosphere, compared with model calculations for secondary and primary pbar production: BESS 95&97 Orito *et al.* (2000), BESS Maeno *et al.* (2000), IMAX Mitchell *et al.* (1996), MASS91 Hof *et al.* (1998), CAPRICE94 Boezio *et al.* (1994), CAPRICE98 Bergstrom *et al.* (1998). The calculations of the $\overline{p}/p$ ratio are from Moskalenko *et al.* (1998) (MSR-1, MSR-2) and Simon *et al.* (1998)(SMR). Possible primary contributions to the $\overline{p}/p$ spectrum arising from evaporating primordial black holes Maki *et al.* (1996) (MMO) and from neutralino annihilation Jungman and Kamionkowski (1994) (J&K) are also shown.

above 10 GeV is thus an important step towards understanding the origin of the diffuse galactic gamma-ray emission.

In this paper, we report the results of a measurement of the $\overline{p}/p$ ratio using the HEAT-pbar detector. In a separate paper (Nutter *et al.*, 2001) we describe this detector and its performance in a flight conducted from Ft. Sumner, NM, in spring 2000. This paper includes a detailed description of the analysis carried out to obtain the final antiproton and proton data sets. Here, we describe the procedure followed to convert the raw energy-dependent $\overline{p}/p$ ratios observed at the instrument to top of the atmosphere (ToA) values. These values will then be presented as a function of energy, and compared with predictions and previous measurements.

2 Results

The number of antiproton ($N_{\overline{p}}$) and proton (N_p) events obtained by applying the data selections described in Nutter *et al.* (2001) to the raw data set from the Ft. Sumner 2000 flight are shown in Table 1. These event counts must now be corrected for secondary antiproton production in the atmosphere above the instrument, and interaction and annihilation losses of antiprotons and protons in the atmosphere and instrument. The average atmospheric overburden during the flight was 7.2 g/cm^2. The calculation of the antiproton production in the atmosphere resulting from this overburden is based on Pfeifer *et al.* (1996). Interaction and annihilation losses are based on the cross sections quoted in Kuzichev *et al.* (1994) and Denisov *et al.* (1973), accounting in detail for the total grammage traversed by a particle in passing through the atmosphere, pressure vessel, and detector. The numbers of antiprotons and protons in each energy bin obtained after applying all of these corrections are shown in Table 1, along with the resulting $\overline{p}/p$ ratios. The errors shown in Table 1 are purely statistical. Systematic errors resulting from uncertainties in the corrections described in this section, and in the background due to particle mis-identification, are estimated to be less that 4% of the $\overline{p}/p$ ratio. Our measurement of the $\overline{p}/p$ ratio in the energy range from 4.5 to 50 GeV is presented in Figure 1, which also summarizes the current status of measurements prior to our work.

3 Discussion

Many predictions for the $\overline{p}/p$ ratio have been published over the years, most based on the observed abundance of light secondary nuclei relative to heavier primaries. In recent years, additional constraints imposed by observations of the diffuse gamma ray flux have been added by Moskalenko *et al.* (1998). In Figure 1 we display, in addition to measured values for the $\overline{p}/p$ ratio, calculations of the expected $\overline{p}/p$ ratio from Moskalenko *et al.* (1998) (MSR-1, MSR-2) and Simon *et al.* (1998)(SMR). Possible primary contributions to the $\overline{p}/p$ spectrum arising from neutralino annihilation (Jungman and Kamionkowski, 1994) (J&K) are also shown. These theoretical estimates are all consistent with the now well measured $\overline{p}/p$ ratio in the low energy region below 3 GeV. The $\overline{p}/p$ ratio predicted by Simon *et al.* (1998) is shown in Figure 1 as a shaded band. This calculation is based on the Leaky Box model, using the absolute proton flux measured by IMAX as normalization. The uncertainties in the flux prediction, reflected by the band in the figure, are primarily uncertainties in the galactic path length distribution. The dashed and solid lines in Figure 1 show the results of calculations by Moskalenko *et al.* (1998), carried out within a self-consistent cosmic ray propagation model. The dashed line represents the case of a nucleon injection spectrum much harder than locally observed, which has been proposed to explain the observed high continuum gamma-ray emission above ~ 1 GeV. A standard nucleon injection spectrum, consistent with the locally observed one, is reflected in the solid line. The inclusion of reacceleration effects within the 'local spectra' calculation would shift the peak in the $\overline{p}/p$ ratio to slightly higher energies and increase the flux at very high energies (> 50 GeV). Our data are in good agreement with the 'standard spectrum' calculations of Moskalenko *et al.* (1998) at high energy, and do not support an antiproton to proton ratio approaching 10^{-3} at energies above 20 GeV, as suggested by recent CAPRICE measurements. Further, our result does not support models which are based on hard nucleon injection spectra. At energies covered by the presented measurements, secondary $\overline{p}$ production with a nucleon injection spectrum consistent with the locally observed one describes the data well. It is clear that further measurements of the high energy $\overline{p}/p$ ratio are called for in order to definitively observe a downturn in the $\overline{p}/p$ ratio at high energy and to measure its energy dependence.

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