A Precise Measurement of Cosmic-Ray Proton Spectrum with BESS Spectrometer

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Abstract

We report on the absolute cosmic-ray proton spectrum in the energy range 1 to 120 GeV as measured by the ’98 balloon flight of the BESS spectrometer, which was launched from Lynn Lake, Manitoba, Canada. The rigidity of the cosmic-ray was measured reliably by continuous tracking in a uniform magnetic field of 1 Tesla. Background-free particle identifications were achieved by the combination of redundant dE/dx and TOF measurements. The interaction loss was corrected by using Monte Carlo simulations. Atmospheric secondary protons were subtracted by adopting the calculation of Papini et al..

1 Introduction:

Protons are the most abundant component among primary cosmic-ray particles. Their absolute flux and spectrum shape are fundamental data in cosmic-ray physics. Precise determination of the primary proton spectrum is also needed to calculate the secondary anti-proton and positron spectra, which will provide information about particle propagation in interstellar space. The absolute energy spectra of primary cosmic-rays is also important for studying atmospheric neutrinos.

The energy spectrum of cosmic-ray protons has been measured in various experiments. However, their resultant absolute fluxes show discrepancies up to a factor of 2 at 50 GeV.

We report here a new precision measurement of the cosmic-ray proton spectrum over the energy range 1 to 120 GeV based on the BESS-’98 flight data. In ’98, a new trigger mode was prepared to record all protons above 6 GeV instead of recording only 1/60 sample of protons as done in the previous flights. It drastically improved statistics in the proton spectrum measurement as reported here.

2 BESS spectrometer:

The BESS detector is a compact, high-resolution spectrometer with a large acceptance to perform sensitive searches for rare cosmic-ray components, as well as precision measurements of the absolute fluxes of various particles (Orito, 1987; Yamamoto, 1998).

All the detector components of the BESS spectrometer are allied in a simple cylindrical shape, as shown in Figure 1. In the central region, a uniform magnetic field of 1 Tesla is produced by a thin super-conducting solenoidal coil. The magnetic field fills a large tracking volume of 0.84 m $\phi \times 1$ m. The geometrical acceptance is precisely determined due to the simple cylindrical shape and the uniform magnetic field.

The outermost detector is TOF (Time-Of-Flight) scintillator hodoscopes. A simple coincidence of the top and bottom TOF hodoscopes initiates the data acquisition sequence. The energy loss (dE/dx) information in the scintillation counters is used to identify the single charged particles. The absolute rigidity is determined by fitting up-to 28 hit points, each with 200 μm spatial resolution.

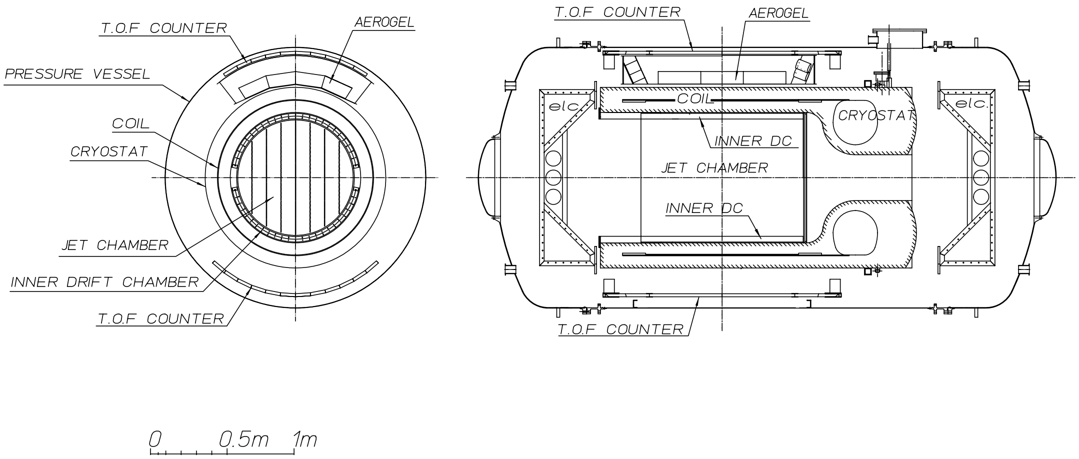


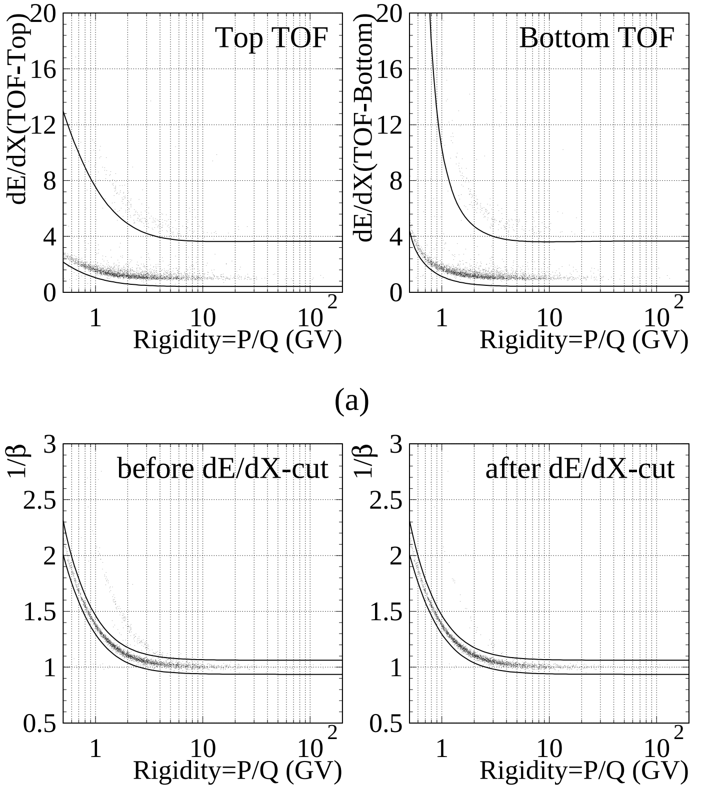
Figure 1: Cross-sectional views of the BESS instrument.

3 Analysis:

3.1 Proton selection: In off-line analysis, we selected the events with a single track fully contained inside the fiducial region of the tracking volume. This selection eliminates rare interacting events. In order to verify this selection, we scanned five hundred events randomly and confirmed that 99.2% of single track events passed this selection criteria and interacting events are fully eliminated.

In order to assure the accuracy of rigidity measurements, event quality such as χ^2 was required. The extrapolated track was checked to ensure that it traversed a correct TOF scintillation counter. This quality-cut efficiency was as high as 94%.

Protons were selected by requiring proper dE/dx and $1/\beta$ as a function of rigidity. Proton bands in this identification are shown in Figure 2. This proton selection efficiency was 98 %. The contamination of double charged particles was negligiblly small. A very pure proton sample was obtained below 3 GV. Deutrons start to come in the proton band around 4 GV.



(a)

(b)

Figure 2: Proton band in dE/dx vs rigidity plane (a) and (b) $1/\beta$ vs rigidity plane.

3.2 Corrections: In order to determine the cosmic-ray proton spectrum at the top of the atmosphere, the following corrections and normalizations were applied to the measured spectrum in the BESS detector.

The total ionization energy loss both in the detector and the residual atmosphere was calculated for each event by summing up the energy losses along the particle trajectory.

The geometrical acceptance of the BESS instrument ($S\Omega$) and the efficiency of single track selection ($\varepsilon_{\text{single track}}$) were calculated using Monte Carlo simulations by GEANT code as shown in Figure 3(a) and (b). On the other hand, the quality-cut efficiencies ($\varepsilon_{\text{Track Quality}} \times \varepsilon_{\text{TOF Quality}}$) were evaluated from actual flight data to be 94%. The energy dependence of these quality-cut efficiencies are shown in Figure 3(c) and (d).

The atmospheric proton contribution, which is produced by interactions of cosmic-rays with residual atmosphere of 5g/cm^2, was to be subtracted. Both analytic calculation (Papini, Grimani, and Stephens, 1996) and GEANT Monte Carlo simulations estimate that the ratio of atmospheric secondary protons to primary cosmic-ray protons is a few percents at 1 GeV and less than 1.5 % above 10 GeV. This effect was subtracted based on the calculation by Papini et al. According to the same Monte Carlo studies as above, the probability that primary cosmic-ray protons can penetrate the residual atmosphere of 5g/cm^2 is about 95 % over the entire energy range.

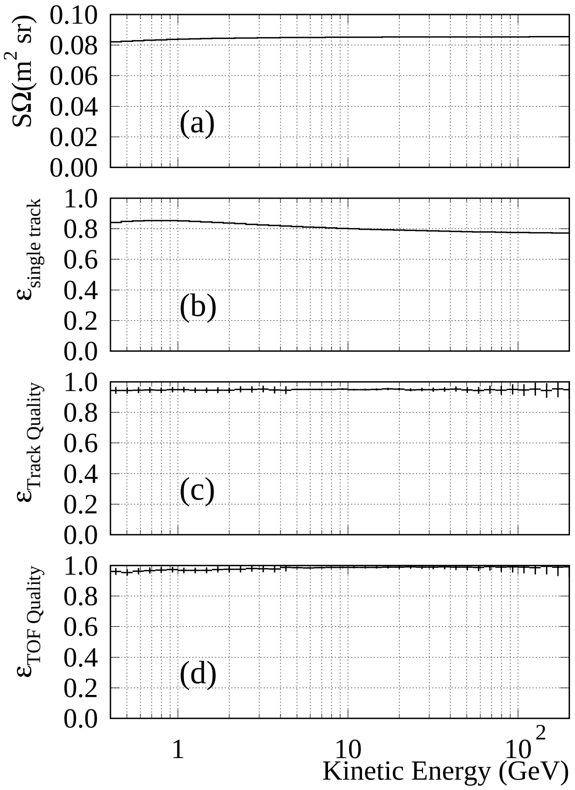


Figure 3: The geometrical acceptance and efficiencies: (a) geometrical acceptance of the BESS detector in this analysis and (b) efficiency of single track selection obtained by Monte Carlo simulation; (c) track- and (d) TOF- quality-cut efficiencies resulted from flight data analysis.

4 Results:

Figure 4 shows the proton spectrum at the top of the atmosphere obtained from the BESS-'98 flight data together with the results of previous experiments (Barbiellini, G. et al., 1997; Menn, W. et al., 1997; Papini, P. et al., 1993; Seo, E.S. et al., 1991; Webber, W.R., Golden, R.L., and Stephens, S.A., 1987). The solid line in Figure 4 (HKKM) is the primary proton flux assumed in the calculation of atmospheric neutrino fluxes by Honda et al.(1995).

The analysis of helium flux and proton/helium ratio are being carried out in a same manner, and to be reported.

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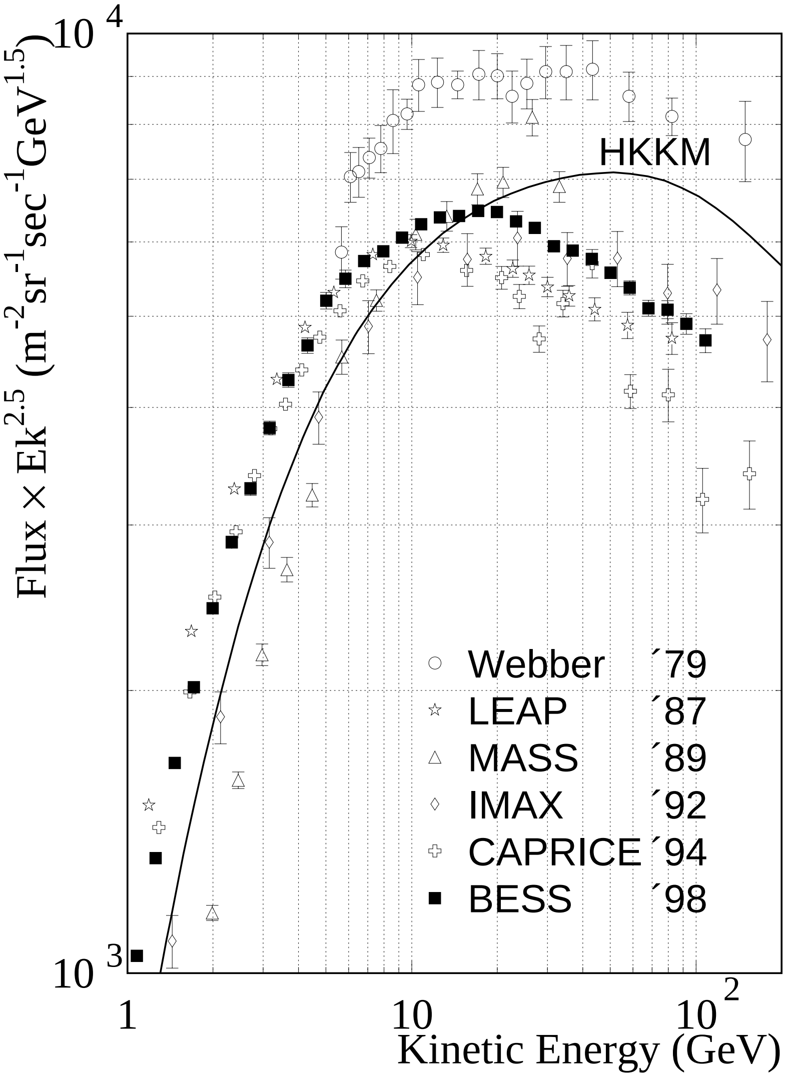

Figure 4: Absolute differential proton spectrum obtained by the BESS-’98 experiment, along with the spectra obtained by previous experiments and assumed in the atmospheric neutrino flux calculation.

References

Boezio, M. et al., ApJ (to be published)
Honda, M., Kajita, T., Kasahara, K., and Midorikawa, S. 1995, Phys.Rev. D52, 4985
Menn, W. et al. 1997, Proc. 25th ICRC (Durban, 1997) 3, 409
Orito, S 1987, Proc. ASTROMAG Workshop, KEK Report 87-19, 111
Papini, P. et al. 1993, Proc. 23rd ICRC (Calgary, 1993) 1, 579
Papini, P., Grimani, C., and Stephens, S. A. 1996, Nuovo Cimento 19C, 367
Seo, E.S. et al. 1991, ApJ 378, 763
Webber, W.R., Golden, R.L., and Stephens, S.A. 1987, Proc. 20th ICRC (Moscow, 1987) 1, 325
Yamamoto, A. et al. 1998, Proc. 21st Intl. symposium on Space Technology and Science (Omiya, 1998) 1578