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Absolute rigidity spectra of protons and helium from 16 to 250 GV

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Abstract. The HEAT-e$^{\pm}$ magnet spectrometer was used in two balloon flights to measure the intensities of cosmic-ray electrons and positrons. However, this instrument also collected a large sample of proton and helium nuclei. We report here the rigidity spectra for these two species up to about 250 GV, and we compare our results with those of other recent experiments. Above approximately 50 GV, the rigidity spectrum of helium appears to be slightly harder than that of protons.

1 Introduction

The HEAT-e$^{\pm}$ instrument combines a magnet spectrometer with a transition radiation detector (TRD), and a lead and scintillator sandwich electromagnetic calorimeter (EC) to distinguish electrons from the larger flux of hadrons. The instrument is seen in Figure 1 and described in more detail in Barwick *et al.* (1997). The detector is triggered with a coincidence between a top plastic scintillation trigger counter and a scintillation signal in the EC. As the primary goal of the experiment is to study electrons, the main trigger requires the equivalent of 0.5 GeV of electromagnetic shower energy deposition in the lower 70% of the EC.

Protons and helium nuclei on occasion produce a trigger signal due to hadronic interactions in the EC or through fluctuations in the single particle energy loss rate. A small (4%) prescaled sample of events which trigger a lower threshold setting (corresponding to a single non-interacting proton) in the EC are also included in the data. The probability for a hadronic shower trigger is essentially independent of particle energy above about 10 GeV/u as determined by a comparison with the prescaled events. From these hadronic events we independently construct rigidity spectra for protons and helium using the elemental charge provided by the energy loss measurement in the trigger scintillators.

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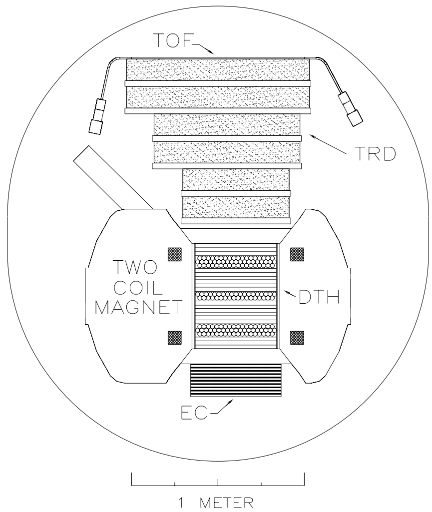

Fig. 1. The HEAT-e$^{\pm}$ instrument: time-of-flight (TOF) scintillator, transition radiation detector (TRD), 1 Tesla superconducting two-coil warm-bore magnet, drift tube hodoscope (DTH) for tracking, and electromagnetic calorimeter (EC).

The experiment has been flown twice, in 1994 from Fort Sumner, New Mexico, and in 1995 from Lynn Lake, Manitoba, Canada. The data from the two balloon flights are combined in this analysis, although efficiencies and trigger acceptances were determined for the two flights separately due to minor performance differences. (NB: This work is performed using the earlier form of the HEAT experiment optimized for electrons (HEAT-$e^{\pm}$) and not the antiproton instrument (HEAT-pbar).)

2 Data analysis

The accuracy in the rigidity measurement varies from event to event due to different magnetic field path integrals. We define a maximum detectable rigidity (MDR) for each event.

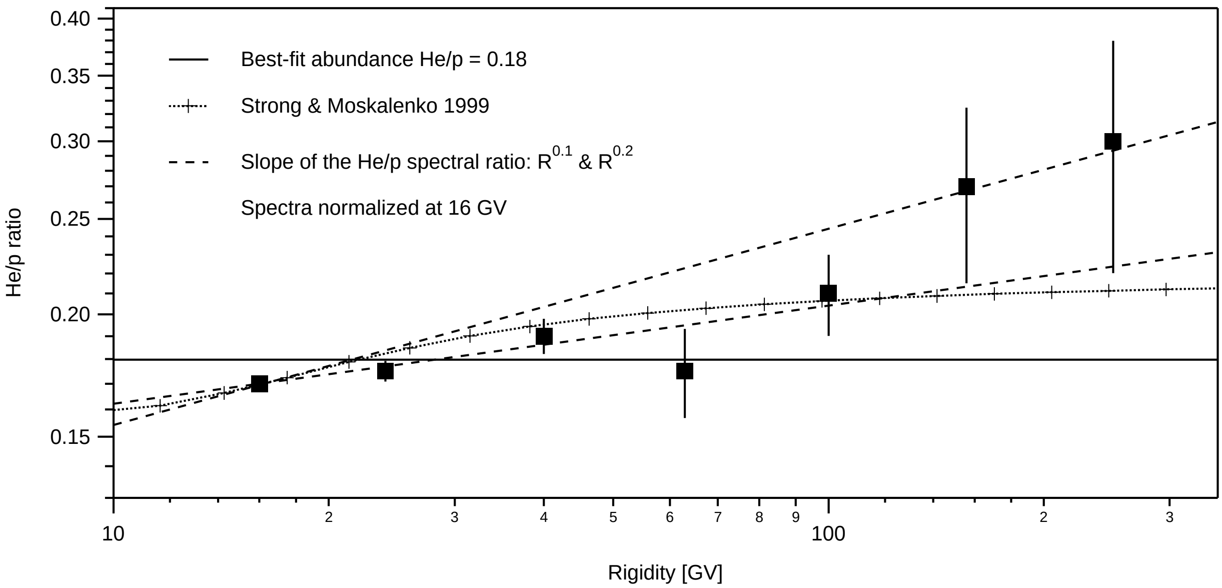

Fig. 2. Helium to proton intensity ratio for magnetic rigidities 16–250 GV. Errors include both statistical and estimates of systematic uncertainties in efficiencies. The solid (constant) line is what one would expect for a simple leaky-box model (constant abundance ratio). The dashed line is the result for the more detailed cosmic-ray propagation code of A. W. Strong (see text for references).

For the present analysis, we require MDR $>$ 200 GV. A particle at the MDR rigidity is one standard deviation removed from an infinite rigidity (straight) track.

Rigidity dependence in the trigger conditions for hadrons above 10 GV was examined by generating the ratio of shower triggers to prescaled triggers. This ratio was found to be independent of rigidity by determining the ratio for both hydrogen and helium events in three rigidity bins ($12 < R < 18$, $30 < R < 50$, and $R > 60$ [GV]).

The events are selected through the following criteria:

– clean trajectory fit through the TRD, the drift-tube hodoscope (DTH), and matching up with the scintillator paddle hit,

– downward-moving (non-splash albedo),

– MDR $>$ 200 GV, and

– ionization loss in the trigger scintillators corresponding to Z=1 or 2.

The MDR selection retains 25% of the protons and 13% of the helium nuclei since the proton trajectory fits are generally of higher quality. A Monte Carlo simulation is used to deconvolve the binned data into fluxes over a range of rigidities from 16–250 GV. The values of the determined He/p flux ratios are adjusted for selection efficiencies and trigger efficiencies.

Detector efficiencies and geometrical factors are determined with a GEANT/FLUKA-based Monte Carlo simulation of the flight detector configuration. Helium is treated in a nuclear superposition model within the FLUKA hadronic simulation, with the nuclear physics interactions (*e.g.*, spallation) handled separately.

3 Results and discussion

The ratios of fluxes obtained in this work are shown in Figure 2 as a function of particle rigidity. The errors include both the statistical uncertainties and an estimate of the systematic uncertainties due to trigger, selection, and prescale efficiencies. The constant line is the result of a simple leaky box calculation using the source rigidity spectra of $dN/dR \propto R^{-2.0}$ for all species and a rigidity-dependent Galactic escape length of the form $\lambda_{esc} \propto R^{-0.6}$ (e.g., Swordy et al., 1990; DuVernois 1997) and an observed best-fit cosmic-ray He/p abundance of 0.18 at these energies. Although the data are consistent with this simple model, there is some tendency for the relative abundance of helium to increase with rigidity. Models with helium source spectra enhanced by $R^{0.1}$ and $R^{0.2}$ and a calculation of a hydrodynamics-based Galactic cosmic-ray propagation model of Strong & Moskalenko (1999), all normalized to the HEAT elemental abundances at 16 GV, are also shown. All of these models have a rise in the helium fractional abundance with rigidity.

The curve marked "Strong" is generated from the cosmic-ray propagation code of A. W. Strong and collaborators (see, for example, Moskalenko & Strong 1998 or Strong & Moskalenko 1999). This is a numerical simulation of cosmic rays simultaneously fitting observed cosmic-ray parameters and gamma-ray observations in the Galaxy within a framework based on the propagation and Galactic physics. The shape of the He/p intensity ratio prediction is a result of the energy-loss and nuclear interactions in propagation. The HEAT data do not allow for a differentiation between the Leaky-Box and the explicitly hydrodynamical propagation code, but the hint of increasing helium fractional abundance can be seen.

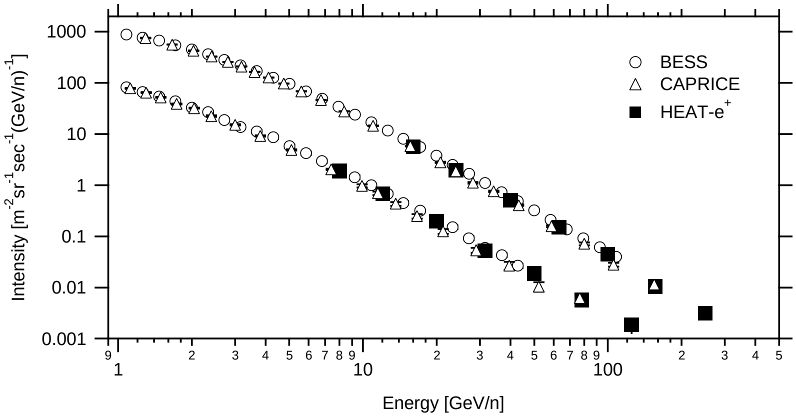

Fig. 3. The HEAT proton and helium energy spectra compared with two recent other recent magnet spectrometer experiments with proton and helium data published—BESS (Seo et al. 1991) and CAPRICE (Boezio et al. 1999). (Error bars are shown, but are typically smaller than the markers on the plot.) Good overall intensity normalization can be seen here.

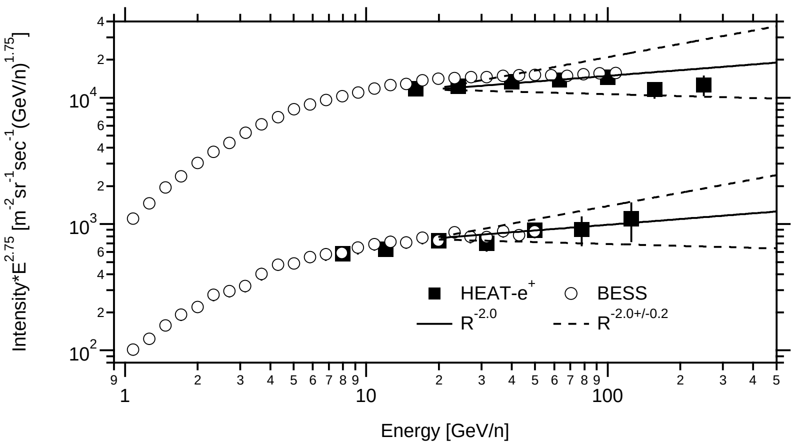

Fig. 4. Rescaling Figure 3 with $E^{2.75}$ to flatten the spectra and leaving only the HEAT and BESS data points for clarity, we see that there is good, but not perfect agreement between the two measurements. Power-law rigidity spectra normalized at 20 GeV to the HEAT data guide the eye to the spectral differences between protons and helium. The helium spectrum observed agrees well with a $dN/dR \propto R^{-2.0}$ source rigidity spectrum while the proton data is more consistent with a somewhat steeper source sprectum.

The rigidity spectra have been converted to an energy per nucleon scale assuming for protons A/Z = 1 and for helium A/Z = 2. Updating the work of Swordy *et al.* (1995), the absolute acceptances for the HEAT instrument are used to normalize the proton and helium fluxes. The results are shown in Figure 3, along with some other recent magnet spectrometer data.

Agreement between the three sets of measurements is quite good (typically within about 10% of each other) and the typical errors are the size of the markers. Following typical practice, we rescale the spectra from Figure 3 by $E^{2.75}$ to flatten the plot and highlight deviations from power-law behavior. This is seen in Figure 4, with only the HEAT and BESS data shown for clarity.

We note that the HEAT proton spectrum is somewhat lower than the BESS spectrum, but otherwise the detailed agreement is relatively good. Superimposed on the data are leaky-box model calculations for source (injection) spectra of the form $dN/dR \propto R^{-j}$ with j=2 (the model used for the ratio plot above) and j=1.8 and j=2.2 reflecting the extreme cases. For the proton spectra, the HEAT data seem to track somewhere between the $dN/dR \propto R^{-2.0}$ and the $dN/dR \propto R^{-2.2}$ models. Subject to the slightly different normalization, the BESS data tend to track in a similar manner.

For the helium however, the two sets of data seem to agree relatively well with a $dN/dR \propto R^{-2.0}$ model. The HEAT data have quite a bit of leverage at the high-energy end, where the observed spectral shape owes much to the source spectrum. At low energies, propagation effects (e.g., energy-loss, nuclear interactions, and heliospheric modulation) are more dominant.

Enlarging the energy scale upward using additional proton and helium data from the JACEE experiment (Asakimori *et al.* 1998) and narrowing the source rigidity power-law spectra range to $dN/dR \propto R^{-2.1} - R^{-1.9}$ yields Figure 5. The JACEE interpretation of the data was a source energy power law spectral fit of $R^{-2.1}$ for helium and $R^{-2.2}$ for protons. These are only slightly steeper than those we would infer only from the HEAT data.

The slightly flatter spectrum for helium has been argued to be consistent not only with the Strong and Moskalenko (1999) propagation prediction, but also with non-linear shock acceleration models of Ellison (1993) and multiple source models of Biermann (1993). In the latter model, the protons in the cosmic rays would be coming from supernovae shock acceleration of the ambient interstellar medium (ISM), while helium would be accelerated out of a super-thermal/stellar wind source (perhaps from Wolf-Rayet stars).

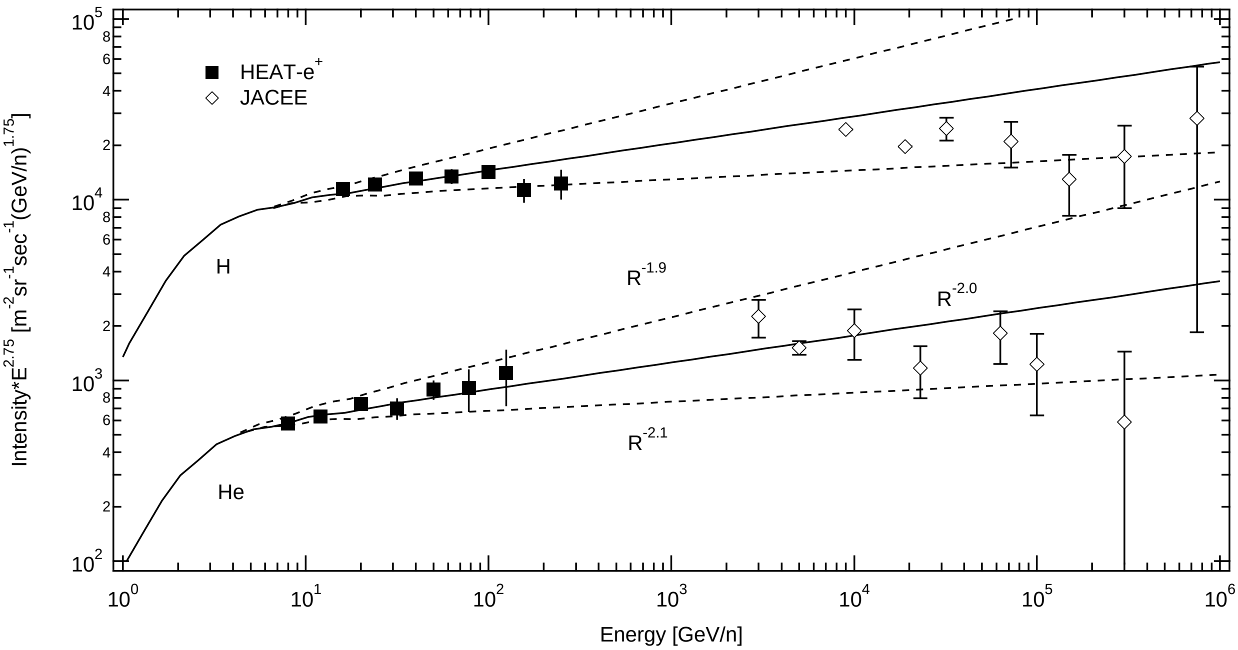

Fig. 5. Taking just the HEAT data from Figure 4 and less extreme source spectra ($dN/dR \propto R^{2.0} \& R^{2.0\pm0.1}$), we plot the high-energy extrapolation of the power-law rigidity guides along with JACEE results (Asakimori *et al.* 1998). High-energy observations of similar fractional uncertainty to the HEAT measurements would clarify the source spectrum at higher energies.

4 Conclusions

The rigidity and energy spectra of protons and helium nuclei over the observed range in the HEAT experiment seem to have slightly different spectral slopes. However, the available data does not rule out a simple leaky-box model with a common power-law rigidity source spectrum. Alternate models, such as the more realistic hydrodynamic and diffusion models of cosmic-ray propagation or differing source injection spectra, lead directly to the differing observed spectral slopes. Measurements with fractional errors similar to these HEAT measurements, but performed at higher energies would help resolve to this matter.

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