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All-Particle Spectrum Measured by ATIC-1

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Abstract: The Advanced Thin Ionization Calorimeter (ATIC), a balloon-borne experiment, is designed to investigate the composition and energy spectra of cosmic rays of charge Z = 1 to 26 over the energy range $\sim 10^{11}$ - $\sim 10^{14}$ eV. The instrument consists of a silicon matrix charge detector, plastic scintillator strip hodoscopes interleaved with graphite interaction targets, and an 18 radiation length deep, fully active bismuth germanate (BGO) calorimeter. ATIC has had two successful long-duration balloon (LDB) flights launched from McMurdo Station, Antarctica in 2000 and 2002. In this paper, we present the all-particle spectrum and the average mass number spectrum extracted from data collected during the first flight, and compare them with results from other direct and indirect experiments.

Introduction

The Advanced Thin Ionization Calorimeter is a balloon-borne experiment designed to measure the composition and energy spectra of cosmic-ray nuclei from hydrogen to iron over the energy range $\sim 10^{11}$ - $\sim 10^{14}$ eV. ATIC has had two successful long-duration balloon flights, launched from McMurdo Station, Antarctica, for 16 days in 2000-2001 and 20 days in 2002-2003. In both flights ATIC employed (1) a silicon matrix charge detector of 80 $\times$ 56 pixels, (2) three layers of plastic scintillator strip hodoscopes, interleaved with graphite interaction targets providing $\sim$0.75 nuclear interaction length for proton, and (3) a calorimeter consisting of eight layers of 40 BGO crystals each. Details of the experiment have been described elsewhere [1]. Signals from the BGO crystals are used to (1) estimate the energies of incident cosmic-ray nuclei by measuring the shower energies from nuclear interactions in the target, (2) together with signals from the hodoscope strips, reconstruct and extrapolate trajectories back to the silicon matrix for accurate charge measurement [2].

Various cosmic-ray nuclei have been studied by analyzing the first-flight data, and the results have been reported elsewhere [3, 4]. In this paper, the all-particle spectrum and the average mass number spectrum are presented, and compared with earlier direct and indirect observations.

Particle Identification

To make the calorimeter energy response function as energy-independent as possible, we select those events which (1) are within the geometry, traversing all 3 layers of the hodoscope and the upper 6 layers of the calorimeter, giving a geometry factor (GF) of 0.24 m^2·sr, and (2) undergo a nuclear interaction above the second calorimeter layer. The interaction probability (f_i) for cosmic-ray nucleus i is estimated using the cross section parameterization, which is a function of the mass numbers of projectile and target nuclei, given in [5] for hydrogen and helium, and in [6] for heavier nuclei. All the mass numbers used for the analysis in this paper have been taken from the periodic table in [7].

Figure 1 shows a charge distribution measured by the ATIC silicon matrix for the selected events. The energy distribution is divided into 2 bins per decade, and in each energy bin, the frequency of each cosmic-ray nucleus i (N_i) is counted within fixed boundaries (e.g. $5.5 < \mathrm{Z_{Si}} < 6.5$ for carbon nucleus). The contributions (loss) from (to) the neighboring nuclei are estimated to have negligible effects on the all-particle analysis.

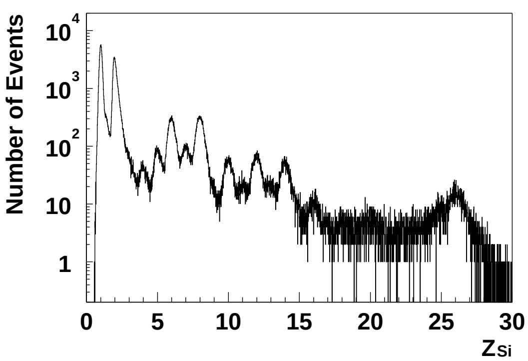

Figure 1: Charge distribution measured by ATIC for all energies. The prominent peaks at 1, 2, 6, 8, 10, 12, 14, and 26 correspond to the cosmic-ray nuclei of hydrogen, helium, carbon, oxygen, neon, magnesium, silicon, and iron, respectively.

All-Particle Spectrum

The all-particle differential flux (F) at the top of the atmosphere is given by

$$F = \sum_i F_i, \tag{1}$$

where F_i is the contribution of cosmic-ray nucleus i. In each energy bin of size ΔE, the frequency of cosmic-ray nucleus i (N_i) is normalized to calculate F_i by

$$F_i = \frac{\mathrm{N}_i}{\Delta E} \times \frac{\beta}{\mathrm{GF} \cdot f_i \cdot \varepsilon \cdot \mathrm{T} \cdot \eta_i}, \tag{2}$$

where β is a correction for the finite energy bin size (0.90), GF is the geometry factor (0.24 m^2·sr), f_i is the interaction fraction for nucleus i, ε is a correction for various inefficiencies caused by the selection criteria [3] and the instrument dead channels (53.2 %), T is live time (224.2 hours), and η_i is a correction for the atmospheric attenuation loss for nucleus i. η_i is estimated by calculating the probability of nucleus i within the geometry to survive the atmospheric overburden of 4.3 g/cm^2, also using the cross section parameterization in [5] and [6].

Figure 2 shows the all-particle energy spectrum measured by ATIC (filled circles), together with other direct measurements by balloon-borne experiments, Ichimura et al. [8], RUNJOB [9], and JACEE [10], as well as indirect measurements by air-shower experiments, DICE [11], CASA-MIA [12], CASA-BLANCA [13], and KASCADE [14]. We find that the ATIC results are in agreement with those of Ichimura et al. below ~10 TeV/particle, and with the results of both RUNJOB and JACEE over the energy range ~10 - ~100 TeV/particle where they do not show significant discrepancies with each other yet.

Average Mass Number

We estimate the average mass number by

$$\langle \ln A \rangle = \frac{\sum_i F_i \cdot \ln A_i}{\sum_i F_i}, \tag{3}$$

where F_i is the contribution of the nucleus i with mass number A_i.

In Fig. 3 we show the average mass number as a function of particle energy measured by ATIC (filled circles). Also shown in the plot are the direct measurements by RUNJOB [9] and JACEE [10], and the indirect measurements

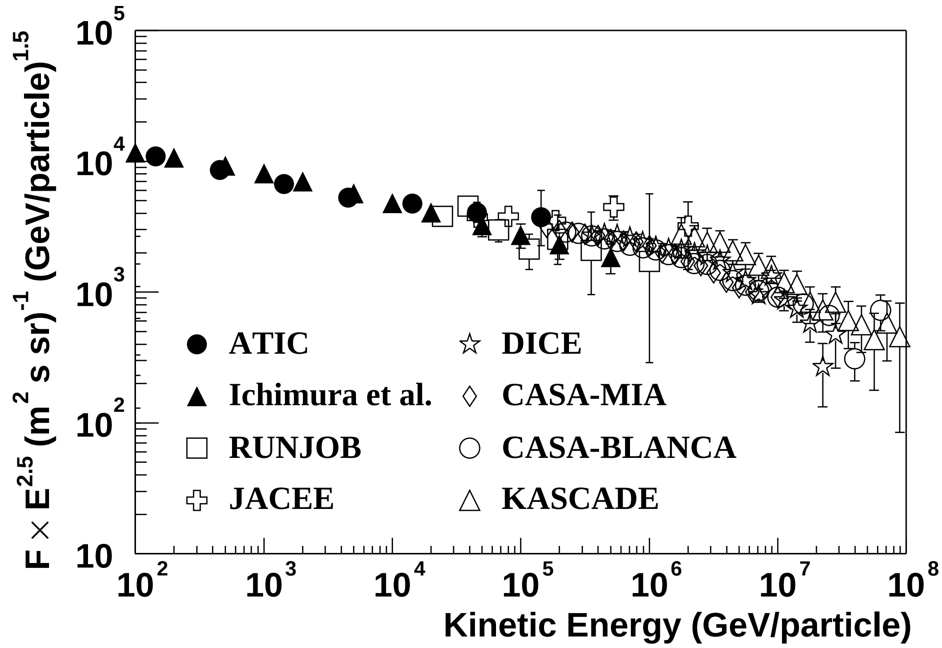

Figure 2: All-particle spectrum measured by ATIC (filled circles), together with those measured by other direct and indirect experiments, Ichimura et al., RUNJOB, JACEE, DICE, CASA-MIA, CASA-BLANCA, and KASCADE.

by DICE [11], CASA-BLANCA [13] and KASCADE [15]. Again, over the energy range $\sim$10 - $\sim$100 TeV/particle, the results of RUNJOB and JACEE do not show significant discrepacies with each other, and are in agreement with the ATIC results.

Summary

We presented the all-particle spectrum and the average mass number spectrum based on the first flight of ATIC. The results are in agreement with those measured by other balloon-borne experiments in the energy region below 100 TeV/particle.

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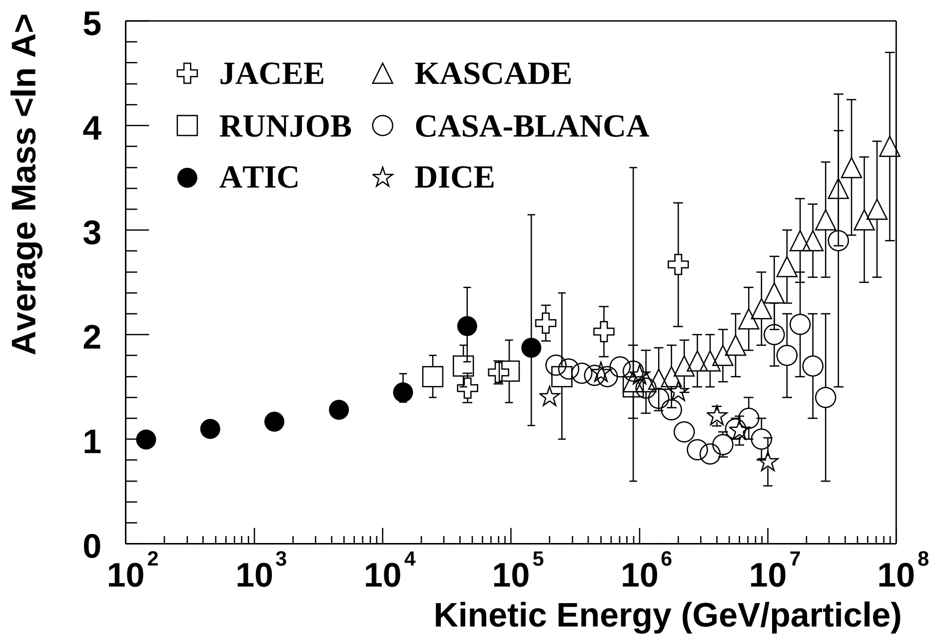

Figure 3: Average mass number as a function of particle energy measured by ATIC (filled circles), together with those measured by other direct and indirect experiments, RUNJOB, JACEE, DICE, CASA-BLANCA, and KASCADE.

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