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ENERGY SPECTRA AND COMPOSITION OF COSMIC RAYS ABOVE 1 TeV PER NUCLEON

(The JACEE COLLABORATION)

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ABSTRACT

Direct measurements of galactic cosmic ray composition have been made above 1 TeV/nucleon in a series of 10 balloon flights beginning in 1979 and continuing through this year. Recent experiments have included exposures of 5 to 6 days each on two Australia to South America flights and a circumpolar flight of 10 days in Antarctica. The updated results have 2 to 3 times larger statistics than our previously published data, and indicate: (1) a single power law proton spectrum up to about 80 TeV, and a deficiency of proton intensity beyond 80 TeV; (2) an overabundance of helium continues to 100 TeV/n; (3) the intensities of heavy elements (C to Fe) at above 1 TeV/n are consistent, within statistical errors, with the extrapolation from lower energy data using the Spacelab 2 spectral indices; (4) an enhancement for these components above 20 TeV/n for (C-O), and above 3 TeV/n for (Ne - S and Z > 17) is suggested.

INTRODUCTION Air shower observations, made by many ground-based stations in the past 3 decades, continue to indicate steepening of air shower size spectrum at about Ne = 10^6 (or around 10^{15} eV),[1] posing a question on the acceleration and propagation mechanisms of high energy cosmic rays. The first direct measurement toward this "knee region" was achieved by the PROTON satellites,[2] reporting no significant changes of spectra of all particles up to 10^{15} eV and helium component up to 2 TeV/n, but an abrupt steepening of proton spectrum above 2 TeV. The Japanese-American-Emulsion-Chamber-Experiment (JACEE) has made direct measurements of cosmic ray composition (protons through iron) between 10^{12} and 10^{15} eV, approaching the "knee", using balloon-borne emulsion chambers.[3] The JACEE experiments did not observe any steepening of the proton spectrum up to several times 10 TeV, but recognized over-abundances of other nuclei toward the "knee".[3,9]

The HEAO satellite experiment[4] observed an increase of Ar/Fe and Ca/Fe ratios above 500 GeV/n. The Intercosmos group indicated an increase of helium above 5 TeV/n.[5] More recent Spacelab 2 experiment indicated that the spectra of Ne, Mg, and Si were steeper than anticipated.[6]

In this paper we present the updated results including data of two long duration exposure flights (JACEE-7 and JACEE-8), with the total exposure factors of 7.11×10^5 m^2 sr s for protons and 1.22×10^6 m^2 sr s for Fe. The details of proton and helium spectra will be reported separately.

EXPERIMENTAL TECHNIQUES The charge (Z) of the primary particles is measured in the emulsion. For protons and helium nuclei, Z is determined by grain-counting with precision better than $\sigma Z = 0.20e$. For light nuclei (Li - B), gap-counting in low-sensitivity emulsions are used. For heavier elements, delta-ray range spectrum measurements were calibrated by ^{16}O and ^{32}S beams at 200 GeV/n,[7] and gave the charge resolution of $\sigma Z = 0.57e$ from C to Ar.

The total gamma ray energy, ΣE_γ, was measured by direct electron-counting in emulsions and/or by photo-densitometry of x-ray films in the emulsion calorimeter. The former method permits energy measurements of ΣE_γ to better than 25% (including cascade fluctuations). The latter, being calibrated by electron-counting, has been used for recent analyses, and retains a resolution of 32%. Some comments are due, however, for a use of x-ray film densitometry. Some photometric measurements saturate at lower electron densities (D = 4 - 6) than the density saturation of x-ray films (D = 7.5); Lack of electron-counting calibrations for truly high energy events above $\Sigma E_\gamma > 50$ TeV could lead to a systematic underestimation of high shower energies.

The overall accuracies in measuring the total observable energy, ΣE_γ, are estimated as 30% for C and 40% for Fe, independent of ΣE_γ over the observed energy region. Also, the partial inelasticity distribution into gamma rays, $f(k_\gamma = \Sigma E_\gamma / E_o$: E_o = primary energy), for nucleus events has been calculated, by using the nucleus-nucleus collision model.[8] The validity of the model has been verified by the recent emulsion experiments by using CERN 60 and 200 GeV/n ^{16}O and 200 GeV/n ^{32}S, and previously, by the JACEE cosmic ray results.[9] For the deconvolution of the E_o spectrum from the ΣE_γ spectrum, the energy conversion factors (Ck_γ) are calculated as typically 0.25 for protons, 0.10 for C, and 0.09 for Fe with small corrections on target material, chamber geometry, and primary spectral index. Effects of possible change of interaction characteristics for central nucleus-nucleus collisions at higher energies is negligible in the inclusive spectrum study.

Absolute fluxes are calculated by taking account of the interaction probability and geometrical collecting efficiency, the detection efficiencies near the energy threshold, atmospheric corrections at depths 3 to 5 g/cm^3, and the flux corrections due to the finite energy resolutions. No corrections for a possible energy dependence of inelasticity coefficient are made since they are presumed, for nucleus-nucleus collisions, to be negligibly small.

RESULTS AND DISCUSSIONS The differential energy spectra of protons, helium, (C - O), (Ne - S), and Fe ($Z \geq 25$) are shown in Fig. 1. The low proton intensity previously observed by us^3 in the energy bin around 100 TeV is indeed reproduced in the long-duration balloon flight experiments. He to proton ratio^3 at 10 TeV/n was 0.082 $\pm$0.019, a factor of two higher than 0.042 $\pm$ 0.003 at 50 to 100 GeV/n.^{10} The present data at 50 (+18, -10) TeV/n indicate 0.163 $\pm$ 0.064, another factor of two increase from that at 10 TeV/n. Almost all medium to heavy components suggest flatter energy spectra. (Ne - S) results from JACEE 1-6 experiments^3 were in some conflict at below 1 TeV/n with unusually steep spectra of Spacelab 2. Recently, however, Muller et al. examined the absolute intensity of the Spacelab data (see Fig.1),^{11} and which is now in agreement with our high energy data above 2 TeV/n.

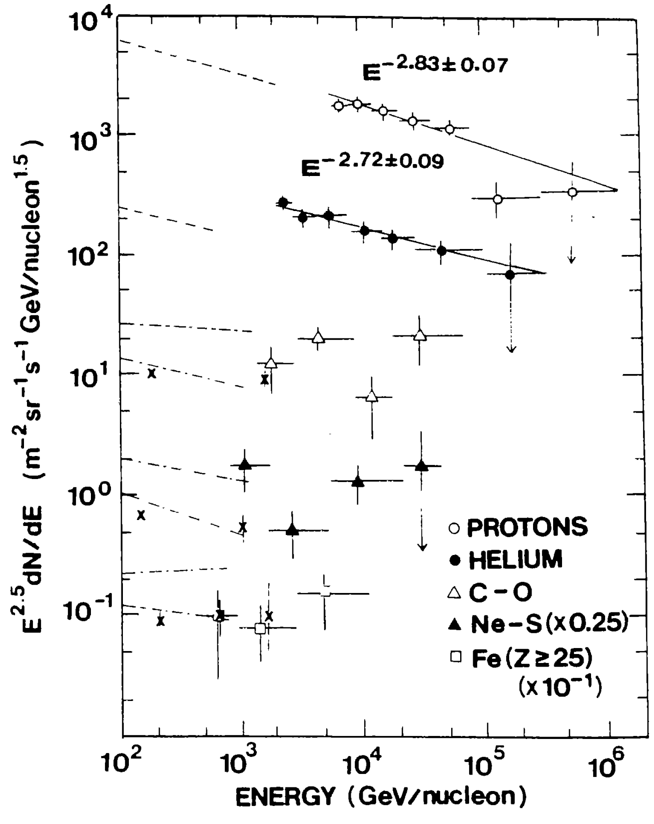
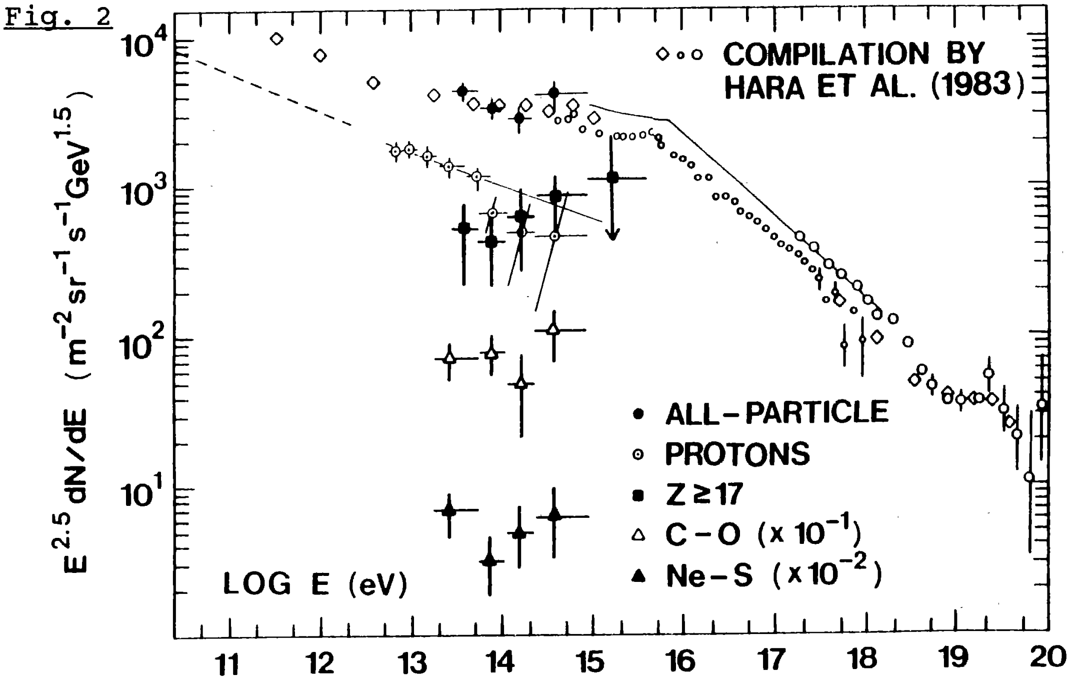


Fig. 1 The differential spectrum (energy per nucleon). Cross points and dotted lines are the latest data and the bounds from Spacelab 2 experiments.

Fig. 2



The total energy spectra are shown in Fig. 2. Enhanced intensities above 200 TeV up to 930 TeV are universally seen for medium to heavy nuclei. The average ln A (mass) of the cosmic rays at about 400 TeV is 2.33 ± 0.27. The intensity rates for p, He, (C-O), (Ne-S), and heavy nuclei ($Z \geq 17$), are 12 ± 9%, 25 ± 14%, 26 ± 12%, 15 ± 8%, and 21 ± 10%, respectively.

Some of current models for the cosmic ray acceleration and propagation mechanisms may explain the present results, noting the decreasing proton component and enhancements of other nuclei. The present statistics, however, still precludes examination of helium and medium to heavy nuclei at 100 TeV/n, and the rigidity-dependent escape model predictions are not yet tested. Further long-duration balloon flights are clearly needed to understand the detailed behavior of high energy cosmic rays at the "knee".

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