ENERGY SPECTRA OF PROTONS AND HELIUM NUCLEI ABOVE 5 TEV/NUCLEON

The JACEE Collaboration

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Abstract: The differential energy spectra of cosmic ray protons and helium nuclei have been measured above ~2 TeV/nucleon in a series of JACEE balloon borne emulsion chamber experiments. The proton spectrum can be represented by a power law with index -2.86 ± 0.07 up to at least 40 TeV, and the helium spectrum has index -2.72 ± 0.09 from 2 TeV/nucleon to 60 TeV/n. In the energy region beyond 100 TeV, much larger statistics are required to critically discuss the validity of the above spectral indices.

Introduction: An intensity enhancement and a bending of the cosmic ray total energy spectrum have been observed by extensive air shower experiments in the energy range 10^{14} - 10^{16} eV. These observations have given rise to numerous speculations about models of propagation and the mechanism of acceleration and the origin of these high energy cosmic ray particles.[1] The first direct measurements were done by the "PROTON" satellite experiments,[2] which reported a steepening of the proton energy spectrum beyond 2 TeV, but no significant change for helium up to 2 TeV/nucleon or in the all particle spectrum up to 10^{15} eV. The Japanese-American-Cooperative Emulsion Experiments (JACEE) were designed to measure energy and chemical composition of the cosmic rays using emulsion calorimeter methods, and to have sufficient collecting power to make spectral measurements beyond the region of the reported steepening.[3] Results from the first 6 flights have been reported recently by Burnett et al.[4] For protons, no change in the energy spectral index was seen up to 100 TeV. For helium nuclei, the results showed a spectrum above 2 TeV/nucleon similar to that of protons, but with an absolute intensity about twice as large as expected from an extrapolation of lower energy data. Such a helium enhancement is consistent with models of propagation including reacceleration.[5] Four additional flights have now been carried out (JACEE 7-10). Although the analysis of these flights is still in progress, we present in this paper updated JACEE results on the energy spectra of protons and helium nuclei, including new data from the long duration Australia-to-South America JACEE 7 and 8 flights.

Flights and Experimental Technique: The flights of JACEE 1 thru 8 have been summarized in Ref. 6. The total exposure factor is 133 m^2hr for JACEE 1 through JACEE 6 and 162 m^2hr for JACEE 7 + 8. The basic design of the detector is approximately the same for all the JACEE flights, having a target section with ~0.2 proton mean free paths and an emulsion calorimeter with vertical depth ~7 radiation lengths. Details of the measurement techniques have been reported in Refs. 3, 4, 6. The charge Z is determined by grain-counting with accuracy σ better than 0.2 for proton and helium. For JACEE 1-6, total gamma ray energy $\Sigma E\gamma$ is assigned to each event by counting the electron tracks in the electromagnetic cascades with an accuracy better than 25%; and for JACEE 7 and 8, $\Sigma E\gamma$ is determined from the optical density of x-ray films at shower maximum with an accuracy of 35%. The data from the JACEE 7 and 8 experiments contribute to this analysis in the energy region $\Sigma E\gamma$ greater than 5 TeV for protons, and 5.3 TeV for helium nuclei. The procedure for deriving the absolute flux and the primary E_0 spectrum from the measured $\Sigma E\gamma$ spectrum have been described elsewhere.[3,4,6]

Results: Figure 1 shows the updated differential spectra of protons and helium. The maximum likelihood power-law fits are respectively, for protons and helium nuclei,

$$\frac{dN}{dE}\Big|_p = (1.30 \pm 0.30) \times 10^{-1} \times E^{-2.86 \pm 0.07}\ (m^2\text{-sr-sec TeV})^{-1}, \quad E \text{ in TeV}$$

and

$$\frac{dN}{dE}\Big|_{He} = (9.96 \pm 1.92) \times 10^{-3} \times E^{-2.72 \pm 0.09}\ (m^2\text{-sr-sec TeV/n})^{-1},$$
$$E \text{ in TeV/nucleon.}$$

A factor $E^{-0.03}$ has been applied to the proton spectrum to correct for the rising interaction cross section.[7]

The proton point at 133 TeV is low compared to this best-fit spectrum. This suggests, then, based on the seven measured events in this bin and one event in the highest energy bin, the possibility of a steepening in the spectrum. We therefore perform a fit separately for the 6-40 TeV region:

$$\frac{dN}{dE}\Big|_p = (7.72 \pm 2.59) \times 10^{-2} \times E^{-2.65 \pm 0.12}\ (m^2\text{-sr-sec TeV})^{-1}, \ 6 \le E \le 40 \text{ TeV};$$

and for the 40 events above 40 TeV,

$$\frac{dN}{dE}\bigg|_p = (1.36 \pm 2.04) \times E^{-3.44 \pm 0.35} \text{ (m}^2\text{-sr-sec-TeV)} \quad , \quad E > 40 \text{ TeV}.$$

This result is not inconsistent with our previous result. Fig. 1 compares the two data sets. The present proton statistics are about 3 times larger than the previous results in the energy region above 20 TeV. The proton flux around 100 TeV was measured to be almost 3 standard deviations below the intensity expected from a single power law spectrum with an exponent of 2.8. For helium, the single event in the highest energy bin does not allow us to draw any conclusions about the spectrum above 60 TeV/nucleon. Additional data (e.g. from JACEE 9,10 and more long duration flights in the future) are needed to fully understand the very high energy characteristics of the protons and helium nuclei.

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References

1. Fichtel, C. E. et al., Ap. J. 300, 474 (1986); Takahashi, Y. et al., Nature 321, 839 (1986).
2. Grigorov, N. L., et al., Proc. 12th ICRC (Hobart) 5, 1760 (1971).
3. Burnett, T. H. et al., Nucl. Instr. and Methods, A251, (1986).
4. Burnett, T. H. et al., Ap. J. Lett., 349, L25 (1990).
5. Seo, E. S. et al., Ap. J., to be published (1991).
6. Parnell, T. P. et al., Cospar 88 (Helsinki) Adv. Sp. Res. (1988).
7. Takahashi, Y. et al., AIP Conf. Proc. on Cosmic Rays and Particle Physics No. 49, 166 (1979).

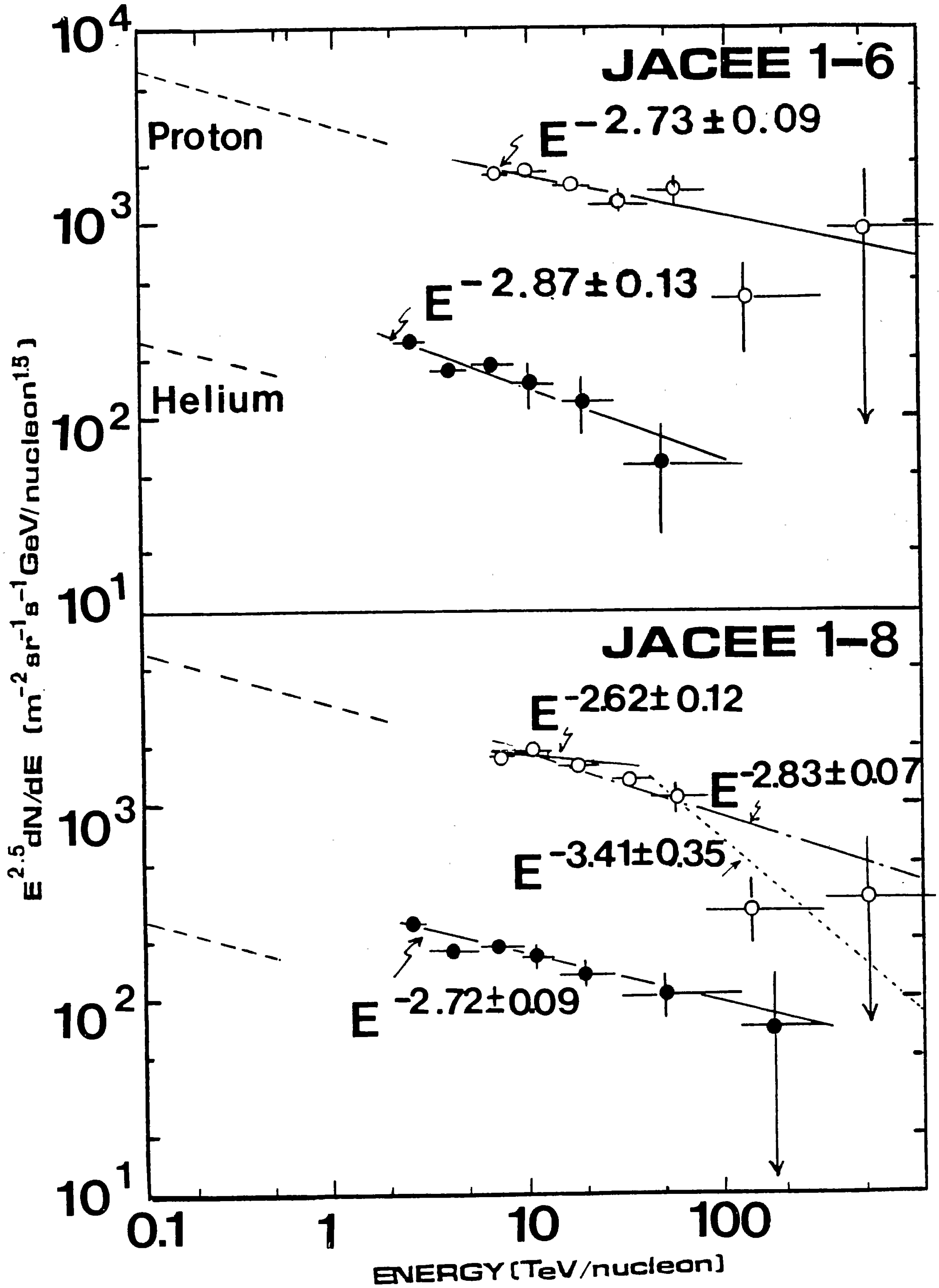

Fig. 1. Comparison of JACEE 1-6 and 1-8 proton and helium results. The proton spectrum must receive the correction for the interaction rising cross section in the index.(see text)