Photon and Helium Energy Spectra above 1 TeV for Primary Cosmic Rays

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Energy spectra of protons and helium nuclei in the primary cosmic rays were measured above 1 TeV in a series of balloon flights of emulsion chambers. Differential spectra may be represented by power laws of indices -2.81 ± 0.13 and -2.83 ± 0.20 for protons and He, respectively. No index change was observed for either species over the energy ranges 5–500 TeV for protons and 2–50 TeV/nucleon for He. Intensities were consistent with extrapolations of previously published data below 1 TeV/nucleon.

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Despite the great interest engendered by the measurement of the cosmic-ray proton spectrum by Grigorov and co-workers on the "proton" satellites,[1] there has been no independent measurement in their energy range reported in well over a decade. Those measurements extended up to about 2 TeV for helium, 20 TeV for protons, and 10^{16} eV for "all particles." The helium and all-particle spectra maintained approximately the same index over the energy range covered, but around 2 TeV it was reported that the proton integral-spectral index changed from -1.7 to -2.3. Balloon observations[2-4] were in agreement with the proton-satellite results below 1 TeV, but none of the balloon measurements extended through the energy region of the reported index change for protons. Such a change in index of the dominant component would strongly affect the relative composition of the cosmic rays over the next few higher decades of energy. On the other hand, the change might indicate the onset of a new type of behavior of nuclear interaction at this energy or be the result of an experimental artifact such as backscattered particles from the calorimeter causing enhancement of signal in the charge-measuring detectors.[5]

In recent years, several air-shower groups[6] have reported changes in the relative chemical composition of cosmic rays above 10^{14} eV. Various methods have been used to infer primary charge, but all were indirect in that the properties of the primary particle before interaction could not be inspected. Whether and in what manner the composition of the cosmic rays may change has direct consequences on the models of confinement[7] in the galaxy and on the question of there being different sources for different elements.[8]

The Japanese-American Cooperative Emulsion Experiment (JACEE) balloon flight series was designed to measure energy and chemical composition of the cosmic rays in the range 10^{12} to 10^{15} eV with use of emulsion calorimeter methods. The data reported here, on protons and helium only, are based mainly on two balloon flights from Palestine, Texas: JACEE-1 in 1979 and JACEE-2 in 1980. Both flights were at atmospheric depths between 3.5 and 5.0 g cm^{-2}. One-ninth of the total exposure of about 100 m^2 sr h was achieved by a previous flight, JACEE-0, in Japan in 1979.

The apparatus was emulsion chambers of area 0.8 m^2 that permitted detailed study of high-energy nuclear interactions and measurement of the electromagnetic cascades ensuing from the interaction.[9] They were launched inverted and rotated 180° upon reaching float altitude to allow easy discrimination against atmospheric secondaries. Shown schematically in Fig. 1, the apparatus consisted of three detectors systems: (1) *the charge*

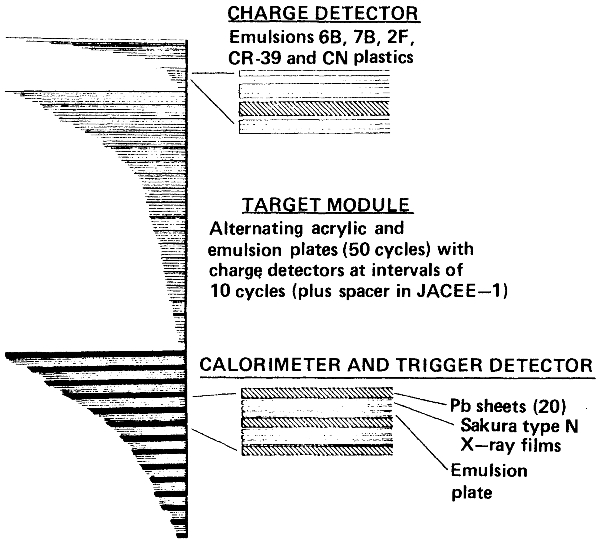

FIG. 1. Experimental configuration of JACEE emulsion chambers (not to scale). There were approximately 600 sheets of material in each chamber.

module at the top for determining primary atomic number by use of a variety of nuclear emulsions and track recording plastics; (2) *the target module* consisting of 70 double-sided emulsion plates and 45 thick acrylic plastic plates; and (3) *the calorimeter*, 7 radiation lengths deep, which contained 20 layers each of lead, x-ray film, and emulsions. Each emulsion plate in JACEE consisted of a sheet of acrylic plastic, on each side of which was bonded a layer of Fuji nuclear emulsion.

Events were detected by visual scanning of the x-ray films for characteristic dark spots produced by electromagnetic cascades in the calorimeter. The detection threshold corresponded to a total gamma-ray energy, $\sum E_\gamma$, of about 300 GeV. The present analysis was based on those events having a $\sum E_\gamma$ above 1.2 TeV, for which the detection efficiency was almost 100%. These events were located in the emulsion plates adjacent to the films and, with use of a microscope, traced upwards through the detector until the first interaction vertex and its primary were found. No tracks parallel to the primary above the interaction vertex were observed for any of the events used in this analysis.

Charge determination for protons and helium nuclei was made by grain counting in thick electron-sensitive plates (Fuji 7B) above the primary interaction vertex and was unambiguous even in the case of nearly vertical tracks.[9] Grain counting and gap counting were used to separate He and Li nuclei.

Individual π^0-decay gamma rays from target module interactions were generally well separated in the calorimeter, and their energies were individually determined by counting closely collimated electron tracks within a circle of radius of 25–50 μm in several emulsion layers. The shower development measurements were then fitted by the transition curves of Nishimura.[10] Calorimeter interactions, on the other hand, contained many overlapping electromagnetic showers which could not usually be individually resolved. The energies of such cascades were determined by comparing the track counts in a larger circle (200 μm radius) with transition curves numerically calculated to include both superposition of many single gamma-ray cascades and the secondary interactions of fragments and charged pions. The measurement error in $\sum E_\gamma$ was given[11] as 20%–30% for the JACEE experiment and was similar to that given by Hotta *et al.*[12] in an accelerator calibration using similar chambers.

From a set of proton or He events, for which the gamma-ray energies have been determined, a spectrum of the secondary quantity $\sum E_\gamma$ was drawn. It has been shown[9, 13] that if a primary cosmic-ray spectrum is given by a simple power law in energy, then the spectrum of the secondary quantity is a power law of the same index, but shifted down in energy (for a given flux) by a constant factor. This factor, $C_{k\gamma}$ (not to be confused with the average gamma-ray inelasticity, $\langle k_\gamma \rangle$), depends on the spectral index and on the distribution function of k_γ (where $k_\gamma = \sum E_\gamma / E_0$). In practice it has been found that the calculated values of $C_{k\gamma}$ are rather insensitive to the form of the inelasticity distribution. For example, calculations using p-Al accelerator results[14] gave a value of $C_{k\gamma}$ of 0.23 while a fit to the direct k_γ measurements of Dake *et al.*[15] for 400-GeV protons at the Fermi National Accelerator Laboratory gave 0.24. The latter value was used in this analysis. $C_{k\gamma}$ for He has been calculated by simulation to be 0.17.

This procedure is only valid if the k_γ distribution does not change over the measured energy range. Recent results[16] from the $\bar{p}$-p collider at 150 TeV show no significant changes in interaction characteristics from those at <1 TeV.

Since a nuclear interaction was required for a primary particle to be detected, the collecting power of the instrument depends on both the geometric aperture and the probability of interaction of a particular nucleus. Values of the geometrical efficiency factor were calculated with use of energy-independent cross sections.

Differential primary spectra for protons and helium nuclei before any corrections were applied are shown in Fig. 2. The solid lines are maximum-likelihood fits to this data which included 60 protons and 29 helium nuclei. While almost the whole geometric factor was used for the highest-energy events ($\sum E_\gamma \geq 20$ TeV), smaller portions of the stack were analyzed at lower energies. The set used in these fits contained data having selection thresholds well above the energy regions at which the detection efficiency may be less than 1. Two corrections were applied to the absolute intensities obtained from the fits. A convolution of a Gaussian error of 25% in experimental measurement of $\sum E_\gamma$ with the power-law spectrum required a reduction in flux of 14%, while additive corrections for atmospheric interactions were 7% and 12%, respectively, for protons and helium nuclei. No correction was made for production of either nucleus in the atmosphere. After application of these corrections, and applying a factor of $E^{-0.03}$ to the proton flux to account for the rising proton cross section,[17] the maximum-likelihood power-law fits were as follows, respectively, for protons and heliums:

$$dN_p/dE = 1.25\times 10^{-5} E^{-2.81\pm 0.13}\ (\mathrm{cm^2\ sr\ s\ TeV})^{-1},$$

$$dN_{\mathrm{He}}/dE = 5.25\times 10^{-7} E^{-2.83\pm 0.20}\ (\mathrm{cm^2\ sr\ s\ TeV/nucleon})^{-1}.$$

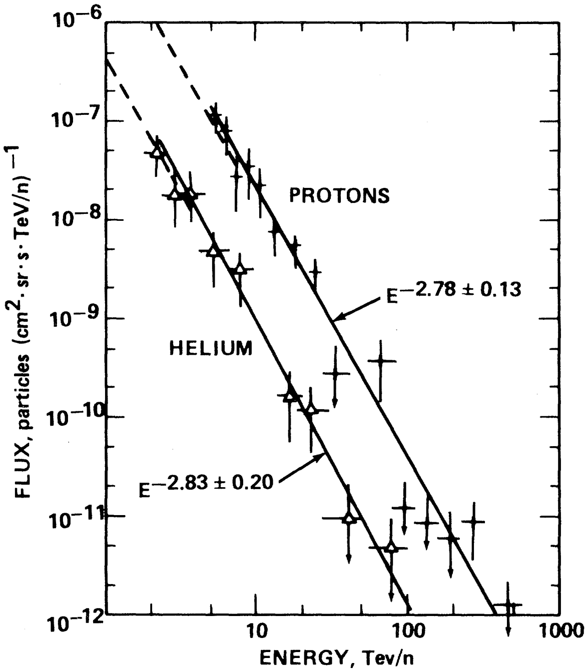

FIG. 2. Differential spectra of protons (plusses) and helium (triangles) nuclei. Both components were well fitted by single power laws of essentially the same index (maximum-likelihood fit, solid line) and both agree well with previously published data below 1 TeV (Ref. 4, dashed-line extrapolation). No break in the proton spectrum was observed up to 100 TeV. Errors shown are in (i) energy—measurement error in ΣE_γ or bin width, whichever is larger; and (ii) flux—statistical error.

TABLE I. Comparison of differential and integral flux values with the data of others at lower or overlapping energies. Values marked with asterisk are extrapolations with quoted equations of fit to the data.

		Differential fluxes [Particles (cm² sr s Tev/nucleon)$^{-1}$]
JACEE	dN_p/dE at 10 TeV	1.9×10^{-8}
	dN_{He}/dE at 10 TeV	7.8×10^{-10}
GSFC[a]	dN_p/dE at 10 TeV*	2.0×10^{-8}
	dN_{He}/dE at 10 TeV*	7.2×10^{-10}

		Integral fluxes above energy E [Particles (cm² sr s)$^{-1}$]		
		1 TeV	10 TeV	20 TeV
JACEE	p	6.9×10^{-6}*	1.1×10^{-7}	3.1×10^{-8}
	He	2.9×10^{-7}	4.2×10^{-9}	1.2×10^{-9}
Proton	p	6.3×10^{-6}	5.0×10^{-8}	9.2×10^{-9}
satellites[b]	He	2.6×10^{-7}	•••	•••

[a] Ref. 4.

[b] Ref. 1.

Statistical errors in flux given by the maximum-likelihood method were ± 13% and ± 20%, respectively, for protons and He nuclei. Systematic errors were estimated to be ± 20% in flux. A comparison of these data with those of others is shown in Table I.

The data presented here agree well in the case of He with the proton-satellite value[1] at 2 TeV and with the fitted line to the Goddard Space Flight Center (GSFC) data[4] extrapolated to higher energy. In the case of protons, the JACEE data are consistent with an extrapolation of the GSFC data but not with the proton-satellite data at 10–20 TeV. No evidence was seen of a change in the spectral index of either component. Our value for the p/He ratio of 25 ± 6 in the energy range 5–50 TeV/nucleon is consistent with 26 ± 3 in the range 60–400 GeV/nucleon (Ref. 4) and with an asymptotic value[18] at high energy of 25–30.

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