THE ASTROPHYSICAL JOURNAL, 349:L25–L28, 1990 January 20

ENERGY SPECTRA OF COSMIC RAYS ABOVE 1 TeV PER NUCLEON

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Received 1989 August 17; accepted 1989 November 1

ABSTRACT

Direct measurements of cosmic-ray nuclei above 1 TeV per nucleon have been performed in a series of balloon-borne experiments with emulsion chambers. The observed all-particle spectrum above 20 TeV is consistent with the results of the *Proton* satellite and many air shower experiments. The proton spectrum is consistent with a power law having an index of 2.76 ± 0.09 up to at least 100 TeV, but an overabundance of helium by a factor of 2 above 2 TeV per nucleon is found when compared with the extrapolation from the low energies. For heavy elements (C through Fe), the intensities around 1 TeV per nucleon are consistent, within the statistical errors, with the extrapolation from lower energy data using the *Spacelab 2* spectral indices. An enhancement for the medium-heavy components (C through Ca) above 200 TeV is indicated. The mean mass above 50 TeV indicates slightly higher values than the results of the air shower experiments.

Subject heading: cosmic rays: abundances

Extensive air shower experiments have shown an intensity enhancement (the "knee") in the cosmic-ray spectrum at 10^{14} to 10^{16} eV, where the shock acceleration theory ceases to provide a continuous power-law spectrum (Hillas 1984). What elements are responsible for this structure has been unknown and is one of the most important questions in cosmic-ray physics. Measurements of the elemental composition in this region are required for understanding the cosmic-ray sources, acceleration, and Galactic containment mechanisms, and for clarifying the air shower data. The first direct measurement toward this region was achieved by the *Proton* satellite experiments (Akimov *et al.* 1970; Grigorov *et al.* 1971), indicating an abrupt steepening in the proton spectrum above 2 TeV, but no significant change in helium up to 2 TeV per nucleon and in the all-particle spectrum up to 10^{15} eV. Recently, the Intercosmos group reported an increase in the abundance of helium above 5 TeV per nucleon (Ivanenko *et al.* 1988). The *HEAO 3* satellite experiment (Binns *et al.* 1988) observed an increase of Ar/Fe and Ca/Fe ratios above 500 GeV per nucleon. More recently, the *Spacelab 2* result (Muller *et al.* 1987; Grunsfeld *et al.* 1988) indicated that the Fe spectrum is flatter and the spectra of Ne, Mg, and Si are steeper than anticipated in the energy region 50 GeV per nucleon to 1 TeV per nucleon, which urged observations of their behavior at much higher energies close to the "knee."

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The Japanese-American Cooperative Emulsion Experiment (JACEE) has made direct measurements of cosmic-ray composition (protons through Fe) between 10^{12} and 10^{15} eV using balloon-borne emulsion chambers (Burnett *et al.* 1983, 1985, 1987*a*). In this *Letter* we present the results from the first six balloon flights on the energy spectra of protons, helium, (C–O), (Ne–S), Fe($Z \geq 25$), ($Z \geq 17$), and all particles in the energy region 10^{13}–10^{15} eV, which allow the first examination of elemental abundances at energies bridging the "knee" and the lower energy regions.

The detector used is the emulsion chamber, shown in Figure 1, which is composed of four parts: (1) a charge-determination module, (2) a target module with ~ 0.2 vertical interaction mean free paths for protons, (3) a spacer module, and (4) an emulsion calorimeter module with about seven vertical radiation lengths. The chamber is mounted in a "flipper" or a "plate shifter" mechanism to eliminate the events which occur during the balloon ascent and descent. Events are detected by visual scanning of X-ray films for dark spots produced by electromagnetic cascades in the calorimeter and are traced upward to find the first interaction vertex and the primary track. Events which interact in the chamber wall are eliminated by checking for associated parallel tracks at the entry point to the chamber.

For protons and helium, the charge, Z, is determined by grain-counting with precision better than $\sigma_Z = 0.2$, and the total gamma-ray energy, ΣE_γ, better than 25% (Burnett *et al.* 1986*a*). For some Fe events, charges were determined with CR-39 plastic track detectors providing a minimum value due to various environmental fading effects during the experiments. However, the majority of the charge assignments for nuclei were derived from the emulsion tracks. The conventional procedure of delta-ray counting to measure charge (Powell, Fowler, and Perkins 1959), which was limited to resolution $\sigma_Z = 1$–2 because of uncertainties of the criterion on delta-ray ranges, has been significantly improved by the application of delta-ray range distribution measurements for ^{16}O and ^{32}S data of 200 GeV per nucleon (Takahashi 1988; Parnell *et al.*

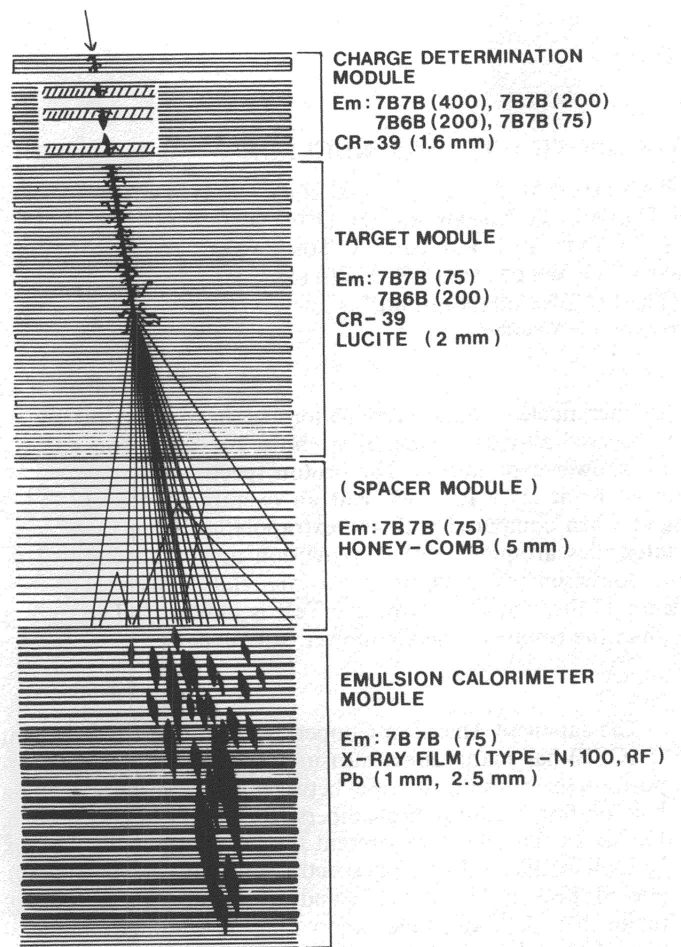

FIG. 1.—Schematic diagram of an emulsion chamber (not to scale). Typical event profile is shown. Spacer module has been used in chambers mainly for interaction studies.

1989). Figure 2 shows a sample of the charge distribution. The curves show the best Gaussian fit with $\sigma_Z = 0.57 \pm 0.10$, approximately constant from C to Ar, and are consistent with the value expected for the 1.5 mm average measured track length.

The total observable energy, ΣE_γ, for heavy nuclei has been determined, taking the mass-dependent shower structure into account, by three-dimensional hadronic and electromagnetic cascade shower codes (Burnett *et al.* 1987*b*) based on the "superposition" model of high-energy nucleus-nucleus collisions (Kinoshita, Minaka, and Sumiyoshi 1981). The overall accuracies in ΣE_γ measurements 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, $f(k_\gamma = \Sigma E_\gamma/E_0$, where E_0 is the primary energy), for

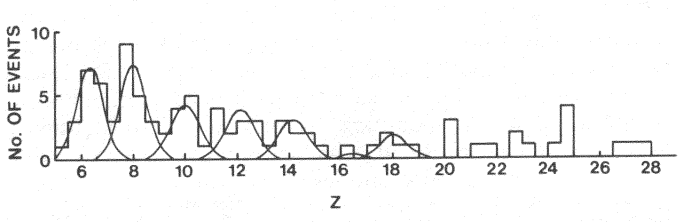

FIG. 2.—Charge distribution derived from the delta-ray range distributions. Curves are the best Gaussian fit with $\sigma_Z = 0.57 \pm 0.10$.

nucleus events has been calculated, by using the same "superposition" model. The validity of the model has been verified by recent emulsion experiments using CERN beams of 60 and 200 GeV per nucleon ^{16}O and 200 GeV per nucleon ^{32}S, and by the JACEE cosmic-ray results (Burnett *et al.* 1987*c*; Takahashi *et al.* 1987, 1989*a*, *b*).

The energy conversion factors (Ck_γ) for the deconvolution of the E_0 spectrum from the ΣE_γ spectrum and the distribution $f(k_\gamma)$ have been calculated as typically 0.25 for protons, 0.10 for C, and 0.09 for Fe, with a small dependence on target material, chamber structure, and primary spectral index, within an uncertainty of less than 20% (Burnett *et al.* 1986*a*, 1987*b*). We assume here that $f(k_\gamma)$ is energy-independent to 1000 TeV, the validity of which has been verified by large accelerator experiments at least up to 150 TeV per nucleon (Alpgard *et al.* 1981; Alner *et al.* 1985). The largest assumption of the present experiments is the validity of the superposition model at very high energy. However, the effect of a possible change in interaction characteristics for central nucleus-nucleus collisions at higher energies is negligible in the inclusive spectrum study, since such events comprise only a few percent of the total number of events at the highest energies in the present experiment (Burnett *et al.* 1986*b*).

Absolute fluxes are calculated by taking into account the interaction probability and geometrical collecting efficiency, the detection efficiencies near the energy threshold (typically 82% for protons at 5 TeV and 97% for Fe at 500 GeV per nucleon), atmospheric corrections at depths 3–5 g cm^{-2} (typically 1.06 for protons and 1.40 for Fe), and the correction factors (typically 0.96 for protons and 0.89 for Fe) of intensities to account for finite resolutions of the ΣE_γ determination. Details of the measurement techniques of heavy nuclei with an emulsion chamber will be reported in a subsequent paper.

Figure 3 shows the differential spectra of the major primary components protons, helium, (C–O), (Ne–S), and Fe($Z \geq 25$). The error bars show only statistical uncertainties. The horizontal bars indicate the energy bin widths which are always greater than the energy resolution. Table 1 gives the total number of events used in this figure and the exposure factors of the highest energy bins. For protons and helium (with ~3 times more statistics than reported previously in Burnett *et al.* 1983), the power-law maximum-likelihood fits are

$$(dN/dE)_p = (9.17 \pm 2.39) \times 10^{-2} E^{-2.76 \pm 0.09} \quad (\mathrm{m^2\ sr\ s\ TeV})^{-1} ,$$

$$(dN/dE)_{\mathrm{He}} = (1.03 \pm 0.23) \times 10^{-2} E^{-2.87 \pm 0.13} \quad (\mathrm{m^2\ sr\ s\ TeV/nucleon})^{-1} ,$$

TABLE 1

NUMBER OF EVENTS USED IN FIGURE 3, AND EXPOSURE FACTORS OF HIGHEST ENERGY BINS

Component	Number of Events	Exposure Factor (m^2 sr s)
Protons	168	3.63×10^5
Helium	107	4.73×10^5
C–O	15	5.42×10^5
Ne–S	15	5.64×10^5
$Z \geq 25$	4	5.71×10^5

NOTE.—Exposure factors used are smaller at lower energies and vary with atomic number of the primary nucleus.

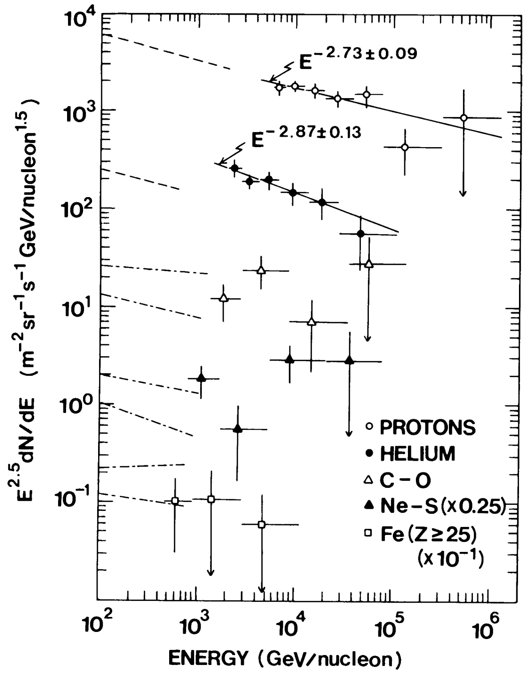

FIG. 3.—Differential spectra (in terms of energy per nucleon) of the major primary components protons, helium, (C–O), (Ne–S), and Fe($Z \geq 25$). Upper (protons) and lower (helium) dashed lines denote the spectra by Ryan *et al.* (1972). Three pairs of dashed-dotted lines represent the low-energy boundaries of the spectra, derived from the spectral indices of O, Mg, and Fe-group ($25 \leq Z \leq 27$) reported by Grunsfeld *et al.* (1988), with the normalization of (C–O), (Ne–S), and ($Z \geq 25$) at 25–50 GeV per nucleon (Juliusson 1974; Caldwell 1977; Lezniak and Webber 1978; Orth *et al.* 1978; Simon *et al.* 1980; Engelmann *et al.* 1983).

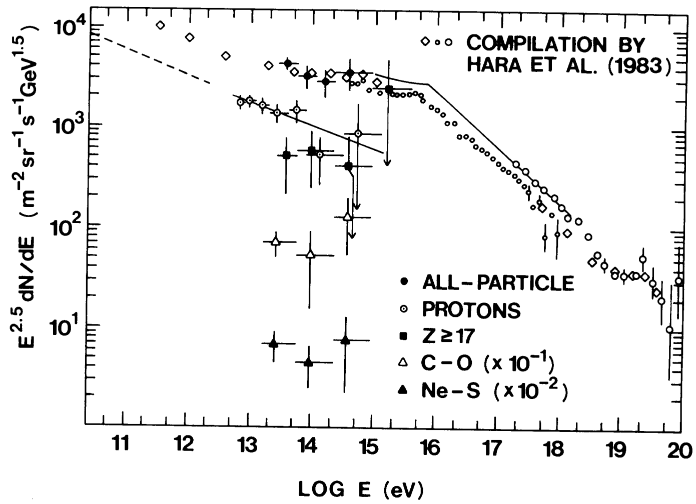

FIG. 4.—Differential spectra for all charged particles, protons, ($Z \geq 17$), (C–O), and (Ne–S), compared with the all-particle spectra compiled by Hara *et al.* (1983), in terms of energy per particle.

where a factor $E^{-0.03}$ has been applied to the proton spectrum to correct for the rising interaction cross section (Takahashi 1979). No indication of a significant change in spectral index for the proton spectrum is observed up to at least 100 TeV, but the helium intensities above 2 TeV per nucleon are about twice the extrapolated value from lower energy data, resulting in a He/P ratio of 0.083 ± 0.025 at 10 TeV per nucleon, compared with 0.042 ± 0.003 at 50–100 GeV per nucleon (Ryan, Ormes, and Balasubrahmanyan 1972; Golden *et al.* 1984). This increase amounts to 100% (+150%–62%) in two decades of the energy. No such energy dependence is expected at this high rigidity regime except for the effect of the scale size of the acceleration region in the shock acceleration model (Blandford and Ostriker 1980).

The intensities of the heavy components seem to agree within the statistical uncertainties, with the extrapolations from low-energy data up to ∼5 TeV per nucleon. However, above this energy, an intensity enhancement is indicated, in particular, for (Ne–S) (to 100%–300%), although statistics are still limited. Here we note that the intensity enhancements more than +23% cannot be attributed to any possible changes of nucleus-nucleus interactions. This particular characteristic seems hard to reconcile with the extrapolations of steeper spectra of the *Spacelab 2* result for Ne, Mg, and Si below 1 TeV per nucleon (Grunsfeld *et al.* 1988).

Figure 4 compares the present data with the all-particle spectra previously compiled by Hara *et al.* (1983). Note that the horizontal axis represents eV per particle rather than GeV per nucleon, and that the (C–O) and (Ne–S) data have been scaled for clarity. The all-particle data agree well with other results. Figure 5 shows the mean mass $\langle \ln A \rangle$ of cosmic rays as a function of energy. The present results give slightly higher values of $\langle \ln A \rangle$ above 50 TeV compared with indirect air shower observations (Watson 1985) but are consistent with low-energy balloon data.

In summary, (1) the proton spectrum does not change from a spectral index of 2.76 ± 0.09 up to at least 100 TeV; (2) an overabundance of helium by a factor of 2 above 2 TeV per nucleon is indicated; (3) the intensities of medium heavy components (C–O) and (Ne–S) seem to be enhanced above 200 TeV; (4) the highest energy event in Figure 4 is a Ca at 4×10^{15} eV, and the ratio of $(17 \leq Z \leq 24)/(Z \geq 25)$ is 0.65 ± 0.44 above 500 GeV per nucleon and 0.79 ± 0.73 above 1 TeV per nucleon, which is not inconsistent with an Ar and Ca enhancement above 500 GeV per nucleon shown by Binns *et al.* (1988).

The present results, indicating some intensity enhancements of nuclei in comparison with those of proton and helium components, are not readily explained by some current models for

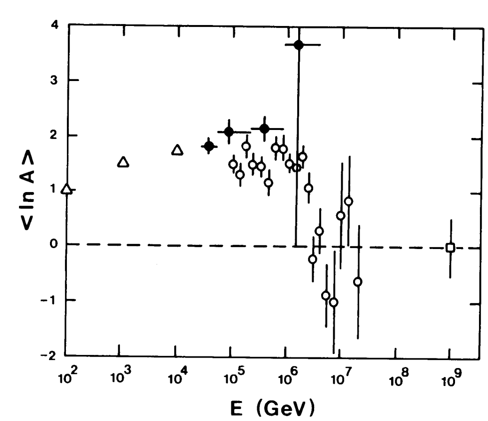

FIG. 5.—Comparison of the mean mass $\langle \ln A \rangle$ with indirect estimates from air showers (*open circles*, *open square*) and low-energy balloon data (*open triangles*) (Watson 1985). Highest energy datum in the present experiment (*solid circles*) is based on one Ca event.

cosmic-ray acceleration and propagation mechanisms. A contribution from discrete source(s) (Blandford and Ostriker 1980; Fichtel and Linsley 1986; Takahashi *et al.* 1986) may be required to explain the suggested departure of the high-energy spectra from extrapolations of lower energy results. Additional data (e.g., from two long duration flights of 1987 and 1988) are needed to study the details of high-energy cosmic rays at the "knee region."

The authors wish to thank the National Scientific Balloon Facility, Palestine, Texas, for successful balloon flights.

This work was supported in part in Japan by the Institute for Cosmic Ray Research, University of Tokyo, the Japan Society for Promotion of Science, the Kajima Foundation, and by the US National Science Foundation, the US National Aeronautics and Space Administration, the US Department of Energy, and the US NSF Alabama EPSCoR Program.

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