ENERGY SPECTRA OF COSMIC RAYS ABOVE 1 TeV PER AMU BY JACEE

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ABSTRACT

Direct measurements of cosmic ray nuclei above 1 TeV amu^{-1} have been performed in a series of balloon-borne experiments with emulsion chambers. The updated results including data of a long duration exposure flight (JACEE-7) indicate; (1) The proton spectrum is a power law with an index of 2.74 ± 0.08 up to at least 100 TeV: (2) An overabundance by a factor of two above 2 TeV amu^{-1} for helium is found compared with the extrapolation from the low energies: (3) For heavy elements (C through Fe), the intensities around 1 TeV amu^{-1} are consistent, within the statistical errors, with the extrapolation from lower energy data using the Spacelab 2 spectral indices: (4) An enhancement for the medium heavy components above 30 TeV amu^{-1} for (C - O) and above 5 TeV amu^{-1} for (Ne - S) is observed.

(1) Introduction:

The first direct measurement towards the "Knee region" of 10^{14} to 10^{16} eV was achieved by the PROTON satellite experiments,[1,2] indicating an abrupt steepening in the proton spectrum above 2 TeV, but no significant change in helium up to 2 TeV amu^{-1} and in the all-particle spectrum up to 10^{15} eV. The Intercosmos group reported an increase of helium above 5 TeV amu^{-1}.[3] The HEAO-3 satellite experiment[4] observed an increase of Ar/Fe and Ca/Fe ratios above 500 GeV amu^{-1}. Recently, the Spacelab 2 result[5] indicated that the Fe spectrum is flatter and the spectra of Ne, Mg, and Si are steeper than anticipated at 50 GeV amu^{-1} to 1 TeV amu^{-1}.

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.[6,7] In this paper, we present the updated results including data of a long duration exposure flight (JACEE-7), with total exposure factors of 5.48 x 10^5 m^2 sr s for protons and 8.85 x 10^5 m^2 sr s for Fe, on the energy spectra of protons, helium, (C - O), (Ne - S), and Fe(Z ≥ 25) above 1 TeV amu^{-1}. The results of proton and helium spectra will be reported separately (OG 6.1-9 of this Conference).

(2) Experimental Techniques:

For protons and helium,[8] the charge, Z, is determined by grain-counting with precision better than $\sigma z = 0.2$, and the total gamma ray energy, $\Sigma E\gamma$ better than 25% (35% for JACEE-7). The majority of the charge assignment for nucleus were derived from tracks in the emulsion. The conventional procedure of delta-ray counting to measure charge, which was limited to the resolution of $\sigma z = 1$ to 2, has been significantly improved by application of the delta-ray range distributions for ^{16}O and ^{32}S data at 200 GeV amu^{-1}.[9] Fig. 1 shows a sample of the primary charge distribution. The curves show the best Gaussian fit with σz of 0.57 ± 0.10, approximately constant from C to Ar, and is consistent with the value expected for the 1.5 mm average measured track length.

The overall accuracies in measurements of the total observable energy, $\Sigma E\gamma$, are estimated as 30% for C and 40% for Fe, independent of $\Sigma E\gamma$ over the observed energy region. Also, the partial inelasticity distribution into gamma rays, $f(k\gamma = \Sigma E\gamma/Eo$: Eo = primary energy), for nucleus events has been calculated, by using the nucleus-nucleus collision model.[10] The validity of the model has been verified by the recent emulsion experiments by using CERN beams of 60 and 200 GeV amu^{-1} ^{16}O and 200 GeV amu^{-1} ^{32}S, and by the JACEE cosmic ray results.[11-13]

The energy conversion factors ($Ck\gamma$) for the deconvolution of the Eo spectrum from the $\Sigma E\gamma$ 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%.[8,14] The effect of some possible change in interaction characteristics for central nucleus-nucleus collisions at higher energies[15] 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. Absolute fluxes are calculated by taking into account the interaction probability and geometrical collecting efficiency, the detection efficiencies near the energy threshold, atmospheric corrections at depths 3 to 5 g cm^{-2}, and the corrections for the resolution of the $\Sigma E\gamma$ determination.

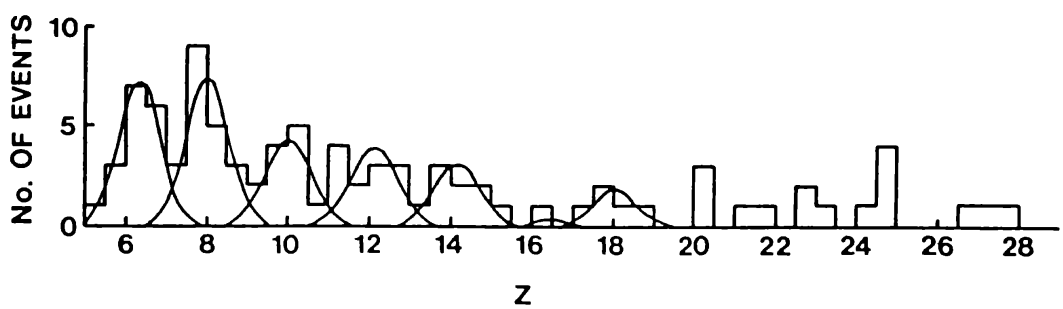

Fig. 1 The charge distribution derived from the delta-ray range distributions. The curves are the best Gaussian fit with $\sigma z = 0.57 \pm 0.10$.

(3) Results and Discussion:

Fig. 2 shows the differential spectra of protons, helium, (C - O), (Ne - S), and Fe($Z \geq 25$) including data of JACEE-7. The power law maximum-likelihood fits with event numbers of 199 for protons and 124 for helium are:

$$(dN/dE)_P = (8.89\pm2.06)\times10^{-2}E^{-2.74\pm0.08}\ (m^2\ sr\ s\ TeV)^{-1},$$

$$(dN/dE)_{He} = (1.01\pm0.21)\times10^{-2}E^{-2.83\pm0.10}(m^2\ sr\ s\ TeV\ amu^{-1})^{-1},$$

where a factor $E^{-0.03}$ has been applied to the proton spectrum to correct for the rising interaction cross section.[16] No indication of a significant change in spectral index for the proton spectrum is observed up to at least 100 TeV, but the helium intensity above 2 TeV amu^{-1} is about twice the extrapolated value from lower energy data, resulting in a He/P ratio of 0.082 ± 0.019 at 10 TeV amu^{-1}, compared with 0.042 ± 0.003 at 50 to 100 GeV amu^{-1}.[17] The intensities of the heavy components seem to agree, within the statistical uncertainties, with the extrapolations from low energy data up to about 5 TeV amu^{-1}. However, an intensity enhancement above 30 TeV amu^{-1} for (C - O) and above 5 TeV amu^{-1} for (Ne - S) is indicated, although statistics are still limited. In particular, this characteristic for (Ne - S) is quite different from the steeper spectra of the Spacelab 2 result for Ne, Mg, and Si below 1 TeV amu^{-1}.[5] These characteristics have also been indicated in the previous results of JACEE 1-6.[7] For Fe, additional data are needed to get statistically meaningful spectral index above 1 TeV amu^{-1}.

The overall results call into question some of current models for the cosmic ray acceleration and propagation mechanisms, and may require a contribution from discrete source(s).[18,19] Additional data (e.g., from a long duration exposure flight of 1988, and further, from future experiments on space station) will be needed to understand the detailed behavior of high energy cosmic rays at the "Knee region".

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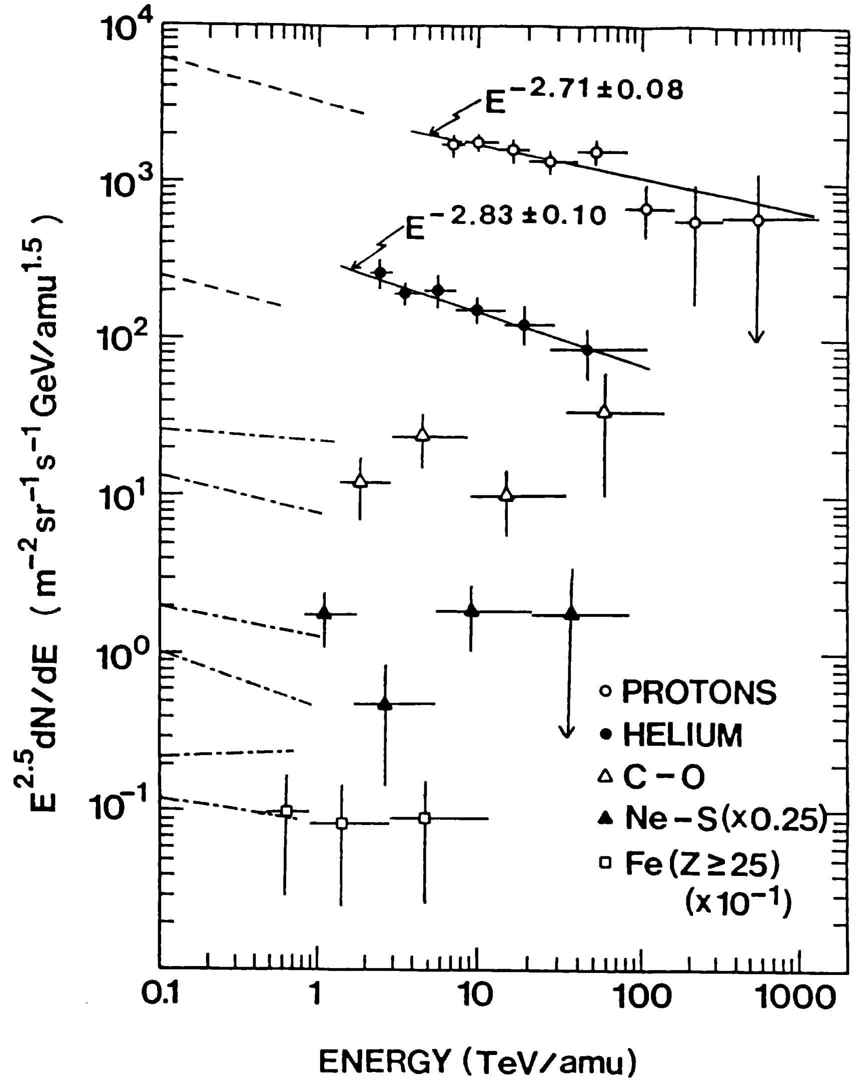

Fig. 2 The differential spectra: protons, helium, (C - O), (Ne - S), and Fe(Z ≥ 25). The upper (protons) and lower (helium) dashed lines denote the spectra by Ryan et al. (1972).[17] Three pairs of dashed-dotted lines represent the low energy boundaries of the spectra, derived from the spectral indices of O, Mg, and Fe-group (25 ≤ Z ≤ 27) reported by Grunsfeld et al. (1988),[5] with the normalization to balloon data of (C - O), (Ne - S), and (Z ≥ 25) at 25 to 50 GeV amu^{-1}.