COMPOSITION AND ENERGY SPECTRA OF COSMIC RAY NUCLEI ABOVE 500 GeV/NUCLEON FROM THE JACEE EMULSION CHAMBERS+

THE JACEE COLLABORATION*

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ABSTRACT

The composition and energy spectra of charge groups(C - O), (Ne - S), and ($Z \geq 17$) above 500 GeV/nucleon from the experiments of JACEE series balloon borne emulsion chambers are reported.

1. Introduction.

Studies of cosmic ray elemental composition at higher energies provide information on propagation through interstellar space, acceleration mechanisms, and their sources. One of the present interests is the elemental composition at energies above 100 GeV/nucleon. Statistically sufficient data in this energy region can be decisive in judgement of propagation models from the ratios of SECONDARY/PRIMARY and source spectra (acceleration mechanism), as well as speculative contributions of different sources from the ratios of PRIMARY/PRIMARY. At much higher energies, i.e., around 10^{15} eV, data from direct observation will give hints on the "knee" problem, as to whether they favor an escape effect possibly governed by magnetic rigidity above 10^{16} eV.

The JACEE balloon flight experiments continue to measure composition and energy spectra of cosmic rays (Z = 1 to 26) directly at energies 10^{12} to 10^{15} eV using large area thin emulsion chambers [1 - 5]. The previous JACEE results indicated no significant change of spectral indices up to 500 TeV and 50 TeV/nucleon for proton and helium spectra, respectively [4]. Flux values of each group (C - O), (Ne - S), and (Fe) at least up to 10^{14} eV also indicated no significant evidence for heavy nuclei dominance within the limited statistics [5]. In this paper, the results for the energy spectra of charge groups (C - O), (Ne - S), and ($Z \geq 17$) above 500 GeV/nucleon are updated.

2. Apparatus and Experimental Procedure.

Details of the apparatus and techniques of JACEE emulsion chambers have been reported in refs. [1 - 5]. Each detector, comprised more than 350 layers of materials, is functionally divided into three sections: (1) the primary charge determination module at the top, (2) the target module where nuclear interactions occur preferentialy (3) the calorimeter at the bottom to measure the energies of released gamma rays from interactions.

Events were detected by visual scanning of X-ray films for dark spots produced by electromagnetic cascades in the calorimeter under the same criterion of darkness (D) in an area of 200 x 200 μm^2. For these events, primary charge Z ($\Delta Z < 1$) above the interaction and the total energy of released gamma rays ΣE_γ ($\Delta \Sigma E_\gamma < 25$ %) were measured [1 - 5].

The maximum value of darkness (D_m) in the cascade development is a function of not only ΣE_γ but also the vertex height (H) from the top of the calorimeter, incident angle (θ), and interaction characterstics (transverse momentum and multiplicity). Among these parameters, the main factors are ΣE_γ and H. For a fixed ΣE_γ value, D_m distributes around some mean value. The width of this distribution $g(D_m)dD_m$ depends on the primary charge (mass) and the chamber design. $g(D_m)$ has been calculated by a Monte Carlo method using the chamber design adopted here, interaction characteristics (CKP and superposition models), and characteristic curves of the response of X-ray films. Then, the detection efficiency $P(Z, \Sigma E_\gamma)$ under the threshold D_m^{th} is calculated by,

$$P(Z, \Sigma E_\gamma) = \int_{>D_m^{th}} g(D_m)dD_m \Big/ \int_{D_m} g(D_m)dD_m \ .$$

In case of calorimeter jets, i.e., H = 0, $P(\Sigma E_\gamma)$ rapidly reaches 100 % at $\Sigma E_\gamma = 1$ TeV for all elements under the threshold level $D_m^{th} = 0.1$ which is a practical threshold, because of no fluctuation of H. On the other hand, in the case of target jets, the practical threshold D_m^{th} becomes about 0.15 and the width of $g(D_m)$ becomes larger due to a fluctuation of H values. This gives higher values of ΣE_γ to obtain $P(\Sigma E_\gamma) = 100$ %. The critical ΣE_γ values have been estimated by the above method for different nuclear species. For light elements such as proton and helium, the critical ΣE_γ was about 1.5 TeV which has been achieved in an analysis of selected JACEE chambers. Under the present standard event selection ($D_m^{th} = 0.3$) the detection efficiency $P(\Sigma E_\gamma \geq 10$ TeV) is confirmed to be 100 % for all elements and for all existing JACEE chambers.

3. Deconvolution of Primary Spectrum.

The observed ΣE_γ spectrum is a convolution of the primary spectrum and the distribution function $f(k_\gamma)$ where k_γ ($= \Sigma E_\gamma / E_0$) is a partial inelasticity into gamma rays; E_0 is primary energy. $f(k_\gamma)$ has been also calculated by the above Monte Carlo method [6], including succesive interactions, assuming its energy independence. The ΣE_γ spectrum $F(\Sigma E_\gamma)d\Sigma E_\gamma$ is given by,

$$F(\Sigma E_\gamma)d\Sigma E_\gamma = \int_{k_\gamma} f(k_\gamma)dk_\gamma \int_{E_0} G(E_0)dE_0 \ \delta(\Sigma E_\gamma - k_\gamma E_0) \ ,$$

where $G(E_0)dE_0$ is primary spectrum. This formula directly shows that the ΣE_γ spectrum is uniquely a power law with the same index as the primary spectrum when $G(E_0)dE_0 \propto E_0^{-\beta}\, dE_0$. The energy conversion factor Ck_γ from the ΣE_γ spectrum to primary spectrum is then given by,

$$Ck_\gamma = [\int_{k_\gamma} k_\gamma^{\beta-1} f(k_\gamma)\, dk_\gamma]^{1/(\beta-1)}$$

Ck_γ is applied to obtain the same flux between the ΣE_γ spectrum and the primary spectrum at $E_0 = \Sigma E_\gamma / Ck_\gamma$. Values of Ck_γ for each element in case of calorimeter and target jets were calculated as follows,

	P	He	N	Mg	Ca	Fe
calorimeter	0.240	0.174	0.100	0.082	0.064	0.058
target	0.222	0.159	0.120	0.117	0.115	0.115

for chambers mainly used in this work [7].

The collecting power of the detectors was calculated by a Monte Carlo method using both the geometric aperture and the probability of interactions for each element. Absolute fluxes above chambers were estimated considering the resolution function of ΣE_γ measurements which is an almost constant Gaussian type with a 25 % width in our case. After atmospheric correction at the depth of 3 - 5 g/cm^2, the flux values at the top of atmosphere were obtained.

4. Results and Discussion.

Figs. 1, 2, and 3 show the results of the integral energy spectra for groups (C - O), (Ne - S), and ($Z \geq 17$) above 500 GeV/nucleon under the present event selection criterion of D_m^{th} based upon a simulation. In Fig. 3, Fe spectrum at energies 20 to 80 GeV/n from the JACEE-3 hybrid detector experiment [8] is also shown. In these figures, the low energy results from two experiments [9, 10], recently reported, are included for comparison. Solid lines are the extrapolation from the flux value at 25 GeV/n of ref. [9] with the spectral indices 1.7 and 1.5. Data around 4 TeV/n for (C - O) and (Ne - S), and those around 1 TeV/n for ($Z \geq 17$) are corrected, by empolying the Monte Carlo calculations for data analysis below the sub-threshold ΣE_γ = 10 TeV. In these figures, at energies higher than sub-threshold, data of each group indicate slightly higher flux values (to about one s.d. from the extrapolated spectra with an index 1.7) with the statistics of only 4, 2, and 1 of 3 (Ca at 78 TeV/n) events for respective groups, while (C - O) data around 1.5 TeV/n with the statistics of 10 events are in agreement with the low energy data for index 1.7. Statistical improvements are obviously desired for our continueing efforts at the highest energies above 10^{14} eV.

Can emulsion chamber technique identfy a bending of the primary spectrum by using of the ΣE_γ method under the convolution of k_γ distribution? Monte Carlo studies have shown a positive answer for this question, at least for heavy nuclei component. If materials of more than about 3 interaction length are available, then the distribution function $f(k_\gamma)$ approaches the Gaussian type with about 35 % width, by virtue of succesive interactions. Hence, it is sufficient to detect any narrow peaks or bends in the energy spectrum, provided sufficient statistics are gathered. For observations above 10^{15} eV, however, the energy resolution becomes poorer than our current observations, because the shower maximum of electromagnetic cascades in the calorimeter becomes too deep for thin chambers currently adopted. Even in this case, emulsion chamber techniques still provide measurements of cosmic ray energy above 10^{15} eV without increasing the thickness of calorimeter if the $e^{\pm}$ pair method is used to augment the $\Sigma E\gamma$ energy determination [11].

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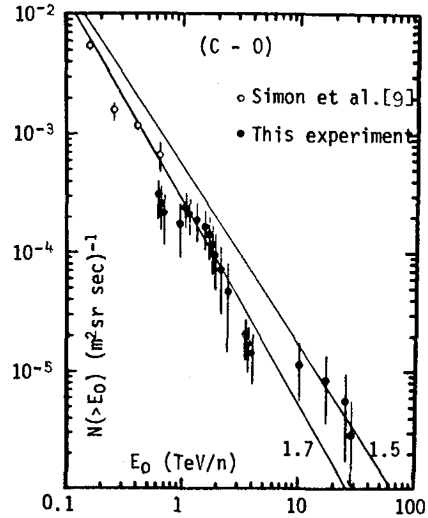

Fig. 1

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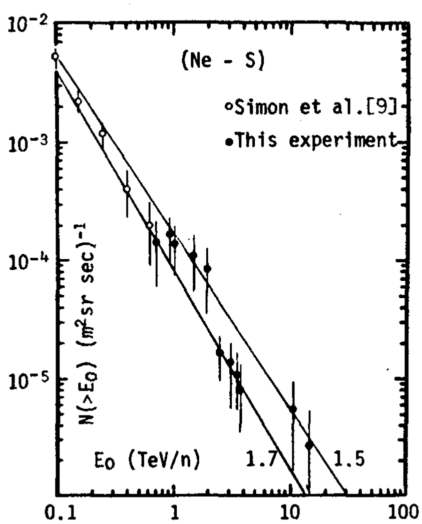

Fig. 2

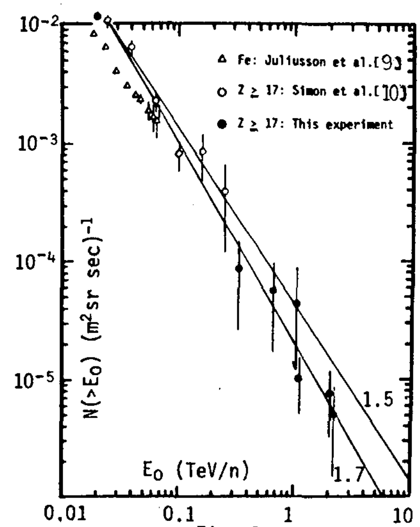

Fig. 3