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Note on Single-Particle Spectra at Cosmic Ray Energies*

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Abstract

It is shown that the primary energies of cosmic ray events analyzed recently at BNL and Vanderbilt University should be, on the average, of the order of only several 10^3 GeV, instead of being greater than 10^4 GeV. The effect on the conclusion of their work is discussed. Our claim is further supported by the various agreements of their experimental results with the theoretical predictions under the alternate choice of lower primary energies. Finally, we discuss the problem of normalization.

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Single particle inclusive distributions have mostly been discussed in the momentum space.^{1,2} Although there are considerable amounts of very high energy cosmic ray emulsion data in terms of angular distribution^{3,4}, they have not been widely used to study the single particle inclusive distributions in the angular space mainly because

- (A) the primary energies of cosmic hadrons can not be well estimated,
- (B) the cosmic hadron interactions initiated in the emulsion may be too complicated to represent meaningfully the single hadron-hadron interactions,
- (C) the cosmic hadrons can not be identified.⁵

To overcome the first two shortcomings, large "calorimetric" type detectors with LiH⁶ or H⁷ have been built. Disregarding the complication in their operation, the detectors are too heavy to fly them to the upper atmosphere to observe hadron interactions of energies greater than 10^3 GeV.

It has been recently demonstrated⁸ by comparing the emulsion and bubble chamber data that (B) is not serious if we restrict ourselves to the events of $N_h \leq 5$, where N_h is the number of heavy prongs. As far as the single particle distributions in angular space is concerned, it is therefore tempting to analyze the cosmic ray data.

A simple analysis of the I.C.E.F.³ and the Chicago group⁴ data has recently been carried out without paying careful attention to (A). We shall first point out that the primary energies should be one order lower in magnitude and discuss its effect on the conclusion.

The Castagnoli's method⁹ is based on two basic assumptions,

- (i) Spectrum Independence; $\beta_c / \tilde{\beta}_1 = \tilde{\rho}_1 = 1$

$$(ii) \text{ Forward and Backward Symmetry; } \sum_{i=1}^{n_s} \frac{\sin \tilde{\theta}_i}{\tilde{\rho}_i + \cos \tilde{\theta}_i} = 1$$

where $\tilde{\beta}_i$ and $\tilde{\theta}_i$ is the c.m. velocity and emission angle of the i -th charged secondary in an event with shower multiplicity n_s and β_c is the c.m. velocity of the interacting system. Denoting E_c to be the estimation of the primary energy E_p with Castagnoli's method, it is well known that E_c overestimates E_p by ~ 2 from the breakdown of (i)¹⁰. The breakdown of (ii) comes usually from the neglect of charged secondaries with large laboratory emission angles, and the partial inclusion of the leading particles; and it contributes also to the overestimation of E_p by E_c . Without some device to exclude the leading particle¹¹, the breakdown of (ii) can contribute considerably to the overestimation of E_p . For one thing, the backward leading (target) particles may turn out to be neutral or appear as heavy prongs.

On the other hand, the E_{ch} -method is based on the assumptions of the constancy of trasverse momentum, i.e.

$$(i) p_t = \langle p_t \rangle = 0.3 \sim 0.4 \text{ GeV}/c$$

and the constancy of inelasticity of charged secondaries, i.e.

$$(ii) K_{ch} = \langle K_{ch} \rangle \simeq 0.3 \text{ for pionization products}$$

$$K_a = \langle K_a \rangle \simeq 0.75 \text{ for all products}$$

While the first assumption is reasonably reliable, the second assumption can be equally reliable if we do not deal with lower multiplicity events. On the other hand, if intranuclear cascade takes place inside the target nucleus, then

$$E_{ch} = 0.4 \text{ GeV} \sum_{i=1}^{n_s} \csc \theta_i \quad (1)$$

which is the estimation of primary energy with E_{ch} -method, may overestimate E_p .

However, because of the fact that the intranuclear cascade is less prevailing in the high energy region,¹² we can hope to reduce its effects by dealing with low N_h events. That E_{ch} is less fluctuating and more reliable in comparing with E_c has been demonstrated with the acceleration data of several ten GeV¹³.

In the analysis of cosmic ray data by Lindern et al.⁸, the events with $n_s \geq 7$ and $N_h \leq 5$ were chosen so that E_{ch} should be more reliable than E_c .

To see this point more clearly, we note that a detailed expression for Eq.(1) should be

$$E_{ch} = \frac{0.35 \text{ GeV}}{\langle N_h \rangle^{0.25} \langle K_a \rangle} \sum_{i=1}^{n_s} c_i \sin \theta_i \quad (1)'$$

where $\langle N_h \rangle^{0.25}$ is introduced to take into account the effect of intranuclear cascade.¹²

$$\langle n_s \rangle \Big|_{N_h \geq 1} \sim N_h^{1/4} \langle n_s \rangle \Big|_{N_h = 0} \quad (2)$$

Since $\langle N_h \rangle = 2.4$ for the sample of cosmic ray events and $\langle K_a \rangle \sim 0.75$, Eq.(1) and Eq.(1)' are equivalent. The criterion $n_s \geq 7$ implies that the fluctuation E_{ch} due to $\langle K_a \rangle$ is not significant.

With the 40 events which they analyzed, we find that the average of E_c , $\langle E_c \rangle = 1.3 \times 10^5$ GeV and the average of E_{ch} , $\langle E_{ch} \rangle = 3.4 \times 10^3$ GeV. That $\langle E_c \rangle$ is larger than $\langle E_{ch} \rangle$ by a factor of ~ 10 can also be seen from the integral spectra of primary events.³ The integral spectrum in terms of E_{ch} is more consistent with that in terms of E_γ , which is the primary energy E_p estimated by electromagnetic cascade. It is also consistent with the energy spectrum of primary cosmic radiation in the high energy region.¹⁴ Therefore, we conclude that the

primary energies of those analyzed cosmic ray events are of the order of several 10^3 GeV instead of being greater than 10^4 GeV.

If the estimated primary energies should be lower by one order of magnitude, then we should accept with caution the conclusion⁸, namely, the inclusive-spectrum cross-section changes in the target-fragmentation region, $\log \tan \theta \geq 0$, approximately as $(\ln s)^{-1}$, where s is the total c.m. energy squared. In fact, the low statistics of the charged secondaries in the $\log \tan \theta \geq 0$ region obscure further the above sensitive conclusion, not to mention the neglect of secondaries with $\theta \geq 90^\circ$ and the problem of normalization to be discussed later.

We, now, proceed to discuss briefly their results, i.e. Fig. 2 of Ref. 8, in the framework of the "emission" model¹⁵ and show that the alternate choice of the primary energies to be of the order of several 10^3 GeV, instead of being more than 10^4 GeV, is consistent. The E_{ch} -distribution for the present sample can be represented roughly by a Gaussian distribution on $\log E_{ch}$ scale, i.e.

$$E_{ch} = (3.0 \pm \begin{smallmatrix} 7.0 \\ 2.0 \end{smallmatrix}) 10^3 \text{ GeV} \quad (3)$$

We, then, have the following:

(a) The model predicts the average charged multiplicity to be

$$\langle n_s \rangle = 2 (2^{\log E_p - 1}) + 1.5 \quad (4)$$

where E_p is the primary energy.¹² With $E_p \approx 3 \times 10^3$ GeV, we have $\langle n_s \rangle \approx 21.5$ which is to be compared with $\langle n_s \rangle_{exp} = 18.8$ of the sample of cosmic ray events.

We note that if the effect of intranuclear cascade as expressed by Eq. (2) is considered, $\langle n_s \rangle_{exp}$ is too low. However, it is this low $\langle n_s \rangle_{exp}$, which, in turn, implies high K_a and so the high ratio of $\langle E_c \rangle / \langle E_{ch} \rangle$.

(b) The model predicts the anisotropy factor $\langle \sigma \rangle$, which is defined as the standard deviation of the $\log \tan \theta$ - distribution and characterizes its width, to be about 0.52 for $E_p = 3000$ GeV. Since the Gaussian distribution of $\log E_{ch}$ implies a Gaussian distribution of the $\log \tan \theta$ peaks¹⁶ with a standard deviation 0.5, we have $\langle \sigma \rangle = [(0.52)^2 + (0.5)^2]^{\frac{1}{2}} \approx 0.72$, which is to be compared with the experimental value of 0.79 as obtained from Fig. 2 of Ref. 8. Considering that the predicted $\langle \sigma \rangle$ refers mainly to the pionization products and the experimental $\langle \sigma \rangle$ includes contributions from those other than the pionization products, the above slight discrepancy is understandable.

(c) The model predicts a scaling near $x = 0$ as¹⁷

$$f(x, p; s) \propto 2^{\log E_p} (= E_p^{0.303}) \quad (5)$$

which is to be compared with $f(x, p; s) = \text{constant}$, as predicted by multiperipheral model.^{1, 18} Here, x is the Feynman variable. Since $x = 0$ corresponds to the position of the central peak in the inclusive $\log \tan \theta$ distribution, the model predicts the same scaling law for the height of the $\log \tan \theta$ peak. Accordingly, the height of $\log \tan \theta$ peak of monoenergetic 3×10^3 GeV events, should increase by a factor of 4 in comparison with that of 28.5 GeV events. However, the cosmic ray sample is not monoenergetic and the peak height has to decrease with the same rate as the width increase, i.e. $\sim 1.5 (= 0.79/0.52)$. It means the actual peak height of the cosmic ray sample should be $4/1.5$ times the peak height of 28.5 GeV events; which gives the predicted peak height to be $15.5 \times 4/1.5 = 44$. This predicted value agrees within the experimental error with the observed value ~ 35 as can be seen from the Fig. 2 of Ref. 8. However, 44 is somewhat larger than 35. Such difference is due to the normalization to be discussed later.

The above various agreements of the experimental results and the predictions of the model provide, thus, additional supports to our claim that the average primary energy of the sample is only of the order of several 10^3 GeV instead of greater than several 10^4 GeV. Since E_{ch} appears to be more reliable than E_c , we have analyzed the cosmic ray events in terms of E_{ch} . For E_{ch} in the region of several 10^2 GeV, the $\log \tan \theta$ - distribution agrees satisfactorily with that of Echo Lake experiment¹⁹ as far as $\langle \sigma \rangle$ is concerned; which, in effect, emphasize the validity of using the emulsion events with $N_h \leq 5$. For $\langle E_{ch} \rangle \approx 3 \times 10^3$ GeV, we find $\langle n_s \rangle \approx 2.7$ and $\langle \sigma \rangle \approx 0.83$, which is to be compared with $\langle n_s \rangle = 18.8$ and $\langle \sigma \rangle = 0.79$ of the present sample.²⁰ $\langle n_s \rangle \approx 2.7$ agrees better with the theoretical prediction if the effect of intranuclear cascade is taken into account¹², i.e. using Eq. (2) for $\langle N_h \rangle = 2.4$

$$\langle n_s \rangle \approx 2.5 \langle N_h \rangle^{0.25} = 2.7 \quad (6)$$

As to the inclusive angular cross-section, we find it almost independent of s (from several 10 to 10^3 (GeV)²) in the region $\log \tan \theta \geq 0$; which renders support to the existence of limiting fragmentation.²¹ The detailed discussion of the inclusive spectra in angular space together with the scaling laws and the comparison with the cosmic ray data will be given elsewhere.

Finally, if $(d\sigma/d \log \tan \theta)/\sigma_t$, where σ_t is the total cross section of the analyzed events, instead of $d\sigma/d \log \tan \theta$ is considered, and $\sigma_t = 22$ mb for $n_s \geq 4$ of 28.5 GeV p-p collisions is taken into account, the histogram of the cosmic rays interactions should be increased relatively by 20%. It means the peak height of cosmic rays events should be $35 \times 1.2 = 42$ (referring to Fig. 2 of Ref. 8). This experimental value agrees very well with the theoretical value of 44.²² On the other hand, it also narrows down the difference between

$(d\sigma/d \log \tan \theta)/\sigma_t$ near $\log \tan \theta \gtrsim 0$.

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