# Inelasticity Distribution of Hadron-Pb Collisions in $10^{14}$ eV (Revised)

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## 1. Experimental Procedure

### 1.1. Pamir Thick Lead Emulsion Chambers.

Emulsion chamber detects multiple particle productions, caused by cosmic-ray hadrons in the chamber, as showers which are initiated by $\gamma$-rays among the secondary particles. Hence the observed energy of the shower is a part of the hadron energy.[1]

Thick lead emulsion chambers, constructed at the Pamir Station (4,300 m, Tadjikistan)[1, 2], have distinguished quality of large thickness (60 cm Pb or 3.2 mean free path of inelastic collision of nucleon) and uniform structure (59 sensitive layers at every 1 cm Pb plate). The detection threshold energy of the chamber is *several* TeV.

The hadron, incident upon the chamber, makes a nuclear collision in the chamber. The surviving hadron and the produced hadrons undergo nuclear collisions again at various depths in the chamber, too. The process is repeated in the chamber until the hadrons, incident and produced, leave the chamber. Consequently a single high energy hadron, incident upon the chamber, produces in the chamber $n$ showers ($n$ = 1, 2, $\cdots$) which have appearance of aligning on the line *and* having the same direction. The event of $n \geq 2$ is called 'successive interactions', while the one of $n = 1$ is called 'single-shower'.

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### 1.2. $z$-distribution

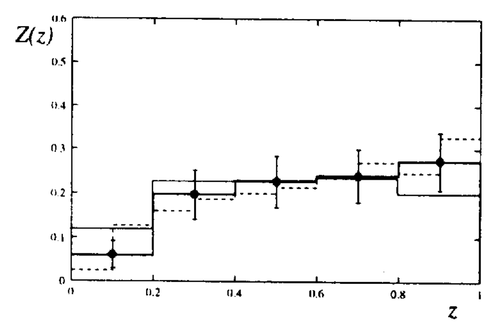


Figure 1. $z$-distributions of the experimental data (the bold solid line) and of the calculation (the thin solid line) where the ***flat*** distribution of the total inelasticity $K$ is assumed. The dashed line is for the case when the best-fitting inelsticity distribution is assumed.

Let us denote the energy of the first, the second, $\cdots$, shower in the event by $E_1$, $E_2$, $\cdots$, and that of the incident hadron by $E_0$. The parameter $z$, defined as $z \equiv E_1/\sum E_i$, is a measure to estimate the inelasticity of the interaction of the first shower.

The distribution of $z$ is shown in Fig. 1 from 66 events which have $\sum E_i > 30$ TeV with $E_{th} =$

4 TeV. Among 66 events, 13 are single-shower events and the rest of 53 events are those of successive interactions.[2] A set of 66 events consists of 32 hadrons in the families and 34 of single arrival.

## 2. Distribution of the inelasticity

### 2.1. $z$-distribution for the assumed inelasticity distribution

According to the experimental data, the energy spectrum of produced particles in $h-A$ collision is approximated by two parts; that of $p-p$ collision in the forward region and enhancement in the central region due to target nucleus effect. Hence we assume that the energy spectrum of produced *charged* pions in $h$–Pb collision is expressed by

$$\varphi(E_0, E, \xi_1, \xi_2)dE = (1-c)(a+1)\xi_1 \frac{(1-x)^a}{x} dx$$

$$+(1-c)(1-\xi_1)\xi_2 \frac{\delta(x-\epsilon)}{\epsilon} dx \qquad (1)$$

where $c = 1/3$, $a = 4.0$ and $x = E/E_0$. One can obtain the total inelasticity from Eq.(1) as

$$K = \frac{3}{2}\int_0^1 x\, \varphi(x, \xi_1, \xi_2)dx = \xi_1 + (1-\xi_1)\xi_2$$

where $\xi_1$ and $\xi_2$ are distributed as $f_1(\xi_1)d\xi_1$ and $f_2(\xi_2)d\xi_2$, respectively.

The $z$-distribution which corresponds to the assumed distributions of $\xi_1$ and $\xi_2$, is

$$Z(z)dz = dz \int\int \underbrace{\delta\left(z - \frac{cKE_0}{cKE_0 + R(E_0, K)}\right)}_{1st}$$

$$\times \underbrace{\theta(cKE_0 - E_{th})\,\theta\,(cKE_0 + R(E_0, K) - E_{tot}(th))}_{2nd}$$

$$\times \underbrace{f_1(\xi_1)d\xi_1\, f(\xi_2)d\xi_2}_{3rd}\ \underbrace{\gamma N_0 u^{\gamma-1} du}_{4th} \qquad (2)$$

with $u = E_{tot}(th)/E_0$. The meaning of the terms in the above formula is;

(1) the first term (the definition of $z$): The energy of the first shower is $E_1 = cKE_0$ with $K = \xi_1 + (1-\xi_1)\xi_2$. $R(E_0, K)$ is the energy sum of the showers ($n \geq 2$), which is calculated analytically by the energy spectrum of $\varphi(x, \xi_1, \xi_2)$ and assumed distributions of $\xi_1$ and $\xi_2$.

(2) the second term: It expresses the experimental conditions that the first shower energy and the total observed energy in the successive interactions exceed the threshold energies of $E_{th}$ and $E_{tot}(th)$, respectively.

(3) the third term: We assume

$$f_1(\xi) = N\left[\,\alpha(1-\xi)^{m_1-1} + \beta\xi^{m_2-1}\right]$$

$$\text{and} \qquad f_2(\xi) = \frac{1}{2\delta}\,\theta(2\delta - \xi) \qquad (3)$$

both of which are normalized to unity.

(4) the fourth term: It expresses the energy spectrum of hadrons ($\gamma = 1.8$), incident upon the chamber.

Fig. 1 shows the $z$-distribution of calculation for the case of the *flat* distribution of $K$ (*i.e.* $m_1 = m_2 = 2.0$, $\alpha = \beta = 1.0$ and $\delta = 0.0$), which differes from that of the experimetal data appreciably.

### 2.2. Comparison of experimental data with calculation

The dispersion between the experimental data and the calculated curve, is defined as

$$D = \sum_{i=1}^{5}\left[\, y_i(exp) - y_i(cal)\,\right]^2 \qquad (4)$$

where $y_i$ is the value of the distribution at $z = z_i$. We calculate the dispersion $D$, varying $m_1$, $m_2$, $\alpha$, $\beta$ and $\delta$ in Eq.(2). The contour map of $D$ on the plane of $K_1 =< \xi_1 >$ and $K_2 =< (1-\xi_1)\,\xi_2 >$ ( with $< K >= K_1 + K_2$ ), shows that $< K >= 0.6^{+0.2}_{-0.5}$ is in the region of $D < 0.01$ for the case of $m_1 = 1.5$. The value is similar to 0.63 (at $\sqrt{s} = 6.8 \times 10^2$ GeV) by Hama and Paiva [4], but smaller than 0.82 (at $E_0 = 100$ TeV) by

[2] In our previous report [3], we made an analysis with 74 events of successive interactions. We found, however, that classification between single-shower and double-shower cannot be made easily, because in most of the cases the second shower has low energy near the detection threshold. Hence, we make re-analysis in the present report including single-shower events.

The decrease of event number of successive interactions from 74 to 53 is due to the revised energy calibration.

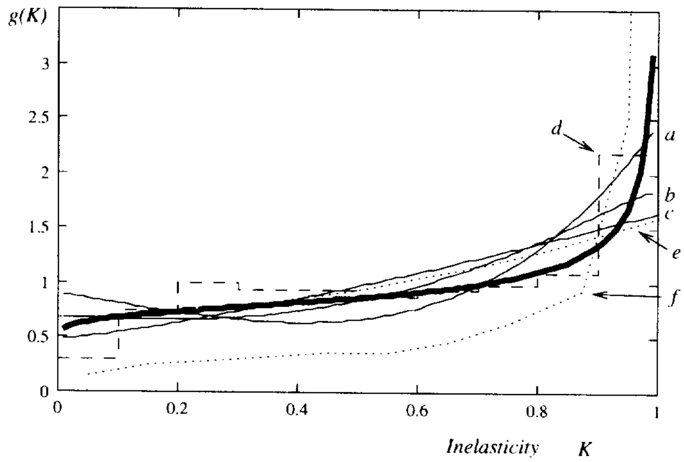


Figure 2. Inelasticity distribution of the best fitting (the thick solid line), where $m_1 = 0.5$, $K_1 = 0.6$, $K_2 = 0.0$. The thin solid lines (*a*, *b*, and *c*) corresponds to the cases of $m_1 = 1.0$, 1.5, and 2.0 (with $K_1 = 0.6$ and $K_2 = 0.0$), respectively. The chain line (*d*) corresponds to the case of $m_1 = 0.5$ with $K_1 = 0.55$ and $K_2 = 0.05$ (consequently $< K >= 0.6$). The dotted lines (*e*, and *f*) are the calculations, based on the theoretical models by Hama and Pavia and by Tamada, respectively.

Tamada[5]. The former calculation is made on the basis of the interacting gluon model, and the latter on the basis of the geometrical model for $h - A$ interactions and UA5 simulation code for particle production.

Detailed study on the dispersion $D$ shows that the best fitting between the experimental data and the calculation is attained by the parameters of $m_1 = 0.5$, $m_2 = 1.125$, $\alpha = 0.26$, $\beta = 0.55$, and $\delta = 0.0$, where $< K >= 0.6$ (with $K_1 = 0.6$ and $K_2 = 0.0$).

The inelasticity distribution of the best fitting is shown in Fig. 2. One can see in the figure that the distributions of $m_1 = 1.0$, 1.5, 2.0 (with $K_1 = 0.6$ and $K_2 = 0$), and even that of $m_1 = 0.5$ (with $K_1 = 0.55$ and $K_2 = 0.05$, leading to $< K >= 0.6$), are similar to the best fitting one, having $D < 0.01$.

The distribution, obtained by Hama and Paiva, is similar to these, too. One by Tamada is different reasonably because of the difference of the average inelasticity.

The event selection criterion of $\sum E_{ob} \geq 30$ TeV corresponds to $E_0 > 100$ TeV and $< E_0 >= 2.3 \times 10^2$ TeV for the hadrons, incident upon the chamber, based on the energy spectrum of total observed energy (with the exponent of $-1.8$ in integral form) and the obtained value of inelasticity.

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ISSN 1340-3745

ICRR

ICRR-Report-434-98-30

# Contribution to Xth ISVHECRI(Gran Sasso, 1998) from CHACALTAYA Emulsion Chamber Collaboration

Edited by A. Ohsawa

(October 1998)

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