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Chacaltaya and Pamir Collaborations

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Inelasticity of Hadron-Lead Collisions, estimated by Thick Lead Emulsion Chambers at the Pamirs

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Abstract

The inelasticity distribution of hadron-lead collisions in the energy region exceeding 10^{14} eV is estimated by 74 events of hadron interactions, observed by thick lead chambers at the Pamirs. The distribution is approximated as $g(K)dK = 3.0 K^{2.0} dK$ (with $\langle K \rangle = 0.75$) as a minimum estimate. The distribution is consistent with that by the simulation made under the assumptions of UA5 algorithm for hadron collisions and of geometrical model for intra-nuclear cascade. It is inferred that the average value of the inelasticity of hadron-nucleon collision is smaller than 0.5 in the energy region exceeding 10^{14} eV.

1. Introduction

The total inelasticity K of multiple particle production is defined as

$$K \equiv \frac{\sum E_p}{E_0} = 1 - \frac{E_s}{E_0} \quad (1)$$

where E_0 is the energy of the incident hadron, E_s that of the hadron after the collision (called 'the surviving hadron') and $\sum E_p$ the energy sum of produced particles, assuming that the surviving hadron and the produced particles can be identified.

The inelasticity is one of the important issues in high energy hadron interactions in the following points. The energy dependence of the average inelasticity impose a strong restriction to the theoretical models of multiple particle production. For example, the energy dependence of the inelasticity, predicted by the theoretical models, varies from strongly decreasing to strongly increasing one [1, 2, 3, 4, 5, 6]. Furthermore, the inelasticity is an indispensable physical quantity for analysis of high energy cosmic-ray phenomena, because it is one of the essential factors which

govern the cosmic-ray propagation in the atmosphere.

The inelasticity was introduced first by the fact that the attenuation of cosmic rays is not so strong as expected by the catastrophic type of nuclear interactions (*i.e.* $K = 1.0$), and was estimated to be 0.5 approximately. Later on the energies of the produced charged particles in multiple particle production were measured by bubble chamber experiments, which showed that the inelasticity has an almost uniform distribution between 0 and 1*, leading to $\langle K \rangle = 0.5$ [7].

If the Feynman scaling law [8] is valid, the average inelasticity remains 0.5 in high energies. The law looked valid up to $\sqrt{s} = 63$ GeV, the maximum available energy at that time [9]. In still higher energies ($\sim 10^{14}$ eV), however, it is shown that the law is violated [10]. And, for example, UA5 simulation code of multiple particle production, which reproduces what UA5 Collaboration observed in the central rapidity region at CERN SPS $\bar{p}p$ collider at the energies

*There is a peak at $K \sim 1.0$ due to the diffraction process.

$\sqrt{s} = 53, 200, 546$ and 900 GeV, predicts $\langle K \rangle = 0.42$ at $\sqrt{s} = 546$ GeV [12].

In the energy region exceeding 10^{14} eV there is no data of the inelasticity except the indirect one by UA5 code, because available high energy accelerators are all collider-type, by which the surviving hadron and/or the particles produced in forward region are not easy to be observed. Hence, in the present paper, we try to estimate the inelasticity in the energy region exceeding 10^{14} eV by the data of cosmic-ray experiment. The data are from hadron-Pb collisions observed by thick emulsion chambers, which are exposed to cosmic rays at the Pamirs.**. The chambers are thick enough (60 cm Pb or 3.2 inelastic collision mean free path of nucleon) for hadrons to make nuclear collisions inside the chamber with $\sim 100\%$ probability.

2. Observation of Hadron Interactions by Emulsion Chamber

Emulsion chamber[11] is a shower detector which consists of lead plates, intervened by sensitive layers of X-ray films and/or nuclear emulsion plates.(Fig. 1) It detects cascade showers and determines their energies.

Fig. 1 Structure of Pamir thick lead chamber. The thickness of the chamber is 60 cm Pb or 2.3 mean free path of inelastic collision of nucleon. The sensitive layers of Russian X-ray film RT-6M are inserted beneath every 1 cm of lead plate after 2 cm lead from the top.

A high energy hadron incident upon the chamber, causes multiple particle production in the

**The minimum-biased database of single showers and families has been created during the stay of V. Kopenkin at Waseda University

chamber through nuclear collision with lead. The electromagnetic component (mainly decay products of π^0 's) among produced particles initiate a cascade shower. Therefore, observed energy of the shower is not that of incident hadron but that of electromagnetic component produced by nuclear interaction of the hadron.

2.1. Pamir thick lead chambers

Pamir thick lead chambers are constructed at the Pamir mountains (4,300 m, Tadjikistan) by Pamir Collaboration [13, 14]. They have distinguished characteristics of large thickness (60 cm Pb or 3.2 mean free path of inelastic collision of nucleon) and uniform structure (See Fig. 1 for the structure). The former assures almost 100 % collision probability of hadrons in the chamber except for those produced near the bottom of the chamber, and the latter does a uniform detection of showers all over the depth of the chamber and the simplest way of energy determination. 74 hadrons for the present analysis are from $57 \text{ m}^2 \cdot \text{yr}$ exposure.

2.2. Successive interactions

The hadron, incident upon the chamber, causes multiple particle production in the chamber. The electromagnetic component of produced particles makes a cascade shower in the chamber, which is recorded by sensitive layers.

The surviving hadron and those produced in the nuclear interaction undergoes nuclear collisions again at various depths in the chamber, and the showers due to these collisions are recorded by sensitive layers, too (See Fig. 2). The process is repeated in the chamber until the hadrons, incident and produced, leave the chamber. These showers are called 'successive interactions' as a whole.

2.3. Distribution of z

Let us denote the energy of the first, the second, $\dots$, shower in the successive interactions by $E_1, E_2, \dots$, and that of the incident hadron by E_0 (Fig. 2). The parameter,

$$z \equiv \frac{E_1}{\sum E_i} \quad (2)$$

is the measure of the inelasticity of the interaction of the first shower, incident upon the chamber. The distribution of z is shown in Fig. 3 from

74 events which contain at least *two* showers of successive interactions and have $\sum E_i > 30$ TeV with $E_{th} = 4$ TeV. A set of 74 events consist of 37 hadrons in the families and 37 of single arrival. Due to limited statistics of events, the histogram has large bins and detailed discussion on the distribution is not possible.

Fig. 2 Illustration of successive interactions in the chamber.

The hadron (the bold solid line), incident upon the chamber, causes a nuclear interaction in the chamber (the first interaction) to produce the electron shower with energy E_1 . The produced pions (the thin solid lines) causes a nuclear collision (the second interaction) to produce the shower with E_2 . The surviving hadron (the bold solid line) causes a nuclear collision again (the third interaction) to produce the shower with E_3 . Successive interactions of three showers are drawn in the chamber.

3. Distribution of Inelasticity

The distribution of z is expressed by

$$Z(z) dz = \frac{dz}{N} \int \delta(z - \frac{y_1 K_1}{q}) \times g(K_1) dK_1 g(K_2) dK_2 h(y_1) dy_1 h(y_2) dy_2$$

$$\times \frac{f(x)}{m+1} dx \gamma E_0^{-\gamma-1} dE_0 \quad (3)$$

because we have

$$E_1 = y_1 K_1 E_0 \quad (4)$$

$$\sum E_i = q E_0 \quad (q : \text{constant}), \quad (5)$$

where y_1 and K_1 are interaction parameters of the first shower, whose distributions are discussed below.

The sum of all the shower energies in successive interactions is proportional, with a reasonable accuracy, to the primary energy of the incident hadron, on the average, because the probability for hadron to penetrate through whole chamber without interaction is negligible and the number of hadrons (including the surviving hadron), produced in the first interaction, is large (> 30).

The integration condition for the above is

$$\begin{cases} y_1 K_1 E_0 \geq E_{th} \\ y_2 K_2 x E_0 \geq E_{th} \end{cases} \quad (6)$$

which requires that the first and the second shower in successive interactions to have their energies above the detection threshold E_{th} .

The term $f(x) dx/(m+1)$, normalized to unity, is the energy distribution of hadrons (including the surviving hadron) after the collision of the first shower. One of these hadrons produces the second shower. The term $\gamma E_0^{-\gamma-1} dE_0$ ($\gamma = 1.8$ from the $\sum E_i$ spectrum) is the energy spectrum of hadrons, incident upon the chamber. The distribution $Z(z) dz$ is normalized to unity by the factor N .

3.1. Distributions of K and y

The inelasticity distribution $g(K) dK$ is assumed to have a hammock-shape between 0 and 1, expressed by

$$g(K) = a(1-K)^n + b K^n \quad (7)$$

with $n = a + b - 1$.

Energy ratio of em-component is assumed to have a uniform distribution between $y = 0$ and $y = 2c$ (with $c = 1/3$). That is,

$$h(y) = \frac{1}{2c} \quad (y = 0 \sim 2c) \quad (8)$$

which leads to $\langle y \rangle = c$.

3.2. Comparison of experimental data with calculation

The best fit between data and the calculated curve gives $q = 0.43$. And the differential distribution of the same parameters, i.e. $a = 0$, $b = 3.0$ and $q = 0.43$, is shown in Fig. 3. The leak of the calculated distribution in $z > 1.0$ is attributed to the fact that the average value is used for the parameter q .

Fig. 3 Differential distribution of $z = E_1 / \sum E_i$ of 74 events of successive interactions. The curve corresponds to the inelasticity distribution of $g(K) = b K^n$ ($b = 3.0$ and $n = 2.0$) with $\langle K \rangle = 0.75$, which gives the best-fitting to the experimental data. (See the discussion in Section 3.)

4. Discussions

- (i) Discussions on experimental details
- (1) The parameter z depends only on the relative values of energies, which are free from absolute calibration and consequently are more reliable in emulsion chamber experiments.
- (2) The value $\sum E_i$ is rather independent of the way of fitting, because it is identical to the total track length of electrons in the showers.
- (3) Besides z there are many other parameters which can be related to the inelasticity distribution, such as $E_i / \sum E_i$, E_i / E_j , etc. One can see, however, that z is better than those above, because the definition is clearer than others.
- (4) Most of cosmic-ray hadrons, incident upon the chamber, are either nucleons or charged pions, whose abundance is approximately equal at

the altitude of the Pamir station. In this sense the estimated distribution of inelasticity is the averaged one by the relative abundance of incident hadrons. One should keep in mind that the inelasticity distribution of pion collisions may be much different from that of nucleon collisions due to the charge exchange process of incident pions, i.e. $\pi^\pm \rightarrow \pi^0$.

- (ii) We made an estimation of the inelasticity distribution of hadron-Pb collisions, using 74 events of successive interactions observed by Pamir thick lead chambers. The way of estimation is free from the absolute values of the energies. The average energy of incident hadrons is 1.6×10^{14} eV from the $\sum E_i$ spectrum and the value $q = 0.43$.

The estimated distribution of inelasticity is,

$$g(K)dK = b K^n \quad (b = 3.0, n = 2.0) \quad (9)$$

with average value of the inelasticity $\langle K \rangle = 0.75$. One should take this value as the minimum estimate.

- (iii) Taking into account that the estimated value of b is the minimum one, the inelasticity distribution of hadron-Pb collision, estimated in this paper, is consistent with the one obtained by simulation [15], where UA5 simulation code is employed for *hadron-nucleon* collisions and the geometrical model is assumed for intra-nuclear cascade. It follows in turn that the inelasticity distribution of *hadron-nucleon* collisions in the energy region exceeding 10^{14} eV is consistent with the prediction by UA5 simulation code [12]. That is, the average inelasticity becomes less than 0.5 (= the average value of the inelasticity in the low energy region) in the energy region exceeding 10^{14} eV.

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References

- [1] G.N. Fowler et al., Phys. Rev. Lett. 56 (1986) 14.
- [2] Z. Włodarczyk et al., Proc. 20th Internat. Cosmic Ray Conf. (Moscow), Vol.5 (1987) 417.
- [3] T.T. Chou et al., Phys. Rev. D32 (1985) 1692.

- [4] T.K. Gaisser et al., Phys. Lett. B219 (1989) 375.
- [5] A.B. Kaidalov et al., Sov. J. Nucl. Phys. 40 (1984) 135.
- [6] R.A.M.S. Nazareth et al., Phys. Rev. D46 (1992) 2896.
- [7] T.K. Gaisser et al., Rev. Mod. Phys. 50 (1978) 859; and the references therein.
- [8] R. Feynman, Phys. Rev. Lett. 23 (1969) 1415.
- [9] F.E. Taylor et al., Phys. Rev. D14 (1976) 1217.
- [10] A. Ohsawa, Prog. Theor. Phys. 92 (1994) 1005.
- [11] J.A. Chinellato et al. (Chacaltaya Emulsion Chamber Collaboration), Prog. Theor. Phys. Suppl. No.76 (1983) 1.
- [12] G.L. Alner et al. (UA5 Collaboration), Phys. Rep. Nos.5 and 6 (1987) 247.
- [13] L.T. Baradzei et al. (Chacaltaya and Pamir Collaboration), Nucl. Phys. B370 (1992) 363.
- [14] T. Arisawa et al., Nucl. Phys. B424 (1994) 241.
- [15] M. Tamada, J. Phys. G 21 (1995) 1387.

A study on hadron-induced shower transition in thick lead chambers

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Three-dimensional development of cascade shower in lead initiated by high energy proton-Pb and pion-Pb interactions are calculated by full Monte-Carlo simulation assuming simple geometrical model for hadron-nucleus interactions. It is shown that fluctuations in shower development is very large but the extraordinary long penetrating showers observed in the Pamir thick lead chamber experiment can not be explained by simple fluctuations of shower development initiated by ordinary hadron-Pb interactions.

1. INTRODUCTION

In Chacaltaya and Pamir collaboration experiments it has been reported[1,2] that there exist exotic phenomena called "Centauro species" in very high energy cosmic-ray nuclear interaction of energy larger than 10^{15} eV . The common characteristics of those exotic phenomena are absence of pions among produced secondary particles and large p_t of produced particles. Although nature of those produced particles is still unknown, there is an argument that those particles are something new different from ordinary hadrons because there found exotic shower-cluster called "mini-cluster" in those hadron interactions and also collision mean free path of those particles is found to be shorter than that of ordinary hadrons. In recent work of Pamir and Chacaltaya collaborations[3], attenuation mean free path of high energy hadrons in super-families of visible energy sum $\Sigma E(\gamma) \geq 700 \text{ TeV}$ observed in thick lead chamber is measured and is found again to be considerably smaller than that of ordinary hadrons. Extraordinary characteristics of those hadrons are also seen in their shower transition behaviour[3] Typical examples of shower transition of those are shown in Fig.1a. In the present paper we study hadron-induced shower transition in lead assuming simple geometrical model for hadron-nucleus interactions, and compare with experimental results.

2. NUCLEAR AND ELECTROMAGNETIC CASCADE IN THICK LEAD CHAMBER

We calculate development of nuclear cascade in the lead chamber under the assumptions that ;
(i) energy spectrum of hadrons arriving upon the chamber is power-law type of $I(\geq E) \sim E^{-1.8}$.
(ii) zenith angle distribution of arriving hadrons is $I(\leq \cos\theta) \sim (\cos\theta)^{-8}$,
(iii) the total thickness of the chamber, T_{eff} , is 60 cmPb, and sensitive layers are inserted every 1 cmPb.

Here we use simple geometrical model for hadron-nucleus interaction. Some details of the model are described in the Ref.[4]. The number of target nucleons that would interact with projectile hadron is sampled from Poisson distribution with an average depending on impact parameter of the collision. Each sub-interaction is treated as a usual hadron-nucleon interaction and phenomenological UA5 algorithm[5] is used for it. Here we assume, for simplicity, all produced particles are pions.

1500 protons and pions, respectively, of $E \geq 50 \text{ TeV}$ are sampled from the above energy spectrum, and nuclear cascades initiated from interaction of those are traced down until energy of all hadrons, both projectile and produced, falls below 0.2 TeV .

Among produced hadrons, neutral pions decay into gamma-rays. Further three-dimensional elec-

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