

Characteristics of hadron-induced cascade showers in a thick lead chamber and their physics implication

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Abstract

Structures of hadron-induced cascade showers observed by Pamir thick lead chambers are compared with those of simulated ones. The simulation calculations are carried out assuming two models VENUS and QGSJET for hadron-nucleus interactions. Applying the same procedure of the analysis both to the experimental data and simulated ones, it is shown that none of those models explain the observed characteristics of hadron-induced cascade showers. The result indicates that the average inelasticity of hadron-Pb interaction in the energy region $E_h \geq 10^{14}$ eV is considerably smaller than usually assumed.

1 Introduction:

Series exposure of homogeneous-type thick lead chamber, composed of 60 cm thick of lead and 59 sensitive layers, were carried out at the Pamir by Pamir collaboration experiment. After processing, some parts of the chambers were shipped to Japan under agreement of joint analysis between Moscow State University and Waseda University, and measurement was done. Some results on the analysis of atmospheric families observed by the chamber have been reported by Kopenkin and Fujimoto (1996). The homogeneous-type thick lead chamber has an advantage that we are able to observe the whole shower development of hadron-induced showers and to study in detail characteristics of hadron-Pb interaction of hadron energy $E_h \geq 10^2$ TeV. In the paper (Barroso et al., 1997), an attempt to estimate inelasticity of hadron-Pb interaction was made by analysing structure of shower transition on spot darkness of the observed hadron-induced showers. A ratio of released energy E_1 at the first interaction to the total energy ΣE_γ released at successive interactions during passage through the whole chamber are compared to theoretical calculations assuming inelasticity as a parameter, and the average inelasticity of hadron-Pb interaction is estimated to be $\langle K_{incl} \rangle \sim 0.6$, considerably smaller than usually considered. In their analysis, E_1 and ΣE_γ were estimated by manually decomposing shower transition into a number of successive interactions in experimental data, therefore it still remains an ambiguity whether the experimental result can be compared directly with theoretical calculations or not. In order to make direct comparison, here we carry out simulation calculations for hadron-induced showers and apply just the same procedure both to experimental data and simulated ones.

2 Pamir thick lead chambers:

Each unit of the chamber has an area of $10m^2$ and is composed of 60 layers of lead plates of 1 cm thickness. The Russian RT6-type X-ray films are inserted every 1 cm of lead except for the first 2 cm of lead. Shower spot due to electron showers initiated by local nuclear interaction are traced down through the entire depth of the chamber. The darkness of the shower spot, D , is measured by a $200 \times 200\mu m^2$ square slit on every-recording film. Detection threshold darkness, D_{min} , of the shower spot is $0.1 \sim 0.2$. Here we set $D_{min} = 0.2$.

3 Simulation calculations:

We use two models for hadron-Pb interaction, one is VENUS (Werner, 1993) and the other is QGSJET (Kalmykov, Ostapchenko & Pavlov, 1994), both of which are considered to be based on

modern QCD-inspired theory and are widely accepted one of the standard models. We calculate development of nuclear and electromagnetic cascade in the lead initiated by hadron-Pb interaction under the assumptions;

- (1) energy spectrum of hadrons arriving upon the chamber is power-law type, $I(\geq E) \propto E^{-1.8}$
- (2) zenith angle distribution of arrival hadrons is $I(\leq \cos \theta) \propto (\cos \theta)^{-8}$
- (3) the total thickness of the chamber is 60 cmPb and sensitive layers are inserted under every 1 cmPb.

For cross-section of hadron-Pb interaction of energy $E(GeV)$, we use following approximations;

$$\begin{aligned}\sigma_{inel}^{p-Pb}(E) &= 1565 + 68.4 \log(E) \quad mb \\ \sigma_{inel}^{\pi-Pb}(E) &= 1329 + 81.0 \log(E) \quad mb\end{aligned}$$

3,000 protons and pions of $E \geq 50\text{TeV}$ are respectively sampled from the above spectrum, and nuclear cascades initiated from interactions of those are traced down until energy of all hadrons falls below 0.2 TeV. For gamma-rays of $E_\gamma \geq 0.2$ TeV which are decay products of produced hadrons, mainly neutral pions, we calculate further three-dimensional electromagnetic cascade development using Monte-Carlo code formulated by Okamoto and Shibata (1987), in which LPM effect is also taken into considerations. Electrons and photons are traced down until their energy becomes 1 MeV. Electron number density, ρ_e , is transformed into darkness, D , of X-ray film, measured by $200 \times 200 \mu m^2$ slit, by using characteristic relation of the Russian RT6-type X-ray film, and finally we obtain shower transition on spot darkness throughout the chamber.

4 Estimation of total released energy, ΣE_γ , and released energy, E_1 , at the first interaction:

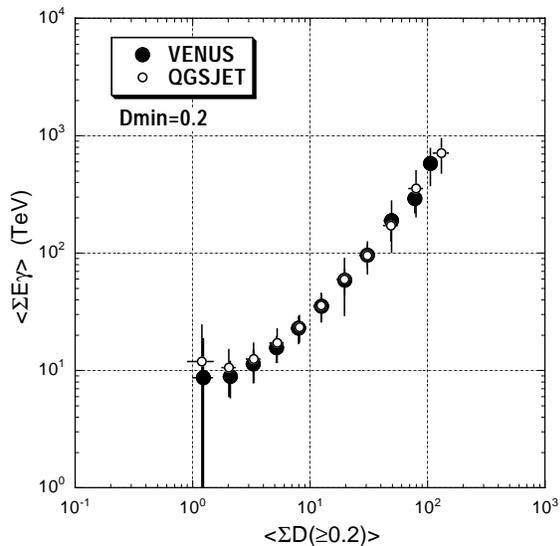


Figure 1: Correlation diagram on ΣD and ΣE_γ in simulated hadron-induced showers

4.1 Total released energy: Total energy, ΣE_γ , of a hadron released in form of gamma-rays during passage through the chamber is estimated from a sum, ΣD_i of the shower-spot darkness of $D_i \geq 0.2$ in its shower transition. We can see rather good correlation between ΣE_γ and ΣD_i . In Fig.1 we show an average dependence of ΣE_γ on ΣD_i in the simulated cascade showers. We see no differences between the two models.

4.2 Released energy E_1 at the first interaction: We define the “first interaction” as the first interaction among successive interactions which give rise to released energy larger than detection threshold energy, 4 TeV, during passage through the chamber. In order to extract shower transition

due to the “first interaction” in the whole shower transition of the event, following fitting procedure is applied for the first 6 layers in which spot darkness is $D \geq 0.2$. Out of the set of standard transition curves D vs. T of showers of electron-pair origin, calculated for the chamber which has a structure just same to the experimental one, the best fit is selected out by choosing the energy value, E_1^{fit} , and the first pair-creation depth, ΔT , by applying computer algorithm for fitting. We also calculate deviation of experimental shower transition from the best-fitted one beyond fitting range by $\delta \equiv \Sigma_{beyond}(D_i - D_i^{stand})/\sigma_i$, where σ_i is a dispersion of darkness of standard transition curve at i -th layer. Fig.2 shows an example of the above procedure which applied to a simulated hadron-induced shower. Fig.3 shows a distribution on E_1^{fit}/E_1 . The distribution has a clear peak around $E_1^{fit}/E_1 = 1$, indicating our present procedure more or less works well.

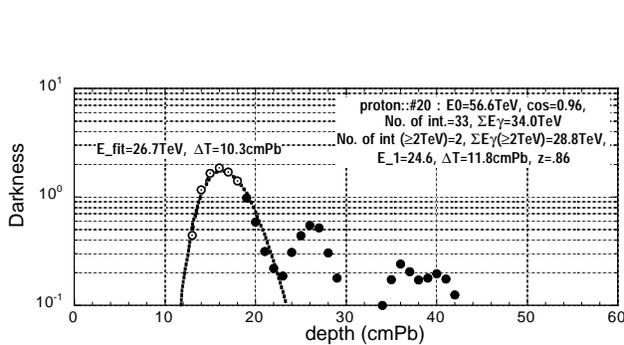


Figure 2: An example of extracting “first” interaction by computer fitting. Solid curve is best-fitted transition curve for the first 6 layers indicated by \odot .

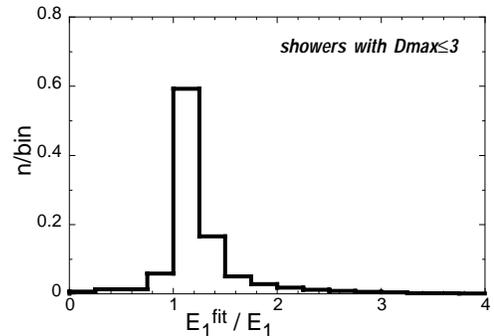


Figure 3: Distribution on E_1^{fit}/E_1 in the simulated hadron-induced showers using QGSJET model.

5 Selection of the events:

Emulsion chamber detects both gamma-ray- and hadron-induced showers. Here we identify a shower as a hadron-induced one if it has $\Delta T \geq 3$ cmPb and/or $\delta \geq 50$. Almost all gamma-ray-induced showers are rejected by these criteria. Further we put selection criteria that darkness at shower maximum, D_{max} , in the shower transition is less than 3 because our standard photometric measurement is limited up to $D = 3$, and sum of spot darkness, $\Sigma D_i (D_i \geq 0.2)$, is larger than 10, corresponding to total released energy $\Sigma E_\gamma \geq 30$ TeV (see Fig.1). In the Pamir thick lead chamber of $57m^2 year$ exposure, we have 89 showers which satisfy the above criteria. Among them 41 are found as a member of atmospheric families and the other 48 as singly-isolated. The same selection criteria are also applied to simulated hadron-induced showers.

6 Results:

We apply the procedure described in the section 4 and get E_1^{fit} and ΣE_γ for each of the above selected events both in the experiment and simulation. Fig.4 shows a distribution on $z \equiv E_1^{fit}/\Sigma E_\gamma$ which is considered to be closely related to inelasticity of the interaction. As is seen in the figure, the experimental data give more or less flat distribution except for the region $z \sim 0.1$. Simulated showers, however, show more events in higher z region. It indicates most of the energy is released in the first interaction in simulated events because of larger inelasticity assumed in the models. Inelasticity which is defined by energy fraction carried by most energetic baryon (meson) in proton (pion)-Pb interaction is ~ 0.75 at $E = 100$ TeV both in VENUS and QGSJET models. The above z -distribution indicates that the inelasticity in experimental hadron-Pb interaction is smaller than assumed in the models.

In order to know how the inelasticity changes the distribution on z , as a trial we calculated proton-induced cascade showers assuming distribution of secondaries in proton-Pb interaction is just same to that in proton-proton interaction. In the figure we show also a result for the case of p-p interaction using QGSJET model where the inelasticity is assumed as $\langle K_{inel} \rangle \sim 0.55$. As is seen in the figure, the experimental distribution is much closer to p-p case. Thus direct comparison of experimental data with simulation calculations also indicates that inelasticity of hadron-Pb interaction is smaller than that usually considered. The same conclusion is also obtained in the analysis on width of hadron-induced showers (Tamada, 1997).

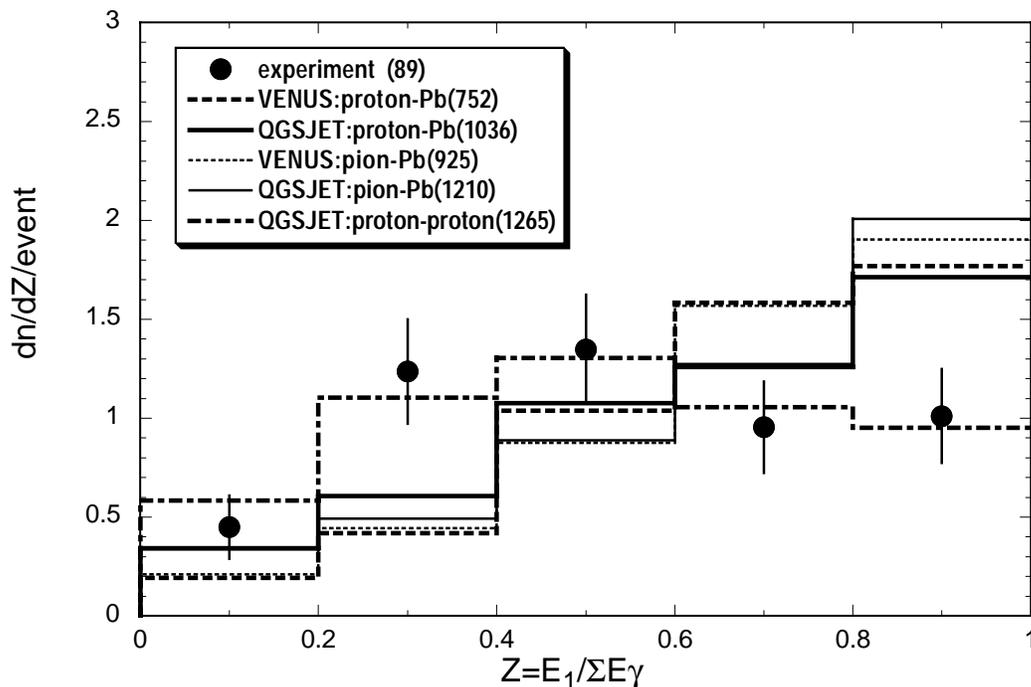


Figure 4: Distribution on z

Acknowledgements

The authors would like to express their sincere thanks to all the members of Pamir and Chacaltaya collaboration experiment, especially the members of Moscow State University who have been involved in using the thick lead chambers from the beginning of the Pamir experiment. The calculations was carried out using IBM RS/6000SP at the computer center of Kinki University.

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