Neutron measurement of the LHCf experiment

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***Abstract*. LHCf is an experiment dedicated to the measurement of neutral particles emitted in the very forward region of LHC collisions. The physics goal is to provide data for calibrating the hadron interaction models that are used in studies of extremely high-energy cosmic rays. LHCf can discriminate the existing models by the measurement of gamma-rays. Furthermore, because measurement of neutrons gives information of elasticity, it is complementary to the measurement of gamma-rays.**

The performances of the LHCf detectors for hadron showers were investigated at the CERN SPS H4 beam line in 2007. The tests were performed using 150 MeV and 350 GeV protons. The detection efficiencies of 11 % and 26 %, the energy resolutions of 21 % and 27 % are obtained for each energy. These results are in agreement with the results of full Monte Carlo simulation. We also simulated for the energy range at the LHC operation and found the efficiency and resolution are almost independent of incident energy over 1 TeV. At 3 TeV, the detection efficiency and the resolution were about 20 % and 40 %, respectively. We also found that the number of shower particles contained in a neutron event is approximately 30 % with respect to that of an electron induced shower with the same energy.

***Keywords*: high-energy cosmic-ray, hadron interaction model, LHC**

I. INTRODUCTION

The origin of high energy cosmic rays has been one of the most important themes in cosmic ray physics. That is studied by means of extensive air shower experiments. However the results are in some cases not fully in agreement because hadron interactions of high energy cosmic rays over 10^{15}eV with atmospheric nuclei has not been fully understood.

To understand the air shower development, the knowledge of pion multi production and leading hadron is important. The former determines the electromagnetic component in the air shower through the π^0 production. The fraction of the pion energy is called inelasticity. On the other hand, the energy fraction of the leading hadron, that penetrates deep in the atmosphere, is called elasticity. It is important to determine these parameters by measuring the particle energy spectra at very forward region of colliders. The UA7 [1] at CERN Sp$\bar{p}$S is so far the only dedicated experiment under such situation. However they measured only the π^0 spectra. Direct determination of the inelasticity from the collider experiments is difficult because all pions from interaction point must be detected. On the other hand, the inelasticity can be calculated from the elasticity which can be determined from the leading hadron energy. The LHCf experiment can measure the leading hadrons produced at LHC collisions. This unique measurement can determine the elasticity directory (inelasticity indirectory). In this paper, we present preliminary results of the LHCf performance for the neutron measurement at very forward region of LHC.

II. THE LHCF EXPERIMENT

The LHCf experiment is one of the LHC physics experiments dedicated for discrimination of hadron interaction models for UHECRs at the LHC energy. The LHC accelerator will have proton-proton collisions at $\sqrt{s}$ = 14 TeV and push the laboratory equivalent collision energy up to 10^{17}eV. The LHCf experiment will measure

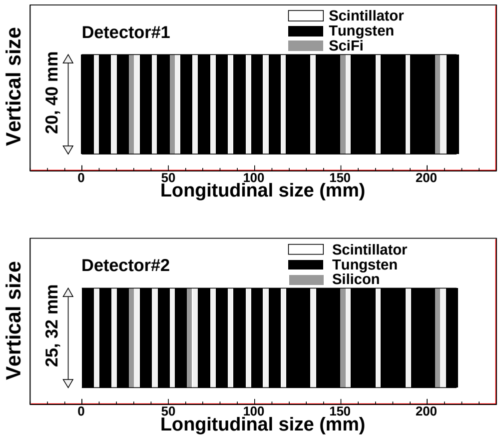

Fig. 1: Longitudinal structure of detector 1 (top) and detector 2 (bottom); black, white, gray boxes indicate the layers of tungsten, plastic scintillator, position sensors (SciFi and Silicon), respectively.

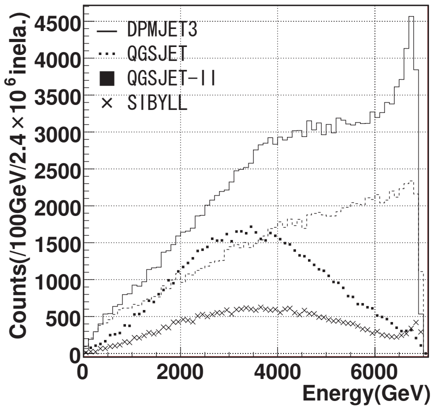

Fig. 2: The energy distribution of neutrons incident on the 20 mm×20 mm calorimeter for various models. The calorimeter is positioned at the center of the neutral particle flux.

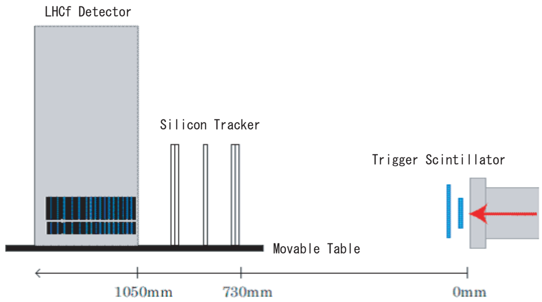

Fig. 3: Setup of the SPS experiment. Beam enters from right along the arrow. Two plastic scintillators were used to trigger beam particles. The silicon tracker, ADAMO [4], was placed in front of the LHCf detector. The two structures shown in the detector are the calorimeters. The detector and ADAMO were placed on a movable stage.

energy and transverse momentum spectra of neutral particles such as the gamma-rays, π^0s and neutrons, emitted in the forward region ($\eta > 8.4$) and operate for about one day during the LHC beam commissioning. The physics and detector performances of the LHCf experiment for the gamma-ray measurement has been presented elsewhere [2] [3].

The LHCf apparatus is composed of two independent detectors for background rejection and redundancy, that are installed ± 140 m from the Interaction Point 1(IP1). Each of the detectors (Arm#1 and Arm#2) has two sampling and imaging shower calorimeters made of tungsten layers (total depth is 44 radiation length and 1.7 interaction length), 16 plastic scintillator layers and 4 position sensitive layers. The transverse cross sections of the two calorimeters in Arm#1 are 20 mm×20 mm and 40 mm×40 mm, and those in Arm#2 are 25 mm×25 mm and 32 mm×32 mm. Four position sensitive layers, which are made of 1 mm×1 mm scintillation fibers for Arm#1 and microstrip silicon sensors (80 μm implantation pitch, 160 μm readout pitch) for Arm#2 , measure the transverse position and the lateral profile of the showers. The structure of the calorimeters are shown in Fig.1.

Fig.2 shows the neutron energy spectra in front of the 20 mm calorimeter predicted with the various models. Here the center of the 20 mm calorimeter is set at the flux peak of the neutral particles. There are significant differences between the predicted spectra, it means difference of inelasticity, of QGSJET, QGSJET-II, DPMJET3 and SIBYLL models. The measurement of the neutron spectrum is expected to give a clearer discrimination of the hadron interaction models than the well studied gamma-rays or π^0 spectra [2]. However, the detector performance such as the detection efficiency and the energy resolution must be determined by the experiment and the simulation. In the following section, the result of SPS beam test and the MC simulation is presented.

III. Performance for the Neutron Measurement

The detectors performance was tested at the CERN SPS North Area H4 beamline from 24 August to 11 September 2007. Both detectors were exposed to electron, hadron and muon beams. Electron beams with energies of 50, 100, 150, 180 and 200 GeV, hadron beams with energies of 150 and 350 GeV and a muon beam with an energy of 150 GeV were used. The setup of the beam test is illustrated in Fig.3. One of the detectors was placed on a movable table in the beam area. Data from the calorimeters and position sensors were recorded when triggered by scintillators placed in front of the detector. For the detail of the setup, see [3].

Monte Carlo simulation was performed for evaluating the performance of the LHCf detectors. In this study, EPICS, which is a widely used simulation code in air

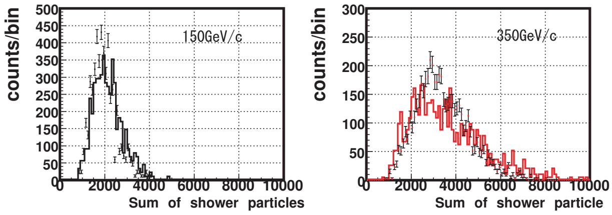

Fig. 4: The distributions of number of shower particles. The results of SPS beam test (dots) and MC simulation (histograms) are plotted. Right: 150 GeV, Left:350 GeV.

shower experiments, was used for the detector simulation. The primary hadron interaction model used in the following sections is DPMJET3 which is also commonly used in air shower simulations.

In the analysis of the SPS data, the conversion factors from ADC to energy deposit in the scintillators are determined by comparing the ADC values and the number of particles in MC simulation for electromagnetic showers. We found these factors are consistent at 2 % level for 50 - 200 GeV electrons [3]. The following condition was applied off-line to the complete set of data to select the interacting hadron events. Events are accepted if any successive three layers record more than 100 MeV energy release and the if the energy release in the third layer of the calorimeter is greater than 50 MeV. This allows selecting only the showers initiated in the forward layer of the calorimeter. These conditions are optimized to analyze low energy hadron events (150 GeV) and must be changed in the case of the LHC events, where the energy is around a few TeV. Using this trigger condition, the detection efficiencies are 11 % and 26 % for 150 GeV and 350 GeV hadrons, respectively. In the simulation, the detection efficiencies are 8 % and 16 % for 150 GeV and 350 GeV hadrons, respectively. The detection efficiency is not very high because the thickness of the LHCf calorimeters is only 1.7 hadron interaction length. The difference between the result of the SPS experiment and MC simulation may come from the position dependence. Because the horizontal size of the LHCf calorimeters is compact, the leakage of the shower particles, that is a function of incident position, reduces the detection efficiency. The position dependence of the detection efficiency must be considered in the further analysis.

The total energy deposit E is defined as $E = \sum \epsilon_i \times d_i$. Here the energy deposit in the i-th layer is defined as ϵ_i while d_i counts the number of tungsten layers in units of two radiation lengths. Fig.4 shows the distributions of E both for the SPS and MC results. We can find a good agreement in these distributions. The fluctuation of each shower is large because of the small longitudinal size of the detector. The energy resolution is defined with $\Delta E/E$, here ΔE is root-mean-square of the distribution of E. The energy resolutions obtained from the SPS data are about 21 % and 27 % for 150 GeV and 350 GeV hadrons, respectively. For the simulation, the energy resolutions are 18 % and 26 % for 150 GeV and 350 GeV hadrons, respectively. We can find an agreement in these results.

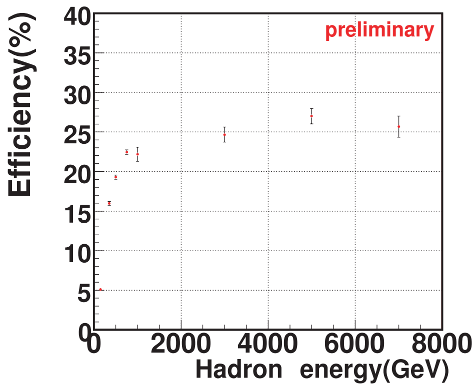

Fig. 5: Detection efficiency of neutron incident events. The threshold of detection is defined that any successive three layers record more than 150 MeV. For high energy, the detection efficiency is around 25 %.

IV. Performance at LHC condition

The performance of the LHCf detectors for the neutron measurement at LHC condition was evaluated by using the MC simulation. In this condition, the incident particle energy is up to 7 TeV. The trigger condition at the LHC situation is defined to get the 100 GeV gamma-rays with nearly 100 % efficiency. This is realized by applying a condition that any successive three layers record more than 150 MeV energy release. Fig.5 shows the neutron detection efficiency as a function of the neutron energy up to 7 TeV. The detection efficiency rises as the incident energy increases up to 1 TeV and it flattens at 25 % over that energy. Fig.6 shows the energy resolution as a function of neutron energy. The energy resolution is also increases up to 1 TeV, and becomes at constant value of ∼40 % over that energy.

The total energy deposit E of a neautron incident shower is smaller than that of a gamma-ray (electron) incident shower of same energy. In the LHCf experiment, the conversion factor from E to gamma-ray incident energy is well determined [3]. To know the neutron incident energy, the inefficiency of the neutron showers must be determined. For example, E is about 2300 MeV for a 150 GeV gamma-rays. While, it is about 860 MeV for a 150 GeV neutron. This is almost same energy deposit for a 50 GeV gamma-ray shower. We calculated E of neutron event divided by E of gamma-ray event at the same energy (860/2300 in the above example). Fig.7 shows the result as a function of neutron incident energy. The ratio is approximately 30 % and has a very weak energy dependence.

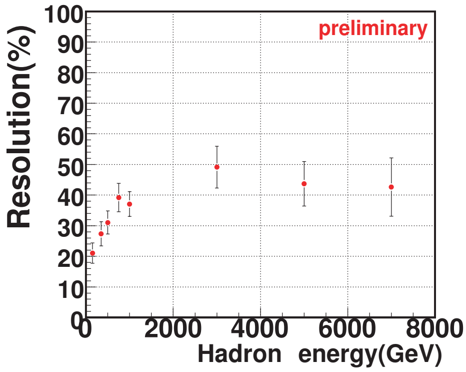

Fig. 6: Energy resolution for neutron events. The energy resolution is about 40 % in high energy.

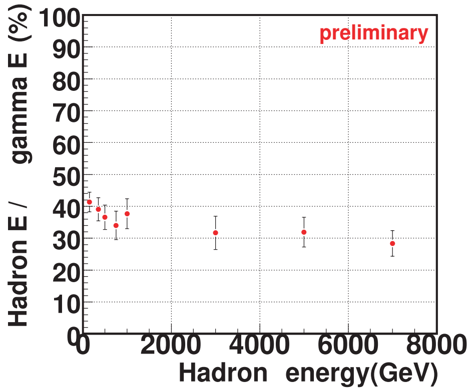

Fig. 7: For the hadron incident events, the number of detection particle become less compared with the same energy of electron event because of the shower leakage. The longitudinal axis shows the ratio of E of neutron and E of gamma-ray event.

V. Summary

LHCf is an experiment to measure the neutral particles at zero degree of 7 TeV proton collisions in the LHC corresponding to 10^{17} eV in the laboratory frame. The neutron data as well as the gamma-ray and π^0 data will be important to verify various hadron interaction models such as QGSJET, QGSJET-II, DPMJET3 and SIBYLL. The neutron spectrum provides the inelasticity that is an important parameter to understand the development of air showers.

The performance of the LHCf detector in hadron measurement was tested by the SPS beam data and MC simulation. The basic performance, the detection efficiency and the energy resolution, was obtained and a rough agreement was found between the experiment and simulation. Some discrepancy found in the comparison will be explained by the position dependence of the detector response. That will be verified in the further analysis considering the lateral beam profile found in the SPS experiment. The performance in the LHC energy was also calculated by the simulation. It appears that the detection efficiency and the energy resolution become flat over 1 TeV.

For the next step, we are carrying out a full MC simulation treating overall physics processes of the LHC p-p collisions, transportation of secondary particles from IP1 to the TAN, and the LHCf detector response. This will give more realistic prediction of the LHCf performance for the hadron measurement at LHC. For this study, the method of particle identification reported in [5] is under development. Finally, LHCf will take first data at LHC in the end of 2009 that can be compared with the predictions calculated with various models. We expect to select the best model and also that these measurement will allow calibrating all the models.

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