Primary Cosmic Rays with Energies above $10^{15}$ eV – Rapporteur Review of Poster Presentations at the 23rd ECRS – Session PCR 2.

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Abstract. Measurements of atmospheric Extensive Air Showers (EAS) are the only way of experimental studies of Primary Cosmic Rays (CR) with energies above $10^{15}$ eV. The final targets of these studies are search for astrophysical origin of these particles and properties of particle production in high energy particle interaction. Works presented at the PCR 2 session in the form of posters reflected the current progress in this area. In this review presented posters were grouped according to CR energy range, astrophysical significance, relation to high energy physics interaction properties and interaction models, and future experiments. 42 posters were submitted for this session. Some of the presented material in posters overlapped in parts with oral presentations.

1. Introduction

Cosmic Rays from the beginning (100 years ago), and especially after discovery of Extensive Air Showers (EAS) by Auger and Maze [1] in 1938, were the source of the highest energy particles. The Nature can provide particles with energies per particle about 10 million times greater than could be obtained in LHC at CERN (more precisely from about $\sim 4 \cdot 10^{12}$ eV for LHC protons to, say, $\sim 10^{20}$ eV at UHE CR). Physics of acceleration of particles to such extremely high energies is not known, and it is a big problem “to be solved”. The physics or astrophysics of the origin of the highest energy CR is probably the greatest mystery to be solved in this century (with some luck).

All measurements of CR at these energies show nearly isotropic direction distribution and very steep, power law like energy spectrum. These particles are atomic nuclei and their trajectories are strongly bent (at least in 10 – 100 parsecs scale) losing direction to their origin (however, there is a chance to make “astronomical ” observation with CR with energies in $10^{20}$ eV range, if they are protons). In the last years some details in CR energy spectra (distinct from power law) in energy range $10^{15} – 10^{17}$ eV were reported. These could be important evidence supporting models of recent (in astronomical scale) and nearby (in astronomical scale) active source (Erlykin and Wolfendale [2]).

At energy range above $10^{15}$ eV CR are studied by measurements of Extensive Air Showers (EAS), i.e. large particle cascades triggered by primary energetic CR particle in the Earth atmosphere. Physics of EAS development is complex. Events undergo fluctuations. Primary CR energy spectrum is very steep, which increases the role of fluctuations.
In this paper we give a brief review of results of selected studies of EAS and CR with energies above $10^{15}$ eV presented in the form of posters at the 23rd European Cosmic Ray Symposium in Moscow, July 3–7, 2012. There were 42 posters to be viewed on this poster session at this conference.

2. High energy physics from studies of CR in the energy range $10^{15}–10^{18}$ eV.

Very big progress in particle acceleration technique and detection capabilities, powered by particle physics, provides facilities (LHC for 7 TeV proton beams) to study particle interaction properties up to laboratory system energy about $10^{17}$ eV (nearly 2 orders of magnitude greater than in Tevatron case). This would provide a cross check (to some extent) to the results of interaction properties suggested by measurements in CR. At the same time high energy interaction models used in EAS simulations can be verified and “fixed” in energy range and kinematical area covered by LHC detectors.

![Figure 1](image)

**Figure 1.** Proton–air inelastic cross section $\sigma_{\text{inel}}^{p-\text{air}}$ predicted by the high energy models, as indicated, and measured (red circle) in the Tien-Shan EAS experiment. (Fig. 3 from presentation by N. M. Nesterova [3]).

N. M. Nesterova [3] presented results of evaluation of inelastic cross section in proton–air collisions from measurements in the Tien–Shan experiment. Measurements were made during the years 1989–2009. The hadron spectra were analysed using data from the hadronic calorimeter together with EAS data. Fig. 1 presents results of measurements and predictions from high energy interaction models used in EAS simulations.

Experiments using X-ray emulsion chambers at mountain altitude or even at supersonic air liner and balloon altitudes observed high energy events where the spots related to the highest energy secondary particles clearly did not have azimuthal symmetry. Instead, they seem to be correlated along a line. It is called coplanarity phenomenon, and is known as unexplained measurements for many years. This problem was addressed in the presentation by A. Managadze and R. Mukhamedshin [4]. As a conclusion they put: “Comparison of experimental data and...
model results demonstrates the necessity of introducing a coplanar particle generation process at energies above $10^{16}$ eV. It might be expected that similar phenomena would be studied soon at LHC experiments dedicated to measure particles in kinematic region of large pseudorapidity.

Separated near-by spots in X-ray emulsions exposed at mountain altitudes (e.g. 600 g/cm$^2$) were called gamma ray families. They originate when some $e^\pm$ and $\gamma$ subcascades, each with energy above a few TeV, pass through the emulsion. Distances between spots are up to about 30 cm. These events are believed to originate from interaction of primary CR deep in the atmosphere, subject to big fluctuations. Observed pattern depends on the height of interaction above the detector and $p_t$, $p_l$ properties of high energy interaction.

Presentation by R. A. Mukhamedshin [5] shows the analysis of events with energy observed in all spots in the range $10^{15}$–$4 \cdot 10^{15}$ eV in PAMIR experiment. Analysis is focused on comparison between interaction properties in very forward dynamic range of high energy interaction models used in simulations of EAS, and measurements. In the Fig. 2 the “natural” dynamic parameters $p_t$, $p_l$ were converted to measured parameters $< p_t >_{x,0.05–0.5}$ and $< R_{\gamma} >_{all}$, i.e. selected average transverse momenta, and somehow evaluated averaged horizontal size, which for given $p_t$ depends on $p_l$ (and also selected threshold energy for spot). Simulations do not reproduce measurements. In the paper [5] authors underline that the method addressed dynamic region of high energy interactions very important for EAS development.

L. Nellen [6] presented results of measurements from the Pierre Auger Observatory. Measurements of muons in EAS with energies around $10^{19}$ eV are presented in the Fig. 3. Comparison of measured muon density with prediction from EAS simulation with CORSIKA code and currently used high energy interaction models shows the large excess of observed muon densities above

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**Figure 2.** Comparison of high energy interaction parameters used in emulsion data analysis and obtained from simulations using different interaction models with results of emulsion PAMIR experiment at mountain altitude.

(Fig. 4 from presentation by R. A. Mukhamedshin et al. [5]).

**Figure 3.** Ratio of observed muon densities at 1000 m from EAS core to simulations for protons as primary CR particles using QGSJET–II high energy interaction model. Predicted ratio for primary iron nuclei is presented as well.

(Fig. 5 from presentation by L. Nellen for PAO [6]).
predictions, even assuming primary iron nuclei. The author examined and discussed other EAS components, and found that they were described satisfactorily by simulations. Muon component is very important, especially for estimation of chemical composition of primary CR. Here we quote from the paper [6]: “We conclude that work is needed on simulations to describe physics at the highest energies before we can extract primary composition reliably.”

Problems with description of high energy interactions were presented during the Conference by T. Pierog in his invited talk: “LHC results and High Energy Cosmic Ray Interaction Models”. New versions of models will be made taking into account new results from LHC. However, not all interesting kinematical regions would be covered by data from CERN (especially in the case of fragmentation region). Therefore some constraints have to be implemented based on results of measurements in Cosmic Rays.

3. Primary CR energy spectrum in the energy range 10^{15}–10^{18} eV.

In the energy range 10^{15}–10^{18} eV CR energy spectrum is changing its slope (so called “knee”), and relative mass composition (with the same energy per particle) is changing, too. These changes are probably due to astrophysical properties of CR, namely acceleration or/and propagation conditions. Interpreting these astrophysical properties is the main target of studies of CR in the energy range 10^{15}–10^{18} eV.

Estimation of the mass composition from EAS measurements is a very complicated and difficult task. Results are usually obtained using simulations of EAS development. As it was shown previously (see page 4 and paper [6]), currently there are problems even with muon densities.

In the presentation #602 by D. Kang et al. [7] (KASCADE–Grande) results of a new approach to data analysis were shown with special attention to the role of high energy hadronic interaction models in data analysis. 3 models were used: QGSJET-II-2, EPOS 1.99, and SIBYLL 2.1. The authors presented all particle spectra in the energy range 10^{16}–4\times10^{18} eV obtained using each of above models, and assuming in the first case that all particles are protons, and in the second case that they are iron nuclei. The ratio between the two cases (all iron/all proton) is about 4, which somehow indicates sensitivity of spectrum reconstruction to the mass composition. In the same time the ratios between spectra obtained using different interaction models for either proton case or iron case are within factor 1.6.

In the Fig. 4 (the same paper [7]) authors present reconstructed primary CR spectra grouping

![Figure 4. CR spectra measured by KASCADE–Grande with experimental data divided into two groups: electron–poor and electron–rich events (see text or original paper for explanation). In this Figure it is also shown that the results depend on high energy interaction model applied in simulations used in data processing.](Fig. 2 from presentation by D. Kang et al. [7]).
measured events in 2 classes named electron–poor and electron–rich (corresponding to heavier and lighter primary nuclei). Selection was done according to the value $Y_{CIC} = \log N_\mu / \log N_{ch}$, where $N_\mu$ and $N_{ch}$ are numbers of muons and charged particles corrected for atmospheric attenuation effects using CIC (Constant Intensity Cuts) method (details were not presented, but intuitively looks reasonable). Threshold values for $Y_{CIC}$ are generally interaction model dependent.

Results presented in the Fig. 4 suggested domination of the heavier component in the CR spectrum in the energy range $10^{16} - 2.5 \times 10^{17}$ eV, however without mass determination between heavy and light mass components, nor even without evidence about stable mass separation between classes. Fig. 4 shows how CR flux depends on the high energy hadronic interaction model used in data interpretation. Authors conclude that the differences are within factor 1.5.

During the oral sessions of this Conference there were a lot of discussions about detailed structure of primary CR spectra and its astrophysical significance as possible indication of a nearby source active in the past. Presentation by Knurenko and Sabourova [8] addressed above topic. In this case measurements of primary CR in the energy range $1.5 \times 10^{15} - 3 \times 10^{18}$ eV were done during 2000–2010 using Yakutsk array (scintillating detectors) with Cherenkov light detectors. The method of measurements allowed authors to determine the position and size of maximum of EAS development in addition to particle detection at the ground level. In the Fig. 5 authors presented primary CR spectra which were no more a combination of the two power law functions, but clearly some structures could be noticed above energy $3 \times 10^{15}$ eV and around $10^{17}$ eV. These structures were discussed in the paper. In one scenario interpretation requires different mass components of galactic CR spectra together with extragalactic components and additional “component yet to be explained” (dominating in the energy range $10^{17} - 10^{18}$ eV). In the second scenario (see Fig. 5) galactic component exceeds energy $10^{18}$ eV and structures in energy spectra are assumed to be due to nearby sources. The second scenario fits better to presented data. Cherenkov light measurements in a few detectors allow to determine the altitude of maximum

**Figure 5.** Primary CR energy spectrum. Red triangles are Yakutsk result. Curves are theoretical predictions; lines refer to the CR origin/propagation models with nearby source: solid line by Berezhko and Völk [9], dotted line by Ptuskin and Zirakashvili [10], (Fig. 4 from presentation by Knurenko and Sabourova [8]).

**Figure 6.** Average $< \ln A >$ of primary mass composition. Curve – expected composition from supernova remnants (Berezhko and Völk [9]). (Fig. 5 from presentation by Knurenko and Sabourova [8]).
of EAS development \( (x_{\text{max}}) \). With information about \( x_{\text{max}} \) and using CORSIKA simulations authors obtained relation between mass composition and primary CR energy, which is shown in the Fig. 6. Such results depend significantly on the interaction model used to determine “border conditions” for \( < \ln A > \) evaluation – the \( x_{\text{max}} \) for primary proton and iron particle.

In the presentation by Ivanov et al. [11] Yakutsk group presented new Cherenkov detector being developed for further and more precise studies of Cherenkov light component in EAS. The new design would have larger FoV and pixelisation of readout of XY position of photons at the cathode surface.

V. I. Galkin [12] presented an idea of using a set of Cherenkov detectors to measure primary CR mass composition with energy above \( 10^{15} \) eV. Set of Cherenkov imagers shall be placed at the altitude about 4 km a.s.l. and observe simultaneously EASs. Results of simulation with different telescope parameters were presented.

R. A. Antonov et al. [13] presented current status of the balloon borne SPHERE–2 experiment measuring Cherenkov light reflected from the snow. Observations were made from 1 km altitude. Presented preliminary spectrum in the energy range \( 10^{16} \cdot 3 \cdot 10^{17} \) eV was not as accurate as measurements made by ground based experiments.

The Tunka array detection system is going to be extended by a set of radio antennas to form a system called Tunka–Rex. The idea is to perform tests and develop EAS radio detection system measuring EAS at the same time as Tunka Cherenkov array. In principle results of both measurements depend linearly on the number of electrons in EAS, especially at the maximum of EAS development. This might be very important step in developing radio detection of EAS. For test the system would measure during moonless nights, as this condition is required by EAS Cherenkov light detections. However, in case when radio detection would achieve comparable detection efficiency, radio detectors could be used by themselves for 24h/day. It is also important that radio detectors are very cheap compared with any other method of EAS detection. The presentation [14] showed the current status of preparation of 20 radio antennas at Tunka site. First radio detectors were displaced and tested in 2009. The set of 20 radio antennas should start operating from the fall of 2012.

At least from the 80-ties of the previous century it is known that measuring of the hadron component of EAS is one of the most promising experimental method to study primary CR mass composition, at least in the energy range \( 10^{15}–10^{17} \) eV. It is also clear, that results of measurements of hadron component are necessary to understand the primary CR energy spectrum and mass composition at this energy range. The main problem are difficulties in measuring of hadrons on a large area. Experiment KASCADE (KArlsruhe Shower Core and Array DEtector) had a large hadron detector in its centre. Hadron attenuation length was analysed in [15], [16]. But KASCADE nor KASCADE-Grande Collaborations did not use hadron data in their final determination of energy spectra for different primary CR masses [17], [18]. At this Conference Yu. Stenkin [19] presented a poster describing realisation of the large hadron detector in form of portable neutron detectors. Measured neutrons originated in EAS hadron interaction in detector vicinity. The relation between hadrons and evaporated neutrons as function of primary CR particle energy is shown in the Fig. 7. 32 detectors capable to measure electrons and neutrons form an experiment called ProtoPRISMA–32 and are deployed around NEVOD detector in Moscow for tests. The final plans are to use such detectors with high altitude experiments like LHAASO at Tibet.

According to the plans presented by Shulzhenko et al. [20], the Moscow Engineering Physics Institute very big water detector NEVOD–DECOR will have EAS array around it. EAS detec-
tor would provide information about shower size and core position which together with muon measurements at NEVOD–DECOR itself (“muon density spectra”) should provide opportunity to study primary cosmic ray spectrum and hadronic interaction characteristics in the energy range $10^{15}$–$10^{19}$ eV. Details of EAS detectors were presented in the paper [20].

High energy muon group detectors could provide important information about mass composition of primary CR. Two posters [21] and [22] presented results from EMMA, underground experiment placed in the Pyhäälmi mine corridors in Finland. The vertical muon energy threshold at the place is about 50 GeV, at about 75 m underground. The detectors (see [21]) are drift chambers of the total area of 240 m$^2$ with position resolution about 1 cm, scintillators with unit size 12 cm $\times$ 12 cm (total area 24 m$^2$), and Limited Streamer Tubes with resolution 2 cm $\times$ 8 cm (total area 174 m$^2$). Paper [21] presents predicted number of muons in EAS event generated by primary proton and iron nuclei with energy from the range $10^{15}$–$10^{16}$ eV. Paper [22] presents preliminary muon number distribution measured during 44 days by one station with 3 detector layers and geometric acceptance about 18 m$^2$sr.

4. Primary Cosmic Rays with energies above $10^{18}$ eV.

The Pierre Auger Observatory (PAO) is the largest operating cosmic ray detector. The second largest is the Telescope Array (TA). Yakutsk array is the longest (in time) operating detector designed to measure the highest energy CR. It is still very vital, developing and implementing new ideas for measurements.

Future of measurements in this area is very interesting: TUS and JEM-EUSO are the experiments prepared to measure the ultra high energy EAS observing atmosphere “looking down” from the space. TUS is already prepared to launch. One year after launch JEM-EUSO should have much larger exposure than PAO at that time, but would measure through a few years.

For the highest energy CR anisotropy studies are the most important target, because there is a chance to find directions to the sources. Poster by J. de Mello Neto [23] (extended version of poster presentation was presented in the oral session with the same title) is about results of PAO for anisotropy measurements. Current status of the big puzzle of initial strong correlation between directions of ultra high energy cosmic ray (UHECR) events (energies > 5.5·$10^{19}$ eV) and directions to Active Galactic Nuclei (AGN) with $z < 0.018$ was presented in the Fig. 8. Correlation is less significant than the initial one, but is still positive and its value “is stabilised”. In the paper an “intrinsig anisotropy” (i.e. catalogue independent method) analysis was performed, as well, and “no statistically significant signal was found”. 

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Mean number of hadrons at the sea level within radius of 50 m from EAS core (black line for primary protons and black triangles for iron) and number of evaporated neutrons (red line and triangles) for primary proton and iron nuclei as function of energy per nucleus. Results of simulations using CORSIKA.

(Fig. 1 from presentation by Yu. Stenkin [19]).
D. Ikeda presented poster [24] about the spectrum and mass composition of UHE CR measured by the Telescope Array (TA) experiment. It is known, that these results are different from obtained by PAO. In the Fig. 9 energy spectra are presented. Data show cut–off in energy spectra at “the end” of the spectrum. The important question (experimental one) is, whether this cut is related to the GZK cut–off effect; in that case it was predicted at energy $5 \cdot 10^{19} \text{eV}$ (see [29]). Primary mass of measured EAS at very high energy could be guessed from observation of the position of the maximum of EAS development $X_{\text{max}}$. The EAS size at $X_{\text{max}}$ could be used as primary particle energy estimation. E.g. since cross section for iron–air interaction is greater than proton–air, we expect that iron induced showers start higher in atmosphere than for protons case, and $X_{\text{max}}$ for iron are smaller than for protons, at least in average terms. Fig. 10 shows results from TA measurements ($< X_{\text{max}} >$ errors are indicated). The figure suggests proton (light mass) composition, and TA result differs here from PAO measurements. In the Fig. 11 measurements of $X_{\text{max}}$ for individual showers are presented. The distributions of $X_{\text{max}}$ individual values in energy intervals have large RMS which also suggest proton mass composi-
Results presented by TA experiment are consistent in sense of primary proton composition and position of energy cut–off in the spectrum (related to GZK effect predicted for protons). However, the discrepancy between PAO and TA results shall be solved by analysis of experimental methodology.

Physicists from the Yakutsk array presented a few posters related to methodology and technologies development for the highest energy CR measurements in their detector. Results of radio (32 MHz) observation of EAS were presented by S. P. Knurenko et al. [26]. Fig. 12 shows measured dependence of the strength of the radio signal with respect to the distance from the EAS core. The decrease of the radio signal intensity is not large (compared with other measured components), but it should be taken into procedure of EAS localisation. Fig. 13 presents the correlation between amplitude of the radio signals and the Cherenkov light flux at 400 m from the EAS core, recalculated to primary particle energy. The correlation is still not very good. Definitely, radio measurements can not be used for EAS energy estimation, yet.

The presentation [27] by S. P. Knurenko and A. Sabourov was devoted to description of a few detectors/instruments used in Yakutsk experiment to determine atmospheric condition, which is very important for Cherenkov light measurements, at least. A station for atmosphere monitoring is operating since 2005. It includes following detectors: the small Cherenkov array, a lidar monitoring atmospheric transparency, and a photometer CE318, recording aerosol content in the atmosphere. Registration system also includes electric field sensor, antennas for measuring E and H components of electric field.

Fluorescence light detector can observe directly the light emitted by N₂ molecules excited by
EAS particles. Fluorescence photons emitted in other direction and then scattered in direction of detector could be observed as well. The poster by M. Giller and A. Śmiałkowski [28] addressed the problem of quantitative description of scattered fluorescence light. Authors presented analytical (approximate) formulae for relative rates of single and double scattered photons in direction of detectors with respect to the number of photons emitted directly to the detector. Separate solutions for Rayleigh and Mie scattering were presented. Such a description could be very useful in computer codes for simulation of EAS measurements applying fluorescence technique.

S. Grigorieva presented poster [29] about different possible astrophysical interpretations of UHE CR energy spectra. The work is focused on the interpretation of observed cut–off near to the end of observed energy spectra. It is underlined that currently observed by PAO cut–off of energy spectra can not be interpreted as observation of GZK cut–off, because the latter was predicted at $5 \times 10^{19}$ eV (higher than PAO result) and for protons. Therefore, in PAO case, energy spectra can be described by including other parameters like source efficiency, distance to source and emitted energy spectra. It was noticed that knowledge about mass composition is crucial in model interpretation of UHE CR measurements. Observation of UHE neutrinos might also solve the source problem (as positive observation would indicate protons in primary UHE CR, and GZK effect). For these tasks new experiments are required.

In the presentation by N. N. Kalmykov et al. [30] different scenarios for UHE CR source models were discussed and compared. These are cluster accretion shocks, active galactic nuclei, pulsars, and gamma ray bursts. Two forthcoming satellite (TUS and JEM–EUSO) experiments parameters are discussed in this contents.

Two posters (by P. Klimov et al. [31] and by A. A. Grinyuk et al. [32]) were presenting the TUS experiment for UHE CR measurements for the first time from space. The idea is to measure from space fluorescence light from N$_2$ molecules excited by huge number of EAS particles. The light would be collected by Fresnel mirror and focused on camera made of cluster of 256 photomultipliers (PMT) (see Fig. 14). The camera is fast enough to measure EAS development in the atmosphere. The time resolution is 0.6 µs. These posters present the last steps of tests, some results from simulation/reconstruction code, trigger simulations, PSF measurements, EAS
detection efficiency estimations etc. The conclusions are that the TUS experiment has been prepared for operation in space. TUS is going to be launched at the Lomonosov satellite probably at the end of 2012.

Three posters (by G. Osteria et al. [33], by T. Mernik et al. [34], and by A. Guzman et al. [35]) presented preparations for JEM–EUSO Mission (see Fig. 15) and for its test EUSO–Balloon experiment (see Fig. 16). JEM–EUSO (Extreme Universe Space Observatory on Japanese Experiment Module) is very big UV telescope for atmosphere observations with 60° FoV opening angle. The camera made of 4932 PMTs, each with 64 anodes/pixels, i.e. 315648 pixels would count numbers of photoelectrons in each pixel every 2.5 µs (400 000 frames/s). These provide

**Figure 14.** The TUS experiment for UHE CR measurements. (Fig. 1 from presentation by A. A. Grinyuk et al. [32]).

**Figure 15.** JEM–EUSO telescope at International Space Station. The figure illustrates the idea of measurements of UHE CR EAS. (Figure from poster by G. Osteria et al. [33]).

**Figure 16.** EUSO–Balloon drawing. (Fig. 3 from paper by G. Osteria et al. [33]).
ground level resolution of 500 m × 500 m from 400 km altitude for vertical observation mode. The main target are measurements of UHE CR (above 5 · 10^{19} eV) with expected rate about 3–4 events per day. It would be very big experiment: the effective Fresnel lens diameter about 2.5 m, the focal surface diameter about 2.5 m, the weight about 2000 kg.

Two posters [34] and [35] presented some details of the software preparation based on the ESAF code: estimation of angular resolution of the EAS event reconstruction, and the EAS pattern recognition. The poster [33] presented the time synchronisation system for JEM–EUSO and for the balloon test experiment EUSO–Balloon.

The launch of JEM–EUSO is planned for beginning of 2017, whereas the first flight of balloon is scheduled for beginning of 2014.

5. Projects for measurements of extremely high energy Cosmic Rays.

The idea of measurements of neutrinos with energy above 10^{20} eV – LORD – was presented by V. A. Ryabov et al. [36]. LORD is the Lunar Orbital Radio Detector. The interacting extremely high energy neutrino in Moon’s regolith would produce coherent Cherenkov radio emission. Radio signals would be refracted at the Moon’s surface and finally might be detected by antenna system orbiting the Moon.

Microwave radiation emission is expected from interactions of free electrons and atmospheric molecules, in the process called Microwave Bremsstrahlung Radiation (MBR). In the poster by J. Alvarez-Muniz et al. [37] it was suggested that in EAS with energy above 10^{20} eV one might expect conditions required by MBR. The work presents the laboratory set-up for 1–20 GHz microwave measurements at the electron beam facility at National Laboratory of Frascati (LNF). The data from measurements using polarised antennas are under analysis.

The presentation by S. Ogio et al. [38] shows results from measurement of microwaves (about 12 GHz) which is predicted to be emitted by EAS. Tests made at Osaka University, at Telescope Array, and at Konan University were described. Further development of electronics and antennas for polarised radiation are planned.

6. Some remarks.

Most of presented posters in this section (PCR 2: Cosmic Rays with energy above 10^{15} eV) addressed experimental aspects of investigations. Posters presented models and astrophysical interpretation of Cosmic Ray energy spectrum referred to measurements, and required still better accuracy of their results.

High energy particle interaction physics in energy range 10^{15} eV – 10^{18} eV is now already accessible in LHC at CERN. Proton–proton (nucleon–nucleon) collisions with CM energy \( \sqrt{s} = 7000 – 14000 \) GeV correspond to laboratory energies 2.6·10^{16} – 1.0·10^{17} eV. LHC detectors nearby to CMS: TOTEM and CASTOR would measure particles inclined from particle beam by 3 – 100 mrad (pseudorapidity \( \eta \) range 3–6.5) in CM reference system. In laboratory reference frame and for particle with \( x = p^C_{1} / p^C_{\text{proton beam}} = 0.01 \) one could study particles at angles 0.2 – 6.7 \( \mu \)rad for primary energy 2.6·10^{16} eV (and 0.1 – 3.3 \( \mu \)rad for 10^{17} eV). These detectors would be able to measure total cross section and some features similar to presented in the Fig. 2 (page 3).

At the same time high energy particle production in the very forward kinematical region would be measured, results would be implemented in high energy interaction models used in the Monte Carlo simulation. This kinematical region is the most important for EAS development description.
Studies of Cosmic Rays in energy range $10^{15}$ eV – $10^{18}$ eV are continuously concentrated on energy spectrum and primary mass composition. Astrophysical models of origin and propagation of Cosmic Rays with energies in this important energy range require very good accuracy of measurements of primary particle energy spectrum. Measured EAS parameters undergo fluctuations. Steep energy spectrum requires very accurate description of these fluctuations to properly evaluate energy spectrum. However, at this conference it was demonstrated, that the high energy interaction models (used in EAS development simulation) need to be modified to properly describe several observations. The same models and simulation codes are used to work out methods and formulae to evaluate primary energies to build up energy spectrum.

To minimize effects of fluctuations it is reasonable to measure many EAS parameters ("observables"), select these which have smaller fluctuations, select places (altitudes) where fluctuations are smaller, select parameters which are sensitive to mass composition, and finally use all possible information. At this conference several groups presented plans of deployment of hadron, Cherenkov light, radio detectors, or add “ordinary EAS detectors” to experiments using other detection methods, so far.

Approach to use many EAS component is especially important for primary mass analysis. The underestimation of number of muons in simulations of EASs (as presented by Nellen [6]; vide Fig. 3 at page 3) might (might not) “produce” an artefact of increasing primary particle mass, when data analysis based only on electron and muon components.

Finally, some effort should be done to enable comparison of results from different experiments. Some information not preprocessed by EAS simulations should be presented (like event rates, measured electron number and muon number distribution, distribution of densities at selected distance etc.), and these would be “model independent”.

In the highest Cosmic Ray energy range (above $10^{18}$ eV) ground level measurements would soon compete with space borne experiments – especially for GZK energy region and above, for search of astrophysical sources and the single particle energy limits. Planned space experiments use the idea of TPC (time projection chamber) for EAS fluorescence measurements. Space experiments would have much larger field of view than not only currently operating ground level arrays, but also planned (i.e. Auger Next). Therefore measurements of ultra high energy Cosmic Rays made from space have much bigger expected statistics of events compared with ground measurements. However the ground based measurements, being nearer to the event than satellites from the atmosphere, are much better for studies of primary particle mass and shower properties. Surface detectors are nearly at maximum of EAS development.

Radio / microwave measurements might (several posters addressed these directions) give in the future a new way to study most energetic cosmic ray events in the ground based experiments.

7. Conclusions/Summary.

The main conclusion is that the most important achievements are still in the future. The community acquired large experience from studies made so far. New observation methods are planned. Measurements made so far used methods which seem to be explored, and the future belongs to simultaneous combination of many components measurements, ground based experiments made on altitudes corresponding to levels of maximum of EAS development (in related energy range), or space borne experiments observing the Earth atmosphere.

Not all presented posters were mentioned here. It is essential to notice that most of papers have shown results of many years of research.

Author would like to express his apology for missing some papers and for inadequate or too short description of many problems. Readers are invited to read and study original texts.

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presented at the session PCR 2.

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