Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B (Proc. Suppl.) 175–176 (2008) 194–197
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

Experiment SPHERE status – 2006 and CR composition determination by means of Cherenkov light LDF

R.A. Antonov[a*], A.M. Anyuhina[a], E.A. Bronvech[a], D.V. Chernov[a], V.I. Galkin[a], A.A.Lubnin[b], D.A.Pushkarev[b], T.I. Sysoeva[b], S.B.Shaulov[b†] F.O.Shihaliev[b], W. Tkaczyk[c], M. Finger[d], M. Sonsky[e]

[a]Skobeltsyn Institute of Nuclear Physics, Lomonosov State University, Moscow 119992, Russia

[b]P.N.Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prospect 53, Moscow 119991, Russia

[c]Department of Experimental Physics of University of Lodz, Poland

[d]Karlov University, Prague, Czech Republic

[e]COMPAS Consortium, Turnov, Czech Republic

The modern status of the SPHERE experiment and the method to determine the primary energy and the kind of the primary nuclear particles is presented. The SPHERE experiment is based on A.E.Chudakov's suggestion to use a new method for investigating the ultra high energy primary cosmic ray energy spectrum [1]. A small device lifted above the snow surface of the Earth detects the Cherenkov light of extensive air showers reflected from the surface. The relatively simple detector SPHERE-2 (spherical mirror 1.5m diameter and retina of 100 pixels) is presented. The next plan of the SPHERE experiment is to start measurements of the cosmic ray spectrum in the energy range $10^{16} - 10^{18}$ eV above the snow surface of Lake Baikal.

1. INTRODUCTION

The SPHERE set up detects the Cherenkov light (ChL) of Extensive Air Showers (EAS) reflected from the snow surface of the Earth. The main goals of the SPHERE experiment are to investigate the primary cosmic ray (CR) energy spectrum in the range $10^{15} - 10^{20}$ eV, to determine the CR nuclear composition and to search for CR sources.

Two detectors were designed for these purposes: SPHERE-1 and SPHERE-2. The first measurements using the SPHERE-1 detector were carried out in 1975-2000 [2–6]. At this stage of the experiment, the detector was lifted by a tethered balloon to a height of 1 km above the snow field.

The SPHERE-2 detector is near completion and the construction will be finished this year [7–10]. We hope to start the measurements above the Baikal Lake snow surface next year. It is suggested that this new, more advanced, detector will be lifted by a tethered balloon to a height of 1-3 km.

The CR experimental data about the nuclear composition at energies of $10^{16} - 10^{18}$ eV are rather poor and controversial. At the same time these data are important for investigating the nature of the knee at energies $3 - 5 \cdot 10^{15}$ eV and for determining the possible contribution of the metagalactic component to the CR flux. The experimental installation for EAS registration must be devised to take into account the possibility of reconstructing the energy, angle of arrival and primary nuclear type.

The mass composition can be obtained from

*Supported by the Russian Foundation for Basic Research, projects 95-02-01325, 98-02-16227, 01-02-16080, 06-02-16198
†speaker: shaul@sci.lebedev.ru

0920-5632/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.nuclphysbps.2007.10.034

the X_{max}[3] determination. This method is most popular for ultra high energy CRs, but their accuracy doesn't allow to make unambiguous conclusions. A new method for determining the CR composition is presented here. The preliminary results of the simulation calculations are discussed. They show the possibility to estimate the mass composition without X_{max} reconstruction.

2. THE SPHERE-2 INSTALLATION

The SPHERE-2 set up consists of a 7-segment spherical mirror 1500 mm in diameter, and curvature radius of 940 mm with a mosaic of 109 photomultipliers PEM-84-3. A Schmidt diaphragm of 930 mm is installed in front of the mirror for better spatial resolution. The viewing angle is 52 degrees. The installation is lifted up during night time by balloon to an altitude of 1-3 km and operates like a camera registering images of light spots on the snow surface during EAS passing through the atmosphere. Each PEM observes an area of diameter of approximately 70 m for 1 km altitude and 210 m for 3 km altitude.

The electronics of the installation detects light pulse profiles with 25 ns resolution in each channel. The dynamic range of each amplifier is $\sim 10^4$ due to use of two 10-bit ADCs and two operational-amplifiers with amplification 1 and 10.

Trigger conditions are as follows: three- (soft master) or seven-fold coincidence (hard master) during 1 μsec is required between pulses from adjacent PEMs.

3. THE METHOD TO DETERMINE THE CR COMPOSITION

The method is based on an analysis of the lateral distribution function (LDF) shape for EAS ChL. One of the advantages of SPHERE installation is a possibility to detect the EAS ChL both in the immediate vicinity of the EAS axis and at large distances. The PEM mosaic 'sees' along the EAS axis and detects ChL LDF each 25 ns. Simulation calculations show that the slopes of the ChL LDF differ remarkably for EAS which are generated by distinct primary nuclei.

3.1. The simulation calculations

The CORSIKA 6.50 program with the QGSJET option was used for the simulation calculations. In the first stage only protons and Fe nuclei with energies of 1 PeV and 10 PeV were investigated. The distributions of Cherenkov photons at the level of light reflection (Baikal Lake, 455m a.s.l.) were stored inside the square 1200×1200 m^2 with $2,5 \times 2,5$ m^2 cells.

The arrival time was divided into 100 cells of 5 ns each. During the second stage those space-time distributions of Cherenkov light were used for SPHERE-2 response simulation and processing in order to restore original shower parameters. The EAS image is presented as 109 pulses with 25 ns resolution, calculated for the given installation and light reflection law.

Only EAS with axes within a vertical cone with half-span of 20 degrees were used. The total number of Cherenkov photons within range of the wave lengths, $\lambda = 310 - 650$ nm, reached reflection level, were received by sum over all cells.

3.2. The results

The main goal of the simulation calculations was to search for ChL measurable characteristics strongly correlated with original shower parameters, first of all with particle energy and primary particle kind. For energy estimation one can use quantities such as Q_{0-500} (integral of the Cherenkov light LDF in 500 m radius circle) or Q_{150} (light density at a distance of 150 m from shower axis). The average values and standard deviations of Q_{total}, Q_{0-500} and Q_{150}, normalized to Fe nuclei, are shown in Table 1. The errors are calculated without considering the background fluctuations and errors in reconstructing the number of electrons.

The procedure for the E_0 determination is inseparable from the one for determining the primary nuclear kind. As a basis indicator of nuclear kind one can use spectral indices of ChL LDF [12]. The new method can utilize the possible simultaneous determination of the EAS energy and kind of primary nuclear due to the possibility of measuring the ChL LDF in a wide range of distances

[3] Depth of EAS development maximum in the atmosphere

Table 1
The ratios of the average photon numbers for p and Fe to Fe and errors

Nuclei	Q_{tot}		Q_{0-500}		Q_{150}	
	$\bar{Q}/\bar{Q}_{Fe}$	σ	$\bar{Q}/\bar{Q}_{Fe}$	σ	$\bar{Q}/\bar{Q}_{Fe}$	σ
p, 1 PeV	1.32	9%	1.56	12%	1.45	10%
Fe, 1 PeV	1	3%	1	5%	1	4%
p, 10 PeV	1.21	3%	1.30	5%	1.19	4%
Fe, 10 PeV	1	0.3%	1	1%	1	2%

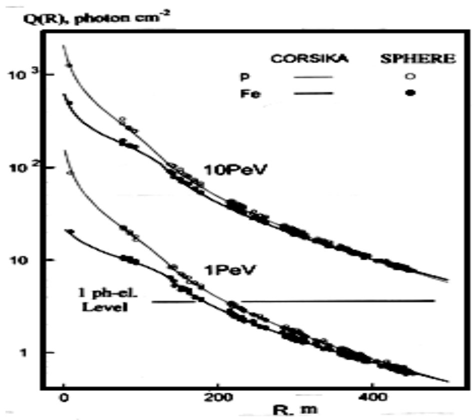

Figure 1. The LDF of the EAS Cherenkov light for p and Fe nuclei with energies 1 and 10 PeV.

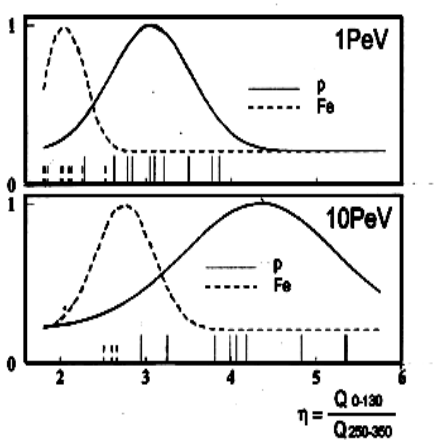

Figure 2. The distributions of the parameter η for p and Fe nuclei with energies 1 and 10 PeV.

from the EAS axis.

These features are shown in Figure 1, which shows ChL LDF for p and Fe with energies 1 PeV and 10 PeV (curves) and estimates of the ChL densities, derived from the response of the individual cells of the PEM mosaic.

The quantization of the PEM pulses and starry sky background weren't taken into account. Figure 1 shows that it is possible to re-establish local densities in centers of cell's fields of vision using integral light signal obtained by individual cells. The level of light density which corresponds to signal of 1 photoelectron per cell is also shown in Figure 1. The good correspondence of light densities and their estimates allows us to conclude that one can estimate the energy with an uncertainty less than 30% when the nuclear kind is determined correctly (90% of events).

The LDF greatest difference for protons and Fe nuclei takes place at distances 0-130 m and their LDF are close enough for distances greater than 250 m from the EAS axis. Due to this fact the experimentally measured parameter $\eta = Q_{0-130}/Q_{250-350}$ was chosen to distinguish the nuclei type.

The η distributions for energies 1 PeV and 10 PeV are shown in Figure 2. These distributions for p and Fe showers intersect only at wings for fixed E_0. These distributions with mean values and dispersions of the Normal type which equal those of real measurements roughly illustrate the situation. Real η distributions are more like gamma-distributions: they have a sharp boundary to the left and exponential tail to the right. Anyway, the η parameter allows us to distinguish showers from p and Fe with uncertainty less than 10%.

4. CONCLUSIONS

The method of the ChL LDF analysis in SPHERE type experiments supplements, rather than replaces, the X_{max} method. Simulation calculations show that this method can substantially improve the estimation of the CR nuclear composition at energy range $10^{16}-10^{18}$ eV. Furthermore it gives a new possibility to measure the individual energy spectra for distinct nuclei groups.

The planning of the ChL LDF method is at the beginning and all results are substantially preliminary.

The measurements at Baikal Lake with SPHERE-2 installation are scheduled to start next year and a few sets of expositions are planned during 2007-2010.

REFERENCES

1. A.E.Chudakov, *Trudy conf. po cosm. lutcham*, (in Russian), p.69, Yakutsk, 1972.
2. Antonov R.A., Ivanenko I.P., Rubtsov V.I. 1975, *Proc. 14th ICRC, Munich*, **9**, 3360.
3. Antonov R.A., Ivanenko I.P., Kuzmin V.A. 1986, *Izvestiya Academii Nauk*, (Russian), **50**, 2217-2220.
4. Antonov, R.A., Chernov D.V., Fedorov A.N., Korosteleva E.E., Petrova E.A., Sysoeva T.I., and Tkaczyk W. 1997, *Proc. 25th ICRC, Durban*, **1**, 60.
5. R.A.Antonov, D.V.Chernov, A.N.Fedorov, E.A.Petrova, T.I.Sysojeva. 1999, *Izvestiya Academii Nauk*, (Russian), **63**, 520.
6. Antonov, R.A., Chernov D.V., Korosteleva E.E., Sysoeva T.I., and Tkaczyk W. 2001, *Proc. 27th ICRC, Hamburg*, v.1, p.60.
7. R.A.Antonov, D.V.Chernov, L.A.Kuzmichev,S.I.Nikolsky, M.I.Panasyuk, T.I.Sysoeva, 2001, *Proc. 27th ICRC, Hamburg*, v.1, p.828.
8. R.A.Antonov, D.V.Chernov, L.A.Kuzmichev, S.I.Nikolsky, M.I.Panasyuk, T.I.Sysojeva, 2001, "Vestnik MGU, ser. fiz." (In Russian), **5**, p.44.
9. R.A.Antonov, S.P.Chernikov, S.I.Nikolsky, M.I.Panasyuk, T.I.Sysojeva. *Kratkie soobshenija po Fizike*, (Russian), 2001, **12**, p.39
10. S.I.Nikolsky, R.A.Antonov, G.E.Verba, P.E.Goldberg, A.V.Pereldic, T.I.Sysojeva, S.V.Fedorov, S.P.Chernikov, Kratkie soobshenija po Fizike, (Russian), 2002, V. 11, P. 32.
11. R.A.Antonov, E.E.Korosteleva, L.A.Kuzmichev, O.A.Maksimuk, M.I.Panasyuk, A.V.Pereldik, A.S.Senanov, D.V.Chernov, S.A.Slavatinsky, T.I.Sysojeva, S.B.Shaulov, Mir. Finger, Mic. Finger, V.V.Lukin, V.A.Kuchin. 2004, Izvestiya Academii Nauk, (Russian), V. 68, P. 1637.
12. A.A.Belyaev, I.P.Ivanenko, B.L.Kanevsky, Electron-photon cascades for cosmic rays of the superhigh energies, Moscow, "Nauka", 1980