Event-by-event study of CR composition with reflected Cherenkov light

Lake Baikal, March 2012

ECRS 2014 KIEL

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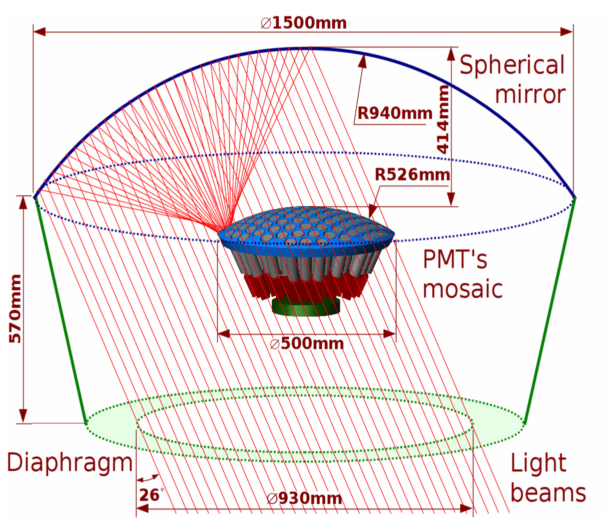
Abstract. We present the first reasonably well systematically controlled results on cosmic ray (CR) composition obtained with the reflected Cherenkov light method. The fraction of CR light component above 30 PeV was reconstructed using the data of the SPHERE experiment which observes Vavilov-Cherenkov radiation of extensive air showers (EAS), reflected from a snow surface of Lake Baikal. We discuss the main sources of systematic uncertainty of the CR light component fraction, a possibility to enhance sensitivity to the primary nuclei mass number by means of multidimensional methods, as well as the ways to lower the energy threshold of CR composition study.



Optical scheme of the SPHERE-2 detector.

SPHERE Statistics

Altitude: H= 200-900m a.s.l.

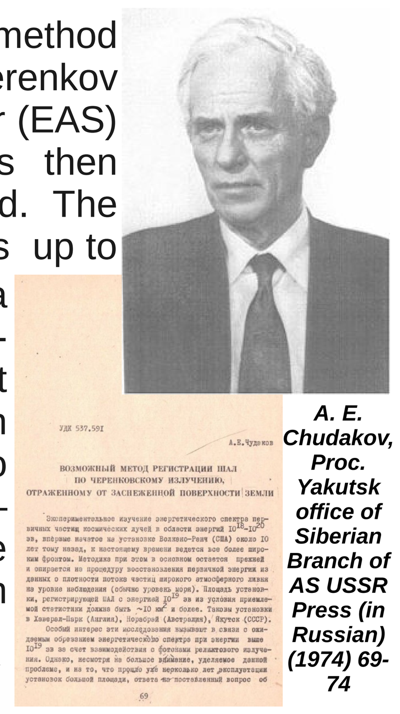
Exposition time ≈ 130 h

Triggers: 33000
EAS events: 1100

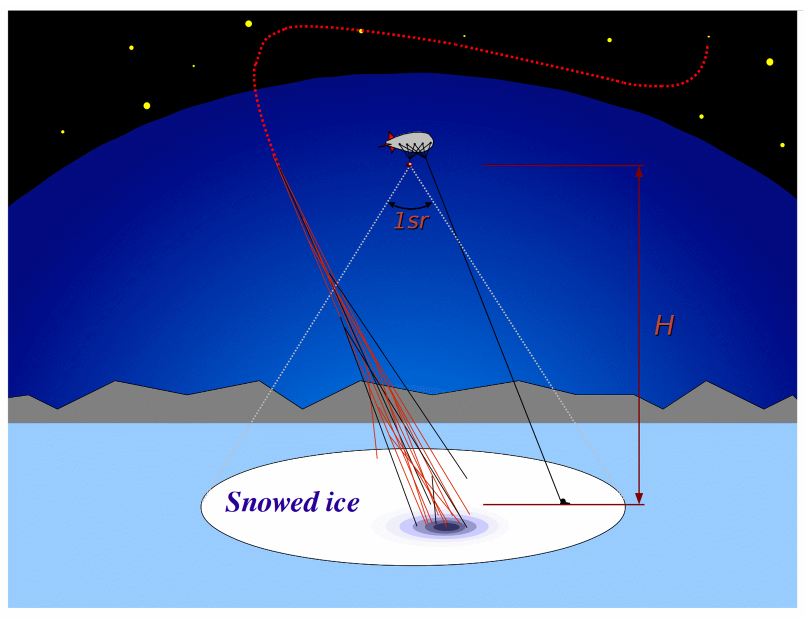
2008-2009: test flights
2010-2013: ~30 hours of exposition/season (February-March):

The reflected Cherenkov light method

The SPHERE experiment is based on the method proposed by A.E. Chudakov. Vavilov-Cherenkov radiation generated by the extensive air shower (EAS) is reflected from the snow surface and is then registered by a detector lifted above ground. The altitude ranges from several hundred meters up to several kilometers. The detector works like a camera and registers the images of Vavilov-Cherenkov radiation spots produced by EAS. At the altitudes up to 1 km the detector can register the EAS images corresponding to primary cosmic rays with energies about 5 – 500 PeV. At 3 km the energies up to 5 EeV are accessible. Measurements were carried out on Baikal Lake with tethered balloon.

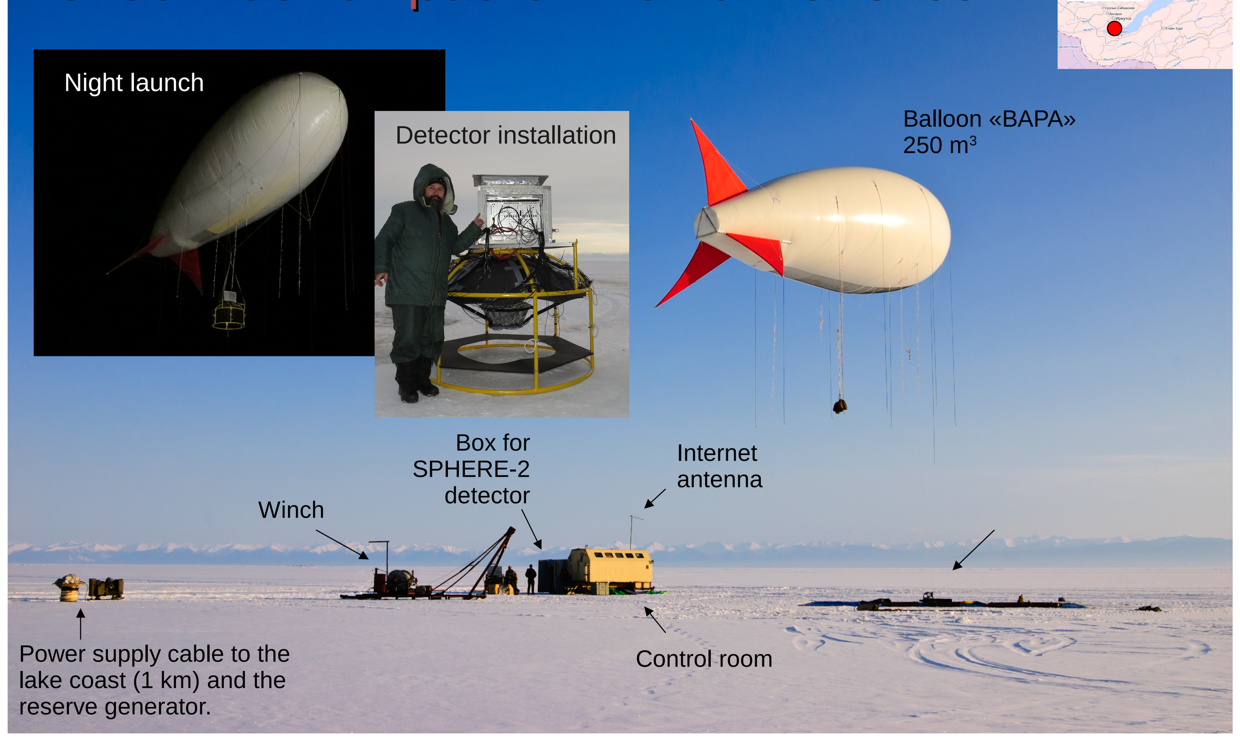


A. E. Chudakov, Proc. Yakutsk office of Siberian Branch of AS USSR Press (in Russian) (1974) 69-74



Scheme of the experiment with tied balloon on Baikal lake. The surveyed area ~$0.75H^2$

Balloon launch pad on Baikal Lake ice



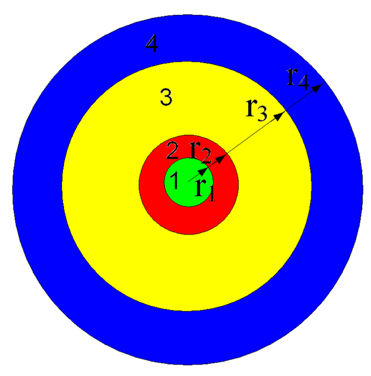
Trial launch of the balloon with an equivalent load to adjust attack angle.

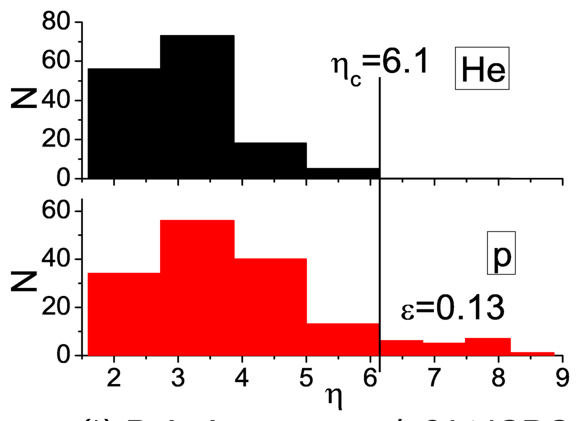
The principle of the primary composition study

- η = LDF steepness parameter sensitive to composition (*);
- also needed for the acceptance estimation at E<30 PeV;

$$\eta(r_1,r_2,r_3,r_4)=\frac{\int_{r_3}^{r_4}2\pi r\cdot\rho(r)dr}{\int_{r_1}^{r_2}2\pi r\cdot\rho(r)dr}$$

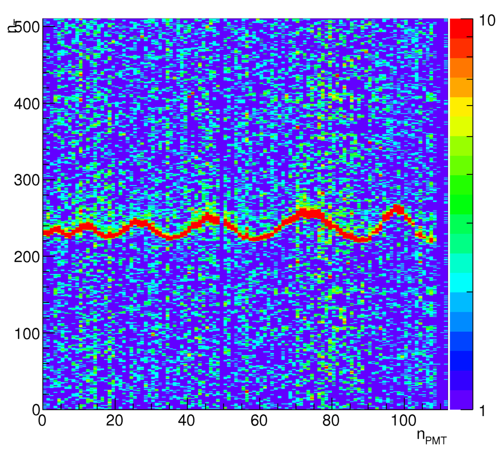
$$r_4 \ge r_3+\delta r,\quad r_3 \ge r_2,\quad r_2 \ge r_1+\delta r$$



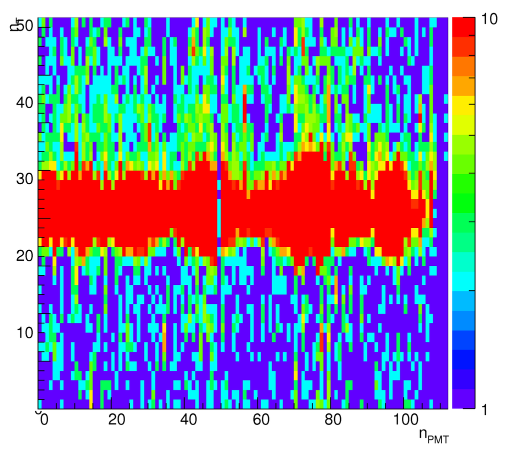


(*) R.A. Antonov et al, 31[st] ICRC (2009), HE.1.3, id. 434

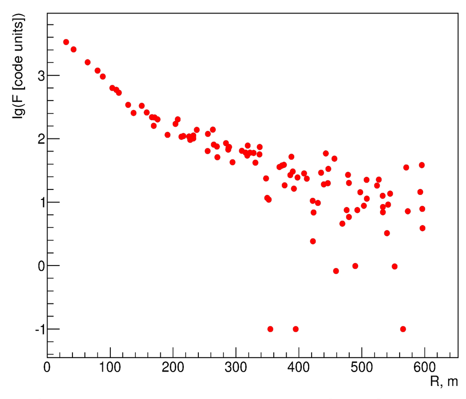
Low-level experimental data analysis



a) Raw experimental event (bins with > 10 code units set to red)



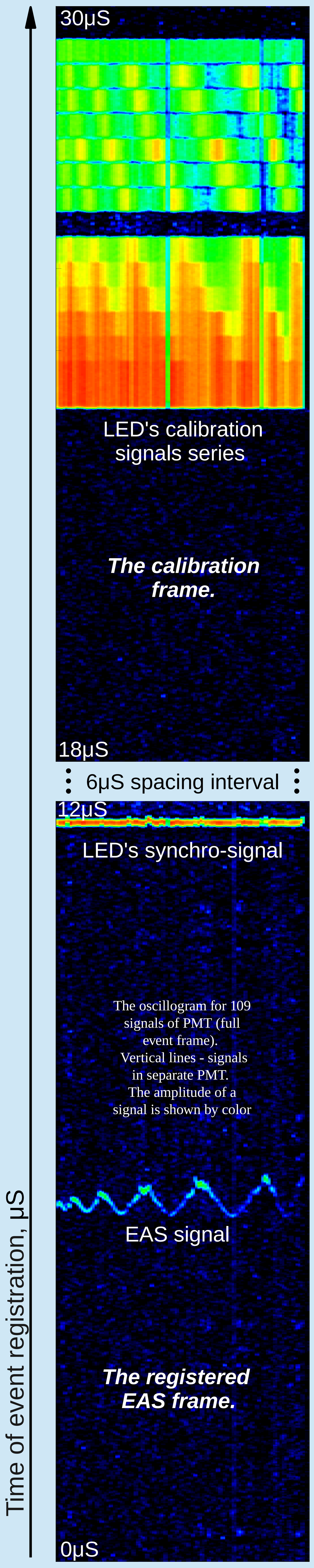
b) The same event after time pattern recognition procedure (adjustment)



c) Reconstructed lateral distribution function (LDF) of Cherenkov light of an observed shower

Possible to probe Lateral Distribution Function (LDF) near to the axis (<50 m) → event-by-event sensitivity to nuclear composition!

Data acquisition and calibration systems



The electronic part of the detector consists of a **data acquisition system (DAQ)**, **trigger system (TS)**, **calibration system (CS)** and operating computer.

The **CS** contains 7 UV light emitting diods (LED) that produce independently controlled light pulses onto the mosaic after each EAS event.

x	x							x						
x	x	x							x					
x	x	x	x							x				
x	x	x	x	x							x			
x	x	x	x	x	x							x		
x	x	x	x	x	x	x							x	
x	x	x	x	x	x	x								x

Sequence of flashes of light-emitting diodes. Duration of each cell - 375nS.

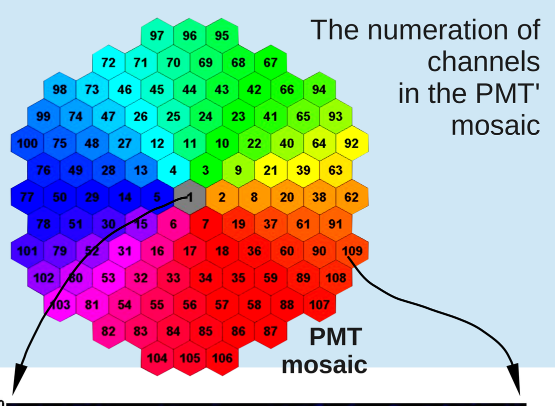
DAQ system contains 109 10-bit FADC channels with 12.5 ns steps.

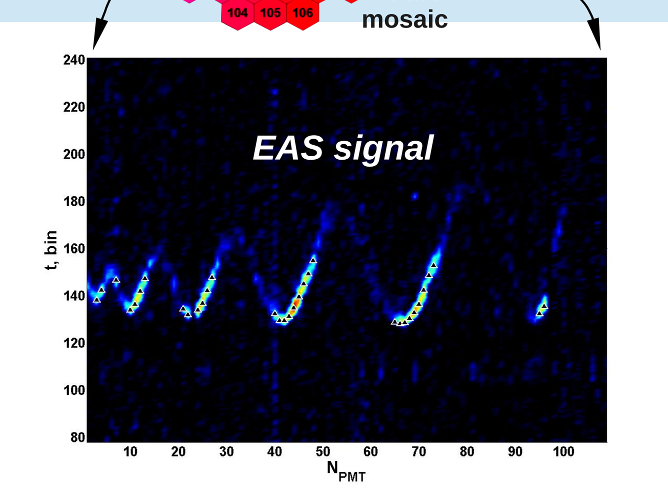
TS allows to detect a Vavilov-Cherenkov radiation spot image on the PMT mosaic (at least 3 adjacent PMTs have signal above threshold within 1 μs interval).

The picture represents the registered data event followed by calibration data.

Each pixel on the figure corresponds to one measurement of the signal in one PMT with step of 12.5 ns. Color indicates the measured intensity.

EAS signal forms a sine-like curve. One "period" of the curve represents signals from one "ring" of PMTs on the mosaic surface:
first "ring" is formed by PMTs N2 to N7, second "ring" – N8 to N19 and so on.

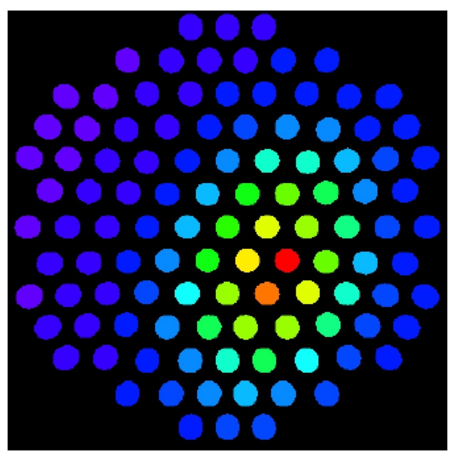




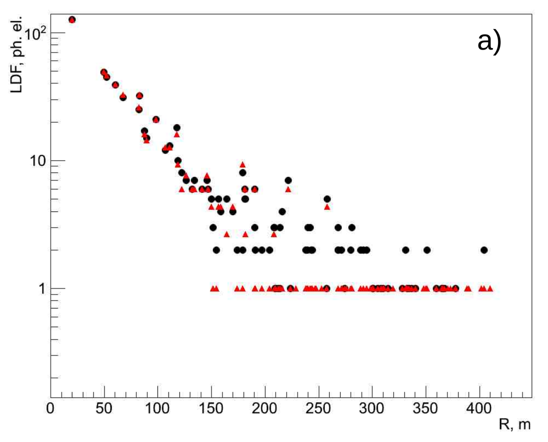
N_{pmt} - number of PMT in mosaic, t – time (1 bin = 12.5 nS)

Amplitude of the curve correlates with zenith angle, phase shift reflects the azimuthal angle.

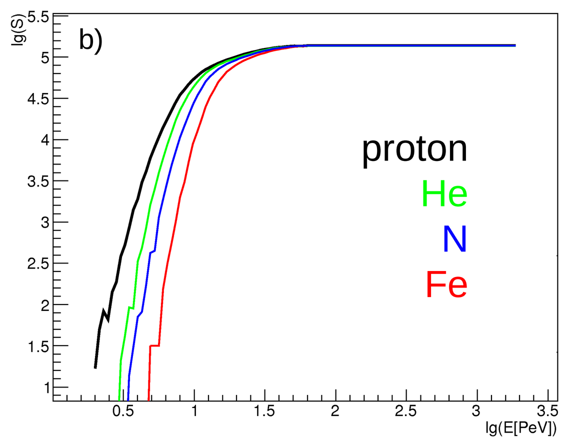
Simulations and energy distribution data - MC comparison



SPHERE-2 field-of-view geometry with model LDF superimposed



Reconstructed LDF for model shower: before (in ph.el., black) and after digitization (in code units, normalized to black points).



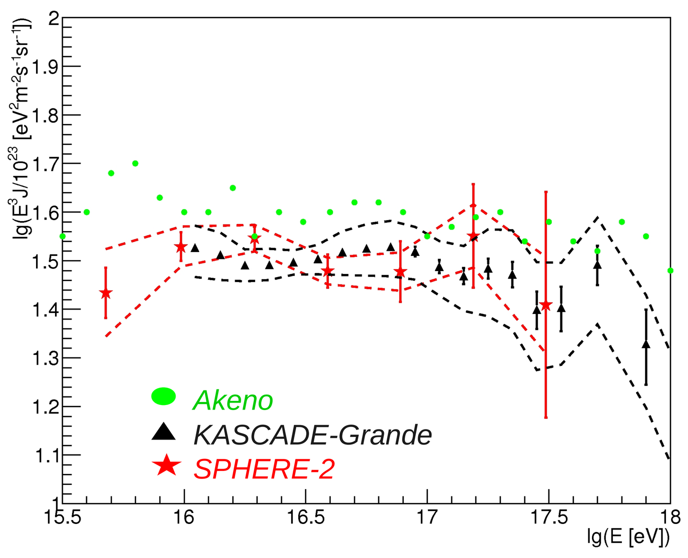
Simulated instrumental acceptance for 2013 data conditions for different nuclear types.

Full direct MC.
Hybrid CORSIKA/Geant4 MC approach.
CORSIKA/(QGSJET-I/II, GHEISHA) [1-4]:10, 30, 100 PeV showers (1.5 k).

~1M simulated events.

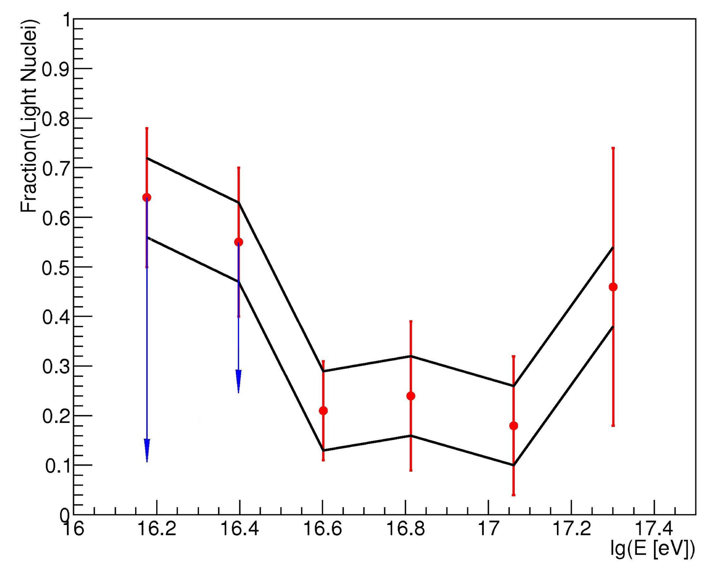
1. D. Heck et al. FZKA 6019 (1998)
2. N. Kalmykov et al, Nucl. Phys. Proc. Suppl. B, **52**, 17 (1997)
3. H.C. Fesefeldt, Technical Report No. PITHA 85-02 RWTH (1985)
4. S. Agostinelli et al., NIM A, **506**, 250 (2003)

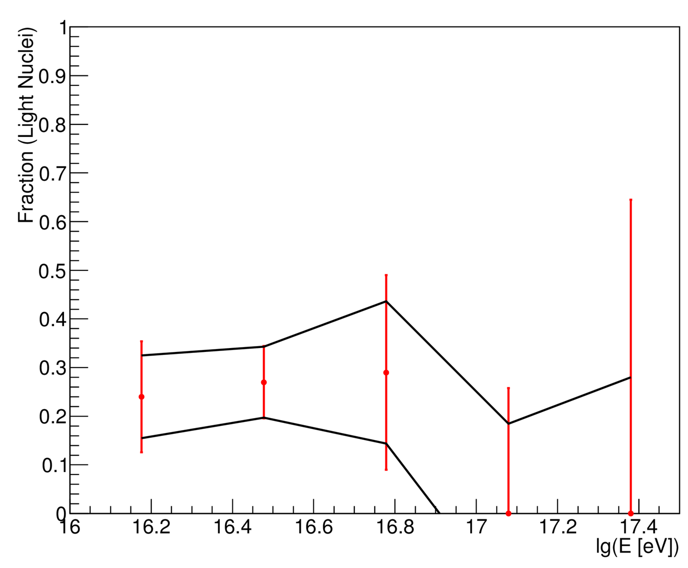
CR spectrum and composition estimations



Reconstructed all-nuclei spectrum

Akeno (M. Nagano et al., J. Phys. G, **18**, 423 (1992))
KASCADE-Grande (W.D. Apel et al., Aph, **36**, 183 (2012))
Other results include: ICETOP (M.G. Aartsen et al., Phys. Rev. D, 88, 042004 (2013))
Yakutsk (S.P. Knurenko et al., 33rd ICRC (2013))





Fraction of light nuclei reconstructed for the 2012 run (left) and the 2013 run (right).

Conclusions

I. The reflected Cherenkov light method is currently mature enough to be competitive with other EAS observation methods, given sufficient observation time.
II. For the first time, a detailed reconstruction of the all-particle CR spectrum at E= 3-300 PeV was performed using reflected Cherenkov light.
III. As well, this technique allows the CR nuclear composition study on event-by-event basis.
IV. Reflected Cherenkov light is a promising signal to study CR at E>100 PeV, either with tethered balloon at H= 2-3 km, or during high-altitude Antarctic flight.

Acknowledgments

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Prospects

I. Spectrum and composition study at E>50 PeV with tethered balloon at H= 2-3 km. SPHERE-type detector with 1000 channels will allow to independently measure the KASCADE-Grande light component "ankle" at 100 PeV with ~4 σ significance during ~400 h exposition (2-3 winter seasons with stable snow cover).
E_{THR}< 10 PeV, ~100 X enhanced statistics w.r.t. the current SPHERE-2 exposition.

II. Measurement of **Ultrahigh Energy Cosmic Rays (UHECR) all-nuclei spectrum** with SPHERE-type detector during long-duration high-altitude Antarctic flight (R.A. Antonov, Russian Cosmic Ray Conference (2014)).
E_{THR}= 100 PeV (Cherenkov light), 1 EeV (fluorescent light).