Mass composition estimation by relative content of muon in air showers with energy greater than 5 EeV

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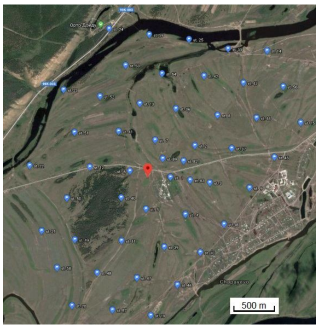
S.P. Knurenko, **I.S. Petrov,**
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, Yakutsk, Russia
Contact: igor.petrov@ikfia.ysn.ru.

Abstract. The paper presents analysis of showers with energy E = 5-50 EeV and zenith angle less than 60 degrees. A quantitative estimation was obtained for muons with a threshold greater than 1 GeV at different distances from the shower axis, and the fraction of muons at a distance of 600 m from the axis. An empirical relationship was found between the fraction of muons and the longitudinal development of the shower – with the depth of maximum development X_{max}. The dependence of the average depth of the maximum of the cascade curve X_{max} on the shower energy E was found. The fluctuations of X_{max} were estimated at fixed energies. Experimental data and calculations by the QGSJETII-04 model for a proton and an iron nucleus were used to estimate the mass composition of cosmic rays of highest energies.

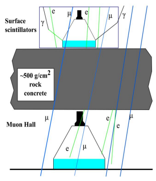
Yakutsk Array

Location: *61°42' N, 129°24' E;* Height: *110 m*
Area of the array: *~8 km²*; Energy range: *$10^{15} \leq E \leq 10^{20}$ eV*
58 stations with 120 scintillation detectors $\varepsilon_{thr} \geq 10$ MeV
Spacing: *500 m*
Yakutsk array measures: charged component; muon component; Cherenkov light. radio emission



Muon detectors

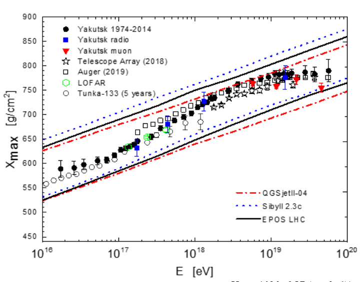
1 Muon detector with S = 190 m²
6 Muon detectors with S= 16-20 m²
3 Muon telescopes with S = 2m²



Air shower statistics registered at the Yakutsk array

Year	Obs. time	N	Data proc.	N_{muon}	N_{ch}	Cherenkov obs. time	Events E≥10EeV
09-10	6154	113138	87%	60618	9897	622	10
10-11	6455	137830	89%	56130	8611	508	15
11-12	6534	155351	91%	54559	9227	482	15
12-13	6515	149381	92%	89430	10219	592	17
13-14	6446	147589	91%	72110	7164	396	15
14-15	6365	140101	72%	82392	7838	429	15

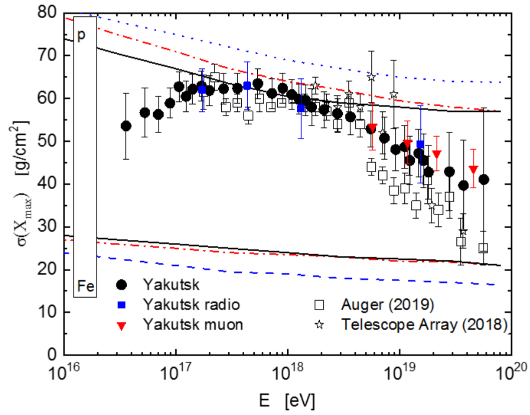
In the table as an example, a part of the data is shown – 2009-2015. It shows observation time, statistics of registered air showers, fraction of analyzed showers, number of showers with registered muons and Cherenkov light and the number of showers with E >10 EeV. N – total number of air showers, N_{muon} – air showers registered by muon detectors, N_{ch} – air showers registered by Cherenkov light detectors.



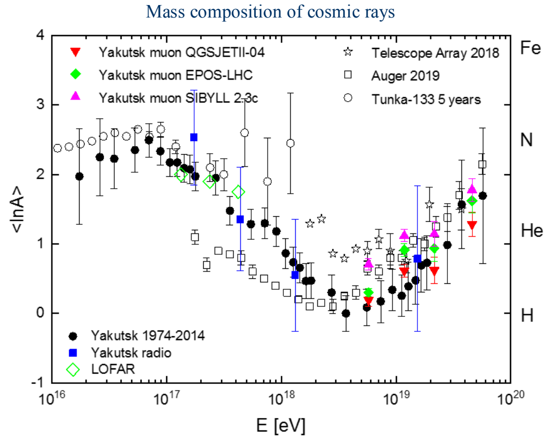
Dependence of X_{max} on E. The figure shows results of small and large air shower experiments. Lines show model simulations for proton and iron nucleus.
Red triangles show preliminary results on depth of maximum estimated by muon component of air showers. X_{max} estimated by formula:

$$X_{max} = (430 + 357\cdot(\sec\theta - 1))\cdot \exp\left(-\left(\frac{\rho_{\mu}}{\rho_{\mu+e}}\right)_{\theta} / (0.526 + 0.374(\sec\theta - 1))\right) + (454 - 75(\sec\theta - 1))$$

X_{max} fluctuation as a function of energy



Mass composition of cosmic rays



The figure shows <lnA> value estimated by muon composition for three different hadronic interaction models: QGSJETII-04, EPOS-LHC, and SIBYLL 2.3c. And its comparions with different experiments. <lnA> value is estimated for energies greater than 5 EeV. Mass composition can be estimated by interpolation formula, using X_{max} from the experiment and X_{max} from the simulation models:

$$< \ln A >= \frac{X_{max}^{exp} - X_{max}^{p}}{X_{max}^{Fe} - X_{max}^{p}} \cdot \ln A_{Fe}$$

Summary

We have obtained preliminary results on mass composition of cosmic rays by analyzing ratio of muon fraction $\rho_{\mu}/\rho_{\mu+e}$, which are shown by red and magenta triangles, and diamond. In the framework of three hadronic interaction models the result indicates increasing of atomic weight of primaries starting from energy 10 EeV.
Results obtained from all three air shower components shows that mass composition mostly consists of protons and lighter nuclei in the energy range 5-8 EeV. It is also shown by elongation rate of X_{max} fluctuation = 78±7 g·cm⁻². Such value is distinctive for air showers produced by mostly protons and helium nuclei. In the range 8-30 EeV, as we can see, mass composition slowly starts to change to heavier component – CNO and iron nuclei.

References:
[1]В.Л. Гинзбург. Современная астрофизика. М., 1970. 192 стр. [2]В.Л. Гинзбург // УФН. 1999, том 160, № 4, 419 – 441. [3] G.B. Gelmini, O.E. Kalashev, and D.V. Semikoz. // CERN-PH-TH / 2007 – 173. [4] P. Bhattacharjee, G. Sigl. Phys. Rev. **327** (2000) 109. [5] F. Halzen & D. Hooper. Rep. Prog. Phys. **65**, 2002, 1025. [6] J.-T. Li, E. Hodges-Kluck, Ye. Stein et al. arXiV:1901.10536 (ApJ in press). [7]K. Mannheim, R.J. Protheroe and J.P. Rachen. 2001. PRD, 63, 023003. [8] H. Kang, D. Ryu & T.W. Jones. 1996. ApJ, 456, 422. [9] J.P. Rachen & P.L. Biermann. 1993, A&A, 272, 161. [10] E. Waxman. 1995. PRL, 75, 386. [11] V.S. Berezinsky et al. // Phys. Lett. B **28** (1969) 423. [12] T. Stanev, P.L. Biermann, T.K. Gaisser. 1993. A&A, 274, 902. [13] J.K. Becker. Phys. Rep. **458**, 2008, 173. [14] M. Ahlers, L.A. Anchordoqui, M.C. Gonzalez-Garcia et al. Astropart. Phys. **34**, 2010, 106. [15] K. Kotera, D. Allard, A.V. Olinto. JCAP. **10**, 2010, 013. [16] G. Gelmini, O. Kalashev, D. Semikoz. // J. Theor. Phys. **106** (2008) 1061. [17] A. Aab, P. Abreu, M. Aglietta et al. //JCAP04(2017)038. [18] R.U. Abbasi, M. Abe, T. Abu-Zayyad et al. //Astropart. Phys. **80** (2016) 131-140 [19] S. Knurenko and I. Petrov. Advances in Space Research **64**, 2570-2577 (2019) [20] E.G. Berezhko, S.P. Knurenko, L.T. Ksenofontov. // Astroparticle Physics **36** (2012) pp. 31-36 [21] W. Hanlon, J. Bellido, J. Belz et al. Proc. 2016 Int. Conf. Ultra-High Energy Cosmic Rays (UHECR2016), JPS Conf. Proc. **19**, 011013 (2018) [22] K-H Kampert and M. Unger. Astroparticle Physics. **35**, No. 10, 2012, page 660-678. [23] S. Knurenko and I. Petrov. EPJ Web of Conference 99, 04003 (2015). [24] S. Thoudam, J.P. Rachen, A. van Vliet, A. Achterberg, S. Buitink, H. Falcke, J.R. Horandel. A&A, **595**, A33 (2016). [25] A. Aab, P. Abreu, M. Aglietta et al. Phys.Rev. D90 (2014) 122006. [26] R.U. Abbasi, M. Abe, T. Abu-Zayyad et al. Astropart. Phys. **64** (2015) 49-62 [27] S.P. Knurenko, A.A. Ivanov, I.Ye. Sleptsov. Nucl. Phys. B (Pros. Suppl.) **196**, p. 391-394 (2009) [28] А.А. Иванов. Письма в ЖЭТФ, т. **87**, вып 4, 2008, стр. 215-219 [29] P. Abreu, M. Aglietta, E.J. Ahn et al. Astrophys. J. Suppl. **203**, 34 (2012).[30] С.П. Кнуренко, И.С. Петров. Письма в ЖЭТФ, т. **107**, вып. 11, с. 709-716 (2018). [31] S. Ostapchenko. Phys. Rev. D **83**, 014018 (2011). [32]А.А. Атрашкевич, Н.Н. Калмыков, Г. Б. Христиансен, Письма в ЖЭТФ, **33**, 236 (1981) [33] V.S. Berezinsky, S.I. Grigorieva, B.I. Hnatyk, APh **21**, 617 (2004) [34] В.П. Артамонов, Б.Н. Афанасьев, А.В. Глушков и др. Изв. РАН, сер. физ., т.**58**, №12, 92-97 (1994) [35]Y. Egorov, Z. Petrov, S. Knurenko. Proc. of Science **301**, 462 (2018) [36] S.P. Knurenko, Z.E. Petrov, I.S. Petrov. NIM A 866, 230–241 (2017) [37] С.П. Кнуренко, В.А. Колосов, З.Е. Петров и др. Наука и Образование, № 4, с. 46–50 (1998).