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Mass Composition of Cosmic Rays in the 0.8–2 EeV Energy Range: Muon Measurements from the Upgraded Yakutsk EAS Array

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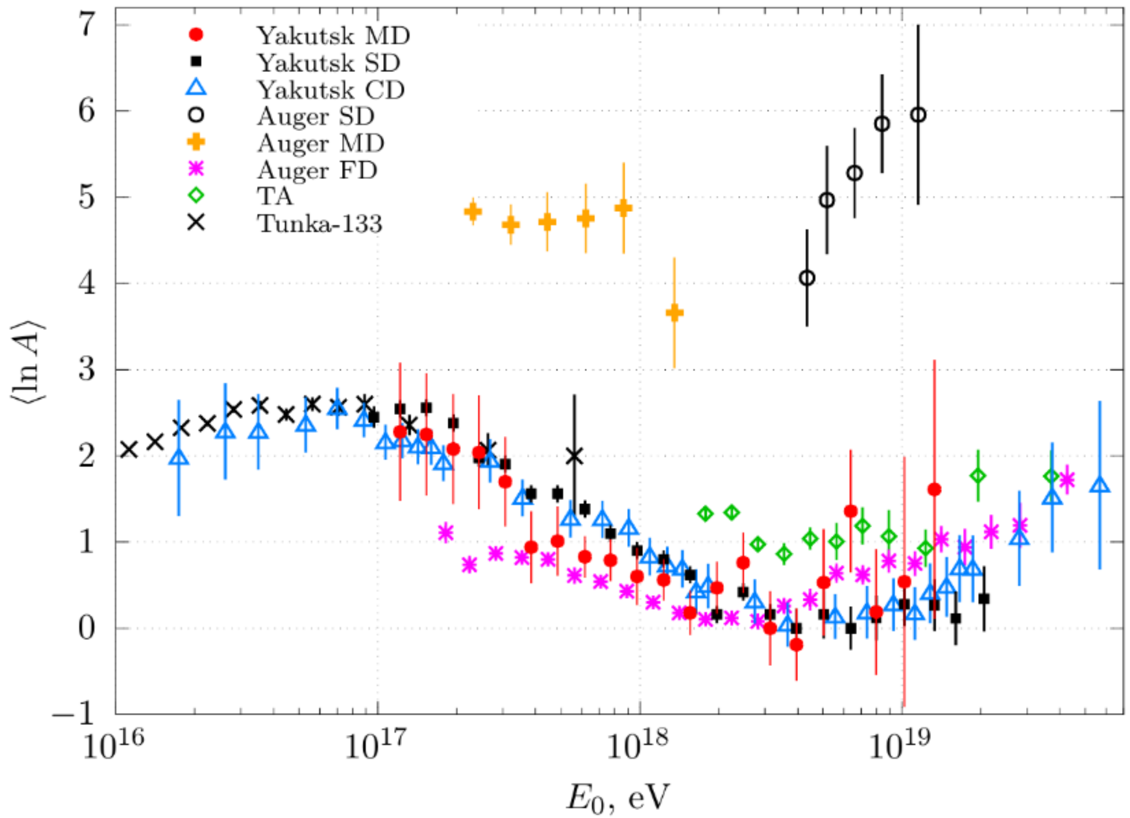
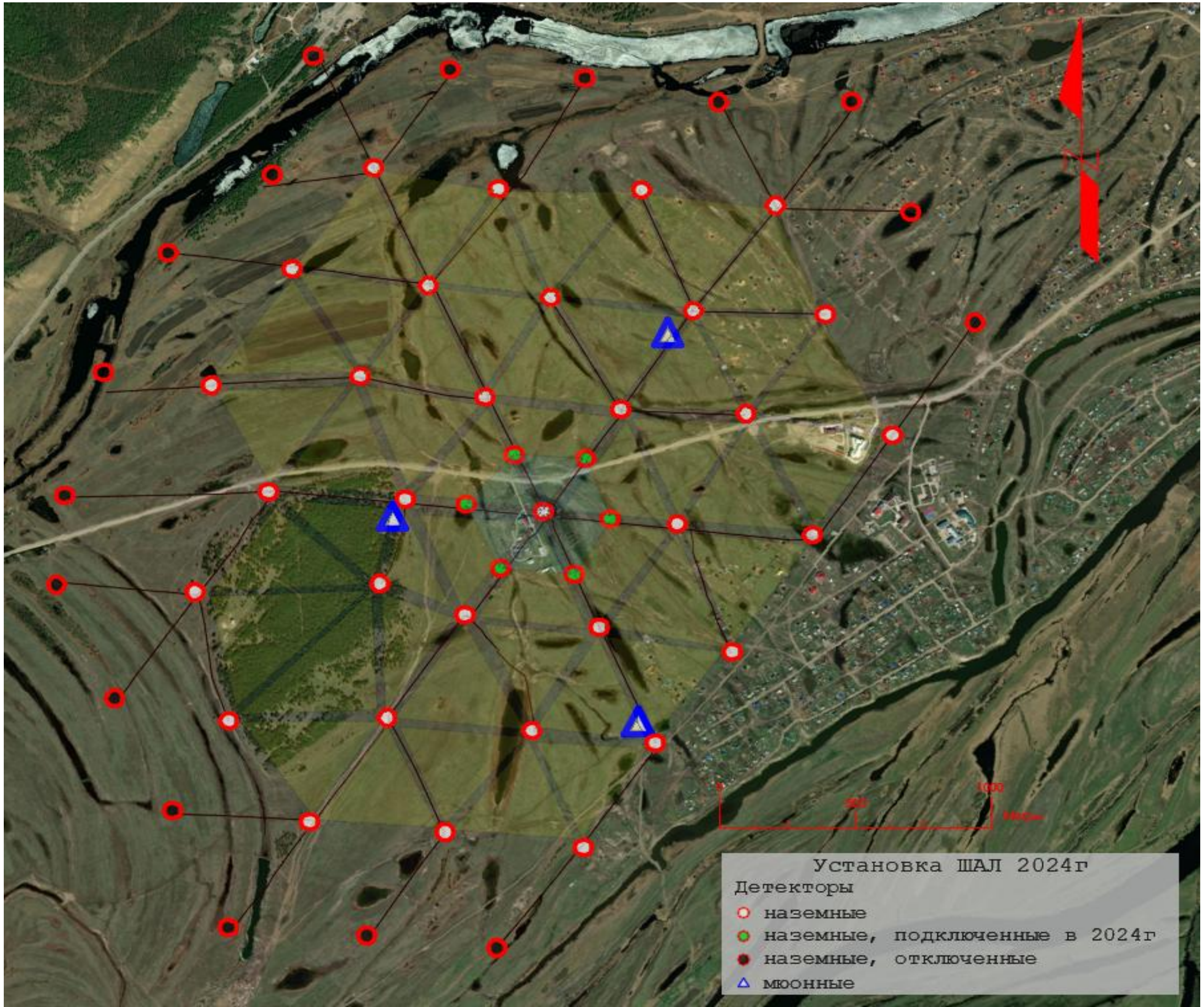
The composition of cosmic rays (CR) of ultra-high energies ($E \geq 10^{17}$ eV) can only be studied using extensive air showers (EAS). The results of recent experiments demonstrate a contradictory picture of the CR composition, which follows from the analysis of the average characteristics of the EAS.



Estimates of the average mass composition of CR.

Yakutsk EAS Array. Basic parameters



Total area of detector placement
1973-1991 – 17.3 km^2;
1991-2010 – 10.4 km^2;
2010-2018 – 8.2 km^2;
2021 to the present day – 4.8 км^2

Main trigger energy threshold - 5×10^{16} eV

Dynamic range of particle density measurement – 10^4

Accuracy of measuring the arrival time of shower particles - 10 ns

yakutsk-array.ru

The arrival direction of the EAS is determined by the response delays of ground-based detectors.

To locate the axis of the shower, a lateral distribution function (LDF) is used in the form:

$$S(\theta, r) = S_{600}^{exp}(\theta)\left(\frac{600}{r}\right)\left(\frac{600 + r_M}{r + r_M}\right)^{b_s(\theta)-1}$$

$r_M \approx (7.5 \times 10^4/P) \times (T/273)$ - Moliere radius

$$b_s(\theta) = 1.38 + 2.16 \times \cos\theta + 0.15 \times \log_{10}(S_{600}^{exp}(\theta))$$

The arrival direction, the axis coordinates of the shower and $S_{600}^{exp}(\theta)$ are determined by minimizing of corresponding χ^2

$$E = E_1 \times S_{600}(0^\circ)^B \ \ [\mathrm{eV}] \ ,$$

$$S_{600}(0^\circ) = S_{600}^{exp}(\theta) \times \exp((\sec\theta - 1) \times 1020/\lambda) \ \ [\mathrm{m}^{-2}] \ ,$$

$$\lambda = (450 \pm 44) + (32 \pm 15) \times \log_{10}(S_{600}^{exp}(\theta)) \ \ [\mathrm{g/cm}^2] \ ,$$

where $E_1 = (3.76 \pm 0.3) \times 10^{17}$ eV and $B = 1.02 \pm 0.02$.

This is close to the model of ultra-high energy hadron interactions QGSjet-II.04

The method of muon correlation

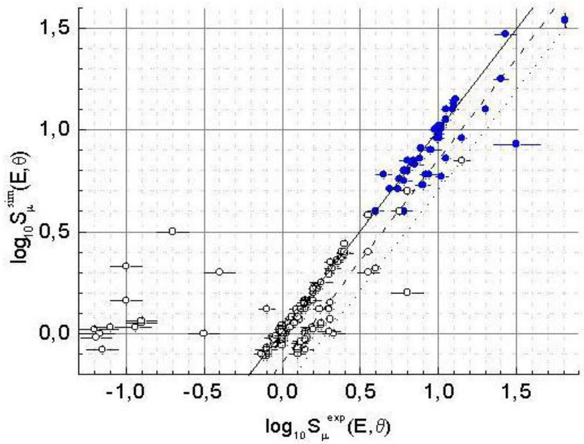
In [*Glushkov et al. JETP Letters, **120**, 396 (2024)*] the method for determining the type of primary particle in individual events is proposed. This method uses the correlation parameter:

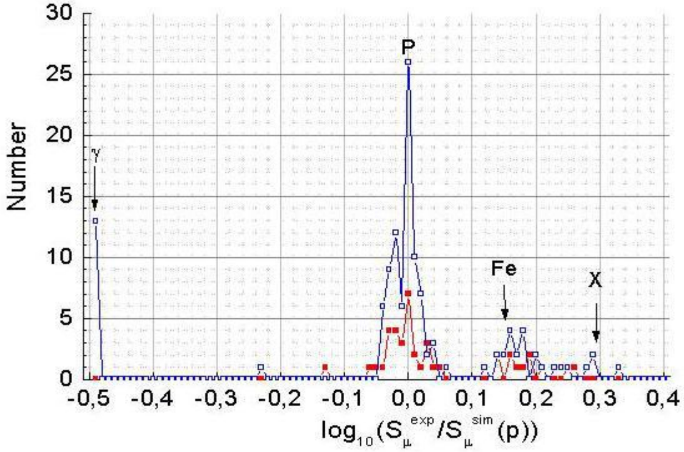
$$\eta = \frac{S_\mu^{exp}(E,\theta,r)}{S_\mu^{sim}(p,E,\theta,r)}$$

$S_\mu^{exp}(E,\theta,r)$ the response density of the muon component in the EAS measured in the experiment,

$S_\mu^{sim}(p,E,\theta,r)$ the same but obtained as a result of simulating an extensive air shower using one or another model of hadron interactions.

The method was tested on a sample of 127 EAS with the energy $E > 1.25\times10^{19}$ eV.





Results. Probable composition of CRs

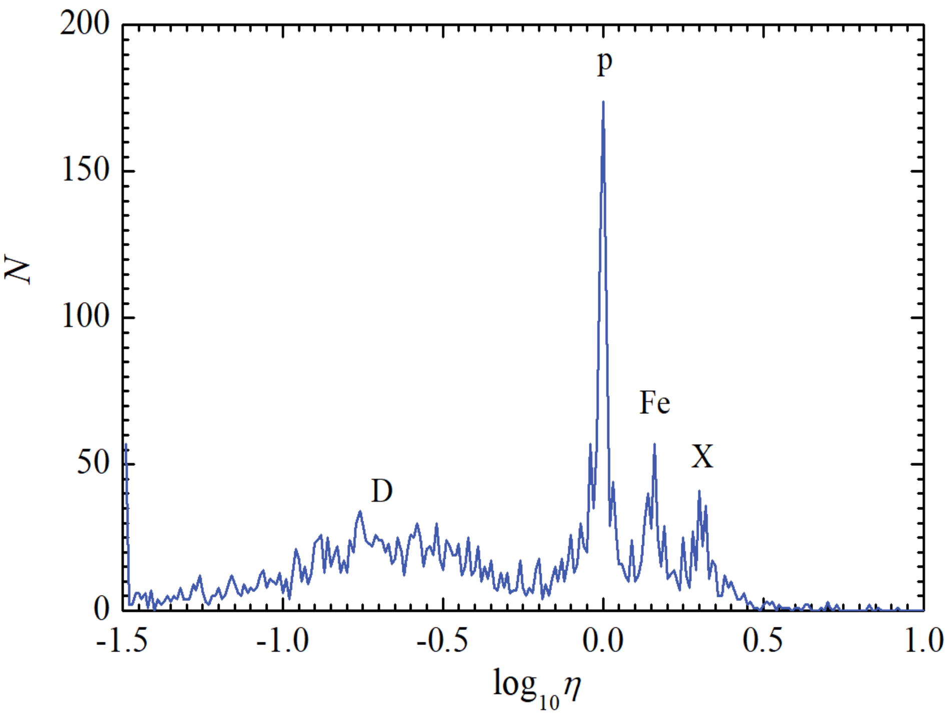


Figure. The ratios of the muon response densities η at the distance from the axis r = 600 m, obtained experimentally and and simulated by the model QGSJET-II.04 for the primary protons.

The analysis included EASs whose axes were located in the central ring of the array with a radius of 850 m. At these distances, the MD densities have the maximum shower statistics and are found with the best accuracy.

The figure shows the correlations of pairs of muon densities in a sample of 2484 EAS with energies $E = (8–20)\times10^{17}$ eV and angles $\theta \leq 60°$.

$$\langle\Delta_{p-\mathrm{Fe}}\rangle = \log_{10}\left[\frac{S_\mu^{\mathrm{sim}}(Fe,E,\theta,600)}{S_\mu^{\mathrm{sim}}(p,E,\theta,600)}\right] \approx 0.16,$$

$$\langle\Delta_{p-\mathrm{X}}\rangle = 2.2\times\langle\Delta_{p-\mathrm{Fe}}\rangle \approx 0.35.$$

Table. The number of EAS in energy intervals.

$\langle\log_{10}E\rangle$	p	w_p	Fe	w_{Fe}	X	w_X	D	w_D	Total
17.95	317	0.33	53	0.06	67	0.07	520	0.54	957
18.05	213	0.32	45	0.07	55	0.08	361	0.53	674
18.15	182	0.33	40	0.07	40	0.07	287	0.52	549
18.25	108	0.36	23	0.08	28	0.09	145	0.47	304
Total	820	0.33	161	0.07	190	0.08	1313	0.52	2484

Seasonal variations in composition of CRs

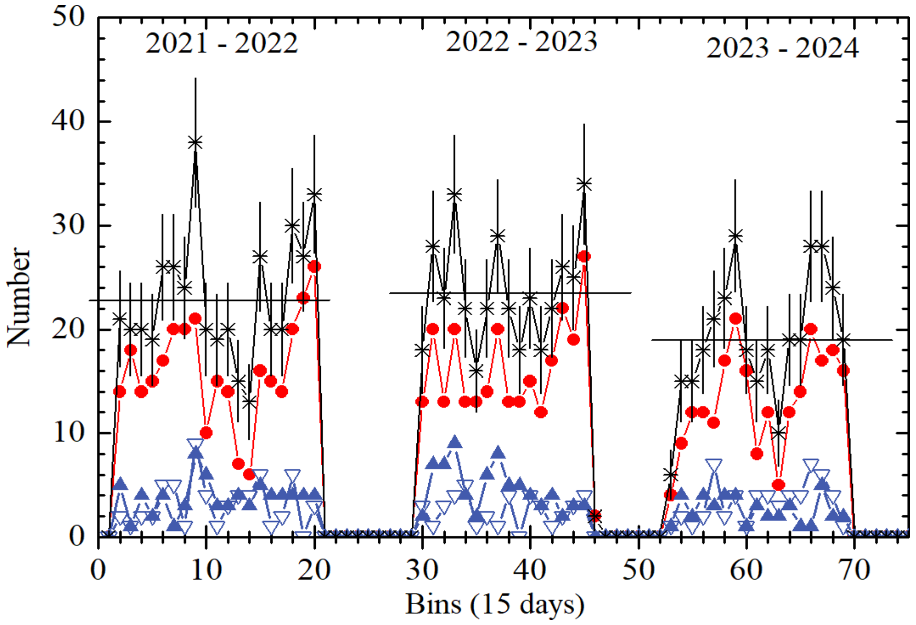


Fig. Number of events with the energy $E = 10^{17.9-18.3}$ eV, from the peaks "p" (●), "Fe" (▽) and "X" (▲). Stars and horizontal lines are sums of this events and their average values

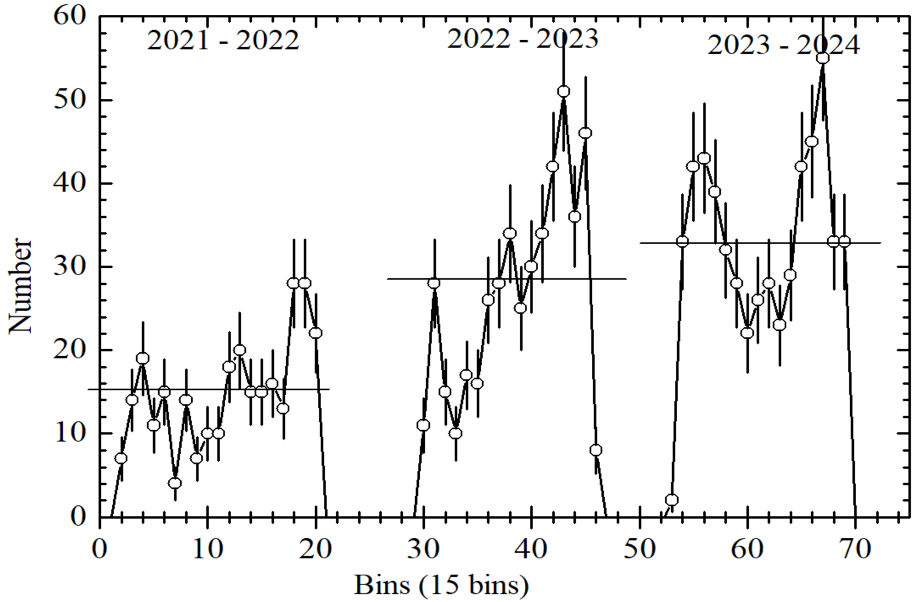


Fig. Number of events with the energy $E = 10^{17.9-18.3}$ eV, from the peak "D". Horizontal lines are their seasonal average values

All three components of CRs do not show significant variation in the years of registration.

There are significant differences in the total number of events in different years of observation, with fluctuations in intensity that cannot be explained by seasonal changes of the atmosphere in Yakutsk.

Zenith-angular characteristics

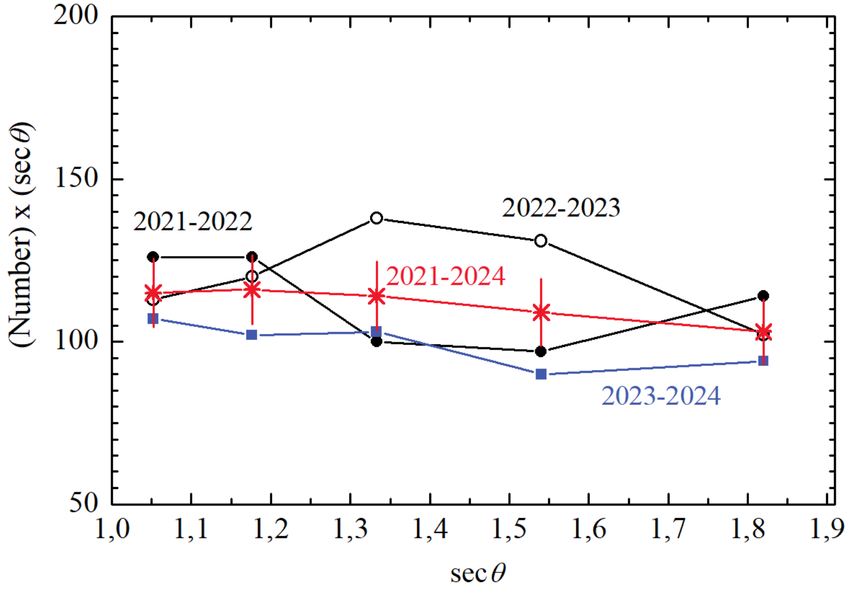


Figure. Number of events from the peaks “p”, “Fe”, “X” in five intervals of zenith angles in different seasons of observations.

Within the statistics, these data have no peculiarities and do not contradict each other.

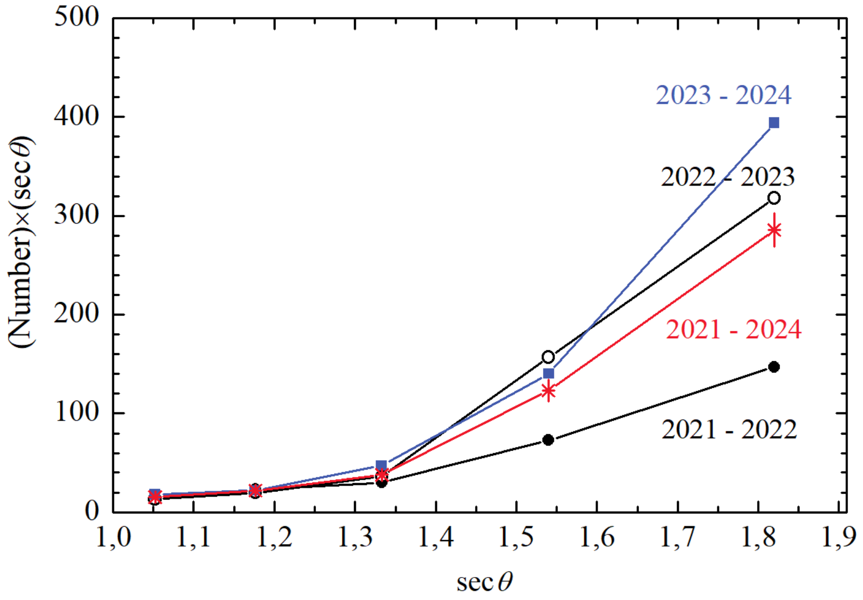


Figure. Zenith-angular dependences of the intensity of the “D” component in different seasons of observations.

For angles with $\cos\theta \geq 0.75$ the values of three independent groups of events are close to each other and have a weak growth. In more inclined showers, a steady increase in its intensity is observed, with a significant difference between them in the years of observation.

The number of triggered SD in the showers

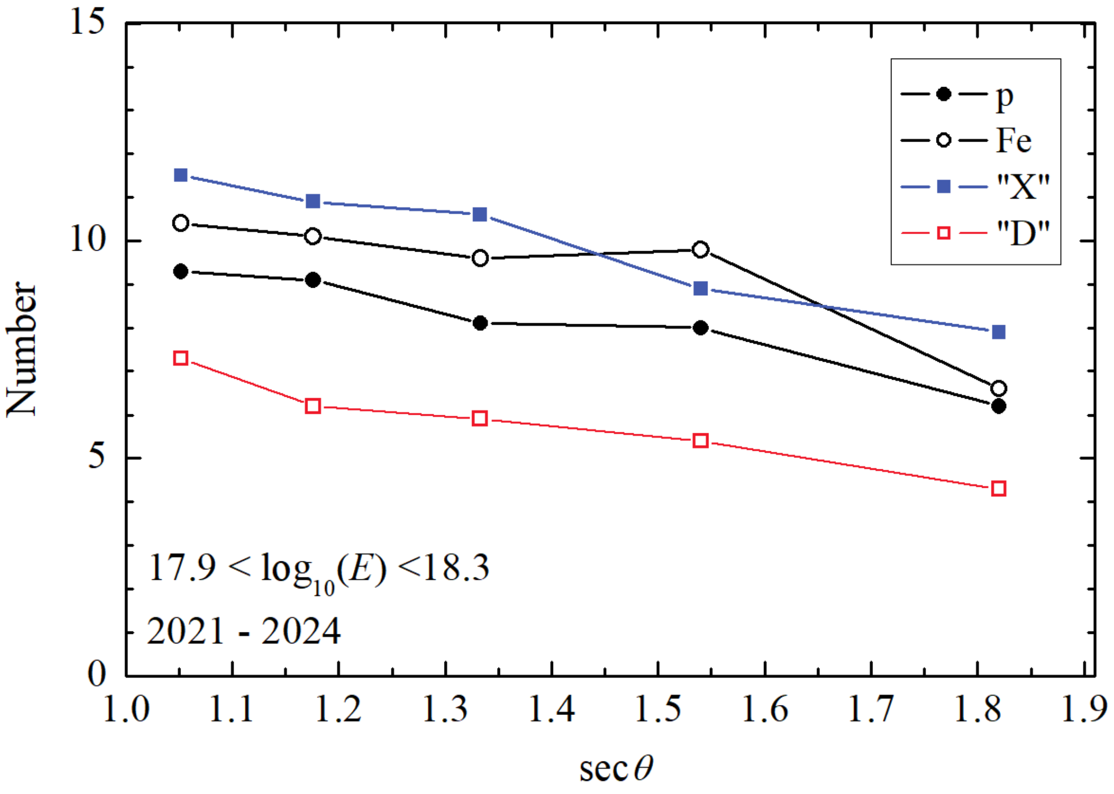


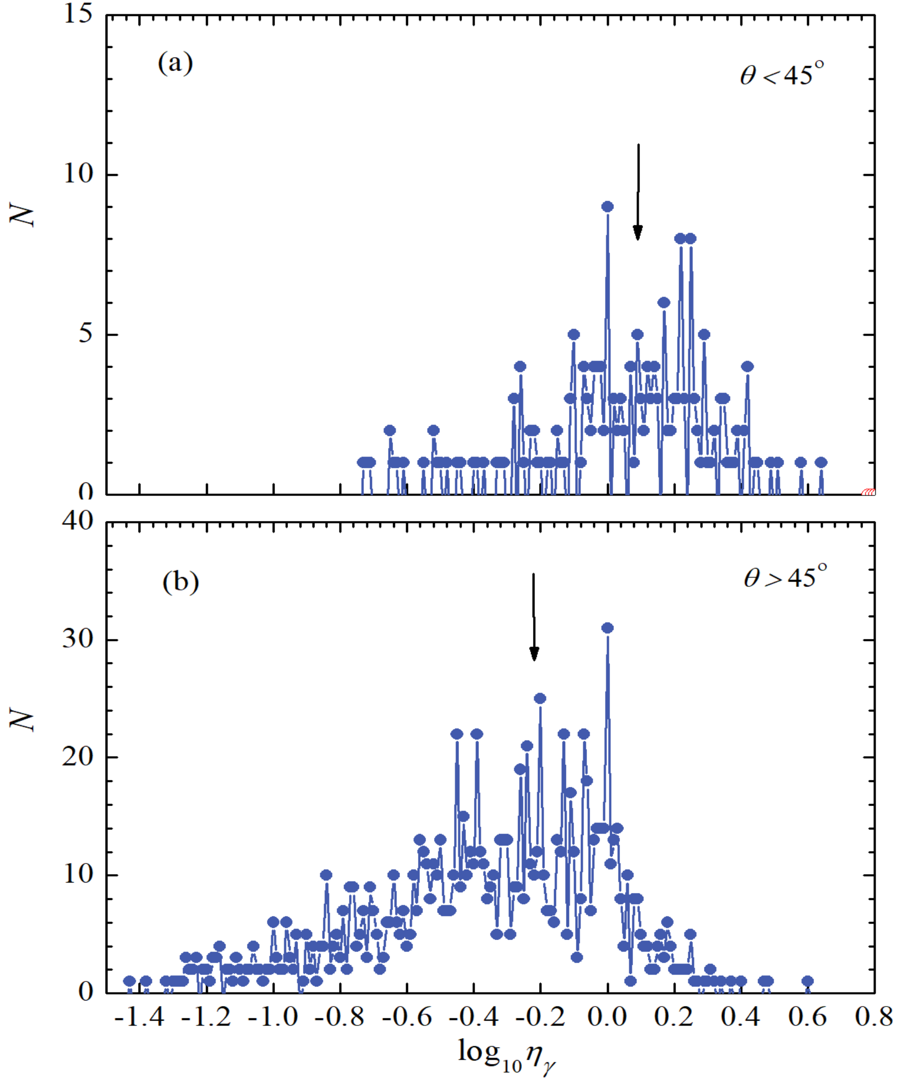
Figure. Average number of triggered stations in individual EAS with $E = 10^{17.9\text{–}18.3}$ eV and $\theta \leq 60°$ for the 2021–2024 observation period.

In all groups, with an increase in the zenith angle, a similar decrease in the number of SDs involved in the registration of EAS is observed.

Probably the “X” component of EASs is caused by some new primary particles heavier than iron nuclei. Therefore, such events have the largest number of triggered SDs.

It can be assumed that the maximum of the EAS cascade curve from the “D” component of CR is much deeper in the atmosphere than from primary protons. This leads to a decrease in the effective area of selection of such events and, accordingly, to the smallest number of triggered SD.

Correlation parameter for primary gamma-rays



$$\eta_\gamma = \frac{S_\mu^{\exp}(E,\theta,600)}{S_\mu^{\mathrm{sim}}(\gamma,E,\theta,600)},$$

Fugure *a* and *b* represent 202 and 1111 “D” events with the mean value $\log_{10}<\eta_\gamma> \approx 0.08$ and –0.22, respectively.

The distribution maximum in Figure *a* is close to “0”, which does not contradict the hypothesis that it is caused by primary gamma-ray.

The distribution in Figure *b* is wider, shifted from “0” to the smaller side. The reason for such behavior of this “D” component is not yet clear.

Example of a primary gamma-ray

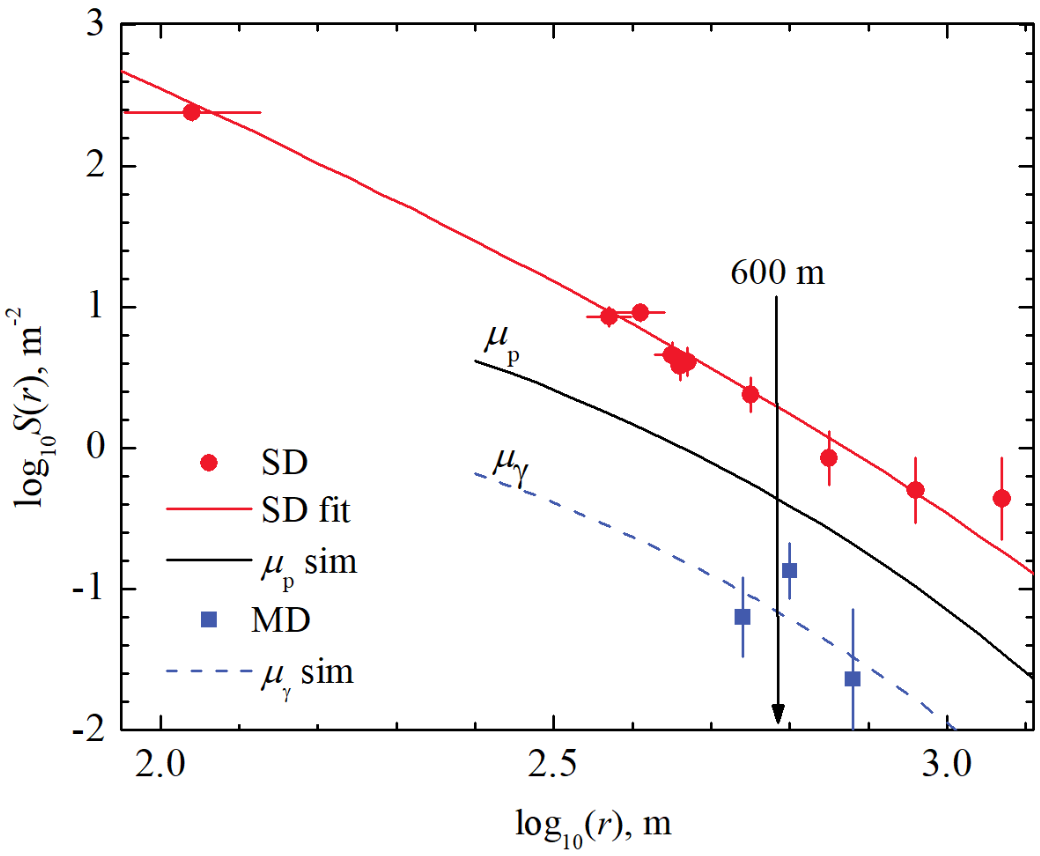


Figure. The LDF of shower №221020 (28.10.2023) with $E = 1.1 \times 10^{18}$ eV, $\theta = 29.5°$ (the axis is located 518 m from the center of the array).

The results obtained here give certain grounds to believe that the "D" component can be considered as a candidate for primary gamma-ray of ultra-high energies (if not entirely, then at least partially). In any case, the event from 28.10.2023 in the Figure is consistent with such an assumption.

Composition of CRs with $\theta \leq 45°$

Table. The number of EASs in the energy intervals with the zenith angle $\theta \leq 45°$, related to specific peaks.

$\log_{10}E$	p	w_p	Fe	w_{Fe}	X	w_X	D	w_D	Total
17.95	244	0.58	41	0.10	48	0.12	84	0.20	417
18.05	130	0.50	36	0.14	41	0.16	53	0.20	260
18.15	113	0.53	27	0.13	32	0.15	41	0.19	213
18.25	62	0.51	15	0.12	20	0.16	24	0.20	122
Total	549	0.54	119	0.12	141	0.14	202	0.20	1011

$$\langle \eta(p) \rangle = 0.99^{+0.08}_{-0.10},$$

$$\langle \eta(\mathrm{Fe}) \rangle = 1.44^{+0.11}_{-0.13},$$

$$\langle \eta(\mathrm{X}) \rangle = 2.31^{+0.16}_{-0.17},$$

$$\langle \eta(\mathrm{D}) \rangle = 0.26^{+0.14}_{-0.10},$$

Let's find the average value:

$$\langle \eta \rangle = w_p \langle \eta(p) \rangle + w_{\mathrm{Fe}} \langle \eta(\mathrm{Fe}) \rangle + w_{\mathrm{X}} \langle \eta(\mathrm{X}) \rangle + w_{\mathrm{D}} \langle \eta(\mathrm{D}) \rangle = 1.08 \pm 0.03.$$

From this value one could erroneously conclude that CRs consist mainly of protons. We have repeatedly come to this conclusion previously, where estimates of the mass composition of primary particles were made from an analysis of various average characteristics of EAS.

Summary

The results of a study on the mass composition of CRs in individual air shower events using the muon correlation method for 2484 EASs with energies 0.8–2 EeV and zenith angles $\theta \leq 60°$ are presented.

The analysis utilizes EASs recorded over three observation seasons (2021–2024) by the Yakutsk EAS array following its major upgrade in 2019–2021.

Our findings confirm the previously reported detection of four distinct groups of primary particles with different origins:

1. The first (p) is formed by primary protons.
2. The second peak (Fe) can be conditionally assigned to iron nuclei.
3. The third (X) contains events with an abnormally high muon content. Its nature has yet to be unraveled.
4. The fourth peak (D) is formed by EASs with an abnormally low muon content. These events do not exclude the possibility that they were generated by primary gamma-rays.