Peculiar high energy cosmic ray stratospheric event reveals a heavy primary origin particle above the knee region of the cosmic ray spectrum

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We wish to put forward an explanation for a peculiar cosmic ray event with energy $\Sigma E_\gamma \geq 2 \times 10^{15}$ eV detected in 1975 by the balloon borne emulsion chamber experiment performed in the stratosphere, at the altitude ≥ 30 km above sea level. For almost 30 years the event has been described as unusual, invoking new exotic mechanisms or models. In our opinion there is no need for an extraordinary explanation. Contrary to the widespread belief, the event gives us an example of ''unrecognized standard physics''. At the same time this event revealed a variety of features which are of considerable interest for cosmic rays, nuclear physics, and astrophysics. Here we show that the observed family is most likely to be a result of a heavy nucleus interaction with an air nucleus. In this case a primary particle would originally have been in the energy region above ''the knee'' of the cosmic ray spectrum.

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I. INTRODUCTION

The present work has been motivated by our recent examination[1,2] of the exotic families from the mountain chamber experiments, which indicated that most of the ''unusual phenomena'' reported previously can be explained within standard hadron interaction physics.

Experimental observations of cosmic ray events in the stratosphere, such as [3–5], tell us that there exists a nuclear interaction with high mutliplicity, as we approach the energy region, say around 1000 TeV [6]. Our next step was to evaluate the heavy primary hypothesis. In present study we analyze one of the most spectacular events, a cosmic ray family detected in 1975 by Lebedev Physical Institue (LPI) cosmic ray experiment [7]. The LPI experiment has been carried out by exposing emulsion chambers on board the balloons on the Trans-Siberian route. The numerous details and information on the event have been extensively and very informatively presented in many papers [7–15], which described the event in conspicuous details. Historically, the high energy leading shower and corresponding nuclear interaction has been named ''Lyuda'', and recently the whole event was named ''Strana''[14,15]. For simplicity, interchangeably, hereafter we will call this event as SL1975 (meaning by that the stratospheric superfamily Strana with the Lyuda event detected in 1975).

From the beginning of the analysis [7–15] it was pointed out that due to the high altitude of observation, there is no significant cascade degradation and secondary interactions in the air, so this event shows the result of almost clean interaction. This event has been interpreted to support the ideas on new mechanisms of high energy interaction and particle production with extremely high multiplicity and large transverse momenta of secondaries [13], the coherent hadron radiation analogous to Cerenkov radiation in electromagnetic fields [16], a single diffractive dissociation [17], but all explanations were based on the assumption of a primary proton [13]. Here we are going to show, that outstanding features of SL1975 are most likely turn into evidence for a heavy nucleus, and the event can be consistently explained within standard physics.

II. EMULSION CHAMBER

The emulsion chamber experiment on balloons was started for the purpose of observing high energy local nuclear interactions.

The chamber had dimensions of (400×500) mm^2 in cross section. The chamber was designed for detailed observation of high energy nuclear events originated in the chamber itself. The details on the design and technical parameters can be found in [7–15]. The chamber consists of the following three sections: target block (162 mm), spacer (53 mm), and the calorimeter (48 mm). The target block is composed of 90 nuclear emulsion plates (~ 300 μm thick), interleaved with plastic plates of 1.5 mm thickness. The spacer is for divergence of secondary particles produced in nuclear interaction. The spacer is composed of 10 sheets of 5 mm thick plastic, interleaved with nuclear emulsions plates. The thickness of the target and the spacer corresponds to 0.5 cascade units, or 0.3 proton nuclear mean free path (MFP) for vertical incidence. The total thickness of the calorimeter was 9 c.u., or 0.26 MFP. The chamber efficiency has been estimated[13] as ϵ ~0.4. The calorimeter is a sandwich of 9 layers of lead plates (5 mm), 9 nuclear emulsion plates, and 18 X-ray films. The nuclear emulsion plates are electron sensitive and are scanned under a microscope. The shower energy is estimated by measuring its longitudinal development in the chamber. When an electron or a gamma ray (we call them as gamma ray hereafter) passes through the

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calorimeter, it initiates an electron shower through the electromagnetic cascade processes. The shower creates a dark spot on the X-ray films which can be recognized by unaided-eye scanning. The absolute error in the energy measurement was considered to be $\sim$30%.

III. DESCRIPTION OF THE EVENT

Here we remind briefly the basic features on the SL1975 event as it follows from the previous studies [7–15].

The event (see Fig. 1) with $\Sigma E_\gamma \geq 2 \times 10^{15}$ eV was detected as a large group of dark spots in X-ray films of the chamber. The incident zenith angle was 30 degrees, and an atmospheric depth was determined as [7] $\sim 18^{+6}_{-2}$ g/cm^2. The duration of the flight was $\sim$160 hours. Multiplicity of the event ($\sim$ 107 showers, 76 were identified as gamma rays), the lateral geometrical spread $\sim$300 mm, and the gamma / hadron ratio of showers showed that the event was most likely the result of a nuclear interaction in the air.

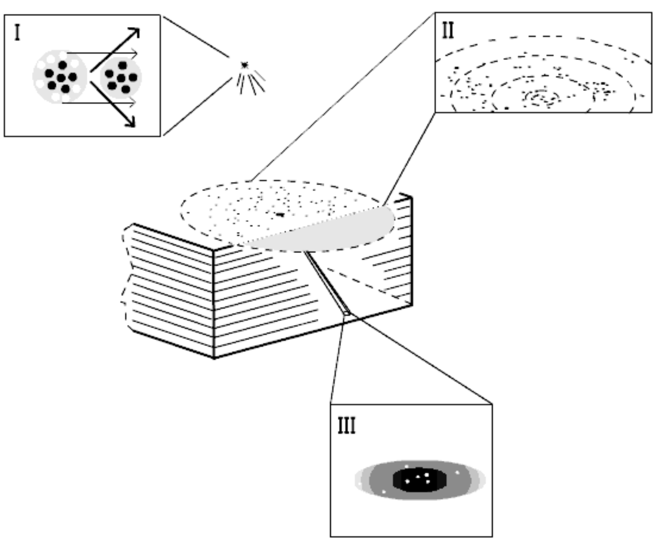

FIG. 1. A schematic view of the topology of the event. Secondary particles produced in the interaction of a heavy nucleus in the atmosphere (a star with rays) are detected as a family of gamma ray showers (a circle with dots surrounded by the dash line) in the chamber (solid line box). The family was detected near the edge of the calorimeter, so showers at the periphery (an area of gray color) were not detected. The inset I shows an incoming particle interacting with an air nucleus. Participant nucleons are presented by black circles and thick arrows, and spectator nucleons − by white circles and thin arrows. The inset II shows, that if a set of circles (tens of mm in radii) have been drawn over the target map, then one could search for specific configurations in the distribution of showers (dots). For instance, some previous studies [8] recognized ringlike structures. The inset III is representing an image of a dark diffused area (a halo) of a few mm radius observed in x-ray emulsion film in the center of the event. The halo is formed by superposition of showers. It was possible to identify some showers (white dots) within the halo area. Images are not to scale and for illustration purposes only.

The unique nuclear interaction of a leading particle was found in the target [7,12]. This leading particle was described as a cluster of hundreds of tracks found through the microscopic observation on nuclear emulsion plates. As has been noted in previous studies, it was impossible to identify correctly the primary particle charge due to the high background [12]. In the center of the family there was a halo, a large diffused dark area of a few mm in diameter observed in x-ray films. The halo was considered to be originated by the bundle of secondaries originated by leading particle. There have been recognized concentric ringlike structures [8] of showers at the large distances from the center of the family. Also, an alignment of the most energetic showers located in the center of the event, has been reported recently [13]. The family was detected near the edge of the detector (see Fig. 1). Because of the edge, $\sim$30% of showers at the periphery (with $R \geq 30$ mm from the family center) were not detected, and should be taken into account, as has been pointed out by previous analyses.

IV. A NEW PICTURE OF THE EVENT

Here we wish to suggest an explanation for the formation of this event in an ordinary interaction of a heavy primary cosmic ray particle with an air nucleus. The novel feature of our explanation is the consideration of spectator nucleons, the Fermi motion of the nucleons in the nucleus, and accounting of the processes contributed to the formation of observed pseudorapidity distribution of secondary particles. We approach the problem with a known, familiar cosmic ray physics assumptions.

A. Scenario of the event formation

A scenario of the formation of the present event can be described as following. At the altitude H above the chamber, in the atmosphere a heavy primary cosmic ray nucleus A had an interaction with an air nucleus. The number of projectile nucleons participated in the interaction can be expressed as A_{part}. Assuming normal pion multiple production mechanism, after the interaction there are: secondary particles (mainly pions) produced in the interaction of each of A_{part} nucleons, A_{part} outgoing nucleons, and $A_{\mathrm{spect}} = A - A_{\mathrm{part}}$ spectator nucleons. Spectator nucleons A_{spect} do not participate in the interaction. They can be visualized as almost monoenergetic beam of nucleons with average energy (E_0/A) per nucleon. The lateral spread of this bundle of spectators is governed by the Fermi transverse momentum ($p_F \sim 200$ MeV/c). The transverse momenta of nucleons participated in the interaction, as well as secondary particles, is much larger, that is ($p_t \sim 0.4 - 0.5$ GeV/c). This value has been determined by mountain emulsion chamber experiments which studied interactions of cosmic ray nucleons with carbon target at energies $E_0 \sim 100$ TeV. Also the mean value of the transverse momentum of showers observed in the present event has been estimated earlier[7], using energy weighted lateral spread of family showers, ER (TeV mm), which has been approximated by an exponential function e^{-p_t/p_0}, with $p_0 = (0.43 \pm 0.1)$ GeV/c.

B. Pseudorapidity distribution

The geometrical configuration of the event is reflected by the pseudorapidity ($\eta = -ln[\tan(\theta/2)]$) distribution of secondary particles. The pseudorapidity distribution of particles in this event may be visualized as a superposition of three parts: one corresponds to the spectator nucleons, another—to the outgoing nucleons from interaction occurred in air, and the rest—to secondary pions produced in the interaction. Owing to the difference in transverse momenta, spectator nucleons are situated in the family center, and secondary particles—at the periphery of the event. Because of the effect of the threshold, particles at large distances from the center can not be detected in full.

1. Algorithm

Maximum pseudorapidity value of secondary particles from the interaction is expressed as $\eta_{\mathrm{part}} = ln(2 \times E_0/p_t)$, where $p_t \sim 0.4$ GeV$/c$. Minimum rapidity value of spectator nucleons is $\eta_{\mathrm{spect}} = ln(2 \times E_0/p_F)$, and is higher than η_{part}. In the projectile rest frame the system is assumed to be a spherical ball of Fermi gas with the Fermi momentum p_F. In this case we can get analytical expression for the spectators versus pseudorapidity as: $dn/d\eta = 3 \times A_{\mathrm{spect}} \times C1 \times C2$, where $C1 = e^{(-2\delta)}$, $C2 = \sqrt{(}1 - e^{-2\delta})$, and $\delta = \eta - \eta_{\mathrm{spect}}$. Assuming that the inelasticity K is a flat distribution in an interval $[0; 1]$, one can expect the participant nucleons pseudorapidity density to be in the form $A_{\mathrm{part}} \times e^{-\delta_{\mathrm{part}}}$, where $\delta_{\mathrm{part}} = \eta - \eta_{\mathrm{part}}$. Because of the difference between p_t and p_F, the relative position of participant nucleons is shifted to the left from spectators on the pseudorapidity axis. The shift is equal to $ln(p_t/p_F)$. The pseudorapidity density distribution of charged pions ($dn/d\eta$) can be obtained either using simple phenomenological expression from [18] $xdn/dx = 0.12 \times [(1 - x)^{2.6}]/x$, where the Feynman variable x is given by the ratio of the secondary particle energy E to the incident energy E_0, or from simulation calculation, for instance [13]. The maximum value of pseudorapidity for pions is determined by η_{part}. As a result, we have the particle density distribution ($dn/d\eta$) versus pseudorapidity (η) presented in Fig. 2, where $\eta = 0$ at the Fermi momentum $p_F \sim 200$ MeV/c.

2. Comparison with experiment

In the real situation of the experiment we have a chamber with a limited efficiency $\epsilon < 1$, so not all nucleons are detected. In this case the observed number of nucleons in the chamber is expressed as $N_{\mathrm{obs}} = N_0\epsilon$, where N_0 is the number of nucleons (either spectators or participants) for the ideal chamber ($\epsilon = 1$). Experimental observation gives the energy E and the geometrical position R for the family showers. Usually the position of showers is measured referring to the direction of the family energy weighted center, which is defined as $R_{\mathrm{center}} = \Sigma ER/\Sigma E$. It is inevitable for the cosmic ray experiment, that such choice of the reference does not always exactly coincide with the real position of the axis of the family incident upon the chamber. In present case of SL1975 we assume that the real center of the family is located in the halo. The experimental particle density distribution on pseudorapidity $\eta \sim lnR$, where R is a distance of a shower from the halo center, is superposed on the expected distribution (see Fig. 2). This approach does not depend on absolute energy determination in the experiment. The forwardmost region, that is a spectator bundle, corresponds to the area of $R \sim 1$ mm from the halo center. Some showers can be in the "gap" between spectator and participant nucleons, simply because particle can have a transverse momentum different from the assumed average value.

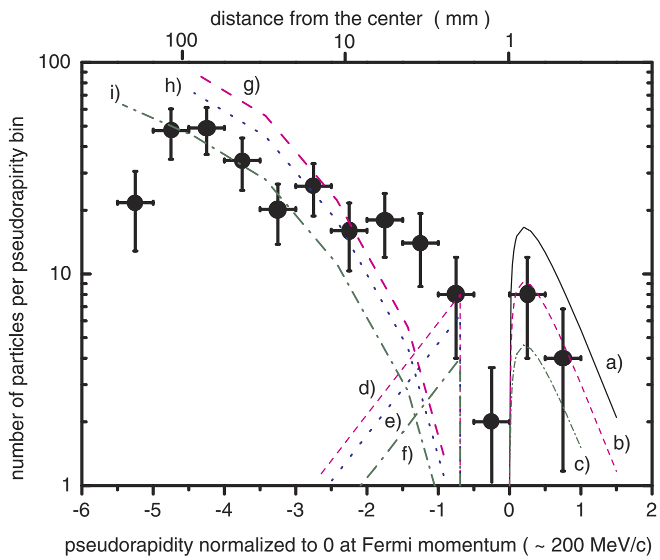

FIG. 2 (color online). The pseudorapidity distributions. Correction for the edge of the detection has been made. Circles: experimentally observed showers of the event. Lines: the analytical distributions for spectator nucleons ($A_{\mathrm{spect}} = 36$, solid line (a), $A_{\mathrm{spect}} = 20$, dash line (b), $A_{\mathrm{spect}} = 10$, dash-dotted line (c)), projectile participant nucleons ($A_{\mathrm{part}} = 20$, dash line (d), $A_{\mathrm{part}} = 16$ dotted line (e), $A_{\mathrm{spect}} = 10$, dash-dotted line (f)), and charged pions and gamma rays originated by projectile participant nucleons ($A_{\mathrm{part}} = 20$, dash line (g), $A_{\mathrm{part}} = 16$ dotted line (h), $A_{\mathrm{part}} = 10$, dash-dotted line (i)), detected in the chamber with detector efficiency $\epsilon \sim 0.4$.

V. RESULTS

A. Leading shower

One of the most puzzling features of the event has been a very high energy leading shower, located at the center of the event (see the pseudorapidity distribution in Fig. 3). It was found [7] that this particle interacted in the 12th layer of the target. The multiplicity of tracks observed along the track of the leading particle is large. But these tracks are not necessarily to be the secondary particle multiplicity. One can notice that experimental pseudorapidity distribution indicates an increase of multiplicity of tracks at any given bin. This increase (with depth) of the rapidity density distribution possibly suggests the development of a nuclear electromagnetic cascade and interactions of secondary particles in the target. The rapidity density distribution of shower tracks in the central jet is obtained not from a single layer, but from the whole set of layers in the target. At the beginning of the distribution, the density is not distorted by secondary interactions. We can recognize "a plateau" in the distribution. Most likely it is formed by secondary particles originated in the interaction. According to the previous analysis, tracks could not be resolved within 2 μm at the layer 13. In terms of the pseudorapidity this would correspond to $\eta_{\max} = -ln(R/2H) = -ln(2 \times 0.001/2/1.8) \sim 7.4$. The minimum value of pseudorapidity is determined by the radius R of the area where the tracks are counted, and the maximum can be assumed as an angle corresponding to the $R = 2$ μm. For instance, for $R \sim 200$ μm at the last layer of the target, the corresponding pseudorapidity interval would be $\sim 7 - 11.8$. Looking within the same angle (the same pseudorapidity bin), along the longitudinal development of the leading shower through the target, one would encounter the multiplication of tracks due to the cascade development. At the beginning of the distribution the rapidity density is small, because there is no cascade development. (For instance, pseudorapidity $\eta = 4$ corresponds to $R \sim 2$ mm in the middle of the target. So, in this case the track counting would include the contribution from neighboring showers.)

Let us assume, that the number of tracks increases due to the pair creation, gamma radiation, and secondary nuclear interactions. After passage of a thin material T (c.u.), the number of electrons can be estimated as $\sim 2T/\lambda_{\text{pair}} + 4T^3/6(\lambda_{\text{pair}})^2/\lambda_{\text{rad}}[ln(E_0/E) - 1]$, where $\lambda_{\text{pair}} = 9/7$, and radiation length $\lambda_{\text{rad}} = 1$. The number of charged pions can be estimated as $n_\pi \sim (T/\lambda_{\text{nucl}}) \times {<}n{>}$, where ${<}n{>}$ is an average multiplicity in interaction. After $T \sim 0.3$ $c.u.$ an average multiplicity can increase up to $\sim 2 - 3$ times. The absolute value of the observed rapidity density suggests, that the leading particle is not a proton, but a deuterium, or even an alpha particle. Following the direction of this particle, after the target and spacer, one can find a halo in the calorimeter (see Fig. 1). As we have found, the central part of the halo area is mainly formed by the spectator nucleons.

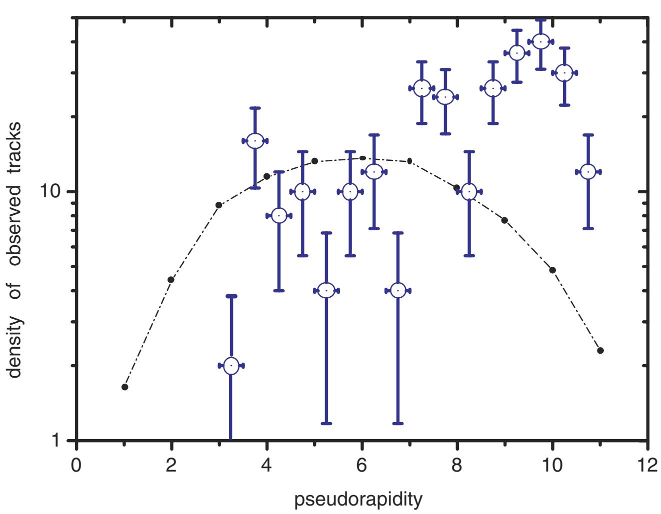

FIG. 3 (color online). The pseudorapidity density distribution (normalized to the size of the bin) of tracks observed [7,8,12,13] in the interaction of the leading particle. Solid line shows the simulated (by the QCD inspired models, from[13]) distribution of tracks originated by two nucleons with $E \sim 100$ TeV.

B. Halo

Halo has been considered as one of extraordinary features in this event (see Fig. 1, the inset III). It was noted in previous studies, that the present halo has wider spread, comparing with a simple assumption of an electromagnetic cascade origin. As we can conclude from our analysis, this halo is not an extension of a single leading jet, but is originated by the bundle of spectators. Because of the high background in the halo area, it is not easy to recognize all individual cores. There have been distinguished a few cores within the halo area [13]. According to our hypothesis they are most likely to be spectators.

C. Comment on asymmetry of showers

In previous studies this event has attracted a lot of attention due to the lateral distribution of showers (see Fig. 1 and 2). According to previous analyses, at large distances from the family center, these showers appeared to be arranged in the form of "concentric rings"[8]. In our analysis these distant showers are in the pion region, where one has to consider possibilities of statistical fluctuations in case of a large number of showers (see Fig. 2, the upper scale).

The alignment (arrangement into a line) of a few most energetic showers has been found recently [13] in the center ($R \sim 10$ mm) of the event, as well as inside of the area of $R \sim 1$ mm within halo. According to our analysis, there are spectator nucleons and participant nucleons in the center. The observed energies of showers (for instance, spectators) are determined by interactions in the chamber.

The original bundle of spectators is assumed to be almost monoenergetic. Thus, the arrangement into a line in a target diagram of three most energetic showers within this bundle, can be formed due to fluctuations. Nevertheless, the appearance of many peculiar structures and clusters in the SL1975 event, possibly suggests the heavy primary origin signature. Certainly, the accelerator study of specific features of nucleus collisions will help to clarify this point in the near future.

D. Characteristics of primary particle

1. Mass

In the present experiment the target is an air nucleus. The atmosphere mainly consists of nitrogen ($A = 14$) and oxygen ($A = 16$). Other gases (such as Argon ($A = 40$)) make up less than 1%. In present case the primary particle mass can be estimated as $A = A_{\text{spect}} + A_{\text{part}}$. Without any extraordinary assumptions, one can estimate the number of the projectile participant nucleons as $A_{\text{part}} \sim A_{\text{target}}$. Figure 2 shows that experimental observation is consistent with an assumption of $A_{\text{target}} = 16$, and $A_{\text{spect}} \sim 20$. Since collisions can be either central or peripheral, we can consider a variety of cases (for instance, shown in Fig. 2). Taking into account that a single event is in question, and there are some statistical uncertainties, mass can be evaluated at least as $A > 20$.

2. Energy

The primary particle energy E_0 (per nucleon) can be estimated using the relation $E_0 \sim p_F H/R_F$, where Fermi momentum $p_F \sim 200$ MeV/c, radius Fermi $R_F \sim 1$ mm, and H is the height. The height H has been previously estimated ([7,12,13]) within the range from $\sim$100 m, up to $1 - 2$ km. For the production height $H \sim 1 - 2$ km, E_0 would be in the range $\sim 200 - 400$ TeV/nucleon. An assumption of $H = 100$ m (and, correspondingly, $E_0 \sim 20 - 40$ TeV/nucleon) , would be in contradiction with the observed energy of the event (≥ 2000 TeV). It is worth to note that the JACEE experiment detected [6] a local interaction of a heavy primary particle ($A = 40$) in the energy region 100 TeV/nucleon.

VI. CONCLUSION

In this paper we infer the mass of a primary particle as well as the primary energy from measurements of a family detected at balloon altitude. At the top of the atmosphere we do not observe a family, because there is no material for an interaction. When a detector is exposed in the atmosphere at the depths, comparable to the MFP of heavy primaries, as in the present experiment, the probability to observe heavy primary as a family (not as a local interaction in the chamber), increases. From a single measurement one have to deduce two unknowns: the composition and the dynamic of particle interactions. Nevertheless, if the family has been of the heavy primary origin, there are certain objective patterns we would expect to see, that might tell us the story. The SL1975 is most likely to be a result of a heavy nucleus ($A > 20$, $E_0 \sim 200 - 400$ TeV/nucleon) interaction with an air nucleus. In this case a primary particle would originally have been in the energy region above "the knee" ($3 - 4 \times 10^{15}$ eV) of the cosmic ray spectrum.

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