Exotic models are no longer required to explain the Centauro events

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We argue that too much exotic scene setting is not necessary for the explanation of the Centauro events observed by the mountain based emulsion chambers. We show that a proper understanding of the detector helps to find a mundane solution to the "decades old cosmic ray mystery." We conclude that the exotic events observed so far are not inconsistent with the incorrect evaluation of the detector response and misinterpretation of the experimental signal.

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I. INTRODUCTION

Since their original report [1] by the Chacaltaya x-ray emulsion chamber experiment [2], the Centauro events (cosmic ray families with observed energy $\Sigma E \sim$ 200–300 TeV detected at mountain altitudes) have been discussed in hundreds of papers, studied by many experiments. Some mountain experiments did not see exotic events [3,4], another experiment claimed observation of similar candidate events [5]. All searches at accelerators were negative [6–8].

Based on the supposition that the Centauro events constitute a very special anomalous set of data, there were proposed many exotic models ranging from exotic primaries [9,10] to "the new physics mechanisms" of hadron interaction [11,12]. Recently, on the basis of misleading presentation of the experimental situation, there was even a claim of "quantitative support" to the mini-black-hole interpretations [13] of the Centauros.

We believe that in the case of a controversial experimental signal, it is important to reanalyze thoroughly the original x-ray films and emulsion plates, check previous records and data sets, reexamine the reasoning that led to the "exotic" claims, and critically assess the possibility of experimental, methodological, and human errors. This process is not less important than contemplating new scenarios that would "rock the physics world."

A few years ago we reexamined [14] original x-ray films, emulsion plates, and data of the Centauro-I event, which has been recognized as "decades old cosmic ray mystery." Based on original films, plates, and data, we showed that previous experimental description [1,15] of Centauro-I was not right. Because of the incorrect arrival angle measurements [1,15], two different events were mixed up. We presented a solution to the puzzle [16], using standard physics. For instance, one could consider a narrow air family passing through a gap between blocks in the upper chamber.

The purpose of the present paper is to show new evidence, that "other Centauro events" from the original paper [1] can be explained by peculiarities of the Chacaltaya detector. We provide new examples and give new experimental information. We show that so-called "exotic signal" observed so far in cosmic ray experiments using a traditional x-ray emulsion chamber detector can be consistently explained within the framework of standard physics.

II. EXPERIMENTAL SETUP

A. The Chacaltaya detector

The detector, which reported an exotic signal, was not constructed to hunt for Centauro. Originally the Chacaltaya detector was designed to study multiple production of pions produced in cosmic ray hadron interactions with the target material (carbon) [2]. This objective determined a particular type of the detector. The Chacaltaya emulsion detector (see Fig. 1) is made of the upper and the lower chamber with the target in between. There is an air space between the target and the lower chamber. The chambers, upper and lower, consist of several layers of photosensitive materials, such as x-ray films and nuclear emulsion plates, interleaved with lead plates with thickness of 0.5 or 1.0 cm. The upper detector ($\sim$ 8–10 cm Pb [17]) serves as a filter of atmospheric electromagnetic showers. An electron or γ-ray (all particles of the electromagnetic component are referred to as γ-rays hereafter) incident on the chamber produces a cascade shower through a chain of electromagnetic interactions with lead nuclei (Pb). When an electron shower propagates through a sensitive layer in the chamber, it produces a dark spot (with darkness D) on the x-ray film. The spot darkness D is measured by the photometer. The detection threshold of spot darkness D_{th} is ($\sim$ 0.1), varying with the background darkness and other film conditions. A high energy hadron interacts with lead (Pb) or carbon (C) nuclei. Nuclear interactions produced in the target layer ($\sim$ 23 cm of carbon) are detected as γ-rays in the lower detector. The signature of such a process is the decay of pions (π^0), which are generated in these colli-

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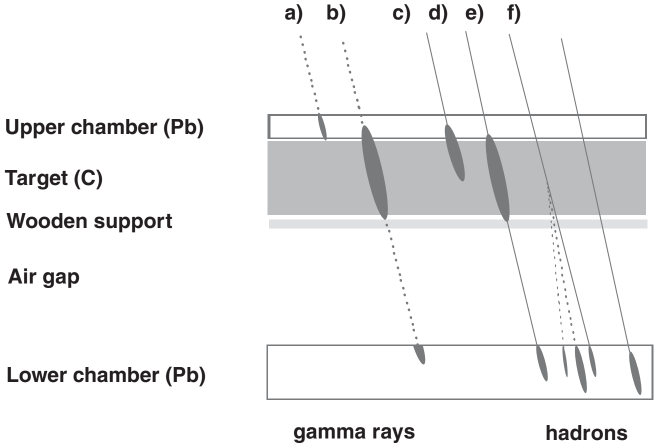

FIG. 1. Basic structure of the Chacaltaya chamber. A γ-ray (dotted lines) produces a cascade shower through a chain of electromagnetic interaction with lead nuclei (Pb). A high energy hadron (solid lines) interacts with lead or carbon (C) nuclei. Neutral pions (π^0) are generated in these collisions. Pion decay results in γ-rays. Shower identification in the Chacaltaya chamber: (a) γ-ray without continuation; (b) γ-ray with continuation; (c) Pb-jet in the upper chamber without continuation; (d) Pb-jet in the upper chamber with continuation; (e) showers from a C-jet in the target; (f) Pb-jet in the lower chamber.

sions. Pion decay results in γ-rays. The energy detection threshold of showers observed in x-ray film is $\sim$1 TeV. In lead, the ratio of the interaction length to the radiation length (or cascade unit) is $\sim$30, 1 cascade unit is $\sim$0.56 cm Pb. In carbon material this ratio is close to $\sim$1. The thickness of the target layer is $\sim$0.3 mean-free path for the nuclear interactions, or $\sim$0.4 radiation length for the electromagnetic processes. The γ-rays produced in collisions of hadrons arrive at the lower chamber ($\sim$ 8 cm Pb) with mutual separation, due to the air gap ($\sim$ 1.6 m). For instance, a γ-ray with the energy $E_\gamma = 1$ TeV has an average lateral spread $R = H * p_t/E_\gamma = 320\ \mu$m, where $p_t = 200$ MeV$/c$, and the air gap $H = 1.6$ m. The total thickness of the Chacaltaya detector is less than $\sim$1.5 nucleon mean-free path.

1. Shower identification

The identification of showers is shown in Fig. 1. A jet originating from the nuclear interaction in the target layer is called ‘‘C-jet.’’ The C-jet study was the main objective of the Chacaltaya detector. According to [1], ‘‘the showers observed in the lower detector are all local nuclear interactions of hadrons.’’ These showers were classified in the following way: Pb-jet-upper, C-jet, Pb-jet-lower. Showers detected in the upper chamber were identified in [1] as the following: atmospheric γ-ray showers which are ‘‘becoming observable before ten radiation length and having multicores with characteristics of air cascade’’; hadrons—showers which are ‘‘becoming observable deep in the detector (at ten radiation length or more), or with a double-peaked shower transition curve showing successive interactions’’; and unidentified showers—‘‘the rest’’ of the showers.

B. Uniform x-ray emulsion lead chamber

In this work we use the results of a collaborative work, of the Moscow State University and Waseda University groups (Waseda-MSU) in a joint study, as a part of the Chacaltaya-Pamir collaboration, of cosmic ray events recorded by thick Pb chambers exposed at the Pamirs. The detectors called thick lead chambers were designed by MSU [18] and constructed at the Pamirs (4370 m above sea level) in Tajikistan. After the processing of x-ray films in Russia, they were shipped to Japan. X-ray films have been analyzed in Japan by the joint Waseda-MSU team. Analysis of the total exposure 57 m^2 yr was reported in [4]. Basically, the Pamir x-ray chamber has an area of 10 m^2 and consists of 20 units. The chamber is homogeneous in structure and uniform in detection efficiency of electron showers. For instance, each unit of the 60 cm Pb chamber is a stack of 58 (59) x-ray emulsion films and 1 cm lead plates. The chamber thickness is $\sim$4 nuclear mean-free path. The x-ray emulsion chamber detects showers initiated by γ-rays and hadrons. Usually, the energy detection threshold in the Pamir experiment is $\sim$4 TeV. The detected shower is traced through the chamber. The data set (D_i, t_i), where D_i is the spot darkness at the ith layer at depth t_i, determines the shower transition curve. Hadrons and γ-rays arrive at the detector as a group of parallel showers called a ‘‘γ-hadron family.’’

1. Shower identification in the thick lead chamber

The conventional method of shower identification is based on the curve (D, t) fitting around the position of the shower maximum ($D_{\max}$). Figure 2 gives an illustration. The identification of the shower origin is made by a criterion on depth shift Δt: a hadronic origin for $\Delta t > 6$ c.u., and a γ-ray origin for $\Delta t < 6$ c.u. The showers in the upper part of the chamber consist of γ-rays and hadrons. This hadronic fraction can be corrected statistically taking into account the hadron attenuation length in Pb.

To study the individual shower transition curve observed in the upper part, we have to use an improved method of identification [19]. The shower transition curve often has plural local maxima. We set the curve fitting region around the first maximum ($D_{\max-1}$) and obtain the best fitted curve. Then, a comparison is made over the extended region beyond the first maximum, between the observed data and an extension of the best fitted curve. The result can be expressed as $\chi^2_{\rm tail}$ [19]. The distribution of $\chi^2_{\rm tail}$ is different for showers of γ-ray origin and of hadronic origin. Thus, $\chi^2_{\rm tail}$ can be used for the identification. In the experi-

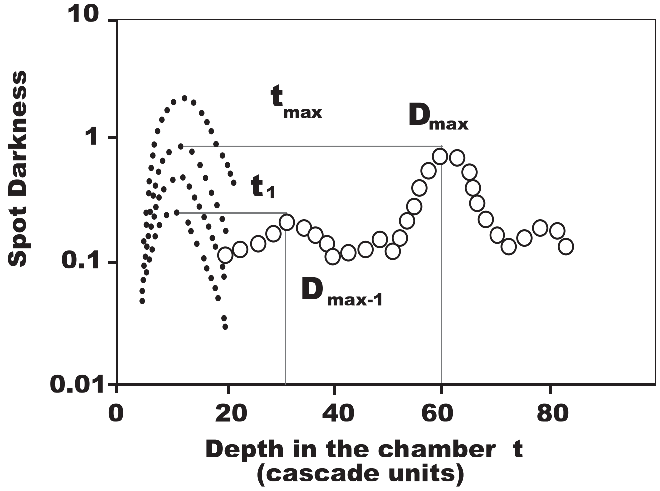

FIG. 2. Illustration of the shower observation (open circles) in the Pb x-ray chamber. t_1 is depth shift from the first local maximum $D_{\max-1}$, and $t_{\max}$ is from the shower maximum $D_{\max}$. Dotted lines are average curves of simulation showers initiated by an electron pair at the top of the chamber ($t = 0$).

ment showers with $\Delta t > 6$ c.u. can be identified as of hadronic origin. Their $\chi^2_{\rm tail}$ distribution, being of hadronic origin, is used to study showers with $\Delta t < 6$ c.u. As a result, all showers are consistently identified as being of gamma-ray or hadronic origin.

III. SPECIAL FEATURES OF THE CHACALTAYA DETECTOR

A. Gap between the chamber blocks

The Chacaltaya detector is not ideal, and the upper and lower chambers have gaps [16,20–22] between the units of the chamber (called blocks). Previous investigations of the Centauro events did not mention this specific feature [1,15,23]. These gaps are formed due to several factors. The lead plates could not be placed exactly next to each other, since all the work was done manually. Films were packed in envelops of bigger size, so there was a paper border around. One can begin with the null hypothesis that the specific features of the detector (for instance, gaps) can be the reason for the exotic description of the experimental event. These specific features of the detector (the gaps between blocks) were not significant for the study of hadron interactions in the target. In the case of the cosmic ray families, the situation is different. The lateral spread of an ordinary γ-hadron family $R_{\rm fam} = \Sigma R_i/N$, where R_i is the distance of a shower i from the energy weighted center, and N is the multiplicity of showers in a family, with energy 100 TeV $< \Sigma E_\gamma <$ 300 TeV, has rather wide distribution, ranging from a $\sim$1 mm to $\sim$100 mm, with the average $\sim$20–30 mm [16]. One can see that consideration of the detector gaps is significant in the case of $R_{\rm fam} \sim W_{\rm gap}$, where $W_{\rm gap}$ is the geometrical width of the gap. As an illustration we present Fig. 3.

B. Effects expected from the gap

We can consider a variety of cases (see Fig. 4), which can be expected in the chamber with gaps. A single family in Fig. 4 is represented by a circle. The circle means that showers from an ordinary family are assumed to be distributed isotropically. If some part of the lower chamber family is in the area of the gap, then this part of the family will be missing. If a family is detected near the very edge of the film, then the "symmetry" will be broken, and the family would appear as a clear asymmetric group, a streak of showers, or a "half-circle." This approach can predict an interesting case (c) of a family observed in the lower chamber and detected near the edge of the films. One would expect that there will be no exact correspondence between the groups of showers observed in the upper and the lower chambers. Some showers will be missed and go undetected. Some γ-rays will pass through the gap. They will be detected directly by the lower chamber. As one can see from Figs. 3 and 4, this experimental setup implies that, contrary to [1], there is no automatic correlation between the location of a shower in the lower detector and an identification of the shower as a hadron.

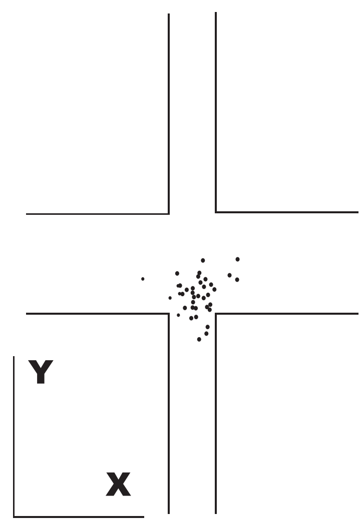

FIG. 3. Comparison of lateral spread of the event I-12 observed in the lower chamber with the geometrical size of the gap between blocks in the upper chamber. The solid lines show the edges of the blocks in the upper chamber. Circles stand for showers detected in x-ray films. The size of the gap in the y-direction is $W_y = 19$ mm, and $W_x = 8$ mm in the x-direction (using average numerical values estimated by [22]). The photographic image of the event I-12 can be found in [24]. Another image from [24] shows a part of the family detected in the upper block S-55. This family S-55 was incorrectly considered as a part of Centauro-I for 30 years. Images of the event and blocks are for illustration purposes only.

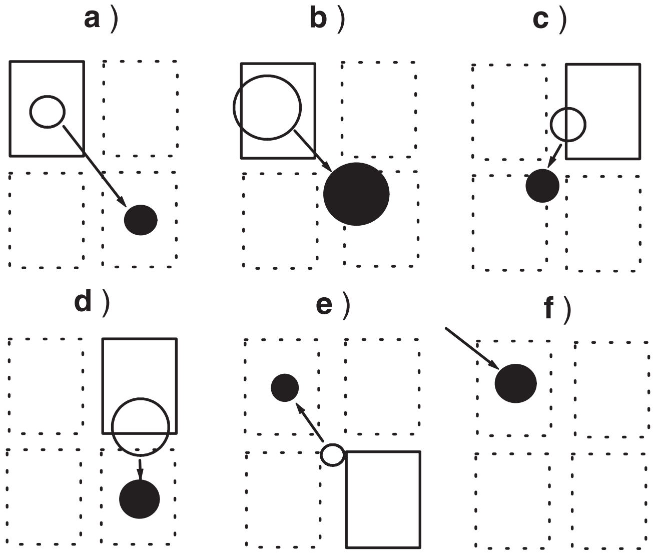

FIG. 4. An illustration of families, detected in the chamber with gaps. (a) An air family detected in the chamber without interference of gaps. (b) A widespread family can lose some showers, which will be missed in the gaps. (c) A family can be detected near the edge. One would expect that there will be no exact correspondence between the shower patterns in the upper and the lower chambers. (d) The central part of the family can pass through the gap. Some showers could be detected in the upper blocks. (e) A narrow air family passing through the gap between blocks. (f) A hypothetical case of a family arriving to the lower chamber, without passing through the upper level. It could have occurred only if some irregularities in the chamber assembling/disassembling procedure were involved. Open circle: a family in the upper chamber; solid circle: a family in the lower chamber; arrow: the direction of the family propagation; solid lines: blocks in the upper chamber; dotted line: blocks in the lower chamber.

C. Application to the real chamber

Considering simple assumptions about the Chacaltaya detector, one has to remember that in the real experimental setup there is no exact geometrical correspondence (in vertical direction) between every corner of each block in the upper and the lower chamber. The whole structure of the upper chamber platform was supported mainly by a frame of wooden beams (~ a few cm) and could be shifted, distorted, or subjected to environmental factors. In other words, the actual geometrical size of the gap $W_{\rm gap}$ is not constant, and the path of the bundle of particles through the actual detector can favor many possibilities which could lead to the abnormal, or exotic outcome. The two-storied design of the Chacaltaya detector assumes that the chamber assembling procedure must be as follows: the upper chamber is constructed first, and the lower chamber second. The disassembling procedure has to be done the other way round. In evaluation of the exotic signal, one should not forget a possibility (whatever improbable this assumption looks like) that some irregularities in assembling or disassembling of the chamber could happen to occur.

IV. THE CENTAURO-I EVENT

In 1972 the Chacaltaya mountain chamber experiment conducted by the Brazil-Japan Collaboration [1] discovered a cosmic ray family located in chamber 15, blocks I-12 and S-55. Chamber 15 was the first large scale (44.2 m^2 the upper detector and 32.4 m^2 the lower) two-storied chamber at Chacaltaya [17]. In so-called normal cases, a family in the upper detector is assumed to be several times larger, in number as well as in energy, than its continuation in the lower detector. The situation with Centauro-I was the opposite. The upper half of the event Centauro-I [1] did not allow one to imagine its lower half, and vice versa. Because of this imbalance the name "Centauro-I" was chosen. According to the original analysis [1], the event was composed of only one γ-ray and 49 hadrons [1]. The old description of the Centauro-I event assumed that there were two cosmic ray families associated with the event. According to the old story [1], one group of showers was located in the upper part of the detector (block S55), and the other in the lower part (block I-12).

A. The new picture of Centauro-I

In 2002 we found [14] that the experimental situation with the Centauro-I event has changed dramatically. It was pointed out [16] that the previous description [1] of Centauro-I was incorrect. According to the new analysis [14,16], there is a difference in incident angles between the upper and lower events. We showed that there is only one family related to Centauro-I, and this is the family detected in the block I-12. The upper part (the event in block S-55) does not belong to Centauro-I. This family S-55 was incorrectly [1,15] considered as a part of the event for almost 30 years. A very famous illustration of Centauro-I [1] that has been reproduced ever since by numerous papers, showed the horizontal wooden bar (~ 30 cm thickness) from the supporting frame, where many hypothetical hadron interactions took place. This detail was significant in previous descriptions [1,15], in order to justify attenuation of hadrons in the material of the detector (additional wooden bar increased the thickness of the target layer). This depiction is no longer valid, since the expected geometrical position of the I-12 at the top of the chamber is very far (~ 50 cm) from this wooden bar.

On the x-ray film I-12 consists of ~40 showers. The number of tracks in the nuclear emulsion plates is larger, and is simply explained by the difference in the energy detection threshold $E_{\rm th}$ between x-ray films ($E_{\rm th} \sim$ 1–3 TeV) and nuclear emulsion plates ($E_{\rm th} \sim$ 0.1–0.3 TeV) [1]. We showed [16] that the multiplicity, the lateral spread distribution, and the differential energy spectrum of showers look similar to a narrow air family passing through a gap between blocks in the upper chamber.

V. OTHER CENTAURO EVENTS FROM [1]

Since the first encounter of the Centauro-I event, there has been a systematic survey of further similar examples. The new mechanism of hadron interaction of the Centauro type has been elaborated [11]. It was hypothesized that the parent atmospheric interactions can happen not only in the vicinity of the chamber, but at high altitudes as well. The characteristic features believed to be pertinent to the description of the phenomenon were (i) large number of hadrons N_h and (ii) small number of γ-rays. There was one more characteristic point, assumed to be related to the description of the exotic events. This is the hadronic energy fraction Q_h of the total observed energy of the event. It was believed that the Centauro events correspond to the families with very high values of Q_h and N_h. Thus, four further candidates, named Centauro-II, III, IV, V, have been found. The total observed energy of the so-called Centauro events is in the range ~200–300 TeV (with $E_{\mathrm{th}} \sim 1$ TeV). It is worth adding that Centauro-II, III, IV were detected in the same Chamber 17, during the same exposition [1]. It was mentioned in numerous occasions (for instance, it was stated clearly in [16]) that none of the candidate events could stand alone as clearly as Centauro-I (if one uses its previous description [1]).

A. The new picture of the Centauro events

Originally the Centauro-I event [1] has been noticed due to the difference in size, in number as well as in energy, of the upper and lower families. Since Centauro-I is reduced now to the family I-12, naturally the upper and the lower parts are converged. We reexamine the Centauro events from [1] based on the same original approach, considering separately their upper and lower parts. We use original numerical information [1] presented in Table I. We calculate the following quantities: (i) the ratio of the energy detected in the lower detector ΣE_{low} to the total sum $\Sigma E_{\mathrm{vis}} = \Sigma E_{\mathrm{up}} + \Sigma E_{\mathrm{low}}$ (the upper ΣE_{up} and lower detectors ΣE_{low}) of visible energies, and (ii) the ratio of the number of showers detected in the lower detector ΣN_{low} to the total number of showers $\Sigma N_{\mathrm{vis}} = \Sigma N_{\mathrm{up}} + \Sigma N_{\mathrm{low}}$.

The result is presented in Figs. 5 and 6. Using our working model, one can find that the relation of the event to the position of the gaps correlates with the high value of energy ΣE_{low} (or large number of showers ΣN_{low}) detected in the lower chamber. Particularly interesting is the new evidence that the chamber peculiarities contribute to the formation of the "exotic family" signal observed in the lower chamber. In previous studies it was mentioned [11] that the events Centauro-II and Centauro-III did not have "exact correspondence" between the upper and the lower blocks. In other words, it means that these families were detected at the film edges. This fact has been confirmed by the analysis of the original films and plates in [20]. As an illustration of this situation, one can look at the case (c) from Fig. 4. Now, if one substitutes the word "lower" with

TABLE I. Summary of the Centauro events. (Numerical data for Centauro-I, II, III, IV, V are taken from [1]. There were also interesting remarks [1] about these events. Centauro-I: 4 additional showers in the upper detector were observed (so, the total number was $N = 7 + 4$), but omitted, as "not belonging to the same generation." These "omitted showers" ($N = 4$), together with counted ($N = 7$), belong to the family S-55 (see text) detected in the upper chamber. Because of the incorrect evaluation of the incident angles, S-55 has been part of Centauro-I for 30 years. The same procedure ("omission") has been done also for other events. Centauro-IV: 1 "air cascade" was omitted. Centauro-V: 1 hadron in the lower chamber was omitted, because it was considered as surviving nucleon.)

Event	C-I	I-12	C-II	C-III	C-IV	C-V
Chamber number	15	15	17	17	17	16
Observed showers						
(in upper detector)	7	0	14	42	76	53
(in lower detector)	43	~40	23	21	23	12
(total)	50	~40	37	63	99	65
Observed energy sum						
(in upper detector)						
ΣE_{up} TeV	28.1	0	57.6	150.1	195.5	231.4
(in lower detector)						
ΣE_{low} TeV	202.5	~200	145.8	119.8	90.1	53.4
(total)						
ΣE_{vis} TeV	230.6	~200	203.4	269.9	285.6	284.8

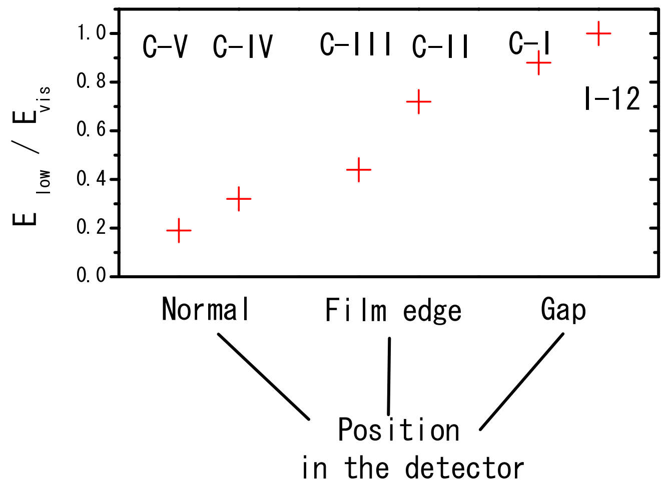

FIG. 5 (color online). Diagram of the detector features and the energy fraction observed in the lower detector $\Sigma E_{low}/(\Sigma E_{low} + \Sigma E_{up})$. A character C stands for "Centauro." The numerical data were taken from [1]. One can see correlation between the specific features of the detector and the energy detected in the lower chamber. "C-I" stands for Centauro-I in its original description [1]. In 2003 it was found that there is only family related to Centauro-I. This is the family detected in the block I-12. The event has no upper part corresponding to its lower part. The event I-12 is consistent with an assumption of a narrow air family passing through the gap in the upper detector. In previous studies it was mentioned [11] that the events C-II and C-III did not have "exact correspondence" between the upper and lower blocks. In other words, these families were detected at the film edges, near the gaps [20]. As an illustration of this situation, one can look at case c from Fig. 4. The "Normal" position means that exact pattern of showers was available.

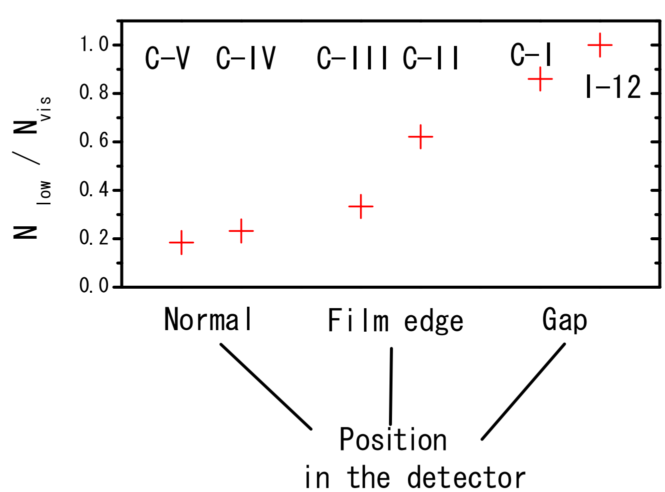

FIG. 6 (color online). Diagram of the detector features and the fraction of showers observed in the lower chamber $\Sigma N_{low}/\Sigma N_{vis}$. One can see the correlation between the specific features of the detector and the number of showers detected in the lower chamber. Marks are the same as in Fig. 4.

the word "hadron," then there is an apparent "phenomenon." As we have shown above, there is no automatic correlation between the location of a shower in the lower chamber and an identification of the shower as a hadron [1]. If one starts with the exotic hypothesis that some events are "anomalous," one would assign primarily a hadronic origin to any shower observed in the lower chamber [1]. Thus, we have an alternative explanation for Centauro-II and Centauro-III using standard physics.

One can see from Figs. 5 and 6 that for Centauro-IV and Centauro-V the quantity $\Sigma E_{low}/\Sigma E_{vis}$ is ~0.2–0.4, and $\Sigma N_{low}/\Sigma N_{vis}$ is ~0.2–0.3. In so-called normal case, a family in the upper detector is assumed to be several times larger, in number as well as in energy [1]. Figure 7 shows that in terms of $\Sigma E_{low}/\Sigma E_{vis}$ and $\Sigma N_{low}/\Sigma N_{vis}$ Centauro-IV and Centauro-V are not different from ordinary families. We also show $\Sigma E_{low}/\Sigma E_{vis}$ and $\Sigma N_{low}/\Sigma N_{vis}$ calculated for the families observed in the thick lead chamber experiment [4]. In this case N_{low} and E_{low} was calculated for the showers with $\Delta t > 20$ c.u. Since $N_{vis} \geq 10$ in the Centauro events, one has to use the same condition for the analysis of ordinary families. This is because, in a family of a few showers N_{vis}, large fluctuations of the quantities $\Sigma N_{low}/\Sigma N_{vis}$ and $\Sigma E_{low}/\Sigma E_{vis}$ can also occur.

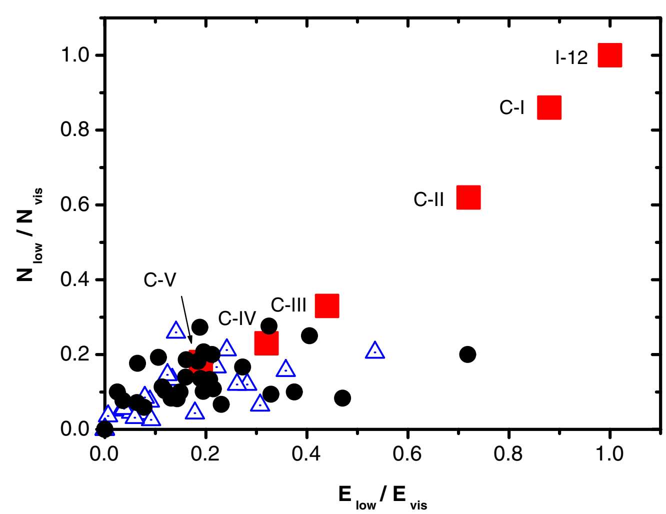

FIG. 7 (color online). Diagram of the fraction of showers $\Sigma N_{low}/(\Sigma N_{low} + \Sigma N_{up})$ and the energy fraction $\Sigma E_{low}/(\Sigma E_{low} + \Sigma E_{up})$ observed in the lower detector. Triangles stand for ordinary families from Chacaltaya [1]. Circles stand for the families detected in the Pb thick chambers (selection criteria for these families were $E_{th} = 4$ TeV; total observed energy 100 TeV $< \Sigma E_{vis} <$ 1000 TeV; N_{low} and E_{low} was calculated for showers with $\Delta t > 20$ c.u.) In both sets the multiplicity is set as $N_{vis} \geq 10$. Squares with labels (similar to Fig. 4) show the Centauro events. "C-I" stands for Centauro-I in its original description [1]. C-II and C-III were detected at the film edges, near the gaps [20].

B. Hadron fraction

The physical meaning of the ratio $\Sigma E_{\rm low}/\Sigma E_{\rm vis}$ is similar to the quantity Q_h, that is the hadronic energy fraction of the total observed energy. Previous analysis of Centauro-IV and Centauro-V was based on the Centauro interaction model which considered the old description of Centauro-I [1] to be correct. It was reported [1] that the quantities Q_h and N_h are very high in Centauro-IV and Centauro-V. Our analysis of $\Sigma E_{\rm low}/\Sigma E_{\rm vis}$ and $\Sigma N_{\rm low}/\Sigma N_{\rm vis}$ shows that these exotic families are similar to the normal ones. So, if an exotic mechanism is involved, one must explain the detection of hadrons primarily in the upper chamber, and observation of the quantities $\Sigma N_{\rm low}/\Sigma N_{\rm vis}$ and $\Sigma N_{\rm low}/\Sigma N_{\rm vis}$, comparable with that expected for ordinary families in the low chamber. If standard physics is valid, then γ-rays, but not hadrons, should contribute most to the energy and multiplicity of the family observed in the upper chamber. Of course, this situation would be different, if some γ-rays were misidentified as hadrons.

In order to evaluate this hypothesis, we have to understand how our detector works in recognition of γ-rays and hadrons in general. Also we have to have a clear image of the whole sample of γ hadron families detected at mountain altitudes. We discuss these topics in the next section.

VI. OTHER EXOTIC FAMILIES, IDENTIFICATION, AND INTERPRETATION

A. The Chacaltaya exotic events

The Chacaltaya experiment favored the picture of hadron interactions with dominance of exotic, ''hadron rich'' families [1,11,15,25]. Many other families, which showed some peculiarities, such as low fraction of electromagnetic component [1], ''anomalous attenuation'' [11,26], very short (almost half of the geometrical value) mean-free path of cosmic ray hadrons [11], halo [25,27], ''anomalous transition curves'' [11,25], showers with starting points at small depths, and a long tail showing ''strong penetration'' [28], were classified into several exotic classes. The classification of showers observed in the upper chamber was made mainly from consideration of the individual shower transition curve [1].

B. Mundane explanation

We follow an alternative way and apply in our analysis standard physics. To study hadron characteristics in a cosmic ray family, we have to get the appropriate detector. Deep lead chambers with several ($\sim$ 4) nucleon mean-free path thicknesses [18] provide this opportunity for an unambiguous identification of a shower origin. Then, the separation of γ-rays and hadrons can be done, and the hadron fraction can be corrected statistically taking into account the hadron attenuation length in Pb medium. According to the experiment with thick Pb chambers, the showers in the upper part of the chamber consist of γ-rays and hadrons. Figure 8 presents the distribution of a number of shower spots (with darkness $D > 0.1$) detected in x-ray films in the thick x-ray emulsion lead chambers. At small depth there is a peak (at $\sim$10 cascade units) in the distribution. It corresponds to showers of γ-ray origin. The tail at larger depths reflects showers of hadronic origin. If the position of the peak is observed very deep in the chamber (see dotted line in Fig. 8), this will indicate the arrival of a family during the assembling or disassembling.

To eliminate possible effects of methodical nature as much as possible, recently we made a comparison [4] of the family data (with observed energy above 100 TeV) from the Chacaltaya experiment and the Pamir experiment without identification of shower origin (γ-ray or hadron). We found [4] that data from different experiments are consistent with each other and with simulation, too. Even in terms of energy flow, when we use the same energy intervals, and showers are not classified into γ-rays or hadrons, the longitudinal and lateral behavior of the family development observed by different x-ray emulsion chamber experiments is almost the same.

As we have seen above, the Chacaltaya detector was not designed to study cosmic ray γ-hadron families. Figure 8 shows that the detector must be thick enough, in order to analyze hadrons unambiguously, and to study the hadron attenuation. In exotic phenomenology, showers with starting points at small depth and long ''tails'' looks similar to a narrow beam of γ-rays and a hadron. We found no evi-

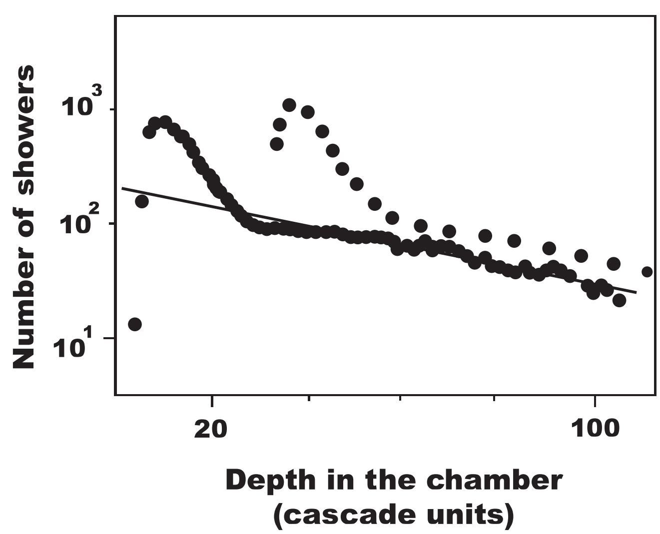

FIG. 8. The distribution of number of shower spots with $D > 0.1$ detected in x-ray films at every depth in the thick lead chambers (exposure time 57 m^2 yr). The peak at small depths corresponds to showers of electromagnetic origin. The tail at larger depths corresponds to showers of hadronic origin. Dotted line: an illustration of family showers detected during the assembling or disassembling period. The solid line shows the fitted exponential slope.

dence for these exotic showers beyond statistical fluctuation [4].

So, the identification of showers such as hadron or γ-ray in the experiment could be the main source of differences. We reported in [4] that most of the exotic phenomena can be explained within standard hadronic interaction physics. We concluded [4] that the apparently inconsistent results of various experiments are most likely from the differences in the estimation of the detector response.

C. Primary cosmic ray composition

In order to interpret consistently γ hadron family experimental results, one must consider primary composition of cosmic rays [3,29,30]. The experimental families, produced by the primary cosmic rays (which are not only protons, but also nuclei), can have large multiplicity, for instance, $N_{\rm vis} \sim 100$ [31]. The lateral and longitudinal characteristics of these normal families [4] are indistinguishable from the so-called "exotic events" [1]. Experiment and simulation showed [4,31] that if a family is originated by a heavy primary particle [3,31], then the fraction of hadron energy Q_h can be very large in ordinary families. Also, experiment and simulation showed [4] that a leading shower in a family, originated by a primary proton, can carry a substantial part of the total observed energy.

VII. EVENTS WITHOUT ACCOMPANYING SHOWERS IN THE UPPER LAYERS

Following a solution to the Centauro puzzle [16], finding a heavy primary origin explanation for a peculiar cosmic ray event detected by the balloon experiment performed in the stratosphere [31], as well as taking into account recent revival of the interest to the exotic signal in cosmic rays [13], we decided to consider once again, from a new perspective, an old data set of families detected in the Pamir thick x-ray emulsion chambers.

In our previous study [4] we made complete scanning and measurements over the total available area, analyzing all showers (both of single and family arrival), their lateral and longitudinal profile, and taking notes of the experimental procedure. To eliminate the background, a traditional method of the experimental data analysis utilizes a special set of trigger conditions, including the location of a shower in the chamber, the energy threshold (~ 4 TeV), etc. For instance, it is required to consider only those showers, whose trajectory crosses the top of the chamber, and eliminate those that come from the side of the detector (so-called "side-showers").

The characteristic feature of the event I-12 (the remaining part of Centauro-I) can be formulated as follows: the event must be observed deep inside the detector and without accompanying showers in the upper layers. Figure 8 illustrates this situation. Such events have been found in the uniform x-ray emulsion lead chambers [5,16]. Sometimes, a family is found in the middle of the chamber, and there are no parallel shower tracks in the upper layers. In such a case there is a trivial explanation [5,16]: the arrival of an air family during the assembling or disassembling period, which lasts a few days.

Another important consideration involves the threshold problem. The setting of the threshold is crucial in counting of individual shower cores, particularly if one is interested in large multiplicity events. In our new study we considered the whole data set, considering all detected showers, without restrictions on their location or energy.

VIII. UNUSUAL STRUCTURELESS EVENT, DETECTED AT MOUNTAIN ALTITUDES

We encountered an unexpected structureless event of a few (~ 5 cm) radius detected in x-ray films located at the bottom layers of the homogeneous thick lead chamber. For simplicity hereafter we will call this event "SDX6987" (meaning the structureless event, numbered as 6987, detected in x-ray film). The SDX6987 event appeared as a very faint and diffused dark area. None of the individual showers were found in the area (see Fig. 9). Contrary to the traditional image of a halo [4] of a similar size, the event exhibited very low darkness ($D \leq 0.03$–0.05) above the local background level of the x-ray film. The event penetrated at least three layers of lead plates, and was recognizable even at the last one. Taking into account an approximate relative position of SDX6987 in successive layers of x-ray films, it was concluded that the arrival

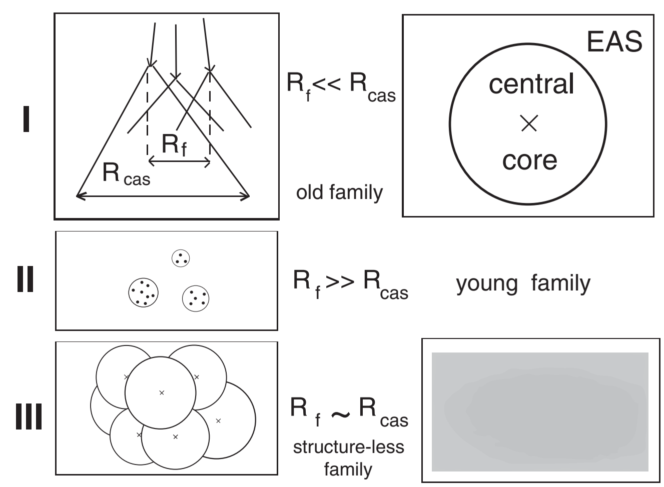

FIG. 9. A schematic view of the cosmic ray families. The inset (I) shows an example of an old family (EAS stands for an extensive air shower), with ($R_{\rm fam} \ll R_{\rm cas}$), where $R_{\rm fam}$ is the geometrical spread of the family, and $R_{\rm cas}$ denotes spread of an air cascade. In this case, one can recognize a core in the event. The inset (II) presents a young family ($R_{\rm fam} \ll R_{\rm cas}$), which shows clusterlike structure. The inset (III) gives an image of the structureless event.

direction might be close to the vertical. By tracing back to the chamber top, we found no shower tracks.

It would be quite exotic to assume that the event had passed through the whole chamber without any trace, and suddenly started to develop in an unusual way, just near the bottom layers of the chamber. A possibility of some chemical, or mechanical irregularities, which could happen particularly in the geometrical area of SDX6987, for instance, during x-ray film processing, could be also ruled out. This is because the event was recognized in a few consecutive layers, the whole area of the films did not show any unusual characteristics, and above all, there were no similar events in the rest of the experimental data. Thus, we assume that the event has been detected, perhaps, during the assembling or disassembling period.

IX. SCENARIO OF THE SDX6987 EVENT FORMATION

To satisfy the observation, the production mechanism of the event should meet the following conditions: large multiplicity, and almost equal energy of secondaries. A proton primary would not satisfy the multiplicity criteria. A heavy primary particle is easier to consider; for instance, a bundle of spectator nucleons, with Fermi momentum $p_t \sim 200$ MeV. In this case several considerations should be taken into account. If an iron nucleus interacts at very high altitude, near the top of the atmosphere, then there will be almost no signal at the mountain altitude. Also, due to the short mean-free path, it is very unlikely to get an iron nucleus interaction near the chamber. The answer is somewhere in between. Here we consider a simple model which explains the picture of the event formation. We introduce two parameters: geometrical spread of a family R_f, and geometrical spread of an air cascade $R_{\rm cas}$. Figure 9 shows a schematic view of families for different values of R_f and $R_{\rm cas}$.

In the case of the structureless event, the spread of a family is comparable to the spread of an individual air cascade. Let us assume that a family is originated at the altitude H above the chamber by N γ-rays with individual γ-ray energy as E_γ, and transverse momentum as p_t. The spread of a family is given by $R_f = (p_t * H)/E_\gamma$, and the spread of a cascade $R_{\rm cas} = K/\epsilon$, where ϵ is an energy threshold in the detector, and K is decascading constant ($K = 11$ TeV mm). Assuming the production height as $H \sim 10$ km, the transverse momentum $\sim$200 MeV, using the condition $R_f \sim R_{\rm cas}$, we obtain $(\epsilon/E_\gamma) = (K/Hp_t) \sim (1/200)$. For a family to be structureless, $(\epsilon/E_\gamma) \sim (1/200)$. If $(\epsilon/E_\gamma) \geq (1/200)$, one can recognize individual air cascade. If $(\epsilon/E_\gamma) \leq (1/200)$, then there is just one centerlike EAS. For each air cascade we have $(\epsilon/E_\gamma) = (K/Hp_t) \sim (1/200)$, and $(E_\gamma) = 200 * \epsilon$. We can assume that the event SDX6987 was formed due to the overlapping of numerous cascades from nucleons at the late stage of development. We have the following estimations of numerical values: $R_{\rm cas} \sim 50$ mm, $\epsilon \sim 200$ GeV, the production height $H \sim 10$ km, and the primary energy of a nucleon $\sim$40 TeV. If so, the most likely origin of the structureless event SDX6987 would be: an iron nucleus with primary energy $E_0 \sim 10^{15}$ eV, which interacted with an air nucleus ($A \sim 14$) at the height $H \sim 10$ km above the chamber. The event is formed by overlapping of the old age cascades from γ-rays initiated by the spectator nucleons (multiplicity $N \sim 40$).

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