MULTIPHOTON DECAYS OF HEAVY PARTICLES*

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Decays of two heavy particles, produced in cosmic ray interactions, are presented. These particles decay into one charged particle and four photons each. The photons converted into electron pairs very close to the decay vertex. Attempts to explain this decay topology with known particle decays are presented. Unless both events represent a $b \to u$ transition, which is statistically unlikely, then other known decay modes for charmed or bottom particles do not account satisfactorily for these observations. This could indicate, possibly, a new decay channel.

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1. Introduction

Cosmic rays provide an opportunity to study nuclear interactions at energies exceeding those accessible at particle accelerators, since the energy spectrum of cosmic rays extends up to at least 10^{20} eV. However, the cosmic ray flux falls rapidly with energy. In consequence, event statistics which can be collected in a single experiment is usually small compared to that in accelerator experiments. In cosmic ray experiments, due to limited statistics, it is sometimes difficult to distinguish between genuine effects and background fluctuations. In the past many discoveries in particle physics were first made using cosmic ray beam, although they started as "anomalies" in cosmic ray interactions. These anomalies were later either confirmed as first hints of some new physics or they were eventually understood in terms of known physics and/or detector properties. An example might be discovery of charmed particles which were first seen in a cosmic ray interaction [1], but could not be proved as new particles until after charm was discovered in accelerator experiments and the appropriate backgrounds evaluated [2]. Other effects like the difference in lifetimes of charged and neutral D mesons, large transverse momentum tail, jet production and rise of nuclear interaction cross section with energy were also first seen in cosmic ray interactions, before they were confirmed in accelerator experiments. On the other hand, there are cosmic ray anomalies which so far have not been confirmed nor understood. Undoubtly, the most widely known anomalies are "centauros"-interactions in which large isospin asymmetries among produced pions are observed.

In this paper we show analysis of heavy particle decays recorded in cosmic ray interactions. The observed features of these decays are difficult to understand completely based upon known high energy phenomenology.

2. Experimental technique

Interactions of cosmic ray nuclei at high energies have been studied by the JACEE Collaboration with emulsion chambers exposed to cosmic radiation in balloon flights at altitudes 3–5 g/cm^2 [3]. Charged particle tracks are recorded in nuclear emulsion plates in the emulsion chambers. The chambers consist of specialized sections: *i)* the primary section is devoted to primary particle charge identification; *ii)* the target section, where interactions preferentially occur, is used for determining the multiplicity and emission angles of particles produced at the interaction vertex; *iii)* in the spacer section the produced particles diverge in space before reaching the calorimeter; *iv)* in the calorimeter section the electromagnetic cascades initiated by individual photons and electrons are observed and their energies are measured. The emulsion plates consist of an acrylic base 800 microns thick, coated on both sides with layers of Fuji emulsion 55–200 microns thick. These plates are interleaved with CR39 plastic plates in the primary section, iron target plates in the target section, paper honeycomb in the spacer section and lead plates and X-ray film in the calorimeter.

The charges of the incoming particle and of all the secondaries are measured via grain, gap, and delta ray counting. Coordinates of secondary particle tracks are recorded in many closely spaced emulsion layers so that particle track reconstruction is reliably done. The track measurements give a precise determination of secondary particle emission angles in the forward cone, out to 0.2–0.5 radians. Any kinks larger than about 0.1 mrad are easily detected on most tracks. In the calorimeter section the three-dimensional development of electromagnetic cascades is observed. The number of cascade electrons is counted at several depths and compared with numbers calculated from three-dimensional cascade theory. The energies of cascades initiated by individual photons and/or electrons are determined with average accuracy about 22% over the 30 GeV – 8 TeV energy range. At lower end of this range the errors on energy determination are larger due to fluctuations in cascade development and reach 50%. Details on chamber structure and measurement techniques can be found in Ref. [4].

3. Characteristics of the decays

Heavy particle decays were carefully searched for in a sample of 15 interactions with energy above 1 TeV/nucleon and multiplicity of produced particles smaller than 50. Among these interactions two events were found which contain secondary vertices (the apparent interaction of one of the particles emerging from the first interaction site) with almost identical, characteristic topology: a singly charged particle track undergoes a kink, with four photons apparently emitted from the kink and converting into electron pairs near the emission point. These vertices have multiplicities, transverse momenta, and photon conversion distances, which make their interpretation as nuclear interactions very unlikely. As discussed below, these vertices most probably are due to particle decays.

One of the decays, shown in Fig. 1, was observed in a 50 TeV/nucleon helium interaction (Event 1): He $+$C $\rightarrow$ He $+$ $38n_s$. The details of its analysis were published in Ref. [5]; here we will only briefly quote its main features. One of the secondary particles, denoted particle 1, decays at a distance of 23.35 mm from the production vertex. From the decay vertex of charged particle 1 only one charged particle (1.1) was emitted within a cone of half-angle 30 degrees (*i.e.* 520 mrad). This track undergoes another kink due to a decay 105.8 mm further downstream. The four electron pairs,

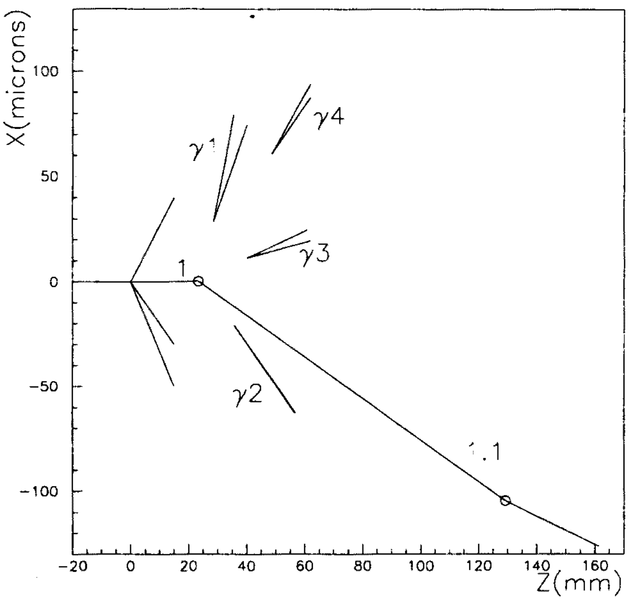

Fig. 1. Projection of decay of particle 1 in Event 1. $\gamma_1, \gamma_2, \gamma_3$ and γ_4 are electron pairs from photon conversions. The decay vertices of particles 1 and 1.1 are marked by circles.

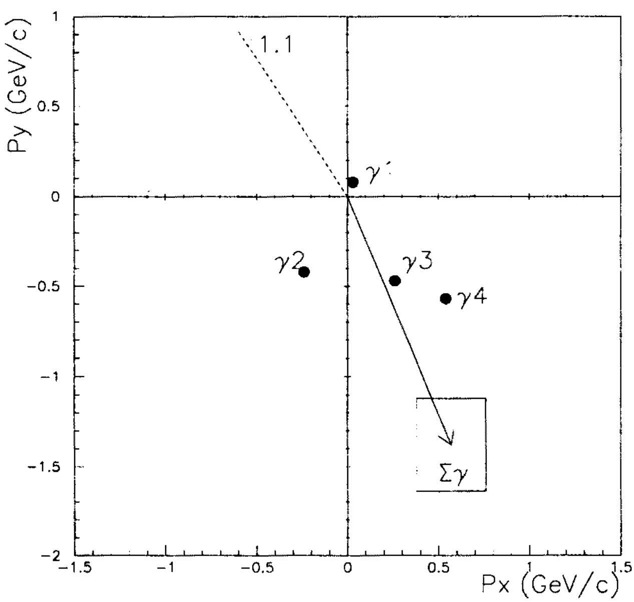

Fig. 2. Transverse momentum balance of decay products of particle 1 in Event 1. The rectangle shows error limits of p_T sum for electron pairs $\gamma_1, \gamma_2, \gamma_3, \gamma_4$. The dashed line shows the direction of p_T of particle 1.1.

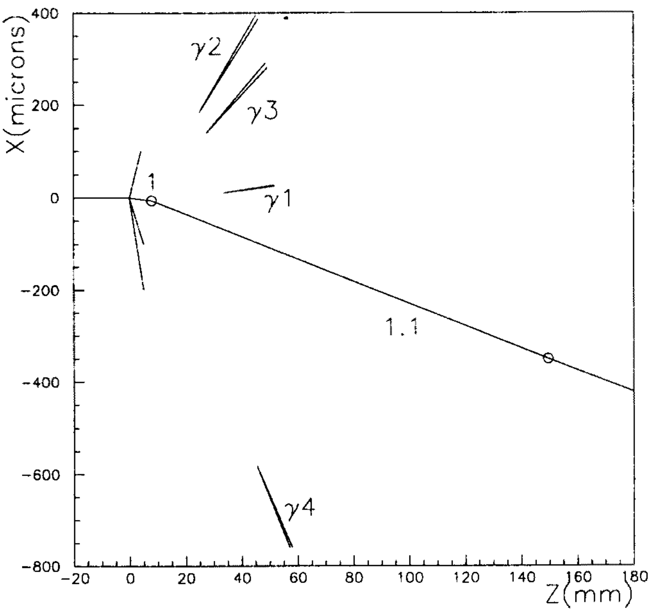

Fig. 3. Decay of particle 1 in Event 2. The notation is the same as in Fig. 1.

presumably resulting from photon conversions, were found in the vicinity of the decay vertex. Their energies and emission angles are listed in Table I. A virtually complete transverse momentum balance at the decay vertex is observed (Fig. 2). This and arguments based on possible decay schemes of particle 1, discussed in Ref. [5] indicate that all decay products of particle 1 were detected. The minimum mass possible for particle 1, assuming zero masses for all its decay products, is 3.8 ± 0.5 GeV, so it must be heavier than charmed particles. This particle was identified as a B meson. Its mass reconstructed from observed decay products, assuming particle 1.1 to be a D_s meson, is 4.8 ± 0.4 GeV.

TABLE I

Energies and emission angles of decay products of particle 1 in the two events. θ and ϕ are polar and azimuthal angles, respectively, relative to direction of the parent particle.

	Event 1				Event 2		
	E(GeV)	θ (mrad)	ϕ (deg)		E (GeV)	θ (mrad)	ϕ (deg)
γ_1	5 ± 4	16.7 ± 0.20	72.1 ± 0.9	γ_1	70 ± 35	1.5 ± 0.10	7.6 ± 3.9
γ_2	130 ± 39	3.7 ± 0.10	239.8 ± 1.8	γ_2	50 ± 25	11.5 ± 0.50	11.5 ± 0.6
γ_3	470 ± 141	1.1 ± 0.10	297.9 ± 4.4	γ_3	50 ± 25	8.6 ± 0.20	22.7 ± 0.8
γ_4	230 ± 69	3.4 ± 0.10	312.6 ± 1.4	γ_4	20 ± 10	14.6 ± 0.20	168.9 ± 0.8
1.1	783 ± 134	1.91 ± 0.04	123.4 ± 1.1	1.1	440 ± 180	1.93 ± 0.03	202.3 ± 0.3

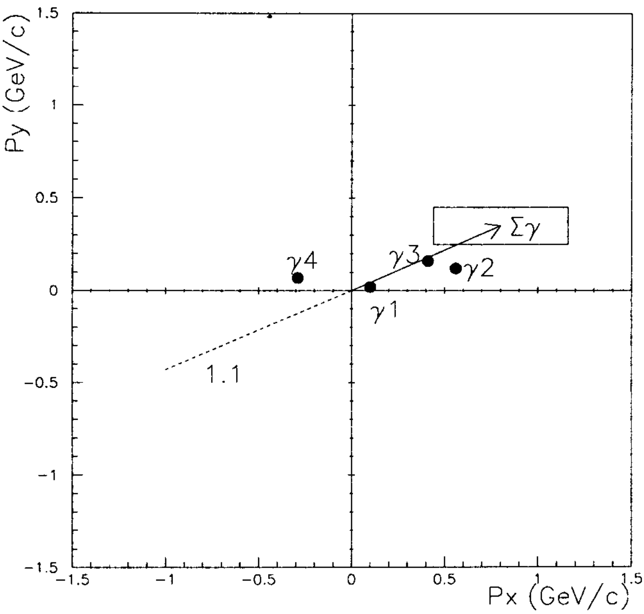

Fig. 4. Transverse momentum balance of decay products of particle 1 in Event 2. The notation is the same as in Fig. 2.

A very similar decay was found [6] in a 4 TeV/nucleon beryllium interaction: Be +Fe → 2He + $8n_s$ (Event 2, shown in Fig. 3). One of the secondary particles, particle 1, produced at the primary vertex, decays after travelling a distance of 7.88 mm. Again, conversions of four photons emitted from the decay vertex are observed and only one charged particle track (1.1) emerges from the decay vertex. This track undergoes another kink within the detector, at a distance of 141.7 mm from the first kink, similar to track 1.1 in Event 1. Presence of other charged particles emitted from the decay vertex of particle 1 is experimentally excluded within a cone of half-angle 10 degrees (175 mrad).

Electromagnetic cascades initiated by three out of the four electron pairs were observed in the calorimeter. Their energies were estimated at 70, 50 and 50 GeV. The energy of the fourth pair was estimated at 20 GeV, based on its opening angle. The accuracy of energy determination in this energy range is of the order of 50%.

Charged particle momenta are not measured in this experiment. The momentum of the charged particle 1.1 can be estimated from the transverse momentum balance at the decay vertex. As seen in Fig. 4, the sum of transverse momenta of the photons has the direction opposite to that of track 1.1, so that the transverse momentum balance between the four photons and the charged particle is complete within experimental errors. The momentum of particle 1.1, determined from this p_T balance is 440 ± 180 GeV/c. This particle undergoes another decay within the detector, 141.7 mm downstream. The decay probability of a 440 GeV kaon on such a short path is $(4.2 \pm 1.7) \cdot 10^{-5}$. It is therefore probable that particle 1.1 is a charmed particle. The lower limit of mass of parent particle 1 (assuming zero masses for all its decay products) is equal 2.5 ± 0.6 GeV. The mass of particle 1 reconstructed with the assumption that particle 1.1 is a D meson, equals 3.9 ± 0.7 GeV. If there were other charged particles emitted from the decay vertex at angles larger than 10 degrees, the mass of particle 1 would have to be larger than masses of known bottom particles. The energies and emission angles of the photons and track 1.1 are listed in Table I. In each of the two events, apart from the four photons originating from particle 1 decay, there are other photon conversions observed, associated with the primary interaction vertex.

4. Discussion

The two decays discussed in this paper show a very close overall similarity, suggesting that particle 1 in Event 2 may also be a bottom particle, although the hypothesis of particle 1 in Event 2 being a charmed particle cannot be ruled out. It is important to stress, however, that the photon conversion distances and emission angles are very well determined in both events. There is no doubt that in each event the four photons discussed point to the decay vertex of particle 1, not to the primary interaction vertex.

The invariant masses of pairs of photons emitted from the decay vertices (Table II) show that the photons in most cases are unlikely to originate from π^0 decays. Only one pair combination in Event 2 reconstructs π^0 mass. All the other combinations result in consistently larger masses. It is therefore probable that some of the photons originated in processes other than π^0 decays, possibly in η meson decays, and/or that there were more photons emitted at the decay vertex, which were not detected.

TABLE II

Invariant masses (in GeV/c^2) of pairs of photons from particle 1 decays in the two events

	Event 1				Event 2		
	γ_1	γ_2	γ_3		γ_1	γ_2	γ_3
γ_2	0.52 ± 0.22			γ_2	0.59 ± 0.21		
γ_3	0.85 ± 0.36	0.79 ± 0.17		γ_3	0.42 ± 0.15	0.17 ± 0.07	
γ_4	0.63 ± 0.27	0.72 ± 0.16	0.76 ± 0.17	γ_4	0.60 ± 0.21	0.81 ± 0.25	0.70 ± 0.25

In both events the distances at which the photons converted into electron pairs are very short: the four photons in the first event converted within 0.38 conversion length, while all four photons in the second event converted within 0.59 conv. length. If there were just four photons emitted from each decay vertex, the probability of such early conversions in the two events would be $4 \cdot 10^{-4}$. The maximum distances at which the search for photon conversions was done are 0.58 and 0.64 conversion lengths, respectively in Events 1 and 2. These correspond to end of the target section of the emulsion chamber. Additional photons are seen in the calorimeter section, however. For photons converting in the calorimeter the accuracy of determination of their direction of flight is poorer than in the target section due to spatial spread of electrons in developing electromagnetic casacades. The larger distance to particle 1 production and decay vertices makes the pointing to these vertices less certain. Hence, it is not possible to distinguish whether the photons converting in the calorimeter originated from the primary interaction vertex or from particle 1 decay vertex. These additional calorimeter photons were therefore assumed to originate from primary interaction vertex. Since only the number of photons converting in the target section (*i.e.* converting early) can be determined reliably, the total number N_γ of photons emitted in the two decays can be estimated only indirectly.

In order to estimate the number of photons emitted from the decays fitting best our data the integral distribution of conversion distances of the eight photons from the two decays is shown in Fig. 5. Also shown are the expected curves for several values of N_γ, the total number of photons possibly emitted in the two decays. The data suggest $N_\gamma \approx 20$, *i.e.* that about 10 photons were emitted in each decay. Of these only four photons in each event would have converted into electron pairs within the scanned regions, while the remaining photons would have escaped detection or converted in the calorimeter section of the emulsion chamber. However, as discussed in detail in Ref. [5], additional, undetected photons emitted from the decay vertex in Event 1 would imply a considerably larger mass of particle 1, so that a strong decay of it into another bottom particle would be possible. On the other hand, it is clear that particle 1 in each event must decay via weak (charged current) interaction, since a particle decaying strongly or electromagnetically would not leave a visible track.

In Event 2 the cascade energies and, consequently, the particle 1 mass, are less accurately determined, but the above argument applies just as well, even if particle 1 is a charmed particle rather than a bottom one. Its observed pathlength implies a typical charm or bottom weak decay lifetime. This favors therefore only four photons being emitted at the decay vertex, but these photons convert into electron pairs unusually early.

Analysis of Event 1 showed [5] that the simplest decay scheme consistent with the data was $B^- \to D_s^- \eta\eta$, with $b \to u$ quark transition. Current e^+e^- data [7] favor $| V_{ub}/V_{cb} | < 0.1$, where V_{ub} and V_{cb} are elements of the

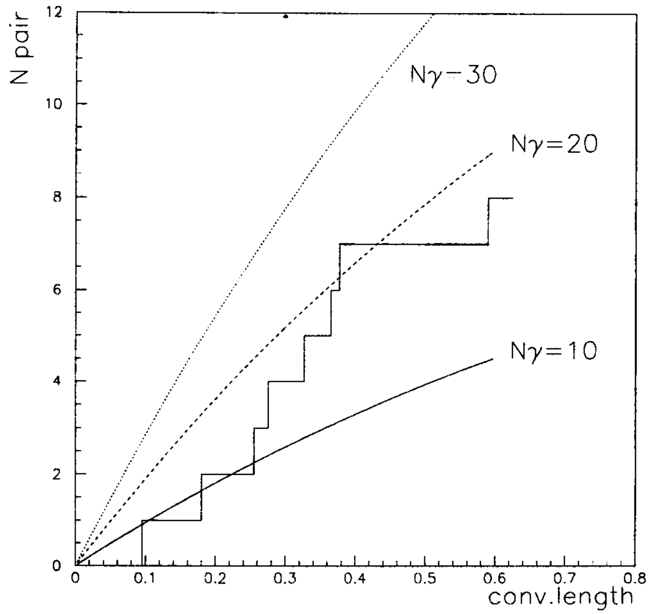

Fig. 5. Integral distribution of conversion distances of the eight photons from the two decays (histogram). The curves show expected distributions for various initial numbers of photons, N_γ.

Cabibbo–Kobayashi–Maskawa matrix, corresponding to $b \to u$ and $b \to c$ quark decays. The $b \to u$ decays should therefore constitute less than 1 % of all bottom decays observed. In our sample of 15 events studied 64 secondary vertices (kinks, vees, 3-prong vertices, *etc.*) were found which are consistent with charm or bottom particle decays. One $b \to u$ decay in such a sample is consistent with the e^+e^- data, and we have no new clues to reinterpret the decay in our Event 1. However, finding another $b \to u$ decay in such a small data sample is much less probable. It is doubtful, statistically, that Event 2 is also a $b \to u$ decay, although such a decay would be consistent with our observation.

While identifying the actual decay channel in Event 2 is not feasible, the overall similarity of decays in Events 1 and 2 may suggest that they are examples of the same, relatively common, decay channel of a bottom particle, with large photon multiplicities. However, any known bottom (or charm) decay modes [8] which might generate such multiphoton decay topology have very small branching ratios. An example might be $B \to \psi(2S)K$, with $\psi(2S) \to \psi(1S)\pi^0\pi^0$, $\psi(1S) \to \gamma\chi_{c0}$, $\chi_{c0} \to \pi^0\pi^0$. The outcome of this chain of decays is $B \to K + 9\gamma$, but its overall probability is 10^{-10}. Modes with fewer photons in the final state are additionally suppressed by the small probability of photon conversion on short distances from the emission vertex. There are many other multiphoton decay modes of bottom particles, but modes with just *one* charged particle in the final state are rare.

In case the two events discussed are examples of decays of *different* particles, their apparent similarity is puzzling, especially that they were found in an event sample so small. It is difficult to reconcile the known branching ratios of heavy particle decays with conversion distances and/or multiplicities of photons emitted in these decays.

Given the difficulty in explaining the observed decay topologies, a question arises "what is a chance that the observed secondary vertices are actually due to nuclear interactions rather than to decays of heavy particles"? To estimate the probability of getting the observed features resulting from secondary nuclear interactions, one needs to consider probabilities of *(i)* nuclear interactions at the observed distances from the primary vertices, *(ii)* charged multiplicity = 1, *(iii)* photon transverse momenta observed, *(iv)* photon conversions within the observed distances (or large photon multiplicity), *(v)* invariant masses of pairs of photons being larger than π^0 mass. The combined probabilities are less than 10^{-8} in each event. These probabilities are even smaller if probability of producing a subsequent kink on track 1.1 is taken into account. The assumption that the secondary vertices are due to nuclear interactions is therefore not justified.

Another hypothesis is that the observed electron pairs are products of decays of some neutral particles rather than of photon conversions. Four such hypothetical particles would be emitted in bottom (or charm) decay and would in turn decay into electron pairs. Invariant electron-positron masses in e^+e^- pairs can be estimated in only 3 pairs in Event 1, in which individual electron energies are reliably measured. These masses turn out to be below 100 MeV. No such particle is known. This evidence for a new particle is too weak to be compelling.

5. Conclusion

The two heavy (most probably bottom) particle decay events found in a sample of 15 low multiplicity cosmic ray interactions show a striking similarity: in both events a singly charged heavy particle decays into just one charged particle and at least four photons. Four of these photons converted within 0.38 and 0.59 conversion length, respectively in the two events. The probability of such early conversions is small ($4 \cdot 10^{-4}$) if there were just four photons emitted in each decay. The observed small conversion distances indicate that there should have been of order 10 photons emitted at each decay vertex. On the other hand, observation of two such multiphoton decays is incompatible with branching ratios of known decays of bottom and charmed particles with the observed topology. Larger photon multiplicities are likely to imply larger parent particle masses, thus enabling their strong or electromagnetic decays, which would contradict the observation.

The decaying particle in one of the events was identified to be a bottom particle. The simplest decay mode compatible with the data is $B^- \to D_s^- \eta\eta$, with $b \to u$ quark transition. Finding two such decays in event sample so small would be incompatible with e^+e^- data on charmless b quark decays. The decaying particle in second event is either bottom or charmed particle and its decay channel cannot be identified. In view of the above it is unlikely that the second decay is also a $b \to u$ decay, but this channel cannot be ruled out.

It may be possible that not all decay products of particle 1 were recorded in the decays discussed. However, those decay products which were detected already allow one to make a conclusion that what is observed is either *(i)* four-photon decays — but the photons convert unusually early in both cases (if both decays represent a $b \to u$ transition, this would in addition be inconsistent with e^+e^- data), or *(ii)* decays with photon multiplicities considerably larger than 4 — but this would be incompatible with branching ratios of known bottom and charm decays, or *(iii)* decays with charged multiplicity larger than 1, with only one charged particle emitted at small angles — but this would imply masses of decaying particles larger than those of known bottom particles, or *(iv)* emission of new, light neutral particles, which in turn decay into e^+e^- — but the available evidence is too weak to be accepted, or *(v)* the observed secondary vertices are actually due to nuclear interactions — but their observed features make this hypothesis improbable, or *(vi)* decays so far unknown.

Since the observed features do not agree with characteristics of known decays, this may be an indication of a new decay channel of a heavy particle. The available data is not yet sufficient to definitely conclude observation of a new decay. Thus, in a sense, these decays are an "anomaly" which waits to be explained.

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