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Long-lived tracks in emulsions: New hadrons or background?

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We discuss the observation of long-lived particle tracks in emulsion chambers in the context of the recent developments in particle physics that hint at the existence of particles with new quantum numbers. Both cosmic ray ($E \simeq 10^4$ GeV) and accelerator ($E = 205$ GeV) events have been reported. We address the following questions: What is the nature of the evidence? What do the observations imply for the production cross sections of new hadrons? What are the backgrounds and how do some of them depend on the accuracy of coplanarity measurements? We reach the following conclusions: Hyperon decay and elastic scattering or diffraction dissociation of a secondary track in the emulsion, mimicking the decay of a long-lived particle, constitute backgrounds at the few- to 50-percent level. Therefore events in which only a single candidate is seen are unlikely to be conclusive; in candidate events in which both members of a possible associated pair of new particles are seen, these backgrounds are suppressed to the 0.01-percent level. If both of the candidates for associated production observed in the cosmic ray energy range are real, we can estimate a production cross section for new particles with hadron beams at the 10–10^2-μb level at 10^4 GeV. From threshold behavior we estimate a production cross section at the 1–10-μb level at Fermilab energies.

I. INTRODUCTION

Developments in theoretical particle physics have for some time been hinting at the requirement of introducing new quantum numbers such as charm and/or color.[1] Such ideas have gained increasing credibility over the past year due to the experimental discovery[2] of a family of particles associated with the long-lived $\psi(3.1)$. Moreover, recently observed features of ν- and $\bar{\nu}$-induced interactions appear to require the existence of hadrons with a new quantum number and with mass of ~2 GeV.[3] More recently a narrow state at 1.865 GeV, decaying in $K\pi$ and $K\pi\pi\pi$, has been observed in electron-positron annihilation.[4] It is most likely the charmed analog of the K meson. Despite a considerable experimental effort, however, the associated production of long-lived particles in hadron collisions has escaped observation. This would provide unambiguous evidence for the existence of a new quantum number in the few-GeV mass range. In the charm scheme we would observe

$$pp \to pp\bar{D}D + \cdots ,$$

$$pp \to pp\bar{C}C + \cdots ,$$

or

$$pp \to pC\bar{D} + \cdots , \text{ etc.,}$$

analogous to the associated production of strange particles, $pp \to ppK^+K^- \ldots$, $pp \to pp\Lambda\bar{\Lambda} \ldots$, or $pp \to p\Lambda K^+$. The D and C particles [charmed analogs of the K and Λ (see Ref. 1 for notation)] are expected to be heavy[1] (1.5–5 GeV), and therefore their production will be suppressed—especially at present accelerator energies, which correspond to the threshold regime (see Fig. 3). Moreover, the lifetimes of such new heavy hadrons might lie in the range 10^{-12}–10^{-14} sec (Ref. 1) and hence be difficult to detect in bubble chambers exposed at accelerators.

These lifetime estimates of charmed hadrons are obtained by scaling the process $\mu \to e + \nu + \bar{\nu}$ in mass. Indeed, the elementary process $c \to s + u + \bar{d}$, i.e., the weak decay of a charmed quark into ordinary quarks, should approximately determine the width of charmed hadrons:

$$\Gamma(c \to \text{hadrons}) \propto \left(\frac{m_c}{m_\mu}\right)^5 \Gamma(\mu \to e\nu\bar{\nu}) \tag{1}$$

$$\simeq 10^{13}\ \text{sec}^{-1} . \tag{2}$$

The distance l traveled by a charmed particle of momentum p can be calculated from Eqs. (1) and (2):

$$l = \gamma c \tau \tag{3}$$

$$= (1\text{–}10 \text{ microns}) \times p \text{ (in GeV)} . \tag{4}$$

The lifetime sensitivity of bubble chambers and emulsions is shown in Fig. 1. The shaded area shows the expected track length of a (nonrelativistic) charmed particle. This band shifts to the right with momentum of the particle according to Eq. (4).

Emulsion chambers of the type used in cosmic ray experiments thus have two advantages in a

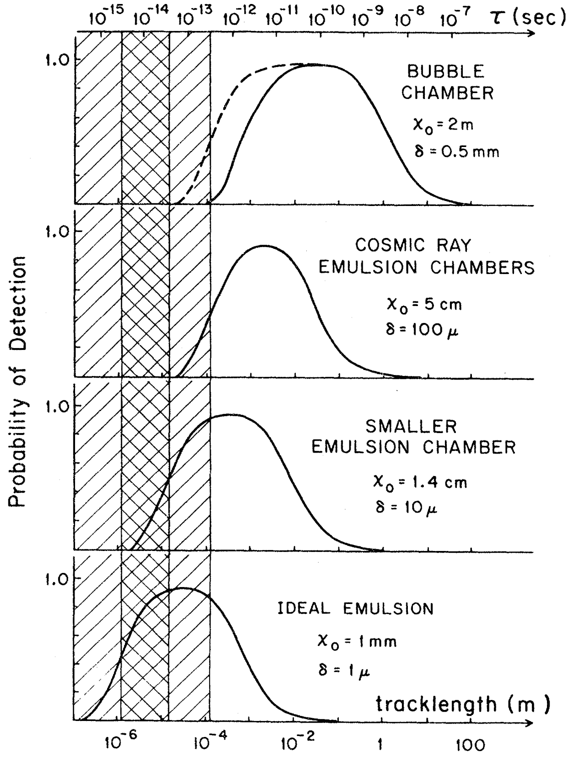

FIG. 1. Track sensitivity of bubble chambers and different types of emulsions. The cross-hatched area is the expected range of (nonrelativistic) charmed particles. (The single-hatched area indicates the ambiguity of this estimate.) This band shifts to the right with increasing momentum of the particle according to Eq. (4). The dashed line is the optimal resolution to be expected from bubble-chamber-type detectors.

search for "charm." (From now on we use "charm" in the general sense as a generic name for the new quantum number.)

(1) They provide an ideal detector for tracks with lifetimes in the range $10^{-12}-10^{-14}$ sec.

(2) They can be flown in balloons for exposure to cosmic rays of ~ 10^4 GeV, where the production cross sections are most likely substantially increased.

In fact, several candidates for new particles have already been observed with emulsion chambers, mostly in cosmic ray exposures above 10^4 GeV. In Fig. 2 an event observed by Sugimoto *et al.*[5] is schematically reproduced. Among the secondaries of a nuclear interaction with 1.84×10^4 GeV incident energy one observes a pair of particles decaying after lifetimes (in their rest frames) of about 10^{-12} sec. Each one decays into a charged particle and a pair of γ rays, observed through the development of their electromagnetic shower in a stack of lead plates below the producer layer of the chamber. The producer layer consists of a sandwich of nuclear emulsion and metaacryl plates. A study of the photon pairs associated with each track reveals that the neutral decay products of the left track and the right track are probably an η meson and a π^0 meson, respectively. Possible interpretations of this event (biased by charm)[6] are

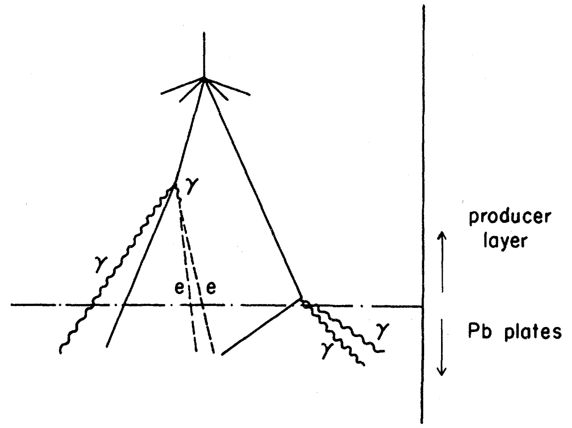

FIG. 2. The candidate for associated production of new hadrons from Ref. 5. Solid lines represent unidentified charged particles, presumably hadrons.

$$\begin{tikzcd} NN \to F^{*\pm} \arrow[ddr] & F^{*\mp} + \text{anything} \arrow[d] \\ & \pi^0\pi^\pm \\ & \eta\pi^\pm \end{tikzcd}$$

or

$$\begin{tikzcd} NN \to D^{\mp} \arrow[ddr] & D^{\pm} + \text{anything} \arrow[d] \\ & \pi^\pm\eta \\ & \pi^\pm\pi^0 . \end{tikzcd}$$

The second possibility is suppressed in the conventional Glashow-Iliopoulos-Maiani (GIM) charm scheme.[6] An allowed possibility would be $D^+ \to \bar{K}^0\pi^+\pi^0$, but this is somewhat unlikely because of the observed coplanarity of the event. Pair production of charmed baryons is also a possibility. The measured opening angles, lengths, and energies of the different tracks imply that the masses of these particles are in the vicinity of 1.5–2.5 GeV and that the lifetimes are in the range $10^{-13}-10^{-12}$ sec., depending on the identities of the charged decay products. The calculated invariant energy of the $D\bar{D}$ pair is ~4–5 GeV. This number is of course reminiscent of the structure in the e^+e^- total cross sections at 4.1 GeV. The event also has the typical phase-space structure of a pair production of heavy particles in the central region. The energies of the heavy particles are ~100 and ~300 GeV as compared to an incident energy of 1.8×10^4 GeV (Feynman $x \simeq 0.01$).

The first such event seen in an emulsion chamber was reported by Niu *et al.* in 1971 (Ref. 7) and immediately interpreted by Hayashi *et al.*[8] as production of a new hadron containing a fourth quark, i.e., as production of a charmed hadron. In this event, one charged track decayed into a charged particle and a π^0 and another charged track decayed into a charged hadron and missing neutrals. If these tracks are interpreted as new hadrons, their masses and lifetimes are in the appropriate range (though the lifetime is about one order of magnitude shorter than in Ref. 5). Moreover, the invariant energy of the two tracks again turns out to be in the SLAC 4.1-GeV bump. However, in this case the heavy hadrons appear to be well into the forward fragmentation region; we return to this point in the conclusion.

The potential importance of these events is obvious. Several candidates have been published in the literature, and they have recently been summarized in Refs. 9 and 10 (see also Table II). Because of their importance we feel that a closer look at their implications for the production cross section of new hadrons, as well as their relevance to present accelerator searches (including many emulsion experiments) is warranted. These calculations are performed in Sec. II of this paper. In Sec. III we discuss possible backgrounds that can simulate tracks of massive new particles in emulsion chambers. We find that the background due to decay of strange particles, to diffraction dissociation or elastic scattering of secondaries in the detector, and to production of direct leptons that subsequently radiate can indeed be significant unless both members of a possible produced pair are observed in an event. We summarize our conclusions in Sec. IV. We have attempted to make the conclusion a self-contained unit.

II. NEW-HADRON-PRODUCTION CROSS SECTIONS

From the observation that Hoshino *et al.*[10] detected two events with possible new hadrons out of a total sample of 365 interactions in the Fermilab exposure and from the observation that in the 10^4 GeV energy range the frequency of such events is about 1 out of 20–40 (Ref. 9), one can make a rough estimate of a corresponding production cross section and its energy dependence. The results are shown in Fig. 3, along with accelerator data on production of known massive hadrons produced in pp collisions in the central region. We use the model of Ref. 11 to provide a convenient representation of the energy dependence of the production cross sections.

Taking these cross sections *at face value*, we conclude that the yield of charmed particles multiplied by their two-body-decay branching ratio is at least an order of magnitude larger than the $\psi(3.1)$ yield in hadronic interactions. This result is suspicious in view of other accelerator searches, but not necessarily wrong. Some searches were performed in the diffraction region, where the cross section is expected to be much smaller[12]; others might have been looking at a suppressed two-body decay mode. Indeed, the emulsion analysis does not unambiguously reveal the nature of the decay products. However, it is very unlikely that all these events can be successfully accomodated in the GIM[13] charm scheme. For example, the conventional estimate for the leptonic branching ratio of charmed particles is 10–20%. Given the cross section of Fig. 3, we can calculate the direct-lepton signal in hadron collisions from new-particle production. Even with the most favorable assumptions (e.g., at 300 GeV $B_{\text{hadrons}}\sigma \cong \sigma \cong 0.03$ mb, $B_{\text{leptons}} \sim 10\%$) we exceed the measured direct-lepton yield at Fermilab[14] by more than an order of magnitude at $p_T = \frac{1}{2} M_D \cong 1$ GeV for two-body decay (and at slightly smaller p_T for three-body decay).

Anticipating our conclusions that only events in which both members of a possible produced pair

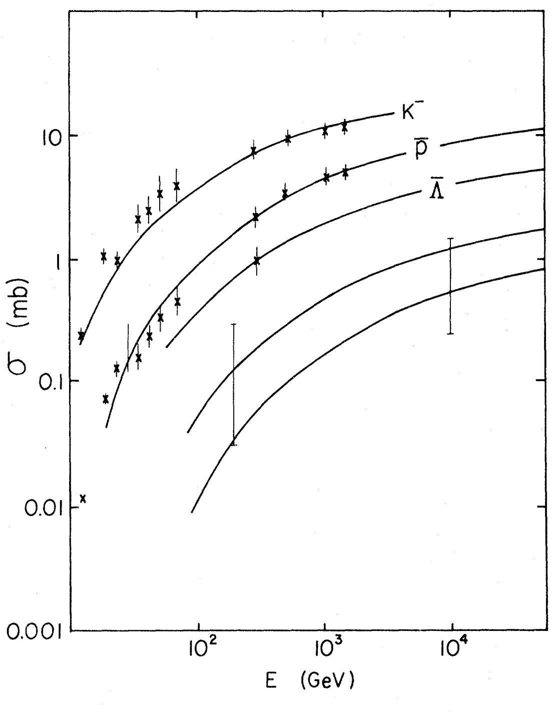

FIG. 3. Excitation curves for production of massive particles. The two large error bars represent estimates of new-particle production from Refs. 9 and 10. Solid lines are from the calculation of Ref. 11.

are observed provide convincing evidence for charmed-particle production, we are left with the two (cosmic ray) candidates of Refs. 5 and 7. Our knowledge of the primary flux allows us to calculate their production cross section. At 10^4 GeV we obtain the lower limit of 0.03 mb shown in Fig. 4. Is this a more acceptable yield than the ones obtained in the previous section on the basis of the totality of events? Noting that K's are the "charmed particles" of ϕ (i.e., the ϕ meson has hidden strangeness in analogy with the hidden charm of ψ) we propose as a rough phenomenological guess that

$$\frac{\sigma_{\text{charm}}}{\sigma(pp\to\psi x)}=\frac{\sigma(pp\to K^- x)}{\sigma(pp\to\phi x)}\,. \tag{5}$$

We obtain at Fermilab energies

$$\sigma_{\text{charm}}=(1-10)\ \mu\text{b}\,. \tag{6}$$

This estimate agrees nicely with the general trend of particle production in the central region as a function of the produced mass (see Fig. 5). SLAC data[4] tell us that $D^0\to K^-\pi^+$ is half a percent of all the events at 1.87 GeV. Present folklore, that above charm threshold half of the e^+e^- cross section is "new physics" and half of "new physics" is due to a heavy lepton, translates this 0.5% into a two-body branching ratio

$$B_{K\pi}=\frac{D^0\to K^-\pi^+}{D^0\to \text{all}}\simeq 2\%\,. \tag{7}$$

From Eqs. (6) and (7) we obtain

$$B_{K\pi}\sigma_{\text{charm}}\simeq(0.01-0.1)\ \mu\text{b}\,. \tag{8}$$

This normalization, combined with the energy dependence of Fig. 3, is shown as the solid line in Fig. 4 along with present experimental upper limits on charm production.[15] These upper limits have been obtained for $m_D > 2$ GeV. If in fact $m_D < 2$ GeV,[4] then these experiments give considerably higher upper limits. For this reason, and because of the (nonexistent) statistics involved in our estimate at 10^4 GeV, we conclude that a $\sigma(pp\to D)\simeq 0.03$ mb cross section at 10^4 GeV is not inconsistent with present phenomenological biases or accelerator upper limits.

III. SOURCES OF BACKGROUND

The typical candidate for a massive new particle with lifetime 10^{-12}–10^{-14} sec is the apparent decay of an energetic prong (or inferred neutral) a short distance from the primary interaction that produced it. Two such examples are shown in the single event[5] in Fig. 2. This is the only event in which all decay products of candidates for both members of an associated production are seen. In other cases only one candidate is seen, or some candidates have some missing decay products. Possible sources of background for these types of events include decay of known hyperons unusually

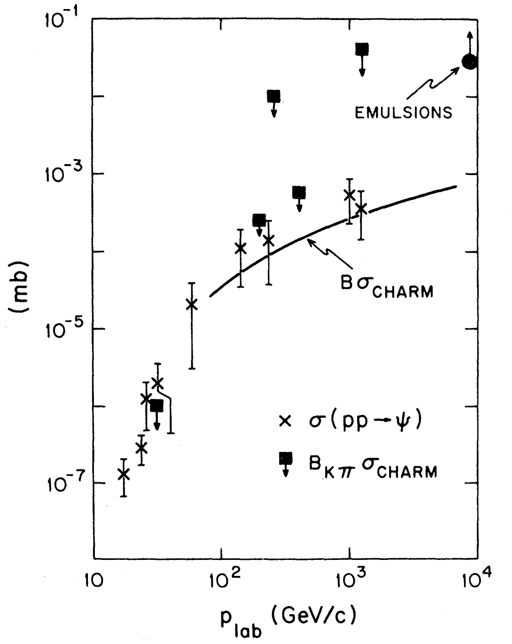

FIG. 4. Experimental upper limits on the production of charmed mesons $B_{K\pi}\sigma_{\text{charm}}$ are compared to the ψ cross section (×), the model calculation of Sec. II (solid line), and a lower limit calculated from the emulsion exposures of Refs. 5 and 7 (●).

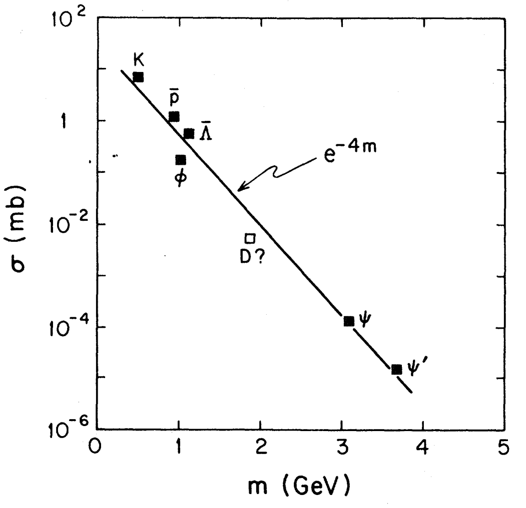

FIG. 5. Compilation of inclusive cross sections for different particle types as a function of mass at $p_{\text{lab}}=300$ GeV (ϕ point at 150 GeV). We show our σ_{charm} estimate of Eq. (6) for comparison.

soon after production, diffraction dissociation or elastic scattering of a secondary, and scattering of a prompt lepton from the initial interaction.

As a preliminary to calculations of these backgrounds, we summarize the properties of the various cosmic ray emulsion chambers. The target for high-energy nuclear interactions in the chambers used in Refs. 5 and 7 is a producer layer that consists of a sandwich of plastic slabs of thickness $\lesssim 1$ mm coated with thin layers of emulsion ($\sim 50\ \mu$m). Total thickness of such producer layers is of the order of a few centimeters. This configuration is ideally suited to looking for decays of energetic (>10 GeV), massive (1–3 GeV) particles with lifetimes in the range of 10^{-12}–10^{-14} sec. Downstream from the producer layer is several radiation lengths of lead plates alternating with films of emulsion. This analyzer layer is used for converting γ rays and electrons and estimating their energies.

The bulk of the material in the producer layer is plastic, so that most interactions take place in light nuclei. Furthermore, the long path length obtained for charged tracks (because they pass mostly through light materials) gives an increased lever arm on the tracks for somewhat better determination of angles and coplanarity than might be possible in emulsion alone. However, the charged-particle tracks are seen only when they pass through the emulsion films ($\sim$every 1 mm) and not while they are in the plastic (most of the path length). This point is crucial for estimating background, because, for example, recoil nuclei from elastic or quasielastic collisions of secondary prongs in the plastic will not be seen unless the recoils are energetic enough to reach a nearby emulsion film. Such an elastic scatter in the plastic can mimic decay of a charged prong from the primary interaction into another charged prong and a missing neutral.

In Table I we summarize the properties of the producer layer and the analyzer layer of the detectors of Refs. 5, 7, and 10. The other cosmic ray events discussed in Ref. 9 were observed with different configurations of emulsion, spacers, and heavy metal, and we refer the reader to the original references[16-20] for details. Here we concentrate on a discussion of background for the emulsion-chamber events, among which appear to be the best examples of possible new particles.

In considering sources of background, we have made no attempt to evaluate purely experimental problems such as stray γ rays or the possibility that two apparently related tracks are actually from separate events. Rather, we have taken energy estimates, vertex locations, angle measurements, etc., and estimates of corresponding uncertainties as stated by the authors, and looked for possible alternative explanations in terms of known particles and processes. The events considered, together with possible backgrounds and estimates of their probabilities, are summarized in Table II. (In making these estimates we have assumed that the entire producer layer has been scanned. If only a portion of its total thickness has been scanned, backgrounds will be reduced proportionately.)

Hyperon decay

The most obvious source of background is a known particle with a two-body decay mode (e.g., $\Lambda \to \pi^- p$ or $\Sigma^+ \to p\pi^0$) that decays unusually soon after production. This has, of course, been considered by the authors and has been ruled out by them in cases where both decay products are seen and the mass of the parent particle can be reconstructed. This possibility can also be ruled out when only the charged decay product is seen provided p_T is measured and larger than allowed by hyperon decay.

We consider one example explicitly. In the accelerator event AJ-21 (Ref. 10) a neutral V is observed about 800 μ after the 205-GeV interaction with an opening angle of 5.69×10^{-2}. If the lower-energy track is a π^- and the higher-energy track a p then $M_{\text{neutral parent}} \cong 1.66 \pm 0.15$ GeV. The alternative identification of charged tracks leads to a still higher mass ($\cong 1.94$ GeV). Thus this V is unlikely to be a Λ. A quantitative estimate of this background is given by

$$B \cong N \times \frac{\sigma_\Lambda}{\sigma_{\text{inel}}} \times P(>4\sigma) \times \frac{1}{2}\,\frac{\Delta}{\gamma c \tau_\Lambda}\,, \qquad (9)$$

where N is the number of events in the sample, P

TABLE I. Properties of emulsion chambers.

	Ref. 5	Ref. 7	Ref. 10
Producer layer			
Thickness of plastic & other light nuclei	11 cm	3.92 cm	1.22 cm
Thickness of Pb	0	0.5 cm	0
Thickness of emulsion	0.61 cm	0.49 cm	0.174 cm
Analyzer layer			
Thickness of Pb	3 cm	2 cm	2 cm
Acceptance	0.1 m^{2}sr[a]	0.1 m^{2}sr[b]	

[a] Authors' estimate. [b] Our estimate.

TABLE II. Catalog of possible new hadrons in emulsions. x^0 denotes missing neutrals other than π^0 or η^0; X denotes possible new hadron; $h^\pm$ is a hadron or muon. The quantities E_0 and n_{ch} refer to the primary interaction in which the X were produced.

Events	Primary energy and n_{ch}	$E(X)$	Backgrounds and probabilities Decay of known hyperon	Diffraction dissociation	Elastic scattering	Direct lepton
Ref. 7 6B-23 $X^\pm \to h^\pm + \pi^0$ $X^\pm \to h^\pm + x^0$	$E_0 \sim 10$ TeV $n_{\mathrm{ch}} = 70$	4 TeV <6 TeV	$\Sigma^+ \to \pi^+ n$, etc., $\sim 0.1\%$	$\sim 1\%$ $\sim 10\%$	$\left.\begin{matrix} \\ \sim 20\% \end{matrix}\right\} \sim 10^{-4}$	
Ref. 5 BEC-II $X^\pm \to h^\pm + \pi^0$ $X^\pm \to h^\pm + \eta^0$	$E_0 \cong 18.4$ TeV $n_{\mathrm{ch}} = 27$	110 ± 17 GeV 330 ± 65 GeV	$<10^{-6}$ for $\Sigma^+ + \bar{\Sigma}^-$ $\searrow \bar{p}\pi^0$ $\searrow p\pi^0$	$<10^{-4}$ for $p \to p\pi^0$ and $\pi \to \pi\eta^0$ in same event		
Ref. 9 11C-34 Complex (possible cascade)	$E_0 \sim 20$ TeV $n_{\mathrm{ch}} = 70$	?				
Ref. 16 T-star $X^0 \to \pi^0 x^0$ $X^0 \to \pi^0 x^0$	$E_0 \sim 20$ TeV $n_{\mathrm{ch}} = 36$	>2.4 TeV >1.6 TeV	$K_S^0 \to \pi^0\pi^0$?			
Ref. 17 ST-2 $X^\pm \to h^\pm \eta^0 x^0$ $X^0 \to \pi^0 x^0$	$E_0 \sim 25$ TeV $n_{\mathrm{ch}} = 51$	? >1 TeV	$\Lambda \to \pi^0 n$ $\sim 0.1\%$			
Ref. 18 Bo-607 $X^0 \to \pi^0 x^0$	$E_0 = 6$ TeV	>2 TeV	$\Lambda \to \pi^0 n$ 0.3%	$n \to \pi^0 n$ 0.1%		Prompt e^+e^- pair is possible. % not known.
Ref. 10 AJ-20 $X^\pm \to h^\pm x^0$	$E_0 = 205$ GeV $n_{\mathrm{ch}} = 17$	$>13 \pm 3$ GeV		$p \to \Lambda K^+$ or $\pi \to K^0 K^+$, etc., $\sim 10\%$	$\sim 20\%$	
Ref. 10 AJ-21 $X^0 \to h^+ h^-$	$n_{\mathrm{ch}} = 16$	39 GeV	5×10^{-6}	0.1%		
Ref. 19 $X^0 \to he[\nu] + x$	$E_0 = 300$ GeV $n_{\mathrm{ch}} = 4$	>9 GeV	6×10^{-4}			
Ref. 20 (2 events) $X \to e + x$	$E_0 = 200$ GeV $n_{\mathrm{ch}} = 13$ $n_{\mathrm{ch}} = 10$	>1 GeV >0.45 GeV				

is the probability of measuring a Λ mass four standard deviations above its true mass, Δ is the thickness of the detector, and $\gamma\tau_\Lambda$ is the dilated lifetime of a Λ with Lorentz factor γ. With[11] $\sigma_\Lambda/\sigma_{\mathrm{inel}} \sim 0.1$ and values of N and Δ appropriate for this experiment, we find

$$B \cong 365 \times 0.1 \times 5 \times 10^{-5} \times \tfrac{1}{2} \times \frac{1.4}{35 \times 7.7} = 5 \times 10^{-6}. \tag{10}$$

Diffraction dissociation

A potential source of background for many of the events is diffraction dissociation of a secondary prong in the target material. For example, a neutron from the initial interaction could dissociate on a nucleus in the producer layer into $p\pi^-$ with invariant mass >1.2 GeV, thus imitating two-body decay of a massive neutral particle. The possible importance of this background has been emphasized by L. W. Jones[21] in connection with the original Niu *et al.* event.[7]

We have used recent data from Fermilab on diffraction dissociation of several-hundred-GeV nucleons to evaluate this source of background quantitatively. The differential cross section, $d\sigma/dM^2$, is shown in Fig. 6 for dissociation of the projectile nucleon into a state of invariant mass M. The solid curve is for $N\rightarrow$ anything (with quantum numbers of incident nucleon) and is taken from the parameterization of P. V. Ramana Murthy *et al.*[22] The lower dashed line shows the data of J. Biel *et al.*[23] for the specific process $n\rightarrow p\pi^-$ ($=p\rightarrow n\pi^+$). The upper dashed curve represents $N\rightarrow N\pi$ and is obtained from the $n\rightarrow p\pi^-$ data by isospin considerations.

The expression for the number of events to be expected from the dissociation background is given by

$$B=N\times\langle n\rangle\times\frac{1}{2}\,\frac{\Delta X}{\lambda_{\mathrm{int}}}\times\frac{\sigma_{\mathrm{diss}}}{\sigma_{\mathrm{inel}}}\times\frac{\langle\theta\rangle}{\pi/2}\,. \tag{11}$$

Here N is the total number of interactions in the sample and $\langle n\rangle$ is the average number of relativistic secondaries appropriate for a given type of background, e.g., charged particles, neutrons, etc. (If only particles within a certain angle of the core are scanned then $\langle n\rangle$ should be appropriately reduced to take this cut into account.) The quantity $\frac{1}{2}(\Delta X/\lambda_{\mathrm{int}})$ gives the probability of the secondary interaction of a charged prong in a detector of thickness ΔX, where the interaction length of the prong is λ_{int} and on the average $\frac{1}{2}$ the detector is available for secondary interactions after the primary interaction. (In all cases considered $\Delta X/\lambda_{\mathrm{int}}\ll 1$.) The quantity $\sigma_{\mathrm{diss}}/\sigma_{\mathrm{inel}}$ is the relative probability of producing a dissociated state with appropriate invariant mass and multiplicity to appear as decay of a new massive hadron. The relative probability of dissociation on a heavy nucleus is presumably somewhat reduced due to screening. Since most of the material in the producer layer of the detectors is light nuclei (plastic), however, we neglect this effect and use the nucleon-target data. Also, we have assumed kaon dissociation to be like nucleon dissociation.

The factor $\langle\theta\rangle/(\pi/2)$ is the average fraction of diffraction-dissociation events for which the decay of the excited state and the recoil of the unobserved struck nucleus are such that the observed decay products and the track which decays are coplanar to within the limits determined by the measurement. For cases in which two decay products are seen the coplanarity condition can reduce the diffraction-dissociation background considerably. If only one decay track is seen there is no coplanarity condition, but the missing neutral must be such as not to convert in the analyzer (e.g., n, Λ, or K_0).

Consider a diffraction dissociation

$$\begin{tikzcd}[column sep=small] X+A \arrow[r] & Y \arrow[d] & +A' \\ & x_1+x_2 & \end{tikzcd}$$

on a nucleus A. It will look like the decay of a track (cr neutral) $X\rightarrow x_1+x_2$ if the direction of X lies in the plane defined by the directions of x_1 and x_2, to within the coplanarity determined by the measurement. Let p_T be the transverse momentum of the recoiling nucleus. If the dissociation $X\rightarrow[Y]\rightarrow x_1x_2$ is to simulate the decay $X\rightarrow x_1x_2$,

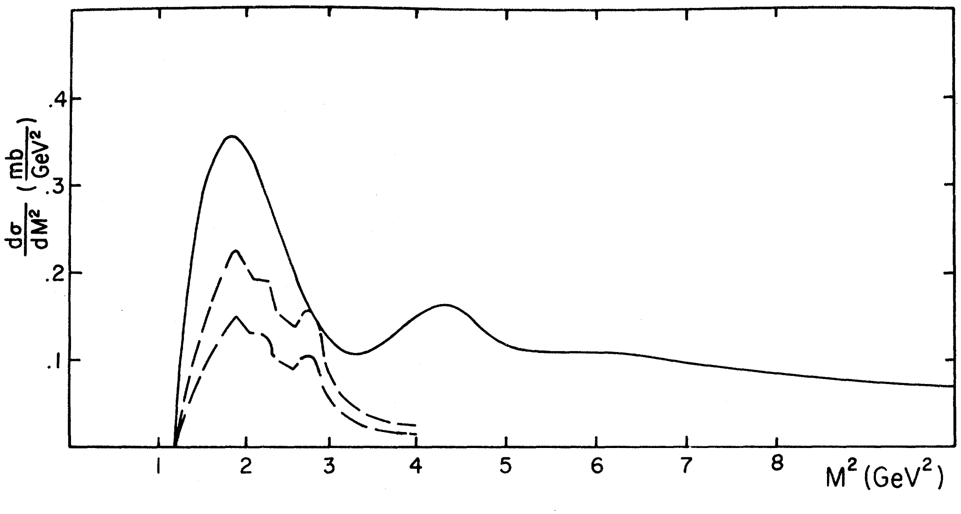

FIG. 6. Diffraction dissociation of a fast nucleon. Solid line: $N\rightarrow$ any state of mass M and quantum numbers of N; lower dashed line: $n\rightarrow p\pi^-$; upper dashed line: $N\rightarrow N\pi$.

the Y must decay in a plane (defined by x_1x_2) rotated with respect to $\vec{p}_T$ by an angle $\leq \theta$ defined by

$$p_T \sin\theta = (E_1 + E_2)\sin\theta_{\text{cop}}\,, \tag{12}$$

where θ_{cop} is the experimental uncertainty in the coplanarity of the directions of X, x_1 and x_2, and E_1 and E_2 are the energies of x_1 and x_2. To estimate $\langle\theta\rangle$, we take $d\sigma/dtdM^2 \propto e^{-B|t|}$. Then

$$\frac{\langle\theta\rangle}{\pi/2} = 2(E_1 + E_2)\theta_{\text{cop}}\left(\frac{B}{\pi}\right)^{1/2}. \tag{13}$$

Near the peak of the distribution in Fig. 6 $B \sim 15$ GeV^{-2} (Refs. 22 and 23), so that

$$\frac{\langle\theta\rangle}{\pi/2} = 4.4\ \text{GeV}^{-1}(E_1 + E_2)\theta_{\text{cop}}\,. \tag{14}$$

For the original experiment of Niu *et al.*[7] (see Table I), $\frac{1}{2}(\Delta/\lambda_{\text{int}}) \sim 0.038$. The total number of jets or primary interactions in the sample of this experiment is not stated. To estimate it we propagate the primary cosmic ray flux down to the depth of the producer layer (260 g/cm^2 of overlying atmosphere plus ~ 15 g/cm^2 air equivalent of lead plates) and multiply by the acceptance of the detector. In Fig. 7 the number of interactions of energy $>E$ per g/cm^2 of target material per m^{2}h srad, for various atmospheric depths is shown. The exposure was the equivalent of one detector flown for ~ 500 h, and we estimate its acceptance to be ~ 0.1 m^2 srad. The minimum-energy interaction accepted is also not stated. If we take $E_{\text{min}} = 2$ TeV, then we estimate $N \cong 0.16$ $[\text{m}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}(\text{g/cm}^2)^{-1}]$, $\times\, 8$ g/cm$^2 \times 0.1$ m^2 srad $\times\, 500$ h $= 64$. (If E_{min} is smaller, N should be correspondingly larger. If some of the interactions in the detector are missed in the scan, then N should be reduced.)

The signature of the candidate event in Ref. 7 is $X^{\pm} \to x^{\pm} + \pi^0$. A dissociation background for this kind of event could be $p(K^{\pm}) \to p(K^{\pm}) + \pi^0$. Since the coplanarity condition [Eq. (14)] reduces the phase space for slow particles drastically, we consider only charged fragments of the primary of the initial interaction as candidates for a background dissociation. Thus $\langle n\rangle \lesssim 1$ in Eq. (11). For dissociation to a state of π^0 plus charged hadron with invariant mass between 1.4 GeV and 3 GeV, we estimate[24] $\sigma_{\text{diss}}/\sigma_{\text{inel}} \sim 0.01$ from the curves in Fig. 6. For this experiment the stated value of accuracy of coplanarity[7] is $\theta_{\text{cop}} \lesssim 2 \times 10^{-5}$ rad. At 10 TeV a typical energy for a fragment X would be 2500 GeV. Substitution of these numbers into Eq. (2) gives $\langle\theta\rangle/\frac{1}{2}\pi = 0.22$.

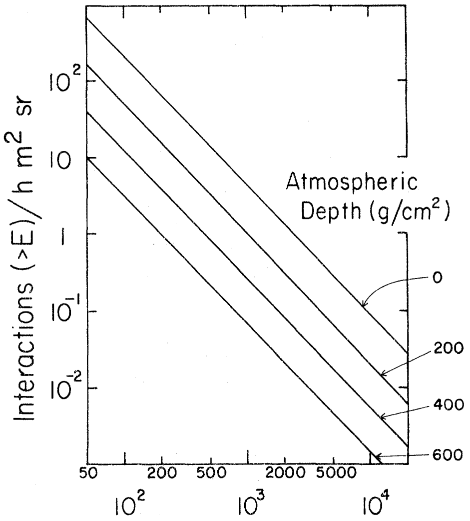

FIG. 7. Interactions calculated for 1 g/cm^2 of target for a detector exposed to the cosmic-ray beam at various atmospheric depths.

Armed with these estimates of the quantities in Eq. (11), we find a background of

$$B \sim 64 \times 1 \times 0.03 \times 0.01 \times 0.22 \cong 0.005\,.$$

The coplanarity condition is crucial for obtaining this small result. Without it, $\langle n\rangle \to \sim 3$ (to include slow p, $\bar{p}$, and $K^{\pm}$), and $\langle\theta\rangle/\frac{1}{2}\pi \to 1$, thus increasing this background by a factor of about 15. If, in addition, three- and higher-body decays are included, then $\langle n\rangle$ must include secondary charged pions, and $\langle n_{\text{ch}}\rangle \sim 15$ at 10 TeV. Also in this case, the total diffraction-dissociation background must be included, and from the solid line of Fig. 6 we estimate $\sigma_{\text{diss}}/\sigma_{\text{inel}} = 0.03$ for $1.4 \lesssim M \lesssim 3$ GeV. For the number of diffraction-dissociation events expected in the sample one then has $B \sim 64 \times 15 \times 0.038 \times 0.03 = 1$. The exhibition of such events, clearly distinguished from the candidates for decay of massive particles, would do a great deal to strengthen the case for observation of new particles with short lifetimes.

As another example of the possibility of diffraction dissociation imitating decay of a massive particle we estimate this effect for the exposure of the emulsion chamber at Fermilab.[10] Consider first the neutral V (event AJ-21). Here we use the cross section for the specific channels $n \to p\pi^-$ and $n \to n\pi^+\pi^-$, which gives $\sigma_{\text{diss}}/\sigma_{\text{inel}} \lesssim 0.02$. In this case θ_{cop} is given as 10^{-4} rad, and for 205 GeV interactions $E_1 + E_2 \sim 100$ GeV. Thus $\langle\theta\rangle/\pi \sim 0.044$. For this detector $\frac{1}{2}(\Delta/\lambda_{\text{int}}) \sim 0.012$. Thus with $\langle n_{\text{fast neutrons}}\rangle = \frac{1}{3}$, the probability that one event of this kind would be seen among the 365 interactions investigated by Niu *et al.* is ~0.1%.

The other accelerator event is of the type $X^{\pm} \to h^{\pm} + x^0$, where x^0 is a missing neutral. In this case there is no coplanarity condition, and $x^0 \neq \pi^0$, η^0 because no γ converted in the analyzer. Possible background dissociations therefore include $p \to n\pi^+$, $p \to \Lambda K^+$, and $\pi^{\pm} \to K^0 K^{\pm}$. We estimate $\langle n\rangle \sim 1$ and $\sigma_{\rm diss}/\sigma_{\rm inel} \sim 0.02$, so that $B \sim 10\%$.

Elastic scattering

A single charged track that undergoes a large-angle scattering (classified as $X^{\pm} \to h^{\pm} + x^0$ in Refs. 9 and 10, where x^0 is not seen) could also be elastic scattering. The calculation of this background basically follows the steps outlined above with $\sigma_{\rm diss}/\sigma_{\rm inel} \to \sigma_{\rm el}(>\theta_{\rm min})/\sigma_{\rm el}$ and $\lambda_{\rm int} \to \lambda_{\rm el}$. Here $\sigma_{\rm el}$ and $\lambda_{\rm el}$ refer to elastic scattering from the appropriate nuclear target and $\theta_{\rm min}$ is the minimum laboratory angle considered to be large-angle scattering. If $\theta_{\rm min}$ is large enough, this background is, of course, negligible; however, as we show below, this is not necessarily the case for possible elastic scatters in the events of Niu *et al.*[7,9,10]

The analysis of the background due to elastic scattering is considerably complicated by the sandwich structure of the producer layer. Typically in elastic scattering in an emulsion (either from a nucleus, a free proton, or a nucleon in a nucleus), the recoil of the target would be visible. In this case elastic scattering of a charged particle could be distinguished from, say, $\Sigma^+ \to \pi^+ n$ by the presence of a heavily ionizing recoil track. In the producer layer, however, the bulk of the material is plastic, and charged particles are only observed in the thin layers of emulsion (separated by approximately 1 mm). Thus elastic scattering can masquerade as $X^{\pm} \to h^{\pm} +$ missing neutral if it takes place in the plastic far enough from an emulsion film so that recoil particles stop in the plastic.

In estimating this source of background, it is necessary to distinguish four kinds of elastic scattering:

(1) Elastic scattering from hydrogen nuclei in the plastic;

(2) True elastic scattering from a C or O nucleus in the plastic;

(3) Inelastic scattering from the nucleus without particle production; and

(4) Scattering from a nucleon in the edge of a nucleus (a subcase of 3).

For case 1 the energy of the recoil proton can be calculated in a straightforward way from $\theta_{\rm min}$ and the energy, E, of the secondary prong that scatters. From the recoil energy a corresponding range can be calculated and compared to the spacing between emulsion films. True elastic scattering from a C or O nucleus is very sharply peaked and gives negligible large-angle scattering. Its contribution to this background can therefore be neglected. On the other hand, inelastic scattering from a nucleus without particle production does have an appreciable high-p_T tail. However, in case 3 the struck nucleus will presumably be excited sufficiently to evaporate nucleons in a significant fraction of such collisions. Energies of evaporation protons typically correspond[25] to a range in plastic of 1.3 mm. This circumstance should greatly reduce this source of background. Scattering from a nucleon in the edge of a nucleus is, apart from Fermi motion of the target nucleon, similar to elastic scattering from a free proton. In particular, if the target nucleon is a neutron, its recoil energy is irrelevant since it cannot be seen in the emulsion (except in the unlikely event that it interacts again). We first estimate the background due to elastic scattering generally. We then comment on the extent to which the possibility of observing recoil particles by scanning emulsion films near the point of scattering serves to reduce this source of background.

Since $\sigma_{\rm el}(>\theta_{\rm min})$ depends on the energy of the secondary particle that scatters, the appropriate generalization of Eq. (11) is

$$B \cong N \frac{1}{2} \frac{\Delta X}{\lambda_{\rm el}} \int_{E_{\rm min}}^{E_0} \frac{dn}{dE} \frac{\sigma_{\rm el}(>\theta_{\rm min}, E)}{\sigma_{\rm el}} dE\,, \qquad (15)$$

where dn/dE is the distribution in lab energy of the secondaries produced in the interaction of energy E_0. $E_{\rm min}$ is a low-energy cut, corresponding to the possible neglect of secondaries at large angle to the core. In Eq. (19)

$$\sigma_{\rm el}(>\theta_{\rm min}, E) \cong \int_{(\theta_{\rm min}E)^2}^{\infty} \frac{d\sigma}{dt}\, dt\,, \qquad (16)$$

where $d\sigma/dt$ is the differential cross section for an appropriate nuclear target in the producer layer of the detector. [Eq. (15) is actually a sum over terms for each kind of scatterer in the plastic.]

Inelastic scattering from a nucleus without particle production can be calculated within the Glauber scheme[26] provided all possible final nuclear states are summed over. Such a calculation thus contains all possible final states of the nucleus, including excited states that decay by γ emission, highly excited states from which nucleons are evaporated, and collisions with nucleons in the periphery of the nucleus. We use the calculation of Ref. 26 to evaluate Eq. (16) for carbon, and estimate the background from this source. For the detector exposed at Fermilab[10] we take $\theta_{\min}=3.6\times10^{-2}$ rad (the angle actually seen in AJ-20 and therefore a conservative choice) the integral in Eq. (15) is 0.21. The corresponding value for elastic scattering from free protons is 0.85, and the weight for this process to occur in plastic is roughly 8%. For the detector exposed at Fermilab $\frac{1}{2}(\Delta X/\lambda_{\mathrm{el}})=0.006$, so the probability per event of seeing an "elastic" scatter with $\theta>3.6\times10^{-2}$ rad is 0.0016. The average number of such scatters expected in the 365 interaction sample is 0.57. If the minimum angle requirement is relaxed to $\theta_{\min}>10^{-2}$ rad the corresponding number is ~3.2.

In the original Niu cosmic ray event[7] a track CC' was of the type $X^{\pm}\to h^{\pm}+x^0$, with a scattering angle of 1.5×10^{-3} rad. This scattered track is a possible partner in associated production of the particle with the apparent decay $X^{\pm}\to h^{\pm}+\pi^0$. Again considering only secondaries with Feynman $x>0$, but now with $E_0\sim10$ TeV, we estimate the weighted sum of the integrals in Eq. (19) to be 1.8 for $\theta_{\min}=1.5\times10^{-3}$ rad. For $E_0\sim20$ TeV the corresponding number is ~1.3. The producer layer of this detector was considerably thicker, and $\frac{1}{2}(\Delta X/\lambda_{\mathrm{el}})\sim0.02$. Thus the probability per observed interaction of such an elastic scatter is $\sim4\%$, and two or three such scatters might have been seen among the interactions scanned by Niu *et al.* from their original cosmic ray exposure.[7]

Since scanning the emulsion chamber involves looking for possible recoil tracks associated with a large-angle scattering, the contribution of scatters in which the residual nucleus evaporates particles cannot be included. Furthermore, even for scattering from free protons or from protons in the nucleus without significant nuclear excitation, only if the energy of the recoiling struck proton is low enough so it is unlikely to reach a neighboring emulsion film can such scattering contribute to background. If we guess that $\lesssim50\%$ elastic scatters do not involve significant nuclear excitation and if we require a range perpendicular to the films of <1 mm, then the fraction of elastic and quasielastic scatters that contributes to background is reduced to about $\frac{1}{3}$ of its total value at 205 GeV and $\theta_{\min}=3.6\times10^{-2}$ and to about 8% of its total value at 10^4 GeV and $\theta_{\min}=1.5\times10^{-3}$. The probability of seeing one such event in the original Niu *et al.* experiment and in the accelerator exposure is therefore roughly the same and about 20%.

Direct leptons

Another potential source of background for $X^{\pm}\to h^{\pm}+x^0$ or $X^{\pm}\to h^{\pm}+\gamma$ is direct electron production, so that $X^{\pm}$ would be an electron produced in the interaction and $h^{\pm}$ the electron after bremsstrahlung. Phenomenologically, the rate expected can be obtained from the observed ratio $e^{\pm}/\pi^{\pm}\sim10^{-4}$ (Ref. 14). In the emulsion-chamber experiments, however, the possibility that $h^{\pm}$ is an electron is presumably ruled out by the absence of a shower in the Pb-emulsion analyzer downstream from the producer layer. In any case, some direct-lepton production could be due to production of charmed hadrons and their subsequent leptonic or semileptonic decay. Indeed, three direct-lepton events obtained in emulsion stacks at Fermilab[19,20] have been interpreted in this way.

In Ref. 19 a V (interpreted as electron + hadron) was seen about 200 μm from the interaction. This distance would appear to rule out alternate sources of direct lepton production such as vector-meson decay. The authors[19] have estimated other sources of background, such as semileptonic decay of Λ or K^0_L, and find it negligible. [Their estimate of $\lesssim10^{-6}$ appears, however, to be the probability that a single Λ or K would decay to $h+e+\nu$ within 200 μm. Presumably this number should be multiplied by the number of events in the sample (800) and by the number of Λ and K^0_L per event at 200 GeV (~0.3). In addition, the distance scanned was 500 μm not 200 μm. Thus $10^{-6}\to6\times10^{-4}$.] The momentum of the decay hadron (9 GeV) is consistent with a parent hadron from the central region of the 300-GeV interaction.

The authors of Ref. 20 see two events with a single electron produced within 3 μm of the interaction (corresponding to a lifetime about 2 orders of magnitude shorter than the event of Ref. 19). To the extent that they can rule out a second electron (as they claim they can) this rules out Dalitz pairs, leptonic decay of neutral vector mesons, and the Drell-Yan process as background.

Summary of backgrounds

The principal background for candidates for new particles of the type $X^{\pm}\to h^{\pm}+\pi^0$ (or η^0) is diffraction dissociation of a fast secondary from the primary interaction. The probability of seeing one such dissociation in the sample scanned is typically at the one to few percent level, depending on the accuracy of the coplanarity measurement. This is about a factor of 20 higher than estimates in Ref. 7 (where we have taken account of the fact that their background estimates are stated as probability per event rather than per sample of events).

For candidates of the type $X^{\pm}\to h^{\pm}+$ missing neutral, the elastic-scattering and diffraction-dissociation backgrounds are comparable and lead one to expect ~ 0.4 such accidentals in a typical sample. Candidates in this category are clearly much less significant than those in which all decay products of the possible new particles are seen.

With backgrounds for single candidates this large, it is important to look for events in which both members of a possible pair of new particles are seen to decay. In this case, the background is given by $N \times \frac{1}{2} P_1 P_2$, where N is the number of events scanned and P_i is the probability per event of seeing a secondary track that looks like a decay of the type i. In the original event of Niu *et al.*[7] a track of the type $X^\pm \rightarrow h^\pm +$ missing neutrals was seen in association with the track $X^\pm \rightarrow h^\pm + \pi^0$. Therefore, for this event $P_1 \sim 5 \times 10^{-3}$, $P_2 \sim 8 \times 10^{-5}$, and if $N = 64$, the estimated background is $\sim 1.3 \times 10^{-5}$. If the coplanarity condition is ignored[27] this number becomes $\sim 2 \times 10^{-4}$.

For the event of Ref. 5 (shown in Fig. 2) both decays were of the type $X^\pm \rightarrow h^\pm + \pi^0$ (or η^0). Apart from possible technical considerations,[28] this is therefore the strongest event. We estimate the background for this event as follows: Judging from the authors' discussion of the coplanarity condition, $\langle \theta \rangle / \frac{1}{2}\pi = 1$ for the diffraction-dissociation background. Thus $\langle n \rangle \sim 3$. From Table I, $\frac{1}{2}(\Delta X / \lambda_{\text{inel}}) \cong 0.07$. Then, with $\sigma_{\text{diss}} / \sigma_{\text{inel}} = 0.01$, the probability per event of one diffraction dissociation that looks like two-body decay is ~ 0.002. The corresponding background for two diffraction dissociations in the same event that looks like pair production is $2 \times 10^{-6} \times$ (number of events in the sample). The latter is not given, but from Fig. 7 and the exposure of 1 m^{2}h sr (Ref. 5) one expects 15 interactions > 2 TeV. Thus the relevant background is $\sim 3 \times 10^{-5}$.

IV. CONCLUSION

In discussing the likelihood that candidates for new particles observed in emulsion chambers are genuine, we have seen that it is crucial to distinguish events containing a single such candidate from events showing two candidates (possible associated production). While it is of course possible for only one member of an associated pair to be seen to decay in the chamber, it is also true that the chances are much larger when only one candidate is seen that the event is spurious.

If P_i is the probability per event of a secondary interaction (e.g., diffraction dissociation or elastic scattering) appropriate to mimic a decay of type i, then the background for events with single candidates is NP_i, whereas the background for candidates for associated production is $N \times \frac{1}{2} P_1 P_2$, where N is the number of events in the sample. In the detailed discussion of backgrounds (preceding section) we have shown that NP is typically one to a few percent for candidates of the type $X^\pm \rightarrow h^\pm + \pi^0$ (or η^0) and ~ 30–40 % for candidates like $X^\pm \rightarrow h^\pm +$ missing neutrals.[29] In contrast, for the two candidates for associated production that we discussed in detail, the background is of order 0.01%.

Among the eight events (from seven different exposures) collected in the review papers of Ref. 9, three[5,7,17] involve possible pair production (all in cosmic rays), three[10,18] contain only one candidate (including both events from the exposure at Fermilab), and one appears to involve multiple production and lacks sufficient information for analysis. In the remaining event[16] it is not clear whether there are candidates for one or for two new neutral hadrons. The assumption that all or most of these candidates are real would lead to the following unlikely set of consequences:

large production cross sections × branching ratio to two-body decay (> 30 μb at 200 GeV and > 0.3 mb at 10 TeV);

small branching ratios to decays including leptons (1% to avoid conflict with observed direct-lepton signal at $p_T \lesssim 1$ GeV);

a preference for production in the fragmentation region (rather than the central region of rapidity);

a preference for production in events with high multiplicity (it is not necessarily unlikely that massive particle production takes place mainly in head-on collisions with high multiplicity[30]; on the other hand, P_i is proportional to multiplicity so that the background is higher in such events);

mainly two-body decays of new hadrons in contrast to expectation.[1]

(The last three conclusions could be influenced by biases that result from the fact the preliminary scanning was apparently for energetic photons from an interaction.)

These considerations, taken together with the existence of backgrounds that we have been able to identify at the level of 0.1–40%, lead us to conclude that it is likely that at least some of the events are spurious. On the other hand, if one or two of the cosmic ray events actually involve associated production of new hadrons, this would be consistent with a cross section as small as, say, 0.03 mb at 10 TeV.[31] The excitation curves in Fig. 3 in turn suggest that this would correspond to a production cross section of ~ 3 μb at 200 GeV. This is small enough to allow a branching ratio to leptons of 10% without conflict with the direct-lepton data.

Presumably the most likely candidates for associated production of new particles are those with possible pair production, preferably where both decay products of each new particle are seen. We have summarized in Table III the masses and lifetimes of the parent particles (calculated for various assumptions about the identities of the charged decay products) for the four candidates for which both decay products were seen. Three of these were from the events[5,7] which show possible associated production of a pair of new particles. For the three cosmic ray candidates for new particles the masses are comparable for some of the decay possibilities (≤ 2 GeV if the new particle is a meson), but the observed lifetimes of these particular particles range over two orders of magnitude.[32] We also note that it is difficult to fit the observed two-body decays $X^{\pm} \to h^{\pm} + \pi^0$ (η^0) into the preferred decay modes of mesons in the conventional charm scheme.[6]

Our quantitative evaluation of backgrounds has been limited by lack of information about the details of past cosmic ray experiments (such as exposure, number of events scanned, energy cuts, etc.). However, our discussion is sufficient to illustrate that one will be able to make a good case for the existence of new hadrons with lifetimes in the range 10^{-12}–10^{-14} sec by collecting a sample of events that show possible pair production in a single exposure of an emulsion chamber. On the other hand, events in which only a single candidate is seen are unlikely to be conclusive.[33] These remarks apply specifically to the production of charmed particles in strong interactions. In fact, as mentioned in Ref. 1, the use of ν interactions may be a cleaner way to look for charm with emulsions. In this case, most events may contain only a single charmed hadron.

In using the emulsion technique for any type of charm search, however, it will be useful to keep the following points in mind:

(1) It is important to be able to find examples of secondary interactions, etc., that are potential sources of background and to show that they can be distinguished from genuine decay of a new massive hadron.

(2) Alternatively, or in addition, it is important to calculate possible backgrounds and demonstrate that they are small.

(3) It is possible[34] that the average multiplicity of the hadronic decay of a charmed meson may be as large as 4. It will therefore be important to design a scanning technique that can distinguish multibody decays from background as well as two-body decays.

(4) Scanning biases associated with the fact that high-energy electromagnetic cascades (e.g., from

TABLE III. Masses (and lifetimes) of possible new particles for various assumptions about the unidentified charged decay products. (Symbols in parentheses in the first column refer only to the event of Ref. 10).

			Niu *et al.*	
	Sugimoto *et al.* (Ref. 5) ~20 TeV event		Ref. 7 ~10 TeV event	Ref. 20 205 GeV event
Charged decay products	Prong 2 $X^{\pm} \to h^{\pm}\eta^0$	Prong 20 $X^{\pm} \to h^{\pm}\pi^0$	$X^{\pm} \to h^{\pm}\pi^0$	$X^0 \to h^+h^-$
X = meson				
$\pi^{\pm}(\pi)$	1.50 ± 0.38 GeV (4.6×10^{-13} sec)	1.59 ± 0.40 (3.1×10^{-12} sec)	1.79 ± 0.17 (2.2×10^{-14} sec)	1.16 ± 0.21 (7.6×10^{-14} sec)
$K^{\pm}(\pi)$	1.66 ± 0.42 (5.1×10^{-13} sec)	1.74 ± 0.44 (3.4×10^{-12} sec)	2.15 ± 0.20 (2.6×10^{-14} sec)	1.35 ± 0.25 (9×10^{-14} sec)
$(K\bar{K})$				1.53 ± 0.16 (10^{-13} sec)
$(p\bar{p})$				2.26 ± 0.11 (1.5×10^{-13} sec)
X = baryon				
$p(\pi)$	1.98 ± 0.50 (6.1×10^{-13} sec)	2.10 ± 0.53 (4.1×10^{-12} sec)	2.95 ± 0.26 (3.6×10^{-14} sec)	1.8 ± 0.3 (1.2×10^{-13} sec)
(pK)				1.9 ± 0.25 (1.3×10^{-13} sec)
$\Sigma(\pi)$	2.23 ± 0.56 (6.8×10^{-13} sec)	2.36 ± 0.59 (4.5×10^{-12} sec)	3.50 ± 0.30 (4.3×10^{-14} sec)	2.1 ± 0.35 (1.4×10^{-13} sec)
(ΣK)				2.2 ± 0.3 (1.4×10^{-13} sec)

π^0 decay) are relatively easy to see in emulsion will have to be overcome.

Note added in proof. We note that the event observed by Sugimoto *et al.*[5] is consistent with the hypothesis of a pair production of the charmed baryon of mass 2.26 GeV (see Table III), recently discovered by Knapp *et al.* [Phys. Ref. Lett. 37, 882 (1976)].

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[24] The mass region 1.4–3 GeV is chosen because it is above the masses of known hyperons and covers the range in which dissociation is primarily to two- and

three-body final states. The numerical estimate is obtained as follows: The area above $M = 1.4$ GeV under the lower dashed curve ($p \rightarrow n\pi^+$) in Fig. 6 is about 150 μb. Isospin considerations then give 75 μb for $p \rightarrow p\pi^0$. The process $p \rightarrow n\pi^+\pi^0$ can also provide a background if a coplanarity condition similar to Eq. (14) is satisfied and if the component of the transverse momentum of the unseen neutron in the $\pi^+\pi^0$ plane is within the uncertainty of the experimental observation that $p_T(\pi^+) + p_T(\pi^0) \cong 0$. The uncertainties in the experiment are such that an unobserved n would probably not spoil the transverse-momentum balance in the $\pi^+\pi^0$ plane. We assume (somewhat arbitrarily) that the total dissociation cross section for $p \rightarrow n\pi^+\pi^0$ is about 225 μb. This is consistent with a measurement at CERN-ISR of ~ 170 μb for dissociation of a proton to the state $p\pi^+\pi^-$ with $M < 2.5$ GeV [P. Strolin, in *Proceedings of the X Rencontre de Moriond, Mêribel-lês-Allues, France, 1975,* edited by J. Tran Thanh Van (Université de Paris—Sud, Orsay, 1975), Vol. 1, p. 47]. Thus we find the order of magnitude estimate, $\sigma_{\text{diss}}/\sigma_{\text{inel}} \sim (0.225 + 0.075)/30 = 0.01$.

[25] C. F. Powell, P. H. Fowler, and D. M. Perkins, *The Study of Elementary Particles by the Photographic Method* (Pergamon, London, 1959).

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[27] The result $\theta_{\text{cop}} = 2 \times 10^{-5}$ quoted in Ref. 7 can be reproduced by taking resolution/target thickness $= 1\ \mu/5$ cm. One micron is the ultimate resolution of an emulsion. When one of the partners in the coplanarity condition is a π^0, however, the resolution is presumably much worse (e.g., tens of microns as in Ref. 5) and it seems hard to justify the small θ_{cop}.

[28] P. Freier, private communication.

[29] The frequency of secondary interactions, such as diffraction dissociation and elastic scattering, that can imitate decay of a new particle in an emulsion chamber is, however, reasonably large, especially before cuts due to coplanarity, recoil prongs, etc., are made. We therefore urge experimenters to catalog all events in the sample and demonstrate that a potential background can be distinguished from the real thing. Another important reason for listing all events scanned is that backgrounds are linearly proportional and cross sections inversely proportional to the number of events in the sample. Evaluation of the results is therefore difficult without this information.

[30] T. K. Gaisser, H. I. Miettinen, C.-I Tan, and D. M. Tow, Phys. Lett. 51B, 83 (1974).

[31] This estimate is based on the assumption that the samples from which the events of Refs. 5, 7, 16, 17, and 18 are taken contain some several hundred to one thousand events altogether. In general the authors have not stated how many events were actually scanned. (Ref. 18 is an exception to this.)

[32] In Ref. 9 an integral lifetime distribution was made for all 16 candidates for new particles included in the summary. Lifetimes were assigned by assuming $M = 2$ GeV for all candidates. Distinct lifetimes for charged and for neutral candidates were found from the slopes of the corresponding histograms. It is not clear to what extent this procedure is meaningful, because apparently no attempt was made to remove from the data the bias of this type of detector to lifetimes in the 10^{-12}–10^{14} sec range. We have benefitted from a discussion of this point with A. K. Mann.

[33] G. B. Yodh [in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, 1975* (Max-Planck-Institut für Extraterrestrische Physik, Munich, 1975), Vol. 11, p. 3936] has stated a similar conclusion in his rapporteur talk at Munich.

[34] H. Harari, in Proceedings of the Summer Institute on Particle Physics, SLAC, 1975 (unpublished), p. 159.