Observation of rare decay modes of the Ξ hyperons*

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In an experiment based on the production of 8150 Ξ^- and 2975 Ξ^0 hyperons, we have detected one example each of the decays $\Xi^- \to \Lambda\mu^-\bar{\nu}$ and $\Xi^0 \to \Lambda\gamma$. The branching ratios of these hitherto unobserved decay modes are $\Gamma(\Xi^- \to \Lambda\mu^-\bar{\nu})/\Gamma(\Xi^- \to \Lambda\pi^-) = (3\pm3)\times10^{-4}$ and $\Gamma(\Xi^0 \to \Lambda\gamma)/\Gamma(\Xi^0 \to \Lambda\pi^0) = (5\pm5)\times10^{-3}$. One event of the decay $\Xi^- \to \Lambda e^-\bar{\nu}$ has also been observed. There is no evidence for $\Delta S = 2$ decays; upper limits on these and other rare decay modes are presented.

I. INTRODUCTION

The determination of the branching ratios of the semileptonic decay modes of the Ξ hyperon was, until 1971, carried out mainly in bubble-chamber experiments.[1] Only four examples of the decay $\Xi^- \to \Lambda e^-\bar{\nu}$ had been found, yielding a branching ratio

$$\frac{\Gamma(\Xi^- \to \Lambda e^-\bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} = (11.5^{+9.0}_{-5.5})\times10^{-4},$$

to be compared with the value of 6×10^{-4}, expected on the basis of fits to the Cabibbo theory.[2] In 1971, an optical spark chamber experiment[3] measured the decays $\Xi^- \to (\Lambda \text{ or } \Sigma^0)e^-\bar{\nu}$, and obtained a branching ratio of

$$\frac{\Gamma(\Xi^- \to \Lambda e^-\bar{\nu}) + \Gamma(\Xi^- \to \Sigma^0 e^-\bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} = (6.8\pm2.2)\times10^{-4}.$$

While this experiment did not distinguish between the $\Lambda e^-\bar{\nu}$ and $\Sigma^0 e^-\bar{\nu}$ modes, it was expected that the decay rate for $\Sigma^0 e^-\bar{\nu}$ would be about a factor of six smaller than that for $\Lambda e^-\bar{\nu}$. Subsequent compilation[4] of the world data for the $\Xi^- \to \Lambda e^-\bar{\nu}$ branching ratio has made use of this assumption to yield a world average of $(7.0\pm2.1)\times10^{-4}$.

There has also been considerable interest in other rare decays of the Ξ hyperons. The $|\Delta S| = 2$ transitions, both semileptonic and nonleptonic, and the hitherto unobserved radiative decays have been the subject of a number of theoretical conjectures and models.[10]

This paper reports on the observation of one event each of the decays $\Xi^- \to \Lambda\mu^-\bar{\nu}$, $\Xi^0 \to \Lambda\gamma$, and $\Xi^- \to \Lambda e^-\bar{\nu}$. Results of the search for other rare decay modes are also presented. This study is based on 860 000 pictures of the Brookhaven National Laboratory 31-in. hydrogen bubble chamber exposed to a beam of 1.75-GeV/c K^- mesons from the Alternating Gradient Synchrotron. The experiment produced a total of 8150 Ξ^- and 2975 Ξ^0 hyperons. The actual numbers of observed Ξ decays are summarized in Table I. These numbers will serve as the basis for computing the effective denominators in the determination of the branching ratios for the rare decays. Details of the experimental setup, properties of the incident beam, and the basic method of data reduction are discussed in a separate paper reporting the measurement of the decay parameters, lifetimes, and spins of the Ξ^- and Ξ^0 hyperons.[5] In the following sections we describe the procedures by which the rare decay modes were searched for, and present the results of that search.

The organization of the paper is as follows: II. Experimental procedures and results: A. General procedure, B. Radiative decays; 1. Procedure, 2. $\Xi^- \to \Sigma^-\gamma$, 3. $\Xi^0 \to \Lambda\gamma$, 4. $\Xi^0 \to \Sigma^0\gamma$; C. $\Delta S = 1$ semileptonic decays; 1. $\Xi^- \to \Lambda\mu^-\bar{\nu}$, $\Lambda e^-\bar{\nu}$, $\Sigma^0\mu^-\bar{\nu}$, $\Sigma^0 e^-\bar{\nu}$, 2. $\Xi^0 \to \Sigma^\pm e^\mp\nu$, $\Sigma^\pm\mu^\mp\nu$; D. $\Delta S = 0$ decays, E. $\Delta S = 2$ decays; 1. $\Xi^- \to ne^-\bar{\nu}$, $n\mu^-\bar{\nu}$, 2. $\Xi^- \to p\pi^-\pi^-$, $p\pi^-\mu^-\bar{\nu}$, $p\pi^-e^-\bar{\nu}$, 3. $\Xi^0 \to pe^-\bar{\nu}$, $p\mu^-\bar{\nu}$, 4. $\Xi^- \to n\pi^-$, 5. $\Xi^0 \to p\pi^-$; III. Conclusions.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. General procedure

The Ξ hyperons used in this study were produced in the reactions

$$K^- + p \to \Xi^- + K^+ \quad (1)$$

$$\to \Xi^- + K^+ + \pi^0 \quad (2)$$

$$\to \Xi^- + K^0 + \pi^+ \quad (3)$$

$$\to \Xi^0 + K^0 \quad (4)$$

$$\to \Xi^0 + K^0 + \pi^0 \quad (5)$$

$$\to \Xi^0 + K^+ + \pi^-. \quad (6)$$

The film was scanned for both the dominant Ξ decays

$$\Xi^- \to \Lambda + \pi^- , \quad (7)$$

$$\Xi^0 \to \Lambda + \pi^0 , \quad (8)$$

and for the following rare-decay modes:

1. Radiative decays:

(a) $\Xi^- \to \Sigma^- + \gamma$, (9)

(b) $\Xi^0 \to \Lambda + \gamma,\ \Sigma^0 + \gamma$. (10a)

2. $\Delta S = 1$ semileptonic decays:

(a) $\Xi^- \to \Lambda + e^- + \bar{\nu},\ \Lambda + \mu^- + \bar{\nu},\ \Sigma^0 + e^- + \bar{\nu},$
$\Sigma^0 + \mu^- + \bar{\nu}$. (11)

(b) $\Xi^0 \to \Sigma^{\pm} + e^{\mp} + \nu,\ \Sigma^{\pm} + \mu^{\mp} + \nu$. (12)

3. $\Delta S = 0$ semileptonic decay:

$\Xi^- \to \Xi^0 + e^- + \bar{\nu}$. (13)

4. $\Delta S = 2$ decays:

(a) $\Xi^- \to n + e^- + \bar{\nu},\ n + \mu^- + \bar{\nu}$. (14)

(b) $\Xi^- \to p + \pi^- + \pi^-,\ p + \pi^- + e^- + \bar{\nu},$
$p + \pi^- + \mu^- + \bar{\nu}$. (15)

(c) $\Xi^0 \to p + e^- + \bar{\nu},\ p + \mu^- + \bar{\nu}$, (16)

(d) $\Xi^- \to n + \pi^-$, (17)

(e) $\Xi^0 \to p + \pi^-$. (18)

The topologies for the dominant decay modes were (i) events with two charged prongs with a kink on the negative prong, accompanied by one or two neutral vees (the $\Lambda \to p + \pi^-$ or $K^0 \to \pi^+ + \pi^-$ decay or both) for Ξ^- decays; (ii) events with zero charged prongs and two neutral vees (the $\Lambda \to p + \pi^-$ and $K^0 \to \pi^+ + \pi^-$ decays both had to be visible) for the Ξ^0 decays from the production reactions (4) and (5); (iii) events with two charged prongs and a neutral vee (the $\Lambda \to p + \pi^-$ decay), for Ξ^0 decays from the reaction (6).

The topologies for the rare decay modes were similar to those for the dominant decay modes, except that they were required to have one of four "rare-decay signatures":

(a) Electron or positron signature, for either a track originating from a kink of a two prong [for decays (11), (13), or (14)] or as one prong of a neutral vee [for decays (12) or (16)]. This signature is defined as a negative or a positive track which describes an arc of at least one quarter of a circle in the bubble chamber and maintains minimum bubble density throughout its track length.

(b) Muon signature, for a track either originating from a kink of a two-prong event [for decays (11) or (14)] or forming one prong of a vee [for decays (12) or (16)]. This signature consists of a positive or negative track which exhibits very high bubble density just before its decay into an obvious positron or electron, with no restrictions imposed on the length of the muon track.

(c) $\Sigma^{\pm}$ signature on a track which originates from a kink on a two-prong event [for decay (9)] or forms one prong of a neutral vee [for decay (12)]. This signature consists of a kink on a positive or negative track, requiring that the bubble density of the track before the kink be consistent with that expected for a $\Sigma^{\pm}$.

(d) The negative track of a two-prong event decays into three charged tracks, one positive and two negative [for decays (15)].

The entire exposure of 860 000 pictures was scanned for candidates for the above decay modes. About 30% of the film was selectively rescanned to determine the scanning efficiencies for each topology. All candidates satisfying the above scanning criteria were measured on high-precision film plane digitizing machines, with the exception that all events from the production reaction (1) followed by the decay (17), and some events from reaction (6), were measured on the Columbia University Hough-Powell Device (HPD), an automatic flying-spot measuring device (for details of the measurements of this subsample, see Refs. 6 and 7). All of the measurements were processed through the geometrical reconstruction and kinematic fitting programs[8] TVGP and SQUAW. Remeasurements were done as necessary. These procedures yielded a sample of ~13 000 events which were candidates for the dominant Ξ decay modes and ~550 events which were candidates for rare Ξ decays. An additional sample of 15 000 events of the topology of zero charged prongs with one or more neutral vees, obtained from the

TABLE I. Summary of observed Ξ events.

Reaction	No. of events	
$K^-p \to \Xi^- K^+$ with Λ visible	2702	(1)
$\to \Xi^- K^0 \pi^+$ with Λ visible,	1171 [a]	(2)
without Λ visible, K^0 visible	258	(3)
$\to \Xi^- K^+ \pi^0$ with Λ visible	430	(4)
Total Ξ^- observed	4561	(5)
Total Ξ^- produced [b]	8150	
$K^-p \to \Xi^0 K^0$ with both Λ, K^0 visible	443	(6)
$\to \Xi^0 K^+ \pi^-$ with obvious K^+, Λ visible [c]	64	(7)
from 2 prong with Λ visible	180	(8)
Total Ξ^0 observed	687	(9)
Total Ξ^0 produced [b]	2975	

[a] Of these, 350 events had both Λ and K^0 decay visible.
[b] These totals were calculated by weighting each observed event with the inverse of the detection probability.
[c] See text for explanation of obvious K^+ (Sec. II B 1).

same film but in a separate experiment measuring the K_S^0 branching ratio,[9] was used to search for the $\Delta S = 2$ decay (18).

Each event in the sample of ~550 rare decay candidates was individually examined by several physicists independently to isolate the very few true rare Ξ decays. In addition, events from the sample of 13 000 candidates for the dominant decay modes which did not achieve a satisfactory kinematic fit to one of the dominant Ξ decays (7) or (8) were reprocessed through a special SQUAW run and examined by physicists for possible rare Ξ decays.

B. Radiative decays

1. Procedure

Candidates for the Ξ^- radiative decay

$$\Xi^- \to \Sigma^- + \gamma \tag{9}$$

came from the rare-decay scan and had the topology of two prongs with a double kink on the negative track. These events were fitted to the multivertex hypotheses

$$\begin{aligned} &K^- + p \to \Xi^- + K^+ \\ &\qquad \searrow \Sigma^- + \gamma \\ &\qquad\qquad \searrow n + \pi^- , \end{aligned} \tag{19}$$

$$\begin{aligned} &K^- + p \to \Xi^- + K^+ + \pi^0 \\ &\qquad \searrow \Sigma^- + \gamma \\ &\qquad\qquad \searrow n + \pi^- , \end{aligned} \tag{20}$$

$$\begin{aligned} &K^- + p \to \Xi^- + K^0 + \pi^+ \\ &\qquad \searrow \Sigma^- + \gamma \\ &\qquad\qquad \searrow n + \pi^- . \end{aligned} \tag{21}$$

The criterion for acceptance as a Ξ^- radiative decay was an acceptable fit to one of the hypotheses (19), (20), or (21).

The search for the Ξ^0 radiative decays

$$\Xi^0 \to \Lambda + \gamma , \tag{10b}$$

$$\Xi^0 \to \Sigma^0 + \gamma \tag{10c}$$

was based in part on zero-prong two-vee events which were found in the dominant decay scan and which failed the multivertex fit:

$$\begin{aligned} &K^- + p \to \Xi^0 + K^0 \\ &\qquad\qquad\quad K^0 \searrow \pi^+ + \pi^- \\ &\qquad \Xi^0 \searrow \Lambda + \pi^0 \\ &\qquad\qquad \searrow p + \pi^- . \end{aligned} \tag{22}$$

This sample of events was subsequently refitted to the following hypotheses:

$$\begin{aligned} &K^- + p \to \Xi^0 + K^0 \\ &\qquad\qquad \searrow \pi^+ + \pi^- , \end{aligned} \tag{23}$$

$$\begin{aligned} &K^- + p \to \Xi^0 + K^0 \\ &\qquad\qquad\quad K^0 \searrow \pi^+ + \pi^- \\ &\qquad \Xi^0 \searrow \Lambda + X^0 \\ &\qquad\qquad \searrow p + \pi^- , \end{aligned} \tag{24}$$

$$\begin{aligned} &K^- + p \to \Xi^0 + K^0 \\ &\qquad\qquad\quad K^0 \searrow \pi^+ + \pi^- \\ &\qquad \Xi^0 \searrow \Lambda + \gamma \\ &\qquad\qquad \searrow p + \pi^- . \end{aligned} \tag{25}$$

Other candidates for the Ξ^0 radiative decays came from the dominant decay scan of two-prong events with a kink on the positive prong which had a bubble density consistent with the decay of a low-momentum or stopping K^+. These events were required to have a vee in the forward direction and be inconsistent with the hypothesis

$$\begin{aligned} &K^- + p \to K^+ + \pi^- + \Xi^0 \\ &\qquad\qquad \searrow \Lambda + \pi^0 \\ &\qquad\qquad\quad \searrow p + \pi^- . \end{aligned} \tag{26}$$

Such events were refitted to (6) and the following hypotheses:

$$\begin{aligned} &K^- + p \to K^+ + \pi^- + \Xi^0 \\ &\qquad\qquad \searrow \Lambda + X^0 \\ &\qquad\qquad\quad \searrow p + \pi^- , \end{aligned} \tag{27}$$

$$\begin{aligned} &K^- + p \to K^+ + \pi^- + \Xi^0 \\ &\qquad\qquad \searrow \Lambda + \gamma \\ &\qquad\qquad\quad \searrow p + \pi^- . \end{aligned} \tag{28}$$

The criteria for acceptance as Ξ^0 radiative decays were good fits to the hypotheses (23) or (6) followed respectively by (24) or (27) where the square of the mass of X^0, when left unconstrained, yielded a value greater than or consistent with zero, but inconsistent with $M_{\pi^0}{}^2$. In the case of the $\Lambda\gamma$ mode, we further required that the events achieved the highly constrained fits to (25) or (28). For the $\Xi^0 \to \Sigma^0\gamma$ decay, where the Σ^0 decays electromagnetically into $\Lambda\gamma$, there was no corresponding chain of fits possible, since the photons in general were not converted into electron-positron pairs in the bubble chamber.

2. The $\Xi^- \to \Sigma^-\gamma$ result

No events achieved a satisfactory kinematic fit to any of the hypotheses (19), (20), or (21).

To evaluate the upper limit on this decay mode, a Monte Carlo program was written to evaluate the detection efficiency. Actual Ξ^- hyperons produced in the two- and three-body final states, taken from the sample of events where the Ξ^- decayed by its dominant $\Lambda\pi^-$ mode, were used. In the Monte Carlo program these Ξ^- were allowed to decay into $\Sigma^-\gamma$, followed by the $\Sigma^- \to n\pi^-$ decay. The result indicated that 40% of these decays would have both the Ξ^- and Σ^- lengths greater than 2 mm and the Ξ^- and Σ^- decay angles (i.e., the angle between the Ξ^- and the Σ^-, and that between the Σ^- and the π^-) larger than 5°. The scanning efficiency for such decays was estimated to be 60%. The denominator in the branching ratio is the total sample of 8150 Ξ^- produced in the experiment.

The 68.3% confidence level upper limit for zero observed events is 1.1, yielding the following upper limit on the branching ratio:

$$\frac{\Gamma(\Xi^- \to \Sigma^- + \gamma)}{\Gamma(\Xi^- \to \Lambda + \pi^-)} \leq \frac{1.1 \times (1/0.4) \times (1/0.6)}{8150} = 5.6 \times 10^{-4}.$$

3. The $\Xi^0 \to \Lambda\gamma$ result

One event was identified as $\Xi^0 \to \Lambda\gamma$. The photograph of the event is shown as Fig. 1. Results of the kinematical fits are summarized in Table II. It should be noted that the event satisfied the four-constraint two-vertex fit to hypothesis (23) with a χ^2 of 2.33, and achieved a very acceptable fit to the seven-constraint hypothesis (25) with a χ^2 of 8.77. When the event was remeasured and reprocessed, the kinematical quantities remained virtually unchanged.

In order to evaluate our experimental sensitivity for observing the $\Xi^0 \to \Lambda\gamma$ decay, the Monte Carlo program described above was modified to generate the $\Xi^0 \to \Lambda\gamma$ decay for real two- and three-body Ξ^0 events which had decayed via the dominant $\Lambda\pi^0$ mode using the Ξ^0 production angles and momentum from the production fit alone. These Monte Carlo events were fed through our kinematical fitting program to determine the fraction that would successfully fake the $\Xi^0 \to \Lambda\pi^0$ decay fit. Such a procedure indicated that 60% would fake the $\Lambda\pi^0$ decay mode, so that the detection efficiency of candidates for the $\Lambda\gamma$ decay in our procedure was 40%. To identify this radiative mode we need a constrained Ξ^0 production reaction and a visible $\Lambda \to p\pi^-$ decay. The denominator in this search is thus the 507 events [lines (6) and (7) on Table I].

We thus obtain the branching ratio

$$\frac{\Gamma(\Xi^0 \to \Lambda\gamma)}{\Gamma(\Xi^0 \to \Lambda\pi^0)} = \frac{1 \times (1/0.4)}{507} = (5 \pm 5) \times 10^{-3}.$$

4. The $\Xi^0 \to \Sigma^0\gamma$ result

One event was found to be consistent with the production of Ξ^0 in the reaction (23) followed by the chain of decays $\Xi^0 \to \Sigma^0\gamma$, $\Sigma^0 \to \Lambda\gamma$, and $\Lambda \to p\pi^-$. As discussed in Sec. B 1 above, however, unless one or both of the photons in the decays were converted into electron-positron pairs in the bubble chamber, it would be quite difficult to demonstrate unambiguously the $\Xi^0 \to \Sigma^0\gamma$ decay mode. The observed event fitted hypothesis (23) well with a four-constraint χ^2 of 2.5 and had a small probability of fitting hypothesis (25) (7-constraint $\chi^2 = 18.2$). When fitted to hypothesis (24), it had a χ^2 of 2.8 with six constraints and yielded M_{X^0} of 80 ± 8 MeV, which is typical of the effective mass expected for the two photons in the $\Xi^0 \to \Sigma^0\gamma$, $\Sigma^0 \to \Lambda\gamma$ decays. Nevertheless, it is impossible to rule out, in the absence of evidence for either γ rays, a fortuitous kinematic situation. For this reason, we quote an upper limit for the branching

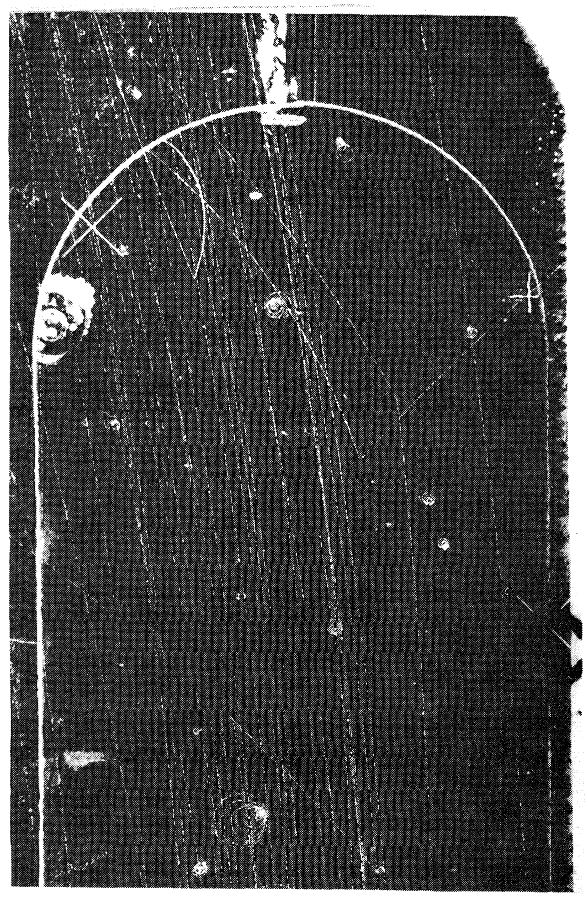

FIG. 1. Photograph of the $\Xi^0 \to \Lambda\gamma$ event. At the zero-prong vertex, the production reaction is $K^-p \to \Xi^0 K^0$. The $K^0 \to \pi^+\pi^-$ decay (on the right, referred to as vee No. 1 in Table II) and the $\Lambda \to p\pi^-$ decay (on the left, referred to as vee No. 2) are both visible.

ratio based on this event.

In order to determine our detection efficiency for this decay mode, the Monte Carlo program was used to generate $\Xi^0 \to \Sigma^0\gamma$ events using actual two- and three-body Ξ^0 events. When these Monte Carlo events were fed through our fitting programs, 88% faked the $\Xi^0 \to \Lambda\pi^0$ decay mode. On the basis of one event, the 68.3% confidence level upper limit is 2.3 events. The denominator is the same as for the $\Xi^0 \to \Lambda\gamma$ search. Thus

$$\frac{\Gamma(\Xi^0 \to \Sigma^0\gamma)}{\Gamma(\Xi^0 \to \Lambda\pi^0)} \leq \frac{2.3/0.12}{507} \sim 4\times 10^{-2}.$$

C. $\Delta S = 1$ Semileptonic decays

1. The decays $\Xi^- \to \Lambda\mu^-\bar{\nu}$, $\Lambda e^-\bar{\nu}$, $\Sigma^0\mu^-\bar{\nu}$, $\Sigma^0 e^-\bar{\nu}$

Candidates for these decays came from two types of events. One category consisted of two-prong events in which the negative track decayed into an obvious μ^- or e^- (i.e., with the μ^- or e^- signature). These events were required to satisfy one of the three Ξ^- production fits (1), (2), or (3).

Another class of candidates came from the scan for the dominant Ξ^- decay and consisted of events with two prongs in which the negative track had a kink, with at least one vee. These events did not carry the μ^- or e^- signature, but were required to satisfy two criteria. The first criterion was a good two- or three-body Ξ^- production fit; the second was that the events had to have a visible $\Lambda \to p\pi^-$ decay and fail the dominant decay fit (7).

The events which satisfied these criteria were examined by physicists using large magnification scanning machines to detect any unusual features which might have escaped the attention of the scanners and to perform bubble-density determination if that proved to be useful. After this careful scrutiny, we have identified one example each of the decay modes $\Xi^- \to \Lambda\mu^-\bar{\nu}$ and $\Xi^- \to \Lambda e^-\bar{\nu}$.

a. $\Xi^- \to \Lambda\mu^-\bar{\nu}$. The $\Xi^- \to \Lambda\mu^-\bar{\nu}$ decay event (frame number 347-1729) made an excellent three-constraint (3C) production fit to hypothesis (1), $K^- + p \to \Xi^- + K^+$, with a $\chi^2 = 2.0$. The Λ particle which decays visibly into a $p + \pi^-$ in the chamber originated from the Ξ^- decay point ($\chi^2 = 0.6$ for the 3C Λ decay fit). However, the event failed the decay fit $\Xi^- \to \Lambda + \pi^-$ with a $\chi^2 = 78$, and failed the multivertex chain of fits

$$K^- + p \to \Xi^- + K^+,\quad \Xi^- \to \Lambda^0 + \pi^-,\quad \Lambda^0 \to p + \pi^-, \tag{29}$$

with a $\chi^2 = 152$. The event is not consistent with the $\Xi^- \to \Lambda e^-\bar{\nu}$ decay, but made a good fit to the $\Lambda\mu^-\bar{\nu}$ decay chain

$$K^- + p \to \Xi^- + K^+,\quad \Xi^- \to \Lambda + \mu^- + \bar{\nu},\quad \Lambda \to p + \pi^-, \tag{30}$$

with a $\chi^2 = 6.1$ for a 7-constraint fit. Thus the evidence for the decay comes mainly from the kinematic fits.

We have considered the possibility that this event is a two-body decay $\Xi^- \to \Lambda + \pi^-$, where the π^- decays into $\mu^- + \bar{\nu}$. A comparison of the missing momentum at the $\Xi^- \to \Lambda + X$ decay vertex with the measured momentum of the π^- or μ^- track indicates that the decay angle in the laboratory for the $\pi^- \to \mu^- + \bar{\nu}$ decay would have been ~16°. Such

TABLE II. Fitted quantities of the $\Xi^0 \to \Lambda\gamma$ event.

K^- beam momentum	1622 ± 10 MeV/c
Ξ^0 momentum	1126 ± 10 MeV/c
Momentum of vee 1 as K^0	753 ± 5 MeV/c
Momentum of vee 2 as Λ	863 ± 16 MeV/c
χ^2 of vee 1 fitted as $K^0 \to \pi^+\pi^-$ (3C)	1.7
χ^2 of vee 1 fitted as $\Lambda \to p\pi^-$ (1C)	737.6
Effective mass of vee 1 as e^+e^-	378 ± 11 MeV
χ^2 of vee 2 fitted as $K^0 \to \pi^+\pi^-$	589.8
χ^2 of vee 2 fitted as $\Lambda \to p\pi^-$	2.8
Effective mass of vee 2 as e^+e^-	273 ± 11 MeV
$K^-p \to K^0 X^0$, $K^0 \to \pi^+\pi^-$ (vee 1): χ^2 (3C)	1.7
M_{X^0}	1304 ± 13 MeV
$K^-p \to K^0\Xi^0$, $K^0 \to \pi^+\pi^-$ (vee 1): χ^2 (4C)	2.3
$K^-p \to \Xi^0 K^0$, $K^0 \to \pi^+\pi^-$, $\Xi^0 \to \Lambda\pi^0$, $\Lambda \to p\pi^-$: χ^2 (7C)	116.5
$K^-p \to \Xi^0 K^0$, $K^0 \to \pi^+\pi^-$, $\Xi^0 \to \Lambda X^0$, $\Lambda \to p\pi^-$: χ^2 (6C)	5.7
$M_{X^0}{}^2$	-6538 ± 4509 MeV^2
$K^-p \to \Xi^0 K^0$, $K^0 \to \pi^+\pi^-$, $\Xi^0 \to \Lambda\gamma$, $\Lambda \to p\pi^-$: χ^2 (7C)	8.8

a large kink would have been observable unless the π^- decayed within the first millimeter of its path. The probability for such decay is ~9×10^{-5} for the average two-body Ξ^- decay. With our effective denominator, we expect approximately $\frac{1}{4}$ of an event from this source. Thus the most probable interpretation of this event is that it is an example of the decay mode $\Xi^- \to \Lambda\mu^-\bar{\nu}$, and we calculate a branching ratio for this decay based on this event. However, as discussed above, this is not an unambiguous example of this decay mode.

In order to estimate our detection efficiency for this decay, the Monte Carlo program was used to determine the rate of loss of genuine $\Xi^- \to \Lambda\mu^-\bar{\nu}$ decays due to their faking the $\Xi^- \to \Lambda\pi^-$ fit. The same program also computed the detection efficiency for our "obvious muon" criterion. In the Monte Carlo program, actual Ξ^- production events were used in conjunction with axial-vector and vector coupling constants in the ratio G_A/G_V of 0.2 for the decays. The result was that only 12% faked the $\Lambda\pi^-$ decay, and 11% satisfied our "obvious muon" criterion. We used in this search only events whose $\Lambda \to p+\pi^-$ decays were visible and, therefore, the Ξ^- decays were kinematically constrained. The effective denominator for this search was the sum of (i) the highly constrained Ξ^- production fits: 2702 $\Xi^- K^+$ events and 350 $\Xi^- K^0\pi^+$ events with a visible $K^0 \to \pi^+\pi^-$ decay (lines 1 and 2 of Table I) multiplied by 0.88, the probability that they do not fake the $\Xi^- \to \Lambda\pi^-$ decay, and (ii) the less constrained production fits, lines 2 and 4 of Table I, multiplied by 0.11, the probability of a visible $\mu^- \to e^-\nu\bar{\nu}$ decay, and 0.84, the scanning efficiency for events with a muon signature. The sum of (i) and (ii) is 2835. We thus obtain the branching ratio

$$\frac{\Gamma(\Xi^- \to \Lambda\mu^-\bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} = \frac{1\pm 1}{2835} = (3.5\pm 3.5)\times 10^{-4}.$$

b. $\Xi^- \to \Lambda e^-\bar{\nu}$. The $\Xi^- \to \Lambda e^-\bar{\nu}$ event was identified with the aid of a δ ray. The event has two prongs with a kink and a vee, which was identified as the decay of a Λ emitted from the Ξ^- decay vertex. The production reaction satisfied the 4-constraint hypothesis (1) with a χ^2 of 2.9. When the event was fitted to hypothesis (29), a low probability was obtained ($\chi^2 = 291$ with 11 constraints). Likewise, the fit to

$$K^- + p \to \Xi^- + K^+,\quad \Xi^- \to \Lambda + \mu^- + \bar{\nu},\quad \Lambda \to p + \pi^- \tag{31}$$

failed. On the other hand, the 8-constraint multivertex fit

$$K^- p \to \Xi^- K^+,\quad \Xi^- \to \Lambda e^-\bar{\nu},\quad \Lambda \to p\pi^-$$

was successfully achieved with a χ^2 of 8.2. Since the electron track did not satisfy our obvious e^- criterion, additional evidence was sought to substantiate the interpretation. Fortunately, a rather large δ ray was attached to the midsection of the 230-MeV/c decay-product track. Since a 230-MeV/c π^- can produce δ rays with momenta no larger than about 2.7 MeV/c, and since the measured momentum of the δ ray was 6 MeV/c, we were able to conclude unambiguously that the decay track could not have been a π^- or μ^-. This reinforced the identification of the event as $\Xi^- \to \Lambda e^-\bar{\nu}$.

According to our Monte Carlo calculation, only 5% of the $\Xi^- \to \Lambda e^-\bar{\nu}$ events would fake the $\Xi^- \to \Lambda\pi^-$ decay. Furthermore, about 42% of the remaining decays would satisfy our obvious e^- criterion. The effective denominator for this search was calculated in the same way as for the $\Xi^- \to \Lambda\mu^-\bar{\nu}$ search, using the appropriate efficiencies of 0.95 and 0.42 instead of 0.88 and 0.11 in Sec. II C 1a above. In addition, since the background due to $\Xi^- \to \Lambda\pi^-$, $\pi^- \to e^-\bar{\nu}$ is negligible, we also use in the denominator the highly constrained Ξ^- production events without visible Λ decay but with an obvious electron signature. We thus get an effective denominator of 4150 events and a branching ratio of

$$\frac{\Gamma(\Xi^- \to \Lambda e^-\bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} = \frac{1\pm 1}{4150} = (2.4\pm 2.4)\times 10^{-4}.$$

We have compiled our own result and the presently available world data[4] on this decay mode and summarized them in Table III.

c. $\Xi^- \to \Sigma^0 e^-\bar{\nu}$ *and* $\Xi^- \to \Sigma^0\mu^-\bar{\nu}$. Our search for the decays $\Xi^- \to \Sigma^0 e^-\bar{\nu}$ and $\Xi^- \to \Sigma^0\mu^-\bar{\nu}$ has yielded no events. The scanning instructions for $\Xi^- \to \Sigma^0\mu^-\bar{\nu}$ were the same as for $\Xi^- \to \Lambda\mu^-\bar{\nu}$; hence, the same events were used. The Monte Carlo calculation indicated, however, that 25% and 9% of the $\Xi^- \to \Sigma^0 e^-\bar{\nu}$ and $\Xi^- \to \Sigma^0\mu^-\bar{\nu}$ events would fake the $\Lambda\pi^-$ decay mode respectively, and 58% and 17% of the remaining events would have the electron or muon satisfying our respective obvious lepton criteria. The effective denominators were calculated in ways similar to those described for the $\Lambda e^-\bar{\nu}$ and $\Lambda\mu^-\bar{\nu}$ modes, and yielded 4363 and 3026 events, respectively. The upper limits for these modes are thus

TABLE III. World data on $\Xi^- \to \Lambda e^- \bar{\nu}$.

	No. of events	Effective denominator	Reference
Columbia-SUNY Binghamton	1	4150	This experiment
Brookhaven	1	155	London *et al.*, Ref. 1
U.C.L.A.	1	155	Carmony *et al.*, Ref. 1
Berkeley	2	1976	Hubbard *et al.*, Ref. 1
E.P.-CERN-London-Rutherford-Bergen	0	260	Jauneau *et al.*, Ref. 12
Berkeley	0	220	Berge *et al.*, Ref. 12
U.C.L.A.	0	717	Trippe, Ref. 4
Total	5	7633	
CERN-Heidelberg	$\frac{\Gamma(\Xi^- \to \Lambda e^- \bar{\nu}) + \Gamma(\Xi^- \to \Sigma^0 e^- \bar{\nu})}{\Gamma(\Xi^- \to \Lambda \pi^-)} = (6.8 \pm 2.2) \times 10^{-4}$		Duclos *et al.*, Ref. 3

$$\frac{\Gamma(\Xi^- \to \Sigma^0 e^- \bar{\nu})}{\Gamma(\Xi^- \to \Lambda \pi^-)} \leq \frac{1.1}{4363} = 2.5 \times 10^{-4},$$

$$\frac{\Gamma(\Xi^- \to \Sigma^0 \mu^- \bar{\nu})}{\Gamma(\Xi^- \to \Lambda \pi^-)} \leq \frac{1.1}{3026} = 3.6 \times 10^{-4}.$$

2. The decays $\Xi^0 \to \Sigma^\pm e^\mp \nu$, $\Sigma^\pm \mu^\mp \nu$

In scanning for these events, we used samples which contained zero- and two-prong events with one or more vees where one track of each vee showed a kink. These events were required to satisfy the constrained production fits (23) or (6). Multivertex fits including the pertinent decays were then attempted. No events were found that satisfied these selection criteria.

The scanning efficiency was maximized by requiring that the length of the kinking track be at least 5 mm long and the angle of the kink be at least 5°. Under these conditions the scanning efficiency for these events was as good as that for the dominant Ξ^0 decays. From our Monte Carlo calculation we found that 70% of the Σ^+ and 84% of the Σ^- in these rare decays would have satisfied the length and decay angle requirements. The denominator for this search was 2975, the total number of Ξ^0 produced. We thus get the upper limits

$$\frac{\Gamma(\Xi^0 \to \Sigma^+ l^- \bar{\nu})}{\Gamma(\Xi^0 \to \Lambda \pi^0)} \leq \frac{1.1 \times (1/0.70)}{2975} = 5 \times 10^{-4},$$

$$\frac{\Gamma(\Xi^0 \to \Sigma^- l^+ \nu)}{\Gamma(\Xi^0 \to \Lambda \pi^0)} \leq \frac{1.1 \times (1/0.84)}{2975} = 4 \times 10^{-4},$$

where $l^\pm$ stands for $e^\pm$ or $\mu^\pm$.

D. $\Delta S = 0$ decay

A search was also made for the $\Delta S = 0$ decay, $\Xi^- \to \Xi^0 e^- \bar{\nu}$, by examining two-prong events whose negative prong had a kink followed by an obvious electron with a momentum between 6 and 12 MeV/c. These events were required to fit one of the Ξ^- production hypotheses, (1), (2), or (3). No such events were found.

The kinematics of the decay of our Ξ^- indicates that the electron momentum spectrum in the laboratory has a maximum of about 12 MeV/c, peaking at about 6 MeV/c. In order to distinguish the decay electrons from δ rays, we require that the electron momentum be greater than 6 MeV/c. The Monte Carlo results on the electron spectrum showed that 27% of the events had obvious electrons exceeding 6 MeV/c in momentum. We estimate that the scanning efficiency for such events is 71%. For the denominator we use the highly constrained sample of 2702 $\Xi^- K^+$ events and 350 $\Xi^- K^0 \pi^+$ with a visible $K^0 \to \pi^+ \pi^-$ decay, weighted by the inverse of the Λ detection efficiency since a visible Λ decay was required for this search, to give $(2702 + 350)/0.575 = 5300$ events. We thus obtain an upper limit of

$$\frac{\Gamma(\Xi^- \to \Xi^0 e^- \bar{\nu})}{\Gamma(\Xi^- \to \Lambda \pi^-)} \leq \frac{1.1 \times (1/0.27) \times (1/0.71)}{5300} \sim 1 \times 10^{-3}.$$

E. $\Delta S = 2$ decays

1. $\Xi^- \to n e^- \bar{\nu}$, $n \mu^- \bar{\nu}$

These $\Delta S = 2$ semileptonic decays were searched for among events which had two prongs with a kink on the negative track followed by an obvious

e^- or μ^- track. If there were vees associated with the events, the vees had to be consistent with K^0 decays and not Λ decays. The events were further required to achieve either of the highly constrained production fits (1) or (3) with a visible $K^0 \to \pi^+\pi^-$ decay. No events were found which satisfied these criteria. The calculated lepton momentum spectrum, using our Monte Carlo program, indicated that 19% and 4% of these decays would have carried the e^- and μ^- signatures, respectively. The scanning efficiency for these events was estimated to be 71%. For the denominator we use the 5300 events discussed in Sec. II D. We thus obtain the upper limits

$$\frac{\Gamma(\Xi^- \to ne^-\bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} \leqslant \frac{1.1\times(1/0.19)\times(1/0.71)}{5300} = 1.5\times10^{-3},$$

$$\frac{\Gamma(\Xi^- \to n\mu^-\bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} \leqslant \frac{1.1\times(1/0.04)\times(1/0.71)}{5300} = 7.3\times10^{-3}.$$

2. $\Xi^- \to p\pi^-\pi^-$, $p\pi^-\mu^-\bar{\nu}$, $p\pi^-e^-\bar{\nu}$

These events would have the very characteristic two-prong topology in which the negative prong would branch into three tracks. The major background to these decays consists of (a) elastic collisions, $K^- + p \to K^- + p$ where the outgoing K^- meson undergoes the τ decay, $K^- \to \pi^+ + \pi^- + \pi^-$ and (b) Ξ^- production events in which the Ξ^- decays into $\Lambda\pi^-$ with the Λ decaying in a short distance (1 mm or less) into $p\pi^-$.

The elastic scattering events [background (a) above] were eliminated by requiring that the candidates achieve any one of the highly constrained production fits (1)–(3) with high probability and *fail* the highly constrained elastic-scatter fit. To discriminate against background (b) above, the remaining candidates were subjected to the requirement that when the positive track in the three prongs was interpreted as a proton and each of the negative tracks was interpreted in turn as a π^-, the effective mass of both $p\pi^-$ combinations lay outside 5 MeV of the Λ mass. No candidates remained after these two criteria were applied. Assuming that the $\Xi^- \to p\pi^-\pi^-$ transition occurred with a constant matrix element, our calculation indicated that 76% of such decays would have the $p\pi^-$ mass outside the Λ mass band. The scanning efficiency for this topology was found to be as good as that for the dominant $\Xi^- \to \Lambda\pi^-$ decays. For the denominator we use 8150, the total number of Ξ^- produced in the experiment. We thus get the branching-ratio limit of

$$\frac{\Gamma(\Xi^- \to p\pi^-\pi^-)}{\Gamma(\Xi^- \to \Lambda\pi^-)} \leqslant \frac{1.1\times(1/0.76)}{8150} = 1.8\times10^{-4}.$$

For the decays $\Xi^- \to p\pi^-\mu^-\bar{\nu}$ and $\Xi^- \to p\pi^-e^-\bar{\nu}$, we used criteria similar to the above and did not require e^- or μ^- signatures. No events were found that could be identified as these decays, and their upper limits are shown in Table IV.

3. $\Xi^0 \to pe^-\bar{\nu}$, $p\mu^-\bar{\nu}$

In the search for these decays, two categories of events were used, one from the rare-decay scan, and one from the scan for dominant decay modes.

(a) The first category consisted of zero- or two-prong events with at least one vee whose negative prong satisfied the signature for obvious e^- or μ^-, and whose positive prong had a bubble density consistent with that of a proton. To eliminate the background due to the semileptonic $\Lambda \to pe^-\bar{\nu}$ or $\Lambda \to p\mu^-\bar{\nu}$ decays, we required that the effective mass of the vee, when interpreted as pe^- or $p\mu^-$, be greater than the mass of the Λ. No Ξ^0 production fit was required.

(b) The second category of events consisted of zero-prong events with two vees from the sample of candidates for the dominant $\Xi^0 \to \Lambda\pi^0$ decays. One of the vees had to fit as a $K^0 \to \pi^+\pi^-$ from the zero-prong vertex. No e^- or μ^- signature was required for the second vee. However, the event had to satisfy the highly constrained multivertex fit to hypothesis (23), but fail the $\Xi^0 \to \Lambda\pi^0$, $\Lambda \to p\pi^-$ fits. In addition the Ξ^0 direction (both the azimuthal and dip angles) had to pass through the vertex of the second vee. The effective mass of the second vee, interpreted as a pe^-, $p\mu^-$, or $p\pi^-$, had to be larger than the Λ mass.

No events were found that satisfied the criteria of either of the two categories above. A Monte Carlo program was written to calculate the sensitivity of the search, generating a fake sample of these decays using the actual two-body Ξ^0 events. The results were that for the $\Xi^0 \to pe^-\bar{\nu}$ mode, 18% had an obvious e^- signature and 54% had a pe^- effective mass larger than the Λ mass. For the $\Xi^0 \to p\mu^-\bar{\nu}$ mode, 3% had an obvious μ^- signature and 72% had a $p\mu^-$ effective mass larger than the Λ mass. Only an insignificant fraction of these decays would fake the highly overconstrained reaction (22).

The effective denominators for this search are as follows. For category (a) above, 2975, the total sample of Ξ^0 produced, is used, multiplied by the efficiencies 0.17×0.54 for the $\Xi^0 \to pe^-\bar{\nu}$ mode and 0.03×0.72 for the $\Xi^0 \to p\mu\bar{\nu}$ mode, or 290 and 64 events, respectively. For category (b), we use the 443 two-body Ξ^0 events [line (6) of Table I] and weight them by 1/0.52, the inverse of the detection probability, to give 860 two-body Ξ^0 events with a visible $K^0 \to \pi^+\pi^-$ decay.

TABLE IV. Summary of results.

Decay modes	No. of observed events	Effective denominator	Decay branching ratios [a]
$\Xi^- \to \Sigma^- \gamma$	0	2000	$<6\times10^{-4}$
$\Xi^0 \to \Lambda\gamma$	1	200	$(5\pm5)\times10^{-3}$
$\Xi^0 \to \Sigma^0\gamma$	1	60	$<4\times10^{-2}$
$\Xi^- \to \Lambda e^- \bar{\nu}$	1	4150	$(2.4\pm2.4)\times10^{-4}$
$\Xi^- \to \Lambda \mu^- \bar{\nu}$	1	2859	$(3.5\pm3.5)\times10^{-4}$
$\Xi^- \to \Sigma^0 e^- \bar{\nu}$	0	4363	$<2.5\times10^{-4}$
$\Xi^- \to \Sigma^0 \mu^- \bar{\nu}$	0	3026	$<3.6\times10^{-4}$
$\Xi^- \to \Xi^0 e^- \bar{\nu}$	0	1000	$<1\times10^{-3}$
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}$	0	2100	$<5\times10^{-4}$
$\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}$	0	2100	$<5\times10^{-4}$
$\Xi^0 \to \Sigma^- e^+ \nu$	0	2500	$<4\times10^{-4}$
$\Xi^0 \to \Sigma^- \mu^+ \nu$	0	2500	$<4\times10^{-4}$
$\Xi^- \to n e^- \bar{\nu}$	0	715	$<1.5\times10^{-3}$
$\Xi^- \to n \mu^- \bar{\nu}$	0	150	$<7.3\times10^{-3}$
$\Xi^0 \to p e^- \bar{\nu}$	0	670	$<1.6\times10^{-3}$
$\Xi^0 \to p \mu^- \bar{\nu}$	0	664	$<1.7\times10^{-3}$
$\Xi^0 \to p \pi^-$	0	1300	$<8\times10^{-4}$
$\Xi^- \to p \pi^- \pi^-$	0	6200	$<1.8\times10^{-4}$
$\Xi^- \to p \pi^- \mu^- \bar{\nu}$	0	6200	$<1.8\times10^{-4}$
$\Xi^- \to p \pi^- e^- \bar{\nu}$	0	6200	$<1.8\times10^{-4}$
$\Xi^- \to n \pi^-$	0	760	$<1.4\times10^{-3}$

[a] Upper limits are quoted at 68.3% confidence level.

This number has to be multiplied by the fraction of these decays with a pe^- or $p\mu^-$ effective mass larger than the Λ mass, 0.54 and 0.72, respectively, and the fraction of these decays without an obvious e^- or μ^- signature, 0.82 and 0.97, respectively, to yield 380 and 600 events, respectively. The upper limits on the branching ratios for these decays are thus

$$\frac{\Gamma(\Xi^0 \to pe^-\bar{\nu})}{\Gamma(\Xi^0 \to \Lambda\pi^0)} \leq \frac{1.1}{290+380} = 1.6\times10^{-3},$$

$$\frac{\Gamma(\Xi^0 \to p\mu^-\bar{\nu})}{\Gamma(\Xi^0 \to \Lambda\pi^0)} \leq \frac{1.1}{64+600} = 1.7\times10^{-3}.$$

4. $\Xi^- \to n\pi^-$

The search for the $\Delta S = 2$ decay, $\Xi^- \to n\pi^-$, was accomplished in conjunction with a different experiment[6,7] using the same film. Approximately 550 000 pictures were digitized on the Columbia HPD automatic film-measuring device (see Refs. 6 and 7 for details). Two-prong events with a negative kink were selected, using the coordinates of the production and kink vertices as provided by our scanners who measured these points on image-plane measuring machines (with typical spatial accuracies of about 0.2 mm). Since most of the negative tracks that kinked were quite short (a few cm in length), the formation of these tracks from the HPD digitizings was difficult due to crossing tracks and background.

A total of 15 113 two-prong events with a negative kink (with and without associated vees) was found. These events were reconstructed using TVGP. Before the events were kinematically fitted, their production vertex coordinates were accurately redetermined by intersecting in three-dimensional space the incoming beam track with the outgoing positive track. Appropriate energy losses were allowed for the various mass interpretations of the positive track. The angles of the short negative kinking tracks were determined with a three-dimensional least-squares fit of the two scan points and the newly obtained vertex point to a straight line, taking into account the appropriate precision of the respective points.

The events were then fitted to reaction (1), ignoring any measurement of the variables of the Ξ^-. All events with the one-constraint χ^2 less than 6 were selected for further analysis.

This final sample consisted of 2409 events. Assuming the identity of the negative track following the kink to be π^-, we transformed its measured momentum into the rest frame of the Ξ^- to obtain P^* by using the fitted variables of the Ξ^- for the Lorentz transformation. A $\Xi^- \to \Lambda\pi^-$ decay would yield P^* of ~140 MeV/c, whereas the decay $\Xi^- \to n\pi^-$ would yield P^* of ~303 MeV/c. The momentum spectrum so obtained for the final sample indicated a very prominent peak centered at 140.5 MeV/c and a general background running from ~50 MeV/c to ~500 MeV/c. A fit of the data from 90 to 194 MeV/c to a Gaussian shape for the $\Xi^- \to \Lambda\pi^-$ signal and a second-order polynomial background yielded 760 ± 24 events in the Gaussian, a half-width σ of 4.9 MeV/c, and a signal-to-background ratio in the peak region of about 9.5 : 1.

In order to obtain the number of $\Xi^- \to n\pi^-$ decays we might have observed, we selected the region $284 \leq P^* \leq 320$ MeV/c for detailed study. A total of 104 events was found in this region, spread quite evenly over nine bins. Of these, 80 events were unlikely two-body Ξ^- production events or poorly measured events because the measured azimuthal and dip angles of the kinking tracks each differed from the fitted Ξ^- angles by more than 2.5 standard deviations. Many of these events were probably three-body Ξ^- events altogether, although some might have been poorly measured two-body Ξ^- events. Of the remaining 24 events, 12 were elastic scattering events, $K^-p \to K^-p$, with the outgoing K^- decaying into $\pi^-\pi^0$ or $\mu^-\bar{\nu}$; two were identified as $K^-p \to K^-\pi^+n$ followed by the K^- decay; nine were $K^-p \to \Sigma^-\pi^+\pi^0$ events, and one was $K^-p \to \Sigma^-\pi^+$, all followed by $\Sigma^- \to n\pi^-$ decay.

We were thus left with no events for the $\Xi^- \to n\pi^-$ decay. The upper limit obtained was

$$\frac{\Gamma(\Xi^- \to n\pi^-)}{\Gamma(\Xi^- \to \Lambda\pi^-)} \leq \frac{1.1}{760} = 1.4 \times 10^{-3}.$$

The effects of the angle selection on the $\Xi^- \to \Lambda\pi^-$ events were also studied. If similar criteria were applied to the entire sample of 2409 events, the background in the $\Xi^- \to \Lambda\pi^-$ signal region would be substantially reduced, and it became difficult to fit reliably the shape of the background to a polynomial curve. Our best estimate of the background yields an upper limit on the branching ratio consistent with the above result.

5. $\Xi^0 \to p\pi^-$

The search for this decay mode was carried out using a sample of ~15 000 vees associated with zero prongs in this film, which was obtained using the HPD in a pattern recognition mode for the measurement of the K^0_S branching ratio in another experiment.[9] The scattergram of the effective masses of these vees, $M(p\pi^-)$ vs $M(\pi^+\pi^-)$, showed prominent bands corresponding to $\Lambda \to p\pi^-$ and $K^0 \to \pi^+\pi^-$ decays. The candidates for $\Xi^0 \to p\pi^-$ were selected to be in the band $1305 \leq M(p\pi^-)$ 1325 MeV. To reduce the background due to $K^0 \to \pi^+\pi^-$ decays, events with $M(\pi^+\pi^-) \leq 650$ MeV were removed. Two events remained after this selection. Both events had large errors on $M(\pi^+\pi^-)$ and made acceptable 3-constraint fits as $K^0 \to \pi^+\pi^-$. When interpreted as $\Xi^0 \to p\pi^-$, both events yielded unphysical Ξ^0 momenta. Both events were therefore interpreted as K^0 decays, and we were left with no $\Xi^0 \to p\pi^-$ events.

A Monte Carlo program was used to generate a sample of $\Xi^0 \to p\pi^-$ decays, using actual Ξ^0 events from this experiment. We found that 90% of these events were within the $1305 \leq M(p\pi^-) \leq 1325$ MeV band, and 67% had $M(\pi^+\pi^-) \geq 650$ MeV.

The denominator for this search consists of all $\Xi^0 K^0$ and $\Xi^0 K^0 \pi^0$ events produced in the experiment. The 443 $\Xi^0 K^0$ events with both K^0 and Λ^0 decays visible (line 6, Table I) has to be weighted by $1/(0.645 \times 0.345 \times 0.8)$, the inverse of the Λ^0 and K^0 detection efficiencies, to yield 2500 $\Xi^0 K^0$ events produced. We estimate another 1250 $\Xi^0 K^0 \pi^0$ events, for a total denominator of 3750 events. We have to reduce this by 0.9 because of the differences in scan efficiencies and fiducial volumes in the K^0_S branching-ratio experiment[9] and the Ξ^0 experiment,[5] and to use the factor 550/860 to account for the different number of photographs used in the two experiments, to obtain an effective denominator of 2160 events. We thus calculate the upper limit for this decay mode to be

$$\frac{\Gamma(\Xi^0 \to p\pi^-)}{\Gamma(\Xi^0 \to \Lambda\pi^0)} \leq \frac{1.1 \times (1/0.9) \times (1/0.67)}{2160} = 8 \times 10^{-4}.$$

III. CONCLUSIONS

We have not found any evidence of $\Delta S = 0$ and $\Delta S = 2$ decays of the Ξ hyperons. Our results are summarized in Table IV.

An example of the radiative decay, $\Xi^0 \to \Lambda\gamma$, has been observed for the first time in this experiment. The branching ratio for this decay is $(5 \pm 5) \times 10^{-3}$. This result is compatible with several theoretical conjectures[10] regarding the dynamics of the decay, but does not distinguish among them.

This experiment has also yielded an example of the hitherto unobserved decay mode $\Xi^- \to \Lambda\mu^-\bar{\nu}$. The branching ratio for this decay mode has been determined to be $(3.5 \pm 3.5) \times 10^{-4}$, which is consistent with the value of $\sim 2 \times 10^{-4}$ based on the Cabibbo theory.[11]

An example of the decay $\Xi^- \to \Lambda e^- \bar{\nu}$ has also been detected in this study. Using our result alone, we obtain a branching ratio of $(2.4 \pm 2.4) \times 10^{-4}$. When combined with data from other experiments (see Table III) which sought to distinguish this mode from the $\Xi^- \to \Sigma^0 e^- \bar{\nu}$ decay, a world average of $(6.6 \pm 3.1) \times 10^{-4}$ is obtained for $\Xi^- \to \Lambda e^- \bar{\nu}$. This is in agreement with the Cabibbo theory prediction of $\sim 6 \times 10^{-4}$. It is interesting to note that the results of the CERN-Heidelberg experiment, which measured the combined branching ratio

$$\frac{\Gamma(\Xi^- \to \Lambda e^- \bar{\nu}) + \Gamma(\Xi^- \to \Sigma^0 e^- \bar{\nu})}{\Gamma(\Xi^- \to \Lambda\pi^-)} = (6.8 \pm 2.2) \times 10^{-4},$$

can be used to extract the branching ratio of $(0.2 \pm 3.8) \times 10^{-4}$ for $\Xi^- \to \Sigma^0 e^- \bar{\nu}$. This branching ratio is consistent with the Cabibbo theory.[2]

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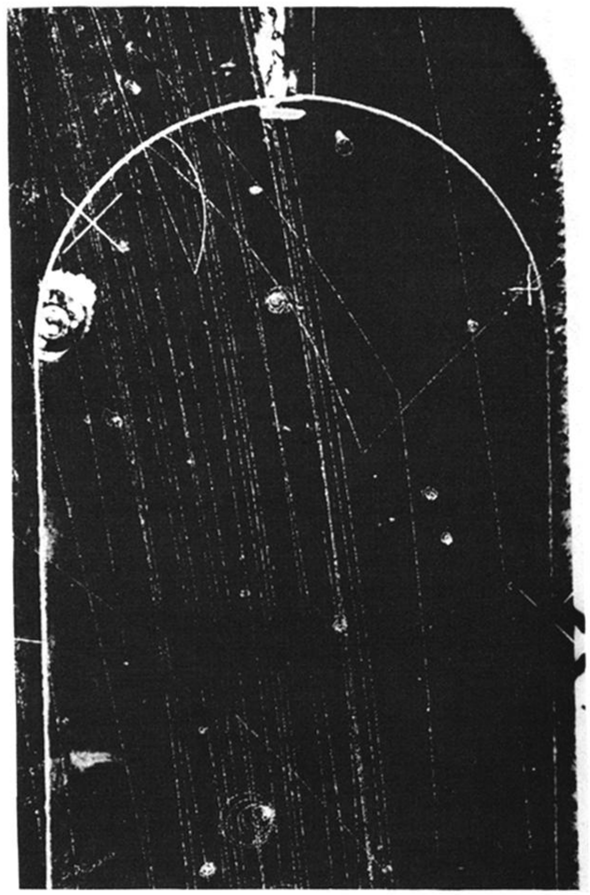

FIG. 1. Photograph of the $\Xi^0 \to \Lambda\gamma$ event. At the zero-prong vertex, the production reaction is $K^- p \to \Xi^0 K^0$. The $K^0 \to \pi^+ \pi^-$ decay (on the right, referred to as vee No. 1 in Table II) and the $\Lambda \to p \pi^-$ decay (on the left, referred to as vee No. 2) are both visible.