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Observation of Λp mass enhancement in the reaction $K^-d \rightarrow \Lambda p \pi^+\pi^-\pi^-$

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A study of Λp mass distribution is made from the analysis of bubble-chamber data of the reaction $K^-d \rightarrow \Lambda p \pi^+\pi^-\pi^-$ at K^- beam momenta of 1.45 and 1.65 GeV/c. A statistically significant peak in the Λp mass distribution is observed at $\simeq$2130 MeV. Another Λp mass peak in the region $\simeq$2195–2210 MeV is also seen but its statistical significance depends on the choice of the background estimate.

I. INTRODUCTION

In the past few years several possible enhancements have been reported in the ΛN invariant-mass distribution[1-15] through experiments performed with K^-d interactions,[1-7] K^- or Σ^- capture in helium[8,9] and K^- capture in CF_3Br,[10] neutron interactions with carbon,[11,12] pp interactions,[13] p interactions with Be,[14] and K^- capture in nuclear emulsions.[15,16] All experiments report enhancements in the Λp or Λn invariant-mass distributions at varying values lying in a broad region of about 2058 to 2570 MeV (Table I). Of all the enhancements reported so far, one that has been found prominently is at $M(\Lambda p) \simeq 2130$ MeV. This was first reported by Dahl *et al.*[1] in the study of K^-d interactions at rest. This was further substantiated by the analysis of Cline *et al.*,[2] where the data on the reaction $K^-d \rightarrow \Lambda p\pi^-$ at K^- beam momenta of 400 MeV/c was analyzed and an enhancement in the Λp invariant-mass distribution at $M(\Lambda p) \simeq 2126$ MeV with a width $\Gamma \lesssim 10$ MeV was reported. This enhancement if interpreted as a resonance in the (Λp) system could be the $I = \frac{1}{2}$, $Y = 1$ member of an SU(3) decuplet which includes a deuteron in the $I = 0$, $Y = 2$ position. An alternative explanation of this peak is due to the conversion process $\Sigma N \rightarrow \Lambda N$, which does not require the introduction of any Λp resonance.[3,4]

Most of the K^-d experiments reported so far have analyzed the $\Lambda p\pi^-$ final state, and a few have analyzed the four-body final state $\Lambda p\pi^-\pi^0$.[6,7] The results of the three-body channel $\Lambda p\pi^-$, from this experiment, have already been published.[5] In this paper we report additional information about Λp mass enhancement from the analysis of the five-body final-state reaction

$K^-d \rightarrow \Lambda p\pi^+\pi^-\pi^-$

at K^- momenta of 1.45 GeV/c and 1.65 GeV/c. (1)

II. EXPERIMENTAL DETAILS AND ANALYSIS

The data used for this analysis consist of 2487 events of reaction(1), having 1117 events with seen $\Lambda \rightarrow p\pi^-$ decay and 1370 events where Λ decay was not seen. This data came from a K^-d bubble-chamber experiment carried out at the Rutherford High Energy Laboratory by a collaboration of Universities of Birmingham, Edinburg, Glasgow, and Imperial College, London. The Saclay 80-cm bubble chamber filled with liquid deuterium was exposed to a separated K^- beam at incident momenta of 1.45 GeV/c and 1.65 GeV/c. For this analysis, the data from the two exposures were combined. The details of scanning, measuring, and kinematical fitting, etc. have been given before in Refs. 17 and 18.

The events of reaction (1) can be ambiguous with any of the following channels:

$$K^-d \rightarrow \Sigma^0 p\pi^+\pi^-\pi^-, \quad \Sigma^0 \rightarrow \Lambda\gamma\,, \tag{2}$$

$$K^-d \rightarrow \Lambda p\pi^+\pi^-\pi^-\pi^0, \tag{3}$$

$$K^-d \rightarrow \Lambda p\pi^+\pi^-\pi^- + \text{neutral}. \tag{4}$$

The main ambiguity comes from channel (2), where the Λ observed may come directly from reaction (1) or as a decay product of Σ^0 in channel (2). Since we have considered the uniquely fitted events for this analysis, the contamination due to ambiguity of this type should be substantially removed. However, as a check to the quality of data we have discussed the resolution of this ambiguity here. For this we examine the distribution of $\cos\theta_\gamma$, where θ_γ is the angle between the directions of Σ^0 and its decay γ in the Σ^0 rest system defined as

$$\cos\theta_\gamma = \left[\frac{2M_\Sigma{}^2 E_\gamma^{\text{lab}}}{E_\Sigma^{\text{lab}}(M_\Sigma{}^2 - M_\Lambda{}^2)} - 1\right]\frac{E_\Sigma^{\text{lab}}}{p_\Sigma^{\text{lab}}}\,,$$

where E and p stand for the energy and momentum of the respective particles. For the $\Lambda p\pi^+\pi^-\pi^-$ events with Λ decay seen, the $\cos\theta_\gamma$ distribution is shown in Fig. 1. All the $\Lambda p\pi^+\pi^-\pi^-$ events gave unphysical values of $\cos\theta_\gamma$, i.e., $\cos\theta_\gamma < -1$, which shows that Λ-Σ^0 ambiguity is absent for these events

Channels (3) and (4) can be kinematically separated from channel (1) by plotting the histograms of missing-mass (M_X) squared. As there is no neutral missing particle in channel (1), this should have the missing-mass distribution peaked at zero (within measurement errors, of course) whereas, the $M_X{}^2$ distribution for channel (3) and (4) should be peaked at $M^2(\pi^0)$ and M^2(neutral), respectively. In Fig. (2a) we have displayed the histogram of the $M_X{}^2$ distribution for channel (1). For a total sample of events (both with seen and unseen spectator protons)[19] the distribution has a peak at zero, except for few events ($\simeq 30$) in the 950-MeV mass region. But the events with seen spectator protons have no such high-missing-mass events. We thus find that channels (3) and (4) are kinematically separable from channel (1) and restricting the missing-mass distribution in a narrow band ($|M_X{}^2| \lesssim 0.05$ GeV^2) around zero, the number of ambiguous events of channel (1) due to channel (3) and (4) is

TABLE I. Summary of observed ΛN mass enhancements.

Author	Momentum p of the incident particles (MeV/c)	Reaction	Peak in the ΛN invariant-mass distribution (MeV)	Width of the distribution (MeV)
Dahl *et al.* (Ref. 1)	$p \leq 450$	$K^- d \to \Lambda p \pi^-$	$\simeq 2130$	···
Cline *et al.* (Ref. 2)	$p = 400$	$K^- d \to \Lambda \pi^- p$	$\simeq 2126$	$\lesssim 10$
Alexander *et al.* (Ref. 3)	$p = 910$, 1007, and 1106	$K^- d \to \Lambda \pi^- p$	$\simeq 2130$	$\simeq 10$
Tan (Ref. 4)	$p = 0$ (at rest)	$K^- d \to \Lambda \pi^- p$	2128.7 2138.8	7 ± 0.6 9.1 ± 2.4
Eastwood *et al.* (Ref. 5)	$p = 1450$ and 1650	$K^- d \to \Lambda \pi^- p$	2129	$\simeq 10$
Sims *et al.* (Ref. 6)	$p = 670$ and 975	$K^- d \to \Lambda \pi^- p$ $\Lambda \pi^- \pi^0 p$ $\Lambda \pi^- \pi^+ n$	2127 ± 1 ($\simeq 2104$)	8 ± 1 ($\simeq 80$) [a]
Sodhi *et al.* (Ref. 7)	$p = 1450$ and 1650	$K^- d \to \Lambda \pi^- \pi^0 p$	$\simeq 2115$	$\simeq 150$
Bunnel *et al.* (Ref. 8)	$p = 0$ (at rest)	$K^-(^4\mathrm{He}) \to \Lambda \pi^- p d$	$\simeq 2130$	···
Cohn *et al.* (Ref. 9)	$p = 0$ (at rest)	$\Sigma^-(^4\mathrm{He}) \to \Lambda n \mathrm{H}^3$	2098	20
Buran *et al.* (Ref. 10)	$p = 0$ (at rest)	$K^-(\mathrm{CF_3Br}) \to \Lambda p \cdots$	$\simeq 2220$	$\simeq 20$
Vishnevskii *et al.* (Ref. 11)	$p \leq 4.3$ GeV/c	$n + {}^{12}\mathrm{C} \to \Lambda N \cdots$	$\simeq 2220$ $\simeq 2573$	$\simeq 40$ $\simeq 80$
Shahbazian *et al.* (Ref. 12)	$p = 7.0$ GeV/c	$n + {}^{12}\mathrm{C} \to p \Lambda K^0 (m\pi)$	2125.2 ± 2.5 2251.4 ± 3.9	20.6 ± 5.2 21.1 ± 5.4
Present work	$p = 1450$ and 1659	$K^- d \to \Lambda p \pi^+ \pi^- \pi^-$	$\simeq 2130$ $\simeq 2200$	··· ···
Mellisinos *et al.* (Ref. 13)	$p = 2400$ and 2850	$pp \to \Lambda K^+ p$	2058 ± 8	30
Piroue (Ref. 14)	$p = 950$	$p(\mathrm{Be}) \to K^+ N \Lambda \cdots$	2360	···
Jain (Ref. 15)	$p = 0$ (at rest)	$K^-(\text{emulsion}) \to \Lambda p \cdots$	2110	$\simeq 20$ [b]

[a] These values of mass and width are according to our interpretation of data (see Ref. 7).
[b] The enhancement reported in this paper was subsequently explained as due to experimental biases (see Ref. 16).

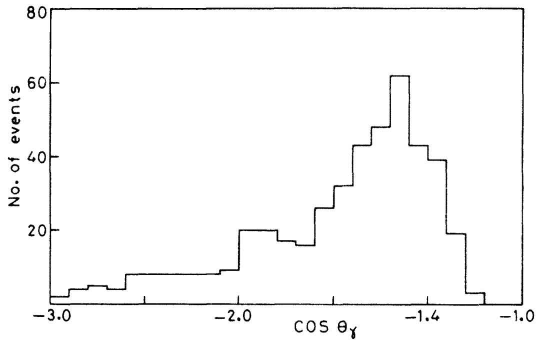

FIG. 1. $\cos\theta\gamma$ distribution for events of the reaction $K^-d \to \Lambda p \pi^+\pi^-\pi^-$.

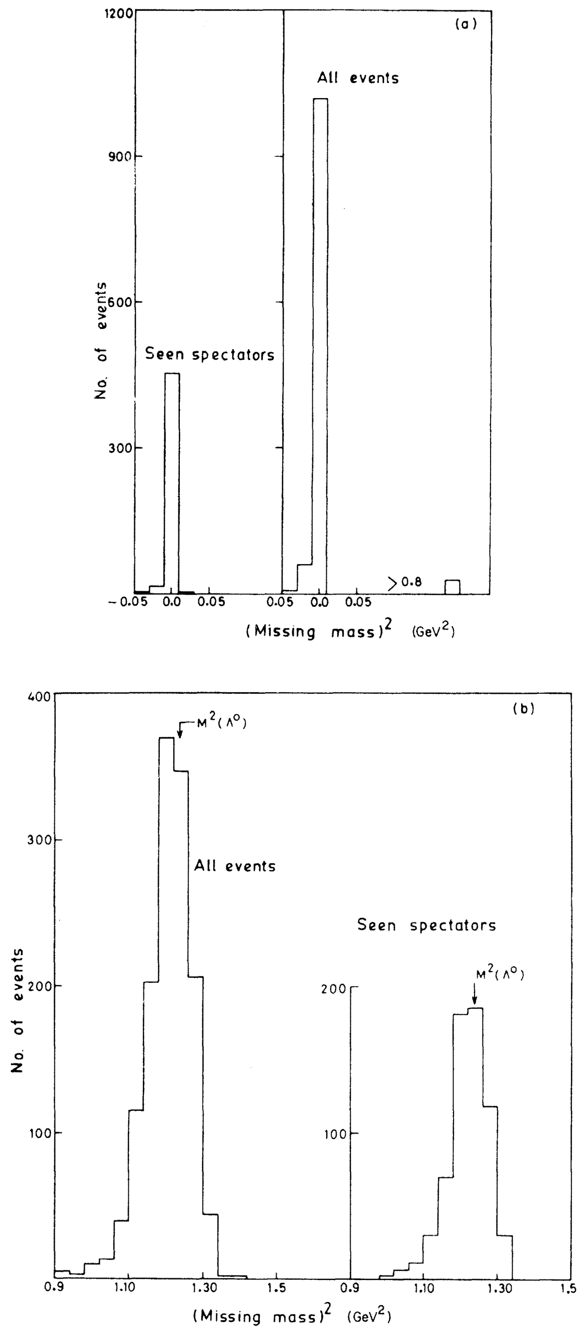

FIG. 2. (a) (missing mass)^2 distribution for $K^-d \to \Lambda p\pi^+\pi^-\pi^-$ (seen Λ decay). (b) (missing mass)^2 distribution for $K^-d \to \Lambda p \pi^+\pi^-\pi^-$ (unseen Λ decay).

considerably reduced to $\simeq 3\%$.

For the one-constraint $\Lambda p\pi^+\pi^-\pi^-$ channel, i.e., where Λ decay was not seen, the missing-mass-squared distribution should be peaked at $M^2(\Lambda^0)$. Figure 2(b) shows the $M_X{}^2$ distribution for this reaction. It clearly shows a peak at $M^2(\Lambda^0)$, as expected, with a small excess of events on the low-missing-mass side, which is removed when a sample of events with visible spectator protons is selected.

III. RESULTS

The Λp invariant-mass distribution for a total of 2487 events of the data is shown in Fig. 3. The enhancement in the 2130-MeV mass region heretofore seen only in three-body and four-body final states of K^-d interactions is seen to be present also in the five-body final state. A spike in the 2060-MeV mass region is also seen which disappears when the events with seen spectator protons were separated. The Λp invariant-mass distribution for 1116 such events (with seen spectator protons) is given in Fig. 4. The absence of the spike, near threshold, in seen-spectator events shows that this was probably due to ambiguities and contaminations in the unseen-spectator events (which have either a one-constraint or a zero-constraint fit). Two enhancements at $\simeq 2130$ MeV and in the 2195–2200—MeV mass region are now visible above the hand-drawn background estimate.

In order to obtain a sample of events in which probably both nucleons in the deuteron take part in the K^-d interactions, we have applied a lower cutoff at 150 MeV/c (Ref. 7)for the momentum (p_s) of the protons in the $\Lambda p\pi^+\pi^-\pi^-$ final state. The Λp invariant-mass distribution for 644 such events (having $p_s \geq 150$ MeV/c) is shown in Fig. 5. This channel contains $\Lambda\pi^\pm$ in the final state and is therefore expected to show a peak, corresponding to well-established $\Sigma(1385)$, in the $\Lambda\pi^\pm$ invariant-mass distributions. The $\Lambda\pi^+$ and $\Lambda\pi^-$ (two combinations per event) invariant-mass distributions are shown in Figs. 6 and 7, respectively. Both these distributions show a peak in the 1385-MeV mass region corresponding to the resonance Σ (1385). To check the interference of these reso-

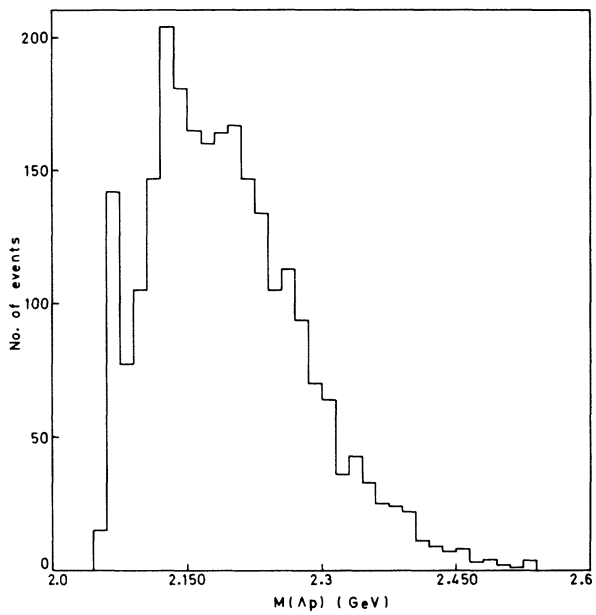

FIG. 3. Λp invariant-mass distribution for all events.

nances on the Λp peak, we have removed the events in the peak region of the $\Lambda\pi$ distribution [i.e., 1405 $\geq M(\Lambda\pi) \geq 1365$ MeV]. The Λp invariant-mass distribution of the remaining events is shown in Fig. 8. The two enhancements, one at $\simeq 2130$ MeV and the

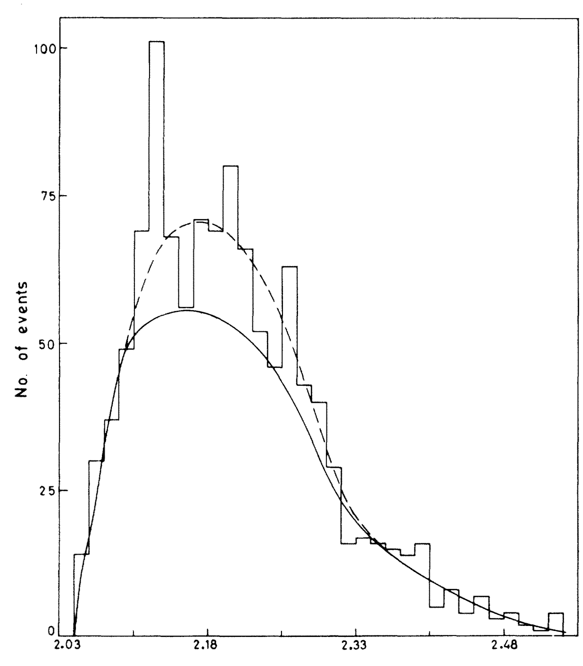

FIG. 4. Λp invariant-mass distribution for events with seen spectators. The solid and dashed curves are two extreme possibilities of the (hand-drawn) background estimate.

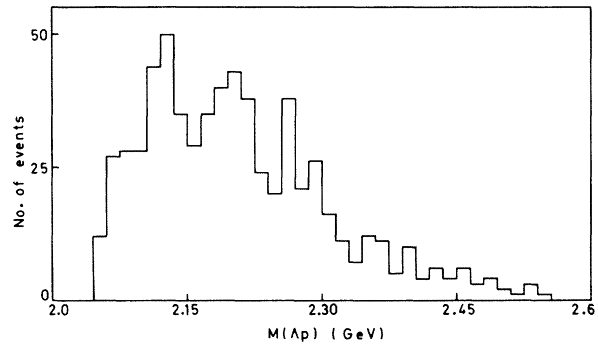

FIG. 5. Λp invariant-mass distribution for events with spectator-proton momentum ≥ 150 MeV/c.

other in the region 2195–2210 MeV are still visible.

It may be remarked that the existence of the second enhancement is sensitive to the choice of the background. An alternative background estimate, shown by the dashed line in Fig. 4, which may be just as good a fit makes the second peak statistically insignificant and leaves only enhancement at $\simeq 2130$ MeV.

IV. DISCUSSION

Our results may be compared with those reported earlier in the $\Lambda p\pi^-$, $\Lambda p\pi^-\pi^0$, and other multibody $\Lambda N\cdots$ final states (Table I). In the three-body channel of K^-d (Refs. 1–6) or $K^-(^4\mathrm{He})$ (Ref. 8) interactions, all experiments have reported one enhancement in the Λp system in the 2130-MeV mass region and having a width $\lesssim 10$ MeV, with the exception of Ref. 4 where an additional Λp mass enhancement at $\simeq 2139$ MeV with a width of ≈ 9 MeV is also reported. The Λp mass enhancement around 2130 MeV is also reported in the four-body channels $\Lambda p\pi^-\pi^0$ (Refs. 6,7) and $\Lambda n\pi^-\pi^+$,[6] but the peak is shifted to a much lower value and the

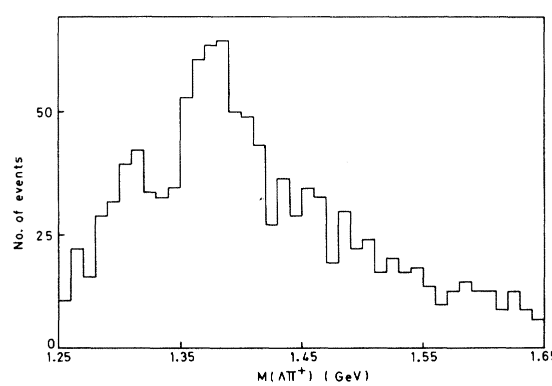

FIG. 6. $\Lambda\pi^+$ invariant-mass distribution (for seen spectators only).

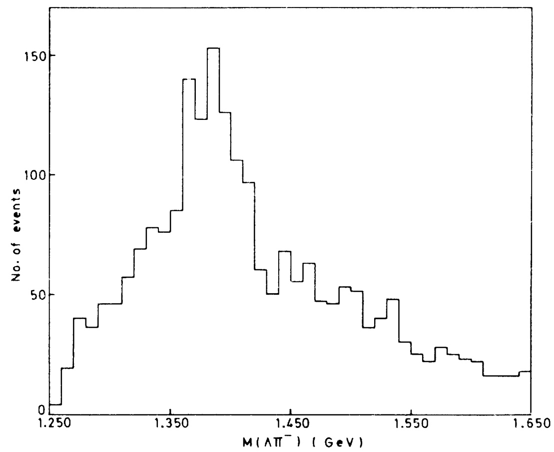

FIG. 7. $\Lambda\pi^-$ invariant-mass distribution (two combinations per event).

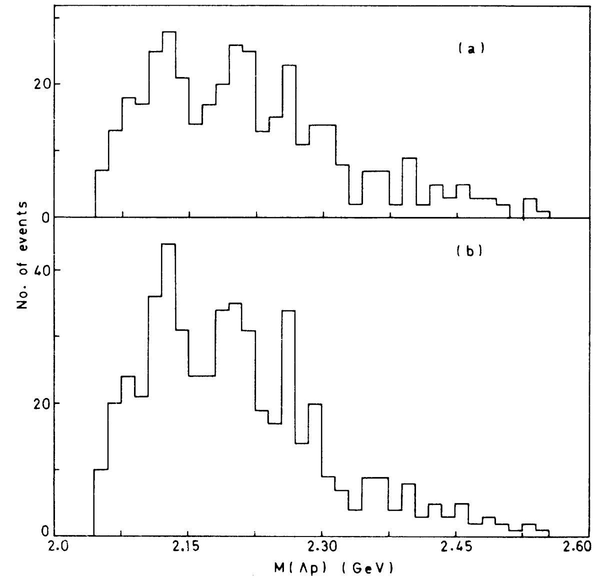

FIG. 8. Λp invariant-mass distribution for events remained after subtracting (a) the events in the $\Lambda\pi^-$ peak region and (b) the events in the $\Lambda\pi^+$ peak region.

width of the distribution is large. The experiments with $\Sigma^-(^4\mathrm{He})$ interactions[9] or K^- interactions with complex nuclei[10] report the Λp mass enhancement peaked at $\simeq 2098$ MeV and $\simeq 2220$ MeV, respectively. Other experiments involving five or more particles in the final state,[11,12] including the present one, report enhancements in the higher-mass region of $\simeq 2200$ MeV and 2250 MeV in addition to the usual 2130-MeV mass enhancement. On the other hand, the experiments with pp and p(Be) interactions[13,14] report enhancement in the Λp mass spectrum in a widely different region of 2058 MeV and 2360 MeV. It is expected that a genuine physical process due to a resonance should show that the position and width of the ΛN mass peak is practically independent of the nature and momentum of the incident particle and also of the reaction channel used. Since this is not the case, a simple resonance interpretation of this effect seems to be doubtful.

A particular difficulty in the interpretation of 2130-MeV Λp mass enhancement is the proximity of the peak to the ΣN threshold, which is $\simeq 2129$ MeV for $\Sigma^+ n$ and $\simeq 2131$ MeV for $\Sigma^0 p$ systems. In fact, attempts[3-5] have been made to explain the Λp mass enhancement due to a kinematical effect involving an intermediate Σ hyperon, i.e., $K^- d \to \pi^-(\Sigma N)$, $\Sigma N \to \Lambda p$. Because of the difficulties of isolating a genuine Λp resonance effect from a ΣN conversion process, the possibility of this effect being due to some combination of both the resonance and conversion process cannot be ruled out. The other reactions sensitive to this effect, viz., free Λp (Ref. 20) and Σp (Ref. 21), scattering experiments, based on rather poor statistics, do not give a clear picture. Keeping all this in view and in the absence of direct experimental proof, we feel that it is too premature to invoke the existence of a dibaryon resonance involving the ΛN system.

The enhancement in the higher-mass interval of 2195–2210 MeV observed in our data (Fig. 8) has been reported earlier by Buran *et al.*[10] in K^- capture in CF_3Br and by Vishnevskii *et al.*[11] and Shahbazyan *et al.*[12] in neutron capture in carbon. However, this result too should be viewed with caution in view of the limited statistics of the present experiment.

ACKNOWLEDGMENTS

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[19]The smallest track length (L_p) of the spectator proton observed in our experiment is $L_p \approx 0.5$ mm corresponding to a proton momentum, $p_s \approx 50$ MeV/c. Thus events having $L_p \gtrsim 0.5$ mm are classified as seen, measurable spectator-proton events. When the spectator proton was not measurable, it was inserted by a fit at the production vertex (See Refs. 17 and 18).

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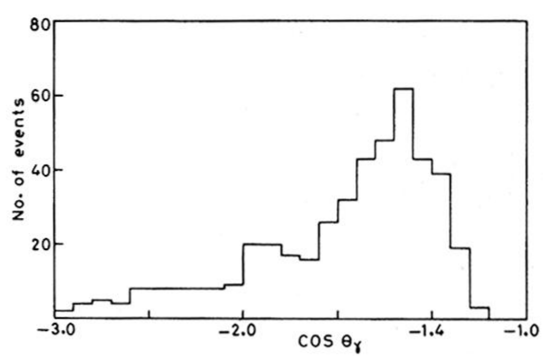

FIG. 1. $\cos\theta\gamma$ distribution for events of the reaction $K^-d \rightarrow \Lambda p\, \pi^+ \pi^- \pi^-$.

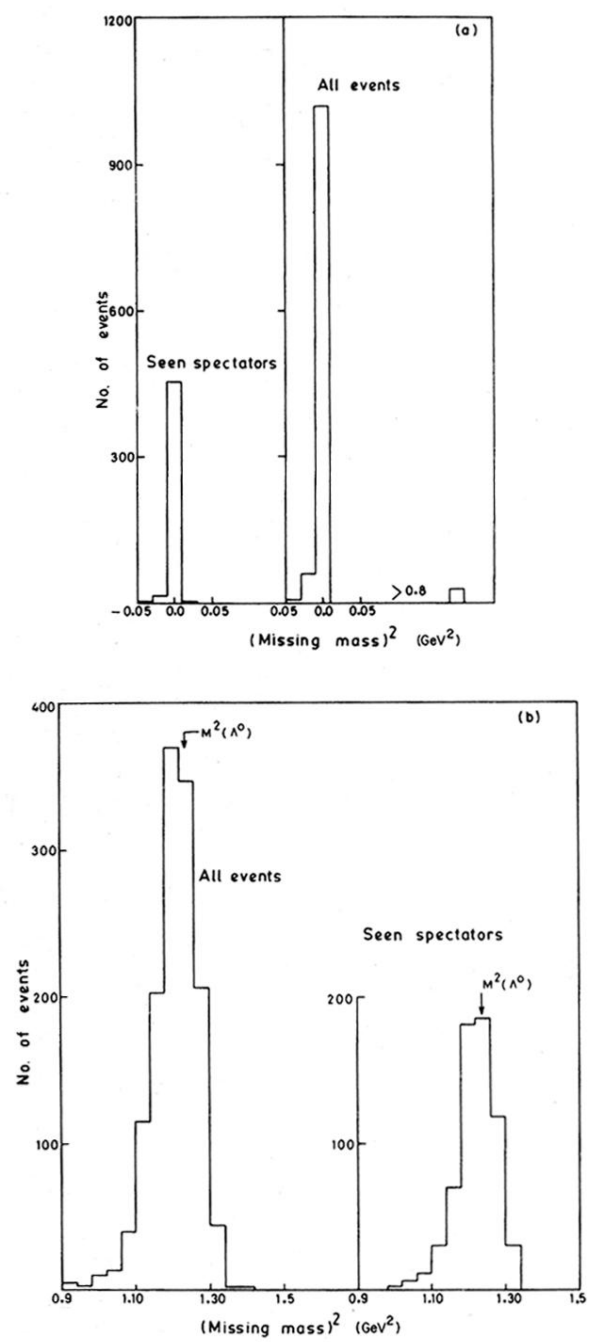

FIG. 2. (a) (missing mass)^2 distribution for $K^-d \to \Lambda p \pi^+\pi^-\pi^-$ (seen Λ decay). (b) (missing mass)^2 distribution for $K^-d \to \Lambda p \pi^+\pi^-\pi^-$ (unseen Λ decay).

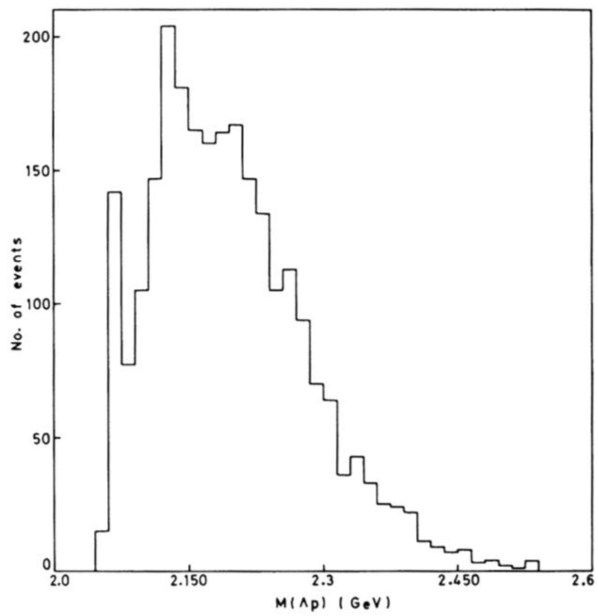

FIG. 3. Λp invariant-mass distribution for all events.

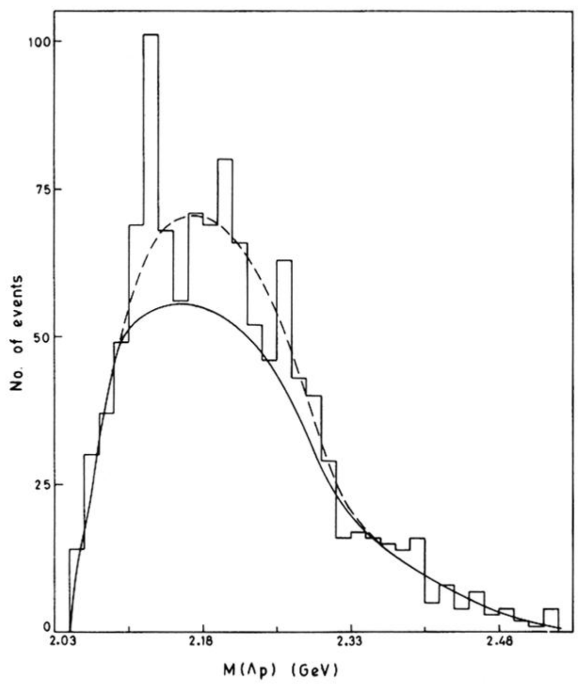

FIG. 4. Λp invariant-mass distribution for events with seen spectators. The solid and dashed curves are two extreme possibilities of the (hand-drawn) background estimate.

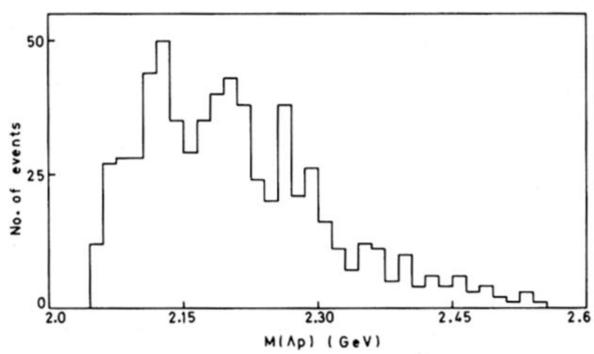

FIG. 5. Λp invariant-mass distribution for events with spectator-proton momentum ≥ 150 MeV/c.

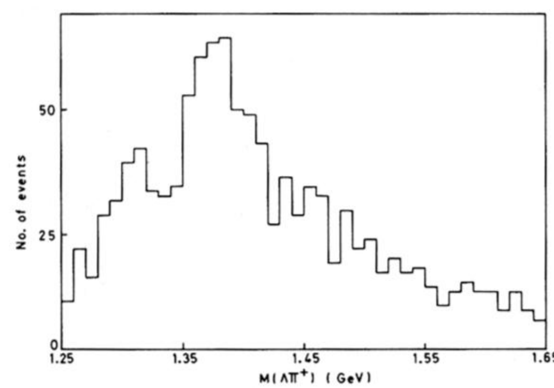

FIG. 6. $\Lambda\pi^+$ invariant-mass distribution (for seen spectators only).

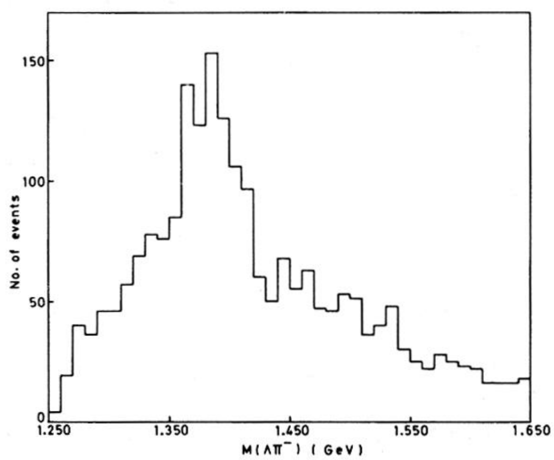

FIG. 7. $\Lambda\pi^-$ invariant-mass distribution (two combinations per event).

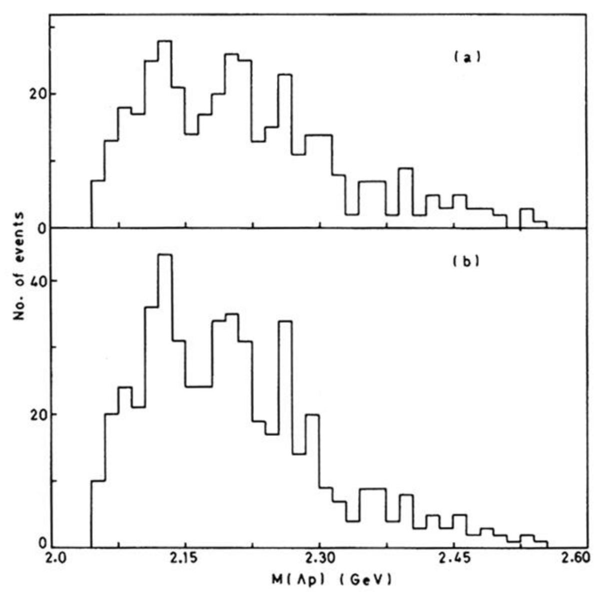

FIG. 8. Λp invariant-mass distribution for events remained after subtracting (a) the events in the $\Lambda\pi^-$ peak region and (b) the events in the $\Lambda\pi^+$ peak region.