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PRODUCTION OF $\Lambda(1405)$ IN K^-p REACTIONS AT 4.2 GeV/c

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From a 130 event/μb exposure of the CERN 2 m hydrogen bubble chamber to a 4.2 GeV/c K^- beam, a high statistics sample of $\Lambda(1405)$ in a production reaction has been isolated. The reaction $K^-p \to \Sigma^+(1660)\pi^-$, $\Sigma^+(1660) \to \Lambda(1405)\pi^+$, $\Lambda(1405) \to \Sigma\pi$ has enabled an almost pure selection of $\Lambda(1405)$ events. A Byers-Fenster spin-parity analysis is in agreement with the $J=\frac{1}{2}$ assignment but gives no parity discrimination. The measured line-shape of the $\Lambda(1405)$ is particularly useful in allowing a better understanding of the nature of this resonance.

1. Introduction

The $\Lambda(1405)$ is conventionally assumed to be a well-established resonance and to represent the $I=0$, strangeness $=-1$, $J^P=\frac{1}{2}^-$ state within the $L=1$ supermultiplet of the three-quark system. Lying roughly 30 MeV below the $\bar{K}N$ threshold, the resonance can only be observed directly in the $(\Sigma\pi)^0$ system of final states of production experiments. It was first reported by Alston et al. [1] in the reaction $K^-p \to \Sigma 3\pi$ at 1.15 GeV/c and subsequently "seen" in several other experiments [2-6]. However these observations suffered from

(i) low statistics,

(ii) difficulties with the reconstruction of final states involving Σ decays, and

(iii) the uncertainty in the removal of backgrounds, particularly that from $\Sigma(1385) \to \Sigma\pi$ whose rate was badly known.

In fact, none of the experiments during the period 1962-1972 were able to demonstrate a convincing signal, to measure the precise mass and width, or to determine the quantum numbers.

Nevertheless, the early multichannel K-matrix analyses of low-energy $\bar{K}N$ reactions [7], particularly those of Kim [8, 9], strongly suggested that the $\Lambda(1405)$ was an s-wave virtual bound state of the $\bar{K}N$ system. It was perhaps these analyses which gave the $\Lambda(1405)$ an added degree of authenticity - so much so in fact that neither the mass nor the width are today any different from the values suggested by Alston more than 20 years ago.

The only experiment which has reported a respectable signal for $\Lambda(1405)$ is that of Thomas et al. [10] in the reaction $\pi^-p \to \Sigma\pi K$ at 1.69 GeV/c. Subsequently, Chao

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et al. [11] demonstrated the importance of such data in constraining the multichannel analyses. Very recently, Dalitz et al. [12] have restated the debate on the nature of the $\Lambda(1405)$ resonance and asked for more precise data on the production line-shape of the $\Lambda(1405) \to \Sigma\pi$. Currently, it is not known whether the interpretation of the $\Lambda(1405)$ as a three-quark state is or is not consistent with its appearance as an unstable $\bar{K}N$ bound state.

From a large exposure of the CERN 2 m hydrogen bubble chamber we have isolated the cleanest and highest statistics sample of $\Lambda(1405)$. Sect. 2 describes the event selection criteria and presents the $\Sigma\pi$ mass spectrum. In sect. 3 a J^P analysis is performed and evidence presented for the $J=\frac{1}{2}$ assignment. Sect. 4 discusses the $\Sigma\pi$ line-shape and compares the predictions of a Breit–Wigner resonance with several dynamical models. Finally sect. 5 derives an upper limit for the $\bar{K}N/\Sigma\pi$ branching ratio.

2. Event selection

We report here the highest statistics sample of $\Lambda(1405)$ in a production reaction. The data are taken from a 130 event/μb exposure of the CERN 2 m hydrogen bubble chamber to a 4.2 GeV/c K^- beam and processed by the Amsterdam-CERN-Nijmegen-Oxford Collaboration. Many final states from this experiment have been analysed and published, and we refer the reader to the paper of Timmermans et al. [13] which describes several aspects of the data discussed below.

Timmermans et al. analysed the $\Sigma(1660)$ resonance with 65 events/μb (approximately 50% of the full data sample). Evidence was presented for two distinct $\Sigma(1660)$ states – one with properties in agreement with the D13 resonance as deduced from formation experiments, and the other with new characteristics, namely:

(i) mass and width compatible with the D13,

(ii) spin parity $=\frac{3}{2}^-$,

(iii) dominant decay into $\Sigma\pi\pi$, of which $97\pm8\%$ was determined to be $\Lambda(1405)\pi$,

(iv) produced only at small t.

With the complete data sample, we therefore use the production mechanism of fig. 1 to isolate a clean sample of $\Lambda(1405)$ from the reactions

$$K^-p \to \Sigma^+\pi^-\pi^+\pi^-, \qquad 14\,368 \text{ events}, \tag{1}$$

$$K^-p \to \Sigma^-\pi^+\pi^+\pi^-, \qquad 11\,723 \text{ events}, \tag{2}$$

$$K^-p \to n\bar{K}^0\pi^+\pi^-, \qquad 38\,692 \text{ events}. \tag{3}$$

In each case, an event was only accepted if it had (i) a kinematic fit probability greater than 1%, (ii) a fitted beam track with parameters consistent with the nominal beam, and (iii) both production and decay vertices within a limited fiducial volume. The events have been weighted to compensate for the loss of decays with short projected lengths (≤ 5 mm for $\Sigma^\pm$, ≤ 3 mm for K^0) and of decays outside the fiducial

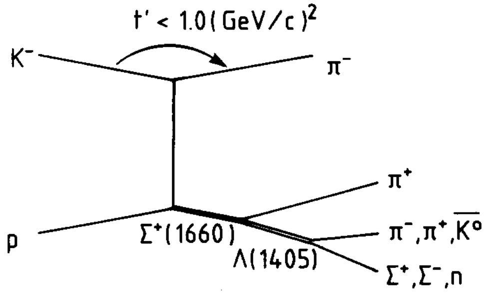

Fig. 1. Production mechanism for $\Lambda(1405)$.

volume. In addition, the charged sigmas have been weighted to compensate for the loss of decays with small projected decay angles ($\leqslant 60$ mrad). This latter procedure is particularly important for the $\Sigma^+ \to p\pi^0$ decay and is described in detail by Timmermans [14]. Table 1 lists some of the characteristics of the reactions (1)-(3).

Fig. 2a shows the $\Sigma^+\pi^-\pi^+$ mass spectrum from reaction (1) with the selection $t'(p \to \Sigma\pi\pi) < 1.0\ (\mathrm{GeV}/c)^2$. A prominent peak corresponding to $\Sigma^+(1660)$ is seen superimposed on a small, gradually rising, background. Fig. 2b shows the $\Sigma^+\pi^-$ mass spectrum for those events which fall within the $\Sigma^+(1660)$ region ($1.60 \leqslant M(\Sigma^+\pi^-\pi^+) \leqslant 1.72$ GeV). The superimposed curve is the result of a Monte Carlo calculation for the $\Sigma\pi$ spectrum assuming phase space decay of the $\Sigma(1660)$. The Monte Carlo generated events were normalised to reproduce the observed $\Sigma^+\pi^-\pi^+$ mass spectrum between 1.60 and 1.72 GeV. A clear enhancement is seen, centred around 1.4 GeV but with an asymmetric shape, together with a much smaller peaking above 1.50 GeV. This latter enhancement is due to the decay $\Sigma(1775) \to \Lambda(1520)\pi$ and is found to grow substantially when the upper limit of the $\Sigma(1660)$ mass selection is increased. We estimate that the background under the $\Lambda(1405)$ peak is no more

TABLE 1

Characteristics of the final states

Reaction	Final state	No. of kinematic fit constraints	Unweighted no. of events	Select $\Sigma(1660)$ and $t' < 1.0\ \mathrm{GeV}^2$	Average weight
(1)	$\Sigma^+\pi^-\pi^+\pi^-$	4C	14 368	766	1.61
	$\Sigma^+\pi^-\pi^+\pi^-$ $\hookrightarrow p\pi^0$	4C	5 319	353	1.74
	$\Sigma^+\pi^-\pi^+\pi^-$ $\hookrightarrow n\pi^+$	4C	9 049	413	1.49
(2)	$\Sigma^-\pi^+\pi^+\pi^-$	4C	11 723	1106	1.26
(3)	$\bar{K}^0 n\pi^+\pi^-$	1C	38 692	61	1.18

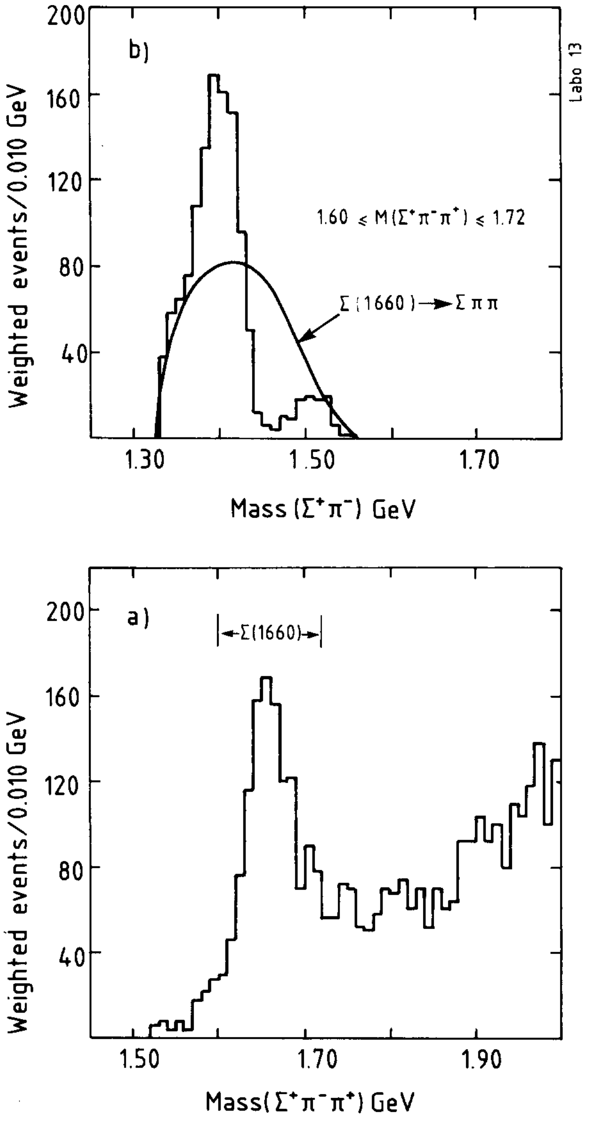

Fig. 2. Invariant mass distributions: (a) $M(\Sigma^+\pi^-\pi^+)$ from the reaction $K^-p \to \Sigma^+\pi^-\pi^+\pi^-$ at 4.2 GeV/c with the restriction $t'(K^- \to \Sigma^+\pi^-\pi^+) < 1.0(\text{GeV}/c)^2$, (b) $M(\Sigma^+\pi^-)$ with the additional selection $1.60 \leq M(\Sigma^+\pi^-\pi^+) \leq 1.72$ GeV. The superimposed curve represents the result of a Monte Carlo calculation for $\Sigma(1660) \to \Sigma\pi\pi$.

than a few % – consistent with the very small intensity between the $\Lambda(1405)$ and the $\Lambda(1520)$.

Fig. 3 shows the $\Sigma^-\pi^+\pi^+$ and $\Sigma^-\pi^+$ mass spectra from reaction (2) with the same selections of t' and mass as described above. We note that the $\Sigma^+(1660)$ is

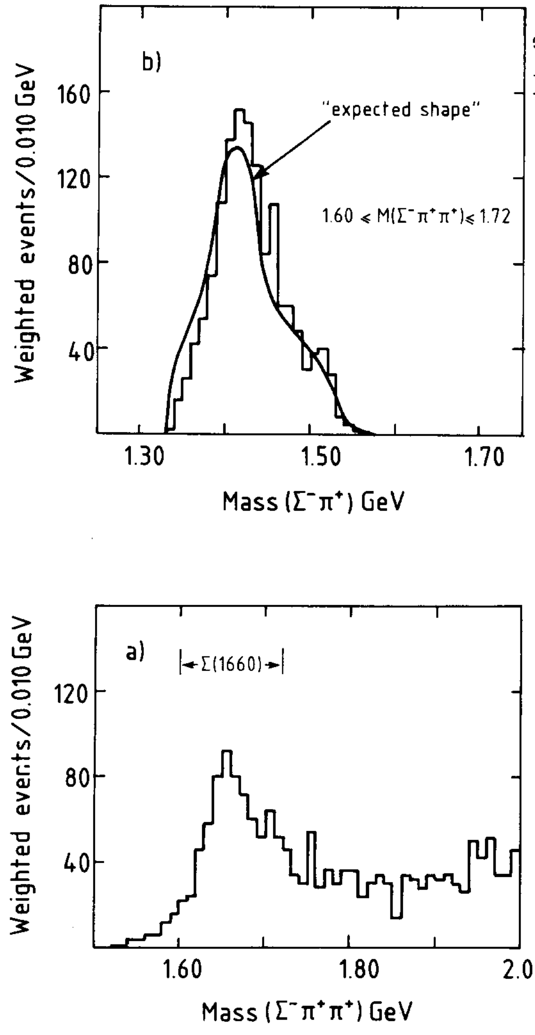

Fig. 3. Invariant mass distributions: (a) $M(\Sigma^-\pi^+\pi^+)$ from the reaction $K^-p \rightarrow \Sigma^-\pi^+\pi^+\pi^-$ at 4.2 GeV/c with the restriction $t'(K^- \rightarrow \Sigma^-\pi^+\pi^+) < 1.0(\mathrm{GeV}/c)^2$, (b) $M(\Sigma^-\pi^+)$ with the additional selection $1.60 \leq M(\Sigma^-\pi^+\pi^+) \leq 1.72$ GeV. The superimposed curve represents the spectrum shape expected from reaction (1).

not as prominent in this reaction and, for each event selected, there are two $\Sigma^-\pi^+$ combinations to be plotted. Thus we expect, at least, a 50% background across the entire $\Sigma^-\pi^+$ mass spectrum. The curve shown in fig. 3b was calculated from reaction (1) and represents the normalised sum of $\Sigma^+\pi^-$ and $\Sigma^+\pi^+$ (with $\Sigma^+\pi^-\pi^+$ in the $\Sigma(1660)$ region). Apart from a small scale shift, the observed mass spectrum is therefore consistent with that of fig. 2b. Timmermans et al. [13] have previously pointed out the difference between the numbers of $\Sigma^+\pi^-\pi^+$ and $\Sigma^-\pi^+\pi^+$ events since from isospin considerations one expects a 1:1 ratio. Significant interference effects must be present in the $\Sigma^-\pi^+\pi^+$ channel to explain the discrepancy.

Subsequent analysis will therefore be confined to reaction (1).

3. Spin-parity analysis

Following Byers and Fenster [15], the complete distribution function to describe the process

$$\Lambda^* \to \Sigma^+\pi^- , \qquad \Sigma^+ \to p\pi^0 , \tag{4}$$

is given by Byers [16]:

$$F = \sum_{\substack{L=0 \\ (L \text{ even})}}^{2J-1} \sum_{N=-L}^{L} Z_L^M D_{M0}^{(L)}(\phi_\Sigma, \theta_\Sigma, 0) + \alpha_\Sigma \cos\psi \sum_{\substack{L=1 \\ (L \text{ odd})}}^{2J} \sum_{M=-L}^{L} Z_L^M D_{M0}^{(L)}(\phi_\Sigma, \theta_\Sigma, 0)$$

$$+ \gamma(2J+1)\alpha_\Sigma \sin\psi \sum_{\substack{L=1 \\ (L \text{ odd})}}^{2J} \sum_{M=-L}^{L} Z_L^M [L(L+1)]^{-1/2} C_{M1}^{(L)}(\phi_\Sigma, \theta_\Sigma, 0) , \tag{5}$$

where $Z_L^M = (-1)^{J-1/2}(2J+1)^{1/2} C(JJL; \frac{1}{2} - \frac{1}{2}) t_L^M$, ϕ_Σ, θ_Σ are the spherical angles of Σ in the Λ^* rest frame, ψ is the angle between the p and the Σ^+ in the Σ rest frame, $C_{M1}^{(L)} = -\frac{1}{2}[D_{M1}^{(L)} - D_{M-1}^{(L)}]$, α_Σ is the Σ^+ decay asymmetry ($=-0.979$), γ is the $\Lambda^*\Sigma$ relative parity.

The moments of this distribution function have been determined using the program developed by Berge [17] and described in the thesis of Timmermans [14]. For even L, we calculate the moment estimates Z_L^M, whereas for odd L we calculate both the moment estimates Z_L^M from the longitudinal polarisation and $\gamma(2J+1)Z_L^M$ from the transverse polarisation. Thus, with sufficient statistics it is possible to determine both the spin and parity of the state Λ^*.

Since the Λ^* is a decay product of the parent $\Sigma(1660)$, we start with the t-channel transversity frame for the production of $\Sigma^+(1660)$ and define the reference coordinate systems for the successive decays via

$$\hat{z}_{i+1} = \hat{q}_{i+1} ,$$
$$\hat{y}_{i+1} = \hat{z}_i \times \hat{q}_{i+1} ,$$
$$\hat{x}_{i+1} = \hat{y}_{i+1} \times \hat{z}_{i+1} ,$$

where $\hat{q}_{i+1}$ is the direction of baryon ${}_{i+1}$ in the rest frame of baryon$_i$.

We have selected the $\Lambda(1405) \to \Sigma_p^+\pi^-$ events by restricting the $M(\Sigma^+\pi^-\pi^+)$ within the range 1.60–1.72 GeV and the $M(\Sigma^+\pi^-)$ within the range 1.33–1.46 GeV. A total of $349\Sigma_p^+\pi^-$ events with mean weight 1.78 gave the moments in table 2a. All moments were found to be consistent with zero, including those for $L=4$, 5, 6

TABLE 2a

Moments for the decay $\Lambda(1405) \to \Sigma^+\pi^-$, $\Sigma^+ \to p\pi^0$

		$M=0$		$M=1$		$M=2$		$M=3$	
		Re	Im	Re	Im	Re	Im	Re	Im
$L=1$	L	−0.13		−0.08	0.02				
		±0.24		±0.16	±0.16				
	T	−0.09	0.06	−0.34	−0.62				
		±0.33	±0.31	±0.30	±0.34				
$L=2$		0.07		0.08	0.07	0.03	−0.04		
		±0.18		±0.12	±0.11	±0.12	±0.12		
$L=3$	L	−0.22		−0.37	0.06	0.11	−0.23	−0.17	0.22
		±0.39		±0.25	±0.23	±0.25	±0.25	±0.26	±0.23
	T	0.27	0.70	0.67	0.69	1.55	0.74	−0.43	−0.10
		±1.22	±1.17	±1.20	±1.34	±1.22	±1.13	±1.26	±1.11

TABLE 2b

Moments for the decay $\Lambda(1405) \to \Sigma^+\pi^-$, $\Sigma^+ \to p\pi^0$ and $n\pi^+$

	$M=0$		$M=1$		$M=2$		$M=3$	
	Re	Im	Re	Im	Re	Im	Re	Im
$L=2$	0.08		0.02	0.09	0.09	−0.06		
	±0.11		±0.08	±0.07	±0.07	±0.07		

and 7 which are not given in the table. For even L, we even tried combining the Σ_p^+ and Σ_n^+ samples, giving 796 total events with mean weight 1.60. Again, no significant non-zero moment was found (see table 2b for $L=2$).

If the Λ^* had spin J, then all moments with $L > 2J$ would be expected to vanish. Our data are thus perfectly consistent with the hypothesis $J=\frac{1}{2}$, but cannot rule out the possibility of higher spins. Assuming that $J=\frac{1}{2}$, the ratio of the transverse and longitudinal polarisation moments is in fact $= \gamma$, the $\Lambda^* - \Sigma$ relative parity. Unfortunately the measured moments do not allow discrimination between the two hypotheses $\gamma = \pm 1$ (see table 2a). We have tried other selections of data, in particular, choosing different regions of the decay distribution $\Sigma^+(1660) \to \Lambda^*\pi^+$, but without success. In conclusion, it appears that the Λ^* is produced without any degree of polarisation – thus ruling out the possibility of a parity measurement. This result is fully compatible with the $\Sigma(1660)$ analysis of Timmermans et al. [13] which found all $L=$ odd moments to be consistent with zero. One would not therefore have expected a polarised $\Lambda(1405)$.

4. The Λ(1405) line-shape

We have already remarked on the asymmetrical line-shape of the $\Lambda(1405)$ in fig. 2b. This asymmetry becomes even more apparent when we try to fit the $(\Sigma^+\pi^-)$ mass spectrum with the following Breit–Wigner parametrization:

$$\frac{d\sigma}{dm} = \frac{\rho \cdot q \cdot m \cdot \Gamma(q)}{(m_R^2 - m^2)^2 + m_R^2 \Gamma^2(q)}, \tag{6}$$

where $\Gamma(q) = \Gamma_R q / q_R$, $q(q_R)$ is the decay momentum of $\Sigma\pi \to \Sigma + \pi$ at mass $m(m_R)$, ρ is the decay momentum of $\Sigma\pi\pi \to \Sigma\pi + \pi$, and $m_R(\Gamma_R)$ is the mass (width) of the resonance. The BW function has been folded with the experimental $\Sigma^+\pi^-$ mass resolution (FWHM = 7 MeV) and fitted to the data over the mass range 1.330–1.470 GeV with a chi-squared minimization technique.

Fig. 4 shows the result of this fit. The mass and width are determined to be 1391 ± 1 MeV and 32 ± 1 MeV respectively, for a χ^2/NDF of 256/11. Clearly the fit is very poor. Attempts to improve the quality of fit by using variations of the BW function have been uniformly unsuccessful. Even a 2-channel formalism [18] to try and reproduce the fast fall of intensity at the opening of the $\bar{K}N$ threshold (~ 1.435 GeV) showed no appreciable improvement and resulted in wildly fluctuating resonance parameters. None of the fits tried could reproduce either thte rapid rise of intensity at $\Sigma\pi$ threshold nor the rapid decrease near $\bar{K}N$ threshold.

In a discussion on low-energy kaon-nucleon scattering Dalitz et al. [12] have demonstrated the importance of the $\Sigma\pi$ mass spectrum to discriminate between various extended K-matrix analyses. With the older data of Thomas et al. [10] it appeared that the effective range expansions gave better agreement than the single pole expressions. The new data presented here have very recently been incorporated by Dalitz et al. [19] into their K-matrix analyses. Their best fit, using an effective range expansion, to the $\Sigma^+\pi^-$ mass spectrum below $\bar{K}N$ threshold is displayed in fig. 4. Clearly, the agreement is very much better than the Breit–Wigner fit.

Very recently Veit et al. [10] have extended the cloudy bag model and applied it to $I = 0$ s-wave $\bar{K}N$ scattering including both the $\bar{K}N$ and $\Sigma\pi$ channels. Their calculations (normalised to the data below 1.47 GeV), see fig. 4, give a reasonable description of the observed $\Sigma\pi$ mass spectrum. It is worth noting that, in addition to the $\Lambda(1405)$ resonance, the model contains a single bare mass quark state at a much higher energy (around 1630 MeV), to which the data are rather insensitive.

5. The $\bar{K}N/\Sigma\pi$ branching ratio

If the observed $\Sigma^+\pi^-$ mass spectrum of fig. 4 represents the $\Lambda(1405)$ line-shape then, in principle, we might have a chance to detect a $\bar{K}N$ decay above $\bar{K}N$ threshold. Of the two possibile decay channels (K^-p, $\bar{K}^0n$) only $\bar{K}^0n$ has the full

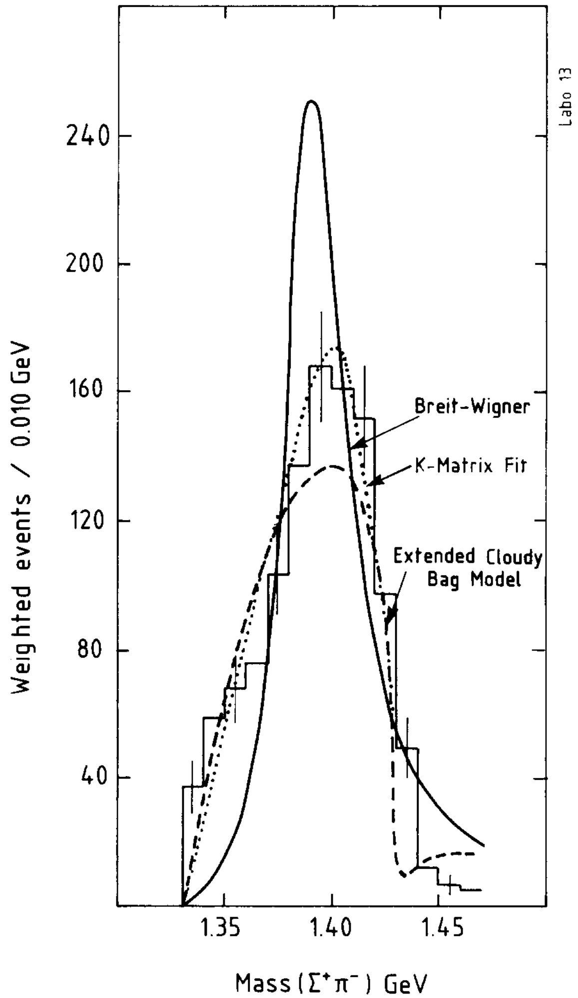

Fig. 4. Invariant mass distribution of the $\Sigma^+\pi^-$ system from the reaction $K^-p \to \Sigma^+\pi^-\pi^+\pi^-$ at 4.2 GeV/c with the restrictions $t'(K^- \to \Sigma^+\pi^-\pi^+) < 1.0 (\text{GeV}/c)^2$ and $1.60 \leq M(\Sigma^+\pi^-\pi^+) \leq 1.72$ GeV. The curves represent models described in the text.

statistics of the experiment. Fig. 5 shows the $\bar{K}^0 n\pi^+$ and $\bar{K}^0 n$ mass spectra from reaction (3) with the selection $t'(p \to \bar{K}^0 n\pi^+) < 1.0 (\text{GeV}/c)^2$. In contrast to the $\Sigma^+\pi^-\pi^+$ spectrum of fig. 2a, no indication of $\Sigma(1660)$ production is seen. Within the $\Sigma(1660)$ mass region $(1.60 \leq m(\bar{K}^0 n\pi^+) \leq 1.72$ GeV) no prominent peaking of the $\bar{K}^0 n$ spectrum is seen close to the $\bar{K}N$ threshold (1.437 GeV), although some production of $\Lambda(1520)$ is indicated.

We can now use these data to provided an upper limit to the relative branching ratio $\Lambda(1405) \to \bar{K}N/\Sigma\pi$. Assuming that all the events in the mass region 1.437-

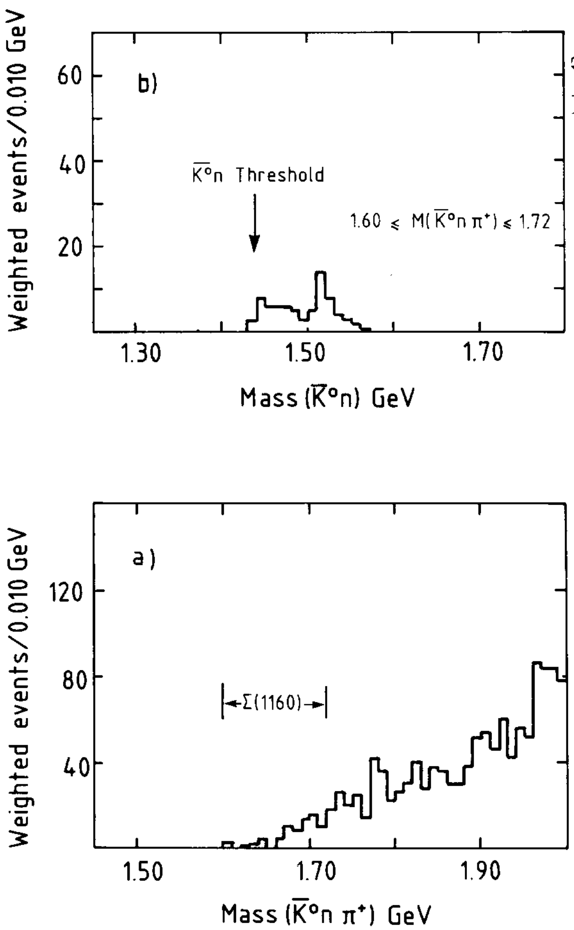

Fig. 5. Invariant mass distributions: (a) $M(\bar{K}^0 n\pi^+)$ from the reaction $K^- p \to \bar{K}^0 n \pi^+ \pi^-$ at 4.2 GeV/c with the restriction $t'(K^- \to \bar{K}^0 n\pi^+) < 1.0(\mathrm{GeV}/c)^2$, (b) $M(\bar{K}^0 n)$ with the additional selection $1.60 \leqslant M(\bar{K}^0 n\pi^+) \leqslant 1.72$ GeV.

1.470 GeV are due to $\Lambda(1405)$ and neglecting resolution smearing, the data of figs. 2b and 5b yield (after appropriate correction for isospin and $\bar{K}^0$ visibility factors)

$$\Lambda(1405) \to \frac{\bar{K}N}{\Sigma\pi} < 3.0 \text{ (95\% confidence limit)}.$$

6. Conclusions

We have presented evidence that in the reaction $K^- p \to \Sigma^+(1660)\pi^-$ at small momentum transfer, the decay mode $\Sigma^+(1660) \to (\Sigma^+\pi^-)\pi^+$ allows a very clean sample of $\Lambda(1405)$ to be isolated. A moments analysis of the 2-step decay $\Sigma(1405) \to$

$\Sigma\pi$, $\Sigma \to \pi N$ has shown the data to be consistent with the spin assignment of $\frac{1}{2}$ but did not allow a parity discrimination.

The asymmetric line-shape of the $\Lambda(1405)$ is incompatible with that expected for a Breit–Wigner resonance, rising quickly after the $\Sigma\pi$ threshold and dropping rapidly in the vicinity of the $\bar{K}N$ threshold. Much better agreement with the data is displayed by the predictions of dynamical models. The debate as to whether the $\Lambda(1405)$ is a pure quark state or a $\bar{K}N$ bound state may soon be clarified.

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