EVIDENCE FOR RESONANT STRUCTURES IN THE $\Lambda_{\bar{p}}$ SYSTEM

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Collaboration

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ABSTRACT - An analysis of the $\Lambda_{\bar{p}}$ system produced forward in the reaction $K^- p \rightarrow \Lambda_{\bar{p}} p$ at 18.5 GeV/c is presented. The data come from an experiment using the CERN Ω' spectrometer. Structures are observed in the $\Lambda_{\bar{p}}$ mass spectrum and in the double moments $H_{LM\bar{L}m}$ describing the decay of the $\Lambda_{\bar{p}}$ system and the subsequent Λ decay, for $L \leq 8$. A Partial Wave Analysis interprets these structures as resonances of spin parities 2^- and 3^+ , masses and widths $M = 2200 \pm 40$ MeV, $\Gamma = 150 \pm 30$ MeV and $M = 2330 \pm 40$ MeV, $\Gamma = 150 \pm 30$ MeV respectively.

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I. Introduction

The study of the $(\Lambda\bar{p})$ system provides a way of searching for strange mesonic states above 2 GeV, a rather unexplored area which is difficult to disentangle using only mesons in the final states. Moreover this baryon-antibaryon resonant system could be interpreted in terms of exotic mesons as suggested in references [1,2,3]. Several searches in this area have been performed leading to controversial results [4] for narrow states.

Recently, two experiments presented results on the forward produced $\Lambda\bar{p}$ system in K^-p interactions. The first one, at 50 GeV/c [5], reported normal width resonant states at 2.26, 2.32 and 2.49 GeV with spin and parity 2^- , 3^+ and 4^- respectively. The other one, at 8.25 GeV/c [6], confirmed the 2^- resonance. The purpose of this study is to look at the same channel at an intermediate energy, between 8.25 and 50 GeV/c, and with higher statistics.

The total beam flux sensitivity is 12 events/nb.

II. Experimental Set-up and trigger

The experiment has been performed at the CERN OMEGA PRIME Spectrometer (Ω') [7] exposed to an RF separated beam. The layout is shown in fig. 1. The incident K^- were identified by a differential Cerenkov counter. The hydrogen target was 60 cm long. The charged multiplicity was given on line by the barrel scintillator (TS) and the high precision chamber (HPC1). The momenta of the outgoing tracks were measured by 6 two-plane MWPC's (B chambers) and 5 three-plane MWPC's (A chambers) placed in a strong magnetic field (~ 18 KGauss). Two drift chambers (DC1, DC2), each of 4 planes, placed in the fringe field of the magnet improved the measurement of the fast tracks momenta. The two multi-cell Cerenkov's C_1 and C_2 are used for particle identification. The hodoscopes H_1, H_2, H_3 , through the momentum-position correlation produced by the magnetic field, enabled the selection of particles in a given momentum range.

During data taking two triggers were defined :

- the "slow" trigger required the coincidence between H_1 and H_2 and the anticoincidence between C_1 and H_2 ; it selected events with K^+ having a momentum between 2.6 and 9.4 GeV/c and protons with momentum above 2.6 GeV/c.
- the "fast" trigger required the coincidence between H_1, H_2 and H_2, H_3 , and the anticoincidence between H_3 and C_2 ; it selected K^+ and protons with momentum above 2.6 GeV/c.

The trigger logic was implemented using MBNIM electronics [8] . More details of the set up and the trigger have been published [9] .

III. Experimental sample

7.2 M triggers were collected and processed in the pattern recognition and geometry program TRIDENT [10]. The requirements of a reconstructed track satisfying the trigger conditions, a reconstructed beam track and a charged multiplicity from 2 to 7 in the Ω' chambers reduced the sample to 3.7 M events. These events were passed through a special program [11] improving the efficiency in reconstructing V^0 vertices. In order to select the reaction

$$K^- p \rightarrow \bar{\Lambda} p p \quad (1)$$

the following conditions have been required :

- a reconstructed V^0 with a triggering positive track.
- two oppositely charged tracks or a single negative attached to the main vertex.

The remaining 37300 events were then processed through the kinematics program CINEMA [12] which performs a multivertex 5C(2 prongs + V^0) or 2C(1 prong + V^0) fit, using hypothesis (1) and

$$K^- p \rightarrow \Lambda K^- K^+ \quad (2)$$

$$K^- p \rightarrow \Lambda \pi^- \pi^+ \quad (3)$$

11 841 events fitted the hypothesis (1) with a χ^2 probability greater than 1%. For these events the $(p\pi^-)$ effective mass spectrum, obtained from the measured values for the momenta of the tracks attached to the secondary vertex is given in fig. 2. The resolution on the Λ measured mass (half width half maximum on fig. 2) is 4 MeV. By using the fitted errors on the tracks we calculate the error on the $\bar{\Lambda} p$ mass and obtain a mean value of 8 MeV.

Furthermore due to the difficulty in reconstructing V^0 's for which the decay tracks crossed only a few planes of wire chambers and the loss of tracks in the median plane of the apparatus due to chamber inefficiencies, we accept events only if :

$$X_{V^0} < - 50 \text{ cm}$$

$$\lambda_{\bar{p}} < 3 \text{ or } \lambda_{\bar{p}} \geq 21 \text{ mrad}$$

where X_{V^0} is the X coordinate of the V^0 vertex (fig. 1) and $\lambda_{\bar{p}}$ is the dip angle of the antiproton ; these cuts leave us with 10 196 events fitting reaction (1) with a probability greater than 1%.

The two step decay of the $(\Lambda\bar{p})$ system is described by two sets of angles $\Omega_1(\theta_1, \phi_1)$ and $\Omega_2(\theta_2, \phi_2)$ as shown in fig. 3. The first one defines the direction of the Λ in the t-channel helicity frame. Similarly, the second one defines the direction of the p in the Λ rest frame with reference to the z_2 axis along the direction of the Λ in the $\Lambda\bar{p}$ centre of mass system, and the y_2 axis along $z_1 \times z_2$.

The uncorrected $\Lambda\bar{p}$ effective mass spectrum is presented in fig. 4. A broad enhancement above threshold is observed, which is a common feature of diffractively produced systems. The threshold enhancements are usually explained by kinematic (Deck) effects combined with resonance production [ref. 13]. In the former case, the Λ may be preferentially emitted in the forward hemisphere ($\cos \theta_1 > 0$) in the $\Lambda\bar{p}$ rest frame. In the latter case, there must be no forward backward asymmetry (unless interference occurs). Hence the non resonant background may be reduced if we select events with $\cos \theta_1 < 0$. We show in fig. 5 the $\Lambda\bar{p}$ effective mass spectra for the two complementary samples.

A clear peak appears around 2.25 GeV and a shoulder at about 2.4 GeV for the sample where we expect the resonance signals to be more easily detected. This can be considered as a first indication for resonance production in the $\Lambda\bar{p}$ system, but no definitive conclusion can be drawn before a Partial Wave Analysis is performed.

The momentum transfer distribution $t'_{(K^- \rightarrow \Lambda p^-)}$ for the 10196 selected events is shown in fig. 6. From this raw spectrum and from the fact that the t' acceptance is constant at least up to 0.6 GeV^2 , we can conclude the dominance of peripheral production : 83 % of the events have a t' smaller than 0.8 GeV^2 . In order to select the diffractively produced events we keep only events with $t' < 0.8 \text{ GeV}^2$. This does not affect the structures discussed above. Events with (Λp^-) mass greater than 2.84 GeV are not used in the PWA, leaving us with a sample of 7047 events. For this sample, 840 events (12 %) are affected by the kinematical ambiguity between hypotheses (1) and ((2) or (3)) ; among these, 140 events (2%) have the best χ^2 -probability in favor of the last two hypotheses. On the other hand, using the Cerenkov information, we can assign a mass to the negative particle at the main vertex ; this information disagrees with the $\bar{p}$ hypothesis for less than 7% of events (488 events). Due to the partial overlap of these two contamination estimations, we used all these events in our analysis ; however we ensured that the ambiguous events were not responsible for particular peaks in the Λp^- effective mass.

IV. Geometrical acceptance

The mass range $2.04\text{--}2.84 \text{ GeV}$ was divided into 20 bins of 40 MeV and for each bin we generated 10 000 Monte Carlo events of channel (1). Each event was defined at fixed beam momentum by the set of kinematical variables :

$$\left\{ M_{\Lambda p^-}, t'_{(K^- \rightarrow \Lambda p^-)}, \theta_1, \phi_1, \theta_2, \phi_2 \right\}$$

where

- $M_{\Lambda p^-}$ was generated according to a flat distribution inside each bin.
- t' was generated according to $\frac{dN}{dt} \propto \exp(-5 t')$. This corresponds to diffractive production [14] and is roughly verified by our data.
- $\cos\theta_1, \phi_1, \cos\theta_2, \phi_2$ were generated according to flat distributions.

For each set of kinematical variables, we have generated 50 configurations in the Ω' reference system defined by the set

$$\{\phi, X, Y, Z, d\}$$

where

- ϕ is the azimuthal angle of the final state around the incident beam, generated according to a flat distribution.
- X, Y, Z are the primary vertex coordinates. X was generated flat between the target limits $[-165, -105]$ cm; Y and Z were generated according to the experimental distributions.
- d is the distance between primary and secondary vertices. It was generated according to the Λ lifetime distribution.

A configuration was accepted if all the selections and the trigger conditions were satisfied. Furthermore to ensure the Λ measurability the proton and the π^- tracks were required to cross at least 4 chambers. Among the 50 configurations, the accepted fraction defines the geometrical acceptance factor "a" of the individual event considered :

$$a(M_{\Lambda p}, t'_{K^- \rightarrow \Lambda p}, \theta_1, \phi_1, \theta_2, \phi_2) \quad (4)$$

Various checks of the acceptance program were performed. In particular fig. 7 shows : a) the apparent Λ lifetime^(*), b) the X distribution, c) the $\cos\theta^*$ distribution (θ^* being the angle between the direction of the Λ in the laboratory system and the direction of the decay proton in the Λ center of mass). The simulation (dashed lines) generally reproduces the data (full lines). In the Λp mass region considered, the average acceptance is 0.47.

(*) Since the simulated Λ lifetime distribution is dependent on the momentum of the Λ in the laboratory fig. 7a shows as an example the comparison for Λ with momentum $9.5 < P_{\Lambda} \leq 11.5$ GeV/c where the majority of events is concentrated.

V. Moments analysis

In order to perform a Partial Wave Analysis (PWA) of the $\Lambda\bar{p}$ system, we need the moments of the angular distribution $W(\Omega_1, \Omega_2)$ which are defined for each mass bin as :

$$H_\alpha = \int W(\Omega_1, \Omega_2) D_{Mm}^L(\Omega_1) D_{m0}^\ell(\Omega_2) d\Omega_1 d\Omega_2$$

where α stands for $\{L, M, \ell, m\}$ and the D_{Mm}^L are the Wigner functions.

The normalization of the moments is such that H_{0000} is the total number of events in the bin. Due to the limited geometrical acceptance of the apparatus, the true angular distribution $W(\Omega_1, \Omega_2)$ differs from the observed one $W^{\text{obs}}(\Omega_1, \Omega_2)$. The corresponding observed moments are calculated, using the data, according to the expression :

$$H_\alpha^{\text{obs}} = \sum_{\text{events}} D_{Mm}^L(\Omega_1) D_{m0}^\ell(\Omega_2)$$

In order to find the maximum values for L and M up to which the moment analysis has to be performed, we reconstructed the $(\Lambda\bar{p})$ decay angular distribution

$$I(\Omega_1) = \sum_{L,M} \frac{2L+1}{4\pi} H_{LM00}^{\text{obs}} D_{M0}^{L*}(\Omega_1)$$

Then the $\cos \theta_1$ and ϕ_1 reconstructed distributions were compared to the observed distributions and a χ^2 was calculated. The addition of terms with $L > 8$ and $M > 2$ brought no significant improvement to the χ^2 values. Thus the analysis is limited to $H(LM\ell m)$ moments with $L \leq 8, |M| \leq 2, \ell \leq 1$, and $|m| \leq 1$, which corresponds to a total of 93 moments. The Linear Algebra Method [14] relates the observed and the true moments by :

$$H_\alpha^{\text{obs}} = \sum_{\alpha'} A_{\alpha\alpha'} H_{\alpha'} \quad (5)$$

The acceptance correlation matrix elements $A_{\alpha\alpha'}$ are calculated, using the acceptance "a" defined in §III, according to the expression :

$$A_{\alpha\alpha'} = \frac{(2L'+1)}{4\pi} \frac{(2\ell'+1)}{4\pi} \iint D_{Mm}^L(\Omega_1) D_{m'o}^{\ell'}(\Omega_2) a D_{M'm'}^{L'*}(\Omega_1) D_{m'o}^{\ell'*}(\Omega_2) d\Omega_1 d\Omega_2$$

We checked that the 10 000 simulated events per bin gave us enough accuracy by setting the acceptance $a = 1$. The result was a matrix with diagonal terms of typical values of $1 \pm 5 \cdot 10^{-3}$ and the off diagonal ones $0. \pm 5 \cdot 10^{-6}$.

The true moments H_{α} , for $L \leq 8$ and $|M| \leq 2$, were obtained solving the linear system (5) by triangulation.

Fig. 8a, 8b and 8c show the true moments H_{L000} , H_{L100} and H_{L200} up to $L = 8$; fig. 8d shows the linear combination $H_L^- = H_{L011} - H_{L01-1}$ up to $L = 8$.

The linear combination $H_L^+ = H_{L011} + H_{L01-1}$ and the moment H_{L010} (not shown) are consistent with zero in agreement with no Λ polarization in the production plane.

We make the following observations :

i) The behaviour of the H_{L000} moments suggests the presence of waves with angular momentum at least equal to 3.

ii) In general the $M = 1$ moments are smaller than the corresponding $M = 0$ moments, but are significantly different from zero for masses less than 2.3 GeV, while the H_{L200} are small and generally consistent with zero. This indicates a dominance of helicity zero amplitudes.

VI. Cross section and production mechanism.

We have determined the cross section for forward Λp^- production. The number of events corrected by the geometrical acceptance is given by the integral of H_{0000} over the considered mass and t' range ($2.04 < M < 2.84$ GeV, $t' < 0.8$ GeV²). The electronics efficiency, track reconstruction efficiency, losses due to secondary interactions and the $\Lambda \rightarrow p\pi^-$ decay branching ratio have been taken into account. We obtained a cross section of 4.2 ± 0.5 μ b, the error being mainly due to uncertainties on the correction factors. We fitted our cross section

value together with those of references [5 , 6] and obtained the following dependence :

$$\sigma \propto p_{\text{lab}}^{-n}, \text{ with } n = 0.80 \pm 0.05$$

This slow decrease of the cross section with p_{lab} is one of the characteristics of a diffractive production mechanism. In addition, we notice that the slope of $\frac{dN}{dt'}$ is about $5(\text{GeV})^{-2}$. This is the expected value for diffractive production of a mass near 2 GeV [15]. Finally, a break is present in the t' distribution at about 0.35 GeV^2 (the acceptance in t' being flat up to 0.6 GeV^2). Such a break has already been observed for diffractively produced $\pi\pi\pi$, $K\pi\pi$, $\pi\pi^+$ and $\Delta^{++}\pi^-$ systems [16]. All these observations suggest the dominance of a diffractive production mechanism in reaction (1), although the non zero values of the $M = 1$ moments indicate the presence of other mechanisms.

VII. Partial Wave Analysis

A Partial Wave Analysis was performed using the formalism developed in ref.[17] with the following hypotheses :

- spin coherence at the nucleon vertex
- factorisation of production and decay amplitudes
- natural parity exchange
- helicity zero unnatural parity ($\Lambda\bar{p}$) states

The 3rd and 4th hypotheses are suggested by the indications of a dominant diffractive dissociation mechanism and by the smallness of the H_{L200} moments. The H_{L100} moments given by the interference of helicity zero and helicity one amplitudes are not negligible indicating the presence of helicity one amplitudes. However using all the possible spin-parity and helicity states would imply too many unknowns for the presently available statistics. We have then limited the PWA to helicity zero amplitudes neglecting contributions from the natural spin-parity series.

Then, the $\Lambda\bar{p}$ production and decay amplitude can be written as

$$J_{\lambda\mu}^A = N^A F_{\lambda\mu}^A$$

where :

- i) λ, μ are the helicities of Λ and $\bar{p}$,
- ii) A is the spin parity of $(\Lambda\bar{p})$ system.
- iii) N^A is the $(\Lambda\bar{p})$ production amplitude by natural parity exchange, with helicity 0,
- iv) $F_{\lambda\mu}^A$ is the decay amplitude.

The moments $H_{LM\ell m}$ can be expressed as linear combinations of products of amplitudes of the form :

$$H_{LM\ell m} = \sum_{\substack{AA' \\ \lambda\mu \\ \lambda'}} C(A, A', \lambda, \lambda', \mu) \cdot J_{\lambda\mu}^A \cdot J_{\lambda'\mu}^{A'*} \quad (7)$$

The coefficients C are calculated using the Clebsch-Gordan coefficients and the asymmetry parameter (0.642) of the Λ . The explicit form of the $H_{LM\ell m}$ is given in the Appendix.

For this PWA we use the H_{L000} and the H_L^- defined above ; we are then left with 17 observables, for which only states with spin up to 4 contribute. The corresponding waves are

$$S_{++}, P_{++}, P_{+-}, D_{+-}, D_{++}, F_{++}, F_{+-}, G_{+-}, G_{++}$$

where the subscripts indicate the helicities λ and μ of the Λ and $\bar{p}$ respectively. The letter indicates the spin of the $\Lambda\bar{p}$ state. Choosing arbitrarily the S_{++} phase as a reference, we have 17 unknown parameters. An unconstrained fit using these 17 parameters shows that the cross section of the P_{++} wave is small compared to the cross sections of the other waves. In addition the χ^2 values change only slightly when the P_{++} modulus and phase are set to zero. We then remove the P_{++} wave and obtain a constrained fit. (*)

(*) A priori in such an analysis with 17 parameters and 17 observables, we must have the Barrelet type ambiguities for amplitudes. We have tried many fits with different initial values of the parameters and we always found a small P_{++} contribution. So removing the P_{++} resolve these ambiguities [18].

The results of the fit are shown in figs 8a and 8d for the moments and in fig. 9 for the moduli and phases of the waves. Good fits are obtained in all 20 mass bins with a mean probability $P(\chi^2)$ of 0.3. From an inspection of fig. 9 we remark that only the P_{+-} , D_{++} and F_{+-} waves show structures compatible with resonances.

Fitting the modulus of the three waves to a pure relativistic Breit-Wigner gives probabilities of 0.51, 0.67 and 0.94 respectively. A fit to a 4th order polynomial gives probabilities $P(\chi^2)$ of 0.46, 10^{-6} and 0.04 respectively. In addition the phases of the waves D_{++} and F_{+-} show variations in the region of the peaks while the phase of the wave P_{+-} is almost constant in the region of the peak. Consequently we keep only the D_{++} and F_{+-} waves as resonance candidates. The curves on fig. 9 show the result of the fit for the moduli and the predicted phase variations.

For each bin of mass, there are four ambiguous solutions for the phases which are related by the following transformations T_1, T_2 and their product $T_1 T_2$

$$T_1 \begin{cases} \phi^{J^{++}} \rightarrow -\phi^{J^{++}} \\ \phi^{J^{+-}} \rightarrow \pi - \phi^{J^{+-}} \end{cases}$$

$$T_2 \begin{cases} \phi^{J^{++}} \rightarrow \pi - \phi^{J^{++}} \\ \phi^{J^{+-}} \rightarrow -\phi^{J^{+-}} \end{cases}$$

Each transformation is applied simultaneously to all the phases and leaves the H_{L000} and H_L^- unchanged. The phases presented in fig. 9 were obtained by choosing the solution corresponding to the best continuity for the phases of the D^{++} and F^{+-} waves.

We emphasize that the Breit-Wigner formulae have been fitted over the whole range of mass $2.08 < M_{\Lambda\bar{p}} < 2.84$ GeV with no additional background. The resonance parameters and cross sections are presented in table I, together with those obtained at 8.25 and 50 GeV/c. The results at different energies are in good agreement.

The results obtained from the Partial Wave Analysis of the two step decay $R \rightarrow \Lambda\bar{p}$ and $\Lambda \rightarrow p\pi^-$ are reinforced by the study of the $(\Lambda\bar{p})$ mass spectrum, for events with Λ emitted backward ($\cos\theta_1 < 0$). This spectrum, corrected for acceptance, has been fitted with a fourth order polynomial background plus two Breit-Wigner functions and is shown in fig. 5a. The resonance parameters for the best fit ($M_1 = 2.23 \pm 0.02$ GeV, $\Gamma_1 = 0.150 \pm 0.03$ GeV; $M_2 = 2.42 \pm 0.03$ GeV, $\Gamma_2 = 0.140 \pm 0.04$ GeV) agree with those obtained by the P.W.A. given in table I; this fit probability is $P(\chi^2) = 0.63$. Our experiment is the first to present such evidence based on the mass spectrum.

VII. Concluding remarks

The study of 10196 events of the reaction $K^-p \rightarrow (\Lambda\bar{p})p$ shows that the $(\Lambda\bar{p})$ system is peripherally produced with characteristics in qualitative agreement with a diffractive dissociation mechanism. No narrow structures are present in the $(\Lambda\bar{p})$ mass spectrum.

A PWA performed under the hypothesis of natural parity exchange dominance gives evidence for two resonances of spin parity 2^- ($M = 2.20$ GeV) and 3^+ ($M = 2.33$ GeV), decaying into $\Lambda\bar{p}$; these results obtained with higher statistics and less assumptions than in previous analyses, are corroborated by the study of the $(\Lambda\bar{p})$ mass spectrum.

The $J^P = 2^-$ resonance has been observed in K^-p interaction at 8.25, 18.5 and 50 GeV/c whereas the $J^P = 3^+$ resonance is only seen at 18.5 and 50 GeV/c. In addition, a $J^P = 4^-$ resonance ($M = 2.49$ GeV) has been reported only at 50 GeV/c. The production cross sections are of the same order of magnitude and show only a weak dependence on the incident momentum.

In fig. 10 we plot the three resonances on the Chew-Frautschi plot for the strange mesons. We note that they seem to lie on a linear trajectory with a slope of $\alpha_M = 1.7 \text{ GeV}^{-2}$. However this value is clearly different from the value for the classical Regge trajectories ($\alpha_M \approx 1 \text{ GeV}^{-2}$) and also different from the predictions of several models for baryonium trajectories given in ref. 1 ($\alpha_M = 0.63 \text{ GeV}^{-2}$) and ref. 3 ($\alpha_M = 0.85 \text{ GeV}^{-2}$).

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T A B L E 1

MASS, WIDTH AND CROSS SECTION OF
 Λ_p^- RESONANCES PRODUCED IN K^-p INTERACTIONS.

P_{lab}	8.25 GeV/c ref. [6]			18.5 GeV/c this experiment			50 GeV/c ref. [5]		
J^P	M GeV	Γ GeV	σ μb	M GeV	Γ GeV	σ μb	M GeV	Γ GeV	σ μb
2^-	2.23 ± 0.05	~ 0.2	1.5 ± 0.5	2.20 ± 0.04	0.15 ± 0.03	0.56 ± 0.20	2.26 ± 0.02	0.21 ± 0.05	0.58 ± 0.09
3^+	not reported			2.33 ± 0.04	0.15 ± 0.03	0.62 ± 0.20	2.32 ± 0.03	~ 0.25	0.54 ± 0.08
4^-	not reported			unseen			2.49 ± 0.02	~ 0.25	0.28 ± 0.04

A P P E N D I X

RELATION BETWEEN THE $(\Lambda\bar{p})$ DOUBLE MOMENTS AND THE SPIN AMPLITUDES

The general relations between the $H(LM\lambda m)$ and the spin amplitudes are given in reference [17]. Assuming the hypothesis of §6, the equation (7) has the following form

$$H(L0\lambda m) = \frac{2(\delta_{\lambda 0} + \alpha_{\Lambda} \delta_{\lambda 1})}{\sqrt{2(2L+1)(2\lambda+1)}} \sum_{JJ'} \sqrt{(2J+1)(2J'+1)} \langle J0J'0 | L0 \rangle \times$$

$$\sum_{\substack{\lambda\mu \\ \lambda'\mu'}} (-1)^{\mu+1/2} J_{\lambda\mu}^A J_{\lambda'\mu'}^{A'} \langle J-\alpha J' \alpha' | Lm \rangle \langle \frac{1}{2} - \lambda \frac{1}{2} \lambda' | \lambda m \rangle$$

where :

$J_{\lambda\mu}^A$ is the production and decay amplitude of $(\Lambda\bar{p})$ states of spin parity $A = J^P$ with $P = (-1)^{J+1}$

λ, μ are the helicities of Λ and $\bar{p}$

$\alpha = \lambda - \mu$; $\alpha' = \lambda' - \mu$

α_{Λ} is the asymmetry parameter of the Λ

$\delta_{\lambda 0}, \delta_{\lambda 1}$ are Kronecker symbols

Hereafter we give the expressions for the $H(L000)$ and the $H^-(L)$ for $L \leq 8$. The $(J_{\lambda\mu}^A J_{\lambda'\mu'}^{A'})$ products stand for $\text{Re}(J_{\lambda\mu}^A J_{\lambda'\mu'}^{A'})$ and $\text{Im}(J_{\lambda\mu}^A J_{\lambda'\mu'}^{A'})$ in the relations of $H(L000)$ and $H^-(L)$ respectively. For the asymmetry parameter we used the value $\alpha_{\Lambda} = .642$

$$H(0000) = 2. |S_{++}|^2 + 2. |P_{++}|^2 + 2. |P_{+-}|^2 + 2. |D_{++}|^2 + 2. |D_{+-}|^2 + 2. |F_{++}|^2 \\ + 2. |F_{+-}|^2 + 2. |G_{++}|^2 + 2. |G_{+-}|^2$$

$$H(1000) = 2.309 S_{++} P_{++}^* + 2.066 P_{++} D_{++}^* + 1.789 P_{+-} D_{+-}^* \\ + 2.028 D_{++} F_{++}^* + 1.912 D_{+-} F_{+-}^* + 2.016 F_{++} G_{++}^* + 1.952 F_{+-} G_{+-}^*$$

$$H(2000) = 1.789 S_{++} D_{++}^* + .8 |P_{++}|^2 - .4 |P_{+-}|^2 + 1.571 P_{++} F_{++}^* + 1.283 P_{+-} F_{+-}^* \\ + .571 |D_{++}|^2 + .286 |D_{+-}|^2 + 1.533 D_{++} G_{++}^* + 1.4 D_{+-} G_{+-}^* \\ + .533 |F_{++}|^2 + .4 |F_{+-}|^2 + .519 |G_{++}|^2 + .442 |G_{+-}|^2$$

$$H(3000) = 1.512 S_{++} F_{++}^* + 1.328 P_{++} D_{++}^* - .767 P_{+-} D_{+-}^* \\ + 1.320 P_{++} G_{++}^* + 1.043 P_{+-} G_{+-}^* + .901 D_{++} F_{++}^* \\ + .319 D_{+-} F_{+-}^* + .825 F_{++} G_{++}^* + .532 F_{+-} G_{+-}^*$$

$$H(4000) = 1.333 S_{++} G_{++}^* + 1.164 P_{++} F_{++}^* - .713 P_{+-} F_{+-}^* + .571 |D_{++}|^2 \\ - .381 |D_{+-}|^2 + .774 D_{++} G_{++}^* + .212 D_{+-} G_{+-}^* + .364 |F_{++}|^2 \\ + .061 |F_{+-}|^2 + .324 |G_{++}|^2 + .162 |G_{+-}|^2$$

$$H(5000) = 1.050 P_{++} G_{++}^* - .664 P_{+-} G_{+-}^* + 1.024 D_{++} F_{++}^* \\ - .724 D_{+-} F_{+-}^* + .634 F_{++} G_{++}^* + .041 F_{+-} G_{+-}^*$$

$$H(6000) = .938 D_{++} G_{++}^* - .685 D_{+-} G_{+-}^* + .466 |F_{++}|^2 \\ - .350 |F_{+-}|^2 + .280 |G_{++}|^2 - .014 |G_{+-}|^2$$

$$H(7000) = .863 F_{++} G_{++}^* - .669 F_{+-} G_{+-}^*$$

$$H(8000) = .403 |G_{++}|^2 - .323 |G_{+-}|^2$$

$$\begin{aligned}
H^-(1) = & .699 S_{++} P_{+-}^* + .541 P_{++} D_{+-}^* + .313 P_{+-} D_{++}^* \\
& + .501 D_{++} F_{+-}^* + .354 D_{+-} F_{++}^* + .482 F_{++} G_{+-}^* \\
& + .374 F_{+-} G_{++}^*
\end{aligned}$$

$$\begin{aligned}
H^-(2) = & .541 S_{++} D_{+-}^* + .419 P_{++} P_{+-}^* + .448 P_{+-} F_{+-}^* \\
& + .173 D_{++} D_{+-}^* + .424 D_{++} G_{+-}^* + .275 P_{+-} F_{++}^* \\
& + .114 F_{++} F_{+-}^* + .309 D_{+-} G_{++}^* + .086 G_{++} G_{+-}^*
\end{aligned}$$

$$\begin{aligned}
H^-(3) = & .458 S_{++} F_{+-}^* + .379 P_{++} D_{+-}^* + .387 P_{+-} G_{+-}^* \\
& - .328 P_{+-} D_{++}^* + .205 D_{++} F_{+-}^* - .096 D_{+-} F_{++}^* \\
& + .161 F_{++} G_{+-}^* + .245 P_{+-} G_{++}^* - .042 F_{+-} G_{++}^*
\end{aligned}$$

$$\begin{aligned}
H^-(4) = & .404 S_{++} G_{+-}^* + .341 P_{++} F_{+-}^* + .316 D_{++} D_{+-}^* \\
& + .199 D_{++} G_{+-}^* - .278 P_{+-} F_{++}^* + .142 F_{++} F_{+-}^* \\
& - .064 D_{+-} G_{++}^* + .098 G_{++} G_{+-}^*
\end{aligned}$$

$$\begin{aligned}
H^-(5) = & .311 P_{++} G_{+-}^* + .294 D_{++} F_{+-}^* - .277 D_{+-} F_{++}^* \\
& + .149 F_{++} G_{+-}^* - .246 P_{+-} G_{++}^* - .111 F_{+-} G_{++}^*
\end{aligned}$$

$$H^-(6) = .274 D_{++} G_{+-}^* + .264 F_{++} F_{+-}^* - .250 D_{+-} G_{++}^* + .123 G_{++} G_{+-}^*$$

$$H^-(7) = .250 F_{++} G_{+-}^* - .242 F_{+-} G_{++}^*$$

$$H^-(8) = .231 G_{++} G_{+-}^*$$

FIGURE CAPTIONS

- Fig. 1 Layout of the Ω' spectrometer used in the present experiment.
- Fig. 2 Effective mass spectrum of the $(p\pi^-)$ for the secondary vertices. The arrow shows the Λ nominal value.
- Fig. 3 Reference systems and angle definitions for the two step decay of the (Λp^-) system.
- Fig. 4 Effective mass spectrum of the (Λp^-) system (uncorrected for acceptance).
- Fig. 5 Effective mass spectra of the (Λp^-) system,
a) for $\cos\theta_1 < 0$, b) for $\cos\theta_1 > 0$.
The histograms correspond to the data uncorrected for the acceptance. The points with error bars show the corrected mass spectrum and the curve reproduces the results of the fit described in sect. VI.
- Fig. 6 Distribution of the momentum transfer t' ($K^- \rightarrow \Lambda p^-$), uncorrected for acceptance.
- Fig. 7 Comparison of the real data (full line) to the simulated data (dashed line).
- a) the rest lifetime for Λ 's with laboratory momenta between 9.5 and 11.5 GeV/c.
b) the X coordinate of the primary vertex.
c) the $\cos\theta^*$ distribution. θ^* is the angle between the direction of the Λ in the lab. system and the direction of the decay proton in the Λ centre of mass.
- Fig. 8 a) H_{L000} moments up to $L = 8$ corrected for geometrical acceptance.
The points with error bars correspond to the experimental data and the circles correspond to the moments reconstructed by the PWA.

- b) H_{L100} moments up to $L = 8$ corrected for geometrical acceptance.
- c) H_{L200} moments up to $L = 8$ corrected for geometrical acceptance.
- d) H_L^- moments up to $L = 8$ corrected for geometrical acceptance.
The points with error bars correspond to the experimental data and the circles correspond to the moments reconstructed by the PWA.

Fig. 9 Moduli and phases of the fitted waves. The curves show the Breit-Wigner functions with the fitted parameters given in Table I.

Fig. 10 Chew-Frautschi plot for strange mesons.

FIG-1

FIG-2

FIG-3

FIG-4

FIG-5

FIG-6

FIG-7

FIG-8a

FIG-8b

FIG-8c

FIG-8d

FIG-9

FIG-9

FIG:10