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EVIDENCE FOR A Λ_p^- RESONANCE WITH SPIN-PARITY 2^-

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ABSTRACT

A moments analysis of the $\bar{\Lambda}p$ system produced forwards ($t < 1 \text{ GeV}^2$) by 8.25 GeV/c K^- mesons in the reaction $K^- p \rightarrow \bar{\Lambda}pp$ has been performed. Significant structure is observed in the double moments $H(LMlm)$ describing the decay of the $\bar{\Lambda}p$ system and the subsequent Λ -decay for $L \leq 4$. This structure can be interpreted in terms of the production of a resonance of spin-parity $J^P = 2^-$, with a mass and width of $2235 \pm 50 \text{ MeV}$ and $\sim 200 \text{ MeV}$ respectively. The production cross section for the $\bar{\Lambda}p$ decay mode is $\sim 1.5 \text{ } \mu\text{b}$.

1. INTRODUCTION

Recently evidence has been presented for the diffractive production of a series of unnatural parity resonances decaying to $\bar{\Lambda}p$ or $\bar{\Lambda}p$ with spin-parities 2^- , 3^+ and 4^- , observed in the reactions $K^-p \rightarrow \bar{\Lambda}pp$ and $K^+p \rightarrow \bar{\Lambda}pp$ at 50 GeV/c [1]. The analysis is based on a method using the double moments describing the sequential decay [2]. In this paper we study the $\bar{\Lambda}p$ system produced forwards in the reaction $K^-p \rightarrow \bar{\Lambda}pp$ at 8.25 GeV/c and make some comparison with the 50 GeV/c data.

Our data come from part of a 5.3×10^6 picture exposure of the CERN 2m HBC to an r.f. separated beam of 8.25 GeV/c K^- . The analysis reported here uses an event sample corresponding to about 150 events/ μb , which represents some 75% of the final statistics. Scanning and measurement are being done for all events containing one or more visible V^0 . The measurements are processed through standard geometry and kinematic fitting programs. Kinematic fits inconsistent with track ionisation density information are rejected. The production and V^0 decay vertices are required to fall in defined fiducial volumes. A weight is then applied to each event which corrects for the probability of not observing the V^0 decay inside the fiducial volume. In the case of Λ^0 s the weight also includes a small correction for loss of Λ^0 s with low π^- laboratory momenta.

2. THE EVENT SAMPLE

The event sample has been selected by requiring a kinematic fit with probability $> 1\%$ for the hypothesis $K^-p \rightarrow \bar{\Lambda}pp$. Since this is a 4C fit at the production vertex the sample should be very clean. However, since the cross section for this channel is relatively small we check the purity of our sample using a method first introduced by Ehrlich et al. [3]. In this method we have used all two-prong events with a visible Λ^0 decay which are consistent with momentum balance. The beam momentum is then adjusted so that momentum balance is exact. Then using energy conservation the mass of the two charged particles is determined, assuming a particle anti-particle pair. We accepted all events with missing

momentum $|p_x| < 600$ MeV/c, $|p_y| < 120$ MeV/c and $|p_z| < 240$ MeV/c^(*) which includes 95% of fits to the $\bar{\Lambda}pp$ channel. The resulting mass squared distribution is shown for a partial sample of our events in fig. 1. A clear peak is observed at the proton mass with a small background, most of which is eliminated by the 4C fit. Events with a fit probability $> 1\%$ for the final state $\bar{\Lambda}pp$ are shown shaded.

For the analysis presented in this paper we are exclusively concerned with forwards production of the $\bar{\Lambda}p$ system (defined by $|t(\bar{\Lambda}p)| < 1$ GeV²). Fig. 2(a) shows the Van Hove plot [4] for the 1291 events selected as belonging to the reaction $K^-p \rightarrow \bar{\Lambda}pp$. Fig. 2(b) shows the azimuthal distribution of the plot. The major fraction of the events lie in segment A and correspond to forward $\bar{\Lambda}p$ production. A few events lie in segment C indicating the presence of forward $p\bar{p}$ production. These two components are clearly well separated. A more difficult question is whether some events corresponding to backward $p\bar{p}$ production lie in segment F; and if so, how many. The cross section for this nucleon exchange process is expected to be small. The dashed histogram in fig. 2(b) shows the 752 events remaining after application of the $|t(\bar{\Lambda}p)| < 1$ GeV² cut. The shape and position of this latter distribution is consistent with that expected for forward $\bar{\Lambda}p$ production. The shift of the peak towards segment F is due to the $\bar{\Lambda}p$ decay distribution (defined by the Λ direction) being somewhat forward peaked at $\bar{\Lambda}p$ mass above 2.3 GeV. No sharp forward peaking of the $\bar{\Lambda}p$ decay distribution is observed in the data which might indicate a contamination of backward $p\bar{p}$ events. If backward $p\bar{p}$ production is present, it would presumably be most important at small $|t(\Lambda)|$. No clear clustering of events at low $|t(\Lambda)|$ is observed in the data. Our checks suggest that any contamination from backward $p\bar{p}$ production in our final event sample is negligible.

Fig. 3 shows the $\bar{\Lambda}p$ mass distribution for our event sample. There is no significant evidence for the presence of any narrow peak.

(*) p_x is along the beam direction. The resolution in p_x , p_y , p_z is 160, 30, 60 MeV/c respectively for full width at half height.

3. DETERMINATION OF THE MOMENTS

The sequential decay of the system $\Lambda\bar{p}$ is described by four angles. θ, φ are the polar and azimuthal angles describing decay to $\Lambda\bar{p}$; here we use the t-channel or Jackson frame [5]. The z-axis is the direction of the incident K^- in the $\Lambda\bar{p}$ rest frame and the y-axis is the normal to the $\Lambda\bar{p}$ production plane in the direction $\vec{p}_{\text{final}} \times \vec{K}^-$. The direction of the Λ in the $\Lambda\bar{p}$ rest frame defines θ and φ . The subsequent Λ decay is described by angles θ' and φ' defined by the direction of the decay proton in the Λ rest frame. The reference frame is defined by choosing the z'-axis as the direction of the Λ in the $\Lambda\bar{p}$ rest frame and the y'-axis in the direction $z \times z'$.

In terms of these decay angles the moments used here are defined by

$$H(LM\ell m) = \sum_i W_i \times D_{Mm}^L(\varphi_i, \theta_i, 0) D_{\ell m}^\ell(\varphi'_i, \theta'_i, 0) \quad (1)$$

where the sum is over all events in a given $\Lambda\bar{p}$ mass interval and W_i is the event weight described above. The normalisation of the moments is such that $H(0000) = \sum W_i$, the number of weighted events.

We have determined for $|t(\Lambda\bar{p})| < 1 \text{ GeV}^2$ the following moments as a function of $\Lambda\bar{p}$ mass;

$$H(LM00)$$

$$H(LM10)$$

$$H^{\pm}(LM11) = H(LM11) \pm H(LM1-1)$$

for $L < 10$ and $M < 2$. We only observe significant moments for $L \leq 4$ in the moments $H(LM00)$ and $H^{\pm}(LM11)$. The $H(LM00)$ moments do not depend on the Λ -decay, while $H^{\pm}(LM11)$ is sensitive to Λ -polarisation in the Y'-direction (i.e. normal to the Λ -production plane). Figs 4-6 show a selection of the determined moments. Those moments not shown in figs 4-6 are consistent with zero.

Structure is observed in all $H(L000)$ up to $L = 4$. Structure is also seen in $H(1100)$, $H(2100)$ and $H(2200)$ as well as the Λ -polarisation dependent combination $H^{\pm}(1011)$. $H(4000)$, $H(2000)$ and $H(2200)$ all show

peaks between 2.1 and 2.3 GeV which are narrow compared to the shape of the mass spectrum $H(0000)$, which could be an indication of resonant behaviour. The moment $H(1000)$, which is one of the largest, has a behaviour different from all other moments in that it rises rapidly from small values at a $\bar{\Lambda}p$ mass ~ 2.3 GeV. We have chosen to use the t-channel frame to describe the $\bar{\Lambda}p$ system since the moments with $M \neq 0$ are somewhat smaller in this frame than in the s-channel frame. We observe no significant variation of the moments over the $|t|$ range used.

In summary we observe significant moments in $H(L000)$ only up to $L = 4$, which implies that an interpretation with spins $J \leq 2$ is sufficient. There is also significant Λ polarisation as indicated by $H^-(1011)$. Further, the relatively narrow structures observed in $H(4000)$ and $H(2000)$ near a mass of 2.2 GeV suggests a possible interpretation in terms of a spin $J = 2$ resonance. The fact that the moments with $M = 0$ are significantly larger than those with $M \neq 0$ indicates that $\bar{\Lambda}p$ states with helicity, $\lambda = 0$ dominate, consistent with a diffractive production mechanism. We will further discuss the production mechanism at 8.25 GeV/c below.

4. INTERPRETATION OF THE MOMENTS

Martin and Nef [2] have presented a method for the interpretation of moments obtained for $\bar{\Lambda}p(\bar{\Lambda}p)$ systems produced diffractively in the reaction $K^-p \rightarrow \bar{\Lambda}pp$ ($K^+p \rightarrow \bar{\Lambda}pp$). As applied to the data at 50 GeV/c [1], the method requires the following assumptions:

- (a) Only $\bar{\Lambda}p$ states with helicity $\lambda = 0$ are important since the moments $H(LM\&m)$ with $M = 0$ dominate.
- (b) Spin coherence is assumed at the lower $p\bar{p}$ vertex.
- (c) Diffractive production combined with the assumption of only $\lambda = 0$ helicity states implies the production of only unnatural parity states.

- (d) Generalised C-parity conservation [6] in production and decay then requires even (odd) spin Λ_p^- states to decay with $S = 0$ ($S = 1$). There is thus only a single decay amplitude for each spin-parity state.

With these assumptions, the number of unknowns (amplitudes and phases) equals the number of moments and a solution for amplitudes and phases can be obtained. This model predicts that the following moments must vanish

$$\begin{aligned} H(L000) &= 0 \quad \text{for } L \text{ odd} \\ H^-(L011) &= 0 \quad \text{for } L \text{ even.} \end{aligned} \quad (2)$$

Even at 50 GeV/c [1] the above conditions are not completely satisfied. At 8.25 GeV/c however, $H(1000)$ is one of the largest moments. Therefore it seems necessary to modify at least some of the above assumptions if we are to be able to interpret our data.

The Λ_p^- production and decay amplitudes are related to the moments by eqs (10-13) of ref. [2]. Here we give the relations for $H(L000)$ and $H^-(L011)$ assuming only $\lambda = 0$ helicity states contribute and that only unnatural parity states are produced.

$$H(L000) = \frac{2}{2L+1} \sum_{JJ'} \sqrt{(2J+1)(2J'+1)} T_0^L(JJ') S_{00}^L(JJ') \quad (3)$$

with

$$T_0^L(JJ') = \rho_{00}^{JJ'} \langle J0J'0/L0 \rangle \quad (4)$$

$$S_{00}^L(JJ') = F_{++}^J F_{++}^{J'*} \langle J0J'0/L0 \rangle - F_{+-}^J F_{+-}^{J'*} \langle J-1J'1/L0 \rangle \quad (5)$$

$$H^-(L011) = \frac{2\sqrt{2}\alpha_\Lambda}{3(2L+1)} \sum_{JJ'} \sqrt{(2J+1)(2J'+1)} T_0^L(JJ') P_{11}^L(JJ') \quad (6)$$

with

$$P_{11}^L(JJ') = F_{+-}^J F_{++}^{J'*} \langle J1J'0/L1 \rangle - F_{++}^J F_{+-}^{J'*} \langle J0J'1/L1 \rangle. \quad (7)$$

$\rho_{00}^{JJ'}$ is the density matrix describing the Λ_p^- states. Assuming spin coherence we can write $\rho_{00}^{JJ'} = H_0^J H_0^{J'*}$. As a result eqs (3) and (6) factorize and we can determine the products $H_0^J F_{\mu\nu}^J$. $F_{\mu\nu}^J$ describes the decay of the Λ_p^- system where $\mu(\nu)$ is the helicity of the $\Lambda(p)$. For unnatural parity states $F_{\mu\nu}^J = -F_{-\mu-\nu}^J$.

From these equations (3-7) we can see that if, as a result of C-parity invariance generalised to SU(3) (R-parity invariance [6]), we only have F_{++} (F_{+-}) non zero for J even (odd), then the conditions (2) follow. It is equally clear that if we wish to describe the moments H(1000) and H(3000) we must allow the possibility of both F_{++} and F_{+-} to be non-zero for some J.

The presence of both F_{++} and F_{+-} terms for a given J can arise either (a) if R-parity invariance is broken, or (b) if natural parity states are produced, for which no restriction on $F_{\mu\nu}$ is imposed by R-parity invariance. It turns out that H(1000) and H(3000) cannot arise from interference between natural and unnatural parity $\bar{\Lambda}_p$ states (see table 1 of ref. [2]). This means that if unnatural parity $\bar{\Lambda}_p$ states dominate, the presence of H(1000) and H(3000) can only be explained by breaking R-parity invariance. We now argue that this is the case.

The most probable mechanism for production of $\lambda = 0$ natural parity $\bar{\Lambda}_p$ states would be π -exchange. The π -exchange cross section can be estimated to be $\sim 1 \mu\text{b}$ from the SU(3) related reaction $\pi^- p \rightarrow p \bar{p} n$, which is dominated by π -exchange and produces natural parity $p \bar{p}$ states with $\lambda = 0$ in the forward direction [7]. This is only 10-15% of our cross section, so natural parity states are not expected to be important.

Fig. 7 shows the cross section dependence for forward $\bar{\Lambda}_p(\bar{\Lambda}_p)$ production with mass $< 2.6 \text{ GeV}$ in $K^- p \rightarrow \bar{\Lambda}_p p$ ($K^+ p \rightarrow \bar{\Lambda}_p p$) as a function of p_{lab} [8]. Using the parametrisation $\sigma \sim p_{\text{lab}}^{-n}$, n is seen to be ~ 0.8 . This value indicates a more rapid fall-off with p_{lab} than many diffractive processes (e.g. $\pi^- p \rightarrow \pi^- p$ or $\pi^- p \rightarrow \pi^- \pi^+ p$) where $n \sim 0.2$, but is similar to the diffractive process $\pi^- p \rightarrow A_2^- p$ and is much slower than for π -exchange processes ($n \sim 2$). Thus at 8 GeV/c forward $\bar{\Lambda}_p$ production has the characteristics of a diffractive process; relatively slow decrease of cross section with increasing p_{lab} and dominance of helicity $\lambda = 0$ states.

R-parity invariance in the production of the $\Lambda\bar{p}$ system requires the assumption that the process occurs via SU(3) singlet exchange. It is known that the Pomeron also contains an octet component [9], and in addition at 8.25 GeV/c a contribution from f exchange is also probable. The couplings of the f meson are identical to those of the Pomeron, and so the addition of f exchange will not invalidate the use of eqs (3-7). Since the exchange is no longer SU(3) singlet, we have a natural explanation for the failure of conditions (2) in our data.

In order to determine whether a resonance interpretation is tenable, we have made an energy dependent fit to the moments $H(L000)$ and $H^-(L011)$ for $L \leq 4$ (the results are unchanged if $H^-(2011)$ and $H^-(4011)$ are omitted from the fits) over the mass range 2.07-2.79 GeV (81 data points).

The fit uses the following amplitudes:

- (a) 0^- background with F_{++} only (F_{+-} is not allowed).
- (b) 1^+ background with independent F_{+-} and F_{++} amplitudes.
- (c) 2^- relativistic Breit-Wigner amplitude with $M_0 = 2.235$ GeV and $\Gamma_0 = 0.2$ GeV. The fact that $H(4000)$ is positive requires any F_{+-} contribution to be small. We therefore only allow an F_{++} amplitude for the resonance.
- (d) 2^- background for F_{+-} only. This is required to give a negative $H(4000)$ observed for $M(\Lambda\bar{p})$ above 2.4 GeV. It is not essential to our interpretation.

The fit determines the amplitudes $A_{\mu\nu}^J = H_0^J F_{\mu\nu}^J$. The resonant amplitude is parametrised by a fixed width Breit-Wigner with the partial width for $\Lambda\bar{p}$ decay, $\Gamma = \Gamma_0 q(M)/q(M_0)$. The real and imaginary parts of the background amplitudes are both parametrised by the form

$$A = (a_0 + a_1 m' + a_2 m'^2) \cdot X^{1/2}$$

where

$$m' = M(\Lambda p) - M_{\Lambda} - M_{p}$$

$$X = \int_{t_{\min}}^{1.0} e^{-Bt} dt \quad \text{with } B = 5 \text{ GeV}^{-2}.$$

The function X is used to parametrize the production phase space. The fits are not sensitive to the value of B used. For the 2^{-} background only the term linear in m' is used.

The parametrisation involves 20 variables, not all of which are necessary for a satisfactory fit. Several fits with a resonant 2^{-} amplitude have been obtained, which differ in the details of the non-resonant amplitudes. A fit can also be obtained with no rapidly varying phases, in which the modulus of the $2^{-}A_{++}$ amplitude is given a Breit-Wigner variation but the phase is kept constant. However, it seems more reasonable to attribute the rapidly rising and falling $2^{-}A_{++}$ amplitude to resonant behaviour.

Using 12 variables the best fit gives a $\chi^2 = 67$ for the 81 data points. The results of the fit are indicated by the curves in figs 4 and 6. The peak in $H(4000)$ arises from the 2^{-} resonance, while the structure in $H(2000)$ and $H(1000)$ near 2.2 GeV is due to interference between the 2^{-} resonant state and the 0^{-} and 1^{+} backgrounds. Neither of the backgrounds have any rapid phase variation. The 0^{-} and 1^{+} contributions to the mass spectrum behave as might be expected, with the S-wave (0^{-}) dominating near threshold and the p-wave (1^{+}) only becoming large well above threshold. The overall phase in the fit is defined by the resonant 2^{-} amplitude being imaginary at the resonance mass. We then find the 0^{-} amplitude is imaginary near threshold and that both A_{+-} amplitudes (1^{+} , 2^{-}) are real throughout the mass range fitted. Thus we have shown that an interpretation in terms of a 2^{-} resonance with 0^{-} and 1^{+} backgrounds can describe our data.

5. CONCLUSIONS

We have studied the decay moments $H(LM\ell m)$ for the decay of the Λ_p^- system produced peripherally at 8.25 GeV/c. The moments have been interpreted using a modification of the method suggested by Martin and Nef [2]. Our data are consistent with an interpretation in terms of a resonance in the $J^P = 2^-$ state with contributions from 0^- and 1^+ backgrounds. Furthermore, this is probably the simplest interpretation. The resonant state has a mass of 2235 ± 50 and a width ~ 200 MeV. The cross section for $|t| < 1 \text{ GeV}^2$ is $1.5 \pm 0.5 \mu\text{b}^{(*)}$. We identify this state with the similar state observed at 50 GeV/c [1] for which the quoted parameters are $M = 2260 \pm 20$, $\Gamma = 210 \pm 50$ and a cross section of $0.58 \pm 0.09 \mu\text{b}$. Thus the 2^- resonance cross section has approximately the same p_{lab} dependence as the total forward Λ_p^- cross section. We also note that our interpretation requires the resonance decaying predominantly through the F_{++} amplitude in agreement with the 50 GeV/c analysis.

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(*) Assuming a width of 200 MeV.

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We use the cross sections and where necessary the mass spectra to estimate the cross sections for $M(\Lambda p) < 2.6$ GeV shown in fig. 7.
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FIGURE CAPTIONS

- Fig. 1 The Ehrlich plot [3] for the reaction $\bar{K} p \rightarrow \Lambda + 2 \text{ prongs}$. The peak at $M_x^2 = 0.88$ demonstrates the presence of the reaction $\bar{K} p \rightarrow \bar{\Lambda} p p$. Events fitting $\bar{K} p \rightarrow \bar{\Lambda} p p$ with probability $> 1\%$ are shown shaded.
- Fig. 2 (a) The Van Hove plot for reaction $\bar{K} p \rightarrow \bar{\Lambda} p p$.
(b) The azimuthal projection of (a). The dashed histogram shows events with $|t(\bar{\Lambda} p)| < 1 \text{ GeV}^2$.
- Fig. 3 The weighted mass distribution $M(\bar{\Lambda} p)$ for events with $|t(\bar{\Lambda} p)| < 1 \text{ GeV}^2$.
- Fig. 4 The moments $H(L000)$ for the $\bar{\Lambda} p$ system. The curves show the fit described in the text.
- Fig. 5 The moments $H(LM00)$ with $M \neq 0$.
- Fig. 6 The moments $H^-(L011)$ which utilise Λ -decay information. The curves result from the fit described in the text.
- Fig. 7 The dependence of $\sigma(\bar{K} p \rightarrow \bar{\Lambda} p p)$ for forward $\bar{\Lambda} p$ production with $M(\bar{\Lambda} p) < 2.6 \text{ GeV}$ together with similar data for $\sigma(K^+ p \rightarrow \bar{\Lambda} p p)$ (the cross section at 50 GeV has been deduced from the published $\bar{\Lambda} p$ spectra).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7