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PARTIAL WAVE ANALYSIS OF $K\overline{K}\pi$ FROM $\bar{p}p \to K^+\overline{K}^0\pi^-X$ AT 8 GeV/c

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We present the results of an amplitude analysis of the spin parity components as a function of mass of the $(K^+\overline{K}^0\pi^-)$ system as produced in the reaction $\bar{p}p \to (K^+\overline{K}^0\pi^-)$ X. Two peaks are observed in the $(K^+\overline{K}^0\pi^-)$ spectrum, one at (1279 ± 2) MeV/c^2 with a width of(21 ± 2) MeV/c^2, and one at (1417 ± 3) MeV/c^2 with a width of (62 ± 5) MeV/c^2. The amplitude analysis was performed in sixteen 20 MeV/c^2 mass intervals from 1.24 to 1.56 GeV/c^2. The waves used for the fitting were $J^{PG} = 0^{-+}, 1^{++}, 1^{+-}$, and background.

1. INTRODUCTION

Many three quark (anti-quark) baryons (anti-baryons) and quark-antiquark mesons have been observed[1]. However, QCD seems also to allow the possibility for other types of bound states, such as exotic hadrons (5 quark states), hybrids (bound states of quarks and gluons), and glueballs (bound states of gluons). These states would best be identified by having quantum numbers which are not allowed for ordinary hadrons. To date, no such objects have been unambiguously observed[2].

A second possibility is to look for exotics that have ordinary quantum numbers, but that can not be classified in the present ordering schemes for hadrons. Here we will discuss the results of an amplitude analysis performed on the reaction $\bar{p}p \to K^+\overline{K}^0\pi^-$ X at 8.0 GeV/c. We will also compare these results with the analysis of the reaction $\pi^-p \to K^+\overline{K}^0\pi^-n$ at 8.0 GeV/c.

2. THE EXPERIMENT

This experiment (BNL E-771) was proposed to observe the $(K\overline{K}\pi)$ final state in three different reactions. The reactions observed are:

$$\bar{p}\,p \to (K^+\overline{K}^0\pi^-) + X$$
$$\pi^-p \to (K^+\overline{K}^0\pi^-) + n$$
$$K^-p \to (K^+\overline{K}^0\pi^-) + Y.$$

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The analysis of the $\bar{p}p$ data is the main subject of this talk. The Brookhaven National Laboratory MPS consists of a liquid hydrogen target and detectors inside a large C magnet and additional detectors downstream of the magnet. Details of the equipment and trigger are explained in more detail in the paper "Search for the U(3.1)..." found elsewhere in this proceeding[3,4,5]. The trigger for this portion of the experiment consisted of detecting the decay $K_S^0 \to \pi^+\pi^-$ and also identifying a positive charged particle heavier than a pion with momentum greater than 1.5 GeV/c. A time-of-flight system and cherenkov counter selected K^{+-}'s from the positive charged trigger particles.

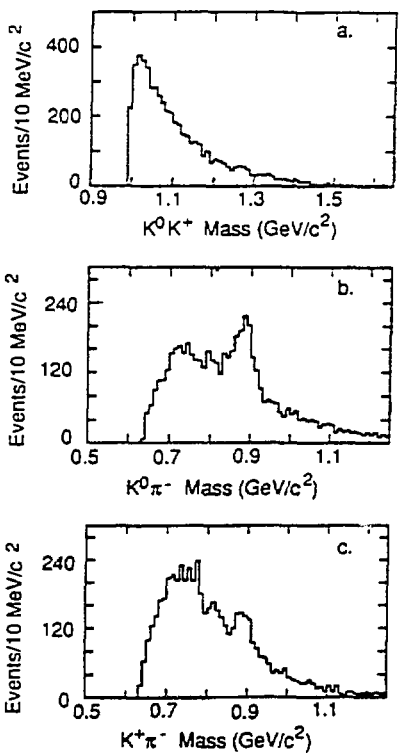

FIGURE 1

Two body invariant masses from $\bar{p}p \to K^+K^0\pi^-X$

3. THE DATA

The three two-body invariant masses are shown in Figure 1. Figure 1a is the $\overline{K}^0K^+$ invariant mass. $\overline{K}^0\pi^-$ is shown in 1b. The $\overline{K}^{*-}(892)$ is clearly seen. $K^{*0}(892)$ is also seen in $K^+\pi^-$. Figure 1c. although it is not as prominent as the $\overline{K}^{*-}(892)$.

The invariant $K^+\overline{K}^0\pi^-$ mass is shown in Figure 2. The prominent features are a narrow peak centered at 1280 MeV/c^2 and broader one centered at 1420 MeV/c^2. As the acceptance is falling with increased mass, it is possible that the second peak, in the $\lambda\eta$ region, is a rise from the K^*K threshold that is cut off by falling acceptance. The acceptance corrected mass distribution still shows a peak in the $\lambda\eta$ region, which indicates that there is at least one resonance present. The invariant $K^-\overline{K}^0\pi^-$ mass for the π^- beam data is shown in Figure 3, and displays features very similar to those of the $\bar{p}$ beam data.

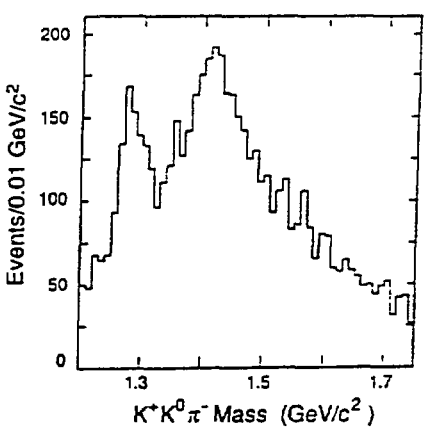

FIGURE 2

Mass distribution of $\bar{p}p \to K^+K^0\pi^-X$

The Dalitz plot is used to examine three-body final states. There are three two-body mass combinations of such a final state. For fixed three-body mass, the phase space distribution is uniform in the Dalitz plot, and any concentration of events in a band indicates an intermediate resonant state. A resonant primary state

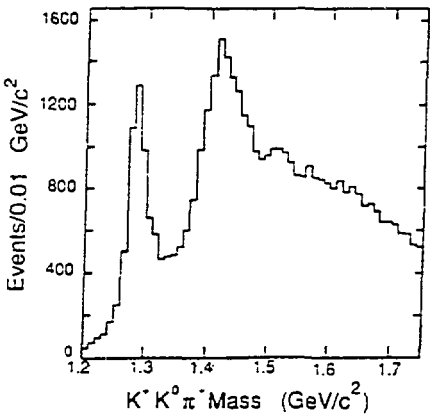

FIGURE 3
Mass distribution of $\pi^- p \to K^+ K^0 \pi^- n$

of a definite J^{PG} will yield a Dalitz plot with a distinct population density. Dalitz plots for some pure waves are shown in Figure 4 where the notation is J^{PG} followed by decay mode. K^* is K^*K and a_0 is $a_0(908)$ π. The pure-wave Dalitz plots were generated using geometrically accepted Monte Carlo events which were weighted using the analysis program [3,5]. Waves of different J^P will not show any interference on a Dalitz plot. However different decay modes with the same J^P can interfere, as can states with the same J^P and isobar, but different G or C. For instance, the 1^{+-} states for the K^*K system have predictable Dalitz plot features. In the 1^{++} wave, with G eigenstate given by $|K^+K^{*-}> - |\overline{K}^0K^{*0}>$, K^* bands parallel to both axes are expected and those bands should overlap. In the 1^{+-} wave, $|K^-K^{*-}> - |\overline{K}^0K^{*0}>$, the bands should be present, but the overlap region should have no events. For interference between the $1^{++}K^*K$ and $1^{+-}K^*K$, one of the K^* bands can be expected to disappear.

$$|K^-K^{*-}> \propto |1^{++}> - |1^{+-}>$$

$$|K^0K^{*0}> \propto |1^{++}> - |1^{+-}>$$

These are seen in Figures 4e and f respectively.

Dalitz plots for the data are shown in 20 MeV/c² ($K^+\overline{K}^0\pi^-$) mass intervals in Figure 5. The solid curves are the boundaries of the plots. The most interesting feature is an asymmetry in the K^* bands that appears around 1.34 GeV/c². In the region from 1.34 GeV/c² to 1.42 GeV/c², the K^{*-} is much stronger than the K^{*0}. This asymmetry disappears at higher masses. This is an indication that the waves $1^{++}K^*K$ and $1^{+-}K^*K$ could be important in the region with the asymmetry. The other interesting feature in the data is that the Dalitz plots do not resemble any of the pure wave Monte Carlo Dalitz plots. This suggests that the $K^-\overline{K}^0\pi^-$ system is composed of a superposition of several different waves.

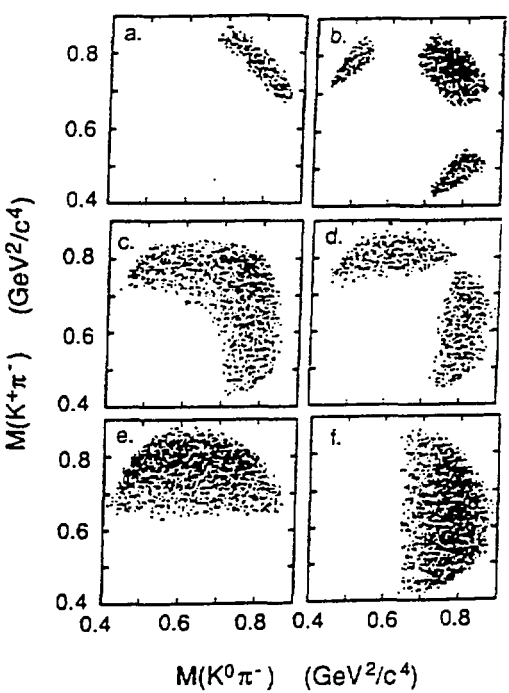

FIGURE 4
Pure wave Dalitz plots for mass (KKπ)=1.42GeV/c² a) 0^+a_0 b) 0^+K^* c) $1^{++}K^*$ d) $1^{+-}K^*$ e) $1^{++}K^*$ and $1^{+-}K^*$, zero phase f) $1^{++}K^*$ and $1^{+-}K^*$, 180° phase

4. AMPLITUDE ANALYSIS

The results of the Amplitude Analysis illustrate the quality of the fits. Monte Carlo events generated according to phase space distributions were weighted by the probability obtained from the amplitude analysis. The distributions for the weighted Monte Carlo events are then compared to the data. The resulting fit appears to be unique, and is shown in Figures 6 and 7.

In the 1.24 to 1.34 GeV/c^2 region, the 1^{--} a_0 (890) π resonance, $f_1(1285)$, is seen quite clearly. There is an enhancement in 0^{--} $a_0\pi$ as well. That can be identified with the η (1280), a 0^{--} $a_0\pi$ resonance that has been observed in other experiments[5]. It is broader than $f_1(1285)$. The phase motion of 0^{--} $a_0\pi$ with respect to 1^{--} $a_0\pi$ is flat, indicating that either the waves are resonating together, or neither is resonating. The background is small in this region.

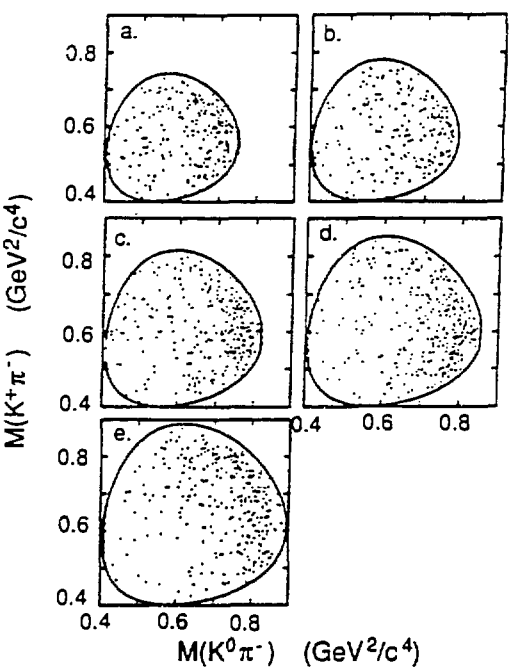

FIGURE 5
Dalitz plots $\bar{p}p \to K^+K^0\pi^-X$
a). 1.34-1.36 b). 1.36-1.38 c). 1.38-1.40
d). 1.40-1.42 e). 1.42-1.44 GeV/c^2

In the 1.34 GeV/c^2 to 1.48 GeV/c^2 region, $1^{--}K^*K$ is rising at the K^*K threshold. 0^{--} $a_0\pi$ peaks later at 1.43 GeV/c^2. The phase motion for 0^{--} $a_0\pi$ with respect to 1^{++} K^*K is flat from 1.35 GeV/c^2 to 1.43 GeV/c^2 and then rises through 180° in the next three mass bins. There are several possible interpretations. Between 1.35 and 1.41, either both $0^{--}a_0\pi$ and 1^{++} K^*K are resonating, or neither is. The rise from 1.43-1.49 indicates that $0^{--}a_0\pi$ is resonating in that region. It seems that one resonance will not describe the predicted number of events and the phase motion. It is impossible to determine whether there are two or three resonances in the region based on these data.

It is seen that $1^{+-}K^*K$ is present in the region that shows the K^* asymmetry described above. After that, it is only present in one bin. $0^{--}K^*K$ is very small everywhere. The background is growing stronger throughout the region. This indicates that there is an increasing amount of non-($K^-\overline{K}^0\pi^-$) events and that perhaps some important waves are turned off in the analysis. There are little data at high ($K^-\overline{K}^0\pi^-$) mass and no conclusions can be drawn from the analysis.

The comparison between the data and the fit is shown in Figures 7a through 7f, for the mass bin centered at 1.41 GeV/c^2. The agreement between the data and the fit is good.

As mentioned, this experiment also took data with a π^- beam[5]. The $K^+\overline{K}^0\pi^-$ mass spectrum from the reaction $\pi^-p \to K^+\overline{K}^0\pi^-n$ is shown in Figure 3, and the results of the amplitude analysis are shown in Figure 8. The data from the π^-p experiment were divided into three -t bins, 0.0 < -t < 0.2 GeV^2/c^4, 0.2 < -t < 0.45 GeV^2/c^4 , and 0.45< -t < 1.0 GeV^2/c^4. A peak seen in the ($K^+\overline{K}^0\pi^-$) spectrum at 1.42 has contributions from $0^{-+}a_0\pi$, $0^{-+}K^*K$, $1^{++}K^*K$, and $1^{+-}K^*K$. The relative contributions vary with the -t region. The behavior of $0^{-+}K^*K$ changes strikingly in the different -t regions. At 0.0 < -t < 0.2 GeV^2/c^4, $0^{-+}K^*K$ is small

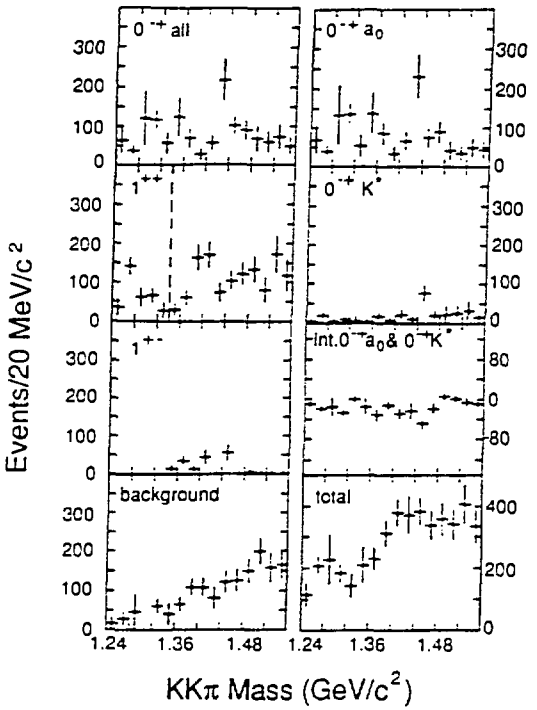

FIGURE 6
Partial-wave for $\bar{p}p \to K^+K^0\pi^-X$

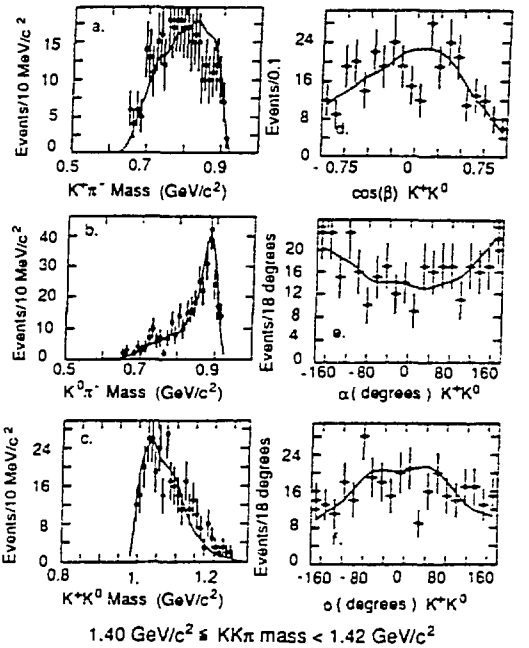

FIGURE 7
Two body mass and angular distributions from $\bar{p}p$ data. Curves are from partial wave fits.

and without structure. For the higher -t regions, there is a clear $0^{--}K^*K$ peak. The contributions of $0^{-+}a_0\pi$ and $0^{-+}K^*K$ for the higher -t regions give evidence for at least two 0^{-+} resonances, one around 1396 $\pm$ 5 MeV/c^2 that decays to $a_0\pi$ and K^*K, and one higher in mass (1450 $\pm$ 10 MeV/c^2) that decays solely to K^*K.

The amplitude analysis shows small η (1295) 0^{--} and large f_1 (1285) 1^{++} peaks. In the 1.4 to 1.5 GeV/c^2 mass region there is a strong 0^{-+} peak at 1.42 GeV/c^2 identified as the η (1420), but the peak is wide and there also exists the possibility of a second 0^{-+} resonance at 1.47 GeV/c^2. Smaller peaks of 1^{++} and 1^{+-} are not ruled out.

5. CONCLUSIONS

We have presented the results of an amplitude analysis of the spin parity components as a function of mass of the $(K^+\overline{K}^0\pi^-)$ system as produced in the reaction $\bar{p}\,p \to (K^+\overline{K}^0\pi^-)$ X. Two peaks are observed in the $(K^+\overline{K}^0\pi^-)$ spectrum, one at (1279 $\pm$ 2) MeV/c^2 with a width of (21 $\pm$ 2) MeV/c^2, and one at (1417 $\pm$ 3) MeV/c^2 with a width of (62 $\pm$ 5) MeV/c^2. The amplitude analysis was performed in sixteen 20 MeV/c^2 bins from 1.24 GeV/c^2 to 1.56 GeV/c^2. The waves used for the fitting were 0^{-+}, 1^{++}, 1^{+-}, and background.

In the 1.3 GeV/c^2 region, two resonances are observed in the amplitude analysis. The $1^{++}a_0\pi$ resonance that peaks near 1.27 GeV/c^2 is identified with the well established f_1(1285). A second resonating wave, seen at the same mass, is $0^{-+}a_0$ (890) π and corresponds to the η (1295). The η (1295) has been seen in $\eta\pi\pi$ and $K\overline{K}\pi$ final states, but it is not as well established as the f_1(1285). In all cases, the η (1295) has been observed

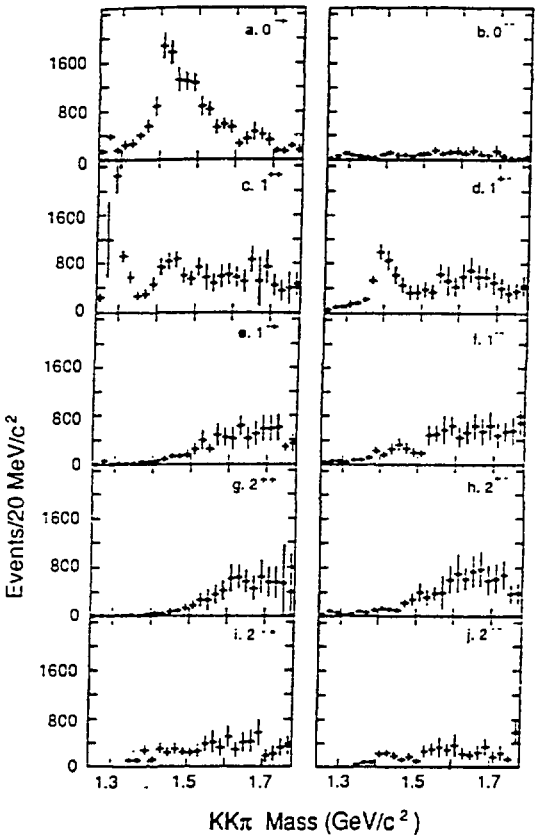

FIGURE 8

Partial waves for $\pi^- p \to K^+ K^0 \pi^- n$

with partial wave analysis techniques.

In the 1.4 GeV/c^2 region, the situation is less clear. There is a peak in the number of events attributed to $1^{++} K^* K$ near 1.40 GeV/c^2 and a second peak attributed to $0^{-+} a_0\pi$ at approximately 1.43 GeV/c^2. The relative phase motion between two waves gives information about the resonant behavior of the waves. A rise (or fall) of the relative phase motion as a function of mass indicates that one of the waves is resonating. If the relative phase motion is flat, either both or neither of the waves is resonating. The phase motion for 0^{-+} a_0 with respect to 1^{++} is constant from 1.35 GeV/c^2 to 1.43 GeV/c^2 and then rises through approximately 180° over the next 60 MeV/c^2. There are several possible interpretations. There is certainly a 0^{-+} $a_0\pi$ resonance around 1.43 GeV/c^2. There may be both a 0^{-+} and a 1^{-+} resonance around 1.40 GeV/c^2. It is also possible that neither wave is resonating in the lower region, and the peak in 1^{++} can be attributed to a rise from the K^*K threshold. Another interesting feature is the lack of structure in $0^{--} K^*K$. A fourth wave, 1^{+-}, is needed only from 1.35 GeV/c^2 to 1.41 GeV/c^2 to account for an asymmetry in the production of $K^{*-}K^+$ and $K^{*0}\overline{K}^0$ states. The background is rising steadily, indicating that perhaps higher spins are needed to describe the system at higher masses.

These results are very similar to the results of the partial-wave analysis of $\pi^- p \to (K^-\overline{K}^0\pi^-)n$ in the momentum transfer region $0.0 < -t < 0.2$ GeV^2/c^4. In that analysis, $0^{--} a_0\pi$ is definitely resonating. $0^{--} K^*K$ is without structure, and there is the possibility of a 1^{--} resonance overlapping a 0^{--} resonance near 1.40 GeV/c^2.

A number of 0^{-+} states have been reported in the region from 1.40 GeV/c^2 to 1.50 GeV/c^2. At least one such resonance is observed in these data. The results of analysis performed on the reaction $\pi^- p \to K^-\overline{K}^0 \pi^- n$ indicate evidence of at least two 0^{-+} states, the lower of which decays strongly to $a_0\pi$, and the higher exclusively to K^*K. These results are in good agreement with the results of Inagaki et. al.[6] from the reaction $\pi^- p \to K^\pm K_S^0 \pi^\mp n$ and the results of Rath et. al[7] in $\pi^- p \to K_S^0 K_S^0 \pi^0 n$. The 0^{--} resonance observed in $J/\psi \to \eta\pi\pi$ and $\pi^- p \to \eta\pi^+\pi^- n$ can be tentatively identified as the same as the lower 0^{-+} state observed in $\pi^- p \to K\overline{K}\pi n$. The 0^{-+} state observed in radiative J/Ψ decay may be a superposition of the two states observed in hadronic reactions with a $K\overline{K}\pi$ final state. It seems likely that neither state is the missing $s\bar{s}$ member of the first radial excitation of 0^{-+} nonet since neither is observed in $K^- p$ interactions.

There is also the possibility of an unexplained 1^{++}

state. There is modest evidence for a 1^{+-} state present at 1.40 GeV c^2 in this analysis and in the $\pi^- p$ analysis at low -t. If a 1^{--} K^*K state is produced in this reaction, it could tentatively be identified as the same state observed in e^+e^- experiments,[8,9] central production experiments at CERN,[10,11] and hadronic J/Ψ decay[12]. There is no place for such a 1^{--} resonance in the lowest 1^{++} nonet, and it seems unlikely that the mass is high enough for this state to be a radial excitation.

The various states discussed above are probably not all $q\bar{q}$ states. It is unfortunate that none of these states can be positively identified as a glueball or exotic, and their nature remains undetermined. The situation in the λ/η region is still confusing even after the analysis of the $\pi^- p$ and $\bar{p}p$ data from this experiment. It seems likely that there are both 1^{++} and 0^{--} states in

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