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LIGHT QUARK SPECTROSCOPY

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1. INTRODUCTION

Since the theoretical discovery of quarks some twenty years ago, they have been the foundation of the classification of hadrons. As there are no contributions to this conference on baryon spectroscopy, I will consider only the meson spectrum.

The ingredients required to describe the spectrum are simple (in this talk q refers to light u, d or s quarks): $q\bar{q}$ pair total spin $S = 0, 1$; relative orbital angular momentum L; and radial wave function (e.g., harmonic oscillator). Even the naive (non-relativistic) quark model works quite well.

The pattern of well-known states in $q\bar{q}$ spectroscopy is quite different from $c\bar{c}$ and $b\bar{b}$. Because of the position of the heavy quark thresholds, the $J^P = 1^-$ radial excitation ladder is well studied by formation in e^+e^- experiments and the $L = 1$ triplets are seen in γ transitions. In the $q\bar{q}$ sector, however, the "leading" high-spin multiplets are best known (in both natural and unnatural J^P) and, since most states have quite large widths, study of underlying radial excitations and L-excitation triplets is extremely difficult. It is important to remember both this contrasting pattern and that the basic structure is the same.

The advent of QCD as a true theory of the strong interaction has altered our perspective. Not only has the color degree of freedom made the spin statistics of the quark model respectable, but gluons open the possibility of entirely new gluonium and hybrid spectroscopies. I will discuss only "normal" hadrons since the other spectroscopies are covered by Lindenbaum[1] and Close[2] later in this session. By studying $q\bar{q}$ spectroscopy we learn about the $q\bar{q}$ confining potential in a regime where relativistic effects are important, indeed theorists now regularly apply QCD ideas to light quark states with some success – particularly in the area of electromagnetic properties.[3,4] Also, without a good understanding of the large number of $q\bar{q}$ states expected in the 1-2 GeV/c^2 mass range, it is difficult to establish the existence of gluonic hadrons.

2. ELECTROMAGNETIC PROPERTIES

Paschalis and Gounaris[3] have succeeded in calculating decay rates of light $J^P = 0^-$ and 1^- mesons in a non-relativistic model with QCD corrections – their results are in good agreement with experiment. On the other hand, the quantitative understanding of baryon magnetic moments has historically been a problem for quark models. Tadić and Trampetić[4] and Mitra and Mittal[5] demonstrate some successes with very different approaches but the problem is still far from solution.

The theoretical problem is being made more difficult by better experimental data. Brenner et al.,[6] have measured the Σ^+ moment in the FNAL hyperon beam with better than 1% accuracy; the high momentum of the beam enabled them to get high statistics and a large spin precession angle ($>2\pi$!). Their result of $2.38 \pm .02$ nuclear magnetons is in agreement with the world average and a factor 6 more precise – it is also in clear disagreement with simple quark models.

3. LEADING RESONANCES

The Serpukhov-Brussels-Annecy-CERN Collaboration[7] see a strong candidate for the $I^G = 0^+$ member of the $J^{PC} = 6^{++}$ octet as a shoulder on the tail of the $h(2040)$ in the reaction $\pi^- p \to \pi^0\pi^0 n$ at 38 GeV/c. Assuming π-exchange, they make a cut in the Gottfried-Jackson frame to emphasize spin 6 and spin 4 (Fig. 1). The new candidate and the h meson behave as expected. From a Legendre Polynomial fit to the angular distributions they obtain a mass 2510 ± 30 MeV/c^2 and width 240 ± 60 MeV/c^2 for the new state – $r(2510)$ – which lies well on a straight trajectory with the f and h in the Chew-Frautschi plot.

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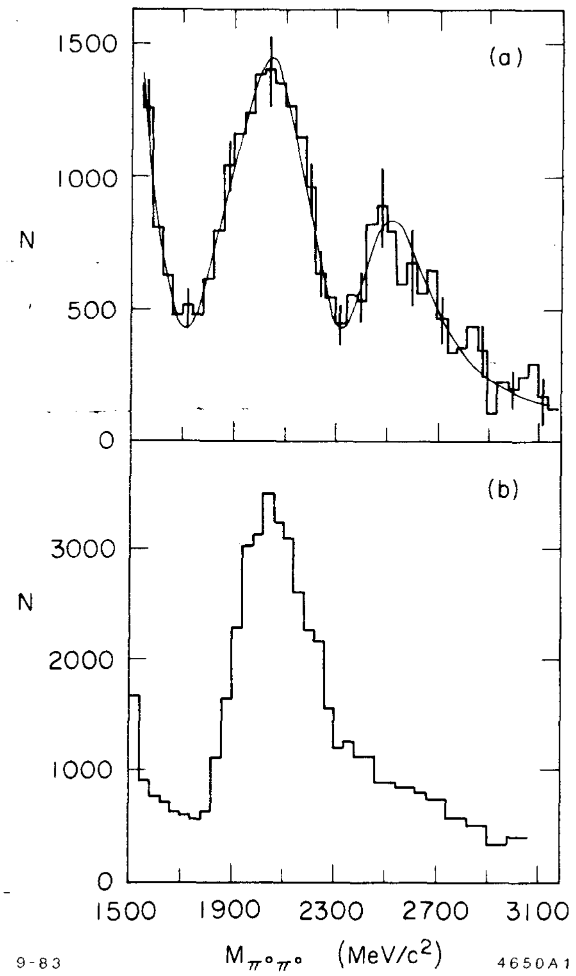

Fig. 1 $\pi^0\pi^0$ mass spectrum[7] cut in the Gottfried–Jackson frame to emphasize (a) spin 6, (b) spin 4.

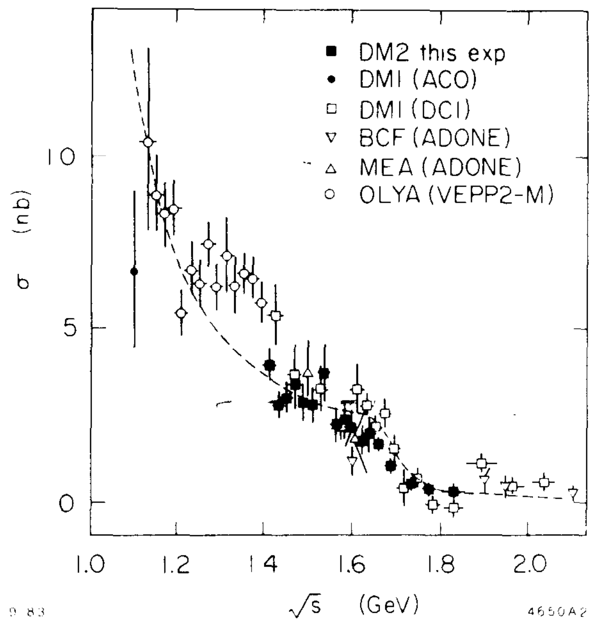

Fig. 2 $e^+e^- \rightarrow K^+K^-$ cross section. Fit includes ρ', ω' and ϕ' contribution.[10]

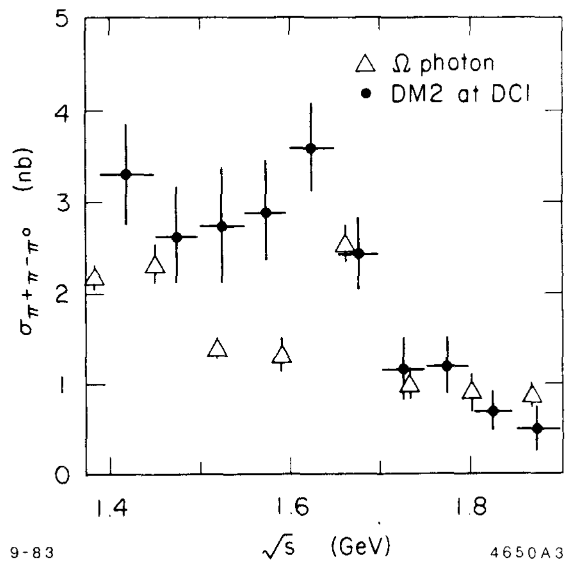

Fig. 3 "γ" $\rightarrow K^+K^-$ cross section from e^+e^- [10] compared with photoproduction[11] (arbitrary scale).

4. ORBITAL AND RADIAL EXCITATIONS

Most of the contributions to this conference relate to assignment of underlying states and attempts to understand the systematics of radial and orbital splittings.

a) Scalar Mesons. Experimentally there is no new information; theoretically there is controversy, particularly over the nature of the S^* and δ which are close to the $K\bar{K}$ threshold. Achasov et al[8] argue strongly for the existence of $q\bar{q}q\bar{q}$ nonets whereas Törnqvist[9] and others believe that they make up a conventional nonet along with the ϵ and κ provided that inelastic thresholds are correctly taken into account. In spite of these problems, the ϵ and κ (which are broad, unlike the S^* and δ) are regularly used as isobars in many 3-body Partial Wave Analyses (PWA).

b) Vector Mesons in e^+e^- and Photoproduction. The DM2 group at DCI[10] again sees the $\rho'(1600)$ clearly in the $\pi^+\pi^-\pi^+\pi^-$ final state and confirms the interesting interference effect in K^+K^- around 1700 MeV (Fig. 2). This now amounts to strong evidence for at least one nonet in this area – two are expected, the first radial and $L = 2$ orbital excitations.

In Fig. 3 we see the results of the DM2 group[10] in $\pi^+\pi^-\pi^0$ compared with the $J^P = 1^-$ intensity extracted from diffractive photoproduction.[11] The two groups disagree on the interpretation of their results – ω' or

ϕ' is possible – but it seems clear that the same object is being seen. For further discussion of photoproduction results, see the talk of Bellini.[12]

c) Three-Body Partial Wave Analyses. By using the isobar model to describe a produced three meson state as a sum of pseudo-two-body decays via well known states (e.g., $K^*(890)$, $\rho(770)$) maximum use can be made of available information. "Waves" are described by the variables $J^P M^\eta$ (Isobar) L where J^P M is the spin-parity and magnetic substate of the three body system, η the naturality of the t-channel exchange and L the angular momentum of the two-body isobar relative to the third meson. Provided a coherent system is produced, the intensities and relative phases of waves can be measured using an extended maximum likelihood fit. The Dubna-Milano Collaboration[13] have analyzed the $\pi^-\pi^-\pi^+$ system produced coherently at 40 GeV/c from nuclear targets. They see (Fig. 4) two quite clean peaks in intensity in the $0^-0^+\epsilon$ S wave at about 1.2 and 1.8 GeV/c^2. Both peaks show phase motion consistent with resonant behavior, and the lower peak agrees with that seen by Daum et al.,[14] produced from hydrogen. Thus, there is now evidence for two radial recurrences of the pion.

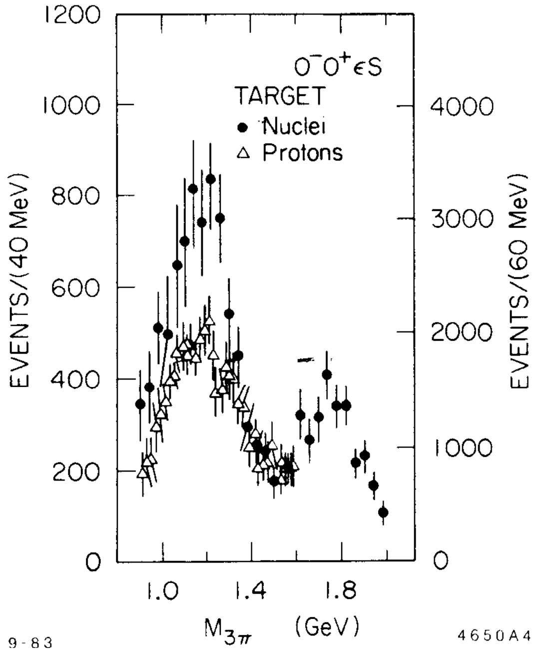

Fig. 4 0^+0^- ϵ S wave in $\pi^-\pi^-$ π^+ system produced on nuclei[13] and hydrogen.[14]

The SLAC-Carleton-NRC Collaboration[15] have analyzed the $\bar{K}^0$ $\pi^+\pi^-$ system recoiling against a neutron in a 1.5 ev/nb exposure of the LASS spectrometer to an 11 GeV/c K^- beam. This analysis provides a clear picture of the natural J^P waves up to a mass of 2.3 GeV/c^2.

The $\bar{K}^0$ $\pi^+\pi^-$ mass spectrum of events used in the analysis is shown in Fig. 5. Its main features are two bumps at about 1450 and 1800 MeV/c^2. The spectrometer acceptance is uniform in all variables, however, the "Δ cut" used to enhance the coherence of the $\bar{K}^0$ $\pi^+\pi^-$ system becomes an increasingly significant bias above 1800 MeV/c^2. Figure 6 shows the Dalitz Plot for events with $\bar{K}^0$ $\pi^+\pi^-$ mass above 1950 MeV/c^2. There is strong production of $K^*(890)$, $K^{**}(1430)$, $\rho(770)$ and $f(1270)$ isobars, all of which were used in the PWA. The natural J^P wave sums are shown in Fig. 7. As expected, 2^+ is the largest contribution in the region of the 1450 bump, but 1^- is substantial; the dominant contribution to the 1800 bump is in fact 1^- with some 3^-. The 2^+, 3^- and 4^+ structures can be identified with leading resonances and the 2^+ structure above 2 GeV/c^2 could be part of the triplet underlying the 4^+. Phases cannot be determined reliably

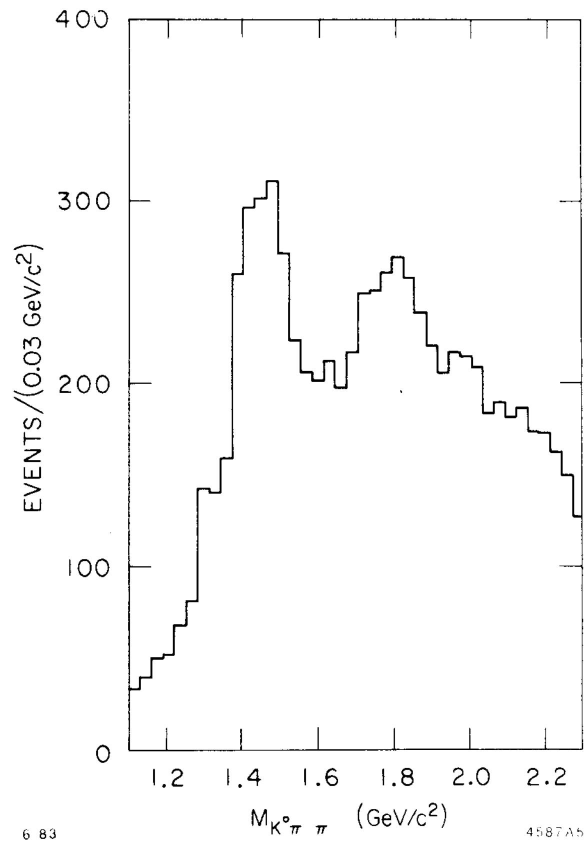

Fig. 5 $\bar{K}^0$ $\pi^+\pi^-$ mass spectrum[15] with $t' < 0.3$ (GeV/c)^2 (7636 events).

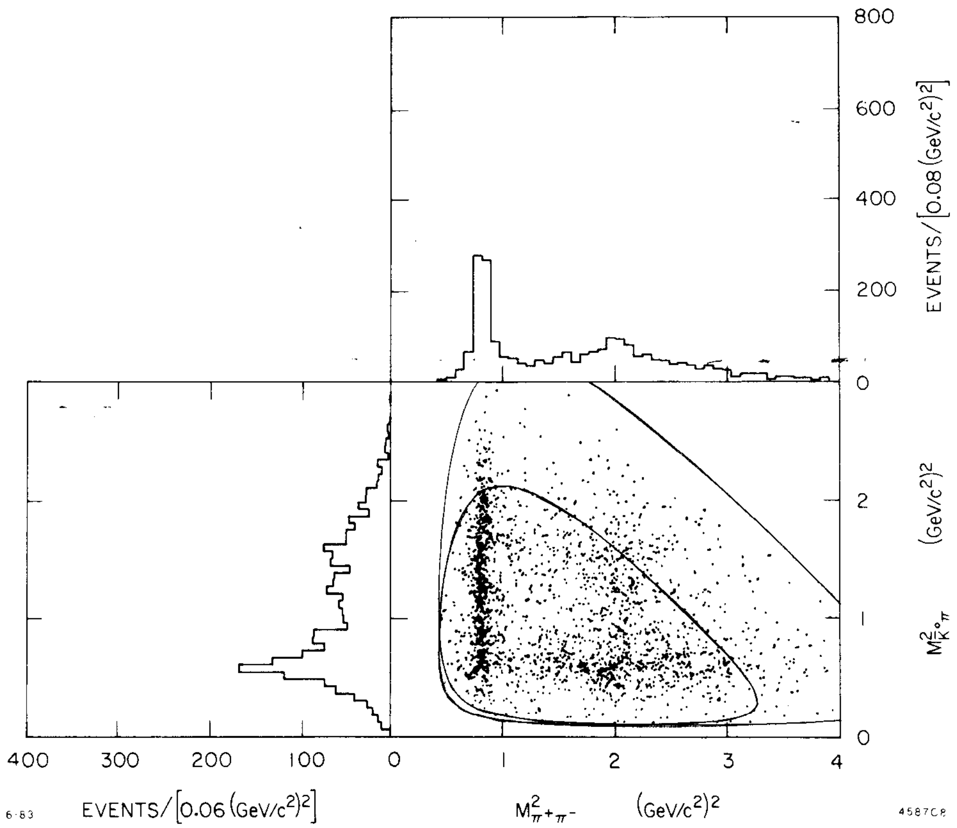

Fig. 6 $\bar{K}^0 \pi^+\pi^-$ Dalitz Plot[15] when $\bar{K}^0 \pi^+\pi^-$ mass > 1950 MeV/c^2.

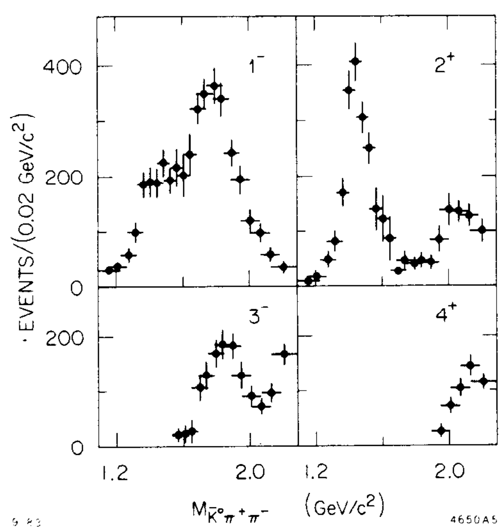

Fig. 7 Natural J^P wave sums from $\bar{K}^0 \pi^+\pi^-$ PWA.[15]

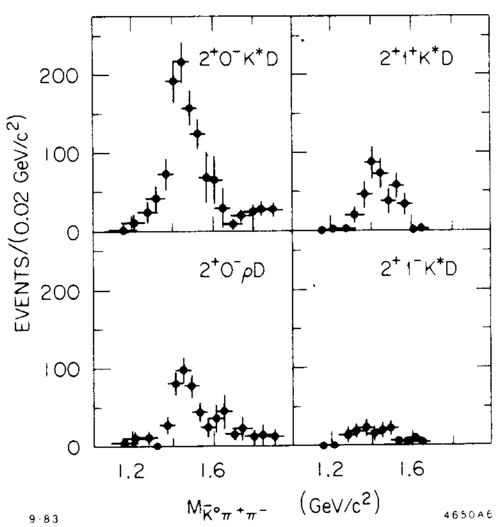

Fig. 8 2^+ waves from $\bar{K}^0 \pi^+\pi^-$ PWA.[15]

above 1950 MeV/c^2, so the high mass 2^+ and 4^+ behavior cannot be proved resonant. Figure 8 shows the waves contributing to the 2^+ intensity and establishes the structure as the leading $K^*(1430)$.

Figure 9a shows the 2^+0^- K^*D and 3^-0^- K^*F wave intensities and phases with resonant phase behavior imposed (the wave shown is the only 3^- wave which is clearly resonant implying that $K^*(1780) \rightarrow K^*\pi$ dominates the inelastic decays). Figure 9b then shows the behavior of the 1^-0^- K^*P and 1^-0^- ρP waves; the intensities and phases clearly indicate a resonance about 1420 MeV/c^2 coupling to $K^*\pi$ and one about 1780 MeV/c^2 dominantly in $K\rho$ with some $K^*\pi$ contribution. Previous $K\pi$ elastic PWA[16] have shown the

1^- wave to be resonant in the 1700-1800 MeV/c^2 region but to have almost zero amplitude around 1400-1500 MeV/c^2. A natural explanation would be to identify the high mass state with the $L = 2$ orbital triplet and assign the 1420 MeV/c^2 state as the first radial excitation, since there are good theoretical reasons[17] for such states to couple very weakly to the elastic channel. Further evidence for these conjectures is that production of the low-lying 1^- has a shallow t' slope whereas the other resonant states have steep slopes indicative of π-exchange. If confirmed, these results would seem to require the existence of the $\rho'(1250)$.

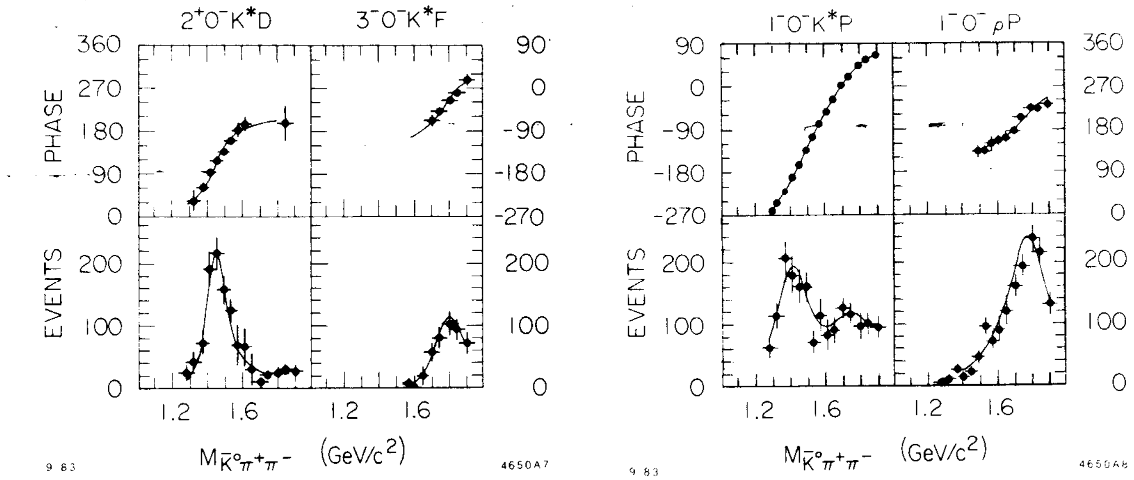

Fig. 9 a) Leading 2^+, 3^- and b) underlying 1^- resonant waves and relative phases.[15] $1^-0^-K^*P$ is the reference wave. The fit includes the $K^*(1430)$, $K^*(1780)$ and two 1^- resonances each having a small background amplitude.

4. CONCLUSIONS

Although the main features of the meson spectrum are clear, much work remains to be done in understanding the underlying states. There is a particular need to resolve the conflicts and ambiguities in data on $J^P = 1^-$ states. Without more progress in this field, the existence, or otherwise, of gluonic hadrons will be very difficult to establish.

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