EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 82-69
7 June 1982

THE POSITIVE PARITY MESONS

L. Montanet

CERN, Geneva, Switzerland

Abstract

New experimental observations on meson resonances in the 1000-1500 MeV mass range are confronted with the expectations of the simple quark model. It is shown that it is possible to present a reasonable interpretation of the available experimental information in terms of a set of four nonets of positive parity states, the 3P_0 , 3P_1 , 1P_1 and 3P_2 .

Submitted to Reports on Progress in Physics

TABLE OF CONTENTS

1. INTRODUCTION
2. THE SCALAR MESON RESONANCES
 - 2.1 Introduction
 - 2.2 Partial wave analysis of the $\pi\pi$ and $K\bar{K}$ systems
 - 2.3 Partial wave analysis of the $K\pi$ system
 - 2.4 The $S^*(990)$ and the $\delta(980)$
 - 2.5 Interpretation of the 0^{++} mesons
3. THE 1^{++} AND 1^{+-} MESON RESONANCES
 - 3.1 The $A_1(1240)$ and the $H(1200)$ resonances
 - 3.2 The $I = 1/2$ $J^P = 1^+$ resonances
 - 3.3 The $D(1285)$ and the $E(1420)$
 - 3.4 The $B(1235)$
 - 3.5 Interpretation of the 1^+ nonets
4. THE 2^{++} NONET
 - 4.1 The $A_2(1310)$
 - 4.2 The $K^*(1430)$
 - 4.3 The $f(1270)$ and $f'(1515)$
 - 4.4 The 2^+ nonet and the quark model

CONCLUSIONS

REFERENCES

FIGURE CAPTIONS

1. INTRODUCTION

The first elements for the building up of a meson spectroscopy, i.e. for quantum states with baryon number zero, were discovered in the 1960-1965's. They were soon identified as pseudoscalar (spin-parity $J^P = 0^-$) and vector ($J^P = 1^-$) objects which, together with the "stable" π and K mesons, formed two nonets of mesons. The 0^- nonet is made of the isovector ($I = 1$) π meson, the isodoublet ($I = 1/2$) K mesons and of two isoscalars ($I = 0$): the η and η' . The 1^- nonet is made of the $I = 1$ $\rho(770)$ meson, the $I = 1/2$ $K^*(892)$ meson and of two $I = 0$ resonances: the $\omega(783)$ and the $\phi(1020)$.

It was soon proposed by Gell-Mann and Ne'eman (Gell-Mann 1962, Ne'eman 1961) to assign these resonances to the octet and singlet representations of $SU(3)$, but with this octet model, it was difficult to understand the origin for these symmetries.

Quarks were introduced in the beginning of 1964 by Gell-Mann and Zweig (Gell-Mann 1964, Zweig 1964) as fundamental objects to represent the lowest representation of $SU(3)$, i.e. $\{3\}$, with the idea that they form all the hadrons which are observed in nature. With this assumption, the mesons are formed by a pair of quark and antiquark. The wave functions of the substates of these unitary multiplets may be written (Dalitz 1965, Morpurgo 1965)

$$\psi(\{\alpha\}, S; Y, I, I_3) = \phi(\{\alpha\}, S) \chi_S g(\{\alpha\}; Y, I, I_3)$$

where ϕ denotes the radial wave function, χ the spin wave function and g the unitarity spin wave function.

For the octet and singlet states, the functions g are written

$$g(\rho^+) = \bar{d}u$$

$$g(\rho^0) = \frac{1}{\sqrt{2}} (\bar{u}u - \bar{d}d)$$

$$g(\rho^-) = \bar{u}d$$

$$g(K^+) = \bar{s}u$$

$$g(K^0) = \bar{s}d$$

$$g(\omega_8) = (u\bar{u} + d\bar{d} - 2\bar{s}s) \frac{1}{\sqrt{6}}$$

$$g(\omega_1) = (u\bar{u} + d\bar{d} + s\bar{s}) \frac{1}{\sqrt{3}}$$

For the isoscalars, the physical states are obtained from two orthogonal linear combinations of the pure octet ω_8 and pure singlet ω_1 states

$$\omega = \omega_8 \cos\theta + \omega_1 \sin\theta$$

$$\phi = -\omega_8 \sin\theta + \omega_1 \cos\theta,$$

and the masses of the members of a nonet are related by the Gell-Mann-Okubo (GMO) mass relation

$$4 m_K^2 = m_\rho^2 + 3 (m_\omega^2 \cos^2\theta + m_\phi^2 \sin^2\theta).$$

If $\tan\theta = \frac{1}{\sqrt{2}}$, the two isoscalar physical states correspond to the states $(u\bar{u} + d\bar{d}) \frac{1}{\sqrt{2}}$ and $s\bar{s}$.

The corresponding angle $\theta_0 = 35^\circ$ is called ideal mixing angle. This concept of ideal mixing is remarkably verified for the 1^{--} nonet and, to some extent, for the axial and tensor mesons as we shall see. It is particularly interesting when combined with the Okubo-Zweig-Iizuka (OZI) rule which states that the hadronic decay processes should correspond to planar connected diagrams. This rule forbids, for instance, the decay of the ϕ -meson, a $s\bar{s}$ state, into non-strange particles.

A review of these quark line rules and of the mass mixing theory has been given by Okubo (1978). We summarize here the relations which are relevant for the present review. The mass mixing theory can be expressed in terms of four constants: the bare mass m_0 , C_1 , C_2 , C_3 and the mixing angle θ

$$m_0^2 = \frac{1}{3} [2 m_K^2 + m_\rho^2]$$

$$C_1 = -\frac{1}{\sqrt{3}} [m_K^2 + m_\rho^2]$$

$$C_2 = \frac{1}{6} [m_\omega^2 + m_\phi^2 - 2 m_K^2]$$

$$C_3 = \frac{2}{3\sqrt{3}} [m_K^2 - m_\rho^2] \mp (\frac{1}{6} xy)^{1/2}$$

$$\text{tg}\theta = \pm \frac{1}{y} (xy)^{1/2}$$

with $x = m_\phi^2 - m^2(\omega_8)$

$$y = m^2(\omega_8) - m_\omega^2$$

$$m^2(\omega_8) = \frac{1}{3} [4 m_K^2 - m_\rho^2]$$

If the quark line rules are exactly satisfied,

$$\text{tg}\theta = \frac{1}{\sqrt{2}}, C_2 = C_3 = 0 \text{ and}$$

$$m_\omega^2 = m_\rho^2$$

$$m_\phi^2 + m_\omega^2 = 2 m_K^2 .$$

If the quark rules are approximatively satisfied, one expects

$$m_0^2 \gg |C_1| \gg |C_2| \gg |C_3| .$$

It is of course natural to extend the simple quark-antiquark model for mesons to the P states, i.e. to states with an orbital angular momentum $L = 1$ between the two quarks. These P states generate four nonets with spin parity C-parity $J^{PC} = 0^{++}, 1^{++}, 1^{+-}, 2^{++}$. The identification of the experimental observations to these nonets has been the stumbling block for meson spectroscopy for more than a decade. Whereas in baryon spectroscopy, high statistics "formation" experiments with incident K or π were gradually leading to a good understanding of several states with higher and higher spins, the meson spectroscopy was stacked with the experimental difficulty of producing good data requesting high statistics and high energy. The properties of the scalar and axial mesons were particularly difficult to establish. However, a series of high statistics, high energy experiments has recently clarified most of the pending questions and, as we shall see, allows to-day to present a nearly complete picture of the $L = 1$ meson nonets.

2. THE SCALAR MESON RESONANCES

2.1 Introduction

The $J^{PC} = 0^{++}$ meson family raises several interesting questions (Hey and Morgan 1978) which could be answered by a good experimental knowledge of its properties. In the context of the gluon-quark approach, we expect as one of the strongest requirements of the theory to observe a nonet of $q\bar{q}$ objects, the 3P_0 nonet, complementary of the well known 3P_2 nonet and of the 3P_1 and 1P_1 axial vector members. Another possibility (Jaffe 1977) has been proposed to interpret the low mass scalar mesons as a nonet of $qq\bar{q}\bar{q}$ objects. It has also been suggested that scalar mesons could be entirely made of gluons (Jaffe 1975, Robson 1977). Several other theories predict the existence of scalars, like the Nambu-Goldstone boson of broken scale invariance (Carruthers 1971).

Four resonances are usually considered as possible candidates for a nonet of scalar mesons: the $\delta(980)$, $S^*(990)$, $\epsilon(1300)$ and $K(1350)$. However, the observed masses and widths quoted for these resonances are inconsistent, a priori, with the expected properties of a $q\bar{q}$ nonet. The $\delta(980)$ is much lighter than naively expected for an $L = 1$ $q\bar{q}$ nonet (the other $L = 1$ nonet resonances range between 1200 and 1400 MeV). The $S^*(990)$ is nearly degenerated in mass with the $\delta(980)$, although it is assumed to represent the $s\bar{s}$ member of the scalar nonet, and therefore should be ~ 200 MeV heavier than the $\delta(980)$. The width of the $\delta(980)$ is much smaller than the width of the $K(1350)$, while they should be comparable. The GMO mass formulae predicts a large deviation from ideal mixing: still, the $S^*(990)$ seems to be a pure $s\bar{s}$ state. For all these reasons, other models than the simple $q\bar{q}$ nonet picture are particularly attractive. Before attempting an interpretation, let us review briefly the experimental material.

The 0^{++} meson family is one of the most difficult to observe. The resonances are broad or they occur near the $K\bar{K}$ threshold, or they are hidden by the production of more dominant states (like the 2^+). However, several high statistics experiments have recently been performed, allowing detailed partial wave analyses of the $\pi\pi$, $K\bar{K}$ and $K\pi$ systems to which the scalar resonances are likely to be coupled. Some of these experiments have

been made with polarized targets, giving the possibility of performing model independent analyses and removing several ambiguities which were persisting otherwise.

2.2 Partial wave analysis of the $\pi\pi$ and $K\bar{K}$ systems

In meson spectroscopy, the $\pi\pi$ system has been one of the most extensively studied final state and one of the most fruitful. Starting with an incident pion, and studying the "peripheral" production of a dipion, one finds that the production is dominated by the "one-pion exchange mechanism" (OPE) giving therefore access to the $\pi\pi \rightarrow \pi\pi$ scattering. However, as discussed below, recent experiments done with a polarized target have shown that OPE, although dominant at low t values, is not the only production mechanism contributing to the $\pi\pi$ final state. Wrong conclusions could be drawn from such a simplified interpretation of the data.

To study the $\pi\pi$ S-wave, it would be convenient to accumulate information on the $\pi^0\pi^0$ system, which couple only to even angular states, but it is experimentally difficult to obtain unbiased data on two neutral pions and most of the detailed analyses are still performed on the $\pi^+\pi^-$ system.

In the absence of nucleon spin measurements, the reaction

$$\pi^- p \rightarrow \pi^+ \pi^- n \quad (2.1)$$

is described by more helicity amplitudes than observables. Additional assumptions are therefore introduced to provide the mixing constraints. The most familiar are:

- spin coherence, which assumes the dominance of the s channel nucleon spin flip in the unnatural spin-parity amplitudes;
- phase coherence, which assumes the coherence of unnatural spin parity amplitudes with helicity $\lambda = 0$ and $\lambda = 1$;
- suppression of the $\lambda > 2$ t channel moments.

Using data obtained with a polarized target, the CERN-Cracow-Munich Collaboration (CCM) (Becker 1979) was able to perform a model independent partial wave analysis of the $\pi^+\pi^-$ system produced at low four-momentum transfer with incident π^- of 17.2 GeV/c. The following $\pi^+\pi^-$ mass and four-momentum transfer ranges were covered:

$$\begin{aligned} 0.58 \text{ GeV} < m(\pi^+\pi^-) < 1.78 \text{ GeV} \\ 0.01 \text{ GeV}^2 < |t| < 0.20 \text{ GeV}^2. \end{aligned}$$

Owing to parity conservation, the angular distributions with a transversely polarized target are of the general form

$$\begin{aligned} I(m, t, \theta, \phi, \psi) = & \sum_{L, M} t_M^L(m, t) \text{Re } Y_L^M(\cos\theta, \phi) \\ & + P_t \cos\psi \sum_{L, M} p_M^L(m, t) \text{Re } Y_L^M(\cos\theta, \phi) \\ & + P_t \sin\psi \sum_{L, M} r_M^L(m, t) \text{Im } Y_L^M(\cos\theta, \phi), \end{aligned}$$

where P_t is the polarization component perpendicular to the beam direction,

$Y_L^M(\cos\theta, \phi)$ are the spherical harmonic functions,
 m is the effective mass of the $\pi\pi$ system,
 t the four-momentum transfer to the nucleon,
 ψ the angle between the normal to the production plane and the polarization direction,
 θ, ϕ the decay angles of the π^- in the $\pi^+\pi^-$ rest frame.

The set of moments t_M^L , p_M^L and r_M^L and their dependence on m and t represent the experimental input of the analysis. Since the t_M^L moments do not depend on the polarization, the CCM Collaboration uses the data coming from their pure hydrogen non-polarized target experiment (Grayer 1974) to determine them.

The following features of the moments are observed:

- the p_M^L moments are generally of the opposite sign to that of the corresponding t_M^L moments and are of comparable magnitude;
- the r_M^L moments are compatible with zero;
- all $M > 2$ moments are negligible, justifying that the amplitudes with helicity > 1 are neglected in the analysis.

The intensity of the S-wave obtained by the CCM Collaboration is shown in fig. 1. The solution is unique, except for the 900-1100 MeV mass range where the familiar up-down ambiguity persists. The results presented in fig. 1 correspond to the "down" solution. In the 1300 to 1700 MeV mass range, this model independent analysis rules out most of the partial wave solutions which have previously been proposed to interpret the S, P and D-wave complex, excepted the β solution of Martin and Pennington (1978) and its variant β' . These solutions require a large S-wave around 1300-1500 MeV, a $\rho'(1600)$ in the P-wave and an $f(1270)$ in the D-wave.

As already underlined, the measurements made with a polarized target allow to test the OPE hypothesis, which corresponds to a spin flip amplitude with $\lambda = 0$. The CCM Collaboration finds that the non-spin flip to spin flip ratio is as large as 28% for the $\rho(770)$ and 16% for the $f(1270)$. This ratio tends to decrease with increasing mass, OPE becoming more dominant above 1100 MeV for the S-wave, 1300 MeV for the P-wave and 1500 MeV for the D-wave. Below these values, a considerable amount of exchange with the quantum numbers of the $A_1(1240)$ is observed.

An investigation of the relative phases of the S- P_0 and S- D_0 transversity amplitudes leads to the conclusion that the strong maximum observed in the S-wave intensity around 1300 MeV corresponds to a broad resonance. The $\pi\pi$ S-wave below 1100 MeV is more complicated, and its properties are strongly coupled to the $K\bar{K}$ channel. A detailed analysis of this mass region is deferred to the next section.

Going back to the properties of the S-wave in the 1300 MeV mass region, we now consider the $\pi\pi \rightarrow K\bar{K}$ channel. Can we confirm the resonance behaviour observed for the $\pi\pi$ final state and can we measure the $K\bar{K}/\pi\pi$ branching ratio?

One must first notice that the K^+K^- system produced in the reaction

$$\pi^- p \rightarrow K^+ K^- n \quad (2.2)$$

is a priori more complicated than the $\pi^+ \pi^-$ system produced in reaction (2.1) since the G parity conservation does not restrict the $K\bar{K}$ system to the $(-1)^{J+I} = 1$ states. One may therefore expect to produce $K\bar{K}$ states with $J^P = 0^+, 1^-, 2^+ \dots$ and $I = 0$ or $I = 1$. However, as long as OPE dominates at small four-momentum transfers, and above a certain mass threshold, the $K\bar{K}$ states with odd G parity are relatively suppressed.

To allow a decomposition of the K^+K^- system into its $I = 0$ and $I = 1$ components, the Effective Mass Spectrometer group at Argonne (EMSA) (Wicklund 1980 and Cohen 1980) has simultaneously analyzed the data from reaction (2.2) and from

$$\pi^+ n \rightarrow K^+ K^- p . \quad (2.3)$$

However, the number of observables is still too small (14 complex amplitudes to be determined from 12 moments with $L \leq 4$ and $M \leq 2$), and the EMSA group introduces the pion-exchange model with absorption (OPEA) to reduce the analysis to a manageable number of parameters. Let us therefore examine the limits of this model applied to the K^+K^- final state by presenting first the results of a model independent analysis made by the CCM Collaboration (Görlich 1980), the partial wave analysis being made in this case on reaction (2.2) measured with a polarized target at 18 GeV/c.

The formalism is identical to the one which was used by the same collaboration for the analysis of reaction (2.1). The t_M^L moment are extracted from a pure hydrogen target experiment and are combined in the partial wave analysis with the p_M^L and r_M^L moments obtained from the polarized target experiment. Fig. 2 shows the mass dependence of the t channel moments for

$$0.01 \text{ GeV}^2 < |t| < 0.20 \text{ GeV}^2$$

and for $M < 2$.

The following observations can be made:

- the mass distribution exhibits a broad peak centred at 1350 MeV and a smaller one around 1700 MeV. They are mainly associated to the D and F-waves, respectively;
- the polarization effects are small, although still significant for some waves below 1500 MeV. The r_M^L moments are small, thus contributions from natural parity exchange must be small;
- all $M > 2$ moments are consistent with zero, thus all helicity $\lambda > 1$ amplitudes can be neglected.

The intensities of the partial waves, which can be directly deduced from the moduli of the transversity amplitudes, themselves calculated from the moments, are shown in fig. 3. Apart from the large D and F-waves, the main contribution comes from an S-wave enhancement centred around 1300 MeV. Notice, in particular, that the P-wave is small (it is compared, in fig. 3, to the tail expected for the ρ meson).

The shape of the S-wave enhancement is similar to the one observed in the 1100-1500 MeV mass region for the $\pi^+\pi^-$ S-wave (fig. 1). It seems therefore reasonable to attribute it to an $I = 0$ state.

Under this assumption, and comparing the data of the two CCM Collaboration experiments (Becker 1979 and Görlich 1980) a branching ratio

$$BR(K\bar{K}/\pi\pi) = 0.068 \pm 0.02$$

can be obtained. Thus the K^+K^- S-wave enhancement can be interpreted as being mainly a $I = 0$ object with high elasticity.

Having shown that, at small four-momentum transfer, the π exchange model with absorption (OPEA) can be applied with some confidence to the π induced K^+K^- final state, we now consider the results of the very high statistics experiments of the EMSA Group. The four-momentum transfer is now reduced to

$$t_{\min} < |t| < 0.08 \text{ GeV}^2.$$

Using the OPEA model, the EMSA Group shows that only two partial wave solutions are acceptable for the magnitude of the amplitudes. They give practically identical values for the partial waves, except that the S and P-waves are interchanged. One of the two solutions exhibits a large S-wave enhancement centred around 1300 MeV (fig. 4) and a small and featureless P-wave. Note that the CCM Collaboration, applying the same model to their unpolarized target data, find the same ambiguity between the S and P-wave, which is only removed in favour of a large S-wave by the introduction of the polarized target data and the model independent analysis (Görlich 1980).

This S-wave enhancement is very similar to the one observed for the $\pi^+\pi^-$ and also for the $K_S^0 K_S^0$ final state of the reaction

$$\pi^- p \rightarrow K_S^0 K_S^0 n \quad (2.4)$$

(Polychronakos 1979 and Wetzel 1976). In fig. 5 the $K_S^0 K_S^0 \langle Y_2^0 \rangle$ data are compared to the predictions deduced from the $K^+ K^-$ solution giving a large S-wave enhancement (the other solution, giving a large P-wave, would grossly underestimate the $K_S^0 K_S^0 \langle Y_2^0 \rangle$ distribution).

To determine the phase of the S-wave, the EMSA Group fixes first the D wave phase by fitting the $\langle Y_4^0 \rangle$ moment with interfering f and f' resonances, and assumes an OPEA production phase of 0° for the f(1270). Note that the $A_2(1310)$ production is small for $|t| < 0.08 \text{ GeV}^2$. Demanding that the amplitudes exhibit reasonable properties, i.e. the dominance of even G parity states (OPEA dominance at small $|t|$), t dependences consistent with the phenomenology of π and B exchange, analogy between reactions (2.2) and (2.3), the EMSA group finds that only two solutions are acceptable, one showing fast variations of both S and P-waves phases, the other one showing on the contrary slow variations for these phases. Since the fast variations of the P-wave phase between 1100 and 1400 MeV do not seem to correspond to any known phenomenon, the solution which exhibits the slow variations is preferred. We should however mention here that it has recently been proposed to interpret some data observed on the $\omega\pi$ final state in photo-production and e^+e^- annihilations, as well as in $p\bar{p}$ annihilations at rest, as a $\rho'(1250)$ resonance with a width of $\sim 150 \text{ MeV}$ (Montanet 1980). But this $\rho'(1250)$ does not seem to have a strong coupling to the $\pi\pi$ and $K\bar{K}$ channels, and probably does not explain fast variations of phases in the

K^+K^- system. Fig. 6 shows the $I = 0$ and $I = 1$ S-wave intensities and phases obtained with the preferred solution.

It is interesting to note that the S-wave t dependences obtained by the EMSA Group for reactions (2.2) and (2.3) are quite different. Whereas reaction (2.3) gives a slope of $(7.4 \pm 1.0) \text{ GeV}^{-2}$, (2.2) gives $(16.5 \pm 1.6) \text{ GeV}^{-2}$, the first one being much flatter than expected for OPEA, the second one much steeper. This difference may be explained by interferences between the $I = 0$ π -exchange induced and the $I = 1$ B-exchange induced amplitudes.

From the magnitude and phase of the $I = 0$ S-wave amplitude (fig. 6), the EMAS Group extracts the magnitude and phase of the T scattering matrix element $T (\pi\pi \rightarrow K\bar{K})$ and obtains the Argand plot shown in fig. 7. It exhibits a Breit-Wigner resonance loop, centred around 1425 MeV and the speed along the loop suggests a width of ~ 160 MeV. The diameter of the loop gives the relative coupling of this resonance to the $\pi\pi$ and $K\bar{K}$ channels, i.e.

$$(x_\pi \cdot x_K)^{1/2} \sim 0.3 \text{ to } 0.4 ,$$

where

$$x_\pi = \Gamma_{\pi\pi}/\Gamma \text{ and } x_K = \Gamma_{K\bar{K}}/\Gamma .$$

This range of couplings corresponds to $0.8 < x < 0.9$ for the largest of the two couplings. Since the $\pi\pi$ elasticity η_0^0 is close to 0.7 in this mass range, we get a consistent result by assuming that the largest coupling is x_π . Then

$$\begin{aligned} 0.8 < x_\pi < 0.9 \\ 0.2 > x_K > 0.1 . \end{aligned}$$

This analysis is model-dependent, but there is ample evidence for the dominance of OPEA, as demonstrated by the EMSA Group itself and also by Görlich (1980) and Loverre (1980). These last authors have compared the production of the $K_S^0 K_S^0$ system for D and S-waves at various incident momenta (4, 6, 7 and 9 GeV/c). The values of $R = \langle Y_0^0 \rangle / \langle Y_4^0 \rangle$ obtained for $1.2 < m(K\bar{K}) < 1.4$ GeV and $|t| < 0.2 \text{ GeV}^2$ are 2.6 ± 0.6 at 4 GeV/c, 3.1 ± 0.2 at 6/7 GeV/c and 2.6 ± 0.2 at 9 GeV/c. It is also found that the phase difference $\phi_{SD} |\phi_S - \phi_D|$ is independent of the incident momentum in the 1300 MeV

mass region. All these observations suggest that the same production mechanism predominates in the production of the S and D-waves. Since the D-wave (the $f(1270)$ meson) is well known to be produced by π exchange, Loverre (1980) conclude that the S-wave is also predominantly produced by π exchange below $|t| < 0.2 \text{ GeV}^2$, i.e. $I = 0$.

However, neither Cohen (1980) nor Loverre (1980) exclude that other exchange mechanisms are present, which could be unimportant at small $|t|$ but would become relatively more sizeable at large $|t|$. In fact, Cason (1976) and Polychronakos (1979) observe a flatter t dependence of the $K_S^0 K_S^0$ S-wave around 1300 MeV than near threshold. The variation of the slope as function of the mass of the $K\bar{K}$ system is not confirmed by the EMSA Group, who finds however, as already indicated, a slope which is different for reactions (2.2) and (2.3) and explains this difference by the interference of the $I = 0$ and $I = 1$ S-wave which occurs over the entire $K\bar{K}$ mass range. More precisely, the EMSA Group finds that the dominant $I = 0$ S-wave has a t dependence compatible with OPEA whereas the smaller $I = 1$ S-wave has the flatter t dependence expected for the B exchange mechanism (fig. 8).

In order to isolate the $I = 1$ S-wave, Martin et al. (1978a), have studied the reaction

$$\pi^- p \rightarrow K^- K^0 p \quad (2.5)$$

at 10 GeV/c. It would seem that this is the best way to study the $I = 1$ ($K\bar{K}$) component. However, it appears that this reaction is dominated, in the 1300 MeV ($K\bar{K}$) mass range, by the natural parity exchange production of the A_2^- meson, the unnatural parity exchange representing only $\sim 15\%$ of the total cross section. Moreover, for the ($K\bar{K}$) $I = 1$ S-wave, the π exchange is of course forbidden, and one expects instead that $I = 0$ and $I = 1$, nucleon spin flip (B exchange) and non-flip (Z exchange) can contribute to the production, with no obvious dominant exchange in the t channel (Irving 1976). An analysis of this $K^- K^0$ data (Martin and Ozmutlu 1979) which includes t dependences in terms of appropriate Regge amplitudes and fixes the P-wave to be compatible with the expected ρ tail concludes that an $I = 1$ ($K\bar{K}$) S-wave must be introduced to fit the data.

This S-wave does not exhibit, however, the t dependence that could be expected from B exchange, being peaked at low t like the t dependence observed for the natural parity exchange production of A_2^- ; it is attributed by Martin and Ozmutlu to Z exchange. For this reason, it is difficult to reconcile these results with those of the EMSA Group since the small $I = 1$ S-wave detected in the K^+K^- final state is attributed to B exchange (fig. 9) and does not present the mass behaviour of a resonance. The intensity of the $I = 1$ S-wave of Martin peaks at 1300 MeV and extends over ~ 200 GeV (fig. 10).

An $I = 1$ S-wave resonance could be expected to be coupled to the $\eta\pi$ system. Unfortunately, very little experimental information is available on this system.

Enhancements are no doubt observed in the K^+K^- , $K_S^0\bar{K}_S^0$, $\pi^+\pi^-$ systems around 1300 MeV, with characteristic phase behaviours suggesting the presence of resonances in $I = 0$ and $I = 1$ S and D-waves. The existence of an $I = 0$ S-wave resonance, mainly coupled to $\pi\pi$ is now well established. We name it $\epsilon(1300)$, although its mass is probably closer to 1400 MeV than to 1300 MeV. Several effects may lead to an apparent width, as measured for instance on the Argand plot, much smaller than its natural one (the $S^*(990)$ resonance, threshold effects, background due to other resonances etc.). The existence of an $I = 1$ S-wave resonance in the same mass region is not ruled out but much more uncertain.

2.3 Partial wave analysis of the $K\pi$ system

This channel presents striking similarities with the $\pi\pi$ interaction. Not only, the P, D and F waves show obvious resonance behaviours (the $K^*(892)$, $K^*(1430)$, $K^*(1780)$, respectively), to be paralleled to the $\rho(770)$, $A_2(1310)$, $g(1700)$, but the more elusive $K\pi$ and $\pi\pi$ S-waves have also several properties in common.

A recent experiment done with the Large Aperture Solenoidal Spectrometer (LASS) at SLAC has led to the accumulation of high statistics data on the reaction

$$K^-p \rightarrow K^-\pi^+n \quad (2.6)$$

at 11 GeV/c (5 events/nb), and the mass independent partial wave analysis performed on these data has firmly established the existence of an $I = 1/2$ $K\pi$ S-wave around 1500 MeV (Ratcliff 1981, Aston 1981) which had been suggested in previous experiments (Estabrooks 1978 and Martin 1978b). We shall base our analysis on the LASS experiment.

The sample used for the partial wave analysis of the $K\pi$ elastic scattering is selected from reaction (2.6) with the cuts

$$t_{\min} < |t| < 0.20 \text{ GeV}^2$$

and the neutron in the final state of (2.6) being defined by the mixing mass cuts

$$0.45 \text{ GeV} < m_{\pi\pi} < 1.05 \text{ GeV}.$$

Within these cuts, 42 000 events are available for the preliminary results discussed here, distributed in the following mass range of the $K\pi$ system

$$0.80 \text{ GeV} < m(K\pi) < 2.30 \text{ GeV}.$$

The model used to describe the $K\pi$ scattering production amplitude is a simplified Regge pole exchange model which allows to isolate the π exchange contribution (Estabrooks 1978). The production amplitudes $L_{\lambda}^{\pm}$ with angular momentum L , t channel helicity λ , and natural (+) or unnatural (-) parity exchange are factorized into mass and t dependent terms in the following way

$$\begin{aligned} L_0 &= g_L \frac{\sqrt{-t}}{\mu^2 - t} \\ L_{1-} &= \frac{1}{\sqrt{2}} g_L L(L+1) \gamma_c \\ L_{1+} &= \frac{1}{\sqrt{2}} g_L L(L+1) (\gamma_c - 2i\gamma_a |t|) \end{aligned}$$

As in the $K\bar{K}$ analysis, the amplitudes with $\lambda \geq 2$ are assumed to be zero.

g_L is related to the $K\pi$ scattering amplitudes a_L by

$$g_L = \eta \frac{m(K\pi) a_L e^{b(t-\mu^2)}}{\sqrt{q}}$$

γ_a is the ρ - A_2 exchange coefficient and γ_c the absorption coefficient (Regge cut),

η, q, μ represent the elasticity, the momentum in the $K\pi$ rest frame and the pion mass, respectively.

As for the $\pi\pi$ and $K\bar{K}$ analysis discussed above, using an unpolarized target, the set of moments t_M^L and their dependence on m and t represent the experimental input of the analysis

$$I(m, t, \theta, \phi) = \sum_{L, M} t_M^L(m, t) \operatorname{Re} Y_L^M(\cos\theta, \phi)$$

To determine the t dependence of the production amplitudes $L_{\lambda}^{\pm}$, the moments $t_M^L(m, t)$ are used, for each mass bin, to determine the coefficients b , γ_c , γ_a and the scattering amplitudes a_L . The points in fig. 11 correspond to the production parameters obtained from the fits and the curves shown represent the functions used for the t integrated partial wave analysis. As already observed for the $\pi\pi$ and $K\bar{K}$ production, the fact that the coefficients γ_a and γ_c tend to zero at large mass implies that the ρ - A_2 and absorption contributions become less important at high mass. They are however significant at low mass.

Since the $K^-\pi^+$ channel contains both isospin 1/2 and isospin 3/2 components, a_L is a mixture of $a_L^{I=1/2}$ and $a_L^{I=3/2}$

$$a_L = a_L^{1/2} + 1/2 a_L^{3/2}$$

Following Estabrooks (1978), $a_S^{3/2}$ is expressed in terms of an effective range parametrization

$$\cotg \delta_S^{3/2} = 1/a + 1/2 r q^2$$

where

$$a = 2.4 \text{ GeV}^{-1} \quad r = -1.8 \text{ GeV}^{-1}$$

$$a_S^{3/2} = \sin \delta_S^{3/2} e^{i\delta_S^{3/2}},$$

the other partial wave amplitudes $a_L^{2/L}$ are assumed to be consistent with zero.

Fig. 12 shows the Argand plot obtained for the $I = 1/2$ S-wave. One sees the typical loop expected for a Breit-Wigner resonance, and determining the point of maximum phase speed ϕ_r , the points at $\phi_r \pm 45^\circ$ and the diameter of the loop, the new SLAC experiment provides the following characteristics for the $K\pi$ $I = 1/2$ S-wave resonance

$$M = 1420 \text{ MeV}$$

$$\Gamma = 240 \text{ MeV}$$

$$x = 0.85 .$$

As underlined by Törnqvist (1982), the mass and width of this resonance, as deduced from the Argand plot, are certainly distorted by the $K\eta'$ threshold, the natural mass and width being more like 1350 MeV and 400 MeV, respectively, once this threshold behaviour is subtracted.

2.4 The $S^*(990)$ and the $\delta(980)$

We now turn to the observations made in the vicinity of the $K\bar{K}$ threshold, where the existence of the two resonances, the $I = 0$ $S^*(990)$ and the $I = 1$ $\delta(980)$ remains to be firmly established.

One of the outstanding questions about these effects is to decide if we are in presence of genuine resonances, following a Breit-Wigner behaviour with associated poles in two Riemann sheets, or if they are the manifestation of $K\bar{K}$ bound states, corresponding to one pole in one Riemann sheet. In the later case, one could be justified to treat these effects as four quark $q\bar{q}q\bar{q}$ states rather than "classical" two quark $q\bar{q}$ states. Even in this case, they should not be taken as an evidence for "exotic" four-quark states since their origin would be linked to two singlets of colour, the K and $\bar{K}$ mesons. Martin, Ozmutlu and Squires (Martin 1977) have presented a detailed analysis in order to answer this question, which has been recently taken back by Irving, Martin and Done (Irving 1981), using new data. Before discussing the conclusions of Martin (1977) and Irving (1981), let us give a brief account of the observations which are at the origin of the problem.

$K\bar{K}$ threshold enhancements have been observed, both for the $K_S^0 K_S^0$ and the $K_S^0 K^\pm$ systems. It has been shown that both $I = 0$ and $I = 1$ amplitudes contribute. One may expect that the $I = 0$ component leads to some particular behaviour of the $\pi\pi$ system, whereas the $I = 1$ component may be coupled to the $\eta\pi$ system. One can therefore anticipate that only coupled channel analyses ($K\bar{K}$ and $\pi\pi$ for $I = 0$, $K\bar{K}$ and $\eta\pi$ for $I = 1$) will give a reasonable interpretation of the set of experimental facts.

Let us first start with the $I = 0$ channel. It is now well established that the $\pi\pi$ phase shift δ_0^0 moves very rapidly from 90° around 800 MeV to 270° and more just above the $K\bar{K}$ threshold. This was observed for the first time in the analysis of the proton antiproton annihilations at rest (Bizzarri 1969)

$$\bar{p}p \rightarrow \omega^0 \pi^+ \pi^- \quad (2.7)$$

which are dominated, for the 3S_1 initial state, by the quasi two-body channels $\pi^\pm B^\mp(1235)$, $\omega^0 f^0(1270)$ and $\omega^0 S^0$, where S^0 represents the $\pi^+ \pi^-$ S-wave. It was found that one gets a good parametrization of this S-wave with three parameters b , c and d

$$|f(m)|^2 = \frac{m^2}{q^2} \frac{1}{\cotg^2 \delta_0^0 + 1}$$

$$\frac{q}{m} \cotg \delta_0^0 \propto \frac{(b^2 - m^2)(c^2 - m^2)}{(d^2 - m^2)}$$

with

$$\begin{aligned} b &= 853 \pm 19 \text{ MeV} \\ c &= 1115 \pm 68 \text{ MeV} \\ d &= 940 \pm 8 \text{ MeV} \end{aligned}$$

A more detailed analysis with increased statistics led the same group in 1972 (Frenkiel 1972) to similar conclusions (fig. 13).

The same behaviour of the $\pi\pi$ S-wave was observed for $p\bar{p}$ annihilations at rest (Diaz 1970)

$$\bar{p}p \rightarrow \rho^0 \pi^+ \pi^-, \quad (2.8)$$

where, again, the dipion recoiling against the ρ^0 meson is mainly an S-wave if the 3S_1 initial state is selected (fig. 14).

The pole d at 940 MeV corresponds to a value of 180° for δ_0^0 and is often referred as a CDD pole.

The first extensive analysis of the $\pi^+\pi^-$ partial waves is due to the CERN-Munich Group (Hyams 1973) who observed a rapid variation of $\eta_0^0 = (1 - |S|^2)^{1/2}$ with a sharp minimum just above the $K\bar{K}$ threshold followed by a nearly constant value of 0.70 (fig. 15). These results were interpreted in terms of a pole in the second and third Riemann sheets (977 - 118) MeV, i.e. in terms of a Breit-Wigner resonance. However, it can be shown (Yndurain 1975, Atkinson 1973 and 1975) that the knowledge of η_0^0 and $\delta_0^0 = \delta_{\pi\pi}$ with the use of analyticity is not sufficient to construct the three amplitudes of interest $f_{\pi\pi \rightarrow \pi\pi}$, $f_{\pi\pi \rightarrow K\bar{K}}$, $f_{K\bar{K} \rightarrow K\bar{K}}$. To determine in addition $\delta_{K\bar{K}}$ and therefore reduce the ambiguity on the K matrix, it is necessary to add the information coming from the $K\bar{K}$ mass spectrum (Aguilar-Benitez 1978).

It is well known that the $K_S^0 K_S^0$ system exhibits a clear threshold enhancement (fig. 16) which, if parametrized in terms of a Breit-Wigner function, gives the typical values

$$M \sim 1040 \text{ MeV} \quad \Gamma \sim 70 \text{ MeV} .$$

Comparing the reactions

$$\bar{p}p \rightarrow \rho^0 S^0 \rightarrow \pi^+\pi^- K_S^0 K_S^0 \quad (2.9)$$

$$\text{and} \quad \bar{p}p \rightarrow \rho^\pm S^\mp \rightarrow \pi^\pm \pi^0 K_S^0 K^\mp, \quad (2.10)$$

Aguilar-Benitez (1978) were able to demonstrate that the $K_S^0 K_S^0$ threshold enhancement is a pure $I = 0$ effect.

One of the solutions proposed by Aguilar-Benitez (1981) satisfies exactly the analyticity conditions, unitarity and, checking a posteriori the crossing conditions by comparing the left-hand cut obtained from the Froissart-Gribov projection to the one directly calculated from the K matrix, one finds that the two methods give consistent results. The values given by this solution for $\delta_{\pi\pi}$, the $K_S^0 K_S^0$ spectrum and the elasticity η are compared in fig. 17 to the experimental data (Hyams 1973 and Aguilar-Benitez 1978).

Using this solution, a search for poles uncovers two of them in the second and third unphysical Riemann sheets. These two poles verify the equation

$$(S_0 - S) - i (\gamma_\pi q_\pi(s) + \gamma_K q_K(s)) = 0$$

to be associated with a Breit-Wigner resonance, γ_π , γ_K and s_0 being real numbers giving the mass and the partial widths of the resonance. Aguilar-Benitez (1978) conclude that the $S^*(980)$ is a resonance coupled to $\pi\pi$ and $K\bar{K}$ with the following features

$$M = 993 \pm 10 \text{ MeV},$$

$$\gamma_\pi \sim 120 \pm 20 \text{ MeV},$$

$$\gamma_K \sim 240 \pm 30 \text{ MeV}.$$

This value of γ_π corresponds to the conventional partial width of $\Gamma_\pi = 58 \pm 9 \text{ MeV}$.

These conclusions are supported by the coupled channel analysis of Fujii and Fukugita (Fujii 1975) who parametrize the partial S-wave matrix directly in terms of pole positions, in an attempt to discriminate between a one-pole and a two-pole description. This second description gives a better interpretation of the elasticity and Fujii-Fukugita conclude that the $S^*(980)$ is most likely a resonance with the following parameters

$$M = 991 \pm 10 \text{ MeV}$$

$$\gamma_\pi = 169 \pm 30 \text{ MeV}$$

$$\gamma_K = 388 \pm 170 \text{ MeV}$$

The agreement of Aguilar (1978) and Fujii (1975) is not too surprising since they use the same set of data for δ_π and η_0^0 (Hyams 1973). It underlines however that similar conclusions can be reached from two different approaches.

Using again the data of the CERN-Munich Group for δ_π and η_0^0 , and those of Cason (1976) for $\pi\pi \rightarrow K\bar{K}$, Estabrooks (1979) also finds, in a coupled channel analysis, that a resonance is needed with a mass close to 1000 MeV and a ratio $\gamma_K/\gamma_\pi \sim 1.8$.

Similar conclusions had already been reached in 1977 (Martin 1977), the simplest parametrization to obtain a good interpretation of the $\pi^+\pi^-$ moments

(Grayer 1974) being given by the superposition of a Breit-Wigner resonance to a background essentially characterized by a phase $\delta_B \sim 90^\circ$ in the $\pi\pi$ channel around the S^* region. The additional interesting result obtained by Martin (1977) was to underline that equivalent good fits could be obtained with more complex parametrizations corresponding to the dominance of $\pi\pi$ or $K\bar{K}$ forces (the "exchange" model) or introducing an ϵ resonance in the $\pi\pi$ channel and a $K\bar{K}$ bound state. However, a parametrization assuming only $q\bar{q}$ forces (the "quark" model) would fail to interpret the data. That the "quark" model would fail does not imply that the S^* is not, at least in part, a $q\bar{q}$ object. It simply underlines that forces in the meson sector are also important, i.e. one needs a significant admixture of $q\bar{q}q\bar{q}$ state in the wave function.

These analyses have been recently refined (Irving 1981) in the light of the new data produced by the EMSA Group (Cohen 1980). The lack of phase variation in $\delta_{\pi K}$ for the $\pi\pi \rightarrow K\bar{K}$ scattering in a mass range extending from 1000 to 1250 MeV and our better knowledge of the $\epsilon(1300)$ resonance suggest the use of a K matrix parametrization with slowly varying contributions to represent the S^* and the introduction of a pole term to account for the $\epsilon(1300)$

$$K = K(\epsilon) + K^0 + 4k_2^2 K^1$$

$$K(\epsilon)_{ij} = \frac{\gamma_i \gamma_j}{M_\epsilon^2 - s}$$

Irving (1981) gets $M_\epsilon = 1397 \text{ MeV}$

$$\begin{array}{lll} K_{11}^0 = 1.5 & K_{22}^0 = -10.3 & K_{12}^0 = 4.2 \\ K_{11}^1 = -0.2 & K_{22}^1 = -24.3 & K_{12}^1 = -4.6 \end{array}$$

or, expressed in terms of T matrix poles,

$$S^* \text{ sheet II } \sqrt{s} = (986 - 7i) \text{ MeV}$$

$$\epsilon \text{ sheet III } \sqrt{s} = (1394 - 118i) \text{ MeV} .$$

The large negative values obtained for K_{22} indicate the presence of a $K\bar{K}$ bound state resonance. This interpretation of the S^* as a $K\bar{K}$ bound state is similar to the interpretation of the $\Lambda(1405)$ hyperon resonance which appears just below the $\bar{K}N$ threshold and is interpreted in terms of a $\bar{K}N$ bound state (Martin 1981) rather than a two-channel ($\pi\Sigma$, $\bar{K}N$) Breit Wigner resonance.

Further information on the S^* comes from the study of the reaction

$$K^- p \rightarrow \Lambda^0 \pi^+ \pi^- \quad (2.11)$$

at 4.2 GeV (Aguilar-Benitez 1981). In this reaction, one may expect that the S^* , seen as a mass peak in the $\pi^+ \pi^-$ system (fig. 18), is produced according to the diagram shown in fig. 19(a).

The curve in fig. 18 corresponds to a pole at

$$\sqrt{s} = (966 - 24i) \text{ MeV (Irving 1981) ,}$$

which is shifted towards lower values and broader than the pole obtained from the $\pi^+ \pi^-$ moments. An intermediate value is obtained by Gidal (1981), who fit the mass peak observed in the inclusive dipion decays of the J/ψ (fig. 20) with a coupled channel Breit-Wigner and find

$$\sqrt{s} = [(974 \pm 4) - (14 \pm 5i)] \text{ MeV .}$$

The strong coupling of the S^* suggests, in that case, that the decay mode (fig. 19(b))

$$\psi \rightarrow \phi S^* \quad (2.12)$$

should be observed. Indeed, when selecting the $\phi \rightarrow K^+ K^-$ in the decay

$$\psi \rightarrow K^+ K^- \pi^+ \pi^- ,$$

Gidal (1981) show clear evidence for the associated decay $\psi \rightarrow \phi S^*$ (fig. 21). No strong $K^+ K^-$ threshold enhancement is observed, however, in the process

$$\psi \rightarrow K^+ K^- \phi , \quad (2.13)$$

suggesting that the S^* pole may effectively occur well below the $K\bar{K}$ threshold.

To summarize, the $S^*(990)$ can be interpreted as a $q\bar{q}$ resonance with a large admixture of a $K\bar{K}$ virtual bound state. Its observed width (in a Breit-Wigner parametrization), is affected by the proximity of the $K\bar{K}$ threshold.

Unfortunately, the experimental information available for the analysis of the $I = 1$ channel near the $K^0 K^\pm$ threshold, and associated with the $\delta(980)$ is much more limited than for the $S^*(990)$.

The observation of a $K\bar{K}$ threshold enhancement with $I = 1$ (Astier 1967) in $p\bar{p}$ annihilations at rest

$$\bar{p}p \rightarrow K_s^0 K^\pm \pi^\mp, \quad (2.14)$$

and in the decay of the $D(1285)$ and $E(1420)$ mesons as been interpreted in terms of a $K\bar{K}$ virtual bound state which could also couple to the $\eta\pi$ system. One of the first clean observation of a mass peak in the $\eta\pi$ system on which most subsequent analyses rely, is due to Gay (1976). Fig. 22 shows the $\eta\pi^-$ effective mass spectrum observed in the reaction

$$\begin{aligned} K^- p \rightarrow \Sigma^+(1385) \pi^- \eta \rightarrow \Lambda \pi^+ \pi^- \eta \\ \eta \rightarrow \pi^+ \pi^- \pi^0, \end{aligned} \quad (2.15)$$

with a curve corresponding to the fit of an S-wave Breit-Wigner parametrization, giving

$$M = (981 \pm 6) \text{ MeV}, \quad \Gamma = (55 \pm 5) \text{ MeV}$$

for the peak observed near 1 GeV.

Using a coupled channel resonance parametrization, with a coupling constant ratio fixed by $SU(3)$: $g_{\eta\pi}^2/g_{K\bar{K}}^2 = 2/3$, one gets a mass of $(975 \pm 9) \text{ MeV}$ and a partial width of $(72 \pm 51) \text{ MeV}$. These values are in agreement with the small excess of events observed near the $K\bar{K}$ threshold for the reaction

$$K^- p \rightarrow \Sigma^+(1385) K^0 K^- \rightarrow \Lambda \pi^+ K^0 K^-. \quad (2.16)$$

However, the observation of a narrow peak below the $K\bar{K}$ threshold does not necessarily imply the existence of a narrow resonance (Flatté 1976, Achasov 1980). If this resonance is strongly coupled to the $K\bar{K}$ channel, the high mass edge of the $\eta\pi$ peak can be imposed by unitarity and its low mass edge by analyticity, the net result being to produce a narrow $\eta\pi$ peak even if the width is as large as 300 MeV. Better constants on the width of the $\delta(980)$ could be obtained from a good determination of the $K\bar{K}$ mass spectrum near the $K\bar{K}$ threshold (Martín 1977).

Experimental data on reaction (2.16) are presently of very little statistical significance. Depending on the size of the $K\bar{K}$ background one is willing to consider, the conclusions on the width of the $\delta(980)$ may vary

from 50 to 300 MeV and its interpretation can accordingly go from a pure $q\bar{q}$ state to a pure $qq\bar{q}\bar{q}$ one.

Attempts have been made (Aguilar-Benitez 1981) to study the reaction

$$K^- p \rightarrow K^+ K^- \Lambda, \quad (2.17)$$

which offers the opportunity to investigate the $K\bar{K} \rightarrow K\bar{K}$ channel. S-P wave interference effects are observed (the $\phi(1020)$ is copiously produced in this reaction). But, large contributions due to non-K exchange in the unnatural parity exchange sector are observed, preventing to draw any firm conclusion on the K exchange amplitude with the present available data.

Bramon and Masso (1980) have investigated the nature of the $\delta(980)$ meson starting from a different experimental observation. Assuming that the dominance of the $\eta' \rightarrow \delta\pi \rightarrow \eta\pi\pi$ decay chain, they obtain

$$\Gamma(\eta' \rightarrow \eta\pi\pi) = g_{\delta\eta'\pi}^2 g_{\delta\eta\pi}^2 (2.1 \times 10^{-5} \text{GeV}^{-3}),$$

leading to $\Gamma(\eta' \rightarrow \eta\pi\pi) = 176 \pm 42 \text{ keV}$ if the $\delta(980)$ is a $q\bar{q}$ state, and $\Gamma(\eta' \rightarrow \eta\pi\pi) = 585 \pm 140 \text{ keV}$, if the $\delta(980)$ is a $qq\bar{q}\bar{q}$ state, the difference coming from the strange quark content of the $\delta(980)$, being zero in the first case. The first prediction falls closer to the experimental value

$$\Gamma(\eta' \rightarrow \eta\pi\pi) = 187 \pm 40 \text{ keV},$$

and leads Bramon and Masso to the conclusion that the $\delta(980)$ is a $q\bar{q}$ meson. Similar conclusions are reached by Intermann and Greenhut (1980).

Additional evidence in favour of the $q\bar{q}$ interpretation for the $\delta(980)$ meson comes from the decay properties of the D(1285) and E(1420) $J^{PC} = 1^{++}$ mesons (Bramon and Masso 1981). The experimental information on these resonances tend to assign both of them to the 1^{++} nonet of $q\bar{q}$ states, the mixing angle approaching its ideal value, i.e. the D(1285) being a non-strange quark resonance whereas the E(1420) is dominantly $s\bar{s}$. In these conditions, one expects that the decay chain $D \rightarrow \delta\pi \rightarrow \eta\pi\pi$ will be more important for the D(1285) than for the E(1420), the reverse being true if the $\delta(980)$ were a $qq\bar{q}\bar{q}$ state with a strange quark component. In practice, the $D \rightarrow \delta\pi \rightarrow \eta\pi\pi$ is observed, not the $E \rightarrow \delta\pi \rightarrow \eta\pi\pi$.

The conclusion for the $\delta(980)$ resonance is similar to the one we have drawn for the $S^*(990)$. Its interpretation in terms of a $q\bar{q}$ resonance with a large admixture of $K\bar{K}$ (and $\eta\pi$) virtual state is probably correct. As for the $S^*(990)$ its mass and width are distorted by the proximity of the $K\bar{K}$ threshold.

2.5 Interpretation of the 0^{++} mesons

We can now summarize the experimental information on the scalar mesons in the following way. One $I = 1/2$, $S = 1$, $J^P = 0^+$ resonance is observed with a mass of ~ 1420 MeV, a width of ~ 240 MeV and a large $K\pi$ elasticity, $x \sim 0.85$.

One $I = 1$, $S = 0$, $J^P = 0^+$ resonance is observed, the $\delta(890)$. It has a mass of ~ 980 MeV, a not well determined width which falls in the 50-300 MeV range, and its couplings to $\eta\pi$ and $K\bar{K}$ are in agreement with SU3, i.e. $g_{\eta\pi}^2/g_{K\bar{K}}^2 = 2/3$.

Two $I = 0$, $S = 0$, $J^P = 0^+$ resonances have been identified. The $\epsilon(1300)$, with a mass of ~ 1400 MeV, a width of ~ 200 MeV, and a dominant $\pi\pi$ coupling. The other one is the $S^*(990)$, which can be interpreted at least in part as a $K\bar{K}$ bound state resonance, not excluding a $q\bar{q}$ component with a relatively large coupling to the $s\bar{s}$ channel.

To complete this summary, one may add that several analyses of the $\pi\pi$ data have led to the conclusion that a low mass isoscalar may still be needed to fit the data, the $\epsilon(800)$, with a mass of ~ 800 MeV and a very large width of 500 to 800 MeV (Estabrooks 1979), and that another $I = 1$ resonance has been suggested, around 1300 MeV, to fit the $(K\bar{K})^\pm$ data. However, none of these other "candidates" is established with certainty.

Can we establish a $q\bar{q}$ nonet with these scalar resonances? Starting from the unique $I = 1/2$ candidate, we can first extract the SU3 octet coupling constant g_8

$$g_8 = \sqrt{\frac{10}{9}} g_{K\pi}^K$$

using $\Gamma = \frac{g^2 |\vec{q}|}{M^2}$ with

$\Gamma_{K\pi}^K = 204 \text{ MeV}$, $|\vec{q}| = 624 \text{ MeV}$, $M = 1420 \text{ MeV}$, we get

$$g_s = 0.85 \text{ GeV}.$$

We then get for the isovector

$$g_{\eta\pi}^\delta = \sqrt{\frac{2}{5}} g_s \text{ and } g_{K\bar{K}}^\delta = \sqrt{\frac{3}{5}} g_s,$$

$$\Gamma_{\eta\pi}^\delta = 96 \text{ MeV for the } \delta(980)$$

giving a total width of 240 MeV.

The apparent width assigned to the $\delta(980)$ meson does not seem to be compatible with the data, but we have underlined that this apparent width may be distorted by the proximity of the $K\bar{K}$ threshold. However, taking $K(1420)$ and $\delta(980)$ as the $I = 1/2$ and $I = 1$ partners of a 0^+ $q\bar{q}$ nonet, it is not possible to find a mixing which would accommodate any pair of the three isoscalar candidates.

Törnqvist (1982) has recently been able to remove this difficulty, and to explain with the same argument the various anomalies noticed for the $q\bar{q}$ nonet of scalar resonances, by taking explicitly into account the effects due to the relevant hadronic thresholds (cusps). Törnqvist considers the complete set of flavour related thresholds and in particular those due to the coupling of the scalar resonances to two pseudo-scalar mesons. Thus, for the $\delta(980)$, the thresholds to be considered are

$$\pi^+\eta, K^+\bar{K}^0, \pi^+\eta', D^+\bar{D}^0, \pi^+\eta_c,$$

$D^+, \bar{D}^0$ and η_c representing the pseudo-scalar $c\bar{d}$, $c\bar{u}$ and $c\bar{c}$, respectively.

For each threshold, a coupling constant is determined according to the standard quark counting rules, the $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ content of the η and η' being taken with the pseudo-scalar mixing angle $\theta_p = -11^\circ$.

The key point of Törnqvist's model is to introduce explicitly the partial width and mass shifts which are related to the various thresholds to be considered and which are given by the imaginary and the real part of the

hadronic self energy diagrams, respectively. It is found that, with an overall coupling constant γ^{SPP} of 0.94 GeV, a bare $u\bar{u}$ meson mass of 1345 MeV, a cutoff of 0.7 GeV/c which fixes the shape of the hadronic form factor, assumed to be flavour independent, and quark mass differences of

$$m_s - m_u = 80 \text{ MeV},$$

$$m_c - m_u = 1042 \text{ MeV},$$

the $\delta(980)$, $S^*(990)$, $\epsilon(1300)$ and $K(1350)$ are predicted with the following masses and widths:

$\delta(980)$	$M = 970 \text{ MeV}$	$\Gamma = 500 \text{ MeV},$
$S^*(990)$	985 MeV	400 MeV,
$\epsilon(1300)$	1390 MeV	1400 MeV,
$K(1350)$	1350 MeV	430 MeV.

The $K(1350)$ falls between the two most important thresholds, $K\pi$ and $K\eta'$ (the $K\eta$ being weakly coupled). The $K\eta'$ threshold, at 1455 MeV, creates a rapid motion on the Argand plot, shifting the mass of the resonance and reducing its width.

The mass shifts due to the $\pi\eta$, $K\bar{K}$ and $\pi\eta'$ thresholds, all close to 1000 MeV, are much more important for the $\delta(980)$ than for the $K(1350)$. Indeed, these hadronic mass shifts explain the most part of the $K(1350)$ - $\delta(980)$ mass difference. Moreover, the $K\bar{K}$ threshold leads to an apparent width of the $\delta(980)$ which is much smaller than its natural one. These conclusions had already been reached by Achasov (1981).

The $K\bar{K}$ threshold plays an even more important role for an $s\bar{s}$ state than for the $s\bar{u}$ and explains that the mass shift observed for the $S^*(990)$ which is assumed to be, at the origin, a bare $s\bar{s}$ state, is the most important of all (in addition, the $\eta\eta$ threshold contributes to this mass shift). As for the $\delta(980)$, these thresholds force the apparent width of the $S^*(990)$ to be much smaller than the natural one.

In the presence of such important threshold effects, the mixing angle becomes energy dependent and complex. Being nearly ideal up to the $K\bar{K}$ threshold (i.e., the bare $S^*(990)$ is a pure $s\bar{s}$ state), the mixing angle changes rapidly above 1 GeV, the $\epsilon(1300)$ being nearly a pure singlet.

The importance of the threshold effects underlined in Törnqvist's analysis confirms the conclusions already reached by Martin (1977) and Irving (1981) that the $\delta(980)$ and the $S^*(990)$ have large $q\bar{q}q\bar{q}$ components in the form of two meson virtual bound states, but it also shows that the $\delta(980)$, $S^*(990)$, $\epsilon(1300)$ and $K(1350)$ resonances are consistent with a $q\bar{q}$ nonet of scalar resonances with an $u\bar{u}$ bare mass of 1345 MeV. This mass is certainly compatible with the $L = 1$ assignment naturally given to a scalar nonet and eight years after the question raised by Morgan (1974): "Is the O^+ nonet respectable?", it seems possible to answer: "yes".

3. THE 1^{++} and 1^{+-} MESON RESONANCES

3.1 The $A_1(1240)$ and the $H(1200)$ resonances

To prove the existence of a resonance, we not only need a statistically significant experimental evidence for it, but also a non-controversial interpretation of the observed effect. The first condition was satisfied relatively soon for the A_1 , but it took more than fifteen years to reach a reasonable understanding of the effect. Even to-day, one can only give a range of possible values for its mass, which very likely lies between 1200 and 1300 MeV.

The main difficulty which we encounter for the interpretation of the data comes from the fact that most observations are made on the coherent diffractive 3π production, a phenomena which is dominated by large re-scattering amplitudes (Deck 1964). These amplitudes interfere with the A_1 production and introduce severe distortions in the mass phase. The first observation of these phenomena was made on the (3π) peak produced near the $\rho\pi$ threshold in very forward π^- scattering on carbon without break-up (Bellini 1963).

It was soon recognized that this broad enhancement has the quantum numbers which we assign to the A_1 , i.e. $J^{PC} = 1^{++}$, $I = 1$, and that it corresponds to an S-wave in the $\rho\pi$ system, but the first partial wave analyses of this (3π) enhancement (Ascoli 1970) showed very little variations

of the 1^+ with respect to other waves. However, introducing a Deck amplitude, rescattering corrections and a direct diffractive A_1 production (Bowler 1975, Basdevant 1977) (fig. 23), it was possible to show that the $(3\pi)^+$ diffractively produced enhancement (Antipov 1973) contains a resonance component with a mass of 1200 to 1300 MeV and a width of 250 to 450 MeV.

More recent results on the coherent π scattering on nuclei (Pernegr 1978) have also shown that the phase of 1^+ S-wave $\rho\pi$ exhibits a forward motion of 90° from ~ 1000 to ~ 1400 MeV, in agreement with the presence of a resonance.

A clear confirmation of these conclusions comes from the results of the analysis of a large statistics experiment done on the 3π diffractive production at high energy (63 and 94 GeV/c) (Daum 1981a). Since this experiment supersedes previous ones in this field and is likely to remain a reference for the discussion of the 1^+ nonet, we shall describe it in more details.

A plan view of the apparatus is shown in fig. 24. A 50 cm liquid hydrogen target (T) is surrounded by a box of lead-scintillator sandwich counters (F) which can be used in various trigger modes. A two-lever arm spectrometer consisting of two magnets (M_1 , M_2) and of five banks of spark chambers (S_1 , S_2 , S_3 , S_4 and S_5) gives precision momentum measurements with a large acceptance (more than 95% for $M(3\pi) < 2.5$ GeV).

Various hodoscopes and counters (P_1 , G, P2/3 and H) were used in the definition of the trigger. Finally, two Cerenkovs (C_1 , C_2) with a pion threshold of 8 and 17 GeV, respectively, were used in the identification of the secondaries.

With this apparatus, 600 000 events corresponding to the reaction

$$\pi^- p + \pi^- \pi^+ \pi^- p \text{ at 63 and 94 GeV/c} \quad (3.1)$$

have been collected to study the properties of the A_1 (and other resonances which we do not discuss here). A 3π mass resolution $\sigma \sim 10$ MeV was achieved, the contamination from other reactions being completely negligible.

The two current methods for the three particle partial wave analysis (Ascoli 1970, 1973, 1974 and Tabak 1974) have been applied to these data. The production amplitudes

$$F_{\lambda_i \lambda_f}^{J^P LM^\eta} (t, M_{3\pi})$$

are functions of the mass of the 3π system, $M_{3\pi}$ produced with a momentum transfer t . J , P and M are the total angular momentum, the parity and the magnetic quantum numbers assigned to the 3π system, respectively. λ_i and λ_f label the initial and final nucleon helicities, respectively. The naturality of the exchange is given by η ($\eta = +1$ for natural parity and $\eta = -1$ for unnatural parity exchange). In the absence of proton polarization measurements, states with different values of η do not interfere. The corresponding amplitudes, odd or even under a reflection in the production plane, are found by linear combinations of the magnetic substates $\pm M$. The 3π system then decays into a "recoil" π and a "dipion" with spin j and magnetic number m . L is the orbital momentum between the recoil π and the dipion. This part of the amplitude can be described in terms of three Euler angles (α , β and γ) and the mass of the dipion. It consists of angular distribution factors

$$D^{J^P LM^\eta}(\alpha, \beta, \gamma)$$

and of Dalitz plot factors.

When the dipion is dominated by a well defined resonance (ρ , f , g) its corresponding amplitude is described by a Breit-Wigner function. For the S-wave dipion, Daum (1981a), use an amplitude of the form

$$\frac{1}{q} e^{i\delta} \sin\delta,$$

where δ is the complex S-wave $\pi\pi$ phase shift and q the momentum in the dipion system.

The intensities and relative phases of the major $M = 0$ waves and the 2^+D1^+ are shown in figs 25 and 26 for momentum transfer t integrated from threshold to 0.7 GeV^2 . As expected the $1^+S0^+(\rho\pi)$ dominates between 3π masses of 1.0 to 1.4 GeV . The $(\epsilon\pi)$ contribution to this wave does not exceed 10%. In the $2^+D1^+(\rho\pi)$ wave, the well behaved A_2 Breit-Wigner resonance dominates with little background.

The large statistics accumulated by Daum (1981a) allow them to study the t dependence of the $1^+S_0^+$ enhancement (fig. 27). It shows the usual broad enhancement at low t , peaked at ~ 1100 MeV, which tends to be displaced towards higher masses as t is increased, to finally present a Breit-Wigner shape centred at ~ 1300 MeV for data selected between $0.3 < |t| < 0.7$ GeV².

The variation of the phase of the $1^+S_0^+(\rho\pi)$ amplitude with respect to other waves is shown in fig. 28. The 1^+ phase increases only by $\sim 30\%$ with respect to the $0^-S(\epsilon\pi)$ phase, in agreement with earlier results. Once the variation of the known A_2 Breit-Wigner is subtracted, the relative phase of 1^+S with 2^+D exhibits a forward motion of $\sim 120^\circ$ between threshold and ~ 1500 MeV, strongly suggesting the presence of a resonance in the 1^+S wave.

To arrive at a quantitative estimate of the characteristics of this resonance, Daum (1981a) apply the model sketched in fig. 23 and which assumes three coherent contributions to the (3π) enhancement:

- A Deck amplitude, written

$$D(M_{\pi\pi}, t_\pi, t) = \frac{A_{\pi\pi}(M_{\pi\pi}, t_\pi) A_{\pi N}(S_{\pi N}, t)}{m_\pi^2 - t_\pi},$$

where $A_{\pi\pi}$ is the $\ell = 1$ $\pi\pi$ and $A_{\pi N}$ the π^-p elastic scattering amplitude.

- A rescattering term which is taken into account by simply replacing the bare Deck amplitude $D(M_{\pi\pi}, t_\pi, t)$ by a function

$$D' = D e^{i\delta} \cos\delta,$$

where δ is the S-wave $\rho\pi$ elastic scattering.

- A term representing the direct production of the A_1 resonance allowed to differ in phase from the Deck amplitude.

Variations in the parametrization of this simple model do not change the basic conclusion, i.e. the presence of an A_1 resonance with a mass peaking around 1280 MeV and a width of the order of 300 MeV. However, using the more sophisticated model of Basdevant and Berger (Basdevant 1977), the resulting fits only require a small direct production ($\sim 10\%$) of the resonance, and this relatively small fraction of direct production

underlines the difficulties to be faced to extract the parameters of a resonance in this huge diffractive effect.

These conclusions have recently received more support from a large statistics experiment done on the forward charge exchange process (Dankowych 1981)

$$\pi^- p \rightarrow \pi^+ \pi^- \pi^0 n \text{ at } 8.45 \text{ GeV/c} . \quad (3.2)$$

In this reaction, the analysis is particularly interesting since it can separate four incoherent contributions having natural and unnatural parity exchange and nuclear helicity flip or non-flip. To help separating the nucleon helicities, which are not measured, characteristic t dependences have been introduced in the parametrization of the partial waves.

Intensities from the natural parity exchange, nuclear helicity flip are shown in fig. 29. The wave with the quantum numbers of the A_1 is quite large and has a Breit-Wigner shape peaking at ~ 1100 MeV. Another important wave, presenting also a maximum around 1100 MeV is the $I = 0$, $J^P = 1^+ \rho\pi$ S-wave. Also shown in this figure is the contribution of the $A_2(1310)$ meson with its well defined Breit-Wigner shape. The intensities corresponding to the natural parity exchange, nucleon helicity non-flip, are shown in fig. 30. They contain again a large contribution of the $I = 0$ $J^P = 1^+ \rho\pi$ S-wave peaking at 1100 MeV and a clean $A_2(1310)$ resonance. The nucleon helicity flip group of waves contains also an exotic wave ($I = 2$) which is sufficiently robust to serve as a phase reference. The relative phases ($I = 1$ and $I = 0$ $J^P = 1^+ \rho\pi$ S-waves) are shown in fig. 31. The forward motion of both $I = 0$ and $I = 1$ waves of $\sim 150^\circ$ establish their resonance behaviour. As in the case of the diffraction discussed above, the mass distributions and phase behaviour can be distorted by a coherent Deck background. To take into account the presence of such a coherent background, Dankowych (1981) use the model applied by Daum (1981a) and find that the best parameters are

$$M = 1240 \pm 80 \text{ MeV}, \Gamma = 380 \pm 100 \text{ MeV}$$

for the A_1 and

$$M = 1190 \pm 60 \text{ MeV}, \Gamma = 320 \pm 50 \text{ MeV}$$

for the $I = 0$ $J^P = 1^+$ called the $H(1200)$.

Once more, one sees that the coherent background distorts the mass spectra so that the apparent peaks due to the resonances occur at ~ 150 MeV below the best mass values found for these resonances. In that respect, the backgrounds in diffraction and charge-exchange data need not be the same, and it is remarkable that the values obtained for the parameters of the A_1 are well compatible once the data have been interpreted to take into account the coherent background. Both experiments (Daum 1981a and Dankowych 1981) also agree on the dominance of the $\rho\pi$ S-wave decay mode of the A_1 , the $\epsilon\pi$ P-wave and $\rho\pi$ D-wave being found to be negligible.

The A_1 has also been looked for in non-diffractive processes such as a $p\bar{p}$ annihilations (Kasper 1979), backward production (Gavillet 1977) and in the semi-leptonic decay of the $\tau^\pm$ (Wagner 1980). These data are however too limited in statistics to allow a detailed study of rather complex reactions.

3.2 The $I = 1/2$ $J^P = 1^+$ resonances

As for the $A_1(1240)$, most of the experimental information on the $I = 1/2$ $J^P = 1^+$ resonances come from the inelastic diffractive reactions

$$K^\pm p \rightarrow K^\pm \pi^+ \pi^- p \quad (3.3)$$

Here again a large coherent background distorts the mass spectra and the phase shifts, the mass and widths obtained for the resonances being model dependent. Unlike the 3π diffractive system, the G-parity cannot be used, for the $K\pi\pi$ system, to select eigenstates of C-parity and the analyses must include both $C = +1$ and $C = -1$ states. However, the fact that resonances in the $K\pi\pi$ system decay through two main decay modes, $K\rho$ and $K^*\pi$ and not through one mode only as for the $A_1(1240) \rightarrow \rho\pi$ provides crucial information for the determination of the mass and width of the resonances.

The most recent and most complete analysis of the $K\pi\pi$ system is the one by Daum (1981b). It is very similar to the analysis made by the same group (Daum 1981a) or the 3π system and described in details in sect. 3.1. It uses the same experimental set-up and relies on the data provided by 200 000 examples of the reaction

$$K^- p \rightarrow K^- \pi^- \pi^+ p \quad (3.4)$$

at 63 GeV/c.

This analysis confirms the existence of two $J^P = 1^+$ resonances as observed in a similar experiment made at SLAC with 13 GeV/c incident $K^\pm$ (Brandenburg 1976, 1977). The 1^+ states are observed in the ρK , $K^* \pi$, $K(1350)\pi$, and $\epsilon(1300)K$ final states, but also in the $K\omega$ final state.

Fig. 32 shows the $K\pi\pi$ mass spectrum (the mass acceptance is flat, going from 40% at low mass to 50% at 2 GeV). This mass spectrum shows clearly two peaks over the large Q enhancement, and a further peak in the L region (~ 1800 MeV) which we do not discuss here. The $K\omega$ spectrum is also shown in fig. 32: the Q enhancement is clearly visible, rising very rapidly from the $K\omega$ threshold.

The partial wave analysis of the $K\pi\pi$ data shows that the 1^+ state is largely dominant at low mass, with a strong peak at the lower Q side and a shoulder at the high mass side of the Q enhancement. The 0^- partial wave has a broad peak centred at 1400 MeV and representing $\sim 25\%$ of the total 1^+ intensity. The 2^+ partial wave is very small (7% of the total intensity) but reproduces the expected slope of the $K^*(1430)$.

The mass region $1.0 < M(K\pi\pi) < 1.6$ GeV where the 1^+ partial wave is dominant has been analyzed in two bins of $t' = t - t_{\min}$: $0 < |t'| < 0.05$ GeV² and $0.05 < |t'| < 0.7$ GeV². The 1^+ system is observed in five separate $K\pi\pi$ channels in $M = 0$:

$$1^+S(K^*\pi), 1^+S(K\rho), 1^+P(\kappa\pi), 1^+P(\epsilon\kappa), 1^+D(K^*\pi),$$

where κ and ϵ represent the S-wave $K\pi$ and $\pi\pi$, respectively. In the $M = 1$ substate (t-channel helicity frame), only two channels are found to be significant: $1^+S(K^*\pi)$ and $1^+S(K\rho)$. Figs 33-35 show the masses and phases (measured relative to the $1^+S(K^*\pi)$ phase) obtained for these channels. The $M = 0$ $K^*\pi$ intensity shows two peaks at 1250 and 1400 MeV, whereas only the lower peak appears in $M = 1$. The $K\rho$ channel shows a single peak at 1300 MeV in both $M = 0$ and $M = 1$ with a phase which initially rises through 60° with respect to $K^*\pi$ and then falls by a comparable amount between 1350 and 1450 MeV. The $\kappa\pi$ intensity and phase show the same features as the $K\rho$,

while the κK channel shows similarity with the $K^*\pi$ one. The $1^+D(K^*\pi)$ follows approximatively the behaviour of the $K\rho$ channel.

All these features of the data are well represented in terms of a model in which two 1^+ resonances are produced diffractively both directly and through rescattering of Deck backgrounds. The curves in fig. 33-35 are the results of the fits obtained with this model.

The $K^*\pi$ $M = 0$ intensity is dominated by a resonance called $Q_2(1400)$ with the mass and width

$$Q_2(1400): \quad M = 1410 \pm 25 \text{ MeV} \quad \Gamma = 195 \pm 25 \text{ MeV}.$$

The $K\rho$ and $\kappa\pi$ $M = 0$ intensities are dominated by another resonance, called $Q_1(1270)$, with the mass and width

$$Q_1(1270): \quad M = 1270 \pm 10 \text{ MeV} \quad \Gamma = 90 \pm 8 \text{ MeV}.$$

These results are in good agreement with the values obtained from non-diffractive Q production. For the $Q_2(1400)$ from charge exchange reaction, Vergeest (1976) finds

$$M \sim 1400 \text{ MeV}, \quad \Gamma \sim 200 \text{ MeV}, \quad K^*\pi \text{ dominant}.$$

For the $Q_1(1270)$, the first evidence comes from the study of $p\bar{p}$ annihilations at rest (Armenteros 1964, Astier 1969) with the mass and width

$$M = 1242 \pm 9 \text{ MeV}, \quad \Gamma = 127 \pm 7 \text{ MeV}, \quad K\rho \text{ dominant}.$$

The $Q_1(1270)$ has also been observed in hypercharge exchange reactions (Crennell 1972, Rodeback 1981) with the mass and width

$$M = 1294 \pm 10 \text{ MeV}, \quad \Gamma = 66 \pm 15 \text{ MeV}, \quad K\rho \text{ dominant}.$$

The production of two 1^+ resonances, close in mass, suggests that the observed resonances Q_1 and Q_2 are mixtures of the two $SU(3)$ octet members Q_A ($C = +1$ octet, like the $A_1(1240)$) and Q_B ($C = -1$ octet, like the $B(1235)$ meson)

$$\begin{aligned} |Q_1| &= - |Q_A\rangle \sin\theta + |Q_B\rangle \cos\theta, \\ |Q_2| &= |Q_A\rangle \sin\theta + |Q_B\rangle \sin\theta. \end{aligned}$$

The couplings of the S-wave $K^*\pi$ and $K\rho$ channels can then be parametrized in terms of the reduced SU(3) couplings of Q_A (F-type) and Q_B (D-type), γ_+ and γ_- , respectively, and the mixing angle θ . Daum (1981b) find with their data

$$\begin{aligned} 50^\circ &< \theta < 70^\circ \\ 0.70 &< \gamma_+ < 0.90 \\ 0.50 &< \gamma_- < 0.70 \end{aligned}$$

The $1^+D(K^*\pi)$ partial wave fits nicely with the absence of $\rho\pi$ D-wave in the $A_1(1240)$ meson and with the D/S ratio of 30% observed for the $\omega\pi$ decay of the $B(1235)$ meson.

The $K\omega$ amplitude follows closely the behaviour and is equal in magnitude (up to phase space factors) of the $K\rho^0$ amplitude, as expected from the quark model.

In summary, the two $I = 1/2$ $J^P = 1^+$ resonances which are expected to be the members of the 1^{++} and 1^{+-} $q\bar{q}$ nonets have been identified. They are linear mixtures of the two resonances observed in the inelastic diffraction of incident $K^\pm$ particles. With a mixing angle of 50° , their masses are

$$\begin{aligned} Q_A: & \quad M = 1330 \pm 15 \text{ MeV for the } 1^{++} \text{ member,} \\ Q_B: & \quad M = 1350 \pm 20 \text{ MeV for the } 1^{+-} \text{ member.} \end{aligned}$$

3.3 The D(1285) and the E(1420)

Two $C = +1$ isoscalar resonances have been observed and most analyses favor for their spin-parity the assignment 1^+ (with the exception of two noticeable cases for the E(1420) with we shall discuss later).

Both resonances are observed in various kinds of hadronic interactions, $\pi^\pm p$, $K^\pm p$, $p\bar{p}$ annihilations in flight. Both resonances have a clear $K\bar{K}\pi$ decay mode and when this decay mode is chosen for their identification,

both of them are usually observed, although with different intensities. Since they have identical quantum numbers, the simultaneous production of the D(1285) and of the E(1420) in $\pi^- p$ and $K^- p$ interactions may suggest that their quark contents is a mixture of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$, i.e. the mixing angle is not ideal.

The D(1285) is observed with the mass and the total width

$$M = 1284 \pm 4 \text{ MeV} \qquad \Gamma = 27 \pm 5 \text{ MeV.}$$

The width of the D(1285) meson being relatively narrow, the experimental resolution has to be carefully estimated to obtain a good measurement of its natural width. One of the best determination is due to Nacash (1978) (fig. 36).

A clear $\eta^0 \pi^+ \pi^-$ decay mode of the D(1285) has been observed: see, for example, fig. 37 which reproduces the results obtained by Evangelista (1981) for the reaction

$$\pi^- p \rightarrow p \pi^+ \pi^- \eta^0 \text{ at } 12 \text{ GeV/c.} \qquad (3.5)$$

The curve represents a fit to a Breit-Wigner with $M = 1278 \text{ MeV}$ and $\Gamma = 26 \text{ MeV}$. It is important to note that no $\eta \pi^+ \pi^-$ is observed at the mass of the E(1420).

Very few experiments have been able to observe the $K\bar{K}\pi$ and the $\eta\pi\pi$ decay modes of the D(1285). Thus the branching ratio of these two modes is not well determined. One of the most reliable result comes from the study of the reaction

$$K^- p \rightarrow \Lambda^0 D^0 \qquad \text{at } 4.2 \text{ GeV/c} \qquad (3.6)$$

with

$$D^0 = K^\pm K^0 \pi^\mp$$

or

$$D^0 \rightarrow \eta^0 \pi^+ \pi^-$$

(Gurtu 1979) who find:

$$BR(D \rightarrow K\bar{K}\pi / D \rightarrow \eta\pi\pi) = 0.42 \pm 0.15.$$

Neither the $K\bar{K}\pi$, nor the $\eta\pi\pi$ Dalitz plot of the D(1285) meson decay is uniformly populated. They present the characteristic features of an intermediate state, namely

$$D \rightarrow \delta\pi \rightarrow K\bar{K}\pi \text{ or } \eta\pi\pi ,$$

with a typical $K\bar{K}$ threshold effect and an enhancement in the $\eta\pi$ mass spectrum at the $\delta(980)$ (fig. 38). However, pure kinematical factors to fit the transition $1^+ \rightarrow 0^-0^-0^-$ could reproduce the Dalitz plots densities without the introduction of dynamical intermediate states (Defoix 1972) and one cannot definitively conclude, for the time being, on the dynamical properties of the D(1285) decay. One must add that the K^*K intermediate state is not observed, even if large phase-space suppression factors are taken into account (Nacash 1978).

Two experiments have come to the conclusion that the D(1285) meson has also a large 4π decay mode (Grassler 1977, Gurtu 1979), this mode being dominated by the intermediate state $\rho\pi\pi$. An average branching ratio (PDG 1982) between these two experiments gives

$$BR(D \rightarrow 2\pi^+2\pi^-/D \rightarrow \eta\pi^+\pi^-) = 0.41 \pm 0.12.$$

In contrast to these results, the E(1420) meson, which is observed with the following mass and width in one of the most recent and complete experiment (Dionisi 1981)

$$M = 1426 \pm 6 \text{ MeV}, \quad \Gamma = 40 \pm 15 \text{ MeV},$$

is uniquely seen to decay into $K\bar{K}\pi$ and this final state is dominated by the intermediate K^*K state

$$Br(E \rightarrow K^*K/E \rightarrow K\bar{K}\pi) = 0.86 \pm 0.12 .$$

All the above description of the properties of the D(1285) and of the E(1420) masses forms a relatively coherent picture with the hypothesis that these two isoscalars $C = +1$, $J^P = 1^+$ resonances are the members of the corresponding 1^{++} nonet, their decay properties suggesting that the D(1285) is mainly a $(u\bar{u} + d\bar{d})$ object, the E(1420) mainly an $s\bar{s}$. This interpretation is now so well supported experimentally, that one could suggest to rename the E(1420) the D'(1420), in similarity with the η , η' , f , f' resonances.

However, this description has left aside two series of important experimental results, which we now discuss briefly.

The first observation of the E(1420) was made in the study of the five body $p\bar{p}$ annihilations at rest (Baillon 1967)

$$p\bar{p} \rightarrow K^0 K^{\pm} \pi^{\mp} \pi^+ \pi^- . \quad (3.7)$$

This reaction was found to be dominated by the production of a new resonance, in the $K^0 K^{\pm} \pi^{\mp}$ spectrum, with a mass of 1425 ± 7 MeV and a width of 80 ± 10 MeV. One should remark here that, if the mass is in good agreement with the mass of the E(1420) known as a 1^{++} resonance to-day, the width observed in the $p\bar{p}$ annihilations at rest is significantly larger. Other features observed in these annihilations are not consistent with the properties of the 1^{++} resonance. First of all, the 1425 MeV enhancement is not accompanied by the D(1285), as it is in other hadronic interactions (fig. 39). One also finds that the $K^* K$ decay mode represents at most 50% of the $K\bar{K}\pi$ decay

$$BR(E \rightarrow K^* K/E \rightarrow \delta\pi, \delta \rightarrow K\bar{K}) = 1.0 \pm 0.10 .$$

A reanalysis of these data (Montanet 1975) shows that this branching ratio represents in fact an upper limit since the direct production of $K^*(892)$ in the five-body $p\bar{p}$ annihilations is more important than the $\delta(980)$ production. The original result assumes no background. However, no $(\eta\pi\pi)$ excess is observed in the E region in annihilations at rest, and the branching ratio $BR(E \rightarrow \eta\pi\pi)$ is larger than 1, at 95% CL. The most striking difference with the 1^{++} state is found in the determination of the quantum numbers. Whereas $C = +1$ is unambiguously observed, through the decay mode

$$E \rightarrow K_S^0 K_S^0 \pi^0 ,$$

and $I = 0$ is strongly favoured, the spin parity 0^- is largely preferred to 1^+ for the production reaction

$$\bar{p}p \rightarrow E\pi\pi . \quad (3.8)$$

One finds an acceptable result for 0^- (1.5 s.d.) but a bad fit for 1^+ (7 s.d.) and the same indications are provided by the decay

$$E \rightarrow K\bar{K}\pi ,$$

with a fit at 1.2 s.d. for 0^- and at 5 s.d. for 1^+ (Baubillier 1967, Montanet 1975).

We must conclude that, apart for its mass, the $K\bar{K}\pi$ enhancement observed in $p\bar{p}$ annihilations at rest cannot be identified to the 1^{++} E(1420) resonance observed in other hadronic interactions.

The characteristics of the $K\bar{K}\pi$ enhancement observed in $p\bar{p}$ annihilations at rest present indeed striking analogies with the recent results obtained on the radiative decay of the J/ψ (Scharre 1980, Aschman 1982)

$$J/\psi \rightarrow \gamma K_S^0 K^\pm \pi^\mp \quad (3.9)$$

and $J/\psi \rightarrow \gamma K^+ K^- \pi^0$. (3.10)

Here again, an enhancement is seen in the $K\bar{K}\pi$ system with a mass of 1440 ± 20 MeV, a width of 50 ± 20 MeV, the spin-parity 0^- being favoured over 1^+ and the $K\bar{K}\pi$ decay being associated with a low mass $K\bar{K}$ enhancement rather than the $K^* K$ mode observed for the 1^+ resonance. As in the $p\bar{p}$ annihilations at rest, no D(1285) resonance is observed in the radiative decay of the J/ψ . Since the $\delta(980)\pi \rightarrow K\bar{K}\pi$ decay mode seems to be favoured, Scharre (1980) have looked for the $\eta\pi\pi$ decay but, as for $p\bar{p}$ annihilations at rest, no enhancement is observed for this channel, an upper limit

$$BR(E \rightarrow K\bar{K}\pi / E \rightarrow \eta\pi\pi)$$

larger than 0.9 being given.

These results have raised considerable interest in the context of the glueball spectroscopy (Ishikawa 1981, Chanowitz 1981, Ono 1982, Lipkin 1982). A systematic discussion of this problem is given by Pinsky (1982), who shows that, interpreted in terms of a glueball, the 1440 MeV $K\bar{K}\pi$ enhancement, called G(1440), could have a reduced $\eta\pi\pi$ decay mode even if $G(1440) \rightarrow \delta\pi$ is dominant

$$BR(G(1440) \rightarrow \eta\pi\pi / G(1400) \rightarrow K\bar{K}\pi) \sim 42\% ,$$

a surprising result which seems to be supported by the available experimental results.

Whatever the interpretation of the $G(1440)$ may be (glueball, $q\bar{q}q\bar{q}$ state, radial excitation of the pseudo-scalar family, etc.), it is probably not a 1^+ resonance and can be ignored for subsequent discussion on the 1^+ nonets.

3.4 The $B(1235)$

For completeness, we shall simply give here the well known properties of the $J^{PC} = 1^{+-}$, $I = 1$ resonance, called the $B(1235)$ meson (Particle Data Group 1982)

$$M = 1232.5 \pm 3.4 \text{ MeV},$$

$$\Gamma = 137.2 \pm 6.6 \text{ MeV}.$$

The only observed decay mode is

$$B(1235) \rightarrow \omega\pi,$$

the two-body decay system being in a D-wave or and S-wave in the ratio

$$D/S = 0.291 \pm 0.052.$$

One should simply add one word of caution when discussing the $B(1235) \rightarrow \omega\pi$ since it has been shown that a $\rho'(1250) \rightarrow \omega\pi$, with $J^P = 1^-$ is observed in some reactions (hadronic annihilation of e^+e^- , $p\bar{p}$ annihilations at rest). The presence of this vector resonance is not always explicitly excluded from the $\omega\pi$ data which are used for the determination of the $B(1235)$ properties.

3.5 Interpretation of the 1^+ nonets

Let us start with the quark rules expected for a nonet of $q\bar{q}$ resonances. Then, for the 1^{+-} nonet, with

$$M_{QB} = 1350 \text{ MeV and } M_B = 1232 \text{ MeV},$$

the isoscalar member of the octet multiplet should have a mass of

$$M_8 = 1387 \text{ MeV}.$$

Assuming ideal mixing between the two 1^{+-} isoscalar, the $s\bar{s}$ member is then expected to have a mass of

$$M_{H'} = 1476 \text{ MeV}$$

if we take for the $1/\sqrt{2}(u\bar{u} + d\bar{d})$ state the H-meson with

$$M_H = 1190 \text{ MeV}.$$

With the reduced coupling constant $\gamma_- = 0.60$ deduced from the $Q \rightarrow PV$ decays, one can predict a partial width of 120 MeV for the S-wave $B \rightarrow \omega\pi$ decay, and taking a D/S ratio of 0.29, a total width of 130 MeV for the $B \rightarrow \omega\pi$, in very good agreement with the experimental observations. One can also predict a partial width of ~ 300 MeV for the $H(1200) \rightarrow \rho\pi$, in good agreement with the experimental observation, and a partial width of ~ 170 MeV for the $H'(1476) \rightarrow K^*K$. This resonance remains the last member of the 1^{+-} nonet to be discovered. Its neutral decay mode

$$H'(1476) \rightarrow K_S^0 K_L^0 \pi^0, \quad K_S^0 \rightarrow \pi^+ \pi^-$$

is difficult to observe since it contains two neutral particles (the K_L^0 and the π^0). Its relatively larger width makes also its charge decay modes

$$H'(1476) \rightarrow K_S^0 K^\pm \pi^\mp \text{ or } K^+ K^- \pi^0$$

rather difficult to observe, in a mass region where several other resonances (the $E(1420)$, the $f'(1515)$) are present. It may be worthwhile to note, in particular, that the C-parity of the 1^{++} $E(1420)$ meson is not firmly established since it essentially relies on the excess of events observed at the overlap of the two $K^*(892)K$ amplitudes ($C = -1$ would correspond to a depletion). Such an excess could also be attributed, partially, to the $\delta(980)\pi$ decay channel. Present statistics do not allow to exclude this possibility.

Turning now to the 1^{++} nonet, we have in principle nine candidates to test the simple quark model: the $A_1(1240)$, the $Q_A(1330)$, the $D(1285)$ and the $E(1420)$. The mass relation between these resonances works quite well with a mixing angle of 47° . Of these 1^{++} resonances the masses of the $D(1285)$ and $E(1420)$ meson are the best known, starting from this information, one expects a mass of 1285 MeV for the A_1 and 1355 MeV for the Q_A with ideal mixing.

Using the reduced coupling constant value $\gamma_+ = 0.80$ as deduced from the $Q \rightarrow PV$ decays, one expects a width of ~ 250 MeV for the $A_1(1240) \rightarrow \rho\pi$ decay, in reasonable agreement with the experimental observations, and a partial width of ~ 50 MeV for the $E(1420) \rightarrow K^*K$ decay, again in good agreement with the experimental observations.

Törnqvist (1981) has recently shown that, in a unitarized quark model which takes explicitly into account the effects due to the hadronic thresholds, the 1^{++} and 1^{+-} nonets fit with the usual symmetry breaking scheme, with a bare $u\bar{u}$ mass of 1316 ± 4 MeV, a mass difference of 97 MeV between the s and u quark, and a reduced coupling constant $\gamma^{APV} = 0.56$, which is the same for the 1^{++} and the 1^{+-} . The $A_1(1240)$ and the $D(1285)$ have a negative mass shift (with $M = 1244$ and 1278 MeV respectively), the $E(1420)$ being predicted at 1439 MeV with a partial width $\Gamma_{KK^*} = 44$ MeV. The second 1^{+-} isosinglet H' is predicted to have a mass of 1400 MeV and a width of 40 MeV, decaying mainly by OZI violation to $\pi^\pm p^\mp$. Such a relatively narrow $\pi\rho$ resonance has not yet been observed in this mass range. The Q_A - Q_B mixing angle is found to be larger than 45° , as in the simpler analysis discussed earlier, and the productions for the mass, widths and branching ratios of the Q_1 - Q_2 resonances are in fair agreement with the experimental observations.

In conclusion, we can say that most of the states of the two nonets of axial mesons, 1^{+-} and 1^{++} , have been observed with the expected properties for the simple $q\bar{q}$ quark model. These nonets have a bare $u\bar{u}$ mass close to 1300 MeV, which is also close to the bare $u\bar{u}$ mass obtained by Törnqvist (1981) for the nonet of scalar mesons and to the mass of the 2^{++} nonet, showing that the spin-orbit splitting seems to be minimal for the $L = 1$ $q\bar{q}$ mesons.

The mixing angles of axial mesons are not far from ideal, the $D(1285)$ and $H(1200)$ being mainly non-strange quark objects. The $E(1420)$, $J^{PC} = 1^{+-}$, fits quite well with this picture, being mainly an $s\bar{s}$ resonance. The deviation from ideal mixing is attributed by Törnqvist (1981) to the presence of hadronic thresholds. These deviations are partly attributed by Schnitzer (1981) to the gluon contributions to the isoscalar states. The main experimental challenge is now to establish the existence of the 1^{+-}

isoscalar resonance $s\bar{s}$ partner of the $H(1190)$, in the 1400-1500 MeV mass range.

4. THE 2^{++} NONET

We have seen in the previous sections that the present experimental information gives support to the simple $q\bar{q}$ model for the 0^{++} , 1^{++} and 1^{+-} states. This model also predicts a nonet of mesons with the quantum numbers $J^{PC} = 2^{++}$, corresponding to the 3P_2 $L = 1$ $q\bar{q}$ system. This nonet of tensors was indeed the first of the four nonets to be well established and we shall now summarize its properties.

4.1 The $A_2(1310)$

The $J^P = 2^+$ $I^G = 1^-$ state decaying into three pions presents all the characteristics of a resonance centred around 1320 MeV with a width of ~ 100 MeV. One of the latest observation has been made by the ACCMOR Collaboration (Daum 1981a) in their study of the reaction

$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p \quad (4.1)$$

with 94 GeV and 63 GeV incident pions, the data being collected at small momentum transfer

$$0.0 \leq |t'| \leq 0.7 \text{ GeV}^2$$

where $|t'| = |t| - |t|_{\min} = |P_b - P_A|^2 - |t|_{\min}$,

$$M_A^2 = |P_A|^2$$

$$|t|_{\min} = |(E_b - E_A)^2 - (\vec{p}_b - \vec{p}_A)^2|.$$

The variation of the intensity of the 2^+ wave and of its phase with respect to another wave, 0^- (expected to be flat in this mass region) are shown in fig. 40. A Breit-Wigner intensity of the form

$$BW(M) = \frac{M\Gamma}{M_0^2 - M^2 - iM\Gamma}, \quad \Gamma = \Gamma_0 \frac{q}{q_0} \frac{M_0}{M} \frac{B(q^2 R^2)}{B(q_0^2 R^2)},$$

where $B(q^2 R^2)$ is a D-wave barrier factor, is fitted to the intensity distribution alone and the phase variation predicted by this fit is shown in fig. 40. In the fitting procedure, the value $R^2 = 10 \text{ GeV}^{-2}$ is used. The parameters M_2 and Γ_0 of the resonance (after corrections are applied to take into account the experimental resolution) are found to be

$$M_0 = 1317 \pm 2 \text{ MeV}$$

$$Q_0 = 96 \pm 9 \text{ MeV} .$$

All these results of the ACCMOR Collaboration are obtained for the $J^P_L M^\eta = 2^+ D1^+(\rho\pi)$ wave, where $J^P = 2^+$ give the spin and parity of the 3π state, $L = 2$ is the orbital angular momentum between one pion and the dipion forming a ρ , M is the magnetic substate and η specifies (at high energy) the naturality of the exchange. The facts that the $A_2(1310)$ is produced by natural spin-parity exchange and that the cross section falls only slowly with the laboratory momentum ($\sigma \sim p_{\text{lab}}^{-0.4}$) lead Daum (1981a) to the conclusion that the $A_2(1310)$ is produced diffractively. This diffractive production of A_2 provides the possibility to study diffraction in a mode which demands that the A_2 be produced with non-zero t-channel helicity and which violates the Gribov-Morrison rule ($\Delta P = (-1)^{\Delta J}$, ΔP and ΔJ being the parity and spin difference between the incident meson and the diffractively produced resonance). In order to reconcile the observed diffractive production of A_2 with the s-channel helicity properties of diffraction and with the Gribov-Morrison rule, Berger, Donohue and Mennessier (Berger 1979) have tried an interpretation in terms of the Deck model corrected for final state interactions. Their conclusion is that the unitarized Deck model cannot describe the diffractive production of the $A_2(1310)$, a dominant direct spin-flip Pomeron coupling being necessary (Irving 1977).

Two other decay modes of the $A_2(1310)$ are well known: a 2^+ resonance is observed for the $K\bar{K}$ and $\eta\pi$ final states with masses and widths compatible with those expected for the $A_2(1310)$. The fact that the branching ratios observed for these decay modes with respect to the $\rho\pi$ do not depend on the nature of the incident particle nor on its momentum gives confidence that we

are dealing with the same object appearing into three different decay modes. Another decay mode

$$A_2 \rightarrow \omega^0 \pi^+ \pi^+, \quad \omega^0 \rightarrow \pi^+ \pi^+ \pi^0$$

has been observed in three different experiments (Chaloupka 1973, Diaz 1974, Karshon 1974). These observations are however not totally consistent. Chaloupka (1973), who study the charged $A_2^-(1310)$ in the reaction

$$\pi^- p \rightarrow A_2^- p, \quad (4.2)$$

give a branching ratio of 0.10 ± 0.05 for

$$\frac{A_2^- \rightarrow (\omega \pi \pi)^-}{A_2^- \rightarrow (\rho \pi)^-}.$$

Diaz (1974), who observe the neutral mode of the $A_2^0(1310)$, give a larger value for this ratio

$$\frac{A_2^0 \rightarrow \omega^0 \pi^+ \pi^-}{A_2^0 \rightarrow (\rho \pi)^0} = 0.28 \pm 0.09.$$

Finally, Karshon (1974), who study the two reactions

$$\pi^+ p \rightarrow A_2^+ p \quad (4.3)$$

$$\text{and } \pi^+ p \rightarrow A_2^0 \Delta^{++}, \quad (4.4)$$

find a ratio of 0.10 ± 0.04 for the first one and 0.29 ± 0.08 for the second one.

It is interesting to note that the two values obtained for the charged $A_2^\pm$ are consistent (0.10 ± 0.05 and 0.10 ± 0.04) as well as the two values obtained for the neutral A_2^0 (0.28 ± 0.09 and 0.29 ± 0.08). If, in addition, we note that the central value obtained for the mass of the neutral $A_2 \rightarrow (\omega \pi \pi)^0$ is larger than the one observed for the other decay modes it is tempting to assume with Karshon (1974) that the neutral enhancement may be due to a superposition of two effects, the $A_2(1310)$ proper and an $I = 0$ resonance around 1350 MeV strongly coupled to $\omega \pi \pi$.

With this remark in minds, it may be better to use only the charge mode for the determination of the branching ratios, and we get for the four important decay modes

$$A_2 \rightarrow \rho\pi \quad (70 \pm 2)\%$$

$$A_2 \rightarrow \eta\pi \quad (15 \pm 1)\%$$

$$A_2 \rightarrow \omega\pi\pi \quad (10 \pm 2)\%$$

$$A_2 \rightarrow K\bar{K} \quad (5 \pm 0.5)\%$$

Using the experimental value (Ape1 1979)

$$\sigma(\pi^- p \rightarrow \eta' n) / \sigma(\pi^- p \rightarrow \eta n) = 0.55 \pm 0.06 ,$$

one can predict that the $A_2(1310)$ partial width into $\eta'\pi$ is of the order of 0.8 MeV. The best experimental results give an upper limit which is close to this value.

To complete this picture, one should mention the preliminary results obtained at Fermilab on the $\pi^+ \rightarrow A_2^0$ electromagnetic transition (Ferbel 1981)

$$\Gamma(A_2^+ \rightarrow \pi^+ \gamma) \sim 0.450 \text{ MeV} .$$

4.2 The $K^*(1430)$ meson

For the mass and width of this well known $J^P = 2^+, S = +1$ resonance, the most recent partial wave analysis (fig. 41) made with the high statistics data obtained at SLAC with an 11 GeV K beam on the reaction (Ratcliff 1981)

$$K^- p \rightarrow K^- \pi^+ n \tag{4.5}$$

gives the following results

$$M = 1428 \pm 3 \text{ MeV}$$

$$\Gamma = 98 \pm 8 \text{ MeV}$$

$$\text{elasticity} = 0.43 \pm 0.01 .$$

The mass assignments obtained in the past from fits to mass distributions were probably too low (~ 1420 MeV) due to the presence of a large S-wave background which peaks at 1380 MeV (sect. 2.3).

The three-body decay mode of the $K^*(1430) \rightarrow K\pi\pi$ represents 37% of the total width, and can be decomposed in the following way (PDG 1982)

$$\begin{aligned} K^*(1430) &\rightarrow K^*(892)\pi & (27 \pm 2)\% \\ K^*(1430) &\rightarrow K\rho & (6.6 \pm 1.5)\% \end{aligned}$$

The quasi two-body decay modes $K\omega$ and $K\eta$ have also been observed but the relative fractions are affected by large errors.

Alike the quasi three-body decay mode of the $A_2(1310) \rightarrow \omega\pi\pi$, the $K^*(1430)$ has a relatively large quasi three-body decay mode (Goldberg 1976)

$$K^*(1430) \rightarrow K^*(892)\pi\pi \quad (12 \pm 4)\% .$$

Measuring the electromagnetic transition $K^+ \rightarrow K^*(1430)$, Ferbel (1981) gives the preliminary results

$$\Gamma(K^*(1430) \rightarrow K^+\gamma) \sim 0.350 \text{ MeV} .$$

4.3 The $f(1270)$ and $f'(1515)$

For the characteristics of the $f(1270)$, and $I^G = 0^+, J^P = 2^+$ state with the dominant decay mode

$$f(1270) \rightarrow \pi\pi ,$$

we refer to the results of the $\pi^+\pi^-$ partial wave analysis made by Becker (1979) who base their study on two high statistics experiments, one of them using a polarized target, and which provide data at low momentum transfer

$$0.01 \leq |t| \leq 0.20 \text{ GeV}^2 ,$$

the incident momentum being 17.2 GeV/c. This model independent analysis of the $\pi^+\pi^-$ final state gives the following parameters for the $I = 0$ $\pi^+\pi^-$ D-wave

$$M = 1273.8 \pm 3 \text{ MeV}$$

$$\Gamma = 183.2 \pm 8 \text{ MeV}$$

$$\text{elasticity} = (84.7 \pm 1.6)\% .$$

As for the $A_2(1310)$ meson, the width given here takes into account a D-wave centrifugal barrier, with $R^2 = 10 \text{ GeV}^{-2}$.

The other decay modes of the $f(1270)$ are much smaller and are difficult to determine. A four pion final state has been observed, but this observation is complicated by the superposition of a possible 4π decay mode of the $D(1285)$ meson. However, the $D(1285)$ being much narrower than the $f(1270)$, it is possible to give the following fraction (PDG 1982)

$$f(1270) \rightarrow 2\pi^+2\pi^- : (2.9 \pm 0.3)\% .$$

If this $2\pi^+2\pi^-$ decay mode of the $f(1270)$ corresponds to the intermediate $\rho^0\rho^0$ state, one expects twice as much for the $(\pi^+\pi^-2\pi^0)$ decay mode. This mode has been observed and could effectively account for $\sim 6\%$ of the total width.

It is important to know the rate $f(1270) \rightarrow K\bar{K}$ for the quark model and the determination of the mixing angle of the 2^+ nonet. In most reactions, three resonances at least, with $J^P = 2^+$, contribute to the $K\bar{K}$ final state: the $A_2(1310)$, the $f(1270)$ and the $f'(1515)$: their interferences make the determination of the $f(1270) \rightarrow K\bar{K}$ rate rather doubtful.

$$f(1270) \rightarrow K\bar{K} (2 \text{ to } 7)\% .$$

Taking the upper limit for $K\bar{K}$, only 2% of the total width are left for other decay modes, not yet completely identified ($K\bar{K}\pi$, $n\pi\pi$, $n\eta$, etc.).

The $f'(1515)$ is a well known isoscalar, $J^P = 2^+$ resonance essentially observed in the $K\bar{K}$ final state. If its mass is known with some accuracy (PDG 1982)

$$M = 1516 \pm 12 \text{ MeV} ,$$

its width is still largely unknown, large discrepancies existing between several observations. The width of the $f'(1515)$ is probably included in the 65 to 160 MeV limits.

As for the determination of the branching ratio of the $f(1270)$ into $K\bar{K}$, the fraction $f'(1515) \rightarrow \pi\pi$ is largely affected by interference effects, and can be included in the 0.5 to 5% limits.

Other decay modes of $f'(1515)$ have possibly been observed ($\eta\pi\pi$, $K\bar{K}\pi$, etc.) and could easily amount to 30% of the total width.

4.4 The 2^+ nonet and the quark model

Using the values of the masses given above for the $A_2(1310)$, the $f(1270)$, $f'(1515)$ and $K^*(1430)$, we can evaluate the Okubo parameters m_0^2 , C_1 , C_2 , C_3 , the mixing angle θ , and the mass of the isoscalar octet f_8 . We find

$$m_0^2 = 1.94 \text{ GeV}^2$$

$$C_1 = -0.178 \text{ GeV}^2$$

$$C_2 = -0.026 \text{ GeV}^2$$

$$C_3 = 0.001 \text{ GeV}^2$$

$$\theta = 20^\circ$$

$$M(f_8) = 1468 \text{ MeV}.$$

One notes that the consistency test

$$M(f) < M(f_8) < M(f')$$

is satisfied. Moreover, the parameters satisfy the inequalities

$$m_0^2 \gg |C_1| \gg |C_2| \gg |C_3|$$

which are expected if the quark line interpretation is correct. In particular, C_3 being very close to zero, the Schwinger mass formula (Dalitz 1965) is verified with a remarkable precision. The mixing angle

is not far from the ideal value $\theta_0 = 35.3^\circ$. The deviation from θ_0 may be related to the partial widths of the $f(1270)$ and $f'(1515)$ into $\pi\pi$. Since we have only given lower and upper limits for $f' \rightarrow \pi\pi$, we can only evaluate the range in which the mixing angle is expected to be found from these partial widths. Taking

$$\Gamma(f' \rightarrow \pi\pi)_{\text{low}} = 65 \times 0.5 \times 10^{-2} = 0.325 \text{ MeV}$$

and

$$\Gamma(f' \rightarrow \pi\pi)_{\text{high}} = 160 \times 5 \times 10^{-2} = 8 \text{ MeV},$$

and taking into account phase-space and centrifugal barrier effects, we find from the relation

$$g_{f' \rightarrow \pi\pi}^2 / g_{f \rightarrow \pi\pi}^2 = \tan^2(\theta - \theta_0)$$

$$\theta_{\text{low}} = 33.7^\circ \quad \theta_{\text{high}} = 27.3^\circ.$$

The mixing angle $\theta = 29^\circ$ deduced from the quadratic mass relations is quite compatible with these limits.

The octet coupling $2^+ \rightarrow 1^- 0^-$ is antisymmetric. Using the appropriate SU3 Clebsch-Gordan coefficients and introducing the phase-space and centrifugal barrier effects, we can compare the partial widths $A_2 \rightarrow \rho\pi$, $K^{*}(1420) \rightarrow K^{*}\pi$, $K^{*}(1430) \rightarrow K\rho$ to the SU3 predictions. We get

	<u>Exp. values</u>	<u>SU3 values</u>
$\Gamma(A_2 \rightarrow \rho\pi)$	67 MeV	Input
$\Gamma(K^{**} \rightarrow K^{*}\pi)$	27 MeV	27 MeV
$\Gamma(K^{**} \rightarrow K^{*}\pi)$	6.6 MeV	6.7 MeV

Similarly, for the coupling $2^+ \rightarrow 0^- 0^-$, which is symmetric, we can compare the partial widths

$$A_2 \rightarrow \eta\pi, A_2 \rightarrow K\bar{K}, f \rightarrow \pi\pi, f' \rightarrow K\bar{K}, K^{*}(1430) \rightarrow K\pi$$

to the SU3 predictions. We now need two input values since, in this case, the singlet amplitude as well as the symmetric octet are coupled. We choose the partial width of $f(1270) \rightarrow \pi\pi$ and $K^{*}(1430) \rightarrow K\pi$ as input and find

	<u>Exp. values</u>	<u>SU3 values</u>
$A_2 \rightarrow \eta\pi$	14.4 MeV	13.1 MeV
$A_2 \rightarrow K\bar{K}$	4.8 MeV	4.6 MeV
$f \rightarrow \pi\pi$	155 MeV	Input
$f' \rightarrow K\bar{K}$	45 to 110 MeV	100 MeV
$K^* \rightarrow K\pi$	42 MeV	Input

Again, the agreement between the experimental values and SU3 predictions is quite satisfactory. In addition, all the other predicted rates are in agreement with the present upper limits of the observations.

One can therefore conclude that the 2^+ nonet behaves very well with respect to SU3 and the quark rules.

5. CONCLUSIONS

One of the corner stones of our understanding of elementary particles is the quark model. Indeed, the quarks have been "invented" to explain the symmetries observed in meson and baryon resonances. Outstanding successes of this quark model have been obtained with the discovery of new meson resonances related to new flavours, the charm and bottom quarks. However, progresses to explain the "light quark" meson spectroscopy have been relatively slow, both on the experimental and theoretical front. Hey and Morgan (1978) have shown how the quark model and its related symmetries are used to explain the structure of the mesons. In this review, we have presented the new experimental information which allows to extend our understanding to the large family of positive parity mesons, generated in the simple quark model with an orbital angular momentum $L = 1$ between the pair of constituent quarks.

The four nonets of scalar, axial and tensor mesons have been identified with the observations made in the 1000-1500 MeV mass range.

The 2^{++} nonet is well known and does not raise serious difficulties for its interpretation. Its mixing angle between the two isoscalars is nearly ideal.

The 1^{++} and 1^{+-} nonets are now in a good shape. One isoscalar remains to be discovered, the $H'(\sim 1450)$, $J^{PC} = 1^{+-}$, partner of the $H(1200)$. The masses and partial widths of the axial mesons are in good agreement with the simple quark model expectations, the mixing angles between the isoscalars showing small departure from ideal mixing.

The 0^{++} family is by far the most difficult one to identify to a standard nonet. However, recent experimental observations and detailed partial wave analysis have largely contributed to a better understanding of this family. Taking into account the mass shifts induced by the threshold of several hadronic channels, it is possible to accommodate the present experimental observations with the expectations of the quark model. These results do not however exclude that some of the scalar resonances, or part of them, have to be interpreted in terms of more complex systems, like four quark objects or meson-meson virtual bound states.

REFERENCES

- Achasov N N et al. 1980 Phys. Lett. 96B 168.
- Aguilar-Benitez M et al. 1978 Nucl. Phys. B140 73.
- Aguilar-Benitez M et al. 1981 Zeitschr. für Phys. 10 299.
- Antipov Yu et al. 1973 Nucl. Phys. B63 141.
- Apel W D et al. 1979 Phys. Lett. 83B 131.
- Armenteros R et al. 1964 Phys. Lett. 9 207.
- Aschman D 1982 Moriond Workshop on New Flavours (Tran Thanh Van ed.).
- Ascoli G et al. 1970 Phys. Rev. Lett. 25 962.
- Ascoli G et al. 1973 Phys. Rev. D7 669.
- Ascoli G et al. 1974 Phys. Rev. D9 1963.
- Astier A et al. 1967 Phys. Lett. 25B 294.
- Astier A et al. 1969 Nucl. Phys. B10 65.
- Aston D et al. 1981 Phys. Lett. 106B 235.
- Atkinson D et al. 1973 Nucl. Phys. B54 263.
- Atkinson D et al. 1975 Nucl. Phys. B98 521.
- Baillon P et al. 1967 Nuovo Cim. 50A 393.
- Basdevant J L and Berger E 1977 Phys. Rev. D16 657.
- Baubillier M 1967 Université de Paris Ph.D. unpublished.
- Becker H et al. 1979 Nucl. Phys. B151 46.
- Bellini G et al. 1963 Nuovo Cim. 29A 896.
- Berger E L et al. 1979 Phys. Rev. D19 2595.
- Bizzarri R et al. 1969 Nucl. Phys. B14 169.
- Bowler K C et al. 1975 Nucl. Phys. B97 227.
- Bramon A and Masso E 1980 Phys. Lett. 93B 65.
- Bramon A and Masso E 1981 Universidad Autonoma, Barcelona, UAB-FT-79.
- Brandenburg G W et al. 1976 Phys. Rev. Lett. 36 703, 706.
- Brandenburg G W et al. 1977 Nucl. Phys. B127 509.
- Carruthers P 1971 Phys. Rep. C1 1.
- Cason N M et al. 1976 Phys. Rev. Lett. 36 1485.
- Chaloupka V et al. Phys. Lett. 44B 211.
- Chanowitz M 1981 Phys. Rev. Lett. 46 987.
- Cohen D et al 1980 Phys. Rev. D22 2595.
- Crennell D et al. 1972 Phys. Rev. D6 1220.
- Dalitz R H 1965 High Energy Physics, Les Houches 1965 p. 273 (C De Witt, M Jacob ed.).
- Dankowych J A et al. 1981 Phys. Rev. Lett. 46 580.

REFERENCES (Cont'd)

- Daum C et al. 1981a Nucl. Phys. B182 269.
Daum C et al. 1981b Nucl. Phys. B187 1.
Deck R T 1964 Phys. Rev. Lett. 13 169.
Defoix Ch et al. 1972 Nucl. Phys. B44 125.
Diaz J et al. 1970 Nucl. Phys. B16 239.
Diaz J et al. 1974 Phys. Rev. Lett. 32 260.
Dionisi C et al. 1981 Nucl. Phys. B169 1.
Estabrooks P et al. 1978 Nucl. Phys. B133 490.
Estabrooks P 1979 Phys. Rev. D19 2678.
Evangelista C et al. 1981 Nucl. Phys. B178 197.
Ferbél T 1981 16ème Rencontre de Moriond (Vol. 2) (Tran Thanh Van ed.).
Flatté S M 1976 Phys. Lett. 63B 224.
Frenkiel P et al. 1972 Nucl. Phys. B47 61.
Fujii Y and Fukigita M 1975 Nucl. Phys. B85 179.
Gavillet Ph et al. 1977 Phys. Lett. 69B 119.
Gay B et al 1976 Phys. Lett. 63B 220.
Gell-Mann M 1962 Phys. Rev. 125 1067.
Gell-Mann M 1964 Phys. Lett. 8 214.
Gidal G et al. 1981 Phys. Lett. 107B 153.
Goldberg J 1976 Lett. Nuovo Cim. 17 253.
Gorlich L et al. 1980 Nucl. Phys. B174 16.
Grässler W et al. 1977 Nucl. Phys. B121 189.
Grayer G et al. 1974 Nucl. Phys. B75 189.
Gurtu A et al. 1979 Nucl. Phys. B151 181.
Hey A J G and Morgan D 1978 Rep. Prog. Phys. 41 675.
Hyams B et al. 1973 Nucl. Phys. B64 134 162.
Intermann G W and Greenhut G K 1980 Phys. Rev. 220 1669.
Irving A 1976 Nucl. Phys. B105 491.
Irving A 1977 Nucl. Phys. B121 176.
Irving A Martin A D and Dones P J 1981 Zeitschr. für Phys. 10 45.
Ishikawa K 1981 Phys. Rev. Lett. 46 978.
Jaffé R L 1975 Phys. Lett. 41 271.
Jaffé R L 1977 Phys. Rev. D15 267.
Karshon U et al. 1974 Phys. Rev. Lett. 32 852.
Kasper P et al. 1979 Nucl. Phys. B156 207.

REFERENCES (Cont'd)

- Lipkin H A 1982 Phys. Lett. 109B 326.
Loverre P F et al. 1980 Zeitschr. für Phys. C6 187.
Martin A D Ozmutlu E N and Squires E J 1977 Nucl. Phys. B121 514.
Martin A D and Pennington M R 1978 Ann. Phys. 114 1.
Martin A D et al. 1978a Phys. Lett. 74B 417.
Martin A D et al. 1978b Nucl. Phys. B134 392.
Martin A D and Ozmutlu E N 1979 Nucl. Phys. B158 520.
Martin A D 1981 Nucl. Phys. B179 33.
Montanet L and Rogers A 1975 CERN/EP Internal Note (unpublished).
Montanet L 1980 XXth Int. Conf. High Energy Phys. Madison 1980 (L. Durand, L.G. Pondrom ed.).
Morpurgo G 1965 Physics 2, 95.
Morgan D 1974 Phys. Lett. 51B 71.
Nacasch R et al. 1978 Nucl. Phys. B135 203.
Ne'eman Y 1961 Nucl. Phys. 26 222.
Okubo S 1978 Sup. to Prog. of Theor. Phys. 63 1.
Ono S and Pène O 1982 Phys. Lett. 109B 101.
Particle Data Group (PDG) 1982 to be published in Phys. Lett.
Pawlicki A J et al. 1975 Phys. Rev. D12 631.
Pernegr J et al. 1978 Nucl. Phys. B134 436.
Pinsky S 1982 Moriond Workshop on New Flavours (Tran Thanh Van ed.).
Polychronakos V A et al. 1979 Phys. Rev. D19 1317.
Ratcliff B N 1981 16th Rencontre de Moriond (Vol. 2) (Tran Thanh Van ed.).
Robson D 1977 Nucl. Phys. B130 328.
Rodeback S et al. 1981 Zeitschr. für Phys. C9 9.
Scharre D L et al. 1980 Phys. Rev. Lett. 97B 329.
Schnitzer H 1981 16th Rencontre de Moriond (Vol. 2) (Tran Thanh Van ed.).
Tabak M et al. 1974 4th Int. Conf. Exp. Meson Spectroscopy Boston 1974 (D. Garelick ed.).
Törnqvist N 1981 Helsinki University Preprint HU-TFT 81-37.
Törnqvist N 1982 Helsinki University Preprint HU-TFT 82-1.
Vergeest S M et al. 1976 Phys. Lett. 62B 471.
Wagner W et al. 1980 Zeitschr. für Phys. C3 193.
Wetzel W et al. 1976 Nucl. Phys. B115 208.
Wicklund A B et al. 1980 Phys. Rev. Lett. 45 1469.
Yndurain F J 1975 Nucl. Phys. B88 316.
Zweig G 1964 CERN/TH/401 and CERN/TH/402 (preprints).

FIGURE CAPTIONS

- Fig. 1 Intensity of the $\pi^+\pi^-$ S-wave obtained by CCM (Becker 1979).
- Fig. 2 The K^+K^- effective mass spectrum and moments of the angular distribution. The p_M^L moments for the $\pi^+\pi^-$ results (Becker 1979) are shown as full lines. Open circles in the mass distribution show the raw data (Görlich 1980).
- Fig. 3 Intensity of the K^+K^- partial waves obtained by CCM (Görlich 1980). Open circles denote possible other solutions. The $|D_0|^2$ and $|F_0|^2$ curves show the results of the fits assuming the coherent contributions of the $f(1270)$, $A_2(1310)$ and $f'(1515)$ for the D-wave and the contribution of the $g(1700)$ for the F-wave. The $|P_0|^2$ curve represents the SU(3) prediction of the ρ -meson tail decaying into K^+K^- .
- Fig. 4 Intensity of the large S-wave solution of the EMSA Group (Cohen 1980).
- Fig. 5 Comparison of the $\langle Y_2^0 \rangle K_S^0 K_S^0$ data (Cason 1976) to the predictions deduced from the large S-wave solution of the EMSA Group (Cohen 1980).
- Fig. 6 Intensity and phase of the $I = 1$ and $I = 0$ K^+K^- S-waves obtained by the EMSA Group (Cohen 1980).
- Fig. 7 Argand plot for the $\pi\pi \rightarrow K\bar{K}$ scattering obtained by the EMSA Group (Cohen 1980).
- Fig. 8 t -dependence of the $I = 0$ and $I = 1$ S-waves (Cohen 1980).
- Fig. 9 t -dependence of the large $I = 0$ S-wave detected by Martin 1978c and compared to the $I = 1$ S and P waves, $|S_B|^2$ and $|\rho|^2$ respectively of Cohen 1980. Also shown are the natural and unnatural parity projection cross section for the $A_2(1310)$ (Martin 1979).

FIGURE CAPTIONS (Cont'd)

- Fig. 10 The $I = 0$ S-wave obtained by Martin 1979. The $|P_0|$ curve represents the contribution of the P-wave, the δ tail curve is an estimate of the $\delta(980)$ contribution.
- Fig. 11 Production parameters obtained by Ratcliff 1981 for the reaction $K^-p \rightarrow K^-\pi^+n$.
- Fig. 12 Argand plot for the $I = 1/2$ $K\pi \rightarrow K\pi$ S-wave scattering (Ratcliff 1981).
- Fig. 13 The $\pi^+\pi^-$ S-wave intensity observed for the $p\bar{p}$ annihilations at rest: $p\bar{p} \rightarrow \omega^0\pi^+\pi^-$ (Frenkiel 1972).
- Fig. 14 The $\pi^+\pi^-$ S-wave intensity observed for the $p\bar{p}$ annihilations at rest: $p\bar{p} \rightarrow 2\pi^+2\pi^-$ (Diaz 1970).
- Fig. 15 Inelasticity of the $\pi^+\pi^-$ S-wave (Hyams 1973).
- Fig. 16 The $K_s^0K_s^0$ threshold enhancement observed in $p\bar{p} \rightarrow K_s^0K_s^0\pi^+\pi^-$ (Aguilar-Benitez 1978). The full line curve represents the results of a fit with a $S^*(990)$ Breit-Wigner with $M = 1040$ MeV and $\Gamma = 65$ MeV.
- Fig. 17 Best fit obtained by Aguilar-Benitez 1978 to the $\pi\pi$ S-wave phase shift and inelasticity of Hyams 1973 and to the $K_s^0K_s^0$ mass spectrum.
- Fig. 18 The $\pi^+\pi^-$ mass spectrum observed in the reaction $K^-p \rightarrow \Lambda\pi^+\pi^-$ (Aguilar-Benitez 1981). The curve represents the results of a fit with a pole at $(966-24i)$ MeV (Irving 1981).
- Fig. 19 Diagrams representing two possible production schemes for the $S^*(990)$.

FIGURE CAPTIONS (Cont'd)

- Fig. 20 Inclusive dipion mass spectrum from the decay of the J/ψ . The curve is the result of the coupled channel fit (Gidal 1981).
- Fig. 21 Dipion mass spectrum for the events which fit $\psi \rightarrow \phi \pi^+ \pi^-$ with $\phi \rightarrow K^+ K^-$ (Gidal 1981).
- Fig. 22 $\eta \pi^-$ mass spectrum for the events which fit $K^- p \rightarrow \Sigma^+(1385) \eta \pi^-$, with $\Sigma(1385) \rightarrow \Lambda \pi^+$ (Gay 1976). The curve is the result of the fit with an S-wave $\eta \pi$ Breit-Wigner with $M = 981$ MeV, $\Gamma = 55$ MeV.
- Fig. 23 Diagrams representing the production mechanism assumed for the $A_1(1240)$ and associated background.
- Fig. 24 Layout of the experimental set-up used by Daum 1981a and 1981b, to study the (3π) and $(K\pi\pi)$ diffractively produced systems.
- Fig. 25 Intensities of the important waves contributing to the diffractive production of the (3π) system (Daum 1981a).
- Fig. 26 The relative phases of the important waves contributing to the diffractive production of the (3π) system (Daum 1981a). All the phases are measured with respect to $1^+ S_0^+ (\rho\pi)$.
- Fig. 27 Variation of the $1^+ S_0^+$ intensity with the 3π mass for four selections of t' :
 (a) $0 < |t'| < 0.05$ GeV², (b) $0.05 < |t'| < 0.7$ GeV²,
 (c) $0.16 < |t'| < 0.30$ GeV², (d) $0.30 < |t'| < 0.70$ GeV²,
 (Daum 1981a).
- Fig. 28 Phase variation of the $1^+ S_0^+ (\rho\pi)$ wave with respect to other waves (Daum 1981a).
- Fig. 29 Intensities for the natural parity exchange, nuclear helicity flip amplitudes for the reaction $\pi^- p \rightarrow \pi^+ \pi^- \pi^0 n$ (Dankowych 1981).

FIGURE CAPTIONS (Cont'd)

- Fig. 30 Intensities of the natural parity exchange, non-flip nuclear helicity amplitudes for the reaction $\pi^- p \rightarrow \pi^+ \pi^- \pi^0 n$ (Dankowych 1981).
- Fig. 31 Relative phases variations for natural parity exchange, nucleon helicity flip amplitudes. The curves show the results of the fit with an $A_1(1240)$ and an $H(1200)$ Breit-Wigner resonance, respectively for the $I = 1$ and $I = 0$ amplitudes. The dashed curves correspond to a fit with no coherent background, the solid curves correspond to the best fit which allows the introduction of a Deck type coherent background (Dankowych 1981).
- Fig. 32 The $K^- \pi^+ \pi^-$ mass spectrum produced at low t . The two peak structure is clear in the Q enhancement (~ 1300 MeV). The $K\omega$ mass spectrum is shown as an insert (Daum 1981b).
- Fig. 33 Partial wave intensities and phases in the Q region for the $1^+ 0^+$ waves and $0 < |t'| < 0.05$ GeV^2 . The phases are measured with respect to $1^+ S0^+ (K^* \pi)$ and the curves show the fits obtained with two Q resonances and a coherent background. The calculated $1^+ S0^+ (K^* \pi)$ and the curves show the fits obtained with two Q resonances and a coherent background. The calculated $1^+ S0^+ (K^* \pi)$ phase variation is also shown (Daum 1981b).
- Fig. 34 Same distributions as in fig. 33, but with $0.05 < |t'| < 0.70$ GeV^2 (Daum 1981b).
- Fig. 35 Partial wave intensities and phases in the Q region for the $1^+ 1^+$ waves and $0.05 < |t'| < 0.70$ GeV^2 . The phases are measured relative to $1^+ S0^+ (K^* \pi)$ (Daum 1981b).
- Fig. 36 $(K\bar{K}\pi)^0$ effective mass distribution for the combined sample of five-body annihilations $\bar{p}p \rightarrow K_S^0 K^{\pm} \pi^{\mp} \pi^+ \pi^-$, $K_S^0 K_S^0 \pi^+ \pi^- \pi^0$, $K_S^0 K^{\pm} \pi^{\mp} M$. The curve is the result of a mass fit to the D^0 enhancement, giving $M = 1282.0 \pm 2.0$ MeV and $\Gamma = 28.3 \pm 6.7$ MeV (Nacasch 1978).

FIGURE CAPTIONS (Cont'd)

- Fig. 37 $\eta\pi^+\pi^-$ effective mass from the reaction $\pi^-p \rightarrow \eta\pi^+\pi^-\pi^-p$ (Evangelista 1981).
- Fig. 38 $\eta\pi^\pm$ effective mass distribution from the $\eta\pi^+\pi^-$ mass combinations lying in the D^0 mass region (Evangelista 1981).
- Fig. 39 $(K_S^0 K^\pm \pi^\mp)$ effective mass squared distribution from the $p\bar{p}$ annihilations at rest: $p\bar{p} \rightarrow K_S^0 K^\pm \pi^\mp \pi^\mp$ (two combinations per event). The dotted histogram corresponds to the double charged $(K_S^0 K^\pm \pi^\pm)$ combinations. The curve is the best fit obtained for the mass spectra and angular distributions for a $J^P = 0^-$ E meson with $M = 1425$ MeV and $\Gamma = 80$ MeV (Baillon 1967).
- Fig. 40 (a) Variation of $2^+ D1^+$ intensity with 3π mass. The curve is the result of a fit with the sum of a D-wave Breit-Wigner intensity and an exponential background intensity; (b) and (c) the phase of the $2^+ D1^+$ amplitude measured with respect to the other five waves important in the A_2 mass region. The curves are the phase of the fitted D-wave Breit-Wigner amplitude resulting from the fit to the mass distribution alone (Daum 1981a).
- Fig. 41 Argand plot for the $K\pi$ D-wave (Ratcliff 1981).

FIG. 1

FIG. 2

b) $m_{KK}(\text{GeV})$

a) $m_{KK}(\text{GeV})$

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

Fig. 9

Fig. 10

Fig. II

Fig. 12

FIG. 13

FIG. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig.21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig.28

Fig. 29

Fig. 30

Fig. 31

FIG. 32

FIG. 33

FIG. 34

$M_{K\pi\pi}$ GeV

FIG. 35

FIG. 36

FIG. 37

FIG. 38

FIG. 39

FIG. 40

FIG . 41