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Issues in Light Hadron Spectroscopy

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Issues in Light Hadron Spectroscopy¹

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Abstract

A high priority in light spectroscopy is to seek out and characterize various types of non- $(Q\bar{Q})$ meson. The large quantity of new data now appearing will present a great opportunity. To identify the non- $(Q\bar{Q})$ intruders one needs to know the regular $(Q\bar{Q})$ pattern well; whole meson families thus become a target for close investigation.

A powerful discovery strategy is to observe the same meson in a variety of reactions. Because mesons appear as resonances, other dynamics can distort the signal in a particular decay channel. Unitarity is the master principle for co-ordinating various sightings of the same resonance. Much of the new spectroscopic information in prospect will come from inferring two-body dynamics from three-body final states. Conventional methods of analysis via the isobar model use approximations to unitarity that need validation.

Of all the meson families, the scalars should be a prime hunting ground for non- $(Q\bar{Q})$'s. Even before the advent of the new results, some revisions of the 'official' classifications are urged. In particular, it is argued that the lightest broad $I = 0$ scalar is a very broad f_0 (1000). One unfinished task is to decide whether f_0 (975) and a_0 (980) are alike or different; several non- $(Q\bar{Q})$ scalar scenarios hinge on this. To settle this, much better data on $K\bar{K}$ channels is needed.

¹Based on an invited talk given at the international spectroscopy conference, Hadron '93, held at Villa Olmo, Como, Italy, June 21-25, 1993.

1 Introduction

I survey immediate prospects for advances in light spectroscopy mid 1993⁽¹⁾. Leaving aside many difficult conceptual problems ⁽²⁾ to which we will have to return another year, the present focus is mesons, in particular non- $(Q\bar{Q})$ mesons ⁽³⁾. To pursue non- $(Q\bar{Q})$ candidates, we need good information on the regular $(Q\bar{Q})$ spectrum. This has been increasingly available in latter years as illustrated by the Regge plot of natural parity non-strange mesons shown in Fig 1. Note the substantial progress in resolving the spectrum of ρ, ω and ϕ excitations of recent years ⁽⁴⁾. This illustrates the value of being able to correlate results from alternative production processes (Sect. 3).

Establishing the existence and measuring the properties of light mesons tends to be a highly non-trivial undertaking. Recall the saga that has preceded our present understanding of the a_1 (1260). In contrast to the simplicities of heavy quark systems, raw experimental findings can be quite misleading. For that reason, much of this survey is devoted to methodology. After a lightning tour of non-(-standard) $Q\bar{Q}$ systems (Sect. 2) and of alternative production processes (Sect. 3), I dwell in some detail on various aspects of resonance classification and the extraction of resonant signals from experiment (Sect. 4). The master principle is unitarity. A problematic aspect of topical importance concerns the analysis of three-body final states to infer two-body dynamics.

Many of the potential complications as to how resonances manifest themselves are exemplified in the scalar system; it is also singled out by models of meson composition as the likely repository for all manner of non- $(Q\bar{Q})$ entities. Much new spectroscopic information is now forthcoming from experiments at LEAR and elsewhere ⁽⁵⁾. Section 5 is therefore devoted to a survey of the pre-existing pattern into which the new information must fit. Some re-assessments of the 'official' classifications are urged; in particular, it is argued that the lightest broad $I = 0$ scalar is a very broad f_0 (1000).

A recent claim to find evidence for a narrow f_0 (750) is examined and found to be unconvincing. Many scenarios for non- $(Q\bar{Q})$ scalars turn on the question: are f_0 (975) and a_0 (980) alike or different? Accurate $K\bar{K}$ data is needed to settle this.

Following this introduction, the sections are entitled:

2 – Types of non-(-standard) $(Q\bar{Q})$ systems; 3 – Alternative production processes; 4 – Discovering and characterizing resonances; 5 – Scalar mesons; 6 – Conclusions and outlook.

2 Types of non (-standard) ($Q\bar{Q}$) systems

In the following, I mainly focus on states below 1.8 GeV.

According to the quark model and QCD ⁽⁶⁾, most known mesons correspond to simple, non-relativistic $Q\bar{Q}$ compounds (to be called M_2 states) which group into flavour nonets distinguished by their orbital and radial excitations. We are seeking states that, in one way or another, depart from this pattern.

Table 1 lists various types of non-standard meson and possible signatures of non- $(Q\bar{Q})$ composition that have been suggested. Of these latter, exotic quantum numbers are obviously decisive. Thus settling the resonance status of candidates with this feature, notably the $\hat{\rho}$ (1405) P wave $\pi\eta$ resonance reported by GAMS ⁽⁷⁾, is of the utmost importance. Likewise, we need to check on the resonance, or more likely non-resonance, status of the broad $I = 2$ threshold enhancement seen in $\gamma\gamma \rightarrow \rho\rho$ ⁽⁸⁾. However, theory and models suggest and experiment seems to confirm that most non- $(Q\bar{Q})$ states will not be thus distinguished and must be sought among ordinary J^{PC} families. Here, unusual production and decay attributes may assist in identification but the prime discovery strategy is to establish the existence of extra states additional to the standard $(Q\bar{Q})$ spectrum. The spotlight of scrutiny has therefore to be directed on to whole families - e.g. $I = 0$ scalars below 1.8 GeV - rather than on individual states. Nonetheless, the types of non- $(Q\bar{Q})$ states listed in Table 1 have their own taxonomies which should help in classifying candidates.

The two non- $(Q\bar{Q})$ species to receive most attention either contain additional constituent quarks or constituent gluons ⁽²⁾ (cf. Table 1). The first group comprises not only molecules ⁽⁹⁾, (M_2, M'_2) but other four and more quark configurations like $(QQ\bar{Q}\bar{Q})$ ⁽¹⁰⁾, including $(N\bar{N})$ bound states ⁽¹¹⁾. Here, I concentrate on molecules, of which different kinds are discussed. All emphasise S -states. The first category, which has a specific (concealed strangeness) flavour structure $K\bar{K}, K\bar{K}(+c.c.)$ etc.⁽¹²⁾, provides the most popular description of the seemingly anomalous and narrow $I = 0$ and 1 scalars f_0 (975) and a_0 (980). The molecule picture predicts a large coupling to $K\bar{K}$ and small and equal $\gamma\gamma$ widths for f_0 and a_0 . On this view, f_0 and a_0 are highly similar structures and we need to find alternative $I = 0$ and 1 candidates for the ground state $(Q\bar{Q})$ nonet. As we shall see, the $I = 1$ spectrum is experimentally much less complicated so perhaps the more promising channel to provide decisive information. Other models make different predictions and we await the verdict of experiment.

Törnqvist ⁽¹³⁾ has proposed a second type of molecule where, as for the

deuteron, the constituents bind by one pion exchange (OPE). By considering different compositions that are allowed by the (OPE) mechanism, he arrives at the following tentative assignments:

$$\begin{aligned}
(\omega\omega + \rho\rho) &\longleftrightarrow AX/f_2(1520)? \\
(\omega\omega - \rho\rho) &\longleftrightarrow f_0(1590)? \\
K^*\bar{K}^* &\longleftrightarrow \theta/f_0(1710)? \\
K\bar{K}^* &\longleftrightarrow f_1(1540)?
\end{aligned}$$

Ericson and Karl (¹⁴) have suggested that Törnqvist's criterion for binding needs refinement.

The other group of non- $(Q\bar{Q})$ species to be considered features mesons built wholly or partly from glue (called Chromocules in Table 1). Both glueballs (GG) and hybrids like $(Q\bar{Q}G)$ arise within theoretical schemes that describe large distance, confining QCD (¹⁵). Hybrids are generally expected to be heavier than 1.8 GeV and I shall ignore them.

In order of ascending mass, the lightest glueballs should be the scalar, tensor and pseudo-scalar. Rather specific predictions emerge from pure SU(3) gauge theory calculations (i.e. omitting dynamical quarks) on the lattice; typical modern findings are (¹⁶):

$$\begin{aligned}
m_{GG}(0^{++}) &= 1550 \pm 50 \text{ MeV} \\
m_{GG}(2^{++}) &= 2270 \pm 100 \text{ MeV} \\
m_{GG}(0^{-+})/m_{GG}(2^{++}) &\gtrsim 1.0
\end{aligned} \tag{1}$$

Insertion of dynamical quarks with realistic light quark masses may considerably modify these values. Meanwhile, they afford a first guide to the masses and especially mass-ratios that may be anticipated. Optimists can readily find candidates among the rich spectrum of $I = 0$ scalars and tensors that experiment provides. Actually proving that such a candidate really is a glueball is hard, although there are a number of properties, like having SU(3) symmetric decays, that one would expect to observe (³).

Also listed in Table 1 are states that do have a $Q\bar{Q}$ composition but of a non-standard type. I first discuss the 'novel hadrons' that arise in Gribov's picture of the QCD vacuum (¹⁷). It is interesting to examine this new scheme alongside more familiar molecular possibilities because of the novel phenomena that it entails (¹⁸). According to Gribov, confinement is due to the formation of a $(q\bar{q})$ condensate involving the very light quarks u and d . Gribov's 'novel hadrons' or 'minions' are

compact ($\sim 1 \text{ GeV}^{-1}$) ($u\bar{u} \pm d\bar{d}$) scalar and pseudo-scalar excitations of this new vacuum. Suggested candidates for the scalar minions are f_0 (975) and a_0 (980) for which the following properties are predicted ⁽¹⁸⁾:

- comparable coupling to $\pi\pi$ and $K\bar{K}$ ⁽¹⁹⁾
- suppressed decay to ‘normal’ hadrons ($\Gamma(f_0 \rightarrow \pi\pi) \sim \frac{1}{10}\Gamma(a_1 \rightarrow \rho\pi)$)
- $\Gamma(\gamma\gamma \rightarrow f_0)/\Gamma(\gamma\gamma \rightarrow a_0) = 25/9$

(recall this last ratio is expected to be 1:1 on the ($K\bar{K}$) molecule picture). There are also predictions for various hard processes ⁽¹⁸⁾.

All the above agencies yield extra states to the standard ($Q\bar{Q}$) spectrum. However, as emphasised by Törnqvist ⁽²⁰⁾, the conventional nonet mass and mixing patterns may also be appreciably distorted by final state interactions (Fig 2). This is likely to be most pronounced for very broad states, e.g. scalars (see Sect. 5 below) and this has been recently confirmed in detailed calculations by Geiger and Isgur ⁽²¹⁾. These latter authors find that, compared to naive quark model estimates, the $I = 0$ scalars experience considerable distortions; the initially non-strange state ($u\bar{u} + d\bar{d}$) has its mass depressed by several hundred MeV and its initially ($s\bar{s}$) counterpart by some 50 MeV with associated change of flavour composition to an approximately octet make-up. Such possibilities need to be borne in mind in attempting to classify the 0^{++} spectrum delivered by experiment. Whilst not adding to the total number of states, it complicates the quest for non-($Q\bar{Q}$) states by distorting the standard mass and flavour patterns.

Yet another potential source of confusion occurs where opening inelastic channels provide a source of non-resonant enhancement. The broad peaking observed in $\gamma\gamma \rightarrow \rho^0\rho^0$ and $\rho^+\rho^-$ cross-sections above threshold ⁽⁸⁾ (which if resonant entail $I = 2$ as well as $I = 0$ states) are probably of this type.

A favourite way to identify non-($Q\bar{Q}$) candidates is to discover states that appear to be extra to the standard ($Q\bar{Q}$) spectrum. One therefore needs a comprehensive model of the ‘normal’ ($Q\bar{Q}$) spectrum (complete with radial excitations) to serve as a template against which to measure abnormalities. One such description (for other possibilities see ⁽²²⁾) is provided by the non-relativistic potential model of Godfrey and Isgur ⁽⁶⁾ and the resulting comparison for $I = 0$ scalars and tensors is shown in Fig. 3. The format is adapted from the excellent review of Burnett and Sharpe ⁽³⁾ with the experimental information updated (details of Fig. 3 are discussed below). These authors show similar diagrams for $I = 0$ unnatural parity levels 1^{+-} and 0^{-+} , not shown here since the phenomenological situation is essentially unchanged. Each of the 1^{+-} and 0^{-+} families appears to possess a ‘spare’ $I = 0$ state. The most likely non-($Q\bar{Q}$) candidates that result

are, for 1^{++} , f_1 (1420), and for 0^{-+} , η (1420), the lighter of the two states into which ι/η (1440) seems to be resolved ⁽²³⁾. Confirming and refining our classification of these unnatural levels is just as important as the corresponding exercise for the natural families but not a prime concern for this year from lack of new experimental input.

The low mass channels like $\eta\pi\pi$ that dominate decays of these low spin unnatural parity families are quite distinct from those that couple to the natural parity levels of Fig. 3. For this reason, study of the unnatural levels – the η 's, f_1 's and h 's – tends to be largely decoupled from that of the corresponding scalars and tensors. It is on these latter that copious information is presently emerging from LEAR⁽⁵⁾ and elsewhere and which will dominate the following discussion.

Fig. 3 shows the experimental situation for $I = 0$ scalars and tensors prior to this meeting. The reason for displaying both spectra together is that scalars and tensors usually couple to the same final states and have to be distinguished by somewhat fallible amplitude analysis; ambiguities and changes of J^P assignment are not infrequent as we shall see.

In all but a few cases, the states shown have been accorded 'confirmed' states in the 1992 Particle Data Tables ⁽²⁴⁾ (henceforth PDG92). (The case for f_0 (1000) is presented in Sect. 5.) Of other 'unconfirmed' states listed in ⁽²⁴⁾, only f_2/AX (1520), f_0 (1525) and f_2 (1810) are included here. 'Confirmed' states are indicated either by open diamonds, \diamond , or circles, \circ , according to whether they are conventionally viewed as $(Q\bar{Q})$ or non- $(Q\bar{Q})$ candidates. 'Unconfirmed' states have question marks; other annotation is explained below and in the caption. θ (1710) ('confirmed') is one of the states for which the favoured J^P assignment has fluctuated. PDG92 follows the MK III collaboration ⁽²⁵⁾ in revising the original 2^{++} finding to 0^{++} – hence f_0 (1710); however, WA76 still report a preference for 2^{++} on the basis of larger statistics ⁽²⁶⁾. Fig. 3 shows both alternatives. As we shall hear ⁽²⁷⁾, a similar tensor-scalar ambiguity seems to arise for the f_2/AX (1520) with a large part of the former pure-tensor signal re-assigned to 0^{++} . The f_0 (1525) decaying to $K\bar{K}$ reported by LASS ⁽²⁸⁾ could be another facet of this state but would then cease to be a natural candidate for the $(s\bar{s})$ quark model state. Yet another scalar signal in this same mass region is the f_0 (1590) of GAMS ⁽²⁹⁾. Much more work is needed to see if f_0 (1525) is really distinct from this.

There are two other aspects of the low-mass f_0 spectrum to which I return in Sect. 5. Firstly, I re-state and amplify the suggestion ⁽³⁰⁾ that the lightest broad $I = 0$ scalar is not f_0 (1400) as recommended by PDG92 but a very broad f_0 (1000). Secondly, I examine and argue against Svec et al's claim to identify a

narrow $f_0(750)$ signal ⁽³¹⁾.

3 Alternative Production Processes

Getting data on mesons means studying meson resonances. A good way to enlarge our knowledge is to study the same final state in different production reactions. This is how our knowledge of vector mesons has been enlarged and refined by collating formation experiments in e^+e^- annihilation and diffractive photo-production ⁽⁴⁾.

Fig. 4 illustrates some of the major reactions that have powered meson spectroscopy but is obviously not exhaustive. Sundry decay processes like K_{e4} have also provided vital information. Different reactions have been emphasised at different epochs as experimental facilities have evolved. Studies of non-diffractive peripheral reactions like $\pi N \rightarrow \pi\pi N$ thus preceded the corresponding studies of central production. In fact, they provide powerfully complementary information; this can be yet further re-inforced by suitable data on decays. Thus properties of $f_0(975)$ are extracted from joint analysis of peripheral and central production and D_s and $J/\psi \rightarrow \phi\pi\pi(K\bar{K})$ decays ⁽³⁰⁾. The guiding principle for such analyses is the enforcement of unitarity (Sect. 4).

Of the various production processes illustrated in Fig. 4, some have been singled out for their potential selectivity of different kinds of meson. For example, two-photon formation of a resonance should be directly related to its charged constituents; the resulting relations among 2γ widths of members of the tensor nonet are well-fulfilled ⁽³²⁾. Within the quark model, the widths for corresponding members of different nonets belonging to the same L-band, e.g. 0^{++} and 2^{++} , are simply related. A purely non-relativistic calculation, ⁽³³⁾ yields a ratio $\Gamma(0^{++})_{Q\bar{Q}}/\Gamma(2^{++})_{Q\bar{Q}} = 15/4$ (times relative phase space factors); relativistic corrections are estimated to reduce the ratio to near two ⁽³⁴⁾. A good way to establish the credentials of $(Q\bar{Q})$ scalar candidates is therefore to observe the expected production in two-photon processes ⁽³⁵⁾ (scalar glueballs and molecules are expected to have much smaller 2γ -widths than the corresponding $(Q\bar{Q})$'s⁽³⁶⁾). Such processes can be a discovery tool in their own right as exemplified by Crystal Ball's claim to see a new resonant signal, $\eta_2(1870) \rightarrow \eta\pi\pi$ $0^+(2^-)$, in $\gamma\gamma \rightarrow \eta\pi\pi$ ⁽³⁷⁾.

In the same simple-minded spirit, other types of reaction should be glue-rich and favour the production of glueballs. The favourite and best studied example has been J/ψ EM decay where the partonic evolution leading to the final state

meson should pass through a two-gluon intermediate state. Although new resonances with serious claim to be considered as glueball candidates, η (1440) and θ (1710), were discovered in this reaction ⁽³⁸⁾, many familiar ($Q\bar{Q}$) systems also feature (Fig. 5). This led Chanowitz to seek a more discriminating criterion in the concept of ‘stickiness’ ⁽³⁹⁾

$$S = \frac{\Gamma(J/\psi \rightarrow \gamma X)}{PS(J/\psi \rightarrow \gamma X)} \times \frac{PS(\gamma\gamma \rightarrow X)}{\Gamma(\gamma\gamma \rightarrow X)},$$

which expresses the ‘two-gluon’ relative to two-photon coupling.

A major source of new spectroscopic information at the present time is from the study of $p\bar{p}$ annihilation, typically to final states comprising three pseudoscalars like $3\pi^0$, $\pi^0\pi^0\eta$ and $\pi^0\eta\eta$ ⁽⁴⁰⁾. Most of the new data are on annihilation at rest and huge statistics are involved. Spectroscopic information is sought from study of the pair-wise dynamics of the final state particles, e.g. $\pi^0\pi^0$, $\pi^0\eta$ and $\eta\eta$, using the isobar model. This imports extra uncertainties (see below), as does the fact that both S and P wave ($p\bar{p}$) atomic states can usually contribute ⁽⁴¹⁾. The rich potential of the new data makes it imperative to explore and calibrate these complications.

4 Discovering and characterizing resonances

4.1 General Remarks

Getting data on mesons means studying meson resonances; all but the lightest meson decay via strong interactions. We have to study them via their decay fragments as we do Z^0 and W^\pm and hope to do for the Higgs. The need to identify mesons as resonances in final state interactions gets harder as the resonance widths get larger. Resonance features get more and more entangled with threshold effects and other ‘background’ dynamics. This problem has maximum scope among scalar mesons, a family of prime interest in the quest for non- $(Q\bar{Q})$ ’s of various binds. Once background and threshold effects enter, the same resonance can present a markedly different appearance in different processes. There is an obvious risk of counting different manifestations as different resonances (the morning star \neq evening star fallacy). We need a universal parameterization to cut through such ambiguities. S -matrix principles, especially unitarity, provide the answer and require that we should characterize resonances by the associated poles in the complex energy plane. Resonance poles are universal; by unitarity they occur at the same place in all reactions to which a given resonance couples. They

yield a stable parameterization and are therefore suitable for compilation. This is well exemplified by the satisfactory consistency of alternative determinations of the $f_0(975)$ (Sheet II) pole position from a large variety of reactions ⁽⁴²⁾ in some of which the f_0 appears as a dip, in others as a peak ⁽⁴⁰⁾. How a given resonance appears in a particular process depends on background phases and flux and phase-space factors. All this is encapsulated in the slogan – **not all bumps are resonances and not all resonances are bumps** (cf. Fig. 6).

Now for some assorted remarks:

- (i) K -matrix poles are **not** suitable objects to identify with resonances.
- (ii) When several channels couple, other parameters besides the complex resonance pole (branching ratios or equivalently coupling constants) are needed to specify a resonance.
- (iii) There is no theoretical reason to disallow very broad resonances - quite the contrary, since such objects obviously dominate the corresponding cross-sections in the sense of duality. This is not to say that experimental claims do not need careful scrutiny. Very broad (and for that matter very narrow) resonances are obviously hard to detect and/or establish ⁽⁴³⁾.

4.2 Resonances close to a 2-body S -wave inelastic threshold

Resonances, especially S -wave resonances like $f_0(975)$ and $a_0(980)$, that occur close and couple strongly to an opening inelastic threshold need special treatment ⁽³⁰⁾. There will in general be twin poles corresponding to a given resonance distinguished by the ‘sheet-structure’ of the complex energy plane induced by the inelasticity (Fig. 7). One pole is ‘below threshold’ (technically on Sheet II in the standard convention); the other is ‘above threshold’ (Sheet III). Each pole introduces a distinct mass and width

$$E_R^N \equiv M_R^N - i\Gamma_R^N/2 \quad (N = II, III)$$

Only in the limit of vanishing inelasticity do these poles correspond to the same complex energy. Generally, Γ_R^{III} is greater than Γ_R^{II} and E_R^{III} in consequence more difficult to establish and measure. Very accurate information is needed on the inelastic reaction; otherwise Γ_R^{III} is poorly determined. If a Breit-Wigner description applies, the associated elastic width, Γ_R^{BW} , a quantity that is often cited, for example in attempts to classify groups of particles with the same J^P , is approximately related to the above Γ_R^N by the formula ⁽³⁰⁾

$$\Gamma_R^{BW} = 1/2(\Gamma_R^{II} + \Gamma_R^{III})$$

The difficulty of fixing Γ_R^{III} explains why widths ranging from sixty to several hundred MeV are ascribed to $a_0(980)$ on the basis of the same data. Analysis of this resonance, and of its companion $f_0(975)$, is seriously handicapped for want of accurate measurements of its $K\bar{K}$ decay. As an example of the problems that arise when $K\bar{K}$ information is lacking, the $a_0(980) \rightarrow \pi\eta$ signal seen in $p\bar{p} \rightarrow \pi\eta\eta$ ⁽⁴⁴⁾ is very well fitted assuming **zero** coupling to $K\bar{K}$.

For resonances that occur just below an inelastic threshold, counting nearby poles can distinguish molecules from regular quark model states and chromocules ^(45,46). A molecular resonance generated dynamically by the scattering forces between the individual ‘atoms’ (e.g. K and \bar{K}) can have just one nearby pole; the existence of two nearby poles on sheets II and III points to some other dynamical origin. Thus, from a recent analysis of a wide variety of processes coupling to $f_0(975)$, Michael Pennington and I concluded that present data disfavour a molecular interpretation for this state ⁽⁴⁶⁾.

4.3 Analysis of multi-channel, multi-reaction data enforcing S -matrix constraints

This is a field in urgent need of fresh ideas. The basic principles - unitarity, analyticity and the like - are not in doubt; the problem is how to implement them adequately yet practicably in the situations that we actually encounter. Reactions that are confined to at most a pair of two-body channels give no difficulty. Problems enter when we have to allow for three, four or more channels and also where three (and more) body final states occur. Both of these complications are present in many of the situations that dominate contemporary spectroscopy. For example, a key issue in scalar spectroscopy (Sect. 5) is to decide how many distinct $I = 0$ resonances there are in the region 1.0 to 1.8 GeV. Many signals have been reported in a variety of reactions yet, even at 1.6 GeV, the number of (effective) channels is at least five. How, using unitarity, is all this information to be correlated? The second complication is equally pressing: how three-body final states can be a reliable source of information on two-body dynamics is central to the exploitation of the wealth of data now available on $p\bar{p}$ annihilation ⁽⁴⁰⁾.

Recall the standard procedure when the final states are few and simple. To establish the existence and properties of a resonance, R , we would ideally like to know the partial wave scattering amplitude T_{ij} connecting all the channels that couple to R . Given a complete set of data on all the relevant σ_{ij} (along with suitable phase information from interference with other partial waves), we

would fit to a unitarity enforcing parameterization such as that provided by the K -matrix ⁽⁴⁷⁾

$$T = \tilde{K}(1 - i\rho\tilde{K})^{-1}$$

Once the number of channels with significant coupling exceeds two, a general K -matrix parameterization ceases to be practical and alternative ways of enforcing the major consequences of unitarity have to be found. Some authors have represented \tilde{K} by a sum of pole contributions which are separately unitarized with neglect of ‘cross-talk’ between the resulting resonant terms ⁽⁴⁸⁾. Once resonances are broad and overlapping, such a representation is almost certainly inadequate.

In practice, even when there are just a few channels, data on the T_{ij} ’s is always insufficient and can be usefully supplemented by information on associated **production processes**. Where these are **non-strongly interacting**, unitarity (indicated schematically in Fig. 8) shows that we can express the associated production amplitudes, $F_i^{(p)}$, in terms of the T_{ij} via the relations ⁽⁴⁹⁾

$$F_i^{(p)}(E) = \sum_j \alpha_j(E)T_{ij}(E)$$

where the $\alpha_j(E)$ are smooth real functions of energy. This form guarantees that resonance poles feed through to the $F_i^{(p)}$ and enables the often very precise and fine-grained information from such production processes to be fully harnessed.

Applications usually involve some retreat from the ‘non-strongly interacting’ requirement for the production processes used. A common situation is where there are additional final state particles to those whose dynamics is studied; for example, information on $\pi\pi$ and $K\bar{K}$ dynamics is extracted from the reactions $J/\psi \rightarrow \phi\pi\pi(K\bar{K})$ treating the ϕ as a spectator ⁽³⁰⁾. In most such cases, the effect of this approximation is likely to be small but important questions do arise in one key application – the analysis of three body final states via the isobar model.

This has crucial relevance to the extraction of spectroscopic information from $p\bar{p}$ annihilation at rest to three body final states like $3\pi^0$, $\pi^0\pi^0\eta$ and $\pi^0\eta\eta$ ⁽⁴⁰⁾. The dynamics studied is that of the various **pairs** of final state particles, $\pi^0\pi^0$, $\pi^0\eta$ and $\eta\eta$. Analysis is based on the isobar model whereby the three-body production amplitude (for each atomic partial wave) is firstly written as a sum of three terms (see lower portion of Fig. 4)

$$F^{123} = F^{1;23} + F^{2;31} + F^{3;12}$$

classified according to which pair interacted last. Each term is a sum of partial wave amplitudes $F_{L_{23}}^{1;23}(s_{23})$, that are subject to 2 and 3 body unitarity requirements. The isobar model assumes that ‘crossed re-scattering effects’ from ‘triangle

diagrams', where one of the emerging pair constituents re-groups with the associated spectator ($1(23) \rightarrow 123 \rightarrow (12)3$), are unimportant. Each isobar component then conforms to the previously considered case with two interacting final state particles and a spectator allowing one to write (omitting the angular momentum label L_{23} and restoring the previous channel labels i and j)

$$F_i^{1;23}(s_{23}) = \sum_j \alpha_j(s_{23}) T_{ij}(s_{23})$$

with the pre-factors α_j again real and slowly varying. Given the great spectroscopic potential of the $p\bar{p}$ data now being analysed, crossed re-scattering corrections to the isobar approximation should be evaluated, at least for selected examples, using standard methods⁽⁵⁰⁾.

5 Scalar Mesons

As we have seen, almost all mechanisms for generating meson resonances predict light scalars; in some cases, only scalars are expected in the low mass region. For this reason alone they are of exceptional interest. Add to this the large mass of new data coming on stream and one sees why scalars are this year's most exciting topic. This last section is therefore devoted to some clearing of the ground in preparation for the new results.

I begin with a quick survey of the 'official' 0^{++} spectrum according to PDG92⁽²⁴⁾. I then focus on two particular questions relating to the $I = 0$ spectrum: firstly, I examine and argue against Svec et al's⁽³¹⁾ claim to identify a narrow $f_0(750)$ signal in peripheral dipion production; then, I restate and amplify the assertion⁽³⁰⁾ that the lightest broad $I = 0$ scalar is not $f_0(1400)$ as recommended by PDG92 but a very broad $f_0(1000)$. This has important consequences for our perception of where we believe the $(Q\bar{Q})$ scalars cluster in mass. I end with some general questions and comments.

According to PDG92, the spectrum of scalars below 1800 MeV comprises the states shown in Fig. 9 – excepting of course the $f_0(1000)$. (Notation as for Fig. 3 in which $I = 0$ scalars were already displayed – cf. related discussion in Sect. 2) How does this spectrum accord with what we might or should expect? Given the success of the naive quark model description of the other nonets, 2^{++} , 1^{++} and 1^{+-} , of the $L = 1$ band, we should certainly expect to find an analogous $0^{++}(Q\bar{Q})$ nonet. We need to equip this with the standard $I = 1/2(K_0)$, $I = 1(a_0)$ and pair of $I = 0(f_0)$ members (the latter may or may not be ideally mixed). Over the

years, opinion has fluctuated as to which of the available states provide the most likely occupants for these slots. In all these gyrations, the K_0 (1430) has been a fixture (its mass used to be somewhat lower – indeed the LASS group ⁽⁵¹⁾ who are the source of the present Table values, report a second fit yielding a mass of 1350 MeV, as indicated in Fig. 9). At first, the known scalars were just sufficient to populate a nonet using the broad $f_0(\epsilon)$, K_0 , f_0 (975) and a_0 (980)⁽⁵²⁾. Later the prevailing opinion came to be that these last two were too light and too narrow to be plausible ($Q\bar{Q}$) candidates (despite arguments that final state interactions can induce exceptional mass and mixing shifts for the scalars^(20,21) and the ambiguities in the concept of resonance width for such near threshold states (cf. Sect. 4.2)). Then came the suggestion that f_0 (975) and a_0 (980) could be $K\bar{K}$ molecules ⁽¹²⁾. Finally possible substitute candidates for the vacated ($Q\bar{Q}$) slots were reported in the guise of a_0 (1320), inferred from analysis of $\pi\eta$ production ⁽⁵³⁾ and f_0 (1525) seen in $K\bar{K}$ ⁽²⁸⁾. It was pointed out that, given these replacements, the ensuing ($Q\bar{Q}$) scalar nonet would closely resemble its other $L = 1$ companions - an attractively simple synthesis ⁽⁵⁴⁾. The empirical evidence for the new states is far from compelling. Each relies on amplitude analysis of a single experiment leading to a scalar signal with the same mass and width as a co-present and dominant tensor state. Whether or not these two signals are confirmed, the existence of alternative $I = 0$ and 1 scalar $Q\bar{Q}$'s is of great importance for our understanding of the quark model – hence the interest in new a_0 and f_0 signals now being reported ^(27,40) (the new a_0 signal is indicated in Fig. 9).

The two remaining states shown in Fig. 9, f_0 (1590) and f_0 (1710), both raise very interesting questions to which I return after discussing f_0 spectroscopy at lower energies.

5.1 Resonances seen in $\pi\pi$ and $K\pi$ phase shifts

As we have seen, properties of the narrow scalars, $f_0(975)$ and $a_0(980)$, can be investigated in a whole variety of reactions in which they appear. For $I = 1/2$ and other $I = 0$ dynamics, we must mainly rely on phase shift analyses based on peripheral di-meson production assuming OPE dominance ⁽⁵⁵⁾. (The lack of a similar direct window on $\pi\eta$ $I=1$ phase shifts may perhaps be remedied by a careful study of $\pi\pi\eta$ final states ⁽⁵⁶⁾.)

Fig 10(a) shows the well-known form of the $K\pi$ S -wave phase shift ⁽⁵¹⁾ from which the K_0 (1350-1430) resonance is inferred with width

$$\Gamma_{K_0} = 290 - 350 MeV$$

where I have indicated the spread of values from both resonance fits reported ⁽⁵¹⁾. From this, we learn that **broad S -wave resonances occur**, a fact that has implications throughout the scalar nonet. Interpreting K_0 conventionally as the $(s\bar{n})$ component of an ideal nonet implies that the corresponding $I = 0$ ($u\bar{u} + d\bar{d}$) state decays to $\pi\pi$ with approximately double the above width (and also reinforces doubts concerning the reported $a_0(1320) \rightarrow \pi\eta$ and $f_0(1525) \rightarrow K\bar{K}$ signals as being too narrow). So what do we learn from the corresponding $I = 0$ phase shifts?

The accepted form of this phase shift, δ_0^0 , from threshold to 1.4 GeV ⁽²⁴⁾ is plotted (modulo 180°) as the full line in Fig. 10(c). Before going into the interpretation of this, I briefly examine the challenge by Svec et al ⁽³¹⁾ to this description of δ_0^0 for dipion masses up to 900 MeV. It is first necessary to supply some historical background.

Prior to the high statistics dipion ($\pi^+\pi^-$) production experiments of the early 70's, discussion of the $I = 0$ $\pi\pi$ S -wave phase shift below 1 GeV was beset by an UP-DOWN ambiguity ⁽⁵⁷⁾ (Fig. 10 (b) ⁽⁵⁸⁾). This arose because the S -wave in $\pi^+\pi^-$ production is inferred from interference with the dominant (P -wave) ρ signal. In principle, this should have been resolved by study of $\pi^0\pi^0$ production but the corresponding experiments have delivered a conflicting verdict ⁽⁵⁹⁾. By common consent, the matter was resolved with the DOWN alternative selected once the $f_0(975)$ signal was clearly de-lined ⁽⁶⁰⁾. Svec et al. ⁽³¹⁾ claim to resuscitate the UP solution in an amplitude analysis of their own and earlier Cern-Munich (CM) ⁽⁶¹⁾ dipion production experiments off polarised targets for $\pi^+\pi^-$ in the mass range 600-900 MeV (That this analysis stops at 900 MeV is a significant limitation.) From the CM data at small t , they find an UP and DOWN solution. Their own data at larger t only yields evidence for the UP alternative. From this, they infer the existence of

$$f_0(750) \quad \Gamma(100 - 250)MeV$$

citing Cason et al's 1983 $\pi^0\pi^0$ results ⁽⁵⁹⁾ in support.

I do not think $f_0(750)$ can possibly be a real effect for the following reasons:

- (a) Absence of corresponding signals in $\gamma\gamma$, central production and sundry decay processes – and, even more compellingly –
- (b) The requirement to join on to the $f_0(975)$ signal in $\pi^+\pi^-$. How this works was spelt out by Pennington and Protopopescu back in 1973 ⁽⁶²⁾. Using Roy's equations, they show that given the existence and observed properties of $f_0(975)$, the DOWN solution does and the UP solution does not reproduce itself through the associated dispersion relations. I conclude that we can forget about $f_0(750)$.

So we are back to the standard form for the $I = J = 0$ phase-shift shown in Fig. 10(c) and ready to address the question: **what is the lightest broad $I = 0$ scalar?** For reasons that I examine below, PDG92's answer is $f_0(1400)$ with width $\Gamma = 150\text{-}400$ MeV. In contrast, Michael Pennington and I⁽³⁰⁾ unhesitatingly plump for something in the range⁽⁶³⁾

$$f_0(1000) \quad - \quad \text{width } \Gamma \simeq 700 \text{ MeV} \quad -$$

for the following reasons:

- (i) Analysis of $\pi\pi$ phase shifts from threshold to 1.4 GeV along with an extensive set of related reactions (the AMP analysis⁽⁴⁷⁾) yields a resonance pole at $(900 - i350)$ MeV (c f. Hyams et al's 1973 result of $(1049 - i250)$ MeV⁽⁶⁴⁾).
- (ii) For an intuitive feel as to what is going on⁽³⁰⁾, take the standard form of δ_0^0 , as shown in Fig. 10(c) (full line) and 'remove' the rapid $f_0(975)$ phase excursion. One then sees a slow, steady ascent of the residual phase shift (dashed line) just like $\delta_{K\pi}$ (Fig. 10(a)).
- (iii) Our resonance spectrum now accords well with the weighted mean of the partial-wave cross-section in line with notions of duality.

How does this square with PDG's $f_0(1400)$ and their casting it in the role of lightest broad f_0 ? PDG base their recommendation⁽²⁴⁾ on an assortment of resonance signals derived from $\pi\pi$, $K\bar{K}$ and $\eta\eta$ final states^(65,66,29). They appear to place most reliance on the paper reporting the AFS experiment on $pp \rightarrow pp\pi^+\pi^-$ ⁽⁶⁵⁾; in particular, they cite an amplitude analysis therein that 'shows that [the] $\pi\pi$ S -wave dominates up to 1.6 GeV with no room left for other scalars besides $f_0(975)$ and $f_0(1400)$!' The first thing to say is that the analysis in question is confined to the subset of data with $M_{\pi\pi}$ above 1 GeV (i.e. after the first precipitate fall of the $\pi\pi$ spectrum). The whole $\pi\pi$ spectrum from threshold to 1.4 GeV has in fact been well-fitted along with a large quantity of other $I = 0$ data in the AMP analysis referred to above⁽⁴⁷⁾. Far from excluding $f_0(1000)$, it strongly reinforces it. What the AFS analysis does do is indicate a second f_0 -resonance signal at $(M = 1420 \pm 20 \text{ MeV}$ with width $\Gamma = 460 \pm 50 \text{ MeV}$), seemingly from the need to fit the second dip in their $\pi\pi$ S -wave spectrum⁽⁶⁵⁾.

Other evidences for $f_0(1400)$ cited by PDG come from an assortment of $K\bar{K}$ ⁽⁶⁶⁾ and $\eta\eta$ ⁽²⁹⁾ production experiments, in each case after amplitude analysis to isolate the S -wave signal. The $K\bar{K}$ experiments disagree even on the qualitative form of the S -wave cross-section below 1400 MeV but mostly concur in finding narrow f_0 signals above 1400 (e.g. Etkin et al.⁽⁶⁶⁾ report $f_0(1463)$, width 118 MeV). Analysis of the $\eta\eta$ experiment⁽²⁹⁾ yields a two hump S -wave from which the authors derive a pair of f_0 -resonances. The upper hump provides one of the

major evidences for $f_0(1590)$ to be discussed below. PDG suggest that the lighter GAMS resonance - $f_0(1220)$, width 320 MeV - is another facet of $f_0(1400)$. Given the proximity of the lower peak to $\eta\eta$ threshold, it would seem more natural to make the link to $f_0(1000)$; only multi-channel fits can decide.

What all this adds up to is persuasive evidence for extra S -wave structure above say 1200 MeV without specifying what that structure actually is. For that, we must mostly await the new (and future) data and comprehensive analyses that include them. However, further f_0 signals are already claimed – not only $f_0(1525) \rightarrow K\bar{K}$ from LASS⁽²⁸⁾ (already discussed), but $f_0(1590) \rightarrow \eta\eta$ (and other channels) from GAMS⁽²⁹⁾ and the scalar metamorphosis of the θ , $f_0(1710)$ ⁽²⁵⁾. Each of these last two could occupy key positions in our final classification. Thus, $f_0(1710)$ (provided its scalar/tensor spin ambiguity is final resolved in favour of scalar) could be the first f_0 radial recurrence, whilst $f_0(1590)$ has been proposed as a candidate for the scalar glueball. As evidence for this latter assignment, GAMS⁽²⁹⁾ especially emphasise the 1590's preference for $\eta\eta$ (and according to them a fortiori $\eta\eta'$) decay modes (however this is from the standpoint of a particular non-standard model of scalar glueball decays). The more conventional expectation would entail a straight-forwardly singlet decay pattern without the avoidance of $\pi\pi$ and $K\bar{K}$ decay modes that GAMS stress. It seems not unlikely that, in the final analysis, the GAMS decay modes, $\eta\eta$, $\eta\eta'$ and 4π , will turn out after all to have $\pi\pi$ and $K\bar{K}$ counterparts, perhaps shifted in mass; if so, it will be very interesting to see what $\pi\pi : K\bar{K} : \eta\eta$ ratios prevail. What appears beyond doubt is that there are surplus scalars – thus non- $(Q\bar{Q})$ candidates. Only future data and careful analyses will tell us how many.

I conclude with a pair of questions that are central to how we view the scalar spectrum overall:

(i) **Is $a_0(980)$ the only $I = 1$ S -wave object below, say, 1600 MeV or is there something else?** This has clear and important (but not decisive - see (ii) below) bearing on the identity of the ground state $I = 1(Q\bar{Q})$. Attention has previously been focused on the GAMS $a_0(1320)$ signal⁽⁵³⁾ (whose empirical shortcomings have already been described). Now we are offered an alternative candidate at higher mass by Crystal Barrel^(27,40).

(ii) **Are the $f_0(975)$ and $a_0(980)$ alike or different?** Very different scenarios would ensue if either or both of f_0 and a_0 were shown to have a large 'true' width in the sense of Sect. 4.2. As illustration, suppose f_0 is confirmed as 'narrow'^(30,45,46) but a_0 is found to be 'broad' as several authors have suggested⁽⁶⁷⁾. Not only would this obviously kill the molecule and 'minion' interpretations

of f_0 and a_0 but, depending on the width and branching ratios actually found, could allow a_0 (980) to be reconsidered as a candidate for the $I = 1(Q\bar{Q})$ (⁶⁸). At present, we cannot rule out such a possibility because we do not really know $\Gamma_{BW}(a_0)$ — for lack of accurate data on $a_0 \rightarrow (I = 1)K\bar{K}$. Likewise we need better information on $(I = 0)K\bar{K}$ to check conclusions on $\Gamma_{BW}(f_0)$. This highlights the pervasive need for improved $K\bar{K}$ data.

6 Conclusions and outlook

That concludes my pre-Como tour of the light meson. What lessons emerge?

First, whilst stressing the key role of unitarity in parameterizing and co-ordinating various resonance signals, I noted the limitations of present practice. Once the number of channels grows (essentially beyond two), or three-body final states, except of very restricted type, enter, present methods are either inadequate or impractical or both. Here is one area calling for fresh ideas.

I touched on the great variety of production process that can bear on meson spectroscopy. Some appear to offer exceptional promise for future exploitation. Two photon production could provide a powerful means of probing $C = +$ mesons and have great potential for discriminating alternative compositions. Present data, being a by-product of e^+e^- annihilation studies, is limited in scope. Custom built photon-photon facilities (⁶⁹) could transform this. Another promising and expanding area is central production, with its ability to produce well-isolated samples of a whole variety of meson final states, not only of natural but also of unnatural parity (⁷⁰). Production systematics need much more study in order to exploit this resource to the full.

A key area for this year is the family of scalars. Surveying the pre-existing information, I restated the argument (³⁰) that the lightest $I = 0$ scalar is a very broad f_0 (1000) and stressed the need for more information on the ubiquitous f_0 (975) and a_0 (980) systems especially in their $K\bar{K}$ final states. Once the new results (^{5,27,40}) are assimilated, we will need to take stock of the enlarged scalar spectrum that emerges.

For contingent reasons, the emphasis this year has been on natural parity states, however possible $J^P = 0^-$ and 1^+ non $(Q\bar{Q})$ candidates like η (1420) and f_1 (1420) are just as interesting and also need much more investigation. Light spectroscopy is a seamless web and we need advance on all fronts to grasp the overall design.

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Table 1: Types of non(-standard) $(Q\bar{Q})$ configuration

In addition to the regular $M_2 \equiv (Q\bar{Q})$ mesons of the non-relativistic quark model which group into (mostly ideal) flavour nonets distinguished by their orbital and radial excitations, we may have:

- **MOLECULES** (M_2, M'_2) – and other four and more quark configurations
- **CHROMOCULES** – glueballs (GG), hybrids ($Q\bar{Q}G$) etc.

If particular mechanisms operate, non-standard types of $(Q\bar{Q})$ system can arise:

- **GRIBOV'S** ‘novel hadrons’ (OR ‘MINIONS’) ($> Q\bar{Q} <_0$)
- **HEAVILY RENORMALIZED** $(Q\bar{Q})$'s

(These can occur where resonances have very large widths leading to nonet mass and flavour patterns being appreciably distorted by final state interactions.)

Non- $(Q\bar{Q})$ Signatures

- **EXOTIC QUANTUM NUMBERS**
- **UNUSUAL PRODUCTION AND DECAY PROPERTIES**
- **SPARE STATES**

Potentially misleading signals for $(Q\bar{Q})$ or non $(Q\bar{Q})$ states could come from:

- **NON-RESONANT ENHANCEMENTS FROM OPENING CHANNELS.**

Figure Captions

- Figure 1. Regge plots for natural parity non-strange mesons listed in ref (24).
- Figure 2. Primordial quark model states may be modified by final state interactions (20).
- Figure 3. $I = 0$ scalar and tensor mesons. Observed states (pre-Como) compared to quark model predictions (6) - see text for details. The case for replacing $f_0(1400)$ by $f_0(1000)$ as the lightest broad $I = 0$ scalar is given in Sect. 5.
- Figure 4. Alternative production processes.
- Figure 5. Branching ratios for $J/\psi \rightarrow \gamma M \times 10^3$ for various mesons M versus mass (numbers taken from ref. (24), † the $\eta(1440)$ entry is via the $K\bar{K}\pi$ mode and $f_0(1710)$ via $K\bar{K}$).
- Figure 6. Example of how bumps need not correspond to resonances nor resonance signals appear as bumps – AFS data on $\pi^+\pi^-$ central production (65) and the corresponding AMP analysis fit (47).
- Figure 7. Resonance and bound state poles and the sheet structure of the energy plane – how their relation is clarified by mapping onto a suitable k - (momentum) plane: (a) and (b) depict one channel examples as for the deuteron (bound state (a)) or corresponding spin-singlet (anti-bound state (b)); (c) and (d) show two-channel examples with k_2 the CM momentum of the inelastic- channel (two-body channels assumed throughout). For resonances like $\rho(770)$ or $f_2(1270)$ far from inelastic threshold, the identity of the physically relevant nearby pole is unambiguous (c); for S -wave resonances close to inelastic threshold, the sheet structure ((d) and (e)) matters (d). Such resonances in general have ‘below threshold’ (Sheet II) and ‘above threshold’ (Sheet III) poles. Molecular resonances arising from intra-hadron forces of finite range only have one nearby pole, as happens for the deuteron (a).
- Figure 8. Diagrams to illustrate unitarity constraints – (a) among a set of scattering amplitudes (T_{ij}) describing strong transitions between a set of connecting channels ($i, j = 1 \dots n$); (b) how amplitudes $F_i^{(p)}$ describing non-strongly interacting production processes (p) leading to the same set of channels ($i = 1 \dots n$) are related to the T_{ij} – for details see refs. (47,30).

Figure 9. Scalar meson spectrum pre-Como (for update see refs. (5,27,40)). States shown are those listed in PDG'92 (24) plus the very broad $f_0(1000)$ (30) argued for in the text. PDG's 'confirmed' states are indicated either by open diamonds, \diamond or circles, \circ , according as they are conventionally viewed as $(Q\bar{Q})$ or non- $(Q\bar{Q})$ candidates. States that are 'unconfirmed' or whose spin is controversial have question marks. Dashed lines indicate possible shifts of assignment mentioned in the text: (a) alternative parametrization of the K_0 ; (b) substitution of the newly reported a_0 signal (27,40) for the 'unconfirmed' $a_0(1320)$ (53); (c) replacement of $f_0(1400)$ by $f_0(1000)$ as candidate for the lightest $I = 0(Q\bar{Q})$.

Figure 10. Aspects of S -wave $K\pi$ and $\pi\pi$ phase-shifts:

(a) $\delta_{K\pi}(I = 1/2)$ according to the LASS experiment (51); (b) the old UP- DOWN ambiguity of δ_0^0 (58); (c) the accepted modern form of $\delta_0^0(I = 0)$ from threshold to 1.4 GeV (24) plotted modulo 180° (full-line), and the residual phase after removal of the $f_0(975)$ signal (dashed line). This latter corresponds to the very broad $f_0(1000)$ (30).

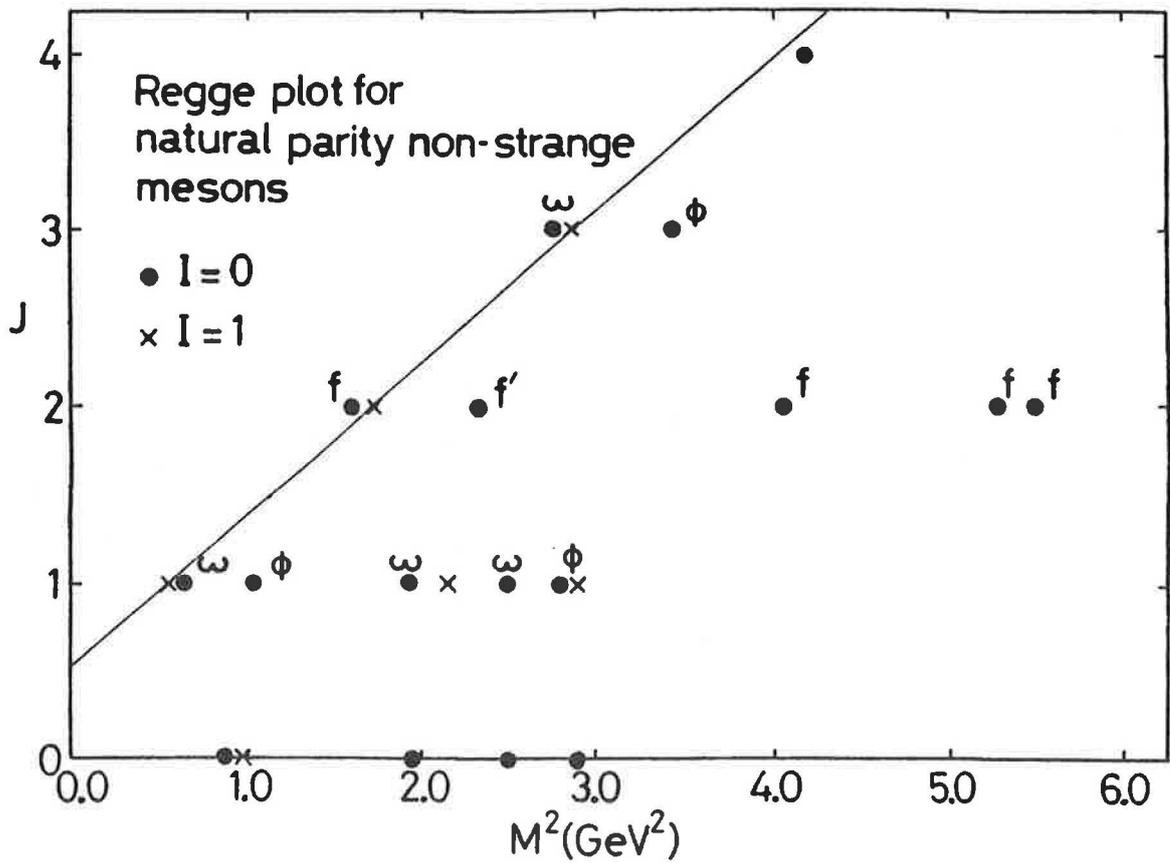


Fig. 1



Fig. 2

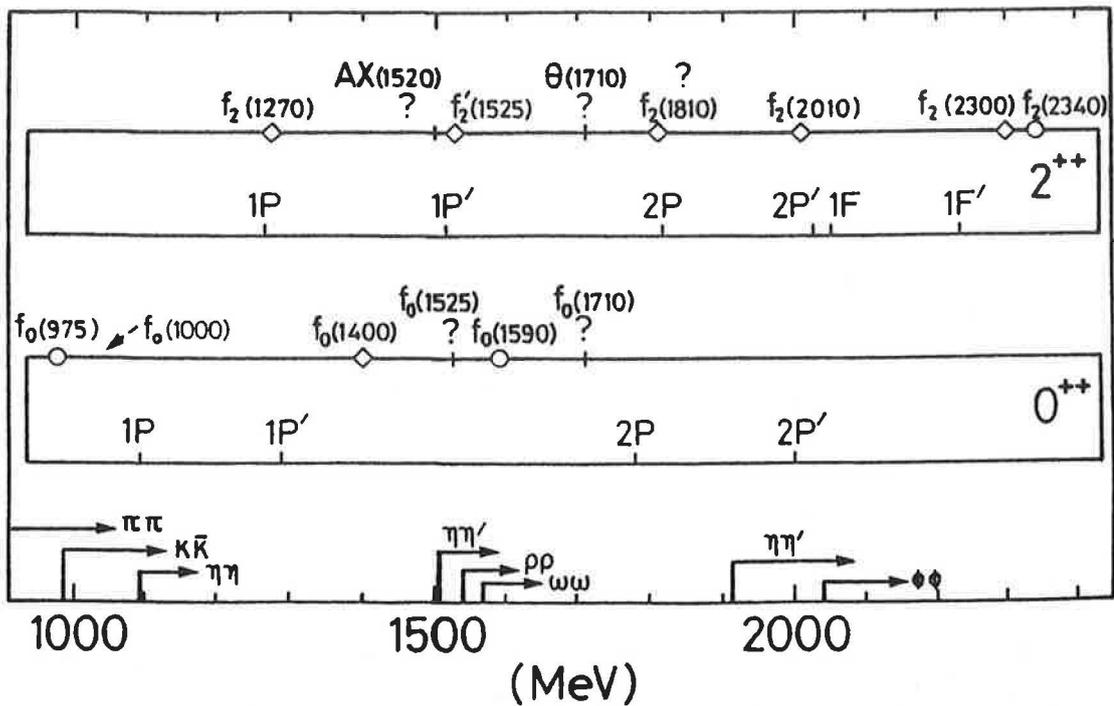


Fig. 3

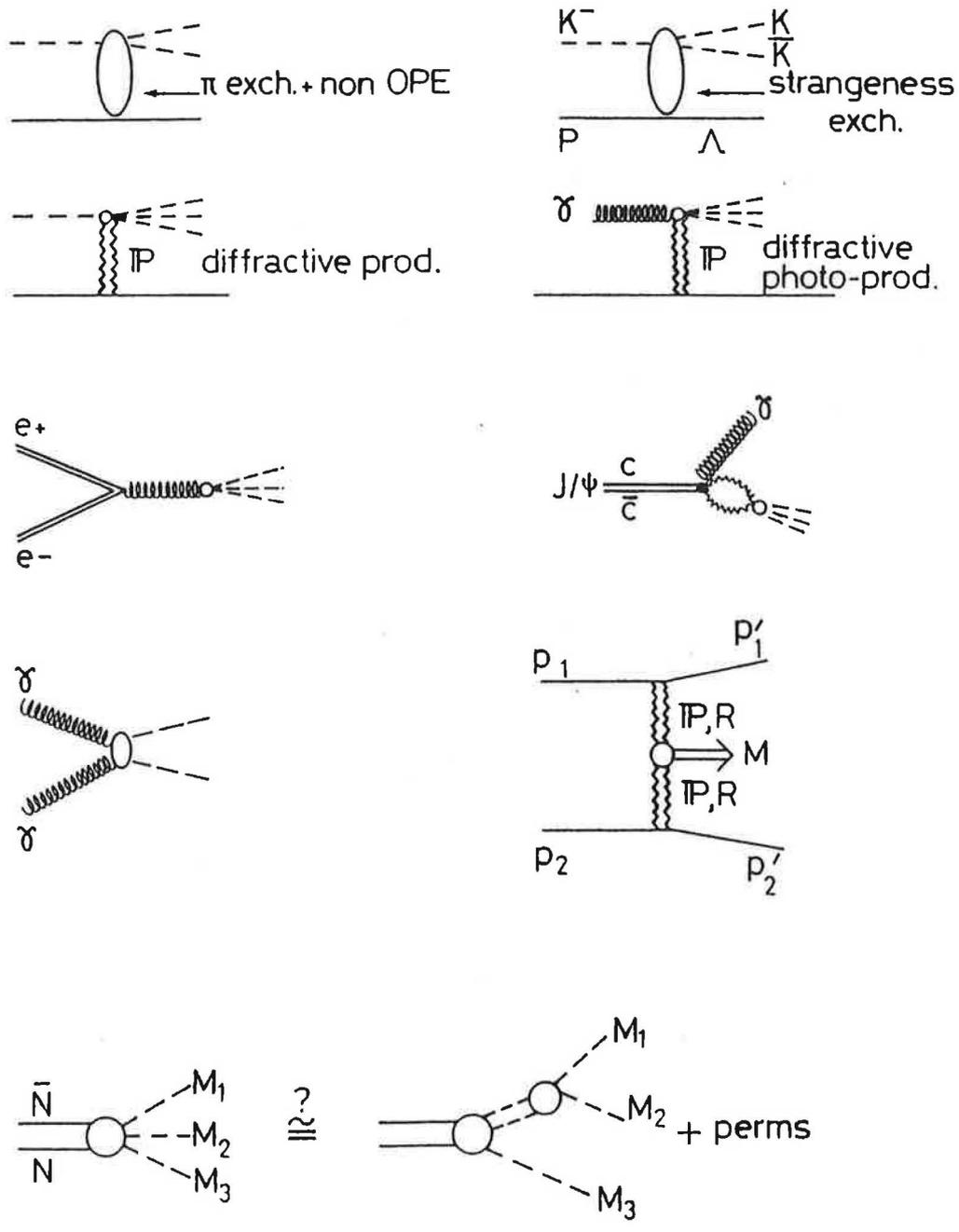


Fig. 4

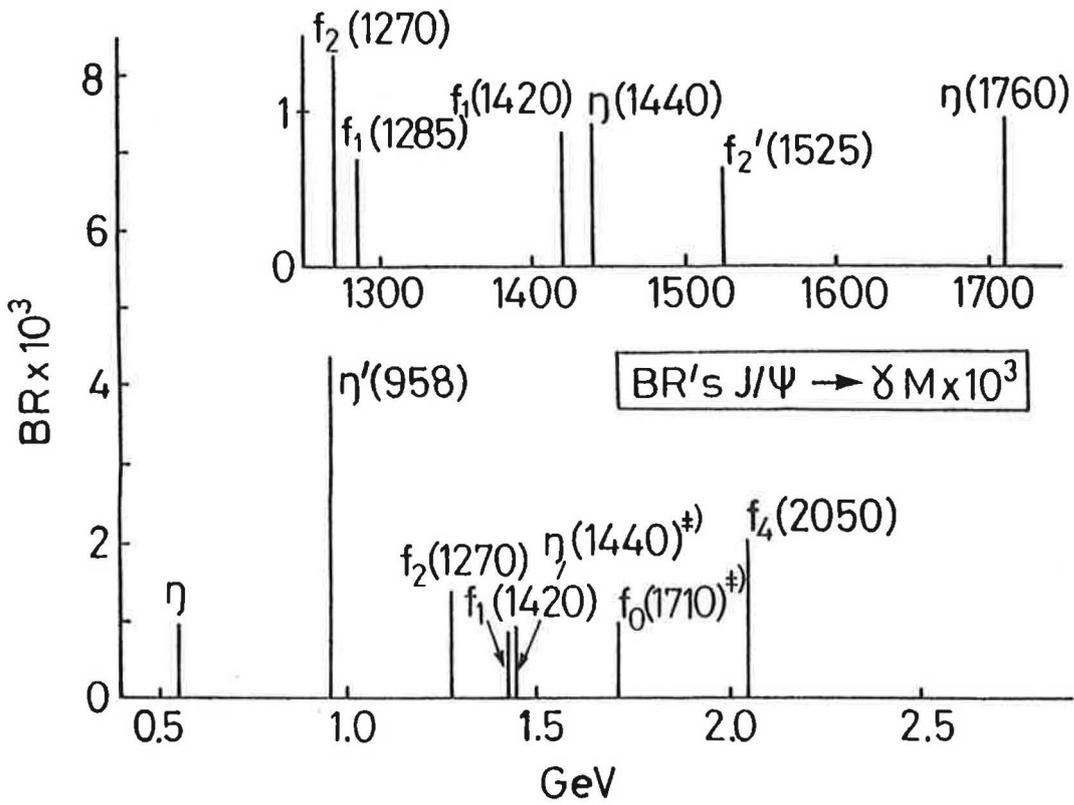


Fig. 5

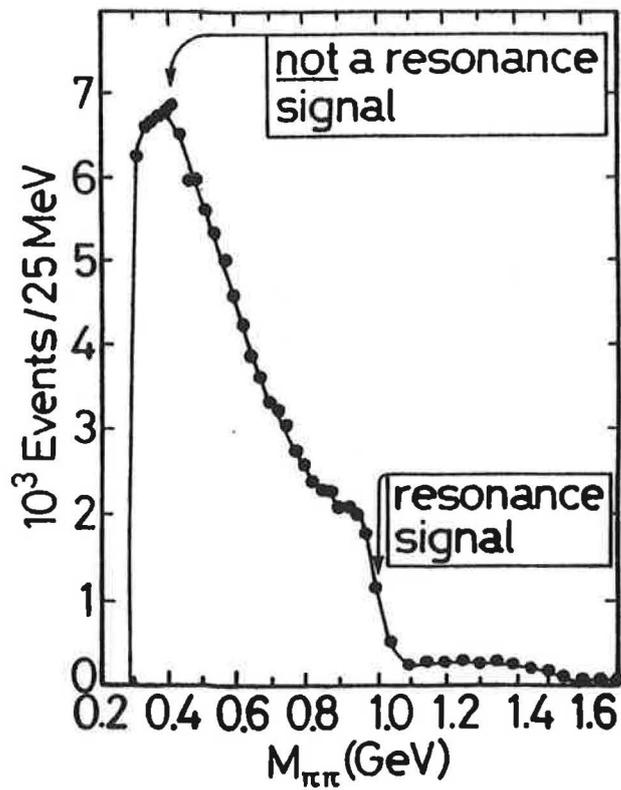


Fig. 6

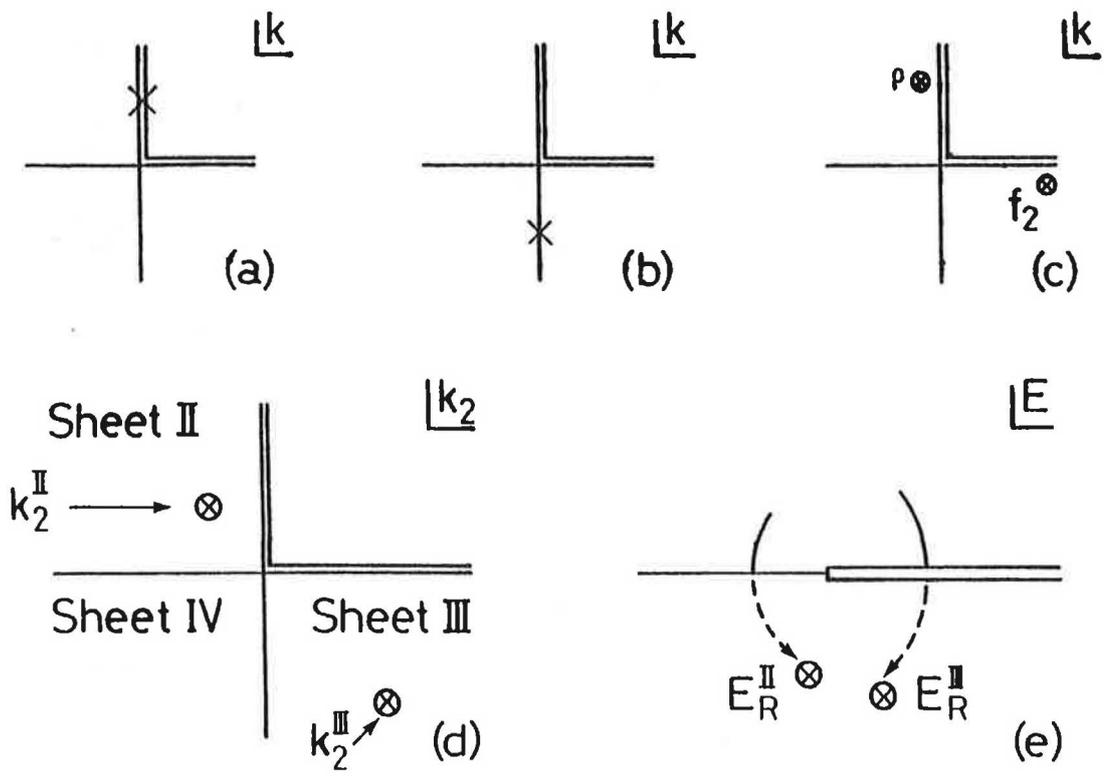


Fig. 7

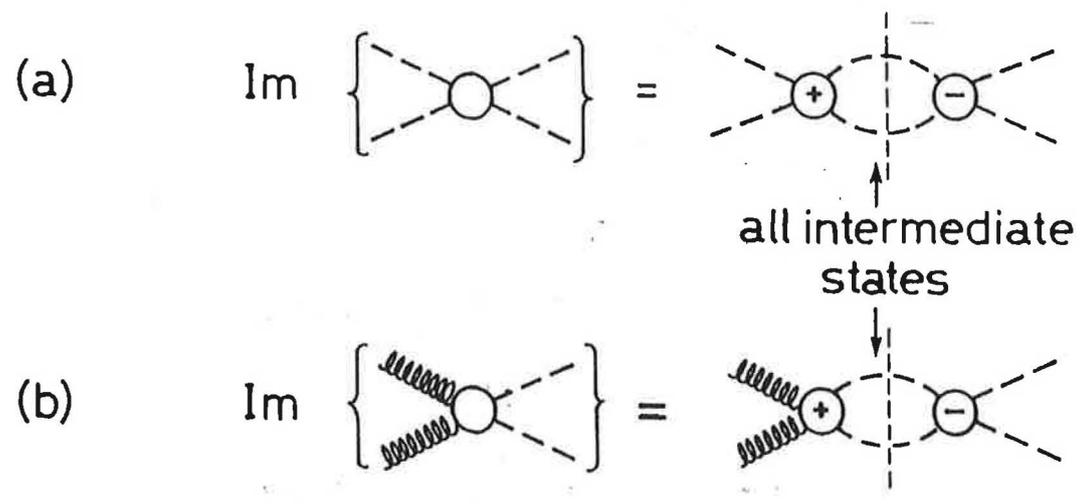


Fig. 8

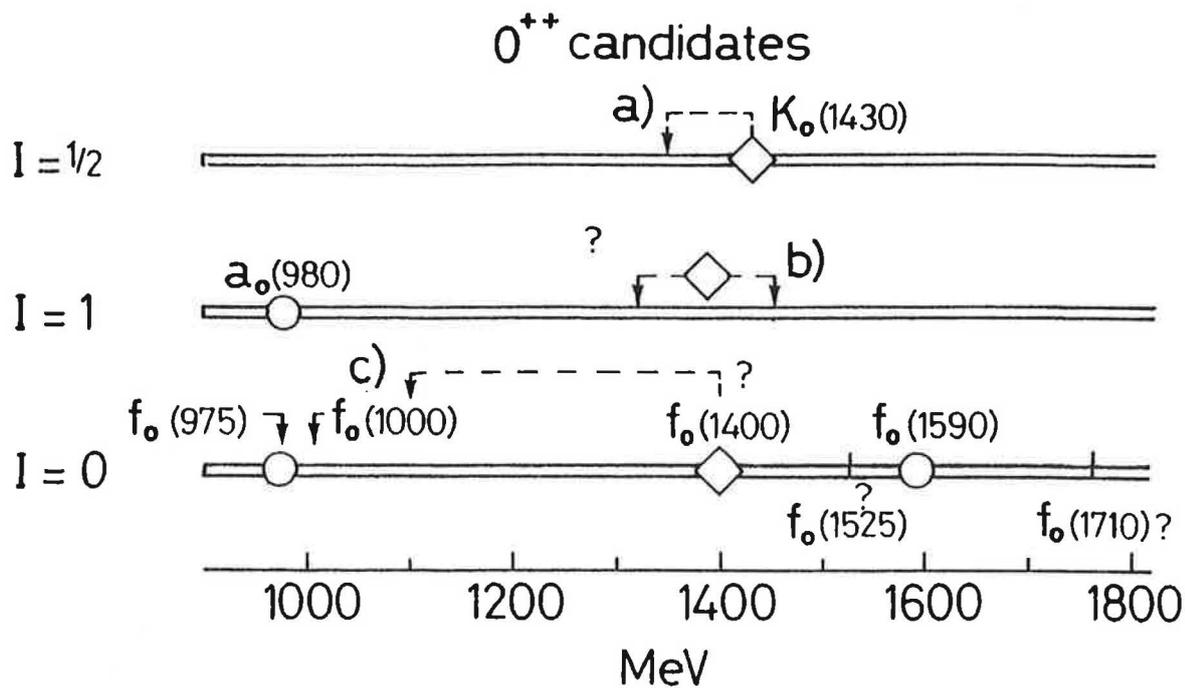


Fig. 9

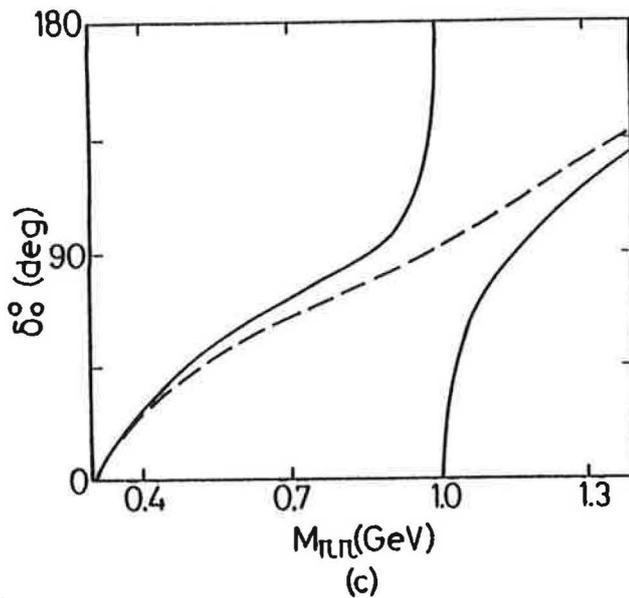
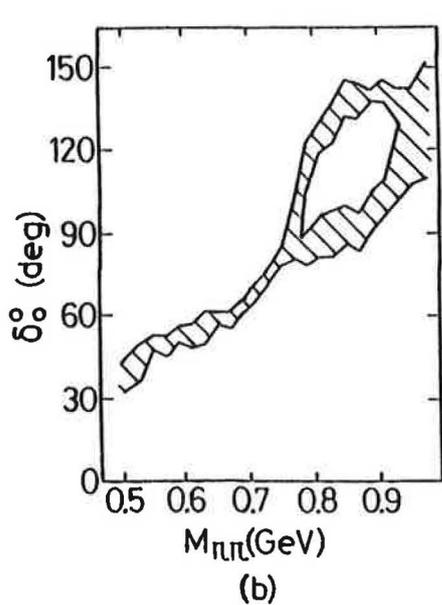
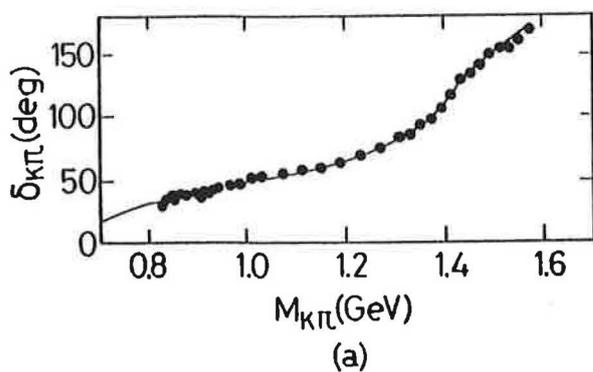


Fig. 10

