

# A low lying scalar meson nonet in a unitarized meson model

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## Abstract

A unitarized non-relativistic meson model which is successful for the description of the heavy and light vector and pseudo-scalar mesons yields in its extension to the scalar mesons for the same model parameters a complete nonet below 1 *GeV*. In the unitarization scheme real and virtual meson meson decay channels are coupled to the quark antiquark confinement channels. The flavor dependent harmonic oscillator confining potential itself has bound states  $\epsilon(1.3 \text{ GeV})$ ,  $S(1.5 \text{ GeV})$ ,  $\delta(1.3 \text{ GeV})$ ,  $\kappa(1.4 \text{ GeV})$ , similar to the results of other bound state  $q\bar{q}$  models. However, the full coupled channel equations show poles at  $\epsilon(0.5 \text{ GeV})$ ,  $S(0.99 \text{ GeV})$ ,  $\delta(0.97 \text{ GeV})$ ,  $\kappa(0.73 \text{ GeV})$ . Not only these pole positions can be calculated in our model, also cross sections and phase shifts in the meson scattering channels which are in reasonable agreement with the available data for  $\pi\pi$ ,  $\eta\pi$  and  $K\pi$  in *S*-wave scattering.

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# 1 Introduction

The rich structure in meson meson scattering at intermediate energies has stimulated many theoreticians to fit the existing quark models to the experimental results [1]-[7]. Especially  $S$ -wave meson meson scattering shows structures which are very intriguing [8]-[18]. Detailed phase shift analyses reveal two pronounced scalar mesonic resonances below  $1\text{ GeV}$ , namely the  $S(975)$  resonance in  $\pi\pi$  [8]-[12] and the  $\delta(980)$  in  $\eta\pi$  [14], [15]  $S$ -wave scattering. The other relevant resonances which appear nowadays in the tables of particle properties [16] are the  $\epsilon(1300)$  in  $\pi\pi$  and  $\kappa(1350)$  in  $K\pi$  [17], [18]  $S$ -wave scattering.

It is well known that these particles cause severe problems if one wants to understand them as quark+antiquark ( $q\bar{q}$ ) states. For instance confronted with the  $SU(3)_{\text{flavor}}$  quark model the resonance positions do not fit the quadratic or linear Gell-Mann Okubo mass relations [4] see however [3]. A possible resonance in  $\pi\pi$   $S$ -wave scattering at  $600\text{ MeV}$  which was poorly recognized in early analyses [8] disappeared from the tables of particle properties in the seventies. But nevertheless some years later this resonance has revived within the bag model due to a solution for the scalar meson problem presented by Jaffe [6] who points out that these resonances stem from  $qq\bar{q}\bar{q}$  states. The large binding energy which is assumed for such configurations, makes the low masses possible which are required by experiment. All kinds of quark configurations [6], [19], [20] and gluon gluon bound states [7] might exist other than the standard  $q\bar{q}$  for mesons and  $qqq$  for baryons. This probably no one doubts, but there is no experimental evidence that they couple significantly to hadron hadron scattering [2], [5].

To select the  $\epsilon(1300)$  resonance as the isosinglet partner of the  $S(975)$ , rather than the  $\epsilon(600)$  is probably the result of bag model interference with the analysis of the  $\pi\pi$   $S$ -wave scattering data, because in the bag model and also in other bound state hadron models, the lowest  $J^{PC} = 0^{++}$  isospin zero  $q\bar{q}$  object fits better with a total mass of about  $1.3\text{ GeV}$  [19], [21].

In this paper we will show that we have no difficulties to explain the scalar mesons within our unitarized quark model and to interpret them as  $q\bar{q}$  states with a meson-meson admixture. However, both the model and the data do not exclude poles in the scattering matrix which do not appear in the tables but nevertheless might be interpreted as resonances.

## 2 The Model

The unitarized quark model is described in many articles. We will therefore confine ourselves to only briefly discuss the main features here and to give a complete list of references, [22]-[27]. In our treatment, meson meson scattering processes couple to  $q\bar{q}$  quark configurations or mesons via the annihilation and creation out of the vacuum of a  $q\bar{q}$  pair. The reverse coupling describes the decay process of a meson or the coupling of a meson to its virtual decay channels. In [22] and [23] the explicit form of a many channel Schrödinger description of such a system is given (see also appendix A). Several meson meson scattering channels are by the *QPC* mechanism [28] coupled to permanently closed  $q\bar{q}$  channels with the same quantum numbers. It is also shown in [22] how to account for relativistic effects and for the effects of one-gluon exchange in the  $q\bar{q}$  channels.

Scattering matrices, phase shifts, cross sections and wave functions can be calculated from the Schrödinger equation by an approximative method, [24], [25], which leads to an  $S$ -matrix which is explicitly analytic in the complex energy plane and unitary.

Phase shifts and cross sections can be checked to be in good agreement with the data if available. In other cases the pole positions of the scattering matrix can be compared with the bound state and resonance positions found by experiment. Wave functions might be compared with those expected from leptonic decays.

It has been our observation [22] that the properties of the  $J^{PC} = 1^{--}$  and  $J^{PC} = 0^{-+}$  mesonic resonances are reasonably well described with a few model parameters: The effective quark masses, where the effective up and down masses could be taken to be equal, one universal harmonic oscillator frequency which describes the confining force in the permanently closed  $q\bar{q}$  channels for all possible flavor configurations and two or three parameters to describe the coupling of the scattering sector to the confinement sector.

In this investigation we applied the model to  $S$ -wave meson meson scattering. The quark and the antiquark in the permanently closed channel(s) move in relative  $P$ -waves, whereas the mesons in the scattering channels are in relative  $S$ - and  $D$ -waves. For the  $\epsilon$  and  $S$  we have used one Schrödinger equation with two permanently closed channels, one for the  $n\bar{n}$  pair and one for the  $s\bar{s}$  pair. The mixing occurs in our model quite naturally via the coupling to scattering channels which contain strange mesons. We will discuss the results furtheron.

In the first place we do not alter the effective quark masses or the universal harmonic oscillator frequency. The only place where we allow some minor changes if necessary is in the potential which couples the confinement and the decay sector. For the vector and pseudo-scalar mesons the so-called color splitting could be accounted for by a component of this potential. As a result

of our calculations for the scalar mesons we conclude that in their case other possible interactions seem to compensate the effects of color splitting. So we decide to choose zero for the parameter which regulated the color splitting in the case of the vector and pseudoscalar particles, and not to take other contributions into account. The only legitimations of the above procedure are the facts that the results came out reasonable and that it is not very relevant for the point we want to make in this paper. The other two parameters in the coupling potential are unaltered, with respect to the same parameters in the case of vector and pseudoscalar mesons.

### 3 Results

Let us first discuss  $S$ -wave  $\pi\pi$  scattering. The lowest bound state of our confining potential for  $J^{PC} = 0^{++}$   $q\bar{q}$  pairs has a mass of about  $1.3 \text{ GeV}$ , which is at precisely the same place as the ground state of other bound state meson models. If we turn on the overall coupling constant of the transition potential, bound states show up as resonances in  $\pi\pi$  scattering. At the model value of the overall coupling constant, which is obtained from the analysis of pseudo-scalar and vector mesons [22], a pole shows up with a real part of about  $1.3 \text{ GeV}$ , which accidentally equals the above mentioned bound state mass. Naively we might expect that one would only find a resonating structure in  $\pi\pi$  scattering in that energy domain. However, figure (1) shows that the calculated phase shifts have structures at much lower energies which indicates that low-lying resonance poles have been generated.

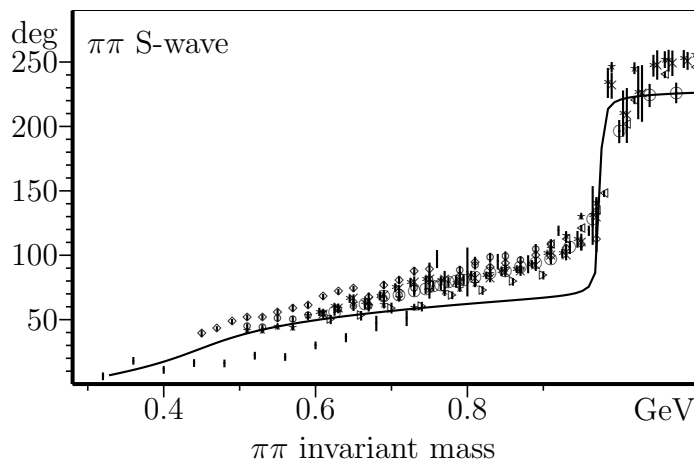


Figure 1:  $\pi\pi$  elastic  $S$ -wave phase shifts. The various different sets of data are taken from ( $\odot$ , [9]), ( $*$ , [12]), ( $\star$ ,  $\times$ ,  $\diamond$ ,  $\triangleleft$ ,  $\triangleright$  respectively for analyses A, B, C, D and E of [10]), ( $\circ$ , [11]) and ( $\cdot$ , [13]). The solid line is our model result.

We can scan the complex energy plane for these poles in the scattering matrix and find one pole at about  $450 \text{ MeV}$  with a  $500 \text{ MeV}$  imaginary part and another pole at the  $S(980)$  position. The imaginary part of the first pole is so large that a simple Breit-Wigner parametrization is impossible and large differences between the “mass” of the resonance and the real part of the pole position will occur. How these poles are connected to the harmonic oscillator bound states is a very technical story which is beyond the scope of this paper, suffice it to state that such a connection exists. As we have discussed in [26] these poles are special features of  $S$ -wave scattering and do not show up in  $P$ - and higher wave scattering, which explains quite naturally why they are not found there.

Figure (1) shows also that the new structures at low energies are in reasonable agreement with the experimental situation. A criticism which might come up if one inspects this figure in more detail is that the theoretical phase shifts do not fit the data to a high precision, but only follow roughly the experimental slope in the data. This is however not a fair criticism since we are comparing our calculations with the *raw data* with unsubtracted background, which are presently the only available data.

In our model we left out of consideration all possible final state interactions in the scattering channels like mesons exchange, Pomeron exchange, quark interchange etc. Moreover, the form of the transition potential may be too simple, for example we have taken a local transition potential and it could also have a more complicated  $r$ -dependence due to more sophisticated meson-decay form-factors. So our calculations better do not follow the data very accurately. It remains however a pity that no analysis exists for meson meson scattering which subtracts the known effects and leaves us with the consequences of the remaining interactions, a strategy which is nowadays popular in analyzing nucleon nucleon scattering data [30], because then we could really see how good the remaining interactions are accounted for in our approach. From our present calculations we must conclude that final state interactions will probably alter the phase shifts a bit in the region around 600 MeV in order to change the slope of the curve towards the data. Note that the phase shifts for low energies are almost completely accounted for by the coupling to the permanently closed  $q\bar{q}$  channels.

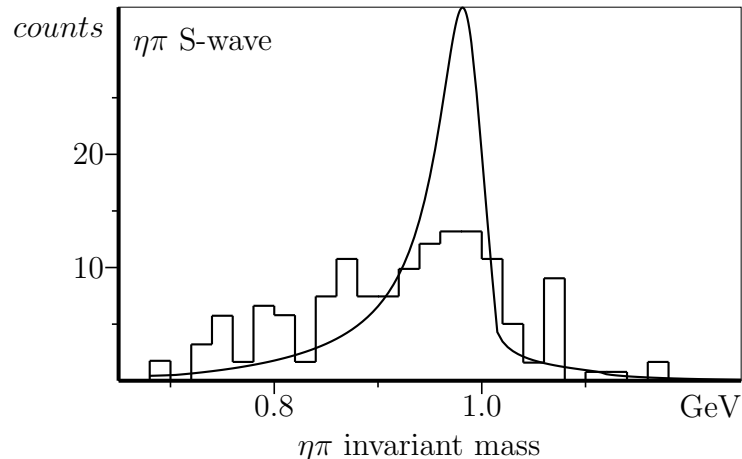


Figure 2:  $S$ -wave  $\eta\pi$  cross section. The solid line is our model calculation. Data are taken from [14].

In  $\eta\pi$   $S$ -wave scattering the data are limited to cross-sections in the energy domain of the  $\delta$ . Here we found that straightforward calculations lead to problems with the position of the  $\delta$

resonance. We suspect that these problems are connected to the U(1) problem. Our strategy in this case will be discussed below, the result is depicted in figure (2) where we shifted the calculated cross-section by 20 MeV in order to get the peak values of the experimental and the theoretical curves on top of each other.

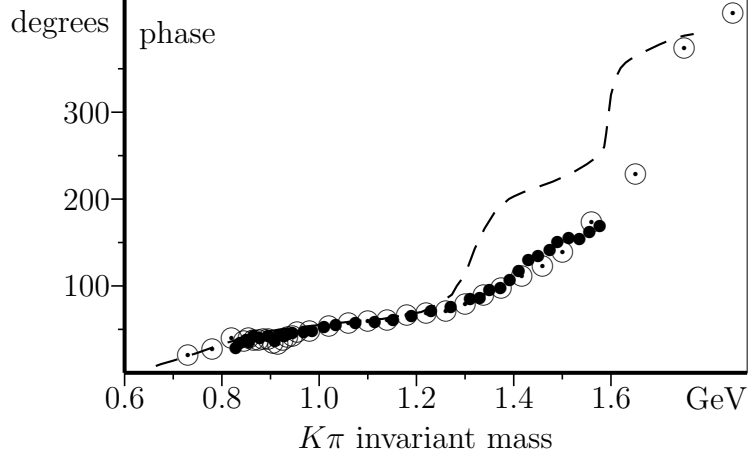


Figure 3: Kaon pion  $I = \frac{1}{2}$   $S$ -wave phaseshifts. Data from [17] and [4] ( $\odot$ ) and from [31] ( $\bullet$ ). The dashed line is our model calculation (not fit).

The results for  $K\pi$  are depicted in figure (3). We see there that the phase shifts for low energies are rather well produced by the model, at higher energies only a rough description of the data is given: The number of resonances at some energies agree with the data but the detailed structure is not reproduced at all. Also here we have problems which are presumably related to the U(1) problem.

In previous investigations [22] we took a nonstrange quark content for the  $\eta$  meson and a strange quark content for the  $\eta'$  meson which is called ideal mixing. The data in the case of scalar mesons are however more sensitive to the quark contents of the  $\eta$ 's and we found the following: The  $\eta K$  channel in the iso-doublet case is much less coupled than follows from our general approach as described in [27] because the data show that there is not much inelasticity below  $\eta'K$ . The best result has been obtained if the  $\eta K$  channel is completely decoupled and  $\eta'K$  enhanced to compensate.

Something similar appears to be necessary in the isoscalar case: If we take for  $\eta$  the  $s\bar{s}$  and for  $\eta'$  the  $n\bar{n}$  system, we find the best results for the  $S$ -pole although the whole  $(\epsilon, S)$  system is not very sensitive to these changes. The  $\delta$  however is very sensitive to our approach since the lowest threshold is  $\eta\pi$ . In the case of the  $\delta$  we have to reduce the  $\eta\pi$  coupling with a factor 1/6 and to enhance the  $\eta'\pi$  coupling to compensate. This would be the case if the  $SU(3)$  mixing

angle between  $\eta_1$  and  $\eta_8$  would be  $+11^\circ$ . The plus is puzzling because Tornqvist [2] claims that he needs the standard  $-11^\circ$  [16] in order to fit the data. A more rigorous study on this point is in preparation, which shows that part of the problems might stem from our choice of transition potential.

## 4 Conclusions

If we only allow minor differences in the transition potential and take some action with respect to the  $\eta$  mesons, we find that the scattering matrices for  $S$ -wave meson meson scattering agree reasonably with the data. An inspection of the complex energy plane shows the following poles in the various scattering matrices:  $S(994 - 20i \text{ MeV})$ ,  $\delta(968 - 28i \text{ MeV})$ ,  $\epsilon(470 - 208i \text{ MeV})$  and  $\kappa(727 - 263i \text{ MeV})$ . Preliminary results show that the  $\epsilon$  and  $\kappa$  poles are rather sensitive to the transition potential. The  $\epsilon$  is however always somewhere around  $500 \text{ MeV}$  central value with a large width. The  $\kappa$  might vary more and even become slightly heavier than  $1 \text{ GeV}$ , with a rather large width. The main conclusion is however that those poles occur as normal  $q\bar{q}$  configurations with a meson-meson admixture.

Our calculations show clearly that there is no need to incorporate  $qq\bar{q}\bar{q}$  channels in our meson model. This indicates that there is no phenomenological reason why genuine  $qq\bar{q}\bar{q}$  configurations couple strongly to meson meson channels.



# A Appendix

The resonances are described by the following set of Schrodinger equations:

$$\left\{ -\frac{d^2}{dr^2} + \frac{L(L+1)}{r^2} + 2\mu(E)V(r) - k^2(E) \right\} \phi_E(r) = 0 \quad , \quad (1)$$

which consist of  $n$  confined (permanently closed) channels and  $m$  free (open or closed scattering) channels. So  $L$ ,  $\mu$ ,  $k^2$  are  $(n+m) \times (n+m)$  diagonal matrices containing the orbital angular momenta, the reduced masses and the momenta of the various channels. They are determined from:

$$E = \sqrt{k^2 + m_1^2} + \sqrt{k^2 + m_2^2} \quad \text{and} \quad \mu = \frac{1}{2} \frac{dk^2}{dE} \quad . \quad (2)$$

Here  $m_1$ ,  $m_2$  stand for the masses of the quarks in the confined channels or the meson masses in the scattering channels. The latter are taken to be the experimental values, the quark masses were determined for the  $J^{PC} = 0^{-+}$  pseudo-scalars and  $J^{PC} = 1^{--}$  vectors to be:

$$m_n = 406 \text{ MeV}, \quad m_s = 508 \text{ MeV}, \quad m_c = 1,562 \text{ MeV}, \quad \text{and} \quad m_b = 4,724 \text{ MeV}. \quad (3)$$

The non-relativistic limit of (2) is used in the confined channels and for energies lower than the threshold also in the free channels.

The  $(n+m) \times (n+m)$  potential matrix reads:

$$V = \begin{pmatrix} V_c & V_{\text{int}} \\ V_{\text{int}}^T & V_f \end{pmatrix} \quad . \quad (4)$$

The confining potential  $V_c$  is a diagonal  $n \times n$  matrix containing the mass-dependent harmonic oscillators:

$$[V_c]_{ii} = \frac{1}{2} \mu_i \omega^2 r^2 \quad . \quad (5)$$

The  $m \times m$  matrix  $V_f$  describes possible final state interactions. The  $n \times m$  transition potential  $V_{\text{int}}$  is taken to be:

$$[V_{\text{int}}]_{ij} = \tilde{g} \omega \, c_{ij} \sqrt{\frac{E}{D}} \frac{r}{r_0} \exp \left\{ -\frac{1}{2} \left( \frac{r}{r_0} \right)^2 \right\} \quad , \quad (6)$$

where  $\tilde{g}$  is the universal coupling constant,  $r_0 = \rho_0 / \sqrt{\mu_i \omega}$  the transition radius and  $E/D$  a phenomenological factor, with  $D = m_1 + m_2$ . The above mentioned parameters were also fixed by the  $J^{PC} = 0^{-+}$  pseudo-scalars and  $J^{PC} = 1^{--}$  vectors to:

$$\omega = 190 \text{ MeV}, \quad \tilde{g} = 10.4, \quad \text{and} \quad \rho_0 = 0.56 \text{ .} \quad (7)$$

In comparison to the  $0^{-+}$  and  $J^{PC} = 1^{--}$  cases, we left out the color term which was necessary for the pseudo-scalar/vector splitting. This is of course not a very serious intervention, since for  $P$ -wave  $q\bar{q}$  systems the color splitting is anyhow much smaller than for  $S$ -wave systems.

The numbers  $c_{ij}$  are the relative decay couplings. If we pursue the concepts behind the confining potential further to the phase of the pair-creation, we are led to the assumption that all the interquark forces are harmonic oscillator forces during this process. This idea provides us a scheme in which the possible decay channels and their relative strengths can be calculated [27]. Their values are listed in table (1).

The  $\eta_n$  and  $\eta_s$  denote the pure  $n\bar{n}$  and  $s\bar{s}$  states respectively. Of course these are not the physical  $\eta$  and  $\eta'$ . See the Conclusions for discussion about this point. The  $\pi\pi$  ( $S$ -wave) scattering is described in one system of equations with two confined channels containing a  $n\bar{n}$  and  $s\bar{s}$  pair. These systems are linked via decay in which strange mesons occur.

decay products		initial mesons			
Channel	Spin	$\epsilon$ and $S$		$\delta$	$\kappa$
		$n\bar{n}$	$s\bar{s}$		
$\pi\pi$	0	3/40			
$\eta_n\eta_n$	0	1/40			
$\eta_s\eta_s$	0		1/16		
$KK$	0	1/40	1/16	1/24	
$\rho\rho$	0	1/40			
$\rho\rho$	2	1/2			
$\omega\omega$	0	1/120			
$\omega\omega$	2	1/6			
$K^*K^*$	0	1/120	1/48	1/72	
$K^*K^*$	2	1/6	5/12	5/18	
$\phi\phi$	0		1/48		
$\phi\phi$	2		5/12		
$\eta_n\pi$	0			1/12	
$\eta_s\pi$	0				
$\rho\omega$	0			1/36	
$\rho\omega$	2			5/9	
$\pi K$	0				1/16
$\eta_n K$	0				1/48
$\eta_s K$	0				1/24
$\rho K^*$	0				1/48
$\rho K^*$	2				5/12
$\omega K^*$	0				1/144
$\omega K^*$	2				5/36
$\phi K^*$	0				1/72
$\phi K^*$	2				5/18

Table 1: Relative quadratic coupling constants  $c_{ij}$  (see text) for the decay process of a scalar meson into a pair of pseudoscalar/vector mesons.

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