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Abstract. An approach to understanding the light scalar meson spectroscopy is briefly reviewed.

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DISCUSSION

The main concern at the moment in particle physics might be called the 3.5×10^9 dollar question (the rough cost of LHC). Specifically, where is the Higgs scalar boson and what are its properties?

The topic under discussion might be called the 3.5×10^1 cent question. That is roughly the cost of making a few Xerox copies of old published experimental data concerning the s-wave channel in low energy pion pion scattering. Specifically we can ask, is there a light scalar meson in this channel?

Are these two topics related? The Higgs sector of the standard model is well known to be formally identical to the SU(2) linear sigma model, which has often been used to describe low energy pion physics. In addition to the pions, the model contains the light scalar called sigma. Of course the scales of the two models are very different- about 100 MeV for the pion physics case and about 250 GeV for the standard model case. The pions are the analogs of the longitudinal parts of the W and Z mesons while the sigma is the analog of the Higgs boson. For this analogy to be most direct, one would expect the Higgs sector of the standard model not to be a fundamental entity but to represent an effective description of a technicolor model [1] of some sort. In addition, the most common treatment of the SU(2) linear sigma model for pion physics considers the (non-linear) limit of the model, where the sigma mass is sent to infinity, to be the correct one.

In any event, the status of the light scalars in QCD is quite interesting in itself. Perhaps it is best to wait for results to emerge from LHC (or Fermilab) and let experiment tell us whether this close analogy [2] exists.

Returning to pi pi scattering, consider an approach using the more conventional non-linear sigma model and compute the real part, R_0^0 of the I=0, J=0 amplitude. This is shown as the solid line in figure 1 of [3]. Very close to the threshold at 280 MeV, one gets the good "current algebra" result. However the curve runs away fast and starts to violate the unitarity bound, $R_0^0 < 1/2$ already at about 500 Mev. Adding the effect of the $\rho(770)$ meson (dashed line) is seen to be in the right direction to restore unitarity but way too small to succeed in the low energy region. There seems to be no way to save unitarity but to include the effect of a light sigma resonance in the 550 MeV region as shown, together with the data, in figure 2 of that paper. Notice that in the non-linear model framwork it is still possible to add the sigma in a consistent way. Finally notice, from figure 4 of that paper, that the addition of the accepted $f_0(980)$ resonance results in convincing agreement with experiment over the large range: threshold - 1100 MeV.

A similar treatment of π - K scattering in the non-linear SU(3) sigma model [4] yielded evidence for a strange analog of the sigma, the kappa. Furthermore, adding the well established scalar, $a_0(980)$ yields [5] a putative full nonet of light scalar mesons. But it is a somewhat puzzling one.

The scalar puzzle is the unusual spectroscopy of the light scalar nonet. At present, the scalars below 1 GeV appear to fit into a nonet as:

$$\begin{aligned} I=0: m[f_0(600)] &\approx 500\,\mathrm{MeV} \\ I=1/2: \quad m[\kappa] &\approx 800\,\mathrm{MeV} \\ I=0: m[f_0(980)] &\approx 980\,\mathrm{MeV} \\ I=1: m[a_0(980)] &\approx 980\,\mathrm{MeV} \end{aligned} \tag{1}$$

This level ordering is seen to be flipped compared to that of the standard vector meson nonet:

$$\begin{aligned} I=1: m[\rho(776)] &\approx 776\,\mathrm{MeV} \qquad n\bar{n} \\ I=0: m[\omega(783)] &\approx 783\,\mathrm{MeV} \qquad n\bar{n} \\ I=1/2: m[K^*(892)] &\approx 892\,\mathrm{MeV} \qquad n\bar{s} \\ I=0: m[\phi(1020)] &\approx 1020\,\mathrm{MeV} \qquad s\bar{s} \end{aligned} \tag{2}$$

Here the standard quark content (n stands for a non-strange quark while s stands for a strange quark) is displayed at the end for each case. The vector mass ordering is seen to just correspond to the number of s-type quarks in each state. It was pointed out a long time ago in Ref. [6], that the level order is automatically flipped when mesons are made of two quarks and two antiquarks instead of a single quark and antiquark. Note that, in the four quark picture, the states in Eq.(1) consecutively have the quark contents: $nn\overline{nn}$, $nn\overline{ns}$, $nn\overline{ss}$ and $nn\overline{ss}$.

In order to confirm our calculations using the non-linear sigma model we redid them [7] using the linear SU(3) sigma model. In order to unitarize the resulting tree level amplitudes we used the K-matrix approach which, from the standpoint of believability has the nice feature that it does not introduce any additional parameters. An equivalent method of unitarization had been previously used [8] in the SU(2) linear sigma model.

As another part of the puzzle one notes that the masses of the putative scalar nonet members are significantly lower than the other (tensor and two axial vector) p-wave quark-antiquark nonets. There are enough other scalar candidates [$a_0(1450)$, $K_0(1430)$ and two of $f_0(1370)$, $f_0(1500,)$ $f_0(1710)$] to make another nonet although the masses of its contents seem somewhat higher than an expected scalar p-wave nonet. Based on the usual effect that two mixing levels repel as well as some more detailed features, it was suggested [9] that a global picture of these scalars might consist of a lighter “four quark" nonet mixing with a heavier “two quark" nonet.

A field theoretic toy model to study these features was introduced in [10]. This model uses a generalized SU(3) linear sigma model and involves two different nonets: M describes both pseudoscalars and scalars containing two quarks while M' describes both pseudoscalars and scalars containing four quarks. There is the interesting feature that the 2 quark vs 4 quark content of each particle is a prediction. Further work in this direction has also been presented by a number of authors [11]-[14].

The M-M' model is a complicated one so we studied it at different levels of approximation [15]. Also there turned out to be an interesting connection to instanton physics [16]. As a brief summary it may be desirable to just display the “typical" results of [17]. These are the masses and the “two quark" vs. “four quark" percentages of the members of all four nonets (light and heavy pseudoscalars and light and heavy scalars). They are listed in Tables 1 and 2. Isospin but not SU(3) symmetry is being assumed. Note that for the I=1/2 and I=1 states, the prime denotes the heavier particle. For the I=0 particles there are four states of each parity and they are denoted by subscripts 1, 2, 3, 4 in order of increasing mass. Altogether, considering the isospin degeneracy, there are 16 different masses. The 8 inputs comprise the pion decay constant, the four masses: [m_π, $m_{\pi'}$, m_a, m'_a], the strange to non strange quark mass ratio (which is related to assuming a value for m_K) and the sum and the product of all the four I=0 pseudoscalar squared masses (Each possible scenario for their identification with physical states was considered).

It is encouraging that the predictions seem to be smooth continuations of those obtained in earlier simplified analyses containing just zero quark mass terms and SU(3) degenerate non-zero quark mass terms. Comparing the pseudoscalar π-π' system with the scalar "partner" a-a' system, for example, one sees that the low mass pion is predominantly of 2 quark nature while the low mass a meson is predominantly of four quark nature. The situation is reversed for the higher mass states π' and a'. It is the same story if one compares the K-K' system with the scalar κ-κ' system. The lightest of the four mixing scalar singlets, the f_1 is to be identified with the "sigma". Actually, the mass listed is a "bare" one. Unitarization of the pi-pi scattering amplitude gives a complex pole position, $z = M^2 - iM\Gamma$ with M = 477 MeV and Γ = 504 MeV, which is roughly like the value extracted from the experimental data in [18].

While it appears a little unusual to think of, say, the ordinary pion as having some four quark content when treated in an effective Lagrangian framework, that is in fact the standard picture in the parton model approach to QCD. In the case of the two scalar nonets, the mass ordering itself naturally suggested such a picture. This picture was then inherited by the pseudoscalars when we chose to describe the scalars via a linear sigma model.

We would like to note that the subject of light scalar meson spectroscopy has received a lot of attention in the last 15 years and that a more complete documentation of this recent work is given in [19].

TABLE 1. Predicted properties of pseudoscalar states: $\bar{q}q$ percentage (2nd column), $\overline{qq}qq$ (3rd column) and masses (last column).

State	$\bar{q}q$%	$\overline{qq}qq$%	m (GeV)
π	85	15	0.137
π'	15	85	1.215
K	86	14	0.515
K'	14	86	1.195
η_1	89	11	0.553
η_2	78	22	0.982
η_3	32	68	1.225
η_4	1	99	1.794

TABLE 2. Predicted properties of scalar states: $\bar{q}q$ percentage (2nd column), $\overline{qq}qq$ (3rd column) and masses (last column).

State	$\bar{q}q$%	$\overline{qq}qq$%	m (GeV)
a	24	76	0.984
a'	76	24	1.474
κ	8	92	1.067
κ'	92	8	1.624
f_1	40	60	0.742
f_2	5	95	1.085
f_3	63	37	1.493
f_4	93	7	1.783

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