Chiral Symmetry and Scalars\footnote{Parallel Session Talk at Hadron2001-Protvino}

S.F. Tuan

Department of Physics, University of Hawaii at Manoa
Honolulu, HI 96822-2219, U.S.A.

Abstract. The suggestion by Jaffe that if $\sigma$ is a light $q\bar{q}$ state $0^{++}$ then even the fundamental chiral transformation properties of the $\sigma$ becomes unclear, has stimulated much interest. Adler pointed out that in fact the seminal work on chiral symmetry via PCAC consistency, is really quite consistent with the $\sigma$ being predominantly $q^2\bar{q}^2$. This interpretation was actually backed by subsequent work on effective Lagrangian methods for linear and non-linear realizations. More recent work of Achasov suggests that intermediate four-quark states determine amplitudes involving other scalars $a_0(980)$ and $f_0(980)$ below 1 GeV, and the report by Ning Wu that study on $\sigma$ meson in $J/\psi \to \omega \pi^+\pi^-$ continue to support a non-$q\bar{q}$ $\sigma$ with mass as low as 390 MeV. It is also noted that more recent re-analysis of $\pi K$ scattering by S. Ishida et al. together with the work of the E791 Collaboration, support the existence of the scalar $\kappa$ particle with comparatively light mass as well.

In an intriguing paper Jaffe [1] pointed out that the QCD “Breit Interaction” summarized by an effective Hamiltonian acting on the quarks’ spin and color indices,

$$H_{\text{eff}} \propto -\sum_{i\neq j} \lambda_i \cdot \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j$$

affirm earlier work [2] that $f_0(980)$, $a_0(980)$, $\sigma(560)$, and $\kappa(900)$ scalars make a nonet with mass spectrum, decay couplings and widths that look qualitatively like $\bar{q}q\bar{q}q$ system. Alford and Jaffe [3] raised the pertinent question that if light $\bar{q}^2q^2$ states are, in fact, a universal phenomenon below 1 GeV, and if $\sigma$ is predominantly a $\bar{q}^2q^2$ object, then the chiral transformation properties of the $\sigma$ have to be re-examined. The $\pi$ and the $\sigma$ are usually viewed as members of a (broken) chiral multiplet. In the naive $\bar{q}q$ model both $\pi$ and $\sigma$ are in $(1/2,1/2) \oplus (1/2,1/2)$ representation of $SU(2)_L \otimes SU(2)_R$ before symmetry breaking. In a $\bar{q}^2q^2$ model, as in the real world, the chiral transformation properties of the $\sigma$ are not clear.
There remains a body of recent literature [4] which retains in essence the $\bar{q}q$ model for the $\sigma$ meson. For instance Törnqvist et al. [4] used chiral-symmetry constraints in their study. Chiral symmetry constraints have been discussed by for instance Oller [5] where it is said that the range of applicability of chiral constraints could be enlarged up to around 0.8 GeV. Because of the model dependence of experimental analysis, current wisdom suggests that $\sigma$ has mass between 400 to 700 MeV and hence the use of chiral constraints would appear to be valid. However in the context of Törnqvist et al. [4] the $4q \bar{q}^2q^2$ scheme is not easy to combine with chiral symmetry constraints, which are crucial to their work. Indeed for weak interactions, their (chiral) results are the same as the strong interaction quark-level linear $\sigma$ model (LSM) $\bar{q}q$ scheme in one-loop order together with the electromagnetic (LSM) analogue [6]. Törnqvist [6] expressed further concern that 4q or rather $2\bar{q}q^2$ meson models and chiral symmetry, the chiral symmetry can of course be imposed in a model like the linear $\sigma$ model (LSM), but then all states $\sigma$, $f_0$, $a_0$ and the pion would be basically 4q states! We shall return to this concern later on in this paper.

On an optimistic note, Adler [7] pointed out that in the original PCAC Consistency Condition paper [8], when analysed for the pion- pion scattering case, led to the conclusion that there had to be a broad low energy pion-pion scattering resonance. This is then quite consistent with the $\sigma$ being predominantly $q^2\bar{q}^2$. Secondly, the numerical estimates of the “sigma term” from current algebra [9], assuming it is $q\bar{q}$ [or $(3,3) + (\bar{3},\bar{3})$] were always an embarrassment, since they were generally off by a factor of two whereas other things worked much better than that (typically of order 10% or less [8]). This again is quite consistent with the dominant spectral weight not being in the $q\bar{q}$ channel. Third, in Zumino’s 1970 Brandeis lectures [10] on effective Lagrangian methods, he discusses nonlinear realizations on pp. 451-454 (see also pp. 481-483, 485); he first describes the linear realization of the $\sigma$ model, stating that $\sigma$...... (is the field) of a scalar isoscalar $\pi - \pi$ resonance. He then shows how by a redefinition the same low energy results arise from a nonlinear transformation involving the redefined pion field only; in this nonlinear transformation, $\bar{\pi}^2$ plays a role analogous to that played by $\sigma$ in the linear case. So again, it is expected that the $\sigma$ should be a two pion state, and hence not surprisingly that it is dominantly $q^2\bar{q}^2$.

Jaffe [11] expanded on his understanding (or lack thereof) of the role of $\sigma$ in chiral symmetry [3]. Since chiral SU(2) symmetry is spontaneously broken, the physical particles do not have to transform as irreducible representations of $SU(2) \times SU(2)$. There is a prejudice (originating in the quark model?) that the pion transforms like $q\bar{q}$, and an even less well justified prejudice that the $\sigma$ transforms in the same way as the pion. However, there does not exist any good reason to think that the transformation properties of the $\sigma$ are linked to those of the pion when $SU(2) \times SU(2)$ is spontaneously broken. Perhaps another way of saying the same thing [12] is that chiral symmetry does not mesh well with either constituent quarks nor with QCD’s current quarks, hence chiral symmetry does not require multi-quark states to fuse into a $q\bar{q}$ state as originally thought.

Experimental evidence for the existence of the scalar $\sigma$ at the low mass value of
390 MeV with total width of order 282 MeV has been recently reported by Ning Wu [13] based on the study of $\sigma$ particle in $J/\psi \rightarrow \omega \pi^+ \pi^-$ from $7.8 \times 10^6$ BESI $J/\psi$ data. There is also the newly reported [14] $\sigma(\pi \pi)$ scalar resonance with a $\sigma$ mass and width of $478 \pm 24 \pm 17$ MeV/$c^2$ and $342 \pm 42 \pm 21$ MeV/$c^2$. Indeed recent re-analysis of the $\pi \pi$ scattering data by S. Ishida et al. [15] shows evidence for the existence of $\sigma$ with comparatively light mass also. This same scattering data [15] for $\pi K$ also showed evidence for the existence of the $\kappa$ particle also of relatively light mass. This is corroborated again by the newly reported [14] $\kappa(K\pi)$ scalar resonance with a $\kappa$ mass and width of $815 \pm 30$ MeV/$c^2$ and $560 \pm 116$ MeV/$c^2$. However Achasov [16] has cautioned that information on these scalars can be obtained only in strongly model dependent ways up to now. It seems reasonable that together with the status of $f_0(980)$ and $a_0(980)$ rather carefully analysed by Achasov and Gubin [17] we do nevertheless have a nonet of $q\bar{q}$ scalars below 1 GeV, though the mass and width of some of these scalars remain to be pinned down more precisely. Coming back to a more theoretical understanding of the situation, Achasov [16] reassured that Törnqvist’s fear [6] that the pion also may end up as a 4q state is strongly overstated. The point is that one can not say that a field contains a fixed number of quarks. It is approximately true only in some energy (virtuality) region. For example, when virtualities of $\sigma$ states have the order of the pion mass they show themselves as two-quark states, the chiral partners of pions, but when virtualities of $\sigma$ states are of the order of 1 GeV (remember a $\sigma$ of mass 700 MeV remains in the acceptable range), they can show themselves as four-quark states. Jaffe [11] elaborated further that the “quark content” of a particular meson is a heuristic concept at best. In some contexts the pion appears to be a $q\bar{q}$ state (for example as a member of an SU(3) meson octet); in others it appears to be a “wave on the chiral vacuum”, which would be a coherent state in the Bogoliubov sense, including arbitrarily high numbers of $q\bar{q}$. The point is that the $\sigma$, the $f_0(980)$, and $a_0(980)$ has always been that the principal features of their mass spectrum, couplings to pseudoscalars, and to electromagnetic fields, are well described by a dominant $qq\bar{q}\bar{q}$ content. Hence there is agreement with Achasov that the quark content can be regarded as “virtuality” dependent. Jaffe [11] also pointed out that his understanding of Jona Lasinio/Nambu spontaneous symmetry breaking where

$$\sigma = \sqrt{1 - \bar{\pi}^2/f_{\pi}^2}$$

$$= 1 - \frac{\bar{\pi}^2}{2f_{\pi}^2} + \ldots$$

is in fact the same as that of Zumino [10] who discussed spontaneous symmetry breaking in the non linear realization case as

$$\delta \bar{\pi} = 2\bar{\alpha}\sqrt{\kappa^2 - \bar{\pi}^2}$$

where $\kappa = (1/2)f_{\pi}$. Expansion of the r.h.s. of (3) in terms of $[\bar{\pi}^2/\kappa^2]$, one would get something very similar to the r.h.s. of (2) up to a multiplicative factor. Hence Jaffe is in agreement with Adler [7].
We have certainly come a long way from the traditional naive quark model classification of hadron states of some 35 years ago [18]. For some trained in the traditional approach like myself, what is described above comes as a surprise bordering on shock. Hence the opportunity to air out these concerns at Hadron2001 is much appreciated. (During the discussions after this talk, Professor J. Schechter pointed out the work of the Syracuse group [19] which addressed quantitatively some of the issues presented here.)

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REFERENCES

1. R.L. Jaffe, hep-ph/0001123, M.I.T. CTP # 2938.
2. R.L. Jaffe, Phys. Rev. D15, 267 (1977); Phys. Rev. D15, 281 (1977).
3. M. Alford and R.L. Jaffe, hep-lat/0001023, MIT-CTP-2940.
4. N.A. Törnqvist et al., hep-ph/0005106; M. Volkov et al., hep-ph/0007131.
5. J.A. Oller, hep-ph/0007349.
6. M.D. Scadron and N.A. Törnqvist (private communications).
7. S.L. Adler (private communication).
8. S.L. Adler, Phys. Rev. 137, B1022 (1965).
9. E. Reya, Rev. Mod. Phys. 46, 545 (1974).
10. B. Zumino, Lectures on Elementary Particles and Quantum Field Theory, Volume 2 (1970) (edited by S. Deser, M. Grisaru, and H. Pendleton).
11. R.L. Jaffe (private communication).
12. J.L. Rosner (private communication).
13. Ning Wu, hep-ex/0104050.
14. Carla Gobel, E791 Collaboration, hep-ex/0012009.
15. S. Ishida et al., Prog. Theor. Phys. 95, 745 (1996).
16. N.N. Achasov (private communication).
17. N.N. Achasov and V.V. Gubin, Phys. Rev. D63, 094007 (2001); see also N.N. Achasov, these Proceedings.
18. R.H. Dalitz, in High Energy Physics (Gordon and Breach, New York, 1966), p. 253.
19. D. Black et al, Phys. Rev. D64, 014031 (2001).