Light Scalar Mesons as Manifestation of Spontaneously Broken Chiral Symmetry [1]

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Abstract

Attention is paid to the production mechanisms of light scalars that reveal their nature. We reveal the chiral shielding of the $\sigma(600)$ meson. We show that the kaon loop mechanism of the ϕ radiative decays, ratified by experiment, points to the four-quark nature of light scalars. We show also that the light scalars are produced in the two photon collisions via four-quark transitions in contrast to the classic P wave tensor $q\bar{q}$ mesons that are produced via two-quark transitions $\gamma\gamma \to q\bar{q}$. The history of spontaneous breaking of symmetry in quantum physics is discussed in Appendix.

1 Introduction

The scalar channels in the region up to 1 GeV became a stumbling block of QCD. The point is that both perturbation theory and sum rules do not work in these channels because there are not solitary resonances in this region.

As Experiment suggests, in chiral limit confinement forms colourless observable hadronic fields and spontaneous breaking of chiral symmetry with massless pseudoscalar fields. There are two possible scenarios for QCD realization at low energy:
1. $U_L(3) \times U_R(3)$ linear σ model,
2. $U_L(3) \times U_R(3)$ non-linear σ model.
The experimental nonet of the light scalar mesons suggests $U_L(3) \times U_R(3)$ linear σ model.

1 $SU_L(2) \times SU_R(2)$ Linear σ Model [1], Chiral Shielding in $\pi\pi \to \pi\pi$ [2]

Hunting the light σ and κ mesons had begun in the sixties. But the fact that both $\pi\pi$ and πK scattering phase shifts do not pass over 90^0 at putative resonance masses prevented to prove their existence in a conclusive way.

Situation changes when we showed that in the $SU_L(2) \times SU_R(2)$ linear σ model [1] there is a negative background phase which hides the σ meson [2]. It has been made clear that shielding wide lightest scalar mesons in chiral dynamics is very natural. This idea was picked up and triggered new wave of theoretical and experimental searches for the σ and κ mesons.

Our approximation is as follows (see Fig. 1):

$$T_0^0 = \frac{T_0^{0(tree)}}{1-i\rho_{\pi\pi}T_0^{0(tree)}} = \frac{e^{2i(\delta_{bg}+\delta_{res})}-1}{2i\rho_{\pi\pi}} = \frac{e^{2i\delta_0^0}-1}{2i\rho_{\pi\pi}} = T_{bg} + e^{2i\delta_{bg}}T_{res},$$

$$T_{res} = \frac{\sqrt{s}\Gamma_{res}(s)/\rho_{\pi\pi}}{M_{res}^2 - s + \mathrm{Re}\Pi_{res}(M_{res}^2) - \Pi_{res}(s)} = \frac{e^{2i\delta_{res}}-1}{2i\rho_{\pi\pi}}, \quad M_{res}^2 = m_\sigma^2 - \mathrm{Re}\Pi_{res}(M_{res}^2),$$

$$T_0^2 = \frac{T_0^{2(tree)}}{1-i\rho_{\pi\pi}T_0^{2(tree)}} = \frac{e^{2i\delta_0^2}-1}{2i\rho_{\pi\pi}}.$$

[1] Talk at The International Bogolyubov Conference "Problems of Theoretical and Mathematical Physics" devoted to the 100th anniversary of N.N.Bogolyubov's birth that was held from August 21 to August 22, 2009 in Moscow at the Russian Academy of Sciences (RAS) and from August 23 to August 27, 2009 in Dubna at the Joint Institute for Nuclear Research (JINR).

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The chiral shielding of the $\sigma(600)$ meson in $\pi\pi \to \pi\pi$ is shown in Fig. 2 with the $\pi\pi$ phase shifts δ_{res}, δ_{bg}, δ_0^0 (a) and the corresponding cross sections (b).

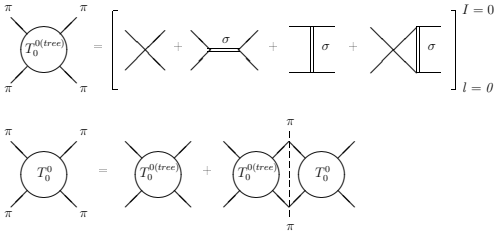

Figure 1: Our approximation.

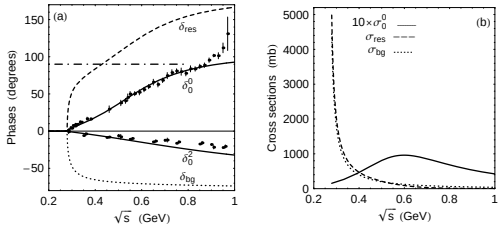

Figure 2: $\delta_0^0 = \delta_{res} + \delta_{bg}$.

3 The σ Propagator [2]

$1/D_\sigma(s)$=$1/[M_{res}^2$–s+Re$\Pi_{res}(M_{res}^2)$–$\Pi_{res}(s)]$. The σ meson self-energy $\Pi_{res}(s)$ is caused by the intermediate $\pi\pi$ states, that is, by the four-quark intermediate states. This contribution shifts the Breit-Wigner (BW) mass greatly $m_\sigma - M_{res} \approx 0.50\,\text{GeV}$. So, half the BW mass is determined by the four-quark contribution at least. The imaginary part dominates the propagator modulus in the region $0.3\,\text{GeV} < \sqrt{s} < 0.6\,\text{GeV}$. So, the σ field is described by its four-quark component at least in this energy (virtuality) region.

4 Four-quark Model

The nontrivial nature of the well-established light scalar resonances $f_0(980)$ and $a_0(980)$ is no longer denied practically anybody. As for the nonet as a whole, even a cursory look at PDG Review gives an idea of the four-quark structure of the light scalar meson nonet, $\sigma(600)$, $\kappa(700-900)$, $f_0(980)$, and $a_0(980)$, inverted in comparison with the classical P wave $q\bar{q}$ tensor meson nonet $f_2(1270)$, $a_2(1320)$, $K_2^*(1420)$, $\phi_2'(1525)$. Really, while the scalar nonet cannot be treated as the P wave $q\bar{q}$ nonet in the naive quark model, it can be easy understood as the $q^2\bar{q}^2$ nonet, where σ has no strange quarks, κ has the s quark, f_0 and a_0 have the $s\bar{s}$ pair. Similar states were found by Jaffe in 1977 in the MIT bag [3].

5 Radiative Decays of the ϕ Meson and the K^+K^- Loop Model [4]

Ten years later we showed that $\phi \to \gamma a_0 \to \gamma\pi\eta$ and $\phi \to \gamma f_0 \to \gamma\pi\pi$ can shed light on the problem of the $a_0(980)$ and $f_0(980)$ mesons. Now these decays are studied not only theoretically but also experimentally. When basing the experimental investigations, we suggested one-loop model $\phi \to K^+K^- \to \gamma a_0/f_0$, see Fig. 3. This model is used in the data treatment and is ratified by experiment, see Fig. 4. Gauge invariance gives the conclusive arguments in favor of the K^+K^- loop transition as the principal mechanism of the $a_0(980)$ and $f_0(980)$ meson production in the ϕ radiative decays.

6 The K^+K^- Loop Mechanism is Four-Quark Transition [4]

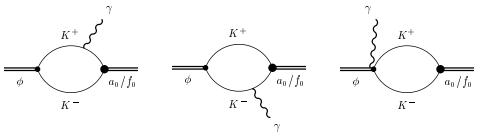

Figure 3: The K^+K^- loop model.

In truth this means that the $a_0(980)$ and the $f_0(980)$ are seen in the ϕ meson radiative decays owing to the K^+K^- intermediate state. So, the mechanism of the $a_0(980)$ and $f_0(980)$ production in the ϕ meson radiative decays is established at a physical level of proof. We are dealing with the four-quark transition. A radiative four-quark transition between two $q\bar{q}$ states requires creation and annihilation of an additional $q\bar{q}$ pair, i.e., such a transition is forbidden by the OZI rule, while a radiative four-quark transition between $q\bar{q}$ and $q^2\bar{q}^2$ states requires only creation of an additional $q\bar{q}$

pair, i.e., such a transition is allowed by the OZI rule. The large N_C expansion supports this conclusion.

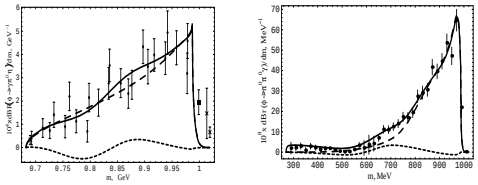

Figure 4: The left (right) plot shows the fit to the KLOE data for the $\pi^0\eta$ ($\pi^0\pi^0$) mass spectrum in the $\phi \to \gamma\pi^0\eta$ ($\phi \to \gamma\pi^0\pi^0$) decay caused by the $a_0(980)$ ($\sigma(600) + f_0(980)$) production through the K^+K^- loop mechanism.

7 Scalar Nature and Production Mechanisms in $\gamma\gamma$ collisions [5]

Twenty seven years ago we predicted the suppression of $a_0(980) \to \gamma\gamma$ and $f_0(980) \to \gamma\gamma$ in the $q^2\bar{q}^2$ MIT model, $\Gamma_{a0\to\gamma\gamma} \sim \Gamma_{f_0\to\gamma\gamma} \sim 0.27\,\text{keV}$. Experiment supported this prediction.

Recently the experimental investigations have made great qualitative advance. The Belle Collaboration published data on $\gamma\gamma \to \pi^+\pi^-$, $\gamma\gamma \to \pi^0\pi^0$, and $\gamma\gamma \to \pi^0\eta$, whose statistics are huge [6], see Fig. 5. They not only proved the theoretical expectations based on the four-quark nature of the light scalar mesons, but also have allowed to elucidate the principal mechanisms of these processes. Specifically, the direct coupling constants of the $\sigma(600)$, $f_0(980)$, and $a_0(980)$ resonances with the system are small with the result that their decays into $\gamma\gamma$ are the four-quark transitions caused by the rescatterings $\sigma(600) \to \pi^+\pi^- \to \gamma\gamma$, $f_0(980) \to K^+K^- \to \gamma\gamma$ and $a_0(980) \to K^+K^- \to \gamma\gamma$ in contrast to the $\gamma\gamma$ decays of the classic P wave tensor $q\bar{q}$ mesons $a_2(1320)$, $f_2(1270)$ and $f_2'(1525)$, which are caused by the direct two-quark transitions $q\bar{q} \to \gamma\gamma$ in the main. As a result the practically model-independent prediction of the $q\bar{q}$ model $g^2_{f_2\gamma\gamma} : g^2_{a_2\gamma\gamma} = 25 : 9$ agrees with experiment rather well. The two-photon light scalar widths averaged over resonance mass distributions $\langle\Gamma_{f_0\to\gamma\gamma}\rangle_{\pi\pi} \approx 0.19$ keV, $\langle\Gamma_{a_0\to\gamma\gamma}\rangle_{\pi\eta} \approx 0.3$ keV and $\langle\Gamma_{\sigma\to\gamma\gamma}\rangle_{\pi\pi} \approx 0.45$ keV. As to the ideal $q\bar{q}$ model prediction $g^2_{f_0\gamma\gamma} : g^2_{a_0\gamma\gamma} = 25 : 9$, it is excluded by experiment.

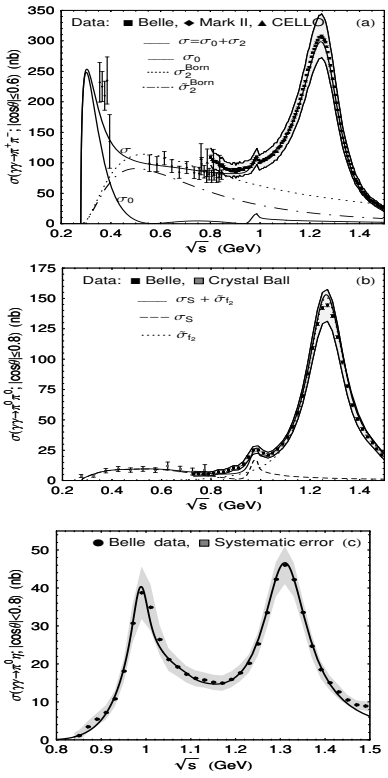

Figure 5: Descriptions of the Belle data on $\gamma\gamma \to \pi^+\pi^-$ (a), $\gamma\gamma \to \pi^0\pi^0$ (b), and $\gamma\gamma \to \pi^0\eta$ (c).

8 Summary [2, 4, 5]

(i) The mass spectrum of the light scalars, $\sigma(600)$, $\kappa(800)$, $f_0(980)$, $a_0(980)$, gives an idea of their $q^2\bar{q}^2$ structure.

(ii) Both intensity and mechanism of the $a_0(980)/f_0(980)$ production in the $\phi(1020)$ radiative decays, the $q^2\bar{q}^2$ transitions $\phi \to K^+K^- \to \gamma[a_0(980)\ /f_0(980)]$, indicate their $q^2\bar{q}^2$ nature.

(iii) Both intensity and mechanism of the scalar meson decays into $\gamma\gamma$, the $q^2\bar{q}^2$ transitions $\sigma(600) \to \pi^+\pi^- \to \gamma\gamma$ and $[f_0(980)/a_0(980)] \to K^+K^- \to \gamma\gamma$, indicate their $q^2\bar{q}^2$ nature too.

(iv) In addition, the absence of $J/\psi \to \gamma f_0(980)$, $a_0(980)\rho$, $f_0(980)\omega$ in contrast to the intensive $J/\psi \to \gamma f_2(1270)$, $\gamma f_2'(1525)$, $a_2(1320)\rho$, $f_2(1270)\omega$ decays intrigues against the P wave $q\bar{q}$ structure of $a_0(980)$ and $f_0(980)$.

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Appendix. Source of Spontaneous Breaking of Symmetry in Quantum Physics

It is appropriate to mention here that Nikolay Nikolaevich Bogolyubov was the pioneer of spontaneous breaking of symmetry in quantum physics.

Usually N.N. Bogolyubov is considered as the first-rate mathematician, the first-rate mechanic, and the first-rate physicist. But in our case the inverse order is more correct. Or rather at such a height the distinction between the mathematician and the physicist is insignificant. It is remembered, how K.F. Gauss checked the sum of the angles in a triangle, formed by three tops in mountains of Harz. The genuine brilliant is Bogolyubov's pioneer work on superfluidity (**1947 [7]**) that triggered research spontaneous breaking of symmetry in quantum physics. Bellow is its history in citations. (NNA translations and comments are my ones.)

L. Landau. The theory of superfluidity of helium II. J. Phys. USSR, 5, 71, 1941.

L.D. Landau. The theory of superfluidity of helium II. JETP, 11, 592, 1941 (in Russian).

NNA translation. "Tisza has suggested to consider helium II as the degenerate ideal boze-gas, supposing that the atoms, being in the ground state (the state with energy equal to zero), move through a liquid without a friction both on vessel walls and on other part of a liquid. But, such an idea cannot be recognized as a satisfactory one. Not to mention that liquid helium has nothing to do with the ideal gas, atoms, being in the ground state, would not behave as "superfluid" ones at all. On the contrary, nothing could prevent the atoms, being in a normal state, to collide the exited ones, i.e., at movement through a liquid they would experience a friction and a "superfluidity" could be not even mentioned."

N. Bogolubov. On the theory of superfluidity. J. Phys. USSR 11 (1947) 23 [Acad. Sci. USSR. J. Phys. 11, (1947). 23-32].

N. N. Bogolubov. On the theory of superfluidity. Proc. Acad. Sci. USSR. Phys. Series, 1947, v. 11, No 1, pp. 77-90 (in Russian).

NNA translation. "We will try to overcome this basic difficulty (*a fluid friction, L.D. Landau, NNA*) and to show that under some conditions in a weakly nonideal Bose-Einshtein gas " the degenerate condensate " can move without a friction on elementary excitations with an enough small speed. It is essential to notice that in our theory these elementary excitations are collective effect and cannot be identified with individual molecules."

F. London. 1948. AMERICAN MATHEMATICAL SOCIETY. MathSciNet Mathematical Reviews. MR0022177 Bogolubov, N. On the theory of superfluidity. Acad. Sci. USSR. J. Phys. 11, (1947). 23-32.

"The object of this paper is an attempt to withdraw from the "couterblast of objections" raised by L. Landau and others [same J. 5, 71-90 (1941)] against the Bose-Einstein theory of liquid helium [Tisza, C.R. Acad. Sci. Paris 207, 1035-1037, 1186-1189 (1938); F. London, Physical Rev.(2) 54, 947-954 (1938)] and to adopt the point of view of the latter. By using the method of second quantization the author tries to show that the phenomenon of superfluidity can be explained on the basis of a theory of the degeneracy of a nonperfect Bose-Einstein gas of certain "quasi-particles" representing elementary excitations of a continuum. The author ignores the fact that there is no Bose-Einstein condensation for quasi-particles which, like the excitations, have no constant particle number. The result is obtained under the condition of certain approximations, neglecting second and higher order terms of a quantity called ϑ, which characterizes the non-commutable part of the quantized wave function. Although it might be justifiable to consider this quantity as small and the series in question as rapidly convergent it nevertheless appears insufficient to drive the entire absence of any interaction from a consideration of a first order approximation alone." *Reviewed by F. London. Copyright American Mathematical Society 1948, 2009.*

L.D. Landau. On the theory of superfluidity. DAN USSR, 61, 253, 1948 (in Russian).

L. Landau. On the theory of superfluidity. Phys. Rev. 75 (1949) 884. Letters to the Editor.

"It is useful to note that N.N. Bogolyubov has succeeded recently, by an ingenious application of second quantization, in determining the general form of the energy spectrum of the a Bose-Einstein gas with a weak interaction between the particles. As it should be, the "elementary excitations" appear automatically, and their energy ϵ as a function of the momentum p is represented by a single curve, which has a linear initial part."

TWENTY SIX YEAS LATER

V.B. Berestetskii .
ELEMENTARY PARTICLES. First ITEP Physics School, Issue I, page 9. ATOMIZDAT, Moscow -1973 (In Russian).

NNA translation. "As an example of the real manifestation of the Goldstone (*1961 [8], NNA*) effect in nonrelativistic quantum mechanics of system of identical particles one can give the result received in 1947 by Bogolyubov. It lies in the fact that the lowest energy excitation of nonideal bose-gas have character phonons. Phonons are massless particles, the complex field is the wave function of the bose-particle in the method of the secondary quantization, the conserved charge is the number of particles, the vacuum is the state of the bose-einstein condensation, the vacuum value of the field $\eta = \sqrt{n}$, where n is the density of particles."

THIRTY ONE YEARS LATER

L.D. Landau and E.M. Lifshitz.
THEORETICAL PHYSICS. VOLUME IX.
E.M. Lifshitz and L.P. Pitaevskii.
STATISTICAL PHYSICS. PART 2. Theory of Condensed State.

CHAPTER III, page 123 (footnote 1).
Moscow "NAUKA" 1978. (In Russian)

NNA translation. "1) The method, expounded below, is due to N.N. Bogolyubov (1947). The use of this method to the bose gas by Bogolyubov was the first example of the consistent microscopic finding of the energy spectrum of "quantum fluids"."

NNA: **As far as could be judged from such an acknowledgement, Nikolay Nikolaevich Bogolyubov is the author of the theory of quantum fluids from the first principles.**

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Uehara S. et al.// Phys. Rev. D. 2008. V. 78. P. 052004;
Uehara S. et al.// Phys. Rev. D. 2009. V. 80. 032001.

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