Nature of Light Scalar Mesons in Bright Light of Photon-Photon Collisions

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Abstract

The surprising thing is that the light scalar meson problem, arising 50 years ago from the linear sigma model (LSM) with spontaneously broken chiral symmetry, has become central in the nonperturbative quantum chromodynamics (QCD), because it has been made clear that LSM could be the low energy realization of QCD. First, we review briefly signs of four-quark nature of light scalars. Then we show 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 $\gamma\gamma \to q\bar{q}$. Thus we get new evidence of the four-quark nature of the lower scalar states.

Outline

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.

At the same time the question on the nature of the light scalar mesons is major for understanding the mechanism of the chiral symmetry realization, arising from the confinement, and hence for understanding the confinement itself.

2. Evidence for the four-quark nature of light scalar mesons.

i) Normal ($q\bar{q}$) and inverted ($q^2\bar{q}^2$) mass spectra.

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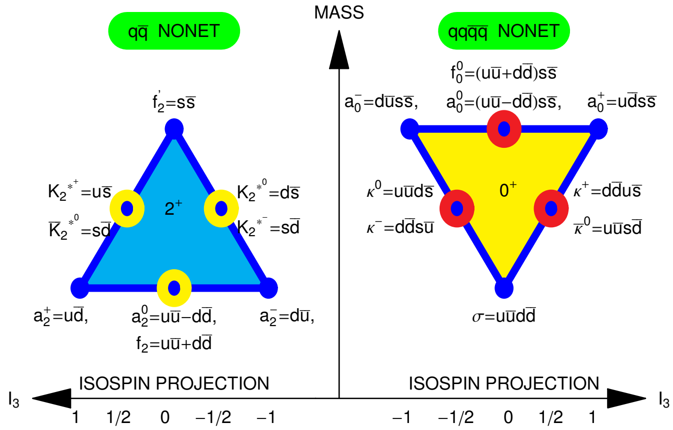

Figure 1: Normal 2^{++} $(q\bar{q})$ and inverted 0^{++} $(q^2\bar{q}^2)$ mass spectra.

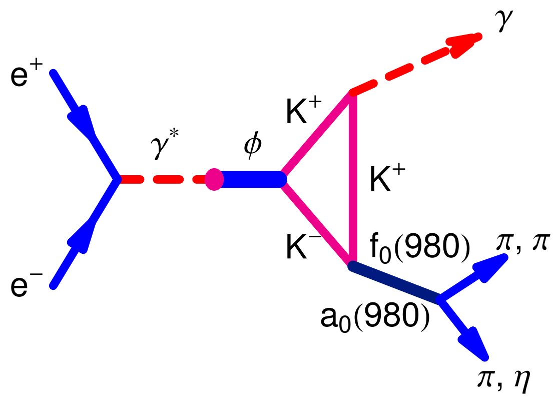

Figure 2: K^+K^- loop mechanism of $f_0(980)/a_0(980)$ production in $\phi(1020) \to \gamma[f_0(980)/a_0(980)]$ decays.

The mass spectrum of the light scalars $\sigma(600)$, $\kappa(800)$, $a_0(980)$, and $f_0\,(980)$ gives an idea of their $q^2\bar{q}^2$ structure. Really, this scalar nonet turns out to be inverted in comparison with the classical P wave $q\bar{q}$ tensor meson nonet (Fig. 1). In the naive quark model such a nonet cannot be understood as the P wave $q\bar{q}$ nonet, but it can be easy understood as the S wave $q^2\bar{q}^2$ nonet, where $\sigma(600)$ has no strange quarks, $\kappa(800)$ has the s quark, and $a_0(980)$ and $f_0(980)$ have the $s\bar{s}$ pair.

ii) The $\phi(1020)$ meson radiative decays about light scalars [1, 2, 3].

At the end of eighties it was shown that the study of the radiative decays $\phi \to \gamma f_0 \to \gamma\pi\pi$ and $\phi \to \gamma a_0 \to \gamma\pi\eta$ can shed light on the problem of $f_0(980)$ and $a_0(980)$ mesons [1]. Now these decays have been studied not only theoretically but also experimentally with the help of the SND and CMD-2 detectors at Budker Institute of Nuclear Physics in Novosibirsk and the KLOE detector at the DAΦNE ϕ-factory in Frascati. When basing the experimental investigations [1], it was suggested the kaon loop model $\phi \to K^+K^- \to \gamma f_0(980) \to \gamma\pi\pi$ and $\phi \to K^+K^- \to \gamma a_0(980) \to \gamma\pi^0\eta$ (Fig. 2). This model is used in the data treatment and is ratified by experiment, see (Fig. 3). Both intensity and mechanism of the $f_0(980)$ and $a_0(980)$ production in the radiative decays of the $\phi(1020)$, via the $q^2\bar{q}^2$ transitions $\phi \to K^+K^- \to \gamma[f_0(980)/a_0(980)]$, testify to their $q^2\bar{q}^2$ nature [1, 2, 3].

iii) Chiral shielding of the $\sigma(600)$ meson in $\pi\pi \to \pi\pi$ and other evidence [6, 7, 8].

Hunting the light σ and κ mesons had begun in the sixties already. But long-standing unsuccessful attempts to prove their existence in a conclusive way entailed general disappointment and an information on these states disappeared from PDG Reviews. One of principal reasons against the σ and κ mesons was the fact that both $\pi\pi$ and πK scattering phase shifts do not

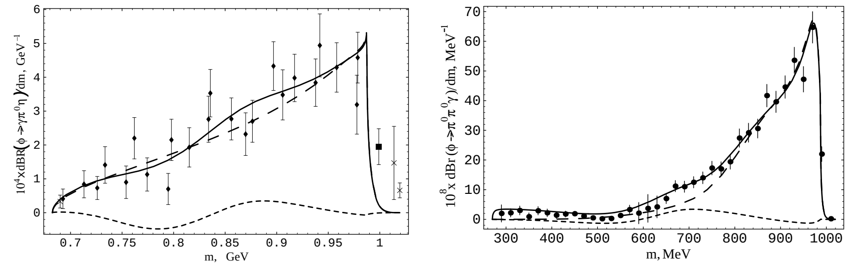

Figure 3: The left and right plots illustrate the fits [2, 3] to the KLOE data for the $\pi^0\eta$ and $\pi^0\pi^0$ mass spectra in the $\phi\to\gamma\pi^0\eta$ [4] and $\phi\to\gamma\pi^0\pi^0$ [5] decays, respectively.

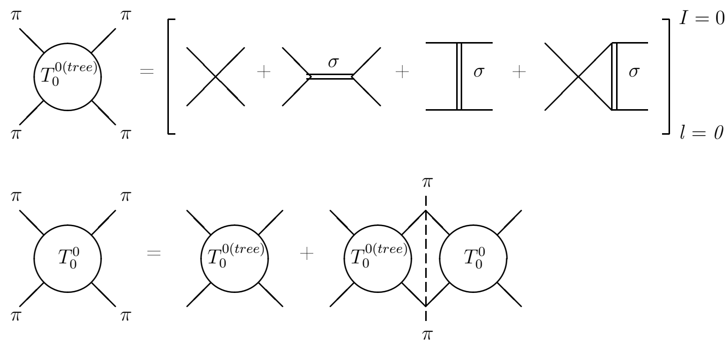

Figure 4: The graphical representation of the S wave $I=0$ $\pi\pi$ scattering amplitude T_0^0.

pass over 90^0 at putative resonance masses. Situation has changed when we showed that in the $SU(2)\times SU(2)$ linear σ model there is a negative background phase which hides the σ meson [6, 7, 8]. 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.

Chiral shielding of the $\sigma(600)$ can be easily revealed with the use of the S wave $I=0$ $\pi\pi$ scattering amplitude T_0^0 satisfying the simplest Dyson equation with the real π mesons in the intermediate state (Fig. 4). It is illustrated in Fig. 5(a) with the help of the $\pi\pi\to\pi\pi$ phase shifts δ_{res}, δ_{bg}, $\delta_0^0=\delta_{res}+\delta_{bg}$ and in Fig. 5(b) with the help of the corresponding cross sections. Note that in the σ meson propagator

$$\frac{1}{D_\sigma(s)}=\frac{1}{M_{res}^2-s+\mathrm{Re}\Pi_{res}(M_{res}^2)-\Pi_{res}(s)}\,,$$

the σ 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 $m_\sigma-M_{res}=0.50$ GeV. So, half the BW mass is determined by the four-quark contribution at least. The imaginary

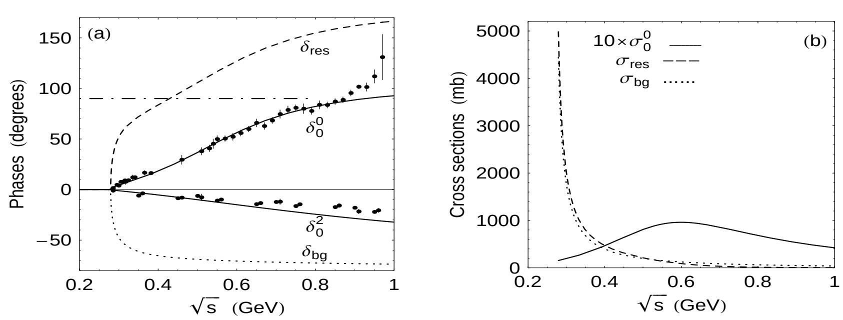

Figure 5: The σ model. Our approximation. Chiral shielding of the $\sigma(600)$.

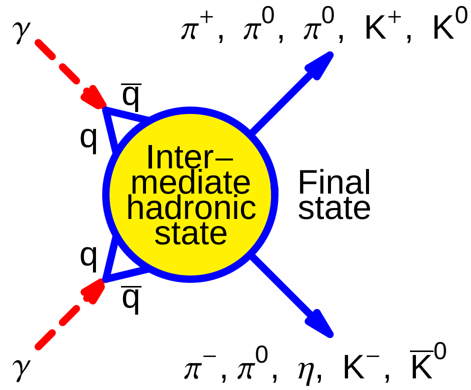

Figure 6: Probe for the quark structure of light scalars.

part dominates the propagator modulus in the region $300\,\mathrm{MeV} < \sqrt{s} < 600\,\mathrm{MeV}$. So, the σ field is described by its four-quark component at least in this energy (virtuality) region.

3. Light scalar manifestations in $\gamma\gamma$ collisions [7, 8, 9, 10, 11, 12, 13].

i) Prediction of the four-quark model. New stage of high statistics measurements, the Belle data [14, 15, 16].

Photons are probes of the quark structure of hadrons. Investigations of the mechanisms of the reactions $\gamma\gamma \to \pi^+\pi^-$, $\gamma\gamma \to \pi^0\pi^0$, $\gamma\gamma \to \pi^0\eta$, $\gamma\gamma \to K^+K^-$, and $\gamma\gamma \to K^0\bar{K}^0$ (Fig. 6) are an important constituent of the light scalar meson physics. Twenty eight years ago we predicted [9] that if the $a_0(980)$ and $f_0(980)$ are the $q^2\bar{q}^2$ MIT bag states, then their $\gamma\gamma$ widths, $\Gamma(a_0(980) \to \gamma\gamma) \sim \Gamma(f_0(980) \to \gamma\gamma) \sim 0.27\,\mathrm{keV}$, are an order of magnitude smaller than those of the $q\bar{q}$ mesons η', $f_2(1270)$, and the theoretical estimates in the $q\bar{q}$ model. Experiment supported this prediction: $\Gamma(a_0 \to \gamma\gamma) = (0.19 \pm 0.07^{+0.1}_{-0.07})\,\mathrm{keV}$, Crystal Ball, $\Gamma(a_0 \to \gamma\gamma) = (0.28 \pm 0.04 \pm 0.1)\,\mathrm{keV}$, JADE, $\Gamma(f_0 \to \gamma\gamma) = (0.31 \pm 0.14 \pm 0.09)\,\mathrm{keV}$, Crystal Ball, $\Gamma(f_0 \to \gamma\gamma) = (0.29 \pm 0.07 \pm 0.12)\,\mathrm{keV}$, MARK II. When in the $q\bar{q}$ model it was anticipated $\Gamma(a_0 \to \gamma\gamma) \approx (1.5-5.9)\Gamma(a_2 \to \gamma\gamma) \approx (1.5-6)\,\mathrm{keV}$, $\Gamma(f_0 \to \gamma\gamma) \approx (1.7-5.5)\Gamma(f_2 \to \gamma\gamma) \approx (4.5-14)\,\mathrm{keV}$.

Recently, the experimental investigations have made great qualitative advance. The Belle Collaboration published data on $\gamma\gamma \to \pi^+\pi^-$ [14], $\gamma\gamma \to \pi^0\pi^0$ [15], and $\gamma\gamma \to \pi^0\eta$ [16], whose statistics are huge. 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 $\gamma\gamma$ system are small and their decays into photons are the four-quark transitions caused by the rescattering mechanisms $\sigma \to \pi^+\pi^- \to \gamma\gamma$, $f_0(980)/a_0(980) \to K^+K^- \to \gamma\gamma$, and $a_0(980) \to \pi^0\eta \to \gamma\gamma$, in contrast to the two-photon 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 for the $2^{++}\gamma\gamma$ coupling constants $g^2_{f_2\gamma\gamma} : g^2_{a_2\gamma\gamma} = 25 : 9$ agrees with experiment rather well; $\Gamma_{f_2\to\gamma\gamma} \approx 2.8$ keV, $\Gamma_{a_2\to\gamma\gamma} \approx 1$ keV. The two-photon light scalar widths averaged over resonance mass distributions are: $\langle\Gamma_{f_0\to\gamma\gamma}\rangle_{\pi\pi} \approx 0.19$ keV [11, 12], $\langle\Gamma_{a_0\to\gamma\gamma}\rangle_{\pi\eta} \approx 0.4$ keV [13], and $\langle\Gamma_{\sigma\to\gamma\gamma}\rangle_{\pi\pi} \approx 0.45$ keV [12]. As to the ideal $q\bar{q}$ model prediction for the $0^{++} \to \gamma\gamma$ coupling constants $g^2_{f_0\gamma\gamma} : g^2_{a_0\gamma\gamma} = 25 : 9$, it is excluded by experiment.

Our statements for the $\sigma(600)$, $f_0(980)$, and $a_0(980)$ resonances are based on the detailed analysis of the new Belle Collaboration data on the $\gamma\gamma \to \pi^+\pi^-$, $\gamma\gamma \to \pi^0\pi^0$, and $\gamma\gamma \to \pi^0\eta$ reaction cross sections for energies up to 1.5 GeV. Owing to huge statistics and high resolution in the invariant mass of the $\pi\pi$ and $\pi^0\eta$ systems in the Belle experiments, clear signals from the

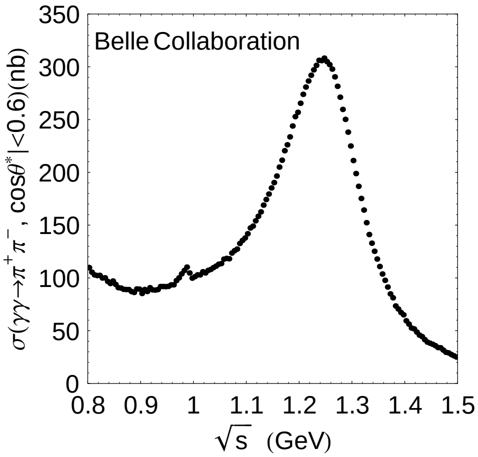

Figure 7: The high-statistics Belle data on $\gamma\gamma \to \pi^+\pi^-$. A clear signal from the $f_0(980)$ has been observed for the first time.

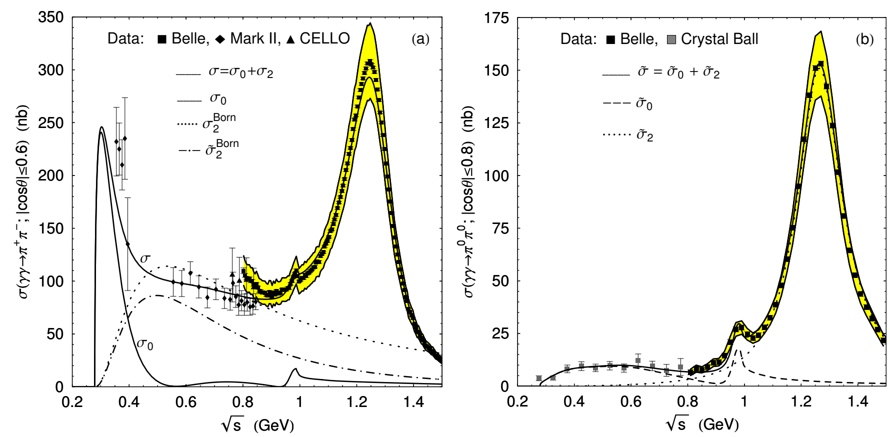

Figure 8: The simultaneous description of the Belle data on $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$. The bands show the size of the systematic errors of the Belle data.

$f_0(980)$ and $a_0(980)$ resonances were detected. The current experimental situation is shown in Figs. 7, 8, and 13.

ii) Dynamics of the $\sigma(600)$ and $f_0(980)$ production in $\gamma\gamma \to \pi\pi$ [7, 11, 12].

To analyze the data on the reactions $\gamma\gamma\to\pi^+\pi^-$ and $\gamma\gamma\to\pi^0\pi^0$, we use a model for the helicity and corresponding partial amplitudes, where the electromagnetic Born terms caused by the one-pion and one-kaon exchanges modified by form factors and strong elastic and inelastic final-state interactions in $\pi^+\pi^-$ and K^+K^- channels, as well as the contributions due to the direct interaction of the resonances with photons, are taken into account (Figs. 9, 10). Thus, symbolically, Amplitude = Born + Σ Born $\times$ Strong FSI + Direct. The amplitudes with definite isospin satisfy the Watson theorem in the elastic region. The obtained simultaneous description of the Belle data on $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$ is shown in Fig. 8 [12]. The rescattering production mechanisms of the $\sigma(600)$ and $f_0(980)$ resonances, i.e., the $q^2\bar{q}^2$ transitions, $\gamma\gamma \to \pi^+\pi^- \to \sigma(600)$ and $\gamma\gamma \to K^+K^- \to f_0(980)$) dominate and indicate the $q^2\bar{q}^2$ structure of these states.

We note also the recent analyses relevant to the Belle data on the reactions $\gamma\gamma \to \pi\pi$ [17, 18, 19].

iii) Dynamics of the $a_0(980)$ production in $\gamma\gamma \to \pi^0\eta$ [10, 13].

Recently, we performed the analysis of the Belle data on the reaction $\gamma\gamma \to \pi^0\eta$ [13]. To

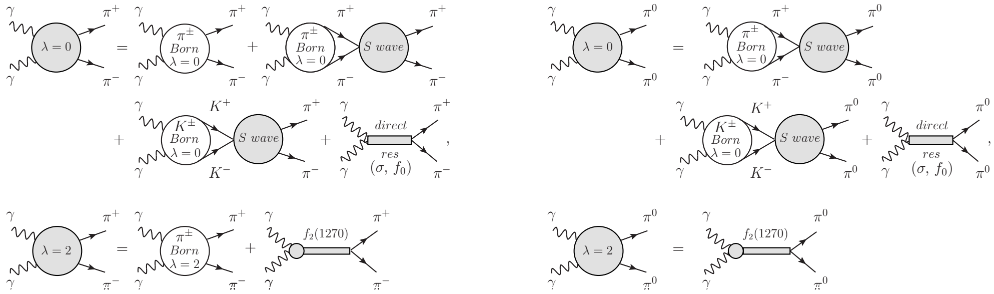

Figure 9: Dynamical model for the helicity amplitudes $\gamma\gamma \to \pi^+\pi^-$ (left) and $\gamma\gamma \to \pi^0\pi^0$ (right).

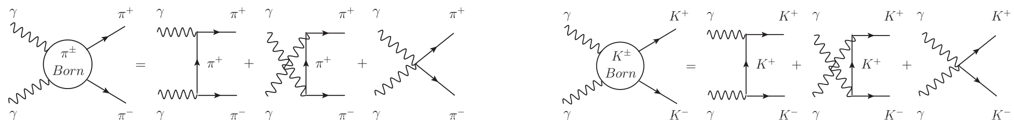

Figure 10: The Born one-pion (left) and one-kaon (right) exchanges modified by form factors.

do this, we have significantly developed the model proposed previously in Ref. [10]. Figures 11, 12 and 13 illustrate our model and the resulting description of the data on the $\gamma\gamma \to \pi^0\eta$ reaction cross section. The experimentally observed pattern is the result of the combination of many dynamical factors. The rescattering contributions are the most essential ones.

The main constituents of the $\gamma\gamma\to\pi^0\eta$ reaction mechanism are the following. The inelastic rescattering $\gamma\gamma\to K^+K^-\to\pi^0\eta$ with K^+K^- produced via the one-kaon exchange mechanism specifies the natural scale for the $a_0(980)$ production cross section in $\gamma\gamma\to\pi^0\eta$. An estimate gives $\sigma(\gamma\gamma\to K^+K^-\to a_0(980)\to\pi^0\eta; |\cos\theta|\leq 0.8)\approx 0.8\cdot 1.4\alpha^2 R_{a_0}/m^2_{a_0}\approx 24\,\mathrm{nb}\cdot R_{a_0}$ in the maximum, where $R_{a_0}=g^2_{a_0K^+K^-}/g^2_{a_0\pi\eta}$. There is the noticeable additional narrowing of the $a_0(980)$ peak due to this mechanism in the $\gamma\gamma\to\pi^0\eta$ channel. The K^* exchange narrows slightly the $a_0(980)$ peak too. However, the $\gamma\gamma\to K\bar{K}\to\pi^0\eta$ rescattering mechanism alone cannot describe the data in the $a_0(980)$ resonance region. The observed cross section can be obtain by adding the Born ρ and ω exchange contribution, modified by the S wave rescattering $\gamma\gamma\to(\pi^0\eta+\pi^0\eta')\to\pi^0\eta$, and the amplitude caused by the direct transitions of the $a_0(980)$ and heavy a_0' resonances into photons. Each of the contributions of these two mechanisms are not too large in the $a_0(980)$ region. But the main thing is that their coherent sum with the contribution of the inelastic rescattering $\gamma\gamma\to K\bar{K}\to\pi^0\eta$ leads to the considerable enhancement of the $a_0(980)$ resonance manifestation.

One of the results of our analysis consists in the preliminary information obtained on the S wave amplitude of the reaction $\pi^0\eta\to\pi^0\eta$ (Fig. 14), which is important for the low-energy

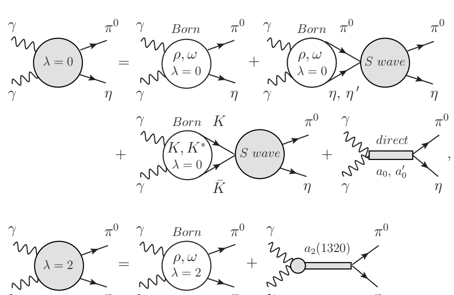

Figure 11: Dynamical model for the helicity amplitudes $\gamma\gamma\to\pi^0\eta$.

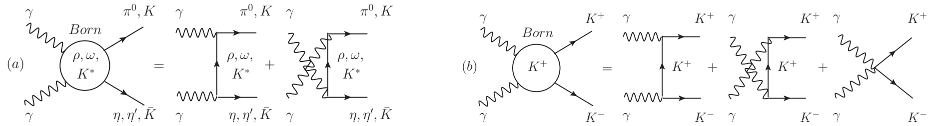

Figure 12: (a) The ρ, ω, K^*, and (b) K Born exchanges modified by form factors.

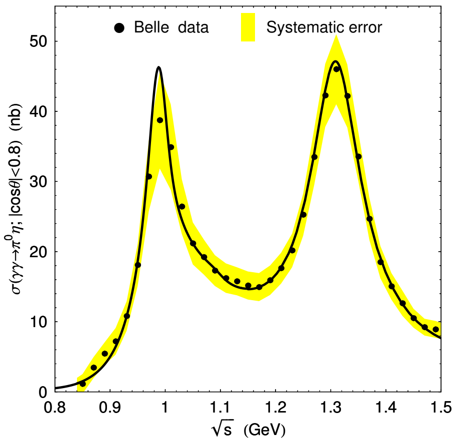

Figure 13: The description of the Belle data on $\gamma\gamma \to \pi^0\eta$.

physics of pseudoscalar mesons.

4. Future trends: the $\sigma(600)$, $f_0(980)$, and $a_0(980)$ investigations in $\gamma\gamma \to K\bar{K}$ and in $\gamma\gamma^*$ collisions [13].

The Belle Collaboration has investigated the $\gamma\gamma\to\pi^+\pi^-$, $\gamma\gamma\to\pi^0\pi^0$, and $\gamma\gamma\to\pi^0\eta$ reactions with the highest statistics. However, similar information is still lacking for the processes $\gamma\gamma\to K^+K^-$ and $\gamma\gamma\to K^0\bar{K}^0$. The S wave contributions from the K^+K^- Born term, $f_0(980)$, and $a_0(980)$ resonances near thresholds of these two channels are not clearly understood. They can be measured with the Belle, L3, CLEO, and KLOE-2 detectors.

There are also the promising possibility of investigating the nature of the light scalars in $\gamma\gamma^*$ collisions. If the $\sigma(600)$, $f_0(980)$, and $a_0(980)$ are $q^2\bar{q}^2$ states, their contributions to the $\gamma\gamma^*\to\pi\pi$ and $\gamma\gamma^*\to\pi^0\eta$ cross sections should decrease with increasing Q^2 more rapidly than the contributions from the classical tensor mesons $f_2(1270)$ and $a_2(1320)$. A similar behavior of the contribution from the $q^2\bar{q}^2$ exotic resonance state with $I^G=2^+$ and $J^{PC}=2^{++}$ to the $\gamma\gamma^*\to\rho^0\rho^0$ and $\gamma\gamma^*\to\rho^+\rho^-$ cross sections was recently observed by the L3 Collaboration [20].

5. Summary.

- 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.
- Both intensity and mechanism of the $a_0(980)/f_0(980)$ production in the radiative decays of $\phi(1020)$, 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.
- Both intensity and mechanism of the scalar meson decays into $\gamma\gamma$, namely, the $q^2\bar{q}^2$ transitions $\sigma(600)\to\pi^+\pi^-\to\gamma\gamma$, $f_0(980)/a_0(980)\to K^+K^-\to\gamma\gamma$, and $a_0(980)\to\pi^0\eta\to\gamma\gamma$ indicate their $q^2\bar{q}^2$ nature also.
- In addition, the absence of $J/\psi\to\gamma f_0(980)$, $\rho a_0(980)$, $\omega f_0(980)$ in contrast to the intensive

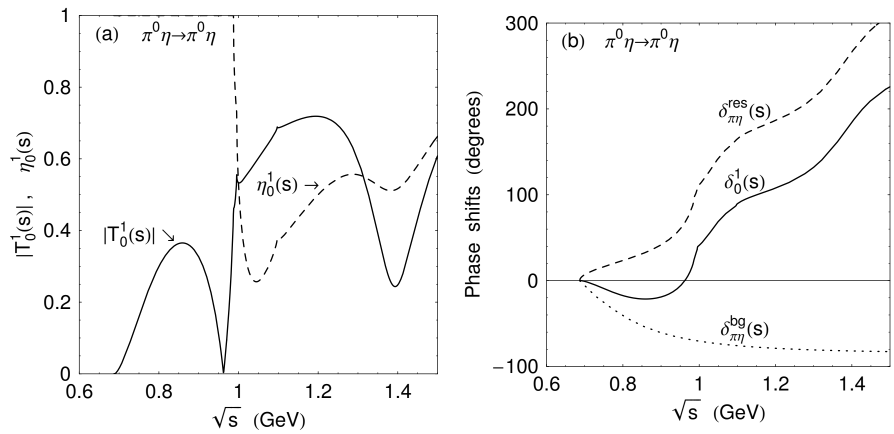

Figure 14: Modulus of $T_0^1(s)$, inelasticity $\eta_0^1(s)$ (a), and phase shifts (b) of the S wave amplitude $\pi^0\eta \to \pi^0\eta$ (here the $\pi\eta$ scattering length $a_0^1 = 0.0098 m_\pi^{-1}$ is in agreement with the chiral theory expectations $(0.005 - 0.01)m_\pi^{-1}$).

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

- It seems also undisputed that in all respects the $a_0(980)$ and $f_0(980)$ mesons are strangers in the company of the well established $b_1(1235)$, $h_1(1170)$, $a_1(1260)$, $f_1(1285)$, $a_2(1320)$, and $f_2(1270)$ mesons which are the members of the lower P wave $q\bar{q}$ multiplet.

This work was supported in part by the RFFI Grant No. 10-02-00016 from the Russian Foundation for Basic Research.

References

[1] N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. B **315**, 465 (1989).

[2] N.N. Achasov and A.V. Kiselev, Phys. Rev. D **68**, 014006 (2003).

[3] N.N. Achasov and A.V. Kiselev, Phys. Rev. D **73**, 054029 (2006).

[4] A. Aloisio et al. (KLOE), Phys. Lett. B **536**, 209 (2002).

[5] A. Aloisio et al. (KLOE), Phys. Lett. B **537**, 21 (2002).

[6] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **49**, 5779 (1994).

[7] N.N. Achasov and G.N. Shestakov, Phys. Rev. Lett. **99**, 072001 (2007).

[8] N.N. Achasov, in Proceedings of the 15th International Seminar QUARKS'2008 (Eds. V.A. Duk, V.A. Matveev, V.A. Rubakov), INR RAS, Moscow, 2010, Vol. 1, p. 3; arXiv:0810.2601 [hep-ph] (2008).

[9] N.N. Achasov, S.A. Devyanin, and G.N. Shestakov, Phys. Lett. B **108**, 134 (1982); Z. Phys. C **16**, 55 (1982).

[10] N.N. Achasov and G.N. Shestakov, Z. Phys. C **41**, 309 (1988).

[11] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **72**, 013006 (2005).

[12] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **77**, 074020 (2008); Pisma Zh. Eksp. Teor. Fiz. **88**, 345 (2008).

[13] N.N. Achasov and G.N. Shestakov, Phys. Rev. D **81**, 094029 (2010); Pisma Zh. Eksp. Teor. Fiz. **92**, 3 (2010).

[14] T. Mori et al. (Belle), Phys. Rev. D **75**, 051101 (2007); J. Phys. Soc. Jap. **76**, 074102 (2007).

[15] S. Uehara et al. (Belle), Phys. Rev. D **78**, 052004 (2008).

[16] S. Uehara et al. (Belle), Phys. Rev. D **80**, 032001 (2009).

[17] M.R. Pennington, T. Mori, S. Uehara, Y. Watanabe, Eur. Phys. J. C **56** 1 (2008).

[18] Y. Mao, X.-G. Wang, O. Zhang, H.-Q. Zheng, Z.-Y. Zhou, Phys. Rev. D **79** 116008 (2009).

[19] G. Mennessier, S. Narison, X.-G. Wang, arXiv:1009.2773 [hep-ph] (2010).

[20] P. Achard et al. (L3), Phys. Lett. B **568**, 11 (2003); Phys. Lett. B **597**, 26 (2004); Phys. Lett. B **604**, 48 (2004); Phys. Lett. B **615**, 19 (2005).