THE RIDDLE OF THE $f_0(980)$ AND $a_0(980)$: ARE THEY THE QUARK–ANTIQUARK STATES?

A.V. Anisovich, V.V. Anisovich, L.G. Dakhno, V.N. Markov,
M.A. Matveev, V.A. Nikonov, A.V. Sarantsev
Petersburg Nuclear Physics Institute RAS, Russia

The nature of mesons $f_0(980)$ and $a_0(980)$ is of principal meaning for the systematics of scalar states and search for exotic mesons. This is precisely why up to now the people lively discuss the problem of whether the mesons $f_0(980)$ and $a_0(980)$ are the lightest scalar quark–antiquark particles or they are exotic states, like four-quark ($qar{q}qar{q}$) states [1], $K\bar{K}$ molecule [2] or minions [3] – see, for example review [4] and references therein.

Investigations of the PNPI group [4–13] favoured the opinion that $f_0(980)$ and $a_0(980)$ are dominantly $q\bar{q}$ states, with a small (10–20%) admixture of the $K\bar{K}$ loosely bound component. There exist both qualitative arguments and calculations of certain reactions that support this idea. First, let us discuss the qualitative arguments.

(i) In hadronic reactions, the resonances $f_0(980)$ and $a_0(980)$ are produced as standard, non-exotic resonances, with compatible yields and similar distributions. This was observed in the meson central production at the high energy hadron–hadron collisions (data of GAMS [15] and Omega [16] Collaborations) or in hadronic decays of $Z^0$ mesons (OPAL Collaboration [17]).

(ii) The supposed exotics of $f_0(980)$ and $a_0(980)$ was often argued relying on a surprising proximity of their masses, while it would be natural to expect the variation of masses in the nonet to be 100–200 MeV. Note that Breit–Wigner resonance pole, which determines a true mass of the state, is rather sensitive to a small admixture of hadron components, if the production threshold for these hadrons lays nearby. As to $f_0(980)$ and $a_0(980)$, it is easy to see that a small admixture of the $K\bar{K}$ component shifts the pole to the $K\bar{K}$ threshold independently of whether it is above or below threshold. Besides, the peak observed in the main mode of the $f_0(980)$ and $a_0(980)$ decays, $f_0(980) \to \pi\pi$ and $a_0(980) \to \eta\pi$, is always slightly below the $K\bar{K}$ threshold that mimics Breit–Wigner resonance with the mass below 1000 MeV ($K\bar{K}$ threshold). This imitation of a resonance created the legend about a “surprising proximity” of the $f_0(980)$ and $a_0(980)$ masses.

In fact, the mesons $f_0(980)$ and $a_0(980)$ are characterised by not one pole (as is the Breit–Wigner case) but two poles (as in Flatté formula or $K$-matrix approach), and these poles are rather different for $f_0(980)$ and $a_0(980)$ [4,5]. Note that Flatté formula is unable to give us adequate description of spectra near these poles. So we should apply more complicated representation of the amplitude [5] or the $K$ matrix approach [6], see also [15].

In parallel with the above mentioned qualitative considerations, there exist convincing arguments which favour the quark–antiquark nature of $f_0(980)$ and $a_0(980)$:

(I) Systematics of mesons on linear trajectories on the $(n,M^2)$ and $(J,M^2)$ planes ($n$ is the radial quantum number of meson $M$ and $J$ its spin) support quark–antiquark structure of $f_0(980)$ and $a_0(980)$ [6]. The states which can be put on linear $(n,M^2)$- and $(J,M^2)$-trajectories are quark–antiquark states. Vice versa: the states which do not belong to linear trajectories should be considered as exotics. It occurred that $f_0(980)$ and $a_0(980)$ lay comfortably on linear $q\bar{q}$ trajectories and, together with $f_0(1300)$ and $K_0(1415)$, they form the lowest scalar nonet with rather good accuracy. Also, on the basis of this systematics, the second $(n = 2)$ scalar nonet was reconstructed: $f_0(1500)$, $f_0(1750)$, $a_0(1520)$, $K_0(1850)$ [5,7–9].

(II) The $K$-matrix analysis has been carried out in [5,9] as well as in a series of precedent papers for the states with isotopic spins $J = 0, 1, 1/2$, i.e., for $f_0$, $a_0$ and $K_0$ mesons. Such analysis allowed us to reconstruct the characteristics of real mesons and so-called “bare states” – the states which precede real mesons before switching on the decay channels. The performed analysis allowed us to construct two first scalar nonets also in terms of
bare states and to trace the transformation of corresponding poles by switching on gradually the decay processes. The resonances, which are the descendants of bare $q\bar{q}$ mesons with $n = 1$, are $a_0(980)$, $f_0(980)$, $f_0(1300)$, $K_0(1430)$ and those with $n = 2$ are $a_0(1520)$, $f_0(1500)$, $f_0(1750)$, $K_0(1850)$. The $K$-matrix analysis points to the existence of a broad resonance $f_0(1200 - 1600)$, which does not belong to linear trajectory, thus being the candidate for exotic state. The decay constants of this broad states, $f_0(1200 - 1600) \rightarrow \pi\pi, K\bar{K}, \eta\eta, \eta'\eta'$, are compatible with the glueball nature of this resonance. According to this analysis, $a_0(980)$ and $f_0(980)$ are dominantly the quark–antiquark states and $f_0(980)$ has a considerable $s\bar{s}$ component, of the order of 60–70%. The results of this analysis are summarised in the review [8] and Chapter V of the monograph [11].

(III) Hadronic decay of the $D^+_s$-meson, $D^+_s \rightarrow \pi^+f_0(980) \rightarrow \pi^+\pi^+\pi^-$: on the quark level, the decay goes as $c\bar{s} \rightarrow \pi^+s\bar{s} \rightarrow \pi^+f_0(980)$ just prov- ing the dominance of the $s\bar{s}$ component in $f_0(980)$. Our analysis [12] showed that $2/3$ $s\bar{s}$ is contained in $f_0(980)$, and this estimate is supported by the experimental value: $BR(\pi^+f_0(980)) = 57\% \pm 9\%$, and $1/3$ $s\bar{s}$ is dispersed over the resonances $f_0(1300)$, $f_0(1500)$, $f_0(1200 - 1600)$. So the reaction $D^+_s \rightarrow \pi^+f_0$ is a measure of the $1^3P_0s\bar{s}$ component in the $f_0$ mesons, it definitely tells us about the dominance of the $s\bar{s}$ component in $f_0(980)$, in accordance with the results of the $K$-matrix analysis. The conclusion about dominance of $s\bar{s}$ component in $f_0(980)$ was also made on the basis of the analysis of the decay $D^+_s \rightarrow \pi^+\pi^+\pi^-$ in papers [13–21].

(IV) Radiative decays $f_0(980) \rightarrow \gamma\gamma$, $a_0(980) \rightarrow \gamma\gamma$ agree well with the calculations [13] based on the assumption of the quark–antiquark nature of these mesons. Let us emphasize again that the calculations favour the $s\bar{s}$ dominance in $f_0(980)$.

(V) Radiative decay $\phi(1020) \rightarrow \gamma f_0(980)$ was a subject of lively discussion in the latest years: there existed an opinion that this decay strongly contradicts the hypothesis of its $q\bar{q}$ nature [22–24]. However, our calculations [13–14] carried out within both relativistic and nonrelativistic approaches showed that the $q\bar{q}$ nature of $f_0(980)$ agrees well with data. In [14], we focus precisely on the problems, that appear when Siegert’s theo-

References

[1] R. Jaffe, Phys. Rev. D 15, 267 (1977).

[2] J. Weinstein and N. Isgur, Phys. Rev. D 41, 2236 (1990);
Yu. S. Kalashnikova et al., Eur. Phys. J. A 24, 237 (2005).

[3] F.E. Close, et al., Phys. Lett B 319, 291 (1993).

[4] D.V. Bugg, Phys. Rep., 397, 257 (2004).

[5] V.V. Anisovich, V.A. Nikonov, V.A. Sarantsev, Yad. Fiz. 65, 1583 (2002) [Phys. Atom. Nucl. 65, 1545 (2002)]; Yad. Fiz. 66, 772 (2003) [Phys. Atom. Nucl. 66, 741 (2003)].

[6] V.V. Anisovich and A.V. Sarantsev, Eur. Phys. J. A 16, 229 (2003).

[7] A.V. Anisovich, V.V. Anisovich, A.V. Sarantsev, Phys. Rev. D 62, 051502 (2000).

[8] V.V. Anisovich and A.V. Sarantsev, Yad. Fiz. 66, 960 (2003) [Phys. Atom. Nucl., 66, p 928 (2003)].

[9] V.V. Anisovich, Usp. Fiz. Nauk 174, 49 (2004) [Physics-Uspekhi 47(1), 45 (2004)].
[10] A.V. Anisovich and A.V. Sarantsev, Phys. Lett. B 413, 137 (1997).
[11] V.V. Anisovich, J. Nyiri, M.N. Kobrinsky, Yu.M. Shabelski, “Quark Model and High Energy Collisions”, 2nd edition, World Scientific, Singapore, 2004.
[12] V.V. Anisovich, L.G. Dakhno, V.A. Nikonov, Yad. Fiz. 67, 1593 (2004) [Phys. Atom. Nucl. 67, 1571 (2004)].
[13] A.V. Anisovich, V.V. Anisovich, V.A. Nikonov, Eur. Phys. J. A 12, 103 (2001); A.V. Anisovich, V.V. Anisovich, V.N. Markov, V.A. Nikonov, Yad. Fiz. 65, 523 (2002) [Phys. Atom. Nucl. 65, 497 (2002)].
[14] V.V. Anisovich and M.A. Matveev, Yad. Fiz. 67, 634 (2004) [Phys. Atom. Nucl. 67, 614 (2004)]; A.V. Anisovich, V.V. Anisovich, V.N. Markov, V.A. Nikonov, A.V. Sarantsev, “Decay $\phi(1020) \rightarrow \gamma f_0(980)$: analysis in the nonrelativistic quark model approach”, Yad. Fiz. [Phys. Atom. Nucl.], in press, [hep-ph/0403123].
[15] D.M. Alde, et al. Phys. Lett B 397, 350 (1997).
[16] D. Barberis, et al. Phys. Lett B 453, 305 (1999); Phys. Lett B 453, 325 (1999); Phys. Lett B 462, 462 (1997).
[17] K. Ackerstaff, et al., (OPAL Collab.) EPJC 4, 19 (1998).
[18] K.L. Au, D. Morgan, M.R. Pennington, Phys. Rev. D 35, 1633 (1987); D. Morgan and M.R. Pennington, Phys. Rev. D 48, 1185 (1993).
[19] A. Deandrea, R. Gatto, G. Nardulli, et al., Phys. Lett. B 502, 79 (2001).
[20] F. Kleefeld, E. van Beveren, G. Rupp, M.D. Scadron Phys. Rev. D 66, 034007 (2002).
[21] P. Minkowski, W. Ochs, [hep-ph/0209223].

[22] N.N. Achasov, AIP Conf. Proc. 619, 112 (2002).
[23] F.E. Close, Int. Mod. Phys. A 17, 3239 (2002).
[24] M.A. DeWitt, H.M. Choi, C.R. Ji, Phys. Rev. D 68, 054026 (2003).
[25] A.J.F. Siegert, Phys. Rev. 52, 787 (1937).
[26] A.V. Anisovich, V.V. Anisovich, V.N. Markov, M.A. Matveev, and A.V. Sarantsev, J. Phys. G: Nucl. Part. Phys. 28, 15 (2002).
[27] V.V. Anisovich, Pis’ma v ZhETF 80, 845 (2004) [JETP Letters 80, 715 (2004)]; V.V. Anisovich, A.V. Sarantsev, Pis’ma v ZhETF, 81, 531 (2005) [JETP Letters 81, 417 (2005)].