EXISTENCE AND PROPERTIES OF THE $f_0(665)$ STATE AND CHIRAL SYMMETRY

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Abstract

On the basis of a simultaneous description of the isoscalar $s$-wave of $\pi\pi$ scattering (from the threshold up to 1.9 GeV) and of $\pi\pi \rightarrow K\bar{K}$ process (from the threshold to $\sim 1.4$ GeV) in the model-independent approach, it is shown that there exists the $f_0(665)$ state with properties of the $\sigma$-meson, the glueball nature of $f_0(1500)$ is indicated, and the $f_0(1370)$ is assigned mainly to $s\bar{s}$ state. The coupling constants of the observed states with $\pi\pi$ and $K\bar{K}$ systems and scattering lengths $a_0^0(\pi\pi)$ and $a_0^0(K\bar{K})$ are calculated. The existence of the $f_0(665)$ state and the obtained $\pi\pi$-scattering length ($a_0^0 \approx 0.27 m_{\pi}^{-1}$) seem to suggest the linear realization of chiral symmetry.

Key-words: analyticity, unitarity, uniformization, multichannel resonance, scalar meson, QCD nature

1. The scalar-meson sector causes a lot of questions up to now. A strong model dependence of information on these objects (as wide multichannel states) obtained from experimental data makes sometimes the drawn conclusions doubtful. E.g., we have shown [1] that an inadequate description of multichannel states gives not only their distorted parameters when analyzing data but also cause the fictitious states when one neglects important channels. In this report, we show that a large background earlier obtained in various analyses of the $s$-wave $\pi\pi$ scattering [2] hides, in reality, the $\sigma$-meson and the influence of the left-hand branch-point. The state with $\sigma$-meson properties is required by most models (like the linear $\sigma$-models and the Nambu – Jona-Lasinio models [3]) for spontaneous breaking of chiral symmetry.

A model-independent information on multichannel states can be obtained only on the basis of the first principles (analyticity and unitarity) immediately applied to analyzing experimental data and using the mathematical fact that the local behaviour of analytic functions determined on the Riemann surface is governed by the nearest singularities on all sheets. Earlier, we have proposed that method for 2- and 3-channel resonances and developed the concept of standard clusters (poles on the Riemann surface) as a qualitative characteristic of a state and a sufficient condition of its existence [1]. We outline this below for the 2-channel case. Then we analyze simultaneously experimental data on the processes $\pi\pi \rightarrow \pi\pi, K\bar{K}$ in the channel with $I^GJ^{PC} = 0^+0^{++}$. On the basis of obtained pole clusters for resonances, their coupling constants with the considered channels and scattering lengths compared with the results of various models, we conclude on the nature of the observed states and on the mechanism of chiral-symmetry breaking.

2. Two-Coupled-Channel Formalism. We consider the coupled processes of $\pi\pi$ and $K\bar{K}$ scattering and $\pi\pi \rightarrow K\bar{K}$. Therefore, we have the 2-channel $S$-matrix determined

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on the 4-sheeted Riemann surface. The matrix elements $S_{\alpha\beta}$, where $\alpha, \beta = 1(\pi\pi), 2(K\bar{K})$, have the right-hand (unitary) cuts along the real axis of the $s$-variable complex plane ($s$ is the invariant total energy squared), starting at $4m_{\pi}^2$ and $4m_{K}^2$, and the left-hand cuts, beginning at $s = 0$ for $S_{11}$ and at $4(m_{K}^2 - m_{\pi}^2)$ for $S_{22}$ and $S_{12}$. The Riemann-surface sheets are numbered according to the signs of analytic continuations of the channel momenta $k_1 = (s/4 - m_{\pi}^2)^{1/2}$, $k_2 = (s/4 - m_{K}^2)^{1/2}$ as follows: signs $(\text{Im}k_1, \text{Im}k_2) = ++, --, --, +-$ correspond to the sheets I, II, III, IV.

The resonance representations on the Riemann surface are obtained with the help of the formulae, expressing analytic continuations of the matrix elements to unphysical sheets $S_{\alpha\beta}^{L}$ ($L = II, III, IV$) in terms of those on the physical sheet $S_{\alpha\beta}^{I}$ which have only zeros (beyond the real axis), corresponding to resonances:

$$
S_{11}^{II} = \frac{1}{S_{11}^{I}}, \quad S_{11}^{III} = \frac{S_{22}^{I}}{\det S_{12}^{I}}, \quad S_{11}^{IV} = \frac{\det S_{12}^{I}}{S_{22}^{I}},
S_{22}^{II} = \frac{\det S_{11}^{I}}{S_{11}^{I}}, \quad S_{22}^{III} = \frac{S_{11}^{I}}{\det S_{12}^{I}}, \quad S_{22}^{IV} = \frac{1}{S_{22}^{I}},
S_{12}^{II} = \frac{iS_{12}^{I}}{S_{11}^{I}}, \quad S_{12}^{III} = -\frac{S_{12}^{I}}{\det S_{12}^{I}}, \quad S_{12}^{IV} = \frac{iS_{12}^{I}}{S_{22}^{I}}.
$$

(1)

Here $\det S_{12}^{I} = S_{11}^{I}S_{22}^{I} - (S_{12}^{I})^2$. These formulae immediately give the resonance representation by poles and zeros on the 4-sheeted Riemann surface. One must discriminate between three types of 2-channel resonances described by a pair of conjugate zeros on sheet I: (a) in $S_{11}$, (b) in $S_{22}$, (c) in each of $S_{11}$ and $S_{22}$. As seen from (1), to the resonances of types (a) and (b) one has to make correspond a pair of complex conjugate poles on sheet III, shifted relative to a pair of poles on sheet II and IV, respectively. To the states of type (c) one must consider corresponding two pairs of conjugate poles on sheet III. A resonance of every type is represented by a pair of complex-conjugate clusters (of poles and zeros on the Riemann surface) of size typical of strong interactions. The cluster kind is related to the state nature. The resonance, coupled relatively more strongly to the $\pi\pi$ channel than to the $K\bar{K}$ one, is described by the cluster of type (a); in the opposite case it is represented by the cluster of type (b) (say, the state with the dominant $s\bar{s}$ component); the flavour singlet (e.g. glueball) must be represented by the cluster of type (c) as a necessary condition.

For the simultaneous analysis of experimental data on the coupled processes it is convenient to use the Le Couteur-Newton relations [1] expressing the $S$-matrix elements of all coupled processes in terms of the Jost matrix determinant $d(k_1, k_2)$, the real analytic function with the only square-root branch-points at $k_i = 0$. To take into account these right-hand branch-points at $4m_{\pi}^2$ and $4m_{K}^2$ and also the left-hand one at $s = 0$, we use the uniformizing variable

$$
v = \frac{m_{K}\sqrt{s - 4m_{\pi}^2} + m_{\pi}\sqrt{s - 4m_{K}^2}}{\sqrt{s(m_{K}^2 - m_{\pi}^2)}}
$$

(2)

which maps the 4-sheeted Riemann surface onto the $v$-plane, divided into two parts by a unit circle centered at the origin. Sheets I (II), III (IV) are mapped onto the exterior (interior) of the unit disk on the upper and lower $v$-half-plane, respectively. The physical region extends from point $i$ on the imaginary axis ($\pi\pi$ threshold) along the unit circle
clockwise in the 1st quadrant to point 1 on the real axis ($K\bar{K}$ threshold) and then along the real axis to point $b = \sqrt{(m_K + m_\pi)/(m_K - m_\pi)}$ into which $s = \infty$ is mapped on the $v$-plane. The intervals $(-\infty, -b[, -b^{-1}, b^{-1}], [b, \infty)$ on the real axis are the images of the corresponding edges of the left-hand cut of the $\pi\pi$-scattering amplitude. The type (a) resonance is represented in $S_{11}$ by two pairs of the poles on the images of sheets II and III, symmetric to each other with respect to the imaginary axis, and by zeros, symmetric to these poles with respect to the unit circle. On $v$-plane, the Le Couteur-Newton relations are

$$S_{11} = \frac{d(-v^{-1})}{d(v)}, \quad S_{22} = \frac{d(v^{-1})}{d(v)}, \quad S_{11}S_{22} - S_{12}^2 = \frac{d(-v)}{d(v)}. \quad (3)$$

The condition of the real analyticity implies $d(-v^*) = d^*(v)$ for all $v$, and the unitarity needs the following relations to hold true for the physical $v$-values: $|d(-v^{-1})| \leq |d(v)|$, $|d(v^{-1})| \leq |d(v)|$, $|d(-v)| = |d(v)|$.

The $d(v)$-function that already does not possess branch-points is taken as $d = d_Bd_{res}$ where $d_B$ is the part of the $K\bar{K}$ background that does not contribute to the $\pi\pi$-scattering amplitude. On the $v$-plane, $S_{11}$ has no cuts, however, the amplitudes of $K\bar{K} \rightarrow \pi\pi, K\bar{K}$ processes do have the cuts on the $v$-plane, which arise from the left-hand cut on the $s$-plane, starting at the point $s = 4(m_K^2 - m_\pi^2)$. This left-hand cut will be neglected in the Riemann-surface structure, and the contribution on the cut will be taken into account in the $K\bar{K}$ background as a pole on the real $s$-axis on sheet I in the sub-$K\bar{K}$-threshold region; on the $v$-plane, this pole gives two poles on the unit circle in the upper half-plane, symmetric to each other with respect to the imaginary axis, and two zeros, symmetric to the poles with respect to the real axis. Therefore,

$$d_B = v^{-4}(1-pv)^4(1+p^*v)^4, \quad (4)$$

where $p$ is the position of zero on the unit circle. The fourth power in (4) follows from eqs. (1) and from that, for the $s$-channel process $\pi\pi \rightarrow K\bar{K}$, the crossing $u$- and $t$-channels are the $\pi - K$ and $\pi - K$ scattering (exchanges in these channels contribute on the left-hand cut). The function $d_{res}(v)$ represents the contribution of resonances and, except for the point $v = 0$, consists of the zeros of clusters:

$$d_{res} = v^{-M} \prod_{n=1}^{M} (1 - v_n^*v)(1 + v_nv). \quad (5)$$

where $M$ is the number of pairs of the conjugate zeros.

3. Analysis of experimental data. We analyze simultaneously the available experimental data on the $\pi\pi$-scattering [3] and process $\pi\pi \rightarrow K\bar{K}$ [3] in the channel with $I^G J^{PC} = 0^+0^{++}$. As the data, we use the results of phase analyses which are given for phase shifts of the amplitudes ($\delta_1$ and $\delta_2$) and for moduli of the $S$-matrix elements $\eta_a = |S_{aa}|$ ($a=1\pi\pi, 2K\bar{K}$) and $\xi = |S_{12}|$. The 2-channel unitarity condition gives $\eta_1 = \eta_2 = \eta, \quad \xi = (1-\eta^2)^{1/2}$, $\delta_{12} = \delta_1 + \delta_2$.

For a satisfactory description of the $s$-wave $\pi\pi$ scattering from the threshold to 1.89 GeV and process $\pi\pi \rightarrow K\bar{K}$ from the threshold to $\sim 1.4$ GeV, three resonances turned out to be sufficient (solution 1): the two ones of type (a) ($f_0(665)$ and $f_0(980)$) and $f_0(1500)$ of
type (c). I.e., a minimum scenario of the simultaneous description of these two processes does not require the \( f_0(1370) \) resonance, therefore, if this meson exists, it must be relatively more weakly coupled to the \( \pi\pi \) channel than to the \( K\bar{K} \) one, i.e., be described by the cluster of type (b) (this would testify to the dominant \( s\bar{s} \) component in this state). To confirm quantitatively this qualitative conclusion \[7\], we consider also the 2nd solution including the \( f_0(1370) \) of type (b).

**Solution 1:** For \( \delta_1 \) and \( \eta \), 113 and 50 experimental points \[3\], respectively, are used; when rejecting the points at 0.61, 0.65, and 0.73 GeV for \( \delta_1 \) and at 0.99, 1.65, and 1.85 GeV for \( \eta \) which give an anomalously large contribution to \( \chi^2 \), we obtain for \( \chi^2/\text{ndf} \) the values 2.7 and 0.72, respectively; the total \( \chi^2/\text{ndf} \) in the case of \( \pi\pi \) scattering is 1.96.

The satisfactory description for \( |S_{12}| \) is given from the threshold to \( \sim 1.4 \) GeV. Here 35 experimental points \[3\] are used; \( \chi^2/\text{ndf} \approx 1.11 \) when eliminating the points at 1.002, 1.265, and 1.287 GeV (with an especially large contribution to \( \chi^2 \)).

For \( \delta_{12}(\sqrt{s}) \), a satisfactory description is obtained to \( \sim 1.52 \) GeV with \( p = 0.948201 + 0.31767i \) (this corresponds to the pole on the s-plane at \( s = 0.434\text{GeV}^2 \)). Here 59 experimental points \[3\] are considered; \( \chi^2/\text{ndf} \approx 3.05 \) when eliminating the points at 1.117, 1.247, and 1.27 GeV (with an especially large contribution to \( \chi^2 \)). The total \( \chi^2/\text{ndf} \) for four analyzed quantities to describe the processes \( \pi\pi \to \pi\pi, K\bar{K} \) is 2.12; the number of adjusted parameters is 17. In Table 1, the obtained pole clusters for resonances are shown on the complex energy plane \( (\sqrt{s_r} = E_r - i\Gamma_r) \).

### Table 1: Pole clusters for resonances obtained in solution 1.

| Sheet | \( f_0(665) \) | \( f_0(980) \) | \( f_0(1500) \) |
|-------|----------------|----------------|----------------|
|       | \( E, \text{MeV} \) | \( \Gamma, \text{MeV} \) | \( E, \text{MeV} \) | \( \Gamma, \text{MeV} \) | \( E, \text{MeV} \) | \( \Gamma, \text{MeV} \) |
| II    | 610\pm14 620\pm26 | 988\pm5 27\pm8  | 1530\pm25 390\pm30 |
| III   | 720\pm15 55\pm9  | 984\pm16 210\pm22 | 1430\pm35 200\pm30 |
|       | 1510\pm22 400\pm34 |                 | 1410\pm24 210\pm38 |

Now we calculate the coupling constants of these states with \( \pi\pi \) and \( K\bar{K} \) systems \( (g_1 \) and \( g_2 \), respectively) through the residues of amplitudes at the pole on sheet II, expressing the \( T \)-matrix via the \( S \)-matrix as \( S_{ii} = 1 + 2i\rho_i T_{ii}, \ S_{12} = 2i\sqrt{\rho_1\rho_2}T_{12}, \) where \( \rho_i = \sqrt{(s - 4m_i^2)/s}, \) and taking the resonance part of amplitude in the form \( T^{res}_{ij} = \sum_r g_{ir}g_{rj}D_r^{-1}(s) \), where \( D_r(s) \) is the inverse propagator \( (D_r(s) \propto s - s_r) \). We obtain (in GeV units): for \( f_0(665) \): \( g_1 = 0.7477 \pm 0.095 \) and \( g_2 = 0.834 \pm 0.1 \), for \( f_0(980) \): \( g_1 = 0.1615 \pm 0.03 \) and \( g_2 = 0.438 \pm 0.028 \), for \( f_0(1500) \): \( g_1 = 0.899 \pm 0.093 \).

**Solution 2** (analysis with \( f_0(1370) \)): The description of the \( \pi\pi \) scattering from the threshold to 1.89 GeV is practically the same as without the \( f_0(1370) \): \( \chi^2/\text{ndf} \) for \( \delta_1 \) and \( \eta \) is 2.01. The description of data is slightly improved for \( |S_{12}| \) which is reached now up to \( \sim 1.46 \) GeV. For this quantity, we now consider 41 experimental points \[3\]; \( \chi^2/\text{ndf} \approx 0.92 \). However, on the whole, the description is even worse than with the 1st solution: the total \( \chi^2/\text{ndf} \approx 2.93 \) for four analyzed quantities to describe the processes \( \pi\pi \to \pi\pi, K\bar{K} \) (cf. 2.12 for the 1st case). The number of adjusted parameters is 21 where they all are positions of
the poles describing resonances except a single one related to the $K\bar{K}$ background which is $p = 0.976745 + 0.214405i$ (this corresponds to the pole on the s-plane at $s = 0.622\text{GeV}^2$).

In Table 2, the obtained clusters for considered resonances are shown (the cluster for the $f_0(665)$ remains the same as in solution 1, therefore, it is not shown in Table 2). When calculating the coupling constants in solution 2, we should take, for the $f_0(1370)$, the residues of amplitudes at the pole on sheet IV. We obtain (in GeV units): for the poles describing resonances except a single one related to the $K\bar{K}$ system than to the $\pi\pi$ one. This tells about the dominant $s\bar{s}$ component in the $f_0(980)$ state and especially in the $f_0(1370)$ one.

Let us also indicate the scattering lengths calculated for both the solutions. For the $K\bar{K}$ scattering: $a_0^0(K\bar{K}) = -1.188 \pm 0.13 + (0.648 \pm 0.09)i$, $[m_\pi^{-1}]$; (solution1),

$a_0^0(K\bar{K}) = -1.497 \pm 0.12 + (0.639 \pm 0.08)i$, $[m_\pi^{-1}]$; (solution2).

The imaginary part in $a_0^0(K\bar{K})$ means that, already at the threshold of the $K\bar{K}$ scattering, other channels ($2\pi, 4\pi$ etc.) are opened. We see that the real part of the $K\bar{K}$ scattering length is very sensitive to the existence of the $f_0(1370)$ state.

In Table 3, we compare our results for the $\pi\pi$ scattering length $a_0^0$, obtained for both solutions, with results of some other works both theoretical and experimental. We see that our results correspond to the linear realization of chiral symmetry.

Here, we presented model-independent results. Masses and widths of these states that should be calculated from the obtained pole positions and coupling constants are highly model-dependent. Let us demonstrate this.

If $f_0(665)$ is the $\sigma$-meson, then from the known relation $g_{\sigma\pi\pi} = (m_\sigma^2 - m_\pi^2)/\sqrt{2}f_{\pi^0}$ ($f_{\pi^0} = 93.1\text{ MeV}$), we obtain $m_\sigma \approx 342\text{ MeV}$. If we take the resonance part of amplitude as $T^{\text{res}} = \sqrt{s}\Gamma/(m_\sigma^2 - s - i\sqrt{s}\Gamma)$, we obtain $m_\sigma \approx 850\text{ MeV}$ and $\Gamma \approx 1240\text{ MeV}$.

4. Summary. It is shown that the large $\pi\pi$-background usually obtained in various analyses combines, in reality, the influence of the left-hand branch-point and the contribution of a wide resonance at $\sim 665\text{ MeV}$. Thus, a model-independent confirmation of the state, denoted in the PDG issues by $f_0(400 - 1200)$ is obtained.

A parameterless description of the $\pi\pi$ background is given by allowance for the left-hand branch-point in the proper uniformizing variable. Therefore, all the adjusted parameters in describing the $\pi\pi$ scattering are the positions of poles corresponding to resonances, and we conclude that our model-independent approach is a valuable tool for studying the realization

Table 2: Pole clusters for resonances obtained in solution 2.

| Sheet | $f_0(980)$ E, MeV \(\Gamma\), MeV | $f_0(1370)$ E, MeV \(\Gamma\), MeV | $f_0(1500)$ E, MeV \(\Gamma\), MeV |
|-------|---------------------------------|---------------------------------|---------------------------------|
| II    | 986±5 25±8                      | 1530±22 390±28                 |                                 |
| III   | 984±16 210±25                   | 1340±21 380±25                 | 1490±30 220±25                  |
| IV    | 1330±18 270±20                  |                                 | 1490±20 300±35                  |


Table 3: Comparison of results of various works for the $\pi\pi$ scattering length $a_0^\pi$.

| $a_0^\pi$, $m_{\pi}^{-1}$ | References | Remarks |
|--------------------------|------------|---------|
| 0.27 ± 0.06 (1)         | our paper  | model-independent approach |
| 0.266 (2)                |            |         |
| 0.26 ± 0.05             | L. Rosselet et al. [4] | analysis of the decay $K \to \pi\pi\nu\nu$ using Roy’s model |
| 0.24 ± 0.09             | A.A. Bel’kov et al. [5] | analysis of $\pi^- p \to \pi^+ \pi^- n$ using the effective range formula |
| 0.23                    | S. Ishida et al. [6] | modified analysis of $\pi\pi$ scattering using Breit-Wigner forms |
| 0.16                    | S. Weinberg [9] | current algebra (non-linear $\sigma$-model) |
| 0.20                    | J. Gasser, H. Leutwyler [10] | one-loop corrections, non-linear realization of chiral symmetry |
| 0.217                   | J. Bijnens et al. [11] | two-loop corrections, non-linear realization of chiral symmetry |
| 0.26                    | M.K. Volkov [12] | linear realization of chiral symmetry |
| 0.28                    | A.N. Ivanov, N.I. Troitskaya [13] | a variant of chiral theory with linear realization of chiral symmetry |

schemes of chiral symmetry. The existence of $f_0(665)$ and the obtained $\pi\pi$-scattering length ($a_0^\pi(\pi\pi) \approx 0.27$) suggest the linear realization of chiral symmetry.

The analysis of the used experimental data evidences that, if the $f_0(1370)$ resonance exists (solution 2), it has the dominant $s\bar{s}$ component, because the ratio of its coupling constant with the $\pi\pi$ channel to the one with the $K\overline{K}$ channel is 0.12. A minimum scenario of the simultaneous description of processes $\pi\pi \to \pi\pi, K\overline{K}$ does without the $f_0(1370)$ resonance. The $K\overline{K}$ scattering length is very sensitive to whether this state exists or not.

The $f_0(1500)$ state is represented by the pole cluster which corresponds to a flavour singlet, e.g. the glueball.

We think that multichannel states are most adequately represented by clusters, i.e., by the pole positions on all the corresponding sheets. The pole positions are rather stable characteristics for various models, whereas masses and widths are very model-dependent for wide resonances.

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