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D.Krupa[1], V.A.Meshcheryakov, Yu.S.Surovtsev

MULTICHANNEL RESONANCES AND CLOSED CHANNELS (SCALAR SECTOR)

[1]Institute of Physics, Slov.Acad.Sci., Bratislava, Slovakia

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1.In finding out the status (both theoretical and experimental) of the resonances, the multichannel ones set the most number of questions. Especially this concerns the scalar-isoscalar meson sector [1] and is stipulated by the influence of vacuum and such effects, difficult to be taken into account, as the instanton contributions. Note that, for example, for scalar and tensor mesons there are difficulties even with their interpretation as $q\bar{q}$ states. Moreover none of such states is unambiguously identified as a glueball, multiquark state or a hybrid. In this situation it is very important to obtain information about resonances (to be derived from experimental data) which does not depend on specific interaction models.

A model-independent consideration of resonances and their nature can be obtained on the basis of such general principles, as analyticity and unitarity, and the consistent balanced account of the nearest (to the considered physical region) singularities on all the relevant sheets of the Riemann surface of the S-matrix [2]-[8].

Note that in the case of multichannel resonances, ambiguous is not only the determination of their QCD nature, but also the discovery of the resonances on the basis of experimental data. This is clearly illustrated by a situation in the 1 GeV-region of the scalar-isoscalar channel. As is known, the clear resonant manifestations at these energies in the experimental data on $\pi\pi$ scattering have been interpreted as the resonance $f_0(975)(S^*)$. Its rather extraordinary features have brought very different hypotheses about its nature ($qq\bar{q}\bar{q}$[9, 10], gg[11], $q\bar{q}$ with taking account of the final-state interaction [12], the mixture of $q\bar{q}$ and gg [13, 14], the $K\overline{K}$-molecule [15, 16]).

In the analysis of ISR data on central production of meson pairs ($\pi\pi$ and $K\overline{K}$) in pp-collisions [17], instead of the $f_0(975)$ meson in the 1 GeV region three states are obtained: $S_1(991)$–a glueball candidate, $S_2(988)$–a $K\overline{K}$ molecule, $f_0(900)$–a meson broad enough in $\pi\pi$-channel. We argued in works [5, 8] that the neglect of the $\eta\eta$ threshold (possibly also the $\eta\eta'$ threshold) in the analysis [17] could give rise to a imitation of supplementary states in the vicinity of $K\overline{K}$ threshold. We shall here discuss also how this is related with the closed-channel contribution. Note that the subsequent enlarged analysis of the above data and also of data on $\pi\pi$ and $K\overline{K}$ scattering and on decays $J/\psi \to \phi\pi\pi(\phi K\overline{K})$, $D_s \to \pi\pi\pi$ has led the authors of work [17] to give up their original results and interpretation [18].

2. So, let us consider the 3-channel problem, sometimes for the sake of simplicity and clarity appealing to the 2-channel process. The elements of the 3-channel S-matrix $S_{\alpha\beta}$, where $\alpha,\beta = 1(\pi\pi), 2(K\overline{K}), 3(\eta\eta)$, have the right-hand (unitary) cuts along the real axis of the s-variable complex plane starting at $4m_\pi^2$, $4m_K^2$, $4m_\eta^2$. The left-hand cuts, which are related with the crossing-channel contributions and extend along the real axis towards $-\infty$, starting at $s=0$ for S_{11} and S_{12} and at $s=4(m_K^2-m_\pi^2)$ for S_{22} etc., will be neglected in the Riemann-surface structure and their contributions will be taken into account in the background of the corresponding amplitudes. We number the Riemann-surface sheets according to the signs of analytical continuations of the channel momenta–

$$k_1 = (s/4 - m_\pi^2)^{1/2}, \qquad k_2 = (s/4 - m_K^2)^{1/2}, \qquad k_3 = (s/4 - m_\eta^2)^{1/2}$$

as follows: signs $(\mathrm{Im}k_1, \mathrm{Im}k_2, \mathrm{Im}k_3) = +++, -++, --+, +-+, +--, ---, -+-, ++-$ correspond to the sheets I,II,...,VIII. Then, for instance, from the physical region on sheet I we pass across the cut below the $K\overline{K}$ threshold to sheet II, above $K\overline{K}$ threshold but below the $\eta\eta$ threshold to sheet III and above the $\eta\eta$ threshold–to sheet VI.

To elucidate the resonance representation on the Riemann surface, we shall first appeal to the 2-channel problem. Using the reality of the analytic functions and the 2-channel unitarity, one can express analytical continuations of the matrix elements to the unphysical sheets $S_{\alpha\beta}^L$ in terms of them on the physical sheet $S_{\alpha\beta}^I$ [4]:

$$\begin{aligned}
S_{11}^{II} &= \frac{1}{S_{11}^I}, & S_{11}^{III} &= \frac{S_{22}^I}{\det S^I}, & S_{11}^{IV} &= \frac{\det S^I}{S_{22}^I}, \\
S_{22}^{II} &= \frac{\det S^I}{S_{11}^I}, & S_{22}^{III} &= \frac{S_{11}^I}{\det S^I}, & S_{22}^{IV} &= \frac{1}{S_{22}^I}, \\
S_{12}^{II} &= \frac{iS_{12}^I}{S_{11}^I}, & S_{12}^{III} &= \frac{-S_{12}^I}{\det S^I}, & S_{12}^{IV} &= \frac{iS_{12}^I}{S_{22}^I},
\end{aligned} \qquad (1)$$

Here $\det S^I = S_{11}^I S_{22}^I - (S_{12}^I)^2$. Provided a resonance has the only decay mode (1-channel case), the general statement about a behaviour of the process amplitude is that at energy values in a proximity to the resonant one it describes the propagation of a resonance as if the latter were a free particle. This means that in the matrix element the

resonance (in the limit of its narrow width) is represented by a pair of complex conjugate poles on the IInd sheet and by a pair of conjugate zeros on the physical sheet at the same points of complex energy. This model-independent statement about the poles as the nearest singularities holds also when taking account of the finite width of a resonance.

In the case of two coupled channels, formulae (1) immediately give the resonance representation (in the 2-channel problem) by poles and zeros on the 4-sheeted Riemann surface. Here one must discriminate between three types of resonances–which are described: (**a**) by a pair of complex conjugate poles on sheet II and therefore by a pair of complex conjugate zeros on the Ist sheet in S_{11}, (**b**) by a pair of conjugate poles on sheet IV and therefore by a pair of complex conjugate zeros on sheet I in S_{22}, (**c**) by one pair of conjugate poles on each of sheets II and IV, that is by one pair of conjugate zeros on the physical sheet in each of matrix element S_{11} and S_{22}.

As is 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 which are shifted relative to a pair of poles on sheet II and IV , respectively (if the coupling among channels were absent, i.e. $S_{12}=0$, the poles on sheet III would lay exactly (**a**) under the poles on the IInd sheet, (**b**) above the poles on the IVth sheet). To the resonances of type (**c**) one must make correspond two pairs of conjugate poles on sheet III which are reasonably expected to be a pair of the complex conjugate compact formations of poles.

Formulae of type (1) were obtained also in the 3-channel problem [8]. On their basis one establishes the resonance representation on the 8-sheeted Riemann surface through the singularities nearest to the physical region, through poles (and corresponding zeros). In this case one must distinguish seven types of resonances with zeros on the physical sheet in (**a**) S_{11}, (**b**) S_{22}, (**c**) S_{33}, (**d**) S_{11} and S_{22}, (**e**) S_{22} and S_{33}, (**f**) S_{11} and S_{33}, (**g**) S_{11}, S_{22} and S_{33}. For example, in the case of the resonance of type (**g**) there are one pair of complex conjugate poles on each of sheets II, IV and VIII at the same points of s-variable where the zeros lie on sheet I, also two pairs of complex conjugate poles on each of sheets III, V and VII, and three pairs of complex conjugate poles on the VIth sheet (i.e. the resonance is represented by complex conjugate clusters of poles and zeros). The above consideration seems to exhaust the multichannel-resonance division into types, because always the problem of the multichannel-resonance representation by the nearest singularities can be effectively reduced to the above cases. Note also that this resonance division into types is not formal. For instance, in the scalar-meson sector the resonance $f_0(975)$ seems to correspond to type (a), and the resonance $f_0(1590)$ corresponds to one of types without zeros on sheet I in S_{11}. These two resonances have very different QCD natures. Further investigation of this matter can possibly give rise to the model-independent indications of the multichannel-resonance nature on the basis of their pole representation on the Riemann surfaces.

3. In the K-matrix the sole pole on the real axis corresponds to a resonance of the simplest type (only with the sole pair of complex conjugate poles on each of corresponding sheets, i.e. with a pair of zeros on the Ist sheet only in one matrix element S_{ii}). Resonances of other types are described by two and even three poles (for example, when the zeros on the Ist sheet are in S-matrix elements of two coupled processes, by two poles on the real axis).

However, the many-pole representation of a resonance in the K-matrix arises not only for the above resonance types but also as a result of influence of the important energetical-closed channels. Let us explain this in more detail.

In the case of N channels the K-matrix is related with the S-matrix as follows

$$\widehat{S} = \frac{I + i\widehat{\rho}\widehat{K}}{I - i\widehat{\rho}\widehat{K}} \tag{2}$$

where $\rho_i = 2k_i/\sqrt{s}$, $k_i = (s/4 - m_i^2)^{1/2}$. From (2) it is easy to obtain that $\widehat{K} = \widehat{K}^+$, i.e. the K- matrix has no discontinuity when going across the unitary cuts, and the poles corresponding to a resonance lie on the real axis of s-plane.

In practice we deal usually with a reduced K-matrix, $\widehat{K}_R$, corresponding to the M open channels at a considered resonant energy whereas the remaining $N-M$ channels are energetical-closed. A connection between the reduced matrix $\widehat{K}_R$ and the complete K-matrix is given by [19]

$$(\widehat{K}_R)_{ij} = K_{ij} + iK_{i\alpha}[(I - i\widehat{\widehat{\rho}}\widehat{\widehat{K}})^{-1}\widehat{\widehat{\rho}}]_{\alpha\beta}K_{\beta j}. \tag{3}$$

Here $\widehat{\widehat{\rho}}$ and $\widehat{\widehat{K}}$ denote the submatrices being related to the closed channels, $i, j = 1, \cdots, M$ refer to open channels and $\alpha, \beta = M+1, \cdots, N$ correspond to closed ones. It is clear that the resonances can arise both owing to the resonant interaction of particles in the open channels and by virtue of the processes in the closed channels. In the first case each element of the complete K-matrix has a pole at a certain real value of energy $s = m^2$. In proximity to this pole one can write

$$K_{\sigma\tau} = \frac{g_\sigma g_\tau}{s - m^2} + \alpha_{\sigma\tau}(s), \tag{4}$$

where g_σ, g_τ are constants of the resonance couplings with particles of open and closed channels ($\sigma, \tau = 1, \cdots, N$), $\alpha_{\sigma\tau}(s)$ are the background smooth functions. However this pole is absent in the K_R-matrix, since the residue at this pole in (3) is equal to zero, and the position of a pole corresponding to a resonance is renormalized due to the influence of the closed channels, moreover the resonance is described by a number of poles. For example, at the conjecture of negligible background ($\alpha_{\sigma\tau} = 0$) we obtain from (3) with (4):

$$(\widehat{K}_R)_{ij} = \frac{g_i g_j}{s - m^2 + \sum_{\alpha=M+1}^{N} g_\alpha^2\,|\rho_\alpha|}. \tag{5}$$

Consideration of the background does not change the conclusion about the pole at $s = m^2$. For instance, in the 2-channel case with closed channel 2 we should have, with the background,

$$(K_R)_{11} = \frac{g_1^2(1 + |\rho_2|\alpha_{22}) - |\rho_2|[2g_1g_2\alpha_{12} + (s-m^2)\alpha_{12}^2]}{s - m^2 + |\rho_2|[g_2^2 + (s-m^2)\alpha_{22}]}. \tag{6}$$

From formulae (5) and (6) one can see that only when a resonance is not coupled with closed channels in the K_R-matrix there is a pole at $s = m^2$. But even at small couplings of a resonance with particles of closed channels the resonance is represented by a number of poles. (Note that in practice these couplings manifest themselves in the resonance exchanges in reactions crossing to the above closed channels.) A successive explicit consideration of a larger number of channels would reduce the number of poles corresponding to the given multichannel resonance. In particular, for the 2-channel resonance in the 1-channel consideration (formula (6)) at least two poles on the real axis in the vicinity of m^2 describe this resonance. In the 2-channel consideration (for the "complete" K-matrix) there would be, of course, one pole at $s = m^2$, as distinct from the above-discussed case with a resonance of type (c). To understand this situation, we should investigate the pole representation of resonances on the Riemann surfaces. To this end we shall use a uniformization procedure mapping the Riemann surfaces onto a plane.

Note that, as is seen from (3), a pole in the K_R-matrix may arise also in the case when the elements of complete K-matrix are nonsingular. The condition for this pole is that

$$\det(I + |\widehat{\rho}|\widehat{\widehat{K}}) = 0. \tag{7}$$

This pole in the K_R-matrix exists, e. g., if particles in the lowest closed channel attract each other strongly enough to form a bound state provided the coupling between the closed and open channel is weak. Notice, however, that the same condition (7) is required for existing the resonances due to processes both in the open and closed channels. To distinguish these cases, one must again study the pole arrangement on the Riemann surface.

4. Generally, formulae of type (1) are a solution of the multichannel problem in the sense of giving a chance to predict (on the basis of the data on one process) the coupled-process amplitudes at a certain conjecture about the background. We made this before in the 2-channel approach [4]. It was a success to describe ($\chi^2/ndf \approx 1.06$) the experimental isoscalar s-wave of $\pi\pi$ scattering from the threshold to 1.9 GeV, to predict satisfactorily (on the basis of data on $\pi\pi$ scattering) the behaviour of the s-wave of $\pi\pi \to K\overline{K}$ process approximately up to 1.25 GeV. The 2-channel consideration turned out to be effectively sufficient for $\pi\pi$ scattering (the influence of other channels was taken into account by means of a slight violation of the 2- channel unitarity). However this is far from being the case for the coupled processes (note a deviation of the prediction on $\pi\pi \to K\overline{K}$ process from the experimental data above 1.25 GeV where the influence of the $\eta\eta$ channel begins to be noticeable). Therefore taking account of higher thresholds affects slightly the parameters of $f_0(975)$ resonance (though gives further information on it), however it is of vital importance for higher-lying resonances.

On a level with formulae of type (1) it is convenient to use the Le Couteur- Newton relations [20] representing compactly all features given by formulae of type (1) and expressing the S-matrix elements of all coupled processes in terms of the Jost matrix determinant $d(k_1, k_2, \cdots)$ $\equiv d(s)$, the real analytical function with the only square-root branch-points at the process thresholds $k_i = 0$. This was done by us in the 2-channel consideration [7]. The uniformizing variable, which was used,

$$z = (k_1 + k_2)/(m_K^2 - m_\pi^2)^{1/2}$$

maps the whole 4-sheeted Riemann surface onto the z-plane.

An analogous 2-channel approach was also applied in the above works [17, 18]. However the authors of these works neglect the $\pi\pi$-threshold influence and therefore use the momentum k_2 as uniformizing variable. This implies taking into consideration only the nearest to the physical region semi-sheets of the Riemann surface. The neglected singularities (as we examined [3]) give approximately the 10% contribution. However this approximation appreciably narrows the possible considered interval of energy and is not inevitable though simplifies the pole representation of resonances.

In the 3-channel approach it is impossible with the help of a simple function to map the 8-sheeted Riemann surface onto a plane. Therefore the consideration is necessarily developed with neglecting the influence of the $\pi\pi$ threshold. In this case the uniformizing variable may be

$$w = (k_2 + k_3)/(m_\eta^2 - m_K^2)^{1/2}. \tag{8}$$

In Fig.1 those parts of the w-plane, onto which the corresponding sheets of the Riemann surface are mapped, are denoted with the Roman numerals; the thick line represents the physical region (the points w_π, i and 1 are the $\pi\pi$, $K\overline{K}$ and $\eta\eta$ thresholds, respectively). The depicted positions of poles ($*$) and of zeros ($\circ$) give the representation of the type (a) resonance in S_{11} obtained on the basis of formulae analogous (1) [8].

The Le Couteur-Newton relations are somewhat modified with taking account of the used model of the Riemann surface (note that on the w-plane the points w_0, $-w_0^{-1}$, $-w_0$, w_0^{-1} correspond to the s-variable point s_0 on sheets I, IV, V, VIII, respectively):

$$S_{11}=\frac{d^*(-w^*)}{d(w)},\quad S_{22}=\frac{d(-w^{-1})}{d(w)},\quad S_{33}=\frac{d(w^{-1})}{d(w)},$$
$$S_{11}S_{22}-S_{12}^2=\frac{d^*(w^{*-1})}{d(w)},\quad S_{11}S_{33}-S_{13}^2=\frac{d^*(-w^{*-1})}{d(w)}, \tag{9}$$
$$S_{22}S_{33}-S_{23}^2=\frac{d(-w)}{d(w)}.$$

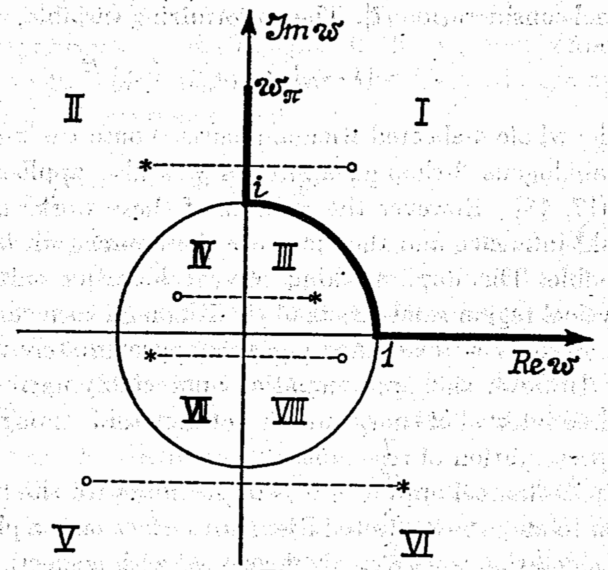

Fig.1

Taking the d-function as $d=d_B d_{res}$ where d_B describes the background and the resonance part has a form:

$$d_{res}(w)=w^{2M}\prod_{r=1}^{M}\prod_{i=1}^{4}(w+w_{ri}^*) \tag{10}$$

(M is the number of resonances) it is easy to obtain the expression for S_{11}, which we applied already in the analysis of $\pi\pi$ scattering, and for other matrix elements.

We analysed all available data on the isoscalar s-wave $\pi\pi$ scattering in the energy region 0.7-1.6 GeV [8] with taking account of $K\overline{K}$ and $\eta\eta$ thresholds. The background is taken in the elastic form:

$$S_{11}^B=e^{2i\delta^B(s)},\qquad \delta^B(s)=a+b\sqrt{s}$$

(from the analysis: $a=-1,376\pm0,056, b=0,6\pm0,0025$).
Satisfactory description ($\chi^2/ndf\approx1.12$) of experimental data is achieved

Table I

	$f_0(975)$		$f_0(1500)$	
Sheet	E,MeV	Γ,MeV	E,MeV	Γ,MeV
II	1017 ± 5	35 ± 7	1496 ± 16	548 ± 35
III	1031 ± 16	128 ± 30	1156 ± 36	146 ± 43
VI	1025 ± 8	23 ± 10	1502 ± 20	614 ± 40
VII	1139 ± 60	108 ± 42	1147 ± 55	145 ± 62

for the phase shift and the elasticity parameter with two resonances (Fig.2). The pole positions of resonances on different sheets in the energy plane ($\sqrt{s_r}=E_r-i\Gamma_r/2$) are presented in Table I. Note that the parameters of the $f_0(975)$ meson were changed somewhat as compared to our 2-channel analysis [7]. As is already discussed in [7], this should not influence the qualitative conclusion about the $f_0(975)$ nature (dominant $qq\bar{q}\bar{q}$ component) but shows a rather strong coupling of this resonance with the $\eta\eta$ system and the importance of taking account of the $\eta\eta$-channel influence to obtain the reliable values of the $f_0(975)$ parameters. The considerable coupling of the $f_0(975)$ meson with the $\eta\eta$ system can manifest itself experimentally, e.g., in crossing processes, such as $\pi\eta$ and $K\eta$ scattering, in the exchanges of this meson. The considerable shift of the $f_0(975)$ pole on sheet VII is stipulated by a great coupling between $\pi\pi$ and $\eta\eta$ channels whereas the coupling between $\pi\pi$ and $K\overline{K}$ channels is suppressed strongly by the phase-space volume (owing to proximity of the $f_0(975)$ mass to the $K\overline{K}$ threshold) whereby it is accounted for a smaller shift of the pole on sheet III. A displacement of the pole on sheet VI, related with influence of the $\eta\eta$ channel, is compensated by the effect of coupling between the $K\overline{K}$ and $\eta\eta$ channels which displaces the pole to the opposite direction (which is explained by the corresponding signs of the channel momenta when continuing onto sheet VI). Many authors have already noted that the $f_0(975)$ width cited in tables [1] is a visible one, the total width of this resonance is ~ 500 MeV.

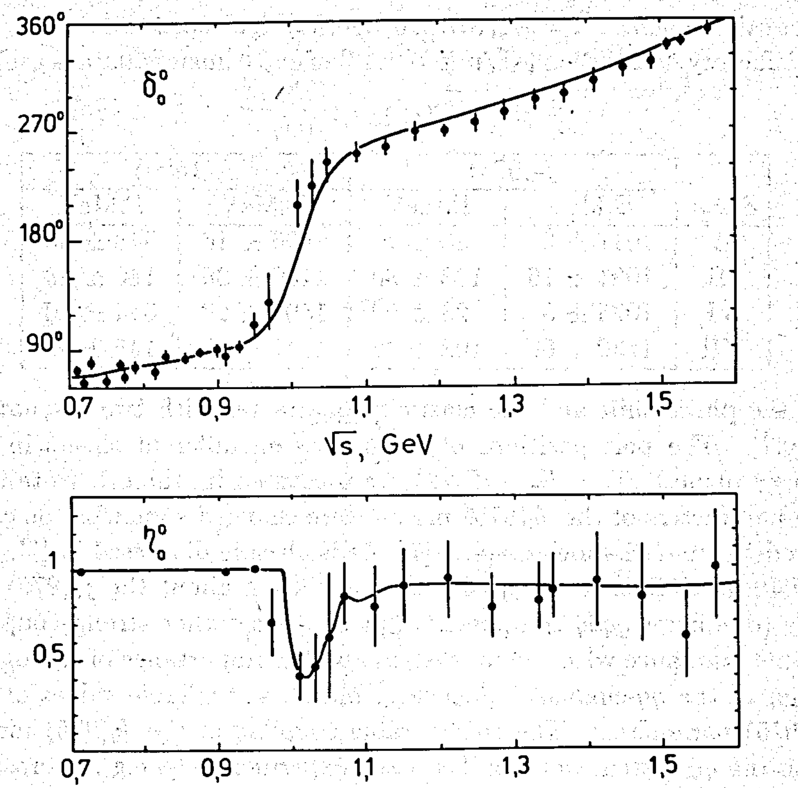

Fig.2. The phase shift and the elasticity parameter of the scalar-isoscalar channel of the $\pi\pi$ scattering obtained on the basis of the χ^2 analysis of the experimental data. The separate characteristic experimental points are depicted.

As to the second resonance, which we denoted symbolically as $f_0(1500)$, the analysis of experimental data shows obviously a resonance manifestation. However here it is impossible to draw a certain conclusion about its parameters since the thresholds of the $\eta\eta'$, $\rho\rho$, $\omega\omega$ channels in this region, with which it may be coupled, are not considered. Notice also that this analysis does not reveal the $f_0(1590)$ resonance by virtue of its comparatively weak coupling with the $\pi\pi$ channel though, of course, this resonance must affect the results due to its rather considerable couplings with the $\eta\eta$ and $\eta\eta'$ channels.

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Крупа Д., Мещеряков В.А., Суровцев Ю.С. E2-93-461
Многоканальные резонансы и закрытые каналы
(скалярный сектор)

На основе аналитичности и унитарности обсуждается проблема многоканальных резонансов в 2- и 3-канальном подходах. Получено модельно-независимое полюсное представление многоканальных резонансов как реализация идеи о доминантности ближайших особенностей на всех соответствующих листах римановой поверхности S-матрицы. Исследуется роль закрытых каналов в формировании резонансов как в K-, так и в S-матричном подходах. Метод проиллюстрирован на примере связанных процессов $\pi\pi \to \pi\pi$, $K\overline{K}$, $\eta\eta$, в изоскалярной s-волне (с χ^2-анализом экспериментальных данных по $\pi\pi$-рассеянию в области энергий ниже 1,6 ГэВ).

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Krupa D., Meshcheryakov V.A., Surovtsev Yu.S. E2-93-461
Multichannel Resonances and Closed Channels (Scalar Sector)

The problem of multichannel resonances is discussed in the 2- abd 3-channel approaches on the basis of analyticity and unitarity. A model-independent pole representation of multichannel resonances is obtained as a realization of the idea of dominance of the nearest singularities on all corresponding sheets of the Riemann surface of the S-matrix. The role of closed channels in forming the resonances is investigated in both the K- and S-matrix approaches. The method is illustrated for coupled processes $\pi\pi \to \pi\pi$, $K\overline{K}$, $\eta\eta$ in the isoscalar s-wave (with the χ^2 analysis of experimental data on $\pi\pi$ scattering in the energy region below 1.6 GeV).

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

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