Analysis of $K\pi$-scattering phase shift and existence of $\kappa(900)$-particle

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Recently we have shown an evidence for existence of $\sigma$-particle in the previous works; where the $\pi\pi$ S-wave phase shift is reanalyzed, by introducing a repulsive background suggested by the chiral symmetry, and by applying a new method of Interfering Breit-Wigner Amplitudes. In this work we also show, reanalyzing the $K\pi$ S-wave phase shift from a similar standpoint, an evidence for existence of $\kappa(900)$, possibly to be a member of $\sigma$-nonet.

§1. Introduction

In our previous works[1,2], we have analyzed the iso-singlet S-wave $\pi\pi$ scattering phase shift, and have shown the existence of a resonance with mass of 535-650 MeV and width of about 350 MeV. These values are consistent with those of $\sigma$ particle, the long-sought chiral partner of Nambu-Goldstone $\pi$ meson, predicted by the linear $\sigma$ model[3]. Independent analyses of the phase shift by several authors[4,5,6] have also suggested its existence. On the other hand anticipation for $\sigma$ existence has been given recently with new interests both[7-17] theoretically and phenomenologically. As a matter of fact a low-mass isoscalar resonance, $f_0(400\sim1200)$ or $\sigma$, has revived in the latest issue of Particle Data Group[18] after its missing over twenty years.

In the phase shift analysis[1,2] on one hand, we have developed a new method of S-matrix parametrization in conformity with unitarity, Interfering Breit-Wigner Amplitude method, in which we use only a few parameters with direct physical meaning (i.e. masses and widths of resonances), in contrast with the conventional $K$-matrix method. On the other hand we have introduced an negative background phase $\delta_{BG}$ of hard core type phenomenologically. This type of background phase shifts[19] was observed historically in the $\alpha$-$\alpha$ scattering, and also in the nucleon-nucleon scattering. In the relevant case of $\pi\pi$ system its origin seems to have some correspondence to the “compensating” contact $\lambda\phi^4$ term required by the chiral symmetry in the linear $\sigma$ model.

The $\sigma$-particle is a chiral partner of $\pi$-meson in the linear representation of chiral $SU(2)_L \times SU(2)_R$ group. Taking $SU(3)$ flavor symmetry into account, it is natural to expect existence of scalar $\sigma$-meson nonet as a chiral partner of pseudoscalar $\pi$-meson nonet. In the following we analyze the I=1/2 $K\pi$ scattering phase shift from
§2. Applied formulas

We analyze the I=1/2 S-wave phase shift of $K\pi$-scattering by Interfering Amplitude method in the case of three-channels ($K\pi, K\eta$ and $K\eta^*$, denoted to 1, 2 and 3, respectively) with two-resonances ($\kappa$ and $K_0^*(1430)$) from the $K\pi$-threshold to $\sqrt{s} \sim 1.6$ GeV.

The relevant S-matrix element of $K\pi$-scattering, $S_{11}$, is related to its phase shift (amplitude), $\delta^{BG}_{01}$, by

$$S_{11} = \eta_{11} e^{2i\delta^{BG}_{01}} = 1 + 2ia_0^{1/2},$$

where $\eta_{11}$ is the elasticity. $S_{11}$ is given by product of “individual” resonance-S-matrices $S_{11}^{(R)} (R = \kappa, K_0^*)$

$$S_{11} = e^{2i\delta^{BG}} \prod_{R=\kappa,K_0^*} S_{11}^{(R)};$$

The unitarity of “total” S-matrix (2) is now easily seen to be satisfied by the unitarity of individual S matrices. In Eq.(2) we have also introduced a negative background phase $\delta^{BG}$, taken as a hard core type phenomenologically,

$$\delta^{BG} = -|p_1| r_{c0}^{1/2}; \quad |p_1| = \frac{\sqrt{(s - m_\pi^2 - m_K^2)^2 - 4m_\pi^2m_K^2}}{2\sqrt{s}},$$

$|p_1|$ being the CM momentum of the $\pi K$ system.

Each of $S_{11}^{(R)}$ is given by a corresponding amplitude $a_{11}^{(R)}$ taken as a simple relativistic Breit-Wigner form

$$S_{11}^{(R)} = 1 + 2ia_{11}^{(R)}; \quad a_{11}^{(R)} = -\sqrt{\frac{3}{s-M_R^2+i\sqrt{s}\Gamma^0_R(s)}},$$

where $\Gamma^0_R(s)$ is a total width (partial width of channel 1) of the resonance $R$, given by

$$\Gamma^0_R(s) = \sum_{i=1}^{3} \Gamma_i^{R}(s); \quad \Gamma_i^{R}(s) = \frac{\rho_i}{\sqrt{s}} g_{Ri}^2 = g_{Ri}^2 |p_i|/8\pi s \quad (i = 1, 2, 3).$$

Here $g_{Ri}$’s are coupling constants to the channel $i$ of resonance $R$, and the CM momentum $|p_i|$ for $i = 2, 3$ are defined in a similar way as in Eq.(3). Thus parameters to be used for the fit are totally nine, i.e. resonance masses $M_R$’s (R=\kappa, $K_0^*$), their coupling constants $g_{Ri}$’s (i=1,2,3), and repulsive core radius $r_{c0}^{1/2}$.

\textsuperscript{a} Contributions from the other channels such as $K\pi\sigma$ and $K\pi\pi\pi$ are expected to be supressed by a phase space factor.

\textsuperscript{b} The other elements of $S_{ij}$ ($i \neq 1$ and/or $j \neq 1$) are now irrelevant since of present experimental situations in the corresponding processes.
§3. Mass and width of $\kappa$ and core radius

A high statistics data of the reaction $K^-p \to K^-\pi^+n$ was obtained with 11 GeV/c beam using LASS spectrometer at SLAC. Spherical harmonic moments were used to perform an energy independent Partial Wave Analysis of the $K^-\pi^+$ system from threshold to 2.6 GeV, with $t$-dependent parametrization of the production amplitudes. The obtained $K^-\pi^+$-scattering amplitudes are the sum of I=1/2 and 3/2 components. The I=1/2 S-wave amplitude $a_0^{1/2}$ was determined by subtracting the I=3/2 ($K^-\pi^+/K^-\pi^-$) component, obtained independently by another experiment at SLAC. Here, the “overall” phase was fixed by imposing elasticity constraint to the amplitude in the $m_{K\pi}$ region below 1.29 GeV. We use this amplitude between $K\pi$ threshold and 1.6 GeV for the analysis.

Figure 1(a) and (b) show the result of the best fit to $\delta_0^{1/2}$ and $|a_0^{1/2}|$, respectively, by solid line. The obtained parameters are collected in Table I. The most remarkable feature is that we identify a low-mass resonance $\kappa$ with mass of about 900 MeV in the slowly-increasing phases between the threshold and 1300 MeV. This is due to the role of “compensating” repulsive background $\delta_{BG}$, whose existence is necessarily required from Chiral Symmetry (see ii) and iii) of the following supplementary discussions). As a matter of fact, the original LASS analysis of the data, where a positive $\delta_{BG}$ with an effective range-formulus was introduced, led to existence of only one state $K_0^*(1430)$ with high mass. Since of the compensation between contributions due to $\kappa$ and the repulsive core, the mass value of $\kappa$ ($M_\kappa$) and its coupling to the $K\pi$ channel ($g_{\kappa 1}$) are correlated to the core radius $r_c$. To clarify this situation, various fits are performed with a series of fixed $r_c$ values between 0 to 5.5 GeV$^{-1}$. Fig. 1(c) shows the values of $\chi^2$, $M_\kappa$, $g_{\kappa 1}$, $M_{K_0^*}$, and $g_{K_0^* 1}$ as functions of $r_c$. $M_\kappa$ and $g_{\kappa 1}$ decrease as $r_c$ becomes larger, while $M_{K_0^*}$ and $g_{K_0^* 1}$ do not show such correlations because these values are constrained mainly by the steep phase increase around 1.4 GeV. In the range of 2$\sim$5 GeV$^{-1}$, the $\chi^2$ value shows a parabolic shape, and makes its minimum at $r_c$=3.57 GeV$^{-1}$ where we get the best fit given in Fig. 1(a) and (b) ($\chi^2 = 57.0$ for 42 degrees of freedom; 51 data points with 9 parameters). When $r_c$ becomes smaller than 2 GeV$^{-1}$, the values of $M_\kappa$ and $g_{\kappa 1}$ increase steeply, and the contribution of “$\kappa$-meson resonance” has no more meaning than the positive background. A fit with $r_c$ setting to zero gives large $M_\kappa$ and $g_{\kappa 1}$ values (6.4 GeV and 39 GeV, respectively), and becomes essentially similar to the LASS analysis. This fit has the $\chi^2$ value of 96, which is larger by 40 than of our best fit.

From the $\chi^2$ behavior in Fig. 1(c), we can obtain the upper and lower bounds of error of $M_\kappa$, $g_{\kappa 1}$ and $r_c$ which are given in Table I as five standard deviations from the best fit ($+25$ $\chi$-squares). Corresponding curves with upper and lower values of relevant parameters are also shown in Fig. 1(a) and (b), respectively, by dotted ($r_c$=3.1 GeV$^{-1}$) and dashed ($r_c$=3.975 GeV$^{-1}$) lines.

$^\ast$ In Ref. 20) almost all data points are given with no accurate errors. We will regard the original errors of $K^-\pi^+$ amplitude data[22] equivalent to our relevant errors of I=1/2 scattering amplitude, which might be smaller than those of [21]. This may be a reason why we get a $\chi$-square value larger than that in the LASS analysis.
Fig. 1. Fits to $I=1/2$ $K\pi$ S-wave scattering amplitude; (a) phase shift $\delta_{0}^{1/2}$, and (b) magnitude of amplitude $|a_{1/2}^{0}|$. The solid lines are the best fit with $r_c=3.57\text{GeV}^{-1}$, while the dotted and dashed lines are fits with $r_c=3.1$ and $3.975\text{GeV}^{-1}$, respectively. (c) $\chi^2$, $M_\kappa$, $g_\kappa$, $M_{K^*}$, and $g_{K^*}$ behaviors as functions of core radius $r_c$. Vertical lines represent $r_c=3.57$, 3.1, and 3.975 GeV$^{-1}$, corresponding to the best fit and the fit with $\pm 5$ sigma deviations.

Table I. Resonance parameters of $\kappa(900)$, $K^*_0(1430)$ and core radius. The errors correspond to five standard deviations from the best fit. Two kinds of width, $\Gamma^{(p)}$ and $\Gamma^{(d)}$ defined as $\Gamma^{(b)}=\Gamma_b(s=M^2)(\text{Eq.(5)})$, $\Gamma^{(d)}=N^{-1}\int ds\Gamma(s)/[(s-M^2)^2+s\Gamma(s)^2]$; $N=\int 1/[(s-M^2)^2+s\Gamma(s)^2]$, considering broadness of relevant widths.

|    | $M_\kappa$ | $g_{K\pi}$ | $\Gamma^{(p)}_{K\pi}$ | $\Gamma^{(d)}_{K\pi}$ |
|----|------------|-------------|------------------------|------------------------|
| $\kappa(900)$ | $905^{+65}_{-30}$ MeV | $6150^{+1200}_{-650}$ MeV | $545^{+110}_{-110}$ MeV | $470^{+70}_{-90}$ MeV |
| $K^*_0(1430)$ | $1410^{+10}_{-15}$ MeV | $4250^{+10}_{-70}$ MeV | $220^{+5}_{-5}$ MeV | $220^{+5}_{-5}$ MeV |

$r_c^{1/2}$

$3.57^{+0.45}_{-0.39}\text{GeV}^{-1}$ (0.706$^{+0.03}_{-0.02}$ fm)
**Analysis of Kπ-Scattering Phase Shift**

Fig. 2. I=3/2 Kπ scattering phase shift. Fitting by hard core formula is also shown.

Table II. Phenomenological core radii $r_c$ in ππ and Kπ systems

| System      | $r_c$     |
|-------------|-----------|
| $\pi\pi$    | 0.60±0.07fm |
| $K\pi$      | 0.70±0.09fm |
| $\pi\pi$    | 0.17fm    |
| $K\pi$      | 0.16fm    |

The respective coupling constants to the 2nd channel $K\eta$ are obtained to be much smaller than those to the $K\pi$ channel, i.e., $g_{K2}\lesssim 1.0$ GeV and $g_{K*2}\lesssim 0.9$ GeV, which are consistent to the elasticity constraint mentioned above. The $g_{K3}$ and $g_{K*3}$ couplings to $K\eta'$ channel, are obtained with much larger uncertainties, and their values are omitted here.

§4. Repulsive background in $K\pi$- and $\pi\pi$-systems

In the present analysis, leading to the existence of $\kappa$-meson, introduction of a negative background phase $\delta_{BG}$ of hard core type plays an essential role. This is a similar situation as for $\sigma$-existence in $\pi\pi$-scattering. In the I=2 $\pi\pi$ system, there are no known and/or expected resonances, and this repulsive type phase shift itself is, if it exists, expected to be observed directly. Actually a good fit to the experimental data was obtained\textsuperscript{3} by a similar formula of hard core type as Eq.(3) with the core radius $r_{c0}^2 = 0.17$ fm. The same situation is expected in the I=3/2 Kπ scattering, and we have made a similar analysis on the relevant Kπ-scattering phase shift.\textsuperscript{21} The result is given in Fig. 2. The best fit is obtained with the core radius $r_{c0}^{3/2} = 0.16$ fm, although the fit is somewhat worse than in the case of I=2 ππ system.

The values of phenomenological core radii in the $\pi\pi$ and $K\pi$ systems are collected in Table II. It is quite interesting that they are almost same within the non-exotic channels (that is, $r^0=r^{1/2}$) and within the exotic channels ($r^2=r^{3/2}$), respectively. It seems to be reasonable from the viewpoint of $SU(3)$ flavor symmetry.
§5. Supplementary discussions

Here we give some additional comments on the results of our analysis:

i) It may be interesting and important to compare the properties of $\kappa$-meson obtained above with predictions of the various theoretical models. The SU(3) Linear $\sigma$ Model with the $U_A(1)$ breaking term ($\Sigma\sigma M_1$), the SU(3) Linear $\sigma$ Model without it ($\Sigma\sigma M_2$), and the extended Nambu Jona-Lasinio type model (ENJLM) (including also the $U_A(1)$ breaking term) give the $\kappa$-masses, respectively, as $m_\kappa = 1.2 \pm 0.4$ and $0.4\sim0.9 \pm 0.2$ in GeV, which have a large uncertainty. The values of $\kappa$ decay width are given to be $1.2(0.1)$ GeV in $\Sigma\sigma M_1$ ($\Sigma\sigma M_2$). The properties of $\kappa$ meson in Table I seem not inconsistent with those predicted by the SU(3)-theoretical models with the $U_A(1)$ breaking term ($\Sigma\sigma M_1$ and ENJLM). Accordingly our $\kappa$ meson can be regarded as the member of $\sigma$-nonet, although further investigations are necessary.

ii) Concerning a possible origin of the repulsive background phase $\delta_{BG}$ introduced phenomenologically in this analysis, we should like to note its similarity to the $\lambda\phi^4$ term in $\Sigma\sigma M$. The $\lambda\phi^4$ term represents a strong repulsive and contact (zero-range) interaction between pions and seems to have a plausible property as an origin of $\delta_{BG}$, at least, in the low energy region, where the structures of composite pions may be neglected.

In $K\pi(\pi\pi)$-scattering in $\Sigma\sigma M$ a contribution due to intermediate $\kappa(\sigma)$-production in all $s,t,u$-channels almost cancels$^{23,24}$ in the low energy region with a repulsive force from the $\lambda\phi^4$ interaction. This leads effectively to the derivative (thus small) coupling$^{25}$ of Nambu-Goldstone boson. This cancellation mechanism is guaranteed by chiral symmetry and PCAC. It is notable that in the usual Breit-Wigner formula of S-wave resonance, a non-derivative coupling of $\kappa$ and $\sigma$ resonance is supposed, without taking the “compensating” repulsive interaction into account. This seems to be a reason why $\sigma$ and $\kappa$ resonances have been overlooked in the many phase shift analyses thus far made.

The result given in Table II, that the repulsive core radii in non-exotic channels are much larger than those in exotic channels, may be given$^{29}$ some reason in $\Sigma\sigma M$ as follows: In exotic channels a large amount of strong repulsive force due to $\lambda\phi^4$ interaction is canceled by the attractive force due to crossed-channel exchange of relevant scalar-mesons, while in non-exotic channels there remains some amount of the repulsive force (going to compensate the attractive force due to $s$-channel intermediate production of the scalar mesons in the threshold).

iii) In analysis of the $\pi \pi (K\pi)$-scattering, the importance of $\rho \ (K^*)$ meson effects is often pointed out.$^{30}$ In the S-wave scattering these vector mesons contribute only through the crossed channel exchange diagrams, which are necessarily accompanied by the “compensating” derivative $\phi^4$ interaction,$^{23}$ similarly in the case of the $\lambda\phi^4$ interaction to the $\kappa$ (or $\sigma$) exchange. They exactly cancel with each other at the

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$^*$ This value is quoted in their analysis of case A, where $m_\sigma = 0.604\text{GeV}$, close to our value$^{3,23}$. 

threshold and give only small effects in the low energy region, which may be regarded as included in the background phase.

iv) Finally we give a comment on the behavior of the background phase. In I=2 (I=3/2) channel of S-wave ππ(Kπ)-scattering the fit of phase shifts by hard core formula is satisfactory below \( \sqrt{s} \sim 1.4 \) GeV, as was shown in Fig. 1 in Ref. [2] (Fig. 2). However, the experimental phase shifts in the higher energy region seem to be decreasing [32]. This is a very interesting phenomenon, which reminds us of the soft core in nucleon-nucleon scattering. In this work we applied the hard core type background, implicitly supposing “local” π and K mesons. The above mentioned “soft core” type behavior of phase shifts in the comparatively high energy region seems to suggest the composite structure of π and K as \( q\bar{q} \)-bound states.

§6. Concluding remarks

We have shown a strong evidence for existence of \( \sigma \)-meson in the previous work [1, 2] and of \( \kappa \)-meson in the present work. The existence of these particles has a significant importance in hadron spectroscopy. Since of their light masses (and, for \( \sigma \), of its vacuum quantum number), they will appear in various processes such as \( K \to 2\pi \) decay [10], \( K_{14} \) decay [13], etc.

We have argued that \( \kappa \) meson observed in the present analysis is a member of \( \sigma \)-meson nonet, chiral partner of \( \pi \)-meson nonet. As was discussed in Ref. [1], these particles (we call them “Chiralons”) should be regarded as being different from the ordinary P-wave excited states of \( q\bar{q} \) system since of their light masses. This discrimination may have also some theoretical reasons: In the extended Nambu Jona-Lasinio model as a low energy effective theory of QCD (, in which the existence of \( \sigma \)-meson is predicted), only local composite quark and anti-quark operators are treated, thus missing \( L \)-excited states in principle. The present status of “Chiralons,” [1] is summarized in Table III.

Classification of low mass scalar mesons is still in confusion. One of its main reasons seems to come from mis-identification of the chiral \( \sigma \)-nonet with the \( qq \) \( 3P_0 \) nonet. The properties of this extra-nonet should be further investigated also through the many other production processes, such as \( pp \)-central collision [14], \( \Upsilon \) and \( \Psi \) decays. In this connection especially the properties of observed resonances, \( f_0(980) \) and \( a_0(980) \), are to be clarified in relation [14, 20] to the other members of chiralons, \( \sigma' \) with I=0 and \( \delta \) with I=1.
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