Mem. Fac. Sci., Shimane Univ.,
12, pp. 23–32 Dec. 20, 1978

Pole-Pole Duality in Low Energy Kaon-Nucleon Scattering

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(Received September 6, 1978)

In order to examine the duality structure in low-energy $K-N$ scattering, the experimental phase shifts are analysed by the sum of one-particle-exchange terms in two cases; one includes only t-channel states and the other only u-channel ones. Coupling constants are restricted by other experiments, the universal coupling hypothesis and the unitary symmetry. It is found that a fair agreement with experiments is obtained for both cases and some kind of the pole-pole duality seems to be present.

§1. Introduction

The pole-pole duality, first introduced by Veneziano[1] in his model for scattering amplitude and supplied with the quark-diagram interpretation by several authors,[2] is supposed to be one of the fundamental characteristics of hadron interactions, as well as an exciting extension of the duality of Regge poles and resonances.[3] It is very interesting to examine how the pole-pole duality is realized at low energies.

The Veneziano-type representation[1] is in general not so successful at low energies, because it does not usually give correct description of daughters and has many ambiguous satellite terms. These have crucial effects in reproducing the detailed behaviour of partial-wave amplitudes.

In this paper, we study the duality structure of the low-energy scattering amplitude by a more "phenomenological" approach using the sums of one-particle-exchange terms over "observed" particles, in the way done recently by Yanagida[4] for $\pi-N$ scattering. From the viewpoint of pole-pole duality between non-exotic particles, the elastic $K-N$ scattering may have a particularly simple structure as Σ(baryon exchange in u-channel)$=\Sigma$(meson exchange in t-channel). Here, we examine the scattering considering only non-exotic particles as exchanged states.

The t- or u-pole saturation of a $K-N$ Veneziano-type amplitude was investigated by Kinoshita and Shiga.[5] They found that the contributions from lowest-lying-meson exchanges in the t-channel almost saturate the Veneziano amplitude at low energies, while, the amplitude is not well saturated by the sum of finite terms of baryon exchange contributions in the u-channel.

We consider low-lying mesons or baryons as exchanged particles in the t-channel or u-channel. However, we add the contact interaction terms to the low-lying-baryon-exchange pole terms by taking account of kaon PCAC. The contact terms may be regarded as a representation of contributions from higher-mass baryon states.

In § 2, we shall present some assumptions in this analysis, the particles considered and their interactions. In § 3, the experimental phase shifts are compared with the sum of the one-particle-exchange terms in two cases; one includes only mesons in the t-channel and the other only baryons in the u-channel. There, coupling constants are restricted by other experiments, the universal coupling hypothesis and the unitary symmetry. We shall summarize and discuss the results in § 4.

§ 2. Mesons and baryons to be exchanged and their interactions

We consider the following mesons or baryons[6] to be exchanged:

$$\rho(770, J^P=1^-),\ \omega(783, J^P=1^-),\ f(1270, J^P=2^+)\ \text{ and }\ A_2(1310, J^P=2^+), \tag{2.1}$$

or,

$$\begin{aligned}&\Lambda(1116, J^P=1/2^+),\quad \Lambda(1520, J^P=3/2^-),\quad \Sigma(1193, J^P=1/2^+),\\ &\Sigma(1385, J^P=3/2^+)\ \text{ and }\ \Sigma(1670, J^P=3/2^-).\end{aligned} \tag{2.2}$$

The Φ and f' contributions will be negligible because their couplings to $\bar{N}N$ are disconnected in the quark diagram and so suppressed (the Okubo-Zweig-Iizuka rule[7]).

We suppose the ε, δ and S^* mesons to be $2q2\bar{q}$ exotic states, following the opinion proposed by Jaffe.[8] And they are excluded from the present analysis. The coupling of $2q2\bar{q}$ exotic state to mesons is suppressed by the Freund-Walz-Rosner rule.[9] The σ meson, needed in models of low-energy $N-N$ scattering,[10,11] is also supposed to be a $2q2\bar{q}$ exotic state.[11] The σ may be identified with the ε.

The contribution from $\Lambda(1405, J^P=1/2^-)$ is found to be negligibly small.[12] Thus, the $\Lambda(1405)$ is omitted.

Higher-mass baryons, including the $\Sigma(1765, J^P=5/2^-)$ of the Σ_β trajectory, will have effects mainly on lower partial waves. We assume that their contributions can be represented by the contact interaction terms stated in § 1. The expressions for the contact terms are given below.

We take the following interaction Hamiltonian densities for the mesons and baryons in (2.1) and (2.2):

$$\begin{aligned}&(4\pi)^{\frac{1}{2}} g_{NNV}\bar{\psi} i\gamma_\mu \psi \varphi_\mu + (4\pi)^{\frac{1}{2}} \frac{f_{NNV}}{4m}\bar{\psi}\sigma_{\mu\nu}\psi(\partial_\mu\varphi_\nu - \partial_\nu\varphi_\mu)\\ &+ (4\pi)^{\frac{1}{2}} g_{VKK} i\{(\partial_\mu\phi^+)\phi - \phi^+\partial_\mu\phi\}\varphi_\mu\\ &\qquad\qquad \text{for}\quad (N, N, 1^-)\text{ and }(K, K, 1^-)\text{ vertices,}\end{aligned} \tag{2.3}$$

$$(4\pi)^{\frac{1}{2}}\frac{g_{NNT}}{m}\bar{\psi}\gamma_\mu(\partial_\nu\psi)\varphi_{\mu\nu}+(4\pi)^{\frac{1}{2}}\frac{g_{TKK}}{m}(\partial_\mu\phi^+)(\partial_\nu\phi)\varphi_{\mu\nu}$$

for $(N, N, 2^+)$ and $(K, K, 2^+)$ vertices, (2.4)

$$(4\pi)^{\frac{1}{2}}G_{HNK}\bar{\psi}i\gamma_5\Psi\phi+\text{h.c.} \qquad \text{for } (N, 1/2^+, K) \text{ vertex,} \qquad (2.5)$$

$$(4\pi)^{\frac{1}{2}}\frac{G_{HNK}}{m}\bar{\psi}(1, i\gamma_5)\Psi_\mu\partial_\mu\phi+\text{h.c.} \qquad \text{for } (N, 3/2^{+,-}, K) \text{ vertices.} \qquad (2.6)$$

The nucleon and kaon fields are represented by ψ and ϕ respectively, while Ψ and Ψ_μ represent the $J=1/2$ and 3/2 hyperon fields. Vector and tensor fields are denoted by φ_μ and $\varphi_{\mu\nu}$. The nucleon mass m is introduced to make coupling constants dimensionless. The interactions as given in Eqs. (2.3)~(2.6) are for exchanged particles with isospin zero. For exchange of baryon with isospin one, one replaces $\bar{\psi}\phi$ by $\bar{\psi}\boldsymbol{\tau}\phi$. For the ρ meson, one replaces $\bar{\psi}\psi$ and $\phi^+\phi$ by $\bar{\psi}\frac{\boldsymbol{\tau}}{2}\psi$ and $\phi^+\frac{\boldsymbol{\tau}}{2}\phi$, and for the A_2 meson $\bar{\psi}\psi$ and $\phi^+\phi$ by $\bar{\psi}\boldsymbol{\tau}\psi$ and $\phi^+\boldsymbol{\tau}\phi$. The extra factor 1/2 for the ρ is introduced to conform to the Sakurai's universality convention.[13)]

The Feynman amplitudes of the lowest order diagrams from each contribution of ρ, ω, etc., are given for the above interactions by the usual perturbation calculation. From them, we obtain the real partial wave amplitudes $\alpha_{l\pm}^{(I)}$ for the $K-N$ states with isospin I and total angular momentum $j=l\pm 1/2$ for each exchange of the above particles. The expressions for these partial wave amplitudes are seen, for example, in Reference 14). We note that the definitions of some coupling constants here are different from those in Ref. 14).

To the $1/2^+$ baryon exchange amplitude for the interaction (2.5), we add a contact term by taking account of kaon PCAC. As already stated above, such a contact term is assumed to represent contributions from higher-mass baryons omitted from (2.2). Following Cutkosky et al.,[15)] the adding is done only in the A amplitude as

$$4\pi G_{HNK}^2\left[-\frac{(M-m)}{u-M^2}\right]\longrightarrow 4\pi G_{HNK}^2\left[-\frac{(M-m)}{u-M^2}-\frac{1}{(M+m)}\right]$$
$$=4\pi G_{HNK}^2\left[-\frac{(u-m^2)}{(M+m)(u-M^2)}\right]. \qquad (2.7)$$

Here, M is the mass of the exchanged baryon, and the isospin factor is omitted. The consistency of the final amplitude in Eq. (2.7) with kaon PCAC is seen from the fact that it satisfies Adler's PCAC consistency condition[16)]

$$A^{(I=^1_0)}(s=m^2,\ t=\mu^2,\ u=m^2;\ (\text{mass})^2 \text{ of initial kaon}=0)=0, \qquad (2.8)$$

where μ is the mass of kaon.

The $J=3/2$ baryon exchange amplitudes given by the interactions (2.6) satisfy the condition (2.8). Thus, no more contact terms are needed for them. We note that the interactions (2.6) yield amplitudes consisting of the pole term and some contact terms.[14)]

The partial wave amplitude, which we require, is the sum of the contributions from the above mesons or baryons:

$$\alpha_{l\pm}^{(I)} = \Sigma\alpha_{l\pm}^{(I)}(\text{meson}), \quad \text{or} \quad \Sigma\alpha_{l\pm}^{(I)}(\text{baryon}). \tag{2.9}$$

The unitarity requirements for the S-matrix are satisfied by taking account of the damping effect, i.e. by replacing the real $\alpha_{l\pm}^{(I)}$ as

$$\alpha_{l\pm}^{(I)} \longrightarrow \frac{\alpha_{l\pm}^{(I)}}{1-i\alpha_{l\pm}^{(I)}}, \tag{2.10}$$

and equating the final quantity with $(S_{l\pm}^{(I)}-1)/(2i)$. This is equivalent to take

$$\tan\delta_{l\pm}^{(I)} = \alpha_{l\pm}^{(I)}, \tag{2.11}$$

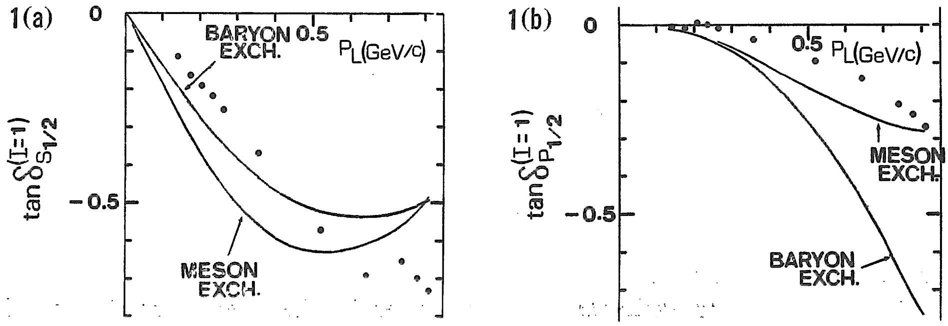
where δ is the phase shift.

§3. Comparison with experiments

We compare the sum of meson exchanges or baryon exchanges with the $I=1$ and 0 phase shifts from phenomenological phase-shift analysis at laboratory momenta up to 0.81 GeV/c, where the inelastic cross section is small.

As experimental phase shifts, the set of the $I=1$ phases (γ solution) of Albrow et al.[17)] and the $I=0$ ones ($\delta^{A\gamma}$ solution) of the *BGRT Collaboration*[18)] is taken. The $I=1$ phases are fairly established in the momentum region under discussion. Although there is another good solution of different type for the $I=0$ state, the $\gamma^{A\gamma}$ solution, this solution is essentially coincident with the $\delta^{A\gamma}$-type one at the momenta where we make the comparison with the theory.

The set of experimental phase shifts is shown in Figs. 1(a)～1(e) and 2(a)～2(e).



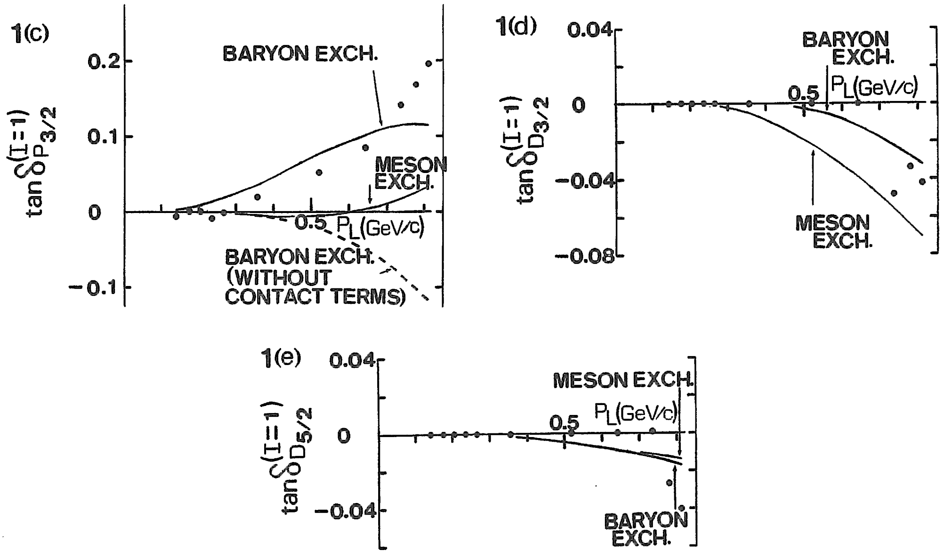
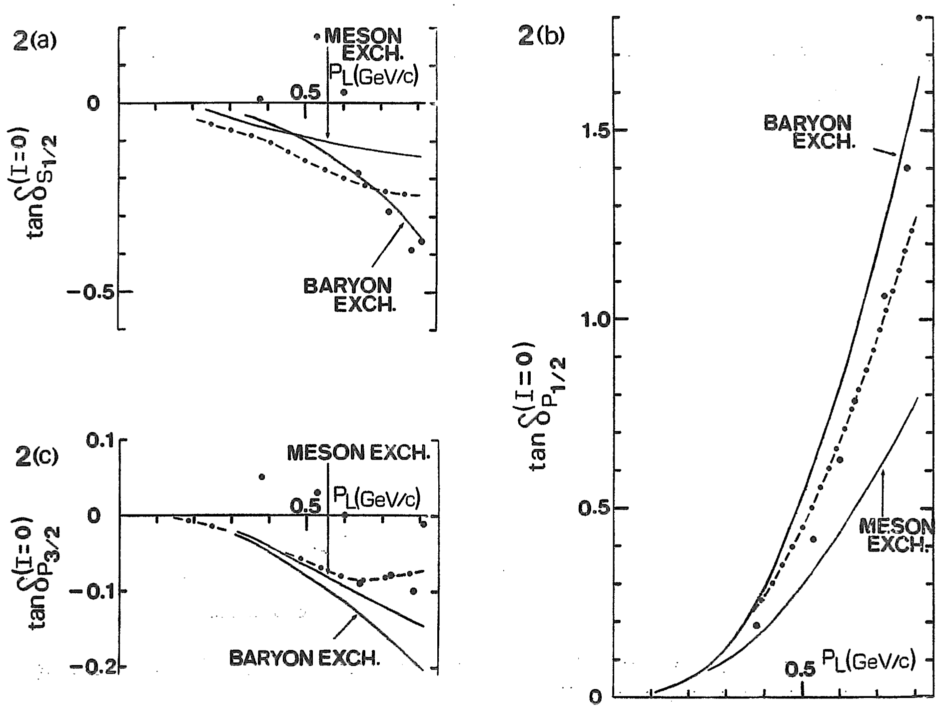


Fig. 1. Phase shifts in the $I=1$ state from the phenomenological phase-shift analysis, and theoretical curves.



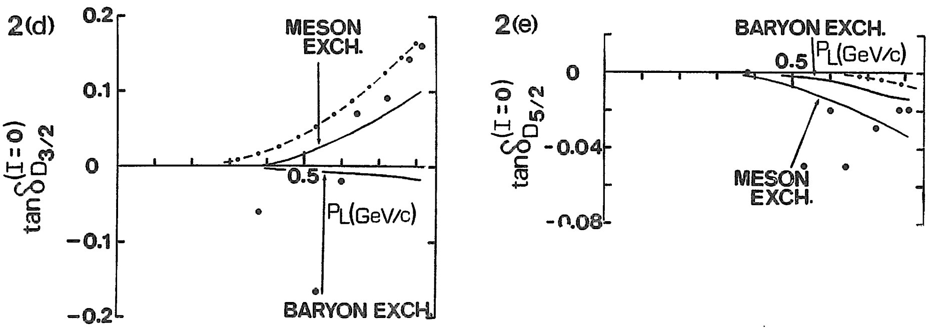


Fig. 2. Phase shifts in the $I=0$ state from the phenomenological phase-shift analysis, and theoretical curves. Phenomenological phases from an energy-dependent phase-shift analysis[18] (D^{BGRT} solution), obtained using experiments at $P_{LAB}=0.60\sim1.51$ GeV/c, are also shown by the dot-dashed curves for the comparison.

3.1 *The meson-exchange model*

First we compare the sum of meson exchanges in the t-channel with experiments.

There are some informations about the coupling constants of considered mesons. The ratios of tensor to vector $\bar{N}N\rho$ and $\bar{N}N\omega$ couplings are determined from the electromagnetic form factors assuming the vector dominance model:[19]

$$f_{NN\rho}/g_{NN\rho}=3.70, \quad f_{NN\omega}/g_{NN\omega}\simeq 0. \tag{3.1}$$

$g_{NN\rho}g_{\rho KK}$ and $g_{NN\omega}g_{\omega KK}$ are predicted from the generalized universal coupling hypothesis[13] in terms of the F-type coupling in the $SU(3)$ symmetry. For the $\bar{N}NV$ vertex, it seems plausible that the $SU(3)$ is obeyed in the Sachs form factors $G_E(t)=g(t)+\frac{t}{4m^2}f(t)$ and $G_M(t)=g(t)+f(t)$ rather than in the coupling constants g and f.[20] Using $g^2_{\rho\pi\pi}=2.84\pm0.50$[21] from observed width and $g^2_{NN\omega}=17\pm5$ from an analysis of the isoscalar form factor[22]*) (or, $g^2_{NN\omega}=8.8\sim13$ from NN data[23]), we have

$$g_{NN\rho}g_{\rho KK}=2.3\sim3.3, \tag{3.2}$$

$$g_{NN\omega}g_{\omega KK}=2.6\sim4.3, \tag{3.3}$$

$$(\text{or, } 2.2\sim3.3). \tag{3.4}$$

Here the ideal mixing is assumed for the vector meson nonet.

For the coupling constants of f and A_2 mesons, detailed informations have not obtained yet. If we take $10\sim20$[24] from NN data as a possible value of g^2_{NNf}, together with $g^2_{fKK}\simeq3.5$ from observed partial width, then we have $g_{NNf}g_{fKK}\simeq-5.9\sim-8.4$. The sign of it is determined from the requirement that the contributions from ω and f

*) An analysis of the isoscalar form factors shows a bump-dip structure in Im F_{1s}. An acceptable fit is afforded by the value of $g^2_{NN\omega}$.[22]

should be destructive each other. All the $\alpha_{l\pm}^{(I=1,0)}(\omega)$ are negative under the restrictions (3.1) and (3.3). While, when $g_{NNf}g_{fKK}<0$, all the $\alpha_{l\pm}^{(I=1,0)}(f)$ are positive.

Restricting the coupling constants of ρ and ω by Eqs. (3.1)$\sim$(3.3) and taking those of f and A_2 mesons as free parameters, we make the fit to the experimental data by minimizing the L^2 defined as

$$L^2=\sum[\alpha_{l\pm}^{(I)}(P_{LAB})-\tan\delta_{l\pm}^{(I)}(P_{LAB})]^2. \tag{3.5}$$

The obtained results (with $L^2=2.4$) are shown in Figs. 1 and 2. The values of coupling constants corresponding to the results are as follows:

$$g_{NN\rho}g_{\rho KK}=3.30,\quad f_{NN\rho}g_{\rho KK}=3.70\times 3.30,\quad g_{NN\omega}g_{\omega KK}=3.14,$$
$$(f_{NN\omega}g_{\omega KK}=0\ \text{fixed}),\quad g_{NNf}g_{fKK}=-6.66,\quad g_{NNA_2}g_{A_2KK}=-1.21. \tag{3.6}$$

3.2 *The baryon-exchange model*

The coupling constants for the resonances $\Lambda(1520)$ and $\Sigma(1670)$ above the $\bar{K}-N$ threshold are restricted by their decay widths:

$$G^2_{\Lambda(1520)NK}=26\sim 46,\quad G^2_{\Sigma(1670)NK}=2\sim 10. \tag{3.7}$$

For the $\Sigma(1385)$ we restrict its coupling constant by the unitary symmetry. The $SU(3)$ invariance gives $G^2_{\Sigma(1385)NK}=G^2_{\Delta(1232)N\pi}/6\simeq 2.8$ with the observed width of $\Delta(1232)$. Alternatively, the observed width of $\Sigma(1385)\to\Lambda\pi$ gives $G^2_{\Sigma(1385)NK}=2G^2_{\Sigma(1385)\Lambda\pi}/3\simeq$ 3.8. We assume, therefore,

$$G^2_{\Sigma(1385)NK}\simeq 2.8\sim 3.8. \tag{3.8}$$

The coupling constants for $\Lambda(1116)$ and $\Sigma(1193)$ are taken as free parameters. After the fitting to data their values will be compared with the unitary symmetry predictions.

We make an L^2-minimum search in the same way as for the meson-exchange model. The obtained theoretical amplitudes are also shown in Figs. 1 and 2. The determined values of coupling constants are

$$G^2_{\Lambda(1116)NK}=17.1,\quad G^2_{\Sigma(1193)NK}=5.88,\quad G^2_{\Sigma(1385)NK}=3.67,$$
$$G^2_{\Lambda(1520)NK}=26.0,\quad G^2_{\Sigma(1670)NK}=2.00. \tag{3.9}$$

If the contact terms for $\Lambda(1116)$ and $\Sigma(1193)$ in Eq. (2.7) are excluded, then we have, from an L^2-minimum search, $G^2_{\Lambda(1116)NK}=4.62$, $G^2_{\Sigma(1193)NK}=1.48$, $G^2_{\Sigma(1385)NK}$ $=3.41$, $G^2_{\Lambda(1520)NK}=26.0$ and $G^2_{\Sigma(1670)NK}=2.00$. It is clear that the smallness of values of $G^2_{\Lambda(1116)NK}$ and $G^2_{\Sigma(1193)NK}$, compared with (3.9), is owing to lower partial waves (the $S_{1/2}$ and $P_{1/2}$ waves) with which the contact terms are concerned. The L^2 value in the case without the contact terms ($L^2=1.1$) is comparable to that in the case with the contact terms ($L^2=1.4$). However, the calculated amplitude for the

$I=1$ $P_{3/2}$ state in the case without the contact terms has a tendency different from experiments, as seen in Fig. 1(c). So, the small values of $G^2_{\Lambda(1116)NK}$ and $G^2_{\Sigma(1193)NK}$ are not plausible.

The values of $G^2_{\Lambda(1116)NK}$ and $G^2_{\Sigma(1193)NK}$ in (3.9) are not incompatible with the predictions from $SU(3)$ and the known value of $\bar{N}N\pi$ coupling ($G^2_{NN\pi}=12.2\sim15.6$[21]), if the symmetry breaking makes $\alpha=D/(D+F)$ slightly larger than its $SU(6)$ prediction 0.6.

The value ~17 for $G^2_{\Lambda(1116)NK}$ is compatible also with the generalized Goldberger-Treiman relation.

From the comparisons of the meson- or baryon-exchange model with experiments seen in Figs. 1 and 2, we find the following:

(a) An acceptable fit is given by each of the two models, with coupling constants consistent with other experiments respectively. Large discrepancies are only in lower partial-wave states (the $S_{1/2}$ and $P_{1/2}$ states) and at comparatively higher momenta.*) Therefore, some kind of the pole-pole duality seems to be present.

(b) If one takes the (meson plus baryon)-exchange model and retains coupling constants consistent with other experiments, one must clearly have theoretical amplitudes much larger than experiments (in the absolute values) for almost all of the partial-wave states. The (meson plus baryon)-exchange model is unlikely.

In Figs. 3(a) and 3(b), we show the theoretical phase shifts for F-wave states given by the coupling constants (3.6) or (3.9). Experimental phases[17,18] obtained at momenta higher than 0.81 GeV/c are also shown.

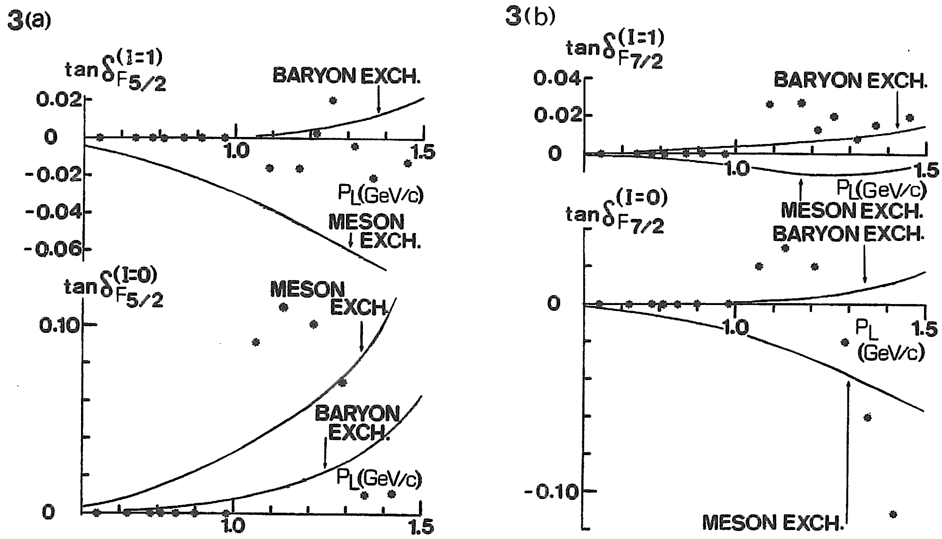


Fig. 3. Theoretical phase shifts in the F-wave states. Pases from the phenomenological phase-shift analysis are also shown.

*) For this judgement an estimate of experimental errors[25,26] has been also taken into account.

(c) The phases predicted by the meson-exchange model are consistent with experiments at higher momenta, as seen in Figs. 3(a) and 3(b). This makes us believe the validity of the meson-exchange model for $K-N$ scattering more firmly. Moreover, it is found that the $\rho+\omega+f+A_2$ exchange, that is, the exchange of the lowest-lying mesons is dominant in the $K-N$ scattering at low energies (see Figs. 1, 2 and 3).
(d) While, the F-wave phases at higher momenta given by the exchange of low-lying baryons in (2.2) are in general smaller than experiments (in the absolute values).*) From the present analysis, it is suggested that the series of baryon exchanges converges slower than that of meson exchanges.

§4. Summary and discussion of results

(1) We have studied the particle-exchange structure of the elastic $K-N$ scattering at low energies by a phenomenological model. We have found that the pole-pole duality between non-exotic particles seems to be present in this process.

The (meson plus baryon)-exchange model is not plausible.
(2) We have assumed the PCAC for kaons in the present analysis. And the contact terms suggested by the PCAC have been added to low-lying-baryon-exchange amplitudes. As the value ~ 17 for $G^2_{\Lambda(1116)NK}$ obtained in this analysis is compatible with the generalized Goldberger-Treiman relation, the PCAC for kaons and the results in this analysis are supposed to have a validity.
(3) The $K-N$ scattering at low energies is dominated by the $\rho+\omega+f+A_2$ exchange.

Acknowledgements

The author wishes to express his sincere thanks to Professor M. Yonezawa for many useful suggestions and continual discussions.

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*) We note that to the F-wave and much higher partial-wave states neither the contact terms added to $J=1/2$ poles nor those added to $J=3/2$ poles gives contributions.

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