# Role of $t$-channel meson exchanges in $S$-wave πN and KN scatterings*

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**Abstract** The low-energy $S$-wave πN and KN scatterings are studied by using the $K$-matrix approach within the meson exchange framework. The $t$-channel meson exchanges, especially ρ and σ exchanges, are found to play a very important role in these two processes. The $t$-channel ρ exchange determines the isospin structure of the scattering amplitudes, it gives attractive force in the low isospin state but repulsive force in the high isospin state. The $t$-channel σ exchange gives a very large contribution in these two processes, while it is negligible in meson-meson $S$-wave scatterings.

**Key words** meson exchange, $K$-matrix, πK, KN

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## 1 Introduction

The πN and KN scatterings are the crucial sources of information about strong interaction. The wealth of accurate data and the richness of structures shown by them provide an excellent but also challenging testing ground for many models.

The πN interaction is one of the most fascinating hadron-hadron interactions for several reasons. Firstly, it is one of the main sources of information about the baryon spectrum. We know that most of the experimental information about the mass, width, and decay of baryon resonances is extracted from the partial wave analysis of πN scattering data. Secondly, the πN scattering has accumulated a large amount of rich and accurate data. It provides a unique place for testing various theoretical approaches, such as meson-exchange model and chiral perturbation theory. Finally, the πN interaction is an important ingredient in many other hadronic reactions, such as meson production in nucleon-nucleon collision.

For the KN scattering, it is worthy to mention that kaons have two properties which make them unique projectiles for investigating nuclear structure. Firstly, they can transfer a new degree of freedom to nucleus, and secondly, in contrast to pions they come in two forms, kaons (K) and antikaons ($\bar{\mathrm{K}}$) which differ substantially in their interaction with nucleus. Because of the strangeness quantum number conserved in strong interactions, the interaction between K and nuclei is rather weak. Consequently, the K meson is a suitable probe for investigating the interior region of nuclei.

Over the past ten years, in a series of papers, the Jülich group has investigated the πN[1, 2] and KN[3] scatterings in the meson exchange framework using the time-ordered perturbation theory. At the same time, much other efforts have also been devoted to the study of the πN[4] and KN[5] scatterings.

As is well known, the conventional $t$-channel meson exchange final state interaction mechanism[6, 7] can give consistent explanation for the broad σ near the ππ threshold, the broad $\kappa$ near the Kπ threshold, the narrow $f_0(980)$ peak near the $\bar{\mathrm{K}}$K threshold, the narrow structure near the $\bar{\mathrm{p}}$p threshold[8], and

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"b1 puzzle" in the $J/\psi \to \omega\pi\pi$ decay[9]. Since the $t$-channel meson exchange plays such an important role in low-energy hadron physics, it is necessary to study the role of $t$-channel meson-exchange contribution in the $S$-wave πN and KN interaction.

The purpose of the present paper is to reveal the $t$-channel meson contribution in $S$-wave πN and KN scatterings, consequently, to give a consistent qualitative explanation for some familiar $S$-wave low-energy meson-meson and meson-baryon scatterings in the meson exchange framework. The role of $t$-channel ρ in $S$-wave meson-meson scattering, such as ππ and πK scatterings, has been studied in Ref. [10]. The $S$-wave phase shift analysis shows that the $t$-channel ρ gives attractive force in isospin $I=0$ channel for ππ scattering (or in $I=\frac{1}{2}$ channel for πK scattering), but repulsive forces in isospin $I=2$ channel for ππ scattering (or in $I=\frac{3}{2}$ channel for πK scattering). The $t$-channel σ exchange gives a very small contribution in ππ and πK $S$-wave scatterings, and can be neglected in these processes. In this paper, we will continue to discuss the role of $t$-channel meson, such as ρ, σ and ω exchanges, in the πN and KN scattering.

The paper is organized as follows. In the next section, we present the method and formulation for calculation. The numerical results and discussions are given in Section 3.

## 2 Method and formulation

The Feynman diagrams for relevant processes are depicted in Fig. 1. As the first step the processes arising from the $s$-channel resonances ($N^*$, $\Delta^*$), $u$-channel baryon ($N, N^*, \Delta, \Lambda, \Sigma$) exchanges, and higher-order diagrams are not considered. The main purpose of this work is to examine the $t$-channel exchange contributions.

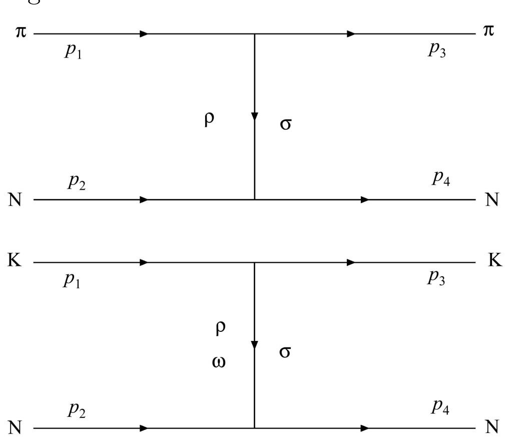


Fig. 1. Tree diagrams for πN and KN scattering with single meson exchange.

We start with the baryon-baryon-meson couplings. The interaction lagrangians are listed as follows:

$$\mathcal{L}_{NN\rho} = -g_{NN\rho}\bar{\Psi}\left[\gamma^\mu - \frac{\kappa_\rho}{2m_N}\sigma^{\mu\nu}\partial_\nu\right]\boldsymbol{\tau}\boldsymbol{\rho}_\mu\Psi, \quad (1)$$

$$\mathcal{L}_{NN\omega} = -g_{NN\omega}\bar{\Psi}\gamma^\mu\omega_\mu\Psi, \quad (2)$$

$$\mathcal{L}_{NN\sigma} = -g_{NN\sigma}\bar{\Psi}\Psi\sigma, \quad (3)$$

For the pseudoscalar-pseudoscalar-vector coupling, we use the $SU(3)$-symmetric Lagrangian[10, 11].

$$\mathcal{L}_{PPV} = -\frac{1}{2}\mathrm{i}G_V\mathrm{Tr}([P,\partial_\mu P]V^\mu), \quad (4)$$

where $G_V$ is the coupling constant, $P$ is the $3\times3$ matrix representation of the pseudoscalar meson octet, $P=\lambda^a P^a$, $a=1,\cdots,8$ and $\lambda^a$ are the $3\times3$ generators of $SU(3)$,

$$P=\sqrt{2}\begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}. \quad (5)$$

A similar definition of $V_{\mathrm{octet}}$ is used for the vector meson octet. In the large $N_c$ limit, the octet and singlet vector mesons can be combined into a single "nonet" matrix $V$[12],

$$V = V_{\mathrm{octet}}+\sqrt{\frac{2}{3}}\omega_0 = \sqrt{2}\begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0+\frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0+\frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}, \quad (6)$$

where the standard $\omega$-$\phi$ mixing is assumed.

In the Gell-Mann representation, the Lagrangian can be expressed as

$$\mathcal{L}_{PPV} = 2G_V f_{abc}P^a\partial_\mu P^b V^{c\mu}, \quad (7)$$

where $f_{abc}$ are the antisymmetric structure constants of $SU(3)$. For example,

$$\mathcal{L}_{\rho\pi\pi} = 2G_V\left[(p^\mu_{\pi^+}-p^\mu_{\pi^-})\rho^0_\mu+(p^\mu_{\pi^-}-p^\mu_{\pi^0})\rho^+_\mu+(p^\mu_{\pi^0}-p^\mu_{\pi^+})\rho^-_\mu\right], \quad (8)$$

$$\mathcal{L}_{\rho K\bar{K}} = G_V\left[(p^\mu_{K^+}-p^\mu_{K^-})\rho^0_\mu+(p^\mu_{\bar{K}^0}-p^\mu_{K^0})\rho^0_\mu\right]+\sqrt{2}G_V(p^\mu_{K^0}-p^\mu_{K^-})\rho^+_\mu+\sqrt{2}G_V(p^\mu_{K^+}-p^\mu_{\bar{K}^0})\rho^-_\mu, \quad (9)$$

$$\mathcal{L}_{\omega K\bar{K}} = G_V\left[(p^\mu_{K^+}-p^\mu_{K^-})\omega_\mu+(p^\mu_{K^0}-p^\mu_{\bar{K}^0})\omega_\mu\right]. \quad (10)$$

The employed pseudoscalar-pseudoscalar-scalar couplings are

$$\mathcal{L}_{\pi\pi\sigma} = \frac{g_{\pi\pi\sigma}}{2m_\pi}\partial_\mu \boldsymbol{\pi}\partial^\mu \boldsymbol{\pi}\sigma, \quad (11)$$

$$\mathcal{L}_{\mathrm{KK}\sigma} = \frac{g_{\mathrm{KK}\sigma}}{2m_\pi}\partial_\mu \bar{\mathrm{K}}\partial^\mu \mathrm{K}\sigma, \quad (12)$$

where $\mathrm{K} \equiv \begin{pmatrix}\mathrm{K}^+\\ \mathrm{K}^0\end{pmatrix}$, and $\bar{\mathrm{K}} \equiv \begin{pmatrix}\mathrm{K}^- & \bar{\mathrm{K}}^0\end{pmatrix}$, and $g_{\pi\pi\sigma} = g_{\mathrm{KK}\sigma}$ due to flavor the $SU(3)$ symmetry.

Using these Lagrangians, we are able to construct the following amplitudes corresponding to the diagrams in Fig. 1, respectively:

$$T^{\rho}_{\pi\mathrm{N}} = -\frac{G_{\mathrm{V}}g_{\mathrm{NN}\rho}}{8\pi}\frac{\mathrm{IF}}{(p_1-p_3)^2-m_\rho^2}\bar{\mathrm{u}}(p_4)\times \left[(\not{p}_1+\not{p}_3)-\frac{\kappa_\rho}{2m_{\mathrm{N}}}(-\not{p}_1\not{p}_3+\not{p}_3\not{p}_1)\right]\mathrm{u}(p_2), \quad (13)$$

$$T^{\sigma}_{\pi\mathrm{N}} = -\frac{g_{\mathrm{NN}\sigma}g_{\pi\pi\sigma}}{16\pi m_\pi}\frac{\mathrm{IF}}{(p_1-p_3)^2-m_\sigma^2}\bar{\mathrm{u}}(p_4)\mathrm{u}(p_2)p_1\cdot p_3, \quad (14)$$

$$T^{\rho}_{\mathrm{KN}} = -\frac{G_{\mathrm{V}}g_{\mathrm{NN}\rho}}{16\pi}\frac{\mathrm{IF}}{(p_1-p_3)^2-m_\rho^2}\bar{\mathrm{u}}(p_4)\times \left[(\not{p}_1+\not{p}_3)-\frac{\kappa_\rho}{2m_{\mathrm{N}}}(-\not{p}_1\not{p}_3+\not{p}_3\not{p}_1)\right]\mathrm{u}(p_2), \quad (15)$$

$$T^{\omega}_{\mathrm{KN}} = -\frac{G_{\mathrm{V}}g_{\mathrm{NN}\omega}}{16\pi}\frac{\mathrm{IF}}{(p_1-p_3)^2-m_\omega^2}\bar{\mathrm{u}}(p_4)(\not{p}_1+\not{p}_3)\mathrm{u}(p_2), \quad (16)$$

$$T^{\sigma}_{\mathrm{KN}} = -\frac{g_{\mathrm{NN}\sigma}g_{\mathrm{KK}\sigma}}{16\pi m_\pi}\frac{\mathrm{IF}}{(p_1-p_3)^2-m_\sigma^2}\bar{\mathrm{u}}(p_4)\mathrm{u}(p_2)p_1\cdot p_3, \quad (17)$$

where $T^{\rho}_{\pi\mathrm{N}}$ denotes the $t$-channel ρ meson exchange amplitude for πN scattering, and IF is the isospin factor listed in Table 1 for various processes.

Table 1. Isospin factors for the two processes.

| process | Exch. Part. | $I$ | IF |
|---|---|---|---|
| $\pi\mathrm{N}\to\pi\mathrm{N}$ | ρ | $\frac{1}{2}$ | −2 |
| | | $\frac{3}{2}$ | 1 |
| | σ | $\frac{1}{2}$ | 1 |
| | | $\frac{3}{2}$ | 1 |
| $\mathrm{KN}\to\mathrm{KN}$ | ρ | 0 | −3 |
| | | 1 | 1 |
| | ω, σ | 0 | 1 |
| | | 1 | 1 |

Usually, hadronic form factors should be applied to the baryon-baryon-meson vertices because of the inner quark-gluon structure of hadrons. Due to the difficulties in dealing with nonperturbative QCD hadron structure, the form factors are commonly adopted phenomenologically. The most commonly used form factor for baryon-baryon-meson vertices in $t$-channel is

$$F(\Lambda,\mathrm{q}) = \frac{\Lambda^2-m^2}{\Lambda^2-q^2}\ , \quad (18)$$

where $m$ and $q$ are the mass and four-momentum of intermediate particle, respectively, and $\Lambda$ is the so-called cut-off momentum that can be determined by fitting the experimental data. The parameters of model are listed in Table 2.

Table 2. Parameters of the model. Free parameters are given in boldface.

| vertex | exchange particle | coupling constant | Ref. | cutoff $\Lambda$ /MeV |
|---|---|---|---|---|
| NNρ | ρ | $\frac{g^2_{\mathrm{NN}\rho}}{4\pi}=0.84$ | [13] | 1500 |
| | | $\kappa=6.1$ | [13] | |
| NNω | ω | $\frac{g^2_{\mathrm{NN}\omega}}{4\pi}=7.563$ | [3] | 1500 |
| NNσ | σ | $\frac{g^2_{\mathrm{NN}\sigma}}{4\pi}=13$ ($m_\sigma$=0.65 GeV) | [14] | 2000 |
| ππσ | σ | $\frac{g^2_{\pi\pi\sigma}}{4\pi}=0.25$ | [2] | 2000 |
| ππρ | ρ | $\frac{G^2_{\mathrm{V}}}{8\pi}=0.364$ | [7] | 1500 |
| K$\bar{\mathrm{K}}$ρ | ρ | $\frac{G^2_{\mathrm{V}}}{8\pi}=0.364$ | [7] | 2000 |
| K$\bar{\mathrm{K}}$ω | ω | $\frac{G^2_{\mathrm{V}}}{8\pi}=0.364$ | [7] | 1500 |
| K$\bar{\mathrm{K}}$σ | σ | $\frac{g^2_{\mathrm{KK}\sigma}}{4\pi}=0.25$ | [2] | 2000 |

In order to isolate the $S$-wave contribution, we have to perform a partial wave decomposition of the amplitudes. Our normalization is described as follows: The differential cross-section in the centre-of-mass system is given by the Lorentz-invariant matrix element $\mathcal{M}$ as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2 s}|\mathcal{M}|^2, \quad (19)$$

where $s$ is the invariant mass squared. The relation between the $T$ matrix and the $\mathcal{M}$ matrix is

$$T = \frac{1}{16\pi}\mathcal{M} = g(s,\theta)+\mathrm{i}h(s,\theta)\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}, \quad (20)$$

here $\hat{\boldsymbol{n}}$ is the unit vector normal to the scattering plane. The amplitude $T$ can be expanded in orbital angular momentum $l$ and total angular momentum $J$,

$$T = \sum_l (2l+1)[f_{l+}\hat{Q}_{l+}+f_{l-}\hat{Q}_{l-}]P_l(\cos\theta), \quad (21)$$

where $P_l(x)$ are the Legendre polynomials and $\hat{Q}_{l\pm}$ are the corresponding projection operators for $J = l\pm\frac{1}{2}$,

$$\hat{Q}_{l+} = \frac{l+1+\boldsymbol{l}\cdot\boldsymbol{\sigma}}{2l+1}, \qquad \hat{Q}_{l-} = \frac{l-\boldsymbol{l}\cdot\boldsymbol{\sigma}}{2l+1}. \quad (22)$$

Then one obtains

$$g(s,\theta) = \sum_l [(l+1)f_{l+}+lf_{l-}]P_l(\cos\theta), \quad (23)$$

$$h(s,\theta) = \sin\theta \sum_l [f_{l+} - f_{l-}] P_l'(\cos\theta), \qquad (24)$$

where $P_l'(x) = (\mathrm{d}/\mathrm{d}x)P_l(x)$. For each partial wave $a = l\pm$, the phase shift is related to $f_a$ by

$$f_a = \frac{\eta_a \mathrm{e}^{2\mathrm{i}\delta_a} - 1}{2\mathrm{i}\rho}. \qquad (25)$$

## 3 Numerical results and discussions

Having described our model, we turn now to compare its results with the experimental data. First of all, we discuss the parameters that enter into our model calculation. All of the coupling constants have been taken from other sources as listed in Table 2. We have varied only the boldface printed values in Table 2. It is worthy to mention that we take the coupling constant of vertex NNω, $g_{\mathrm{NN}\omega}$, as its normal value obtained by the assumption of $SU(3)$ symmetry related to the empirical NNπ coupling. We have not increased $g_{\mathrm{NN}\omega}$ and $g_{\mathrm{KK}\omega}$ as done in Ref. [3]. As discussed in Ref. [3], this increased ω-exchange leads to additional repulsion in $P$- and higher waves too, which, as a whole, seems not to be favoured by the empirical data, especially in the $P_{03}$ and $P_{11}$ channels.

From the formalism given above and using the parameters listed in Table 2, we obtain the $S$-wave πN phase shifts as shown in Fig. 2. The phase shifts given by the $t$-channel ρ exchange (dashed curves) agree with the trend of $I = 1/2$ and $I = 3/2$ experimental data. It is quite clear that the $t$-channel ρ gives attractive force in $I = 1/2$ channel, but repulsive force in $I = 3/2$ channel, which is consistent with the result we obtain in ππ and πK scattering as mentioned above, namely it gives attractive force in the low isospin state but repulsive force in the high isospin state. The $t$-channel σ exchange provides a very large contribution in contrast to its negligible effect in meson-meson scatterings, it gives repulsive force both in $I = 1/2$ and $I = 3/2$ channel. Using the Dalitz-Tuan method[7, 10], we combine the contribution of ρ and σ exchanges. The results are shown in solid curves. It is found that the πN scattering phase shifts are only in qualitative agreement with the experimental data. Evidently, the discrepancies are primarily due to the presence of resonances in these partial waves, which are not yet included in our calculation. As discussed in Ref. [1], the low energy $S_{11}$ phase shift they obtain in their model even changes its sign when all couplings to the N*(1650) resonance are switched off. Therefore, including the resonances in the calculation seems to be very important to obtain quantitative agreement with the $S$-wave πN scattering experimental data.

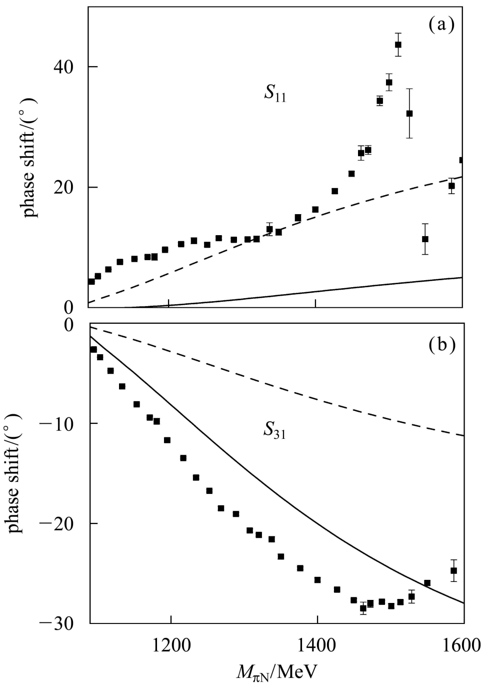


Fig. 2. The $S$-wave πN phase shifts. The dashed curves show the results from only the ρ exchange. The solid curves represent the contribution of $t$-channel ρ and σ exchanges together. The data are from the phase-shift analysis SM95[15].

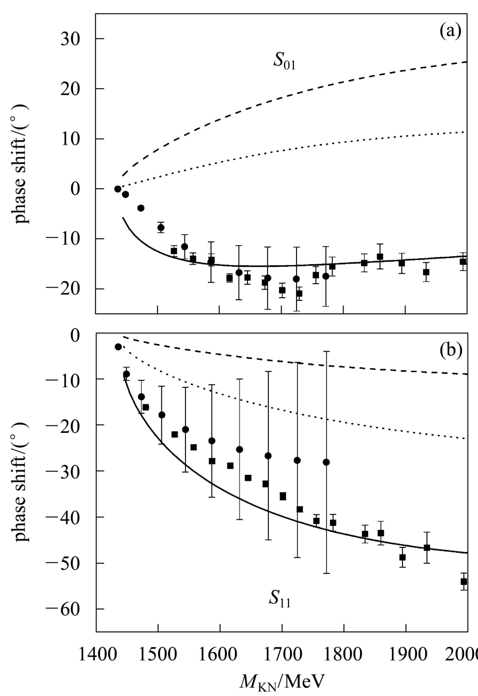


Fig. 3. The $S$-wave KN phase shifts. The dashed curves show the results from only the ρ exchange. The dotted curves represent the contribution of $t$-channel ρ and ω exchanges together. The solid curves involve the $t$-channel ρ, ω and σ exchanges totally. Experimental phase shifts are taken from Refs. [16] (circles) and [17] (squares).

Now, let us turn our attention to KN scattering phase shifts in Fig. 3. The dashed curves show the results from only the ρ exchange. Similar to ππ, πK and πN scatterings, the $t$-channel ρ gives attractive force in $I=0$ channel, but repulsive force in $I=1$ channel. The $t$-channel ω and σ exchanges give repulsive forces both in $I=0$ and $I=1$ channels. The dotted curves represent the contribution of $t$-channel ρ and ω exchanges together. The solid curves involve the $t$-channel ρ, ω and σ exchanges totally. The result agrees with the experimental data quite well up to 2.0 GeV without need to increase the value of $g_{NN\omega}$ and $g_{KK\omega}$. From Fig. 3, it is obvious that σ gives the largest contribution among these three mesons.

Since the cutoff parameters listed in Table 2 are variable, we should make some discussions on them. Firstly, due to the form of form factor we used (see Eq. (18)), the larger value of $\Lambda$ will lead to less suppression of amplitude. Secondly, we find the final phase shifts are not very sensitive to these cutoff parameters in $S_{31}$ channel of πN scattering and in $S_{11}$ channel of KN scattering. If we enlarge one of the cutoff parameters by 2/3, the final phase shifts only change at most by 12%. In contrast, the low isospin channels of these two processes are more sensitive to the cutoff parameters of NNρ, ππρ and K$\bar{\text{K}}$ρ vertices because the isospin factors are −2 or −3 in the low isospin states (see Table 1). However, the cutoff parameters of NNρ, ππρ and K$\bar{\text{K}}$ρ vertices can be well determined in other channels. And the values of them are taken from well known results, so we need not worry about them.

In summary, we study the low-energy $S$-wave πN and KN scatterings in the meson exchange model framework and using the $K$-matrix approach. In view of the result of this paper, plus our previous papers in ππ and πK scatterings, we draw the conclusion that the $t$-channel ρ exchange determines the isospin structures of low-energy $S$-wave phase shifts of these scatterings because of its absolutely different isospin factors in the different isospin states. The $t$-channel ρ exchange gives attractive force in the low isospin state but repulsive force in the high isospin state. In the ππ and πK scatterings, the contribution of $t$-channel $\sigma$ exchange is very small, and it even can be neglected. But in the πN and KN scatterings, it gives a very large contribution.

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