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# Possible existence of $K^{bar}$-hyperon resonances and the origin of $K^{bar}$-hyperon attractions



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A flavor-$SU(3)$-symmetric one-hadron-exchange potential model which describes consistently baryon-baryon and meson-baryon interactions is proposed. The short-range part of the potential model is assumed to have a common range and the strengths based on lattice QCD calculations. This potential model is extended to meson-baryon potentials in strangeness $S$=-2 and -3 sectors. We find strongly attractive $K^{bar}$-hyperon $S$-wave interactions and possible $S$-wave resonances, corresponding to $\Xi^*(I=1/2, J^\pi=1/2^-)$ and $\Omega^*(I=0, J^\pi=1/2^-)$ at around 1.5GeV and 1.8GeV, respectively.

*XV International Conference on Hadron Spectroscopy-Hadron 2013*
*4-8 November 2013*
*Nara, Japan*

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## 1. Introduction

Theoretical understanding of hadron-hadron($HH$) interactions is a longstanding fundamental problem in particle and nuclear physics, since Yukawa's meson-exchange theory. In recent decades, the $HH$ interactions in the strange sectors($S \neq 0$) have been intensively discussed both theoretically and experimentally.

In theoretical studies of $HH$ interactions at low energies (up to 1GeV), three types of models, that is, hadron-exchange models, quark models, and the chiral perturbation models have been discussed. Recently, the first-principle calculations based on the lattice QCD (LQCD) have been performed and have provided quantitative results for not only the short-range but also the long-range part of $HH$ potentials[1]. But the physical models, which must clarify the effective degrees of freedom in interaction mechanisms, have not been established yet. We need a theoretical model to understand the physical picture of the $HH$ interactions, under the condition that the model is justified by QCD.

In this paper, firstly, we propose a one-hadron-exchange potential ($OHEP$) model which describes consistently baryon-baryon ($NN$, $\Lambda N$, $\Sigma N$ and $\Lambda\Lambda$) interactions and meson-baryon ($\pi N$, $KN$ and $K^{bar}N$) interactions. This model assumes the flavor-$SU(3)$ symmetric coupling constants and physical meson masses in $OHEP$[2, 3]. For the short-range part of potentials, we introduce the $SU(3)$-symmetric Gaussian soft core potentials[3]. Their relative strengths are determined by LQCD calculations[1]. Secondly, we extend our potential model to meson-baryon $S = -2$ and $-3$ sectors ($\pi\Xi - K^{bar}\Lambda - K^{bar}\Sigma$ and $K^{bar}\Xi$) and discuss the properties of their $S$-wave interactions[4]. Finally, we discuss resonance and bound state poles of the $S$-matrix on complex-$E$ plane and predict possible existence of exotic baryon states with $S = -2$ and $-3$[4].

## 2. One-hadron-exchange potential model

Our potential model is constructed based on the flavor-$SU(3)$ symmetry. The breaking of this symmetry comes from only exchanged hadron masses, for which we use physical masses.

Our baryon-baryon($BB$) potentials consist of two parts, that is, the long-range part (one-boson-exchange potential, $OBEP$) and the short-range part with Gaussian form:

$$V_{BB} = V(OBEP)[1-\exp(-(r/r_c)^2)]^4 + V_{short}\exp(-(r/r_Q)^2)$$

$V(OBEP)$ is smoothly cutoff by the cutoff function with a common range, $r_c = 0.4$fm for all $BB$ pairs. As exchanged bosons, we consider scalar-, pseudoscalar- and vector-meson nonets with physical masses. Among the $SU(3)$ coupling parameters, $g_{8ps}$, $\theta_{ps}$, $\alpha_{ps}$, $\alpha_v$ and $\theta_v$ are fixed by established or theoretical values. As the range of the short-range part, $r_Q$, we use a common value 0.475fm for all $BB$ pairs. The strengths $V_{short}$ are determined as follows: In even ($L$ =even) states, relative strengths of $V_{short}$ for six $SU(3)$ representations are determined by $L = 0$ results of the LQCD calculations[1]. The remaining one absolute strength in even states and six strengths in the odd states are treated as free parameters determined by phenomenological fit. Number of parameters in our $BB$ potentials are only 17 (10 $SU(3)$ parameters + 7 $V_{short}$ strengths). They are determined by phenomenological fitting to $NN$ phase shifts, $YN$ cross sections and $\Lambda\Lambda$ data.



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| $\pi N$ | pot I | pot II | exp | $KN$ | pot I | pot II | exp |
|---|---|---|---|---|---|---|---|
| $S_{11}$ | 0.2458 | 0.2482 | 0.2473±0.0043 | $S_{01}$ | −0.008 | −0.013 | 0.00±0.02 |
| $S_{31}$ | −0.1496 | −0.1466 | −0.1444±0.0057 | $S_{11}$ | −0.365 | −0.369 | −0.33±0.02 |
| $P_{11}$ | −0.2359 | −0.2340 | −0.2368±0.0058 | $P_{01}$ | 0.166 | 0.179 | 0.08±0.02 |
| $P_{31}$ | −0.1375 | −0.1290 | −0.1310±0.0058 | $P_{11}$ | −0.106 | −0.103 | −0.16±0.02 |
| $P_{13}$ | −0.0862 | −0.0894 | −0.0877±0.0058 | $P_{03}$ | −0.058 | −0.071 | −0.13±0.02 |
| $P_{33}$ | 0.6238 | 0.6235 | 0.6257±0.0058 | $P_{13}$ | 0.047 | 0.040 | 0.07±0.02 |

**Table 1:** $\pi N$ and $KN$ scattering lengths

| | pot I | pot II | exp |
|---|---|---|---|
| $\gamma$ | 2.35 | 2.36 | 2.36±0.04 |
| $R_c$ | 0.660 | 0.700 | 0.664±0.011 |
| $R_n$ | 0.189 | 0.172 | 0.189±0.015 |
| Re($a_{K^-p}$) | −0.666 | −1.019 | See Fig.1 |
| Im($a_{K^-p}$) | 0.462 | 0.398 | See Fig.1 |

**Table 2:** $K^- p$ threshold quantities and scattering length



Our meson-baryon($MB$) potentials are defined in momentum space and have a form given by

$$V_{MB} = V(OHEP)\exp(-q^2/\Lambda_Q^2) + V_{short}\exp(-q^2/\Lambda_Q^2)$$

For one-hadron-exchange part, $V(OHEP)$, we consider $t$-channel meson-exchange, $u$-channel baryon-exchange and $s$-channel baryon-exchange potentials. As exchanged baryons, we employ octet baryons and decuplet baryons. $S_{11}$ and $N(1440)$ are added to get a better fit to $\pi N$ data. All meson-meson-(octet) baryon coupling constants are predetermined by $BB$ potentials given above. For short-range part, we use a common range $\Lambda_Q = 2/r_G$ for all $MB$ pairs. At present stage, we try two cases, $r_G$ =0.40 (pot I) and 0.45fm (pot II). The strength $V_{short}$ for each $SU(3)$ representation is treated as a free parameter. But, in near future they will be constrained by LQCD results.

The results for $\pi N$ and $KN$ scattering lengths are given in Table 1. We find a very good agreement with experimental data. For $S$- and $P$-wave phase shifts, we obtain again a good fitting below $T_{lab} \sim$ 300MeV. But, above this energy we find some deviations from data in $\pi N$ $P_{11}$-, $P_{13}$-waves and in $KN$ $P_{01}$-, $P_{11}$-waves. For $\pi\Lambda$-$\pi\Sigma$-$K^{bar}N$ coupled-channel potentials, we have only two adjustable parameters, $V_{short}$ in $\{8a\}$ and $\{1\}$ (other parameters are determined by fitting to $\pi N$ and $KN$ data). In Table 2 and Fig. 1, $K^- p$ threshold quantities calculated with our potentials are given in comparison with experimental data. We find both pot I and II give a good result. Quantitatively, pot I makes a better fit to data than pot II. Using our potentials (pot I and II), we obtain $K^- p$ cross sections in a good agreement with experimental one, but both potentials give some over(under)estimations in $K^- p \to K^0 n(\pi^+\Sigma^-)$ cross sections at the high (low) energy region. Pot I and II give a pole at $\sqrt{s} = 1393 - 16i$ and $1406 - 6i$MeV, respectively, which corresponds to $\Lambda(1405)$. Our model supports the single-pole picture by Akaishi et al.[5].

| $K^{bar}B$ | $I$ | $\rho$ | $\omega$ | $\phi$ | $scalar$ | $baryon$ | short | total |
|---|---|---|---|---|---|---|---|---|
| $K^{bar}N$ | 0 | $-42.4$ | $-91.7$ | 20.0 | $-25.0$ | 22.4 | $-44.9$ | $-161.5$ |
| $K^{bar}N$ | 1 | 14.1 | $-91.7$ | 20.0 | $-25.3$ | 156.5 | 11.5 | 85.2 |
| $K^{bar}\Lambda$ | 1/2 | 0 | $-84.7$ | 49.6 | $-28.7$ | 6.5 | $-12.1$ | $-69.4$ |
| $K^{bar}\Sigma$ | 1/2 | $-78.4$ | $-87.5$ | 55.9 | $-27.1$ | 30.7 | 18.5 | $-87.9$ |
| $K^{bar}\Sigma$ | 3/2 | 39.2 | $-87.5$ | 55.9 | $-30.0$ | 0 | $-2.2$ | $-24.6$ |
| $K^{bar}\Xi$ | 0 | $-69.4$ | $-70.3$ | 90.7 | $-28.7$ | 14.2 | 7.1 | $-56.4$ |
| $K^{bar}\Xi$ | 1 | 23.1 | $-70.3$ | 90.7 | $-32.7$ | 5.2 | 14.2 | 30.4 |

**Table 3:** Contributions to $K^{bar}$-baryon $S$-wave potentials ($I$:isospin)

## 3. Meson-baryon potentials and $S$-wave resonances in $S = -2$ and $-3$ sectors

We can extend our potential model (pot I and II) to $S = -2$ and $-3$ sectors without any additional parameter, except baryon-exchange mechanisms with excited baryons, $\Xi^*$ or $\Omega^*$, etc, which will be discussed in near future.

In the $S = -2$ sector, we have two problems, $\pi\Xi + K^{bar}\Lambda + K^{bar}\Sigma + \eta\Xi(I = 1/2)$ and $\pi\Xi + K^{bar}\Sigma(I = 3/2)$. In the present calculations, we ignore the $\eta\Xi$ channel because of its high threshold energy. In $I = 1/2$ $S$-wave phase shifts, we find a broad resonance at around $\sqrt{s}$ =1.50-1.55MeV both with pot I and II. We obtain strongly attractive $S$-wave interaction for all of $\pi\Xi$, $K^{bar}\Lambda$ and $K^{bar}\Sigma$ pairs in $I = 1/2$ state. In $I = 3/2$ state, we find weak (attractive) $K^{bar}\Sigma$ and (repulsive) $\pi\Xi$ interactions, and no resonant behavior in phase shifts.

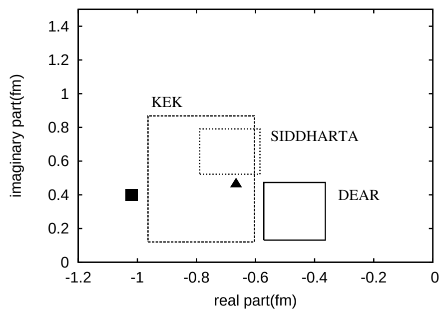


**Figure 1:** $K^-p$ scattering length. Triangle and square are results with pot I and II, respectively. Three rectangular regions denote experimental data.

In the $S = -3$ sector, we have a single channel $K^{bar}\Xi$ problem both in $I = 0$ and $I = 1$. In $I = 0$ state, we find a $S$-wave bound state with pot I. With pot II, we find strongly attractive potential, but its strength is insufficient to make a bound state. In Table 3, the contributions from various exchange mechanisms in $K^{bar}B$ $S$-wave potentials are listed. The values are calculated at $E_{cm} =$ 50MeV above each $K^{bar}B$ threshold. We find that the strong attractions in $K^{bar}N(I = 0)$, $K^{bar}\Lambda$, $K^{bar}\Sigma(I = 1/2)$ and $K^{bar}\Xi(I = 0)$ come commonly from the isospin-dependent $\rho$-exchange and isospin-independent $\omega$-exchange. In $K^{bar}N$ case, $V_{short}$ provides an additional attraction, which is important to make the $\Lambda(1405)$ pole. But, our model cannot say anything about origins of attractive $V_{short}$.

To determine the pole positions for the resonant behavior and a bound state mentioned above, we calculate the $S$-matrix on the complex $E$-plane by extending our potentials to the complex $p$-plane. As a result, we obtain the $S$-matrix poles shown in Fig. 2, where $|S|$ are displayed as functions of the complex $E$. The pole positions are

$$\sqrt{s} = 1510 - 73i(1495 - 84i)\text{MeV with pot I (potII)}$$

for $S = -2, I = 1/2$ and

$$\sqrt{s} = 1796(1802)\text{MeV with pot I (pot II)}$$

for $S = -3, I = 0$. The pole at 1796MeV with pot I is located on the physical plane, but the pole at 1802MeV with pot II is on the unphysical plane, so the former (latter) is a bound (virtual) state.

## 4. Summary

We proposed a potential model describing consistently baryon-baryon and meson-baryon interactions at low energies. Our model consists of two parts, that is, the long-range part given by one-hadron-exchange mechanisms and the short-range part constrained by lattice QCD (if available). Our model satisfies the flavor-$SU(3)$ symmetry, except exchanged hadron masses. Using our potentials, pot I and II, we discussed the properties of meson-baryon $S$-wave interactions in $S = -2$ and $-3$ sectors. We find attractive interactions in $K^{bar}$-hyperon pairs with $I = I_{-}$(the smaller case). The origin of this attraction is common to $K^{bar}N(I = 0)$ case, that is, $\rho$- and $\omega$-exchange. As a result, we predicted two resonance (bound) states: $\Xi^*(J^\pi = 1/2^-)$ with $M \sim 1500$MeV, $\Gamma \sim 160$MeV and $\Omega^*(J^\pi = 1/2^-)$ with $M \sim 1800$MeV. Our model should be refined by several points. (1) The decuplet baryons should be fully considered. (2) Improvement of fitting to experimental data (phase shifts above $T_{lab}$ =300MeV, $K^- p$ cross sections) is needed.

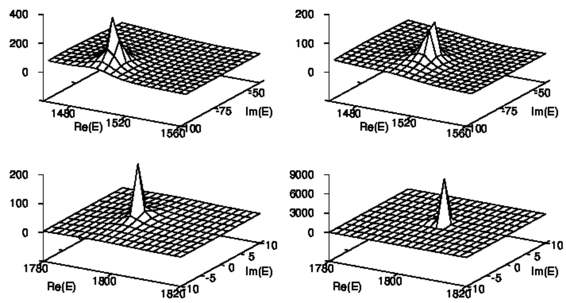


**Figure 2:** $\Xi^*(J^\pi = 1/2^-)$(upper) and $\Omega^*(J^\pi = 1/2^-)$(lower) resonances with pot I (left) and II (right), respectively

## References

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