Studying meson baryon systems with strangeness +1

K P Khemchandani, 1A Martínez Torres, 1F S Navarra, 1M Nielsen and 3, 4L Tolos

1Instituto de Física, Universidade de São Paulo, C.P 66318, 05314-970 São Paulo, SP, Brazil.
2Faculdade de Tecnologia, Universidade do Estado do Rio de Janeiro, Rod. Presidente Dutra Km 298, Polo Industrial, 27537-000, Resende, RJ, Brazil.
3Instituto de Ciencias del Espacio (IEEC/CSIC), Campus Universitat Autónoma de Barcelona, Carrer de Can Magrans, s/n 08193 Cerdanyola del Vallès, Spain.
4Frankfurt Institute for Advanced Studies (FIAS), 60438 Frankfurt am Main, Germany.

E-mail: 1kanchan@if.usp.br

Abstract. We discuss the results of our recent study of the s-wave $KN-K^*N$ coupled interaction. The $K^*N$ amplitude is obtained by calculating t- and u-channel diagrams and a contact interaction. For the $KN$ amplitude we calculate the Weinberg-Tomozawa term obtained from the lowest order chiral Lagrangian. The $KN \leftrightarrow K^*N$ amplitudes are calculated by replacing the photon by a vector meson in the standard Kroll-Ruderman term. The subtraction constants required to calculate the loops are fixed by demanding the $KN$ amplitudes to fit the data available on the isospin 0 and 1 s-wave phase shifts. We find that the coupling between the two channels plays an important role in the isospin 0 configuration. We obtain updated amplitudes and cross sections for the $KN$ and $K^*N$ systems, which can be used to understand some recent findings of $K$, $K^*$ production in $p-p$ and $p-A$ collisions studied by the Hades collaboration. We also look for resonances in these systems but find none.

1. Introduction

We study the s-wave interaction of $K$ and $K^*$ with nucleons with a twofold motivation: one is to obtain reliable amplitudes and cross sections for $KN$, $K^*N$ systems, which can be useful for studies related to strange mesons in nuclear medium, and another is to look for possible resonance formation in these systems. Interaction of strangeness +1 mesons with nucleons is known to be relatively weak since the absence of a light ($u$, $d$) antiquark in the system does not allow formation of a three quark intermediate state, unlike systems like $\pi N$, $\bar{K}N$, $\bar{K}^*N$, etc. Still, the $KN$ amplitudes and phase shifts show some structure in some energy range giving rise to discussions on the possibility of the existence of resonances with positive strangeness since more than four decades (see Refs. [1] for some of the oldest articles on this subject). More recently, an exploration of a narrow pentaquark baryon, $\Theta^+(1540)$, at several experimental facilities was triggered by a signal reported in Ref. [2] but the results seem to be negative (for a review on this, see Ref. [3]). Moreover, an alternative explanation has been brought forward in Refs. [4, 5] for the enhancement of the cross section seen in Ref. [2]. These findings, however, do not imply that no pentaquarks exist. It might be that one has to look for a different mass/width and/or quantum numbers. In fact, evidences for existence of other kind of exotic hadrons are being reported recently, like baryons with an anticharm quark [6, 7, 8, 9, 10], mesons with a tetra quark nature [11, 12, 13, 14], etc. It is, then, also reasonable to contemplate the existence of other exotic states.
of baryons with strangeness +1.

Besides, although finding a baryon with an antistrange (or anticharm) quark would unquestionably confirm existence of a pentaquark structure, it is important to note that some known nonexotic baryons can be essentially understood as pentaquarks. For example, we need a pentaquark structure to understand why the lowest mass nucleon resonance with spin-parity $1/2^-$, $N^*(1535)$, is lighter than the corresponding hyperon, $\Lambda(1405)$. An extra $ss$ component in the wave function of $N^*(1535)$ and $qq$ for $\Lambda(1405)$ plays a crucial role in explaining the properties of these states [15, 16, 17, 18, 19]. Analogously, it is possible that a state with strangeness +1 may also exist.

Another motivation for our present study is to obtain reliable amplitudes and cross sections for the $KN$ and $K^*N$ systems. The need for such an information arises since some recent findings of experimental investigations of $K$, $K^*$ in nuclear medium do not seem to be explained within transport approach or statistical models. For example, a deep sub-threshold $K^{*0}$ production has been reported in Ar+KCl collisions by HADES, with the experimental $K^{*0}$ yield and $K^{*0}/K^0$ larger by about a factor five and two, respectively, as compared to the one obtained from the UrQMD transport approach [20]. The need for reliable information on the in-medium kaon potential has also been discussed in Ref. [21] where the $K^0$ production in $p+\text{Nb}$ reactions at a beam kinetic energy of 3.5 GeV is analyzed by HADES. Also, the attenuation of the $K^*$ and $\bar{K}^*$ states in the hadronic phase of the expanding fireball, as determined by the observation of a strong suppression of the total yield ratios $<K^*>/ <K^+>$ and $<\bar{K}^*>/ <K^->$ in central Pb+Pb collisions compared to p+p, C+C and Si+Si by the NA49 Collaboration [22], was not reproduced using UrQMD [23, 24] or statistical HQG M [25] models. Such findings thus indicate that it is important to look into $KN$ and $K^*N$ interactions in vacuum and in matter.

In the present work, we focus on the $s$-wave interaction of $K$ and $K^*$ with nucleons. We study the $KN$ and $K^*N$ systems by using a formalism based on the chiral Lagrangian and the theory of hidden local symmetry (HLS) of Ref. [26], which treats vector mesons as the gauge bosons. As discussed in the study of vector meson-baryon (VB) systems of Ref. [27], the gauge invariance of the HLS Lagrangian requires the consideration of a contact term together with $s$-, $t$- and $u$-channel interactions, which all turn out to give important contributions. We, thus, solve the Bethe-Salpeter equation using the sum of all these interactions as the VB kernel. We obtain $KN$ interaction from the lowest order chiral Lagrangian. We couple $KN$ and $K^*N$ systems by extending the Kroll-Ruderman theorem for the pion photoproduction by replacing the photon by a vector meson, consistently with the phenomena of the vector meson dominance. This formalism has been earlier applied to strange and nonstrange meson-baryon systems [28, 29] to study dynamical generation of resonances.

In the present work we extend the model of Refs. [27, 28, 29, 30], where exchange of octet baryons was considered in the $s$- and $u$-channel, by including the exchange of hyperon resonances in the $u$-channel too. The couplings of the resonances to meson and octet-baryon channels required in such calculations are taken from Ref. [28].

In the following sections we first present the formalism briefly and then discuss the results obtained in the present work.

2. Formalism

Let us start the discussion by looking at the amplitude for $KN$, which can be obtained from the standard chiral Lagrangian [17]

$$V_{KN}^I = -\frac{C_{KN}^I}{4\gamma_K^2}(\omega + \omega'),$$

where the superscript label $I$ indicates the isospin of the meson-baryon system. A system of a kaon and a nucleon can have total isospin $I = 0$ or 1. The term $C_{KN}^I$, in the equation above,
denotes an isospin coefficient whose value is 0 (−2) for isospin 0 (1), when using average masses for the kaons (K^0, K^+) and the nucleons (n, p). Further, f_K = 113.46 MeV is the kaon decay constant, and ω (ω') corresponds to the energy of the kaon in the initial (final) state. Thus, the KN amplitude is repulsive in the isospin 1 configuration and null in isospin 0. It is clear that these amplitudes cannot result in formation of a resonance. On the other hand, however, these amplitudes may be lacking some information since it is not possible to explain the non-zero KN phase shifts and scattering lengths in isospin 0 and compare them with those available from the partial wave analyses of the relevant experimental data [31, 32, 33, 34]. In the present work, we explore the possibility of improving the situation by coupling KN and K*N channel.

For the K*N interaction we use the general VB Lagrangian of Ref. [27]

\[
\mathcal{L}_{VB} = -g \left\{ \langle B \gamma_{\mu} [V_N^8, B] \rangle + \langle B \gamma_{\mu} B \rangle \langle V_N^8 \rangle + \frac{1}{4M} \left( F \langle \bar{B} \sigma_{\mu\nu} [V_N^{\mu\nu}, B] \rangle + D \langle \bar{B} \sigma_{\mu\nu} \{ V_N^{\mu\nu}, B \} \rangle \right) \right\} \\
- g \left\{ \langle B \gamma_{\mu} B \rangle \langle V_N^{0} \rangle + \frac{C_0}{4M} \left( \langle B \sigma_{\mu\nu} V_N^{\mu\nu} B \rangle \right) \right\},
\]

(2)

where the expressions in the parentheses (…) are related to the anomalous magnetic moment of the baryons. V in Eq. (2) denotes the SU(3) matrix for the vector mesons and V^{\mu\nu} represents the tensor field of the vector mesons,

\[
V^{\mu\nu} = \partial^{\mu} V^{\nu} - \partial^{\nu} V^{\mu} + ig [V^{\mu}, V^{\nu}] .
\]

The subscripts 8 and 0 stand for the octet and the singlet part of the ω and φ wave functions (written within the ideal mixing assumption). The coupling g in Eq. (2) is given by the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin relation (KSRF) [35, 36]

\[
g = \frac{m_{K^{*}}}{\sqrt{2} f_{K}}.
\]

(4)

The constants D = 2.4, F = 0.82 and C_0 = 3F - D are chosen to ensure that the couplings for the φNN, ωNN and ρNN vertices are compatible with the known values. The values of D and F used here were also found to well reproduce the magnetic moments of the baryons in Ref. [37].

It should be mentioned here that Eq. (2) is in good agreement with the VB Lagrangians obtained within other approaches [38, 39].

With the Lagrangian given by Eq. (2) we can calculate Yukawa-type vertices which can be used to calculate t- and u-channel diagrams. Amplitudes corresponding to s-channel are trivially null in the present case since it requires exchange of a strangeness positive baryon. In addition to these contributions, one can obtain a contact term using the commutator part of the tensor field of the vector mesons, the baryons.

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The t-channel amplitude obtained from Eq. (2) for K*N is analogous to Eq. (1), (as also obtained in Ref. [40])

\[
V'_{t,K^{*}N} = -\frac{C_{t,K^{*}N}}{4f_{K^{*}}} (\omega + \omega') \epsilon_1 \cdot \epsilon_2 ,
\]

(5)

where ω(ω') and ε_1(ε_2) represent the energy and the polarization vector of the K*-meson in the initial (final) state, respectively. The values of C_{t,K^{*}N} are 0 and -2 for isospin 0 and 1, respectively, and f_{K^{*}} = 171.12 MeV is the decay constant for K* [41, 42]. Similar to the case of KN, the isospin 1 K*N amplitude is also repulsive while isospin 0 amplitude is null. Since
$K^*$ has spin 1 and the spin of the nucleon $N$ is $1/2$, we can have total spin $S = 1/2$ and $3/2$ for the system in $s$-wave. Notice that Eq. (5) is spin independent, giving identical amplitudes for spin $1/2$ and $3/2$.

Next, the amplitude for exchange of an octet baryon in the $u$-channel and the contact term are obtained as

$$V^I_{u,K^*N} = C^I_{u,K^*N} \left( \frac{g^2}{2M - m} \right) \vec{e}_1 \cdot \vec{\sigma} \vec{e}_2 \cdot \vec{\sigma},$$  \hspace{1cm} (6)$$

$$V^I_{CT,K^*N} = iC^{I}_{CT,K^*N} \frac{g^2}{2M} \vec{\sigma} \times \vec{e}_2 \times \vec{e}_1,$$  \hspace{1cm} (7)

where $m$ ($M$) is the mass of the $K^*$ (nucleon) and $\bar{M}$ represents an average mass for the baryons involved in the process. The isospin coefficients $C^{I}_{u,K^*N}$ and $C^{I}_{CT,K^*N}$ are given in Table 1. It can be seen that the spin structure of these amplitudes leads to different amplitudes for total spin $1/2$ and $3/2$. We obtain $V^I_{CT,K^*N}$ and $V^I_{u,K^*N}$ to be attractive in nature for total spin $3/2$ in isospin 0, and for spin $1/2$ in isospin 1. They are repulsive in the remaining two configurations.

### Table 1. Isospin coefficients for the $u$-channel amplitude and contact term given by Eqs. (6) and (7).

| $I$ | $C^I_u$ | $C^I_{CT}$ |
|-----|---------|------------|
| 0   | $\frac{Dm[(D-3F)m-6\bar{M}]}{6M^2}$ | $D$ |
| 1   | $\frac{12\bar{M}^2+12Fm\bar{M}+(D^2+3F^2)m^2}{12M^2}$ | $-F$ |

Further, we include exchange of those resonances in the $u$-channel for which the couplings to meson-baryon channels have been obtained in Ref. [28] using the same formalism as the present one. To begin with, we do so to restrict the number of unknown parameters to be minimum. But later we find this contribution to be negligibly small (see Ref. [43] for more details) and, thus, we do not consider exchange of more resonances.

To determine the contribution from the exchange of resonances, we write the following phenomenological effective field Lagrangians [44, 45]

$$\mathcal{L}_{NK^*H} = ig_{NK^*H^*} \bar{H}^* K^* N + h.c.,$$

$$\mathcal{L}_{NK^*H^*} = g_{NK^*H^*} \bar{H}^* \gamma^\mu \gamma_5 K^* N + h.c.,$$  \hspace{1cm} (8)

where $H^*$ stands for $\Lambda^*$ or $\Sigma^*$ and $K^*(K^*)$ creates a $K$ ($K^*$) meson. The couplings $g_{NK^*\Lambda^*}$ and $g_{NK^*\Lambda^*}$ have been obtained (in Ref. [28]) by studying VB interaction using the Lagrangian given in Eq. (2). Thus, although we write phenomenological Lagrangians in Eq. (8), the contributions from both vector and tensor VB interaction are embedded in $g_{NK^*\Lambda^*}$ and $g_{NK^*\Lambda^*}$.

Keeping in mind the extended structure of the hadrons and the fact that only the negative energy solution of the Dirac equation contributes to the $u$-channel diagrams for the $s$-wave $K^*N$ interaction, the following form factor is multiplied to all the $u$-channel amplitudes,

$$F(\Lambda, u) = \frac{\Lambda^4}{\Lambda^4 + (u - M_u^2)^2}.$$  \hspace{1cm} (9)
where $u$ is the usual Mandelstam variable, $M_u$ is the mass of the baryon exchanged and $\Lambda$ is a cut-off which we vary in the range 650-1000 MeV.

We sum the $K^*N$ amplitudes obtained from the contact term, $t$-channel and $u$-channel diagrams and use it as the kernel when solving scattering equations.

Finally, we obtain the $KN \leftrightarrow K^*N$ amplitudes using the Lagrangian from Ref. [30]

$$\mathcal{L}_{\text{PBVB}} = -i g_{KR} \frac{2}{f_{\pi}} \left( F' \langle B \gamma_\mu \gamma_5 \{ [P, V^\mu], B \} \rangle + D' \langle \bar{B} \gamma_\mu \gamma_5 \{ [P, V^\mu], B \} \rangle \right),$$

where the subscript PBVB stands for the pseudoscalar meson-baryon–vector meson-baryon Lagrangian and $F' = 0.46$, $D' = 0.8$ ensure that $F' + D' \simeq g_A = 1.26$ [30]. Using Eq. (10) we obtain

$$V_{KNK^*N}^I = i \sqrt{3} \frac{g_{KR}}{2\sqrt{f_K f_{K^*}}} C_{IKNKN}^I,$$

where $g_{KR}$ is obtained using the KSRF relation [30]

$$g_{KR} = \frac{m_{K^*}}{\sqrt{2 f_K f_{K^*}}} \sim 4.53.$$

The coefficient $C_{IKNKN}^I$ is $-2D'$ for isospin 0 and $2F'$ for isospin 1.

3. Results

In the previous section we discussed the $s$-wave $KN$ and $K^*N$ interactions with which the Bethe-Salpeter equation can be solved in its on-shell factorization form [17, 46]

$$T = (1 - VG)^{-1} V,$$

where $V$ is the kernel and $G$ is the loop function which is divergent in nature. We calculate it using the dimensional regularization and fix the require subtraction constants by making a $\chi^2$-fit to the latest data [31] on the $s$-wave isospin 0 and 1 $KN$ phase shifts. The results for the $K^*N$ system are predictions.

![Figure 1](image_url) Scattering phase shifts for the $KN$ system obtained by using the subtraction constants: $b_{KN}^{I=0} = -6.82$, $b_{KN}^{I=1} = 1.84$, $b_{K^*N}^{I=0} = -1.59$ and $b_{K^*N}^{I=1} = -1$ ($\mu = 630$ MeV) and for $\Lambda$ in Eq. (9) varying between 650-1000 MeV. The data from the partial wave analysis, represented by filled circles, boxes and empty triangles are taken from Refs. [31, 32, 33], respectively.
We obtain the best fit with the values of the subtraction constants: $b_{KN}^{I=0} = -6.82$, $b_{KN}^{I=1} = 1.84$, $b_{K^*N}^{I=0} = -1.59$ and $b_{K^*N}^{I=1} = -1$ for the regularization scale $\mu$ fixed to 630 MeV. We show the $KN$ phase shifts obtained with these constants in Fig 1 for the value of the $\Lambda$, in Eq. (9), varied between 650 MeV -1000 MeV. As can be seen from these figures, there is a good agreement between our results and the partial wave analysis data of Refs. [31, 32, 33] for both isospins. However, the results for isospin 0 seem to be slightly sensitive to the the value of the $\Lambda$ used in Eq. (9) while the isospin 1 phase shifts seem to be stable. This apparent stability arises due to a weak $KN \leftrightarrow K^*N$ amplitude in the isospin 1 case.

We show our predictions for the $K^*N$ s-wave scattering phase shifts in Fig. 2 for different spin-isospin configurations. It can be seen in these figures too that the $K^*N$ phase shifts are not very sensitive to the changes in the cut-off $\Lambda$ used in the form factor defined by Eq. (9). These results are of importance for understanding the data related to $K$ and $K^*$ production in $p + p$ and $p + A$ collisions, as reported by HADES [20, 21, 47], STAR [48] and NA49 [22] Collaborations.

Using the amplitudes corresponding to the phase shifts shown in Figs. 1, 2, we search for poles in the complex plane. By coupling the $KN$ and $K^*N$ channels involved, we have calculated the amplitudes for isospin 0 and 1 and spin-parities $1/2^-$ and $3/2^-$. We do not find any pole in none of these configurations. From our work, thus, it can be concluded that a strangeness $+1$ resonance is not generated from $KN$ and $K^*N$ coupled channel dynamics, contrary to the anticharm systems [9]. Also, our results differ from those of Ref. [49] where a narrow, isoscalar
resonance with spin-parity $3/2^-$ was found within a different formalism to study $K\bar{N}$-$K^*N$ coupled systems.

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