A study of the $KN-K^*N$ coupled systems

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Abstract

Motivated by the finding of some charm $-1$ resonances in meson-baryon systems by coupling pseudoscalar and vector mesons, we study the analogous strangeness $+1$ sector. The amplitudes for light vector meson-baryon systems are obtained by implementing the $s$-, $t$-, $u$- channel diagrams and a contact interaction, all derived from Lagrangians based on hidden local symmetry. The pseudoscalar meson-baryon interactions are obtained by relying on the Weinberg-Tomozawa theorem. The transition amplitudes between the systems consisting of pseudoscalars and vector mesons are calculated by extending the Kroll-Ruderman term for pion photoproduction replacing the photon by a vector meson. In addition, the exchange of light hyperon resonances, such as $\Lambda(1405)$ and $\Lambda(1670)$ in the $u$-channel, is included for

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the $KN \rightarrow KN$, $K^*N \rightarrow K^*N$ and $K^*N \leftrightarrow KN$ processes. Although we find these contributions to be negligibly small, a posteriori. We fix the subtraction constants required to calculate the loops by fitting our $KN$ amplitudes to the data available for the isospin 0 and 1 $s$-wave phase shifts. As a result, contrary to the case of charm $-1$, we do not find any exotic resonance in the strange sector in none of the isospin and spin configurations. We finally provide the scattering lengths and the total cross sections for the $KN$ and $K^*N$ systems, which can be useful for studies related to nucleon-nucleon collisions.

1 Introduction

The existence of strangeness +1 baryons is being debated since more than four decades now [1]. More recently, it seemed that the issue was closer to being settled when Spring8 reported the finding of $\Theta^+(1540)$ [2], bringing a lot of enthusiasm in the field. The excitement, however, soon died out due to the failure of other experiments in confirming the existence of this exotic baryon (for a review on this, see Ref. [3]). In fact, an alternative explanation for the enhancement of the cross section seen in Ref. [2] has been brought forward by a recent analysis in Refs. [4, 5]. With this, we seem to have come back to the open question: Do baryons with strangeness +1 exist? The special interest in these baryons arises due to the fact that their wave functions necessarily require five valence quarks.

Indeed, hadrons with five quark structure seem to exist, several studies are providing indications for the need of a five-quark content [6, 7, 8, 9, 10] (and even a heptaquark content [11, 12, 13, 14]) of baryons, but they are not exotic in the sense that a three valence quark configuration is not forbidden for them. What seems to be a nontrivial task is to find those baryons which essentially require a five quark nature. The finding or not finding of such exotic states is important to understand QCD and, in the latter case, to know which mechanism hinders their existence.

The quest for pentaquarks has now been extended to the heavy hadron sector [15, 16, 17, 18, 19] due to the possibility of obtaining good quality data at higher energies at different experimental facilities like BES, BELLE, etc. One of these works [18] is of special interest to us since it motivated the present study. In Ref. [18] a coupled channel calculation was made for anti-charmed meson-baryon systems with a formalism based on unitarity and SU(8) symmetry and it was found that a resonance with spin-parity $1/2^-$ and isospin 0 appears when pseudoscalar meson-baryon and vector meson-baryon channels are coupled. Further, it was emphasized in Ref. [18] that
the uncoupled amplitudes (which are obtained in terms of the Weinberg-
Tomozawa kind of interaction) are null in this case and the resonance is
obtained only as a consequence of coupling the two channels, i.e., due to
the transition amplitude. This led us to question if a similar situation arises
in the light hadron sector and motivated us to verify the same by taking
advantage of our recent efforts put in building a reliable formalism to study
the meson-baryon systems involving both pseudoscalars and vector mesons
[20, 21, 22, 23].

Our study on vector meson-baryon (VB) systems [20] was done by us-
ing Lagrangians based on the hidden local symmetry [24] which treats vec-
tor mesons, consistently with the chiral symmetry, as the dynamical gauge
bosons. We found that the gauge invariance of the Lagrangian enforces the
consideration of a contact term together with $s$-, $t$- and $u$-channel interac-
tions, which all turn out to give important contributions. This result shows
that the low-energy theorems related to the pseudoscalar mesons cannot be
extended to the VB systems. As a result, we find it unavoidable to solve
the Bethe-Salpeter equation using the sum of all these interactions as the
kernel. Later, we coupled VB with pseudoscalar meson-baryon (PB) systems
by extending the Kroll-Ruderman theorem for the pion photoproduction by
replacing the photon by a vector meson in accordance with vector m eson
dominance. With this formalism we have solved coupled channel equat-
ions for strange and nonstrange meson-baryon systems [22, 23], and found dy-
namical generation of several resonances.

In the present work, we extend our formalism to study strangeness $+1$
meson-baryon systems motivated by the findings of Ref. [18]. As we shall
explain in the next section, the $t$-channel interactions, for both PB and VB
cases, are zero in the isospin zero, spin $1/2$ configuration (as also found in
[18, 25]), which already indicates towards the importance of considering the
coupling between the two. Solving coupled channel equations in our f ormal-
ism with the subtraction constants constrained by the available data, we find
no resonance (unlike the results found in Ref. [18] and in a previous study
of strangeness $+1$ systems, especially for $3/2^-$ [25]). Further, we attempt to
extend our model by considering the exchange of light hyperon resonances in
the $u$-channel, for which the necessary couplings are available from our pre-
vious works [22]. But we end up finding these contributions to be negligible.
As a result, we conclude that light meson-baryon dynamics does not lead to
formation of any resonance, contrary to the charmed case. Our work, thus,
does not support the existence of light pentaquarks with spin-parity $1/2^-$ or
$3/2^-$. Further, we provide results for the $KN$ and $K^*N$ systems for differ-
ent spin-isospin configurations, which could be useful for the studies involv-
ing strange mesons in hot and dense nuclear matter. As for strange pseudoscalars, recent results on $K^0$ production have been reported in $p + p$ collisions at 3.5 GeV by the HADES Collaboration showing a dominant resonant production coming from $\Delta(1232)$ and $\Sigma(1385)$ for intermediate energies in the formation of $K^0$ \[26\]. Also, the in-medium kaon potential is needed to describe the $K^0$ production in $p+\text{Nb}$ reactions at a beam kinetic energy of 3.5 GeV analyzed by HADES \[27\]. With regards to $K^*$, a deep sub-threshold $K^*$ production has been reported in Ar+KCl collisions by HADES, with the experimental $K^*$ yield and $K^*/K^0$ being overestimated by about a factor five and two, respectively, when applying the UrQMD transport approach \[28\]. Also, by analyzing the freeze-out temperature using a statistical hadronization model, the experimental results for $K^*$ production seem to indicate the necessity of considering the rescattering of the decay products of $K^*$ in the hadronic matter \[28\]. The importance of the hadronic interactions of the final states is also realized for the $K^*$ production in Au+Au and Cu+Cu at $\sqrt{s_{NN}}$=62.4 and 200 GeV collisions by the STAR Collaboration \[29\]. The attenuation of the $K^*$ and $K^*$ 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 $<K^*>/<K^->$ in central Pb+Pb collisions compared to $p+p$, C+C and Si+Si by the NA49 Collaboration \[30\], was not reproduced using UrQMD \[31,32\] or statistical HQGM \[33\] models. Such findings thus indicate towards the importance of a reliable determination of $KN$ and $K^*N$ interactions in vacuum and in matter.

2 The $KN$ and $K^*N$ amplitudes

A study of the $KN$ and $K^*N$ coupled channel dynamics, made with the aim of looking for generation of resonances in these systems, requires the calculation of the scattering matrix, $T$ in $s$-wave. This can be done by solving the Bethe-Salpeter equation, which in its on-shell factorization form reads as \[8,34\]

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

where the kernel $V$ or potential is obtained from the lowest order Lagrangians based on the hidden local symmetry (as done in Refs. \[20,21,22\]) and $G$ is the loop function of two hadrons. Since we have a pseudoscalar-baryon channel ($KN$) coupled with a vector-baryon channel ($K^*N$), the potential $V$ matrix consists of not only the transitions $KN \rightarrow KN$ and $K^*N \rightarrow K^*N$, but also the process $KN \rightarrow K^*N$ and vice versa.
To determine the $KN \rightarrow KN$ amplitude we use the Weinberg-Tomozawa theorem and consider the lowest order chiral Lagrangian as done in Ref. [8, 25], leading to the following amplitude

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

(2)

In Eq. (2), the superscript label $I$ indicates the isospin of the meson-baryon system. In the present case we can have total isospin $I = 0$ or 1. The coefficient $C_{KN}^I$ is 0 for isospin 0 and $-2$ for isospin 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 $\omega$ ($\omega'$) corresponds to the energy of the kaon in the initial (final) state.

For the case of the $K^*N \rightarrow K^*N$ transition, as shown in Ref. [20], using Lagrangians based on the hidden local symmetry [24], this amplitude gets contribution from $s$-, $t$-, and $u$-channel exchange diagrams together with a contact term (CT) arising from the commutator in the vector meson tensor (for more details we refer the reader to Refs. [20, 22, 23]), and thus

$$V_{K^*N}^I = V_{t}^I + V_{s}^I + V_{u}^I + V_{CT}^I.$$  

(3)

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. The potentials in Eq. (3) are, in fact, spin- (and isospin-) dependent and need to be projected to each configuration. The $t$-channel exchange potential in Eq. (3) is completely analogous to the one in Eq. (2), with $\omega$ and $\omega'$ representing now the energy of the $K^*$ in the initial and final state, respectively [35], and $f_K \rightarrow f_{K^*}$, with $f_{K^*} = 171.12$ MeV being the decay constant of the $K^*$ mesons [36, 37]. Notice, thus, that $V_t$ is spin degenerate, contrary to the total potential in Eq. (3).

Next, for the system studied here, the $s$-channel potential is trivially zero, since it would imply the exchange of a baryon with strangeness +1. The $u$-channel and the contact term potentials contribute and are given by

$$V_{u}^I = -C_{u}^I \left(\frac{g^2}{2M - m}\right),$$

$$V_{CT}^I = C_{CT}^I \frac{g^2}{M},$$

(4)

for spin $S = 1/2$ and

$$V_{u}^I = 2C_{u}^I \left(\frac{g^2}{2M - m}\right),$$

$$V_{CT}^I = -C_{CT}^I \frac{g^2}{2M},$$

(5)
for spin $S = 3/2$. In these equations, $m$ (M) is the mass of the $K^*$ (nucleon), $\bar{M}$ represents an average mass for the baryons involved in the process and the coupling $g$ is given by the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin relation \cite{38,39}

$$g = \frac{m_{K^*}}{\sqrt{2}f_{K^*}}. \quad (6)$$

The coefficients $C^I_u$ and $C^I_{CT}$ are given in Table 1.

Table 1: Isospin coefficients for the amplitudes in Eqs. (4) and (5). The values of $D$ and $F$ are 2.4 and 0.82, respectively \cite{20,21}.

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

It should be emphasized here that the tree-level $u$-channel amplitudes given by Eqs. (4) and (5) correspond to the exchange of a ground state ($J^\pi = 1/2^+$) baryon, as done in Refs. \cite{20,22,23}. In principle, exchange of a baryon resonance with negative parity and/or higher spin can also be considered in the $u$-channel diagram. In the present work we make use of the couplings of the hyperon resonances to both PB and VB channels obtained in Ref. \cite{22}, where the same formalism was applied to strangeness $-1$ meson-baryon systems, and use them as an input here to consider the exchange of some hyperon resonances in the $u$-channel (see examples of such diagrams in Fig. 1).

Figure 1: Diagrams involving $u$-channel exchange of $\Lambda$ resonances.

In the case of the isospin 0 and spin 1/2 $u$-channel amplitude, for example, we can consider contributions from the exchange of the $\Lambda(1405)$ and $\Lambda(1670)$ resonances, which were found to couple strongly to $\bar{K}^*N$, in addition to $\bar{K}N$. 


in Refs. [21, 23]. To determine the contribution from the exchange of these resonances, we use the following effective Lagrangians

$$
\mathcal{L}_{NK\Lambda^*} = ig_{NK\Lambda^*} \Lambda^* K^\dagger N + \text{h.c},
$$
$$
\mathcal{L}_{NK^*\Lambda^*} = g_{NK^*\Lambda^*} \Lambda^* \gamma^\mu \gamma_5 K_{\mu}^* N + \text{h.c}. \quad (7)
$$

Note here that we could have equivalently used the pseudovector description for the $NK\Lambda^*$ Lagrangian [40, 41]. The couplings $g_{NK\Lambda^*}$ and $g_{NK^*\Lambda^*}$ for the $\Lambda(1405)$ and $\Lambda(1670)$ in Eqs. (7) are taken from Table XII of Ref. [22]. We list them below, for completeness,

$$
g_{NK\Lambda(1405)} = 1.2 - i1.4
$$
$$
g_{NK^*\Lambda(1405)} = 0.4 + i1.6
$$
$$
g_{NK\Lambda(1670)} = 2.8 - i0.6
$$
$$
g_{NK^*\Lambda(1670)} = -4.9 - i0.0
$$
$$
g_{NK\Lambda(1670)} = 0.3 - i0.6
$$
$$
g_{NK^*\Lambda(1670)} = -0.9 - i0.3.
$$

(8)

where the subscripts $I$ and $II$ represent the two poles corresponding to $\Lambda(1405)$ at $1358 - i53$ MeV and $1414 - i12$ MeV, respectively, found in the scattering matrix calculated in the complex plane [22]. In Eqs. (7) we consider the modulus of these couplings. Using the Lagrangians of Eqs. (7), we obtain the diagonal amplitudes for the diagrams shown in Figs. 1, within the non relativistic approximation (consistent with the procedure followed to obtain the other amplitudes), as

$$
V_{u,K}^{\Lambda^*} = \left(g_{NK\Lambda^*}/\sqrt{2}\right)^2 \frac{M - m_K + M_{\Lambda^*}}{u - M_{\Lambda^*}^2} \bar{\epsilon}_1 \cdot \bar{\sigma} \bar{\epsilon}_2 \cdot \bar{\sigma},
$$
$$
V_{u,K^*}^{\Lambda^*} = \left(g_{NK^*\Lambda^*}/\sqrt{2}\right)^2 \frac{M - m_K^* + M_{\Lambda^*}}{u - M_{\Lambda^*}^2} \bar{\epsilon}_1 \cdot \bar{\sigma} \bar{\epsilon}_2 \cdot \bar{\sigma}, \quad (9)
$$

with $M_{\Lambda^*}$ being the mass and width of the exchanged $\Lambda^*$ resonance and where $\bar{\epsilon}_1 \cdot \bar{\sigma} \bar{\epsilon}_2 \cdot \bar{\sigma}$ gives a factor $-1$ for spin $S = 1/2$ and $2$ for $S = 3/2$. The factor $-1/\sqrt{2}$ in Eqs. (9) is the Clebsh-Gordon coefficient taking care of the fact that we use $g_{NK\Lambda^*}$ and $g_{NK^*\Lambda^*}$ from Ref. [22] which are isospin projected couplings while the $\Lambda$’s can be exchanged only in the processes: $K^0 p \leftrightarrow K^+ n$ and $K^{*0} p \leftrightarrow K^{*+} n$. Let us also recall that we write the $KN$ and $K^* N$ channels projected on isospin 0 as

$$
| KN_{I=0} \rangle = \frac{1}{\sqrt{2}} \left( | K^+ n \rangle - | K^0 p \rangle \right)
$$
$$
| K^* N_{I=0} \rangle = \frac{1}{\sqrt{2}} \left( | K^{*+} n \rangle - | K^{*0} p \rangle \right). \quad (10)
$$
The transition $KN \to K^*N$ is obtained from the Lagrangian deduced in Ref. [21] using the Kroll-Ruderman term for the photoproduction of a pion, where the photon is replaced by a vector meson which is introduced as the gauge boson of the hidden local symmetry. In this way, we obtain the following amplitude

$$V_{KN,K^*N}^I = i\sqrt{3} \frac{g_{KR}}{2\sqrt{f_K f_{K^*}}} C_{KN,K^*N}^I,$$  \hspace{1cm} (11)

where $g_{KR}$ is the Kroll-Ruderman coupling [21]

$$g_{KR} = \frac{m_{K^*}}{\sqrt{2f_K f_{K^*}}} \sim 4.53,$$  \hspace{1cm} (12)

and the isospin coefficients $C_{KN,K^*N}^I$ are given in Table 2. Note that in our formalism pseudoscalar-baryon and vector-baryon channels couple only in the spin $1/2$ configuration. Thus, the amplitude in Eq. (11) determines the transition $KN \to K^*N$ for isospins 0, 1 and total spin $S = 1/2$. The PB-VB coupling for total spin $3/2$ is zero (as in Ref. [21, 22, 23]). This is consistent with the results obtained in Ref. [42] where the VB amplitudes have been found to change weakly when coupled to pseudoscalar baryon systems.

As can be seen in Fig. 1, the transition amplitude $KN \to K^*N$ can also get a contribution arising from the $u$-channel exchange of hyperon resonances like $\Lambda(1405)$ and $\Lambda(1670)$, which we take into account. Using the Lagrangians given in Eq. (7), we find

$$V_{KN,K^*N}^{\Lambda} = ig_{NK\Lambda} g_{NK^*\Lambda} \frac{M - m_{K^*} + M_{\Lambda^*}}{u - M_{\Lambda^*}^2} \vec{\epsilon} \cdot \vec{\sigma}.$$  \hspace{1cm} (13)

Before proceeding, we must mention that the following form factor is multiplied to all the $u$-channel amplitudes,

$$F(\Lambda, u) = \frac{\Lambda^4}{\Lambda^4 + (u - M_{\Lambda^*}^2)^2},$$  \hspace{1cm} (14)
where \( u \) is the usual Mandelstam variable, \( M_u \) is the mass of the baryon exchanged and \( \Lambda \) is a cut-off which is fixed to 650 MeV, as in Refs. [20, 22, 23].

After determining the kernel \( V \) needed to solve the Bethe-Salpeter equation, the other element required to obtain the scattering matrix is the loop function \( G \) of Eq. (1), which is given by

\[
G(\sqrt{s}, m, M) = i 2M \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P - q)^2 - M^2 + i\epsilon q^2 - m^2 + i\epsilon},
\]

where \( \sqrt{s} \) is the center of mass energy, \( M (m) \) corresponds to the mass of the nucleon (meson) present in the loop and \( P \) is the total four momenta of the system. As can be seen, this loop function is logarithmically divergent and it needs to be regularized using a cut-off or dimensional regularization. In this paper, we use the regularization scheme, in which case, the loop function \( G \) is written, in the center of mass frame (CM), as [9]

\[
G(\sqrt{s}, m, M) = \frac{2M}{16\pi^2} \left\{ a(\mu) + \ln\left( \frac{M^2}{\mu^2} + \frac{m^2 - M^2 + s}{2s} \ln\left( \frac{m^2}{M^2} \right) \right) \right. \\
+ \frac{q_{\text{CM}}}{\sqrt{s}} \left[ \ln( s - (M^2 - m^2) + 2q_{\text{CM}}\sqrt{s}) + \ln( s + (M^2 - m^2) + 2q_{\text{CM}}\sqrt{s}) \right. \\
- \ln( -s + (M^2 - m^2) + 2q_{\text{CM}}\sqrt{s}) - \ln( s - (M^2 - m^2) + 2q_{\text{CM}}\sqrt{s}) \left. \right]\right\}.
\]

In Eq. (16), \( q_{\text{CM}} \) is the on-shell momentum of the particles in the CM, \( \mu \) is the regularization scale and \( a(\mu) \) a subtraction constant, which needs to be fixed, normally, by requiring the amplitudes to fit some experimental data. Thus, the only parameters to be fixed are the subtraction constants required to regularize the loops (since any change in \( \mu \) can be reabsorbed in the value of the subtraction constant \( a(\mu) \)).

With these ingredients we solve Eq. (1) and obtain the scattering matrix for the \( K^0N \)-\( K^+N \) system. The subtraction constants \( a_{KN} \) and \( a_{K^*N} \) present in the loop functions of \( KN \) and \( K^*N \) are fixed by fitting the data available from the partial wave analysis groups [13, 14, 15] on the isospin 0 and 1 \( KN \) phase shifts (\( \delta^0_{KN} \) and \( \delta^1_{KN} \), respectively), which, in our formalism, are related to the scattering matrix through the relation [14]

\[
T^{I,S} = -\frac{4\pi\sqrt{s}}{M} \left( \frac{n^{I,S} e^{2\eta^{I,S}} - 1}{2i q_{\text{CM}}} \right),
\]

were \( \eta^I \) the inelasticity in the isospin \( I \). Finally, using the resulting scattering matrix we also calculate the \( KN \) and \( K^*N \) scattering lengths for different
isospin and spin, \( a^{I,S=1/2}_{K_N} \) and \( a^{I,S}_{K^*N} \), using the relation [8]

\[
a^{I,S} = -\frac{M}{4\pi\sqrt{s}} T^{I,S}.
\] (18)

3 Results and discussions

Let us start the discussions on the results of the calculation by recalling that the Weinberg-Tomozawa interaction for the \( KN \) channel is null for isospin 0 (considering isospin averaged masses in Eq. (2), which leads to \( C^I_{K_N} = 0 \)), which will give null scattering phase shifts. Even the consideration of the differences between the masses leads to nearly zero \( KN \) potential, as shown in Ref. [8] where a scattering length of the order of \( 10^{-27} \) fm was obtained. This alone indicates towards the importance of the coupling between the \( KN \) and the \( K^*N \) channels and/or consideration of additional diagrams, if the available data on the \( S_{01} \) (representing \( L_{\text{Isospin, 2xSpin}} \) partial wave \( KN \) scattering [43, 44, 45] is to be explained.

Next, as discussed in the previous section, the \( t \)-channel interaction in isospin 0 for the \( K^*N \) channel also leads to a null amplitude, which reinforces the importance of the contribution from additional diagrams as considered in our formalism: the coupling between the PB and VB channels and the contributions coming from the VB contact term and the \( u \)-channel diagrams. Out of these different contributions, we find that the ones arising from the exchange of hyperon resonances in the \( u \)-channel diagrams (shown in Fig. 1) are negligibly small in the present case. We anyway proceed by taking all the diagrams into account explained in the previous section. We would like to add here that the hyperon resonance exchange are known to give important contributions in studies of other processes, like those investigated in Refs. [46, 47]. However, we do not find this to be the case for \( KN-K^*N \) systems. This result is similar to the one obtained in Refs. [20, 22, 23] for the exchange of the octet baryons, which was found to give an important contribution to some processes and negligible to others.

To solve the Bethe-Salpeter equation, we need to fix the subtraction constants which are needed to regularize the logarithmical divergence of the loop functions. One way to proceed with the calculations would be to consider the same “natural” values [48] of the subtraction constants \( a(\mu) = -2 \), with \( \mu = 630 \) MeV) as the ones used for the meson-baryon systems with the opposite strangeness \( (S = -1) \) [8]. We show the isospin 0 and 1 \( KN \) phase shifts obtained with these constants in Fig. 2. As can be seen from this figure, although the isospin 1 phase shifts data [43, 44, 45] (shown in the right panel)
can be reasonably reproduced using $a = -2$, the isospin 0 results turn out to be quite different to data (except close to the threshold energy region).

![Figure 2: Scattering phase shifts for the KN system in $S_{01}$ and $S_{11}$ partial waves. The solid lines show the results obtained within our formalism by using the same subtraction constants as those used to reproduce the experimental data for the strangeness $-1$ coupled channel scattering [8]. The data from the partial wave analysis, represented by filled circles, boxes and empty triangles are taken from Refs. [43, 44, 45], respectively.]

In principle, the physics related to the strangeness $-1$ and $+1$ meson-baryon systems is quite different since the presence of a $\bar{s}$- or a $s$-valence quark leads to very different situations: the former allows the existence of a three quark intermediate state while the latter does not. Thus, the subtraction constants required to regularize the loops do not need to be necessarily the same in the two cases. We, thus, make a $\chi^2$-fit to the data [43, 44, 45], simultaneously, on the $s$-wave isospin 0 and 1 $KN$ phase shifts. We find that the best fit is obtained with values $a_{KN} = -2.7$ and $a_{K^*N} = -0.8$ with the regularization scale being $\mu = 630$ MeV. The phase shifts obtained with these subtraction constants are shown in Fig. 3. It can be seen that there is a qualitative agreement between our results and the partial wave analysis data of Refs. [43, 44, 45] for both isospins.

We also calculated the scattering lengths for the $KN$ system using the relation given by Eq. (18) and find $a_{KN}^{I=0} = -0.26$ fm and $a_{KN}^{I=1} = -0.27$ fm. The values found by different partial wave analyses groups for the $KN$ scattering lengths range from are $-0.105 \pm 0.01$ fm [43] to $-0.23 \pm 0.18$ fm [49], for isospin 0, and between $-0.286 \pm 0.06$ fm to $-0.308 \pm 0.003$ fm [43], for the isospin 1 case. Thus, our results are compatible with the available data.

With the assurance of a reasonable agreement between our results and the
available data on $KN$, we analyze the $K^*N$ channel. We first verify whether we find any dynamically generated resonance that can be reflected in the scattering amplitudes in the real axis. With the VB $K^*N$ channel involved, we have the amplitudes for isospin 0 and 1 and spin-parities $1/2^-$ and $3/2^-$. We find no poles in none of these configurations. We, thus, conclude that a strangeness +1 resonance does not get generated due to $KN$ and $K^*N$ coupled channel dynamics, contrary to the findings of the study of the $DN$-$D^*N$ coupled systems in Ref. [18]. It should be also mentioned that a narrow, isoscalar resonance with spin-parity $3/2^-$ was found in Ref. [25] by relying on the Weinberg-Tomozawa Lagrangian to study $KN$-$K^*N$ systems. Our formalism, involving more diagrams and constraints from the experimental data on the subtraction constants, does not result in the finding of any such resonance.

It is also interesting to add that a calculation of the $\pi KN$ system in s-wave led to the generation of a broad state with spin parity $1/2^+$ in Ref. [50]. The present calculation is, in some sense, similar to the one made in Ref. [50], recalling that $K\pi N$ system can be reorganized as $K^*N$ too. However, that would imply a p-wave interaction between the kaon and the pion. Curiously, this difference between the kaon-pion interaction seems to be important for formation of a resonance.

Finally, we would like to present our results on the $K^*N$ system, which might be useful as an input to studies of $K^*$-mesons in hot and dense medium [28, 29, 30]. We show the total cross sections for spin $1/2$ and $3/2$ in the right panel of Fig. 4 which have been calculated as

$$\sigma_S = \frac{1}{2} \sigma_{I=0,S} + \frac{3}{2} \sigma_{I=1,S},$$

(19)
Figure 4: Our results for the total cross sections for the $KN$ (left panel) and $K^*N$ (right panel) s-wave interaction which leads to a total spin $1/2$ (solid line) in the former case and total spin $1/2$ (solid line) and $3/2$ (dashed line) in the latter one. For the sake of comparison, we also show, as the dotted lines in both figures, the results corresponding to the spin-independent amplitudes which were obtained by considering $KN$ and $K^*N$ as uncoupled systems and by taking a t-channel diagram for each one of them. These latter results have been obtained with the subtraction constants $a = -2$, in order to mimic the input used in the previous in-medium studies of the $K$ and $K^*$ mesons \[51, 52, 54\].

\[ \sigma_{I,S} = \frac{1}{4\pi} \frac{M_N^2}{s} |T_{K^*N}^{I,S}|^2. \]  

(20)

The symbols $I$ and $S$ in the above equation represent the total isospin and spin, respectively, $M_N$ is the nucleon mass and $\sqrt{s}$ is the total energy in the center of mass frame. This definition of an isospin averaged cross section is often used in literature \[43\] and an analogous definition is used for isospin averaged amplitudes in the studies of mesons in medium \[51, 52, 53, 54\]. Although we have already shown our results for the phase shifts for the $KN$ channel in Fig. 2 for completeness, we show the corresponding cross sections too in Fig. 4 (left panel). We also show, in Fig. 4, the cross sections obtained by considering a $t$-channel diagram for the uncoupled $KN$ and $K^*N$ systems (as done in Ref. \[35, 55\]), in order to compare with similar inputs used in some previous studies of $K/K^*$ in hot and dense matter \[51, 54\]. We recall that the results obtained in this latter way are spin degenerate.

We also present the scattering lengths calculated using Eq. (18) for the different spin-isospin configurations of the $K^*N$ channel in Table 3.
Table 3: Scattering lengths for the $K^*N$ system.

| $a_{K^*N}^{I,S}$ (fm) | $I = 0$, $S = 1/2$ | $I = 0$, $S = 3/2$ | $I = 1$, $S = 1/2$ | $I = 1$, $S = 3/2$ |
|------------------------|---------------------|---------------------|---------------------|---------------------|
| (0.055,0.33)           | (-0.07,0.02)        | (0.17,0.01)         | (-0.37,0.04)        |

4 Summary

We can summarize the present work by mentioning that a coupled channel calculation involving both pseudoscalar and vector mesons has been done for strangeness $+1$ by taking different diagrams into account to obtain the kernel potential. In case of VB systems, we consider a contact term and the $t$-, $u$-channel diagrams, with an exchange of an octet baryon or a light hyperon resonance for the latter one. For PB channels we consider, in addition to the Weinberg-Tomozawa interaction, the $u$-channel exchange of light hyperon resonances. The exchange of hyperon resonances is found to give a negligibly small contribution. The subtraction constants required to regularize the loop have been fixed by constraining them to fit the available data on the $KN$ phase shifts in the $S_{01}$ and $S_{11}$ partial waves, which leads us to the values $-2.7$ and $-0.8$ for $KN$ and $K^*N$, respectively, for the regularization scale $\mu = 630$ MeV. With the calculations carried out in this formalism, we do not find any dynamically generated resonances. Thus, we rule out the possibility of the existence of a strangeness $+1$ resonance with isospin 0,1 and spin-parity $1/2^-$, $3/2^-$. Finally, we have presented the total cross sections and scattering lengths for the $KN$ and $K^*N$ channels. Indeed, the results presented here are of special interest for $K$ and $K^*$ production in $p+p$ and $p+A$ collisions, as reported by HADES [26, 27, 28], STAR [29] and NA49 [30] Collaborations.

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