Correlation Function from High-Energy Nuclear Collisions and Chiral SU(3) Dynamics

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The two-particle momentum correlation function of a \( K^-p \) pair from high-energy nuclear collisions is evaluated in the \( \bar{K}N-\pi\Sigma-\pi\Lambda \) coupled-channel framework. The effects of all coupled channels together with the Coulomb potential and the threshold energy difference between \( K^- \) and \( K^0n \) are treated completely for the first time. Realistic potentials based on the chiral SU(3) dynamics are used which fit the available scattering data. The recently measured correlation function is found to be well reproduced by allowing variations of the source size and the relative weight of the source function of \( \pi\Sigma \) with respect to that of \( \bar{K}N \). The predicted \( K^-p \) correlation function from larger systems indicates that the investigation of its source size dependence is useful in providing further constraints in the study of the \( \bar{K}N \) interaction.

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Introduction: Low-energy properties of the strong interaction are governed by the symmetry breaking pattern of quantum chromodynamics (QCD). In this context the antikaon \( \bar{K} \) can be regarded as a Nambu-Goldstone boson associated with the spontaneous breaking of three-flavor chiral symmetry. However, its mass is more than three times heavier than that of the pion. Thus, studies involving the antikaon reflect the interplay between spontaneous and explicit breakings of chiral symmetry in low-energy QCD.

The antikaon-nucleon \( \bar{K}N \) interaction at low energy is strongly attractive. It is the main ingredient to generate the \( \Lambda(1405) \) resonance as a \( \bar{K}N \) quasibound state \([1]\). This observation inspired an intense discussion of possible \( \bar{K}- \)nuclear quasibound systems \([2]\). A possible candidate is recently reported by the J-PARC E15 Collaboration \([3]\).

Contrary to its importance in hadron physics and also in nuclear many-body problems with strangeness, empirical information on the low-energy \( \bar{K}N \) interaction is quite limited. The \( K^-p \) scattering amplitude close to threshold is accurately constrained by the measurement of the atomic energy shift and width of \( K^- \) hydrogen \([4]\). There exist several \( K^-p \) cross section data at relatively high momenta, \( p_{\text{Lab}}(K^-) > 100 \text{ MeV}/c \) \([5-12]\). However, the uncertainties of the cross sections from the bubble chamber measurements are large, and almost no data exist in the low-momentum region, \( p_{\text{lab}}(K^-) \leq 100 \text{ MeV}/c \).

One of the promising observables that provides stronger constraints on the \( \bar{K}N \) interaction is the two-particle \( K^-p \) momentum correlation function. It is defined as the two-particle production probability normalized by the product of single-particle production probabilities \([13, 14]\). Theoretically, the correlation function reflects the two-body interactions through the wave function with a suitable boundary condition. On the experimental side, correlation functions have been measured recently in high-energy nuclear collisions for \( p\Lambda \) \([15, 16]\), \( \Lambda\Lambda \) \([16, 17]\), \( \pi\Sigma^- \) \([18]\), \( p\Omega \) \([19]\), \( pK^- \) \([20]\), and \( p\Sigma^0 \) \([21]\) pairs. These data have been used to constrain the pairwise interactions \([14, 22-26]\). Recently the \( K^-p \) correlation function has been extracted from high-multiplicity events of \( pp \) collisions \([20]\). The precision of these data is such that even the \( K^0n \) threshold cusp is visible. In addition the data show a peak in the energy region of the \( \Lambda(1520) \) resonance which couples to the \( \bar{K}N \) d-wave.

For the detailed analysis of the \( K^-p \) strong interaction in comparison with the high-precision data it is mandatory to include the coupled-channel effect, the Coulomb interaction in the \( K^-p \) system, and the threshold energy differences among the isospin multiplets in calculating the correlation function. While theoretical studies of the \( K^-p \) correlation function have been reported in Refs. \([14, 23, 25]\), there is so far no work which takes account of all of these effects.

In the present Letter we investigate the \( K^-p \) correlation function by developing and using a proper coupled-channel framework. Calculations are performed in the charge basis with six channels \( (K^-p, K^0n, \pi^-\Sigma^+, \pi^0\Sigma^0, \pi^+\Sigma^- \) and \( \pi^0\Lambda) \), and the coupled-channel version of the correlation function formula \([25, 27]\) is used. Coulomb interactions between charged particles are treated consistently. The threshold energy differences among the various channels are taken into account when solving the coupled-channel Schrödinger equation. In practice we have adopted the realistic \( \bar{K}N-\pi\Sigma-\pi\Lambda \) coupled-channel potential \([28]\). This potential is constructed starting from chiral SU(3) dynamics \([29, 30]\) and constrained by fits to the existing \( K^-p \) data. It will be demonstrated that the \( K^-p \) correlation function recently measured by the ALICE Collaboration \([20]\) is well explained by our calculations with reasonably tuned source size \( R \) and the source weight in the \( \pi\Sigma \) channels \( (\omega_{\pi\Sigma}) \). The effects of coupled channels...
are important in two ways: the modification of the wave functions in the $K^{-}p$ channel, and the conversion to $K^{-}p$ from $K^{0}n$ and $\pi \Sigma$ generated from the source functions in those channels.

Formalism: In high-energy heavy-ion collisions and high-multiplicity events of $pp$ and $pA$ collisions, the hadron production yields are well described by the statistical model. Under such conditions the correlations between outgoing particles are viewed as generated by the quantum mechanical scattering in the final state.

Consider two asymptotically observed particles, $a$ and $b$, with relative momentum $q = (m_{a}p_{a} - m_{b}p_{b})/(m_{a} + m_{b})$. Let this two-particle state be fed by a set of coupled channels, each denoted by $j$. In the pair rest frame of the two measured particles, their correlation function $C(q)$ is given as [25] [31]:

$$C(q) = \int d^{3}r \sum_{j} \omega_{j} S_{j}(r)|\psi_{j}^{(-)}(q;r)|^{2},$$  

(1)

where the wave function $\psi_{j}^{(-)}$ in the $j$-th channel is written as a function of the relative coordinate $r$ in that channel, with outgoing boundary condition for the measured channel. Furthermore, $S_{j}(r)$ and $\omega_{j}$ are the (normalized) source function and its weight in the $j$-th channel. The correlation function carries the information, through the wave functions $\psi_{j}^{(-)}$, about the interactions in the channels $j$ contributing to the final state under consideration. One can extract this information by properly determining the source function (e.g., by combined fit to data or constraints from other measurements) or by controlling the influence of the source function (e.g., by varying the system size as advocated in Ref. [32]).

We concentrate on the small $q = |q|$ region and assume that only the $s$-wave part of the wave function is modified by the strong interaction. The $j$-th channel component of the wave function with outgoing boundary condition in the $K^{-}p$ channel (channel 1) is given as

$$\psi_{j}^{(-)}(q;r) = [\phi^{C}(q;r) - \phi^{S}(q;r)]\delta_{ij} + \psi_{j}^{(-)}(q;r),$$  

(2)

where $r = |r|$ and $\phi^{C}(q;r)$ is the free Coulomb wave function in the $K^{-}p$ channel, $\phi^{S}(q;r)$ is its $s$-wave component, and $\psi_{j}^{(-)}(q;r)$ represents the $s$-wave function that includes both strong and Coulomb potential effects in the $j$-th channel. This wave function is subject to the outgoing boundary condition in the $K^{-}p$ channel as specified below.

The wave function $\psi_{j}^{(-)}(q;r)$ is computed by solving the coupled-channel Schrödinger equation

$$\mathcal{H}\psi(q;r) = E\psi(q;r),$$  

(3)

$$\psi(q;r) = \{\psi_{1}(q;r), \psi_{2}(q;r), \ldots\},$$  

(4)

with Hamiltonian

$$\mathcal{H} = \begin{pmatrix}
-\frac{\partial^{2}}{\partial \mu_{1}^{2}} + V_{11}(r) & V_{12}(r) & \cdots \\
V_{21}(r) & -\frac{\partial^{2}}{\partial \mu_{2}^{2}} + V_{22}(r) + \Delta_{2} & \cdots \\
\vdots & \vdots & \ddots
\end{pmatrix},$$  

(5)

where the channel indices $j = 1, \ldots, 6$ stand for $K^{-}p$, $K^{0}n$, $\pi^{-}\Sigma^{+}, \pi^{0}\Sigma^{0}, \pi^{+}\Sigma^{-}$ and $\pi^{0}\Lambda$, in this order; $\mu_{1}$ and $\Delta_{j}$ represent the reduced mass in channel $j$ and the threshold energy difference relative to channel 1, respectively. The diagonal potentials $V_{jj}(r)$ include the Coulomb term, $-\alpha/r$, in channels 1, 3, and 5 in addition to the strong interaction. The off-diagonal potentials are given by the strong interaction only. The momentum in channel $j$ is $q_{j} = \sqrt{2\mu_{j}(E - \Delta_{j})}$ with $q \equiv q_{1}$ and $\Delta_{1} = 0$. Through this relation, all the momenta $q_{j}$ can be expressed as functions of $q$. The Schrödinger equation is then solved with the following boundary condition at $r \to \infty$:

$$\psi_{j}^{(-)}(q;r) \to \frac{1}{2i\alpha q_{j}} \left[ \delta_{ij} u_{j}^{(+)}(q;r) + A_{j}(q) u_{j}^{(-)}(q;r) \right] r^{i\alpha q_{j}}$$  

(6)

for open channels ($E > \Delta_{i}$), where $u_{j}^{(+)}$ and $u_{j}^{(-)}$ are the outgoing and incoming waves with a coefficient $A_{j}(q)$. In contrast to the standard scattering problem with normalized flux of the incoming wave in the incident channel, it is the outgoing wave in the measured channel that is normalized for the calculation of the correlation function. In the absence of the Coulomb interaction, $u_{j}^{(+)}(q;r) = e^{\pm i\alpha q_{j}/r}$ are spherical waves, and the coefficients $A_{j}(q)$ are given by $\sqrt{\mu_{j}}(q_{j}/\mu_{j}q_{j})S_{j}(q_{j}),$ with the $S$ matrix $S_{ij}.$ Including the Coulomb interaction we have $u_{j}^{(+)}(q;r) = e^{\pm i\alpha q_{j}/r}$ with $\alpha_{j} = \arg\Gamma(1 + \eta_{ij})$, $\eta_{j} = -\mu_{j}/q_{j}$ with $F(q;r)[G(q;r)]$ being the regular (irregular) Coulomb function. For closed channels ($E < \Delta_{i}$), the asymptotic form is given by substituting $q_{j} = -i\kappa_{j} = -i\sqrt{2\mu_{j}(\Delta_{j} - E)}$ as $\psi^{(-)}(r) \to A_{j}(q)u_{j}^{(-)}(-i\kappa_{j}r)/(2\kappa_{j}r) \propto e^{-\kappa_{j}r}/\kappa_{j}r$. This is because the wave function component of the off-shell state can emerge only in the strong interaction region. For spherically symmetric source functions the correlation function can be written as

$$C(q) = \int d^{3}r S_{1}(r)[|\phi^{C}(q;r)|^{2} - |\phi^{S}(q;r)|^{2}] + 4\pi \sum_{j} \int_{0}^{\infty} dr r^{2} \omega_{j} S_{j}(r)|\psi^{(-)}(q;r)|^{2},$$  

(7)

where the left-hand side depends only on $q = |q|$. The normalization of the source function implies that the weight of the observed channel must be unity: $\omega_{i} = 1$ [27].

The $K^{-}p$ correlation function was calculated in Ref. [15] using the effective $KN$ potential in Ref. [33] within the model space of $K^{-}p$ and $K^{0}n$ channels. Although the effects of the coupled $\pi\Sigma$ and $\pi\Lambda$ channels are implicitly included in the renormalized $KN$ potential to reproduce the scattering amplitude, the proper boundary condition was not imposed because the wave function does not contain explicit $\pi\Sigma$ and $\pi\Lambda$ components. The present calculation reduces to that in Ref. [15] when the channel couplings of $KN \leftrightarrow \pi\Sigma, \pi\Lambda$ are switched off and the $K^{0}n$ source function is ignored. It turns out, however, that there are sizable deviations of the present results from those in Ref. [15]. This indicates the importance of an explicit treatment of coupled channels in the $K^{-}p$ correlation function.
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...parison with the results omitting the Coulomb interaction.

...Coulomb attraction at small momenta, demonstrated by composite local SU(3) dynamics at next-to-leading order [30] which success-

...fully describes the set of existing $K\Lambda$ channel is found to be the largest, $\Lambda$...$

...Among the coupled-channel components, the enhancement by the $K^0n$ channel is found to be the largest, and next in importance is $\pi\Sigma$. The inclusion of the $K^0n$ component also makes the cusp structure more prominent. The $\pi^0\Lambda$ channel couples to $K^-p$ only in the $I = 1$ sector; its effect is relatively weak. Because the calculated wave functions in channels other than $K^-p$ have a sizable magnitude only at small distances, the contributions from these components decrease with increasing source size. This leads to a less pronounced cusp structure for the $R = 3$ fm case.

Now we are prepared to compare the calculated $K^-p$ correlation function with data. We allow for variations of the source size and weights, which can be channel-dependent [23]. Since a given source function with the weight in the relative coordinate is obtained from a product of single-particle emission functions, the weight should be proportional to the product of particle yields. For example, $\omega_{\pi^-\Sigma^+}/\omega_{K^-p} = N(\pi^-)N(\Sigma^+)/N(K^-)N(p)$. The production yields $N(h)$ should be regarded as those of promptly emitted particles in order for those hadrons to couple into the final $K^-p$ channel. Those primary yields are not directly observable. Thus, we regard the source weights $\omega_j$ as parameters. While the effect of the $\pi^0\Lambda$ channel is small and the correlation function is not very sensitive to $\omega_{\pi^0\Lambda}$, the effects of $\pi\Sigma$ channels are important because of the strong $K\Lambda-\pi\Sigma$ coupling. Then we fix $\omega_{\pi^0\Lambda} = 1$ and vary the parameter $\omega_{\pi\Sigma}$ around the reference value, obtained by the simplest statistical model estimate [34], $\omega_{\pi\Sigma}(stat) \approx \exp[(m_K + m_N - m_\pi - m_\Sigma)/T_c] \approx 2.0$ with $T_c = 154$ MeV [35, 36]. As for the source size, the ALICE collaboration fixed $R = 1.18$ fm by assuming the same source size as that of $K^-p$, which was obtained by the femtoscopic correlation fit based on the Jülich $K^-p$ interaction [25], with Coulomb effects treated by the Gamow factor correction. Although this correction describes the Coulomb effect well for light systems such as $\pi^-\pi$, it lacks the necessary accuracy for heavier systems [32]. Thus, we also consider the variation of $R$ in the fitting procedure. While the source size can in principle be channel dependent, possible size differences between channels can be compensated by varying the source weights. We therefore use a common source size in $K\Lambda$, $\pi\Sigma$, and $\pi\Lambda$ channels. We also assume that the source function has a Gaussian shape and the source weight is isospin symmetric.

The measured correlation function is assumed to be described in the form [20]

$$C_{\text{fit}}(q) = \mathcal{N}[1 + \lambda \{C(q) - 1\}],$$

where $\mathcal{N}$ is a normalization constant and $\lambda$ is the pair purity parameter, known also as the chaoticity parameter. The pair purity parameter is experimentally determined through a Monte Carlo simulation, $\lambda_{\text{exp}} = 0.64 \pm 0.06$, so we allow for variations of $\lambda$ within $1\sigma$. We fit the correlation function data in the momentum range $q < 120$ MeV$/c$, where the distortion of the $s$ wave is considered to give the dominant contribution.

In Fig. 2 the $\chi^2$/d.o.f. distribution is plotted in the $(R, \omega_{\pi\Sigma})$ plane. A good fit ($\chi^2$/d.o.f. $\lesssim 1$) is achieved in the region from $(R, \omega_{\pi\Sigma}) = (0.6 \text{ fm}, 0)$ to $(1.1 \text{ fm}, 5.0)$. The source size $R \approx 1$ fm is reasonable for $pp$ collisions, while $\omega_{\pi\Sigma}$ should be consistent with the simple statistical model estimate within a factor of 2 to 3. Thus, we consider parameter

We now employ the wave functions in the full $KN-\pi\Sigma-\pi\Lambda$ coupled-channel framework. The starting point is chiral SU(3) dynamics at next-to-leading order [30] which successfully describes the set of existing $K^-p$ scattering data together with the SIDDHARTA kaonic hydrogen data [4]. An equivalent local $KN-\pi\Sigma-\pi\Lambda$ coupled-channel potential has been constructed to reproduce the corresponding scattering amplitudes [28]. Note that the coupled-channel effects contribute to the correlation function through the wave functions $\psi_j^{(-)}$ including $\psi_{K^-p}^{(-)}$.

Results: The $K^-p$ correlation function and its breakdown into channels are shown in Fig. 1 for source sizes of $R = 1$ fm and 3 fm. We assume a common source function of Gaussian shape for all channels, $S_j(r) = S_R(r) \equiv \exp(-r^2/4R^2)/(4\pi R^2)^{3/2}$ with $\omega_j = 1$. For both source radii $R$ we can see the strong enhancement due to the Coulomb attraction at small momenta, demonstrated by comparison with the results omitting the Coulomb interaction. Also evident is the cusp structure at the $K^0n$ threshold at $q \approx 58$ MeV$/c$. Among the coupled-channel components, the enhancement by the $K^0n$ channel is found to be the largest, and next in importance is $\pi\Sigma$. The inclusion of the $K^0n$ component also makes the cusp structure more prominent. The

FIG. 1. $K^-p$ correlation function with $R = 1$ fm (upper panel) and $R = 3$ fm (lower panel). The long-dashed line denotes the result with $K^-p$ component only. The short-dashed, dotted, and solid lines show the results in which the contributions from $K^0n$, $K^0\Sigma$, and $\pi\Sigma$, and from all coupled-channel components are added, respectively. The dash-dotted line denotes the full coupled-channel calculation without the Coulomb interaction.
sets in this region with $0.5 \leq \omega_{\pi\Xi} \leq 5$ as equally acceptable. On the other hand, if we take the $R = 1.18$ fm as adopted by the ALICE Collaboration, $\omega_{\pi\Xi} \gtrsim 8$ gives a good fit, but such large $\omega_{\pi\Xi}$ values appear to be significantly beyond the statistical model estimate.

Figure 3 shows the fitted $K^- p$ correlation function with $R = 0.9$ fm as an example of a result satisfying $\chi^2/d.o.f. < 1$. The other parameters are chosen as

$$\omega_{\pi\Sigma} = 2.95, \quad \lambda = 1.13, \quad \lambda = 0.58,$$

(9)
to give the minimum value of $\chi^2/d.o.f. = 0.58$. The enhancement in the low-momentum range and the characteristic cusp structure are evidently well reproduced. Recalling the importance of the $\pi\Sigma$ component in the $K^- p$ correlation as shown in Fig. 1 the sizable value of $\omega_{\pi\Sigma}$ indicates that the contribution from the $\pi\Sigma$ source is essential to reproduce the data.

The peak structure seen in Fig. 2 around $q \sim 240$ MeV/c represents the $\Lambda(1520)$ resonance. The contribution from this resonance can be simulated by a Breit-Wigner function:

$$C_{\text{res}} (q) = \frac{b \Gamma^2}{(q^2/2 \mu_{K^-p} + m_p + m_{K^-} - E_R)^2 + \Gamma^2/4},$$

(10)

with parameters $b$, $E_R$, and $\Gamma$. We can isolate the resonance by subtracting $C_{\text{fit}} (q)$ from the correlation data, using the parameters of Eq. (9) and $R = 0.9$ fm. The remaining structure in the interval $150$ MeV/c $< q < 300$ MeV/c is then fitted by Eq. (10). The resulting values of the resonance parameters are $E_R = 1520.9$ MeV and $\Gamma = 9.7$ MeV, consistent with the mass $M_{\Lambda(1520)} = 1517 \pm 4$ MeV and width $\Gamma_{\Lambda(1520)} = 15^{+8}_{-10}$ MeV of $\Lambda(1520)$ listed in Ref. [37]. As shown in Fig. 3 the sum of $C_{\text{fit}} (q)$ and $C_{\text{res}} (q)$ reproduces the peak at $q \sim 240$ MeV very well.

Finally, we give predictions for the $K^- p$ correlation function if extracted from larger systems. In $pA$ and $AA$ collisions the source size is expected to be larger than the one in $pp$ collisions: $R = (1.2)$ fm for high-multiplicity events in $pA$ collisions and $R = (2.5)$ fm in $AA$ collisions. In Fig. 3 we show the theoretical correlation function, Eq. (9), at a system size of $R = 1.6$ fm, using the same parameter set as before, Eq. (9), for demonstration. In order to estimate the uncertainty coming from the less well known $\omega_{\pi\Sigma}$, we vary its value between 0.5 and 5.0. One expects that when the source size is increased, the enhancement of the correlation function is limited to the small $q$ region and the $K^0 n$ cusp becomes less pronounced. The sensitivity to $\omega_{\pi\Sigma}$ is weaker for the larger systems, for which the contribution from the $\pi\Sigma$ source is less important.

Summary: The $K^- p$ femtoscopic correlation function has been analysed using the realistic coupled-channel potential of Ref. [28]. This potential is constructed to reproduce the amplitudes resulting from next-to-leading order chiral SU(3) dynamics [30]. Based on the coupled-channel correlation function formula [25-27], we have developed a scheme to calculate the correlation function consistently including all effects of coupled channels, Coulomb potential and threshold differences in the individual channels. The coupled channels play an important role, enhancing the correlation function and producing a prominent threshold cusp effect. The $K^- p$ correlation function data obtained by the ALICE collaboration [20] are well reproduced. The allowed range of values for the source function weight, $\omega_{\pi\Sigma}$, of the $\pi\Sigma$ channel is roughly consistent with a statistical model estimate.

We have also presented a prediction of the $K^- p$ correlation function for a generic larger system. In this case the driving coupled channels become less important as the source size increases. Analyzing correlation data extracted from collisions of larger systems could provide additional systematics for probing and constraining the $K^- p$ amplitude in low-energy regions not accessible by scattering experiments.

While the $K^{-}N-\pi\Sigma-\pi\Lambda$ coupled-channel approach [28-30]
has successfully passed the present femtoscopy test (though with adjustment of source parameters), it will be useful also to examine alternative models of low-energy $K^−p$ interactions in order to gain more systematic insights into the capabilities of such correlation function studies.

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