KAON–DEUTERON CORRELATION FUNCTION FROM AN EFFECTIVE FIELD THEORY APPROACH*

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We present a study of femtoscopic correlation functions for K^-d and K^+d pairs, and compare our results with recent measurements by the ALICE Collaboration in both Pb–Pb and high-multiplicity pp collisions. The kaon–deuteron wave functions are derived from scattering amplitudes using a unitarized chiral effective theory model describing the elementary interactions of $K^\pm$ mesons with nucleons. We then evaluate the $K^\pm d$ strong scattering amplitudes by solving the Faddeev equations within two distinct frameworks: the Impulse Approximation and the Fixed Center Approximation, which accounts for multiple scatterings. We also incorporate the long-range Coulomb effects between the kaon and the deuteron. We show that the K^-d correlation function exhibits large sensitivity to both the size of the emitting source and the relative momentum of the pair, being heavily influenced by rescattering processes. In contrast, the K^+d correlation function is dominated by the weakly repulsive K^+N interaction, showing deviations from purely Coulombic behavior only at small emission source sizes. Our predictions are in agreement with the ALICE experimental data, and also with the energy-shift and width of the $1s$ level of the kaonic deuterium preliminary results from the SIDDHARTA 2 Collaboration.

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1. Introduction

Over the past two decades, femtoscopy has emerged as a high-precision technique for probing the space-time structure of particle-emitting sources and for detailing the final-state interactions between hadrons generated in the last stage of high-energy relativistic collisions [1–3]. While the technique was initially established for correlations of light mesons, such as pion–pion pairs, recent experimental and theoretical focus has shifted towards more complex systems, for example, deuteron–hadron pairs. These systems can

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help to establish the most relevant production mechanism of light nuclei in hadronic collisions and resolve the ongoing debate between thermal freeze-out models, where nuclei emerge directly from the expanding fireball, and final-state coalescence models, where constituent nucleons merge to form nuclei at later stages [4, 5].

Correlations between a deuteron and a kaon have been successfully measured by the ALICE Collaboration, starting with the precise data on K^+d correlations in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV [6], alongside with data on both the K^+d and K^-d correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [7, 8]. Since a two-body treatment of kaon–deuteron systems is physically well-justified at the relevant momenta [9], a robust interpretation of these complex measurements necessitates a realistic, microscopically grounded description of the kaon–deuteron interaction.

In this work, we introduce a unified, rigorous theoretical framework for kaon–deuteron femtoscopy based on chiral effective elementary interactions. We combine these amplitudes within the Faddeev equations, and compute both the K^-d and K^+d amplitudes. These strong amplitudes are employed, together with a separable treatment of the Coulomb interaction, to obtain the exact pair wave functions necessary for computing theoretical correlation functions to be compared directly with the ALICE data [10].

2. Kaon–deuteron scattering amplitudes

The determination of the K^-d scattering amplitude, T_{K^-d}, requires summing the individual Faddeev partitions, T_p^- and T_n^-, which contain all processes in which the incoming K^- interacts first with the proton or the neutron of the deuteron, respectively. The system of equations reads [10, 11]

$$\begin{aligned} T_p^- &= t_{K^-p} + t_{K^-p} G_0 T_n^- - t_x G_0 T_n^x \,, \\ T_n^- &= t_{K^-n} + t_{K^-n} G_0 T_p^- \,, \\ T_n^x &= t_x - t_{\bar{K}^0 n} G_0 T_n^x + t_x G_0 T_n^- \,, \end{aligned} \tag{1}$$

where T_n^x accounts for the charge exchange channel $\bar{K}^0 nn \leftrightarrow K^- pn$.

In Eq. (1), the two-body elementary s-wave amplitudes t_i refer to the elastic interactions (t_{K^-p}, t_{K^-n}, and $t_{\bar{K}^0 n}$) and the charge exchange interaction t_x corresponding to the transition $\bar{K}^0 n \to K^- p$. These amplitudes are derived from a LO chiral unitary model [12] in coupled-channels, initially developed in Ref. [13]. This model for the kaon–deuteron interaction has previously been employed successfully at low energy at the level of scattering lengths [11]. In the present work, we extend the interaction to finite energy and consider the K^-d amplitudes beyond the threshold, allowing us to account for the correlation functions at finite relative momenta, k^*.

The G_0 function in Eq. (1) represents the free kaon propagator convoluted by the deuteron form factor $F_d(q)$,

$$G_0\left(q^0\right) = \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \frac{F_d(q)}{(q^0)^2 - q^2 - m_K^2 + \mathrm{i}\eta}\,, \qquad F_d(q) = \int \mathrm{d}^3 r\, \mathrm{e}^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} |\phi_d(r)|^2\,, \tag{2}$$

where m_K is the intermediate kaon mass (K^- or $\bar{K}^0$), and the deuteron wave function, $\phi_d(r)$, contains both s-wave and d-wave contributions from the Argonne V18 NN interaction [14].

The system of coupled equations (1) can be solved using the Impulse Approximation (IA), which amounts to exclusively keeping the first terms in T_p^- and T_n^-; or in the Fixed Center Approximation (FCA), which results in the full solution of the algebraic system.

In the simpler IA — or single-scattering approximation — the K^-d amplitude, $T_{K^-d}^{\mathrm{IA}}$, reads

$$T_{K^-d}^{\mathrm{IA}}\left(k', k\right) = \left[t_{K^-p}\left(k', k\right) + t_{K^-n}\left(k', k\right)\right] F_d(q)\,, \tag{3}$$

where $q = |\boldsymbol{k} - \boldsymbol{k}'|/2$ is half the momentum transferred to the deuteron, defined from the initial kaon momentum $\boldsymbol{k}$ and final momentum $\boldsymbol{k}'$.

The full FCA equations yield a more complex amplitude containing all orders of rescattering

$$\begin{aligned} T_{K^-d}^{\mathrm{FCA}} &= \frac{T_{K^-d}^{\mathrm{IA}} + \left(2t_{K^-p}t_{K^-n} - \tilde{t}_x^2\right) G_0 - 2\tilde{t}_x^2 t_{K^-n} G_0^2}{1 - t_{K^-p}t_{K^-n}G_0^2 + \tilde{t}_x^2 t_{K^-n} G_0^3}\,, \\ \text{with} \quad \tilde{t}_x &\equiv \frac{t_x}{\sqrt{1 + t_{\bar{K}^0 n} G_0}}\,. \end{aligned} \tag{4}$$

By comparing the FCA predictions with full exact Faddeev calculations for near-threshold observables [10], we can confidently assign a theoretical uncertainty to the FCA of the order of 10%–30%. This uncertainty lies well within the systematic uncertainties connected to the use of the chiral model used in the elementary two-body matrix elements.

For the K^+d scattering amplitude, one can obtain equivalent mathematical expressions by replacing $K^- \to K^+$, $\bar{K}^0 \to K^0$, $p \to n$, and $n \to p$.

The energy dependence of the K^-d scattering amplitude [10] reveals a pronounced peak just below the K^-pn threshold. This structure is a reflection of the subthreshold $\Lambda(1405)$ resonance, dynamically generated in the $I = 0$ $\bar{K}N$ interaction. The FCA amplifies the strength of this state with respect to the IA due to the multiple rescattering within the deuteron. Conversely, the K^+d amplitude is essentially featureless and inherently weak in strength (both in the IA and the FCA) aligning with the expectation that the K^+N interaction is mildly repulsive and elastic at low energies.

In Table 1, we present results of the scattering lengths at the $K^{\pm}d$ thresholds, for both the IA and FCA approximations. The large real negative part of the $K^{-}d$ scattering length is a signature of the dynamically generated $\bar{K}NN$ state. The large imaginary part reflects the available phase space for conversion channels ($\pi\Lambda N$, $\pi\Sigma N$). In the case of the $K^{+}d$ scattering lengths, the predictions from the IA and FCA frameworks are practically identical due to its weaker interaction.

Table 1. Calculated results for the $K^{-}d$ and $K^{+}d$ scattering lengths, alongside predictions for the strong-interaction energy shift (ϵ_{1s}) and width (Γ_{1s}) of the $1s$ atomic level in kaonic deuterium.

	$A_{K^{-}d}$ [fm]	$A_{K^{+}d}$ [fm]	ϵ_{1s} [eV]	Γ_{1s} [eV]
IA	$-0.586 + i2.145$	-0.47	791	2063
FCA	$-2.062 + i1.767$	-0.43	1124	626

In the same table, we present our predictions for the energy shift (ϵ_{1s}) and total width (Γ_{1s}) of the $1s$ orbital level in exotic kaonic deuterium atom. These quantities present large differences between IA and FCA. In the latter case, the decay width Γ_{1s} is in striking agreement with preliminary estimates from the SIDDHARTA-2 Collaboration [15, 16], though the calculated energy shift is approximately 30% larger.

3. Correlation functions

The application of the two-body amplitude to the femtoscopic correlation function between a $K^{\pm}$ and a d uses the Koonin–Pratt formula [17, 18]

$$C(k^*) = \int \mathrm{d}^3 r \; S_{12}(r) |\Psi(r;k^*)|^2 \,, \tag{5}$$

where $\Psi(r;k^*)$ represents the relative two-body wave function and $S_{12}(r)$ is the normalized relative source function, which follows a Gaussian profile

$$S_{12}(r) = \frac{1}{\left(2\pi R_{Kd}^2\right)^{3/2}} \exp\left(-\frac{r^2}{2R_{Kd}^2}\right) , \tag{6}$$

where the two-body source size R_{Kd} is related to the individual K and d source radii. Here, it is extracted from the experimental analysis of [7].

We restrict the low-energy strong dynamics to the $L = 0$ partial wave, but to all orders in the Coulomb interaction. In this case, we separate the full wave function into the complete Coulomb wave function, its s-wave projection, and the Coulomb + strong s-wave component: $\Psi(r;k^*) = \Phi^{\rm C}(r;k^*) - \Phi_0^{\rm C}(k^*r) + \Psi_0(r;k^*)$. The correlation function reads

$$C(k^*) = \int {\rm d}^3r S_{12}(r)|\Phi^{\rm C}(r;k^*)|^2 + \int 4\pi r^2 {\rm d}r S_{12}(r)\left(|\Psi_0(r;k^*)|^2 - |\Phi_0^{\rm C}(k^*r)|^2\right) . \quad (7)$$

The strong + Coulomb wave function $\Psi_0(r;k^*)$ is determined from the Lippmann–Schwinger equation projected into the s-wave

$$\Psi_0(r;k^*) = j_0(k^*r) + \int_0^\infty \frac{{\rm d}^3q}{(2\pi)^3}\frac{M_d}{E_d}\frac{1}{2\omega_K}\frac{T_{Kd}(q,k^*;\sqrt{s_{Kd}})\, j_0(qr)}{\sqrt{s_{Kd}} - E_d - \omega_K + {\rm i}\eta}, \quad (8)$$

where $j_0(x)$ is the spherical Bessel function, $\omega_K = \sqrt{q^2 + m_K^2}$ represents the intermediate kaon energy, E_d is the corresponding deuteron energy, and $\sqrt{s_{Kd}}$ defines the total invariant energy of the pair in the CoM frame.

To simplify the calculation, the strong and Coulomb scattering amplitudes are assumed to be approximately separable, $T_{Kd} \approx T_{Kd}^{\rm FCA} + T_{Kd}^{\rm C}$ (estimated within a 10% error by comparing the results with the solution of the Schrödinger equation of the same problem). In addition, we apply the on-shell factorization on the strong scattering amplitude within the momentum integral, which we regularize with a momentum cutoff $\Lambda = 1000$ MeV.

In Fig. 1, we contrast our theoretical calculations for the K^-d (top) and K^+d (bottom) correlation functions against the ALICE Pb–Pb collision data ($\sqrt{s_{NN}} = 5.02$ TeV) across three centrality classes (0–10%, 10–30%, and 30–50% corresponding to distinct emitting source radii $R_{Kd} \approx 8.30$ fm, 6.48 fm, and 4.39 fm). In the K^-d case, the Coulomb interaction alone is unable to describe the data. When the strong interaction is included, the correlation function presents a depletion, which is inherited from the subthreshold generated state. The FCA significantly improves over the simplistic IA, yielding a better explanation of the ALICE data. For the K^+d correlation functions, the strong interaction correction is tiny with respect to Coulomb, and essentially any scenario can describe the ALICE data for the three centralities. In this system, much smaller sources — high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV — reveal that the addition of the weakly repulsive K^+d strong interaction is required to match the high-precision experimental measurements. These can be clearly seen in Fig. 2. In the figure, we show the Gaussian radius $r_{\rm eff}^{K^+d} \equiv R_{K^+d}/\sqrt{2}$, which is the one quoted in Ref. [6]. It is related by a factor of $\sqrt{2}$ to ours since they use a Gaussian source $S_{12}(r) \propto \exp(-r^2/(4r_{Kd}^2))$, instead of our Eq. (6).

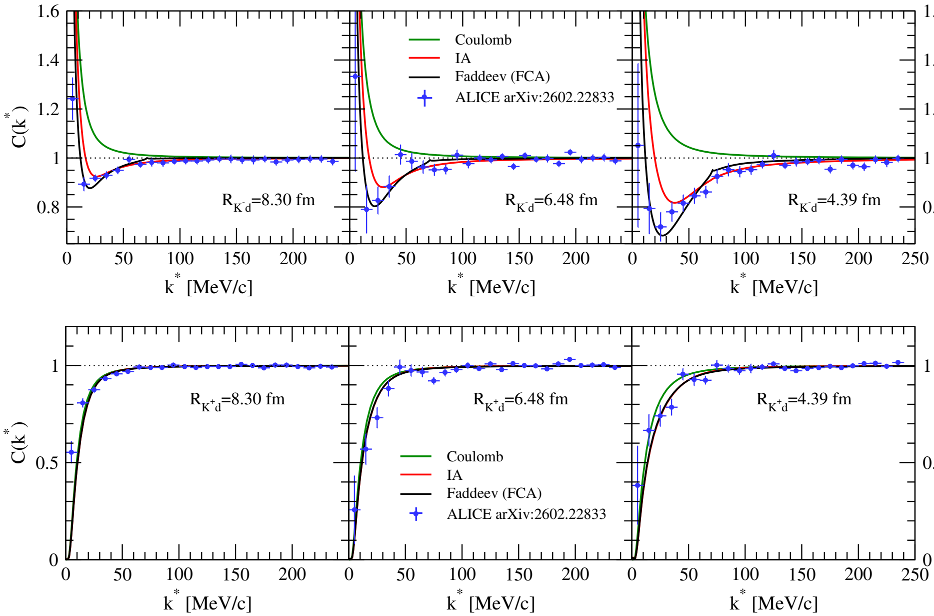

Fig. 1. Top: K^-d correlation functions as obtained from our models (IA and FCA) and from the ALICE data in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at different centralities (0–10%, 10–30%, 30–50%). Bottom: The same for K^+d correlation functions.

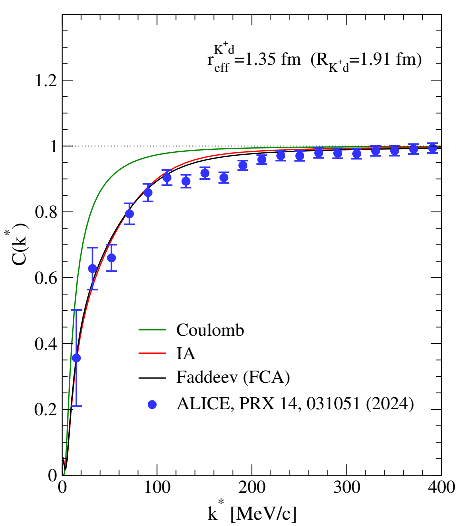

Fig. 2. K^+d correlation function of obtained from our models (IA and FCA) and from the ALICE data in pp collisions at $\sqrt{s} = 13$ TeV.

4. Conclusions

We have developed a unified framework designed to analyze K^-d and K^+d femtoscopy. Our approach combines realistic chiral effective field theory interactions in the elementary K^-N and K^+N sectors with Faddeev equations, evaluated under both the impulse approximation and the fixed-center approximation, to account for the kaon–deuteron interaction. The model includes both strong and Coulomb interactions, combined into the Koonin–Pratt formalism to obtain theoretical two-particle femtoscopic correlation functions.

The K^-d system is dominated by a strong attraction able to generate a subthreshold resonance, which is the three-body manifestation of the $\Lambda(1405)$ states. In this system, multiple-scattering effects are dominant and can only be captured by the FCA, which provides a good agreement with the femtoscopy ALICE data in heavy-ion collisions at all centralities. Conversely, the K^+d system is governed by a weakly repulsive, predominantly elastic potential. Therefore, there are essentially no differences between the IA and the FCA. In fact, departures from the pure Coulomb interaction are not visible in heavy-ion collision data at any centrality. Only in small systems — high-multiplicity pp collisions — a deviation from Coulomb, favoring the inclusion of the strong interaction, is seen in the ALICE data.

Finally, predictions concerning the $1s$ atomic level energy shift and decay width of exotic kaonic deuterium corroborate the importance of multiple scatterings, bringing our theoretical prediction into closer alignment with preliminary empirical data from the SIDDHARTA-2 experiment.

Future theoretical refinements will focus on improving the unitarity of the three-body system by accounting from coherent propagation of the kaon–deuteron systems [19], and refining the factorization assumption between the strong and Coulomb amplitudes.

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