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A study of K^-d and K^+d interactions via femtoscopy technique

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Summary. — Scattering cross-section measurements have been used to study the strong interaction between charged kaons and (anti-)deuterons. However, these studies have not been successful in determining the scattering lengths of the strong interaction between K^+d and K^-d. Moreover, the currently available theoretical predictions for the K^-d scattering parameter are largely based on input from kaonic hydrogen measurements, while no theoretical predictions have yet been published for K^+d. In this work, the first measurements of the scattering lengths of K^+d and K^-d particle pairs are presented. The results were obtained using the femtoscopy technique which is very accurate for studying interactions between two particles with low relative momenta.

1. – Introduction

The femtoscopic study of particle correlations is a well-known method used to better understand the interactions between the two particles under consideration, as well as to study the characteristics of particle emitting sources. This paper focuses mainly on the first of the two applications by studying the correlations of kaon-deuteron pairs. The determination of the interaction parameters of the kaon-deuteron pairs can contribute to the theoretical description of the strong interaction in low-energy QCD as well as to the obtaining of spin-dependent scattering parameters in the strangeness sector. The scattering parameters of the strong interaction could not be measured with other techniques such as scattering or kaonic experiments. Moreover, from a theoretical point of view, these parameters are either poorly known (K^-d) or even unknown (K^+d). Among many systems already studied via the femtoscopy technique, the correlations with deuterons in Pb-Pb collisions have never been experimentally checked. Kaon-deuteron studies were recently done in pp collisions [1] but without measurements of scattering parameters.

2. – Femtoscopy and correlation functions

Femtoscopy of particle pairs studied via correlations as a function of their relative momentum concerns particles in their final states [2]. The correlation function can be defined by the Koonin-Pratt equation:

$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 \mathrm{d}^3 r^*, \tag{1}$$

where $\vec{k}^* = (\vec{p_1} - \vec{p_2})/2$ is a half of kaon-deuteron relative momentum in the pair rest frame (PRF, the pair centre of mass is at rest, $\vec{p_1} = -\vec{p_2}$), $\vec{r}^*$ is the relative separation vector, $S(\vec{r}^*)$ is the two-particle emitting source function and $\Psi(\vec{k}^*, \vec{r}^*)$ is the pair wave function.

The source emission function describes the shape of the source and allows one to estimate the size of the region of homogeneity that can be understood as an area from which particles are emitted with similar velocities and directions. The usual approach in such kind of analysis provides the standard description of experimental data by using the Gaussian parametrization of the source. The source emission function can be described according to

$$S(\overrightarrow{r}) \sim \exp\left(-\frac{r^2}{2R_{Kd}^2}\right), \tag{2}$$

where R_{Kd} is a two-particle femtoscopic source size for non-identical particle pairs.

The wave function in the case of two particles has to take into account the quantum statistics (if particles are identical) and final-state interactions (FSI, Coulomb interaction in case the particles are charged, strong interaction in case the particles are hadrons). In this analysis, the wave function is constructed from FSI without any quantum effects as it concerns non-identical particles. The wave function for kaon-deuteron pairs can be parametrized with the scattering length (f_0) and the range of effective interaction (d_0) [3] in so-called Lednický-Lyuboshitz model [4] expressed by

$$|\psi(r^*, k^*)| = \sqrt{A_C(\eta)}\left[\exp(-ik^*r^*)F(-i\eta, 1, i\xi) + f_c(k^*)\frac{G}{r^*}\right], \tag{3}$$

where A_C is the Gamow factor expressed by $\frac{2\pi}{k^* a_c}[\exp(\pm\frac{2\pi}{k^* a_c}) - 1]^{-1}$, F is the confluent hypergeometric function, $\eta = \frac{1}{k^* a_c}$, a_c is the pair Bohr radius, $\xi = k^* r^* + \overrightarrow{k^*}\overrightarrow{r^*}$, G is a combination of regular and singular s-wave Coulomb functions described in more detail in [4] and $f_c(k^*)$ is a scattering amplitude that can be expressed by

$$f_C^{-1}(k^*) = \frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_C}h(k^* a_C) - \mathrm{i}k^* a_C, \tag{4}$$

where $h(x) = \frac{1}{x^2}\Sigma\frac{1}{n(n^2+x^{-2})} - C + \ln|x|$.

In the experiment, the correlation function is calculated as the ratio of the distributions of pairs of particles from the same collision and from two different collisions. In the first case, the signal of the real correlation is naturally present, as the particles have a chance to see each other. The second case is a reference distribution without any correlation due to the interactions.

3. – Analysis detail

The results of kaon-deuteron femtoscopy study presented here are based on the analysis of data collected in 2018 during the Pb-Pb data-taking period at k a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ by the ALICE experiment [5, 6] working at the LHC [7]. The study has been performed in three centrality intervals (0–10, 10–30, 30–50%) and two charge combination of pairs (pairs with antipairs were merged: $K^+d \oplus K^+\overline{d}$, $K^-d \oplus K^-\overline{d}$). The main detectors used in the analysis are: i) Time Projection Chamber (TPC [8]) and Time-Of-Flight detectors (TOF [9]) for identification of charged particles, ii) Inner Tracking System (ITS [10]) for better reconstruction of the primary vertex and iii) V0 detectors [11] for triggers (Minimum Bias, Central and Semicentral). For this analysis, the primary vertex of the event had to be within 10 cm along

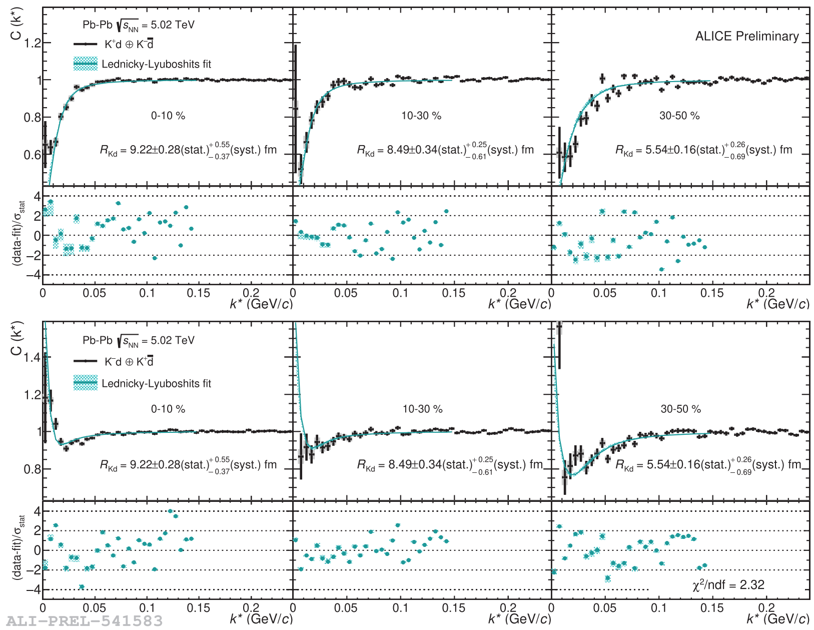

Fig. 1. – Points represents correlation functions for $K^+d \oplus K^-\overline{d}$ (upper row) and $K^-d \oplus K^+\overline{d}$ (bottom row) pairs in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ for three centrality classes. From left to right: 0–10%, 10–30%, 30–50%. Lines show the fit functions of the Lednický-Lyuboshitz model. Lower panels present the difference between the data and model functions divided by the statistical uncertainties of data points.

the beam direction from the centre of the ALICE detector. The transverse momentum (p_T) range of kaons taken to the analysis was 0.2–1.5 GeV/c and for (anti-)deuterons was 0.8–2 GeV/c. The particles were also selected according to their distance of closest approach (DCA) to the primary vertex and were accepted if the DCA was smaller than $\mathrm{DCA}_{XY}(p_T) < 0.0105 + 0.0350/(p_T/(\mathrm{GeV}/c)^{-1.1})$ cm. The pseudo-rapidity (η) for kaons and (anti-)deuterons was in the range $|\eta| < 0.8$ (see footnote ([1])). All track pairs, which share more than 5% of their total hits in the TPC, were excluded from the analysis.

4. – Results

The correlation function of selected tracks is extracted after applying corrections for non-femtoscopic background (*i.e.*, collective motion of the system) and impurity effects (quality of particle identification and fraction of primary particles). The non-femtoscopic background was estimated by extrapolating the linear fit to the correlation function outside the femtoscopic region. The corrections on imperfect particle identification and not primary particles has been established based on both data-driven signal distributions and simulation studies. Two assumptions were made in the theoretical description. First, the source is described by a Gaussian parametrization with a radius R shared between pairs of the same and opposite sign within each centrality interval. The effect of possible non-Gaussianity has been taken into account following the procedure described in [12] and simulation studies of LHYQUID [13] + THERMINATOR2 [14]. Second, the zero-effective-range approximation ($d_0 = 0$) is used. The imaginary and real parts of the

([1]) $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$, where θ is the angle between the particle momentum and the beam axis.

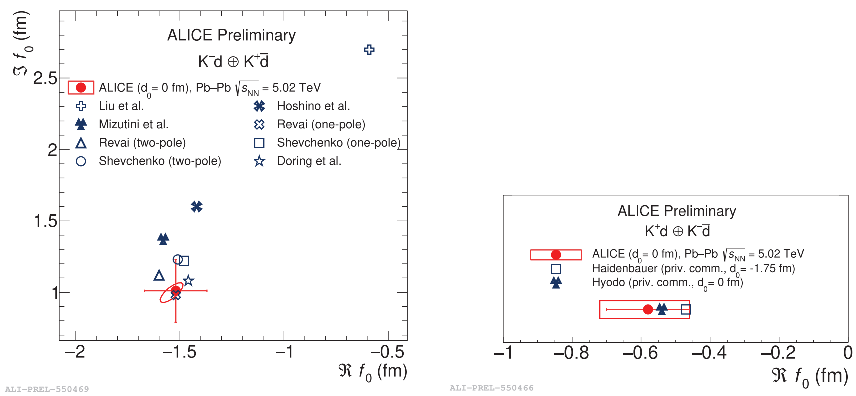

Fig. 2. – Left: comparison of the $K^-d \oplus K^+\bar{d}$ scattering length values measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ shown with red circles together with the theoretical predictions derived by [16-21] shown with blue markers. Right: comparison of the $K^+d \oplus K^-\bar{d}$ scattering length values measured in Pb-Pb collisions with red circles together with the theoretical predictions derived by Profs. T. Hyodo and J. Haidenbauer within private communication.

scattering length (f_0) are the same for all centralities and are treated as free parameters (one scattering length value for same-signs and one for opposite-signs particle pairs). Theoretical functions have been prepared following the Lednický-Lyuboshitz model for different values of the radii and scattering parameters which creates a 3D (for opposite-sign pairs) and 2D (for same-sign pairs) grid with possible solutions. In order to take into account the experimental momentum reconstruction, the theoretical functions were smeared for the experimental momentum resolution. The fitting algorithm is based on a minimum χ^2 of the data to model functions that is calculated simultaneously for all centralities and charge combinations, as the parameters are shared between functions (see similar study [15]). The final result of the analysis is composed of three different values of the femtoscopic radius at each centrality interval and two scattering lengths ($\Re$ and $\Im f_0$ for opposite-sign pairs, $\Re f_0$ for same-sign pairs).

The correlation functions together with the fit in three centrality classes of $K^-d \oplus K^+\overline{d}$ and $K^+d \oplus K^-\overline{d}$ pairs are shown in fig. 1. It is clear that we can reproduce the data using the Lednický-Lyuboshitz model. The parameters derived in the presented fit are the first experimental measurements of kaon-deuteron scattering lengths:

$$K^-d\text{: } \Re f_0 = -1.52 \pm\ 0.16(\text{stat})^{+0.04}_{-0.08}(\text{syst}),$$
$$\Im f_0 = 1.01 \pm\ 0.23(\text{stat})^{+0.07}_{-0.15}(\text{syst}),$$
$$K^+d\text{: } \Re f_0 = -0.58 \pm\ 0.12(\text{stat})^{+0.14}_{-0.12}(\text{syst}).$$

The values of measured scattering parameters were compared in fig. 2 to available theoretical predictions. The predictions for K^-d pairs come mainly from calculations that used inputs of kaonic hydrogen scattering parameters [16-21]. The K^+d scattering values derived in this work are compared to theoretical calculations provided within private communication with Prof. Tetsuo Hyodo and Prof. Johann Haidenbauer as currently there is no published theoretical prediction for this pair combination.

The source radii obtained within simultaneous fit are presented in fig. 3 as a function of the cube root of charged-particle multiplicity density. The radii for kaon-deuteron pairs from Pb-Pb collisions are between 5 and 10 fm. A clear growing trend can be observed, with the size of homogeneity rising with more central collisions.

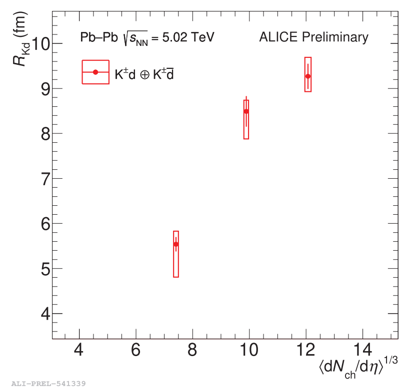

Fig. 3. – Radii as a function of $\langle dN_{ch}/d\eta\rangle^{1/3}$ measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in a simultaneous fit to all kaon-deuteron pair combinations.

5. – Summary

The femtoscopy analysis of pairs of charged kaons and (anti-)deuterons on data from Pb-Pb collisions with ALICE at the LHC allowed for first measurements of the unknown scattering parameters of the strong interaction between $K^+\bar{d}$ and K^-d pairs in a unique way. The obtained parameters are in agreement with most of theoretical calculations. The study provides also estimation of the radii of the particles emitting source of kaon-deuteron pairs in Pb-Pb collisions.

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