Письма в ЭЧАЯ. А. 2011. Т. 8, № 9. С. 148–152

Λp FEMTOSCOPY IN COLLISIONS OF Ar + KCl AT 1.76A GeV WITH HADES

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Results on Λp femtoscopy are reported at the lowest energy so far. At a beam energy of 1.76A GeV, the reaction Ar + KCl was studied with HADES at SIS18/GSI. A high-statistics and high-purity Λ sample was collected, allowing for the investigation of Λp correlations at small relative momenta. The experimental correlation function is compared to corresponding model calculations allowing the determination of the space-time extent of the Λp emission source. The Λp radius is found significantly smaller than that for Au + Au/Pb + Pb collisions in the AGS, SPS and RHIC energy domains, but larger than that for electroproduction from He. Taking into account all available data, we find the Λp source radius to increase almost linearly with the number of participants to the power of one-third.

PACS: 25.75.-q; 25.75.Dw; 25.75.Gz

INTRODUCTION

Two-particle correlations of hadrons at small relative momenta are widely used to study the space-time extent of their source created in heavy-ion collisions or other reactions involving hadrons [1]. Generally, the sign and strength of the correlation are affected by i) the strong interaction, ii) the Coulomb interaction if charged particles are involved, and iii) the quantum statistics in case of identical particles (Pauli suppression for fermions, Bose–Einstein enhancement for bosons). Their interplay makes, e.g., pp correlation functions rather complex with a suppression at very small relative momenta (due to items ii) and iii)) followed by a maximum which results from the short-range attractive potential of their strong interaction. In contrast, correlations of nonidentical hadrons, with at least one partner being uncharged, are sensitive to the strong interaction alone. Hence, Λp correlation functions are well suited to study the spatiotemporal extension of the particle-emitting source, provided the Λp interaction is known [2]. Presently, information on Λp correlations is rather scarce. Due to the necessity of having high statistics of protons and Λ's at small relative momenta, such information is available at high beam energies only. Experimental Λp correlation functions have been reported for central collisions of Au + Au/Pb + Pb by E895 [3] at AGS, by NA49 [4] at SPS, by STAR [5] at RHIC, and, for electroproduction from He, by CLAS [6] at JLab. On the other hand, the higher the energy the wider the particles are distributed in momentum space resulting in a reduced probability of finding pairs with small relative momenta. Thus, at lower beam energies an exceptionally large number of events and the more compact momentum distribution of Λ hyperons might compensate partially their lower production probability. Indeed, such a high-statistics Λ sample is available to us [7, 8], making an analysis of Λp correlations feasible. Furthermore, at low energies the feed-down correction to the Λ is smaller and more reliable, being of importance for comparisons to models applying explicitly to primary Λ's like the model by Lednicky and Lyuboshitz [9] which we use in the present report on the first observation of Λp correlations in heavy-ion collisions at beam energies below 2 GeV per nucleon [10].

1. THE EXPERIMENT

The experiment was performed with the High Acceptance Di-Electron Spectrometer (HADES) at the Schwerionensynchrotron SIS18 at GSI, Darmstadt. HADES, although primarily designed to measure di-electrons [11], offers excellent hadron identification capabilities. A detailed description of the spectrometer is presented in [12], while information on track reconstruction and particle identification can be found in [7, 13, 14]. A ^{40}Ar beam of about 10^6 particles/s with kinetic energy of $1.756A$ GeV ($\sqrt{s_{NN}} = 2.61$ GeV) was incident on a four-fold segmented target of natural KCl with a total thickness of 5 mm corresponding to 3.3% interaction probability. The position resolution of the primary (reaction) vertex amounts to 0.3 mm in both transverse directions, while in beam direction it amounts to 1.5 mm as expected from the finite thickness of the target slices. The data readout was started by a first-level trigger (LVL1) decision, requiring a minimum charged-particle multiplicity $\geqslant 16$ in the time-of-flight (TOF) detectors covering polar angles from 18 to 85°. The integrated cross section selected by this trigger comprises approximately the most central 35% of the total reaction cross section. The corresponding mean number of participants, estimated with the UrQMD transport approach [15] amounts to $\langle A_{\rm part}\rangle = 38.5 \pm 2.5$. About 700 million LVL1 events were processed for the present investigation.

2. THE CORRELATION ANALYSIS

Let $Y_{12}(\mathbf{p}_1, \mathbf{p}_2)$ be the coincidence yield of pairs of particles having the momenta $\mathbf{p}_1$ and $\mathbf{p}_2$. Then the two-particle correlation function is defined as

$$C(\mathbf{p}_1, \mathbf{p}_2) = \mathcal{N} \frac{\sum\limits_{\text{events,pairs}} Y_{12}(\mathbf{p}_1, \mathbf{p}_2)}{\sum\limits_{\text{events,pairs}} Y_{12,\text{mix}}(\mathbf{p}_1, \mathbf{p}_2)}. \tag{1}$$

The sum runs over all events and over all pairs satisfying certain conditions. Event mixing, denoted by the subscript «mix», means to take particle 1 and particle 2 from different events. Due to limited statistics, the six-dimensional correlation function is projected onto one-half of the relative momentum in the pair c.m. frame; i.e., we consider $C(k)$ with $k = |\mathbf{p}_1 - \mathbf{p}_2|/2$. The normalization factor $\mathcal{N}$ in (1) is fixed by the requirement $C(k) \to 1$ at large relative momenta, $k = 0.10{-}0.15$ GeV/c.

In the present analysis we identified the Λ hyperons through their decay $\Lambda \to p\pi^-$. The resulting invariant-mass distribution of events containing at least one additional well-identified proton is displayed in Fig. 1, a, b. Taking the resulting Λ sample (hatched area), we started the correlation study by combining, for each event containing a Λ candidate, the Λ with those protons not already contributing to the Λ. The result is a Λp relative-momentum distribution

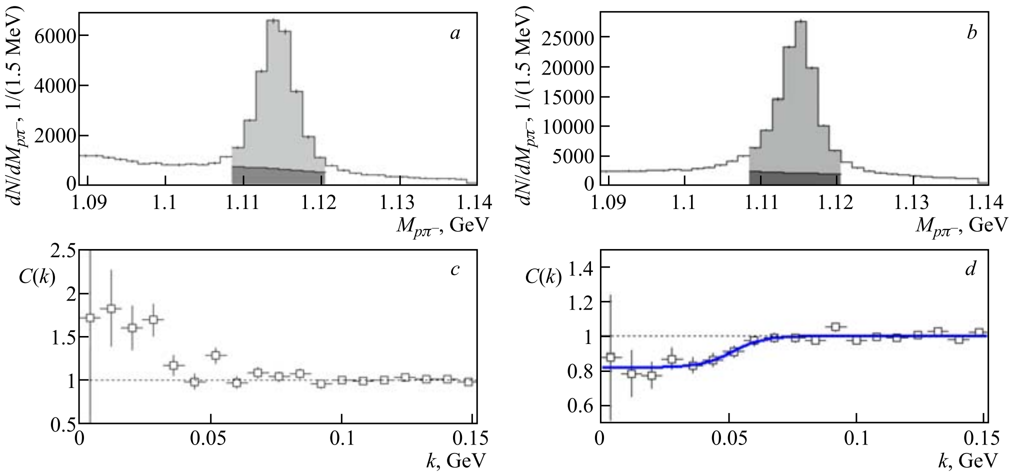

Fig. 1. *a*) The $p\pi^-$ invariant mass distribution. Light and dark hatched areas represent the statistics of the Λ signal and the corresponding Λ impurity, respectively, both contributing to the Λp correlation analysis. *c*) The uncorrected Λp correlation function. *b, d*) The same, but for simulated Λ hyperons with their decay products embedded into true experimental data. The full curve in the panel *d* is a fit with a Fermi-type function (see text) used to correct for reconstruction losses (due to close tracks) of the experimental Λp correlation function displayed left

containing a total of 240,000 proton–Λ pairs. However, only 2,700 (260) pairs contribute to the interesting region of small relative momenta, $k < 0.1\,(0.04)$ GeV/*c*. The resulting raw Λp correlation function is displayed in Fig. 1, *c*, *d*. A clear enhancement at small relative momenta is found, indicating the effect of the strong Λp interaction.

Corrections for the finite small-angle acceptance losses were deduced from simulations. Twenty-five million thermal Λ's (one per event) were generated using the fireball option of the event generator PLUTO. The simulation data are processed through GEANT, modeling the detector response. The GEANT data were embedded into real experimental data and processed through the full analysis chain. Figure 1, *b* displays the resulting p–π^- invariant-mass distribution. The correlation function of, ab initio, uncorrelated pairs of (simulated) Λ hyperons and (experimental) protons is expected to be flat at unity. Figure 1, *d* shows the correlation function of simulated Λ's combined with protons from experimental data. A slight suppression at small relative momenta is visible, indicating the bias of the apparatus and the track-finding losses. The full curve is a fit with a Fermi-type function, $f_{\rm acc}(k) = 1 + A_1/(1 + {\rm e}^{(k-A_2)/A_3})$, used to correct the experimental Λp correlation function for reconstruction losses due to close tracks. The close-track correction is performed via $C(k) \to C(k)/f_{\rm acc}(k)$, while the purity correction is done by the transformation $C(k) \to 1 + (C(k) - 1)$/PairPurity. Here, PairPurity is the product of Λ and proton purities (0.95 ± 0.02). The Λ purity follows from the product of the signal purity of 0.816 ± 0.013 as derived from the $p\pi^-$ invariant mass distribution of Fig. 1, *a* and the feed-down correction of the decay $\Sigma^0 \to \Lambda\gamma$. The corresponding yield ratio of $\Lambda/(\Lambda + \Sigma^0)$ of 0.80 was derived from calculations with the UrQMD transport approach [15]. Recent predictions [16] of the Λp and $\Sigma^0 p$ correlation functions showed very similar shapes and magnitudes of both correlations. However, the

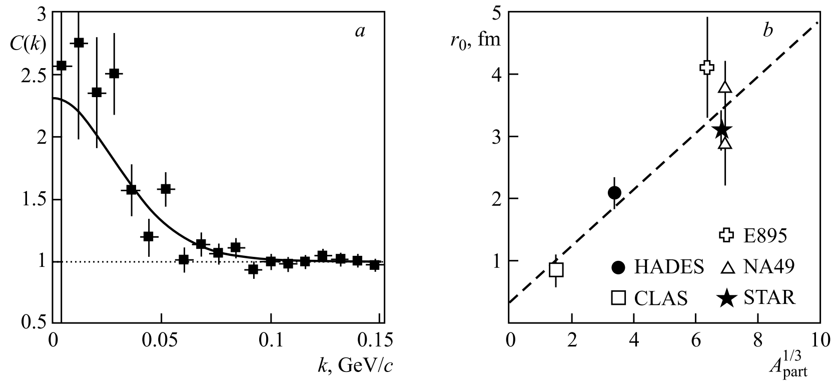

Fig. 2. *a*) The Λp correlation function after close-track and purity corrections. The full curve represents the best fit (see text) with the Analytical Model by Lednicky and Lyuboshitz [9]. *b*) The Gaussian radius of the Λp emission source as a function of system size. The symbols indicate data taken with HADES at SIS, CLAS [6] at JLab, E895 [3] at AGS, NA49 [4] at SPS, and STAR [5] at RHIC, respectively. The dashed line is a linear regression to the data

strength of the residual correlations carried by secondary Λ's from Σ^0 decays, $p\Lambda_{\Sigma^0}$, is expected to be reduced by about 50% by decay kinematics [16]. Hence, we approximated the feed-down correction by a factor of 0.90 ± 0.10.

Finally, we applied a fit to the corrected Λp correlation function (Fig. 2, *a*) with a fit function derived from [9]. Following the procedure described in [5], we used the Λp scattering lengths ($f_0^s = -2.88$ fm, $f_0^t = -1.66$ fm) and effective ranges ($d_0^s = 2.92$ fm, $d_0^t = 3.78$ fm) for the spin singlet and triplet states of the Λp system as given in [2]. The optimum Gaussian radius provided by the fit amounts to

$$r_0 = (2.09 \pm 0.16\,^{+0.12}_{-0.10}\,^{+0.09}_{-0.16}\,^{+0.09}_{-0.11})\ \text{fm}, \tag{2}$$

where the 1st error is the statistical error, while the 2nd, 3rd, and 4th ones represent the systematic errors due to the uncertainties of the close-track correction with embedded Λ's, due to the pair purity correction, and due to a $\pm 25\%$ variation of the scattering lengths entering the model [9], respectively.

3. COMPARISON TO OTHER EXPERIMENTS

The present Λp source radius may be compared to the corresponding radii derived in other experiments. In Fig. 2, *b* we show the Gaussian radius as a function of the number of participants to the power of one-third, $A_{\rm part}^{1/3}$, which is calculated from the centrality and the total size of the corresponding collision system using a geometrical model of penetrating sharp spheres. While for the data measured by NA49 [4] at SPS ($158A$ GeV Pb + Pb, preliminary), by STAR [5] at RHIC (Au + Au at $\sqrt{s_{NN}} = 200$ GeV), and by CLAS [6] at JLab (preliminary results from $e + {}^3$He (^{4}He) at 4.7 (4.46) GeV), the Gaussian radius r_0 is determined using the same model as in the present analysis, the half-maximum radius $R_{1/2}$ derived by E895 [3] at AGS ($6A$ GeV Au + Au) applying an imaging procedure was transformed to a Gaussian radius via $r_0 = R_{1/2}/\sqrt{2\ln 2}$. Clearly, the Λp source radius increases with system size. Similarly to the systematic trends of two-pion [1, 17] and two-kaon [18] source radii, we find an almost linear increase with $A_{\rm part}^{1/3}$.

4. SUMMARY

In summary, we observed, for the first time in heavy-ion collisions at SIS energies, Λp correlations at small relative momenta. The system Ar + KCl at $1.76A$ GeV beam energy was measured with the HADES detector. The Λp correlation function was compared to the output of the model by Lednicky and Lyuboshitz. The present Λp source radius is found significantly smaller than that deduced from Au + Au/Pb + Pb collisions at higher beam energies and larger than that reported for electroproduction from He. It increases almost with $A_{\rm part}^{1/3}$.

Acknowledgements. The HADES collaboration gratefully acknowledges the support by BMBF grants 06DR9059D, 06FY171, 06MT238 T5, and 06MT9156 TP5, by HGF VH-NG-330, by DFG EClust 153, by GSI TMKRUE, by the Hessian LOEWE initiative through HIC for FAIR (Germany), by grants MSMT LC07050 and GA ASCR IAA100480803 (Czech Rep.), by grant KBN 1P03B 056 26 (Poland), by grants FPA2006-09154 and CPAN:CSD2007-00042 (Spain), by grant UCY-10.3.11.12 (Cyprus), by CNRS/IN2P3 (France), by INFN (Italy), and by EU contracts RII3-CT-2005-515876 and HadronPhysics2 No. 227431.

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