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SOURCE-SIZE MEASUREMENTS IN THE $e^3\mathrm{He}(^4\mathrm{He}) \to e'p\Lambda X$ REACTION*

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We report preliminary data on proton–lambda correlations at small relative momentum q in the $e^3\mathrm{He}(^4\mathrm{He}) \to e'p\Lambda X$ reaction at $E_0 = 4.7(4.46)$ GeV using the CLAS detector at Jefferson Lab. The enhancement of the correlation function at small q was found to be in qualitative agreement with theoretical expectations. The size of emission region about 1.5 fm was estimated using Lednický–Lyuboshitz analytical model. The experimental correlation function is compatible with the P-matrix fit of the hyperon–nucleon data. Small relative momentum proton–lambda correlations both for He target and for electroproduction reaction were studied for the first time.

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1. Introduction

It was shown by Wang and Pratt [1] that the $p\Lambda$ finals state interaction (FSI) leads to an enhancement in the $p\Lambda$ correlation function at low relative momentum which allows one to infer the size of the emitting source. The inferred lambda-source parameters may provide new valuable information, because lambdas are strangeness-carrying baryons. In some cases $p\Lambda$ correlations might be more sensitive to the source size than pp correlations because of the absence of the repulsive Coulomb FSI in the $p\Lambda$ system.

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In [2] we already reported data on two-proton correlations at small relative momentum q studied in $eA(^3\mathrm{He},\ ^4\mathrm{He},\ ^{12}\mathrm{C},\ ^{56}\mathrm{Fe}) \to e'ppX$ reactions. Here we report data on $p\Lambda$ correlations at small relative momenta in $e^3\mathrm{He}(^4\mathrm{He}) \to e'p\Lambda X$ reaction for the incident electron energy of 4.7(4.46) GeV. The measured $p\Lambda$ correlation function is affected by the residual correlation from $p\Sigma^0$, $\Lambda\Lambda$ correlations [3] and the pp correlation in the misidentified $p\Lambda$ background. Both these distortion effects play significant role for high-energy heavy-ion collisions at RHIC [4] and LHC. In the CLAS experiment, the $\Lambda\Lambda$ and $p\Sigma^0$ pair production is suppressed with respect to the $p\Lambda$ pair production due to the strong kinematical restrictions. This circumstance provides the possibility to extract and evaluate the pp-correlation effect on the misidentified $p\Lambda$ background. This is an important methodical aspect for high-energy heavy-ion femtoscopy.

2. Data sample and reaction identification

The measurements were performed with the CEBAF Large Acceptance Spectrometer (CLAS) [5] in Hall B at the Thomas Jefferson National Accelerator Facility. The run conditions are described in detail in [6]. Only events with at least two detected protons within momentum interval 0.3–2.0 GeV/c and at least one negative pion within momentum interval 0.1–0.7 GeV/c were accepted. Misidentifying of electrons, negative pions or protons was negligible. Λ's were identified by the decay into $p\pi^-$. The pairs of tracks hitting a single scintillator were excluded from our analysis because they have ambiguous time-of-flight values. To reduce target wall events from eHe ones we tuned up the vertex cut using the empty target run. The contribution of target wall in the selected events was less than 1.5%.

The invariant-mass distribution of proton–pion pairs for combined statistics of both reactions $e^3\mathrm{He} \to e'pp\pi^- X$ and $e^4\mathrm{He} \to e'pp\pi^- X$ is shown in Fig. 1 (left). There are two types of contributions shown in this figure. The first one (lambda contribution) — when both a proton and a pion are from lambda decay. The second one (direct contribution) — when one (a proton or a pion) or both (a proton and a pion) are direct particles. The pairs from Λ decay generate a Λ peak which is clearly seen at the correct position in Fig. 1 (left). The background pairs demonstrate a smooth phase-space dependence. To reduce the background contribution we apply the cuts on the transferred energy: $(\nu - \nu_{\mathrm{min}}) > 0.8$ GeV and on the missing mass: $M^2_{\mathrm{mis}} > 2.1$ GeV^2. Here, ν_{min} is the minimum value of the transferred energy according to strangeness conservation in the strong interactions and M_{mis} is the missing mass for reaction under study. The upper histogram in Fig. 1 (left) corresponds to all $p\pi^-$ pairs (without cuts). The medium histogram in Fig. 1 (left) corresponds to $p\pi^-$ pairs after both cuts on the transferred energy and on the missing mass were applied. The difference between the two histograms is shown by the lower histogram in Fig. 1 (left). After applying the cuts, the lambda-contribution-to-direct-contribution ratio for combined statistics of both reactions $e^3\mathrm{He}\to e'pp\pi^-X$ and $e^4\mathrm{He}\to e'pp\pi^-X$ is increased from 0.74 to 0.99, while only 9% of Λ's are lost. The whole statistics ($^3\mathrm{He} + ^4\mathrm{He}$) in the invariant-mass interval $1.1135 < M_{p\pi^-} < 1.1175$ GeV is: 6376 of $p\pi^-$ pairs from Λ decay, 6427 of direct $p\pi^-$ pairs, *i.e.* 12803 pairs in total.

After all selections, the transferred energy ν is between 1.5 and 4.5 GeV with the mean value of 3.03 GeV. The Q^2 is between 0.6 and 5 $(\mathrm{GeV}/c)^2$ with the mean value of 1.4 $(\mathrm{GeV}/c)^2$.

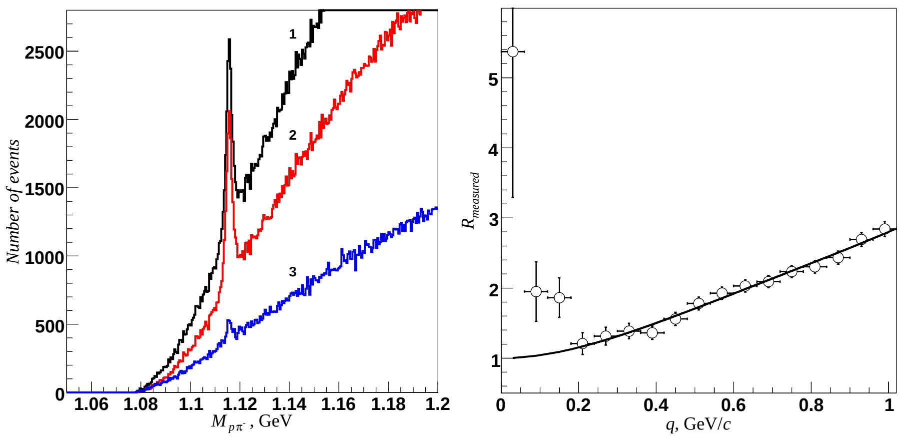

Fig. 1. Left: The $p\pi^-$-pair invariant-mass distribution for $e^3\mathrm{He}(^4\mathrm{He}) \to e'pp\pi^-X$ reaction. Right: The measured $p\Lambda$ correlation function *versus* momentum difference between proton and Λ in $p\Lambda$-pair reference frame. The curve shows a fitted correction due to the long-range correlation.

3. Correlation function

The measured correlation function $R_{p\Lambda}(q) = \frac{N_\mathrm{r}(q)}{N_\mathrm{m}(q)}$ has been defined as the ratio of the measured distribution $(N_\mathrm{r}(q))$ of the three-momentum difference of the two particles to the reference one $(N_\mathrm{m}(q))$ obtained by mixing particles from different events of a given class, normalized to unity at sufficiently large relative momenta [7]. Here, $q = |\boldsymbol{q}|$, $\boldsymbol{q} = (\boldsymbol{p}_p - \boldsymbol{p}_\Lambda)$ is momentum difference between proton and Λ in $p\Lambda$-pair reference frame; all proton–pion pairs within the Λ invariant-mass region are considered as Λ's with the three-momentum $\boldsymbol{p}_\Lambda = (\boldsymbol{p}_p + \boldsymbol{p}_\pi)$.

The measured $p\Lambda$ correlation function is shown in Fig. 1 (right). All experimental cuts are applied. The correlation function shows a pronounced enhancement in the region of small relative momenta q. The smooth increase of the correlation function at $q \geq 0.2$ GeV$/c$ has been observed also for proton–proton correlation function in the reaction $e\mathrm{He}\to\ e'\,p\,p\,X$ reported in our previous paper [2]. This increase (so-called long-range correlations (LRC)) arises mainly due to the neglected momentum conservation in the for mixed events. Empirically, LRC can be parametrized by $R \propto \exp(b\cos\psi)$, where ψ is the angle between the two particles and b is a constant [8]. Practically, LRC is usually fitted by a factor $(1+\mathrm{const.}\times q^2)$ [2]. The LRC corrected proton–lambda correlation function is shown in Fig. 2 (left).

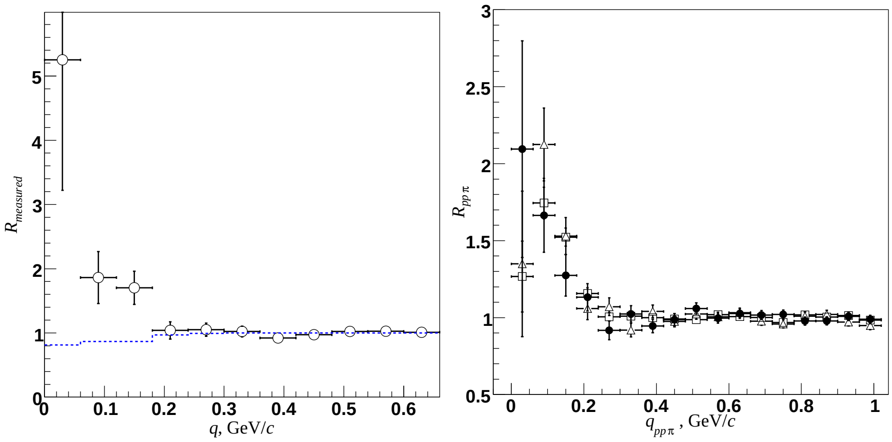

Fig. 2. Left: The measured $p\Lambda$ correlation function *versus* q. The dashed line corresponds to the close-track efficiency correction for the measured $p\Lambda$ correlation function. Right: Comparison of p–$p\pi$ correlation functions, which are measured by three different methods.

Since the $\Lambda \to p\pi^-$ decay momentum (0.101 GeV/c) is relatively small, one has to take into account the close-track efficiency for proton pairs [9] when the $p\pi$-pair mass is close to M_Λ. We apply close-track-efficiency correction for pair of protons in the same manner as in [2]. The close-track efficiency for measured correlation function is shown by the dashed line on Fig. 2 (left).

The $p\Lambda$ correlation function is calculated according to the formula $R_{p\Lambda,pp\pi} = \eta \cdot R_{p\Lambda} + (1-\eta)\cdot R_{pp\pi}$, where $\eta \simeq 0.5$ is the ratio of Λ pairs to $p\pi^-$ pairs when $M_{p\pi} \sim M_\Lambda$. $R_{p\Lambda,pp\pi}$ is the measured correlation function, which is a combination of both $p\Lambda$ and $pp\pi$ correlation functions.

To measure the p–$p\pi$ correlation itself (from direct contribution) we used three different experimental methods (see Fig. 2 (right)). First (•), we have calculated the p–$p\pi^-$ correlation function requiring $M_{p\pi^-}$ out of the Λ peak region (1.1055 GeV$<M_{p\pi^-}<$ 1.1135 GeV and 1.1175 GeV$<$ $M_{p\pi^-}<$ 1.1255 GeV). Second (□), we have calculated the p–$p\pi^+$ correlation function requiring $M_{p\pi^+}$ out of the Λ peak region using the same mass intervals as for the p–$p\pi^-$ correlation function. And the third ($\triangle$), we have calculated the p–$p\pi^+$ correlation function requiring $M_{p\pi^+}$ in the Λ peak region (1.1135 GeV$< M_{p\pi^+} <$ 1.1175 GeV). We can conclude that all the three methods are in agreement within statistical errors. It should be noted that $R_{pp\pi} \neq 1$ and consistent with the pp-correlation function measured in [2] smeared out by adding a pion momentum. The statistical errors in $R_{pp\pi}$ are two times smaller than those in the measured $R_{p\Lambda,pp\pi}$.

Fig. 3 (left) shows the derived proton–lambda correlation function $R_{p\Lambda}(q)$ corrected for the close-track efficiency, "long-range" correlations(LRC), and direct p–$p\pi$ contribution. Statistical and systematic errors have been added in quadrature.

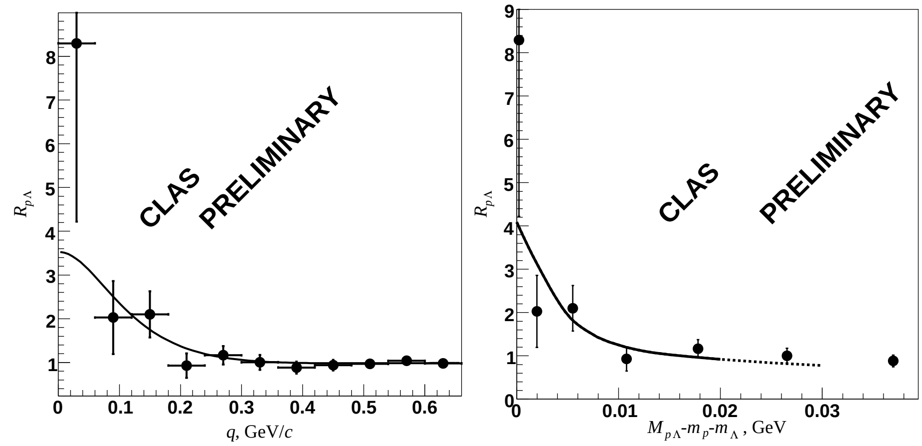

Fig. 3. Left: The derived proton–Λ correlation function $R_{p\Lambda}$. Solid curve corresponds to the source size parameter $r_0 = 0.85$ fm. Right: The derived proton–Λ correlation function *versus* the invariant mass of proton and lambda. The curve represents the description of the experimental data by the P-matrix approach.

4. The source size

The two-particle correlation function $\mathcal{R}(\boldsymbol{p}_1, \boldsymbol{p}_2)$ at small k^* values (k^* is the momentum of one particle in the two-particle c.m. system) is basically given by the square of the wave function of the corresponding elastic transition $ab \to ab$ averaged over the distance $\boldsymbol{r}^*$ of the emitters in the two-particle c.m. system and over the particle spin projections [10]:

$$\mathcal{R}(\boldsymbol{p}_1, \boldsymbol{p}_2) \doteq \langle |\psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*)|^2 \rangle$$
$$\doteq 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 + \frac{2\mathrm{Re} f^S(k^*)}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\mathrm{Im} f^S(k^*)}{r_0} F_2(Qr_0) \right], \quad (1)$$

where $F_1(z) = \int_0^z dx e^{x^2-z^2}/z$, $F_2(z) = (1 - e^{-z^2})/z$, and ρ_S is the emission probability of the two particles in a state with the total spin S; we assume the emission of unpolarized particles, *i.e.*, $\rho_0 = 1/4$ and $\rho_1 = 3/4$ for pairs of spin-1/2 particles. The analytical expression in Eq. (1) corresponds to the Gaussian $\boldsymbol{r}^*$ distribution $d^3N/d^3r^* \sim \exp(-\boldsymbol{r}^{*2}/4r_0^2)$.

The nonsymmetrized wave function describing the elastic transition can then be approximated by a superposition of the plane and spherical waves, the latter being dominated by the s-wave, $\psi^{S(+)}_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) \doteq \exp(-i\boldsymbol{k}^*\boldsymbol{r}^*) + f^S(k^*)\frac{\exp(ik^*r^*)}{r^*}$. The s-wave scattering amplitude $f^S(k^*) = \frac{\eta^S \exp(2i\delta^S)-1}{2ik^*} = (1/K^S - ik^*)^{-1}$, where $0 \leq \eta^S \leq 1$ and δ^S are, respectively, the elasticity coefficient and the phase shift; K^S is a function of the kinetic energy, *i.e.*, an even function of k^*. In the effective range approximation, $1/K^S \doteq 1/a^S + \frac{1}{2}d^S k^{*2}$, where a^S and d^S are respectively the s-wave scattering length and effective radius at a given total spin S; in difference with the traditional definition of the two-baryon scattering length, we follow here the same sign convention as for meson–baryon or two-meson systems.

The K^S function and the low-energy scattering parameters are real in the case of only one open channel, as in the near threshold $p\Lambda$ scattering. For $p\Lambda$ system, we use the values from [1]: $a^0 = 2.88$ fm, $a^1 = 1.66$ fm, $d^0 = 2.92$ fm, and $d^1 = 3.78$ fm. The curve in Fig. 3 (left) corresponds to $r_{\rm rms} = 1.5$ fm ($r_0 = 0.85 \pm 0.25$ fm). We neglect here the emission duration which is effectively absorbed in the parameter $r_{\rm rms}$. Calculated curve is in reasonable agreement with the data. Measured source size proved to be consistent with the one for semi-inclusive two-proton electroproduction reaction for ^{3}He and ^{4}He target at approximately the same initial energy [2]. Experimental systematic errors on $r_{\rm rms}$ arise mainly from the uncertainty in the direct p–$p\pi$ contribution ($\approx 10\%$ with respect to statistical errors), $\Sigma \to \Lambda\gamma$ contribution($\approx 20\%$) [12], close-track efficiency correction ($\approx 5\%$), the correction for long-range correlations ($\approx 5\%$), and the correction for momentum resolution ($\approx 2\%$).

5. The $\boldsymbol{P}$-matrix approach to the $\boldsymbol{\Lambda p}$ FSI

Twenty years ago the data set on low-energy hyperon–nucleon (YN) interaction available at that time was successfully described [13] within the framework of the Jaffe–Low P-matrix [14]. The P-matrix establishes the connection between the scattering data and the multiquark states. From that point of view the coupled ΛN–ΣN channels with $I = 1/2$, $J^P = 0^+$ are particularly interesting. It has been known for a long time that a pole exists near the $\sum^+ n$ threshold in the $^3S_1$ hyperon–nucleon scattering amplitude [15, 16]. There has been a good deal of controversy concerning the position of this pole and its nature [16–18]. The P-matrix analysis performed in [13] favors the identification of this structure with the SU(3) partner of the deuteron. Such a pole may be called a $\sum N$ bound state and a Λp resonance, or an unstable bound state according to the classification of [18]. The genuine six-quark state [19] cannot be responsible for the structure near the $\sum N$ threshold, since the corresponding pole moves away from the physical region when the coupling between the quark and hadronic channels is turned on [13].

We applied the P-matrix analysis of the YN interaction to the new CLAS data on Λp correlation near threshold. The P-matrix approach was reformulated in the spirit of the Migdal–Watson FSI theory [20]. The energy region, where the resulting equations can be applied, is not as wide as the applicability region of the original P-matrix. We were not permitted to use our approach up to the $\sum N$ threshold. However, our present study confirms the conclusions made in [13] on the location and the nature of the pole near the $\sum N$ threshold since, the new CLAS data will be rather accurately described by the set of the P-matrix parameters obtained in [13]. The correlation function $R_{p\Lambda}(\varepsilon)$ ($\varepsilon = M_{p\Lambda} - m_p - m_\Lambda$, where $M_{p\Lambda}$ is the invariant mass of $p\Lambda$ pair) calculated according to P-matrix [14] analysis of the YN interaction is presented in Fig. 3 (right). The corresponding spin-averaged scattering length and effective radius are $a = 2.44$ fm, $d = 2.64$ fm. The agreement with the experimental data is reasonable.

6. Conclusions

Being summarized, the small relative momentum correlations between proton and Λ produced in eHe interactions at 4.5–4.7 GeV have been investigated. Small relative momentum $p\Lambda$ correlation function both for He nuclei and for electroproduction reaction were measured for the first time. The data clearly show a narrow structure in the correlation function in the region of small relative momenta ($q < 0.2$ GeV/c) which is in qualitative accordance with theoretical expectations. The important p–$p\pi$ correlations were studied. It was shown that p–$p\pi$ pairs in the region of $M_{p\pi} \approx M_\Lambda$ are correlated. The measured proton–Λ correlation function was corrected for the p–$p\pi$ correlations. The source size for the strangeness-production reaction proved to be consistent with the one measured in semi-inclusive two-proton-production reaction. The experimental proton–lambda correlation function is compatible with the P-matrix fit of the hyperon–nucleon data.

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