Lambda-proton correlations in relativistic heavy ion collisions

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The prospect of using Λp correlations to extract source sizes in relativistic heavy ion collisions is investigated. It is found that the strong interaction induces a large peak in the correlation function that provides more sensitive source size measurements than pp correlations under some circumstances. The prospect of using Λp correlations to measure the time lag between lambda and proton emissions is also studied.

Two-particle correlations have proven to be a powerful tool for determining source sizes and lifetimes in heavy ion collisions. At low energies, correlations of protons, neutrons and intermediate mass fragments have provided information on the space-time extent of the collision systems [1]. At relativistic energies, pion, kaon and proton correlations have greatly enhanced our understanding of the dynamics of heavy-ion collisions [2]; these correlations provide different but complementary information. For instance, heavier particles are more affected by collective flow, thus making the mass-dependence of source sizes a test of our picture of explosive flow in heavy ion collisions; freeze-out conditions may be different for pions, kaons and protons, thus comparing parameters inferred from their correlations allows one to test the conjecture of sequential freeze-out.

In this letter, we explore lambda-proton (Λp) correlations as a candidate of interferometric study. We find that an enhancement to the correlation function at low relative momentum allows one to infer the size of the emitting source. The inferred lambda source parameters may provide valuable information because lambdas are strangeness carrying baryons. Unlike two-proton (pp) system, the Λp system has no repulsive Coulomb interaction. Thus the enhancement from the strong interaction better survives when source sizes become large. We illustrate the sensitivity of Λp correlations and show that for large sources, they might be more sensitive than pp correlations, but not as sensitive as coalescence measurements. We also study the possibility to determine whether lambdas and protons are emitted simultaneously by comparing the correlations for positive and negative values of the projected outward relative momentum.

The correlation of two particles from a chaotic source may be estimated by assuming that they interact only with each other after they are emitted from space time points x_a and x_b [3],

$$C(\mathbf{p}_a,\mathbf{p}_b) = \frac{\mathcal{P}(\mathbf{p}_a,\mathbf{p}_b)}{\mathcal{P}(\mathbf{p}_a)\mathcal{P}(\mathbf{p}_b)} \approx \frac{\int d^4x_a d^4x_b S_a(p_a,x_a)S_b(p_b,x_b)|\phi_{\rm rel}(\mathbf{p}_b-\mathbf{p}_a)|^2}{\int d^4x_a d^4x_b S_a(\mathbf{p}_a,x_a)S_b(\mathbf{p}_b,x_b)} \quad (1)$$

In principle, the correlation depends on the size and shape of the source described by function $S(\mathbf{p},x)$, which provides the differential probability of emitting particles of momentum $\mathbf{p}$ at a space-time point x. However, for the purposes of our study we will ignore the momentum dependence of the source functions and assume a Gaussian form for S.

$$S(x_a) = \delta(t)\exp\left(-\frac{x^2+y^2+z^2}{2R_g^2}\right), \quad (2)$$

where R_g is the Gaussian size of the source.

The correlation function's sensitivity to the source size depends on the form of the relative wave function, $\phi_{\rm rel}$. The relative wave function is determined by the relative strong interaction, the relative Coulomb interaction, and in the case of identical particles, symmeterization constraints. Since the Λp system involves non-identical particles, and interacts mostly through the s-wave channel at low relative momentum, it is largely insensitive to details about the shape of the emitting source. However, since the strong interaction is short range, the enhancement of the correlation function at low relative momentum is highly sensitive to the size. Furthermore, the lack of a Coulomb repulsion, which dominates pp correlations at low relative momentum, allows the Λp correlation function to remain sensitive to the volume for fairly large sources.

An Urbana-type potential which was motivated from low energy Λp scattering and hypernuclei bind energy data [4] is used to generate the relative wave functions.

$$V_{\Lambda p} = V_C - \left(\bar{V} - \frac{1}{4}V_\sigma \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_p\right)T_\pi^2, \quad (3)$$

where V_C is a Woods-Saxon repulsive core.

$$V_C = W_C\left[1+\exp\left(\frac{r-R}{d}\right)\right]^{-1}, \quad (4)$$

with W_C=2137 MeV, R=0.5 fm, d=0.2 fm. The modified one-pion exchange tensor potential

$$T_\pi = \left(1+\frac{3}{x}+\frac{3}{x^2}\right)\frac{e^{-x}}{x}\left(1-e^{-cr^2}\right)^2, \quad (5)$$

where x=0.7r and c=2 fm^{-2}. The spin-independent part of the attractive potential is characterized by $\bar{V} = 6.2 \pm 0.05$ MeV, while the spin-dependent part is small, $V_\sigma = 0.25 \pm 0.25$ MeV, and not well determined.

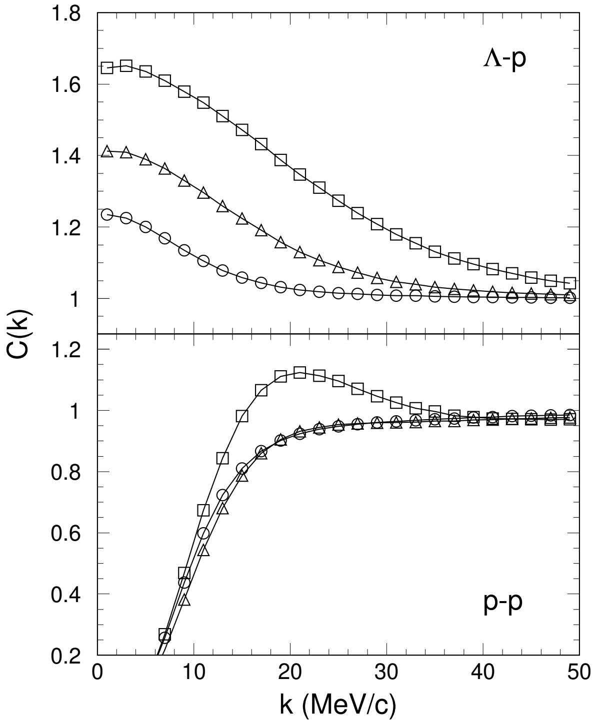

FIG. 1. Λp (upper panel) and pp (lower panel) correlation functions for R_g=4 fm (squares), 6 fm (triangles) and 10 fm (circles). For larger sources, Λp correlations provide a more sensitive determination of the size.

The correlation functions for $R_g = 4, 6$ and 10 fm sources are illustrated in Fig. 1 as a function of k, which is one half of the relative momentum, $k = |\mathbf{p}_\Lambda - \mathbf{p}_p|/2$, as measured in the pair center-of-mass frame. Also shown are pp correlations for the same source sizes. Clearly, Λp correlations are more sensitive than pp correlations for determining larger source sizes. Despite the fact that the pp scattering length is considerably longer, Coulomb effects obscure the sensitivity of pp correlation for sources larger than approximately 6 fm. Thus, even though statistics for Λp correlations are reduced compared to pp statistics, they may provide a more accurate determination of the source size under some circumstances. Correlations involving neutrons, such as nn or pn, are also free of a relative Coulomb interaction, and given the large nn and pn scattering lengths, provide sensitive correlations. However, neutrons are notoriously difficult to measure, whereas lambdas can be measured with a charged-particle detector through its $\pi^- p$ decay channel. Another candidate for source size measurement is deuteron coalescence [5]. Statistically, coalescence should provide the most accurate determination of source parameters of all baryonic probes as coalescence does not suffer from Coulomb effects, and employs the entire strength of a bound state rather than the fraction represented by a rise in the scattering phase shift.

For illustration, we have used the same source size for both lambdas and protons, and assumed thermal momentum distributions. To eliminate the Lorentz factor effect and also for computational reasons, we have used thermal temperature T=3 MeV. However, the Lorentz factor effect is small due to the large lambda and proton masses. For instance, the difference in the correlation functions between T=3 and 300 MeV is less than 5%. For the interest of experimental feasibility of Λp correlation measurements, for T=300 MeV, a total of 20 million pairs results in, from pure phase space population, 10 pairs in $0<k<5$ MeV/c (hence 30% statistical uncertainty), 70 pairs in $5<k<10$ MeV/c (12%), 800 pairs in $25<k<30$ MeV/c (4%), and 70 000 pairs in $0<k<50$ MeV/c.

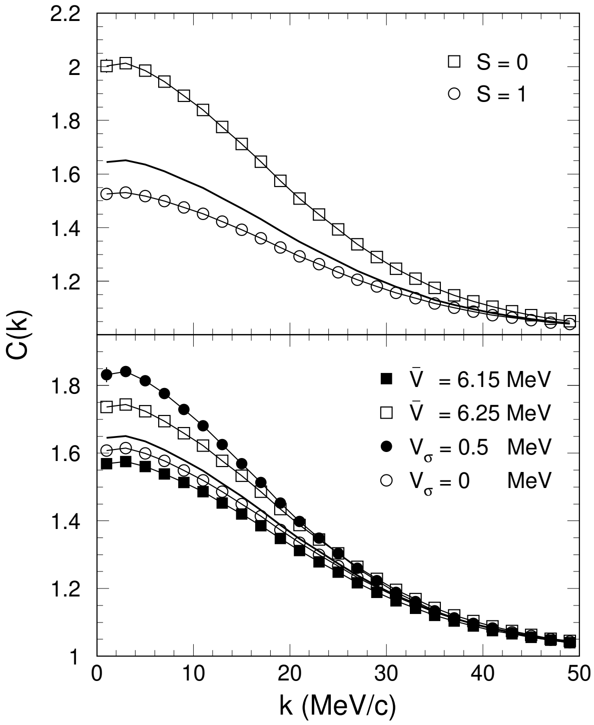

FIG. 2. Upper panel: the spin decomposition of the Λp correlation function for a R_g=4 fm source, with the spin-averaged result represented by the thick solid line. Lower panel: the sensitivity of the correlation function to the uncertainties in the potential parameters. Default values ($\bar{V}$=6.2 MeV, V_σ=0.25 MeV) are represented by the thick solid line. Changing $\bar{V}$ yields the results represented by the squares; changing V_σ yields the results represented by the circles. The uncertainties in the parameters translate to a $\pm$0.5 fm uncertainty in the extracted source size.

The Λp correlation function is one fourth spin singlet (S=0) and three fourths spin triplet (S=1). To illustrate the spin dependence, correlation functions are presented for a R_g=4 fm source in the upper panel of Fig. 2, separately for S=0 and S=1 pairs. If V_σ in Eq. (3) were zero, the two contributions would be identical. As V_σ is not well understood, $0 < V_\sigma < 0.5$ MeV [4], measuring the spin dependence of the correlation function could in principle determine V_σ.

The sensitivity of the spin-averaged correlation function to the parameters $\bar{V}$ and V_σ is illustrated in the lower panel of Fig. 2. Using the stated uncertainties [4], $\bar{V} = 6.2 \pm 0.05$ MeV and $V_\sigma = 0.25 \pm 0.25$ MeV, the correlation function for a R_g=4 fm source is shown for a range of parameters. The results suggest that the uncertainties in the potential parameters translate into an approximately $\pm$0.5 fm uncertainty in the source size extracted from the correlation function at k<25 MeV/c, while the large k tail has better constrain on the source size.

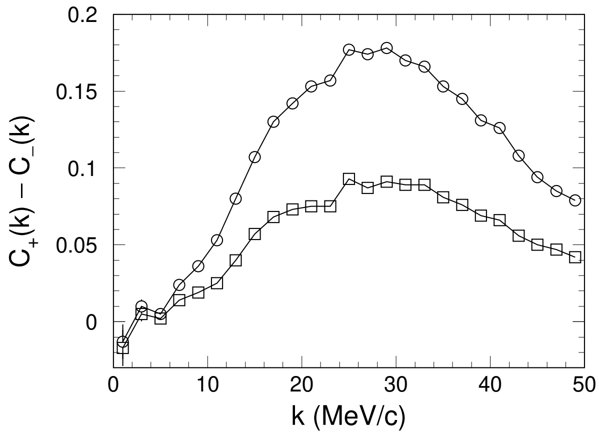

FIG. 3. The difference in the Λp correlation functions for positive and negative values of k_z is shown assuming that both lambdas and protons are characterized by 4 fm sources, but are separated by 1.5 fm (squares) or 3 fm (circles) in z. Such a separation might result if the lambdas would escape earlier than the protons. Small-scale fluctuations are due to fluctuations in the Monte Carlo procedure.

Recently, Lednicky *et al.* [6] have shown that correlations of non-identical particles can provide information revealing whether the particles are emitted simultaneously. If the lambdas are emitted before the protons in such a way that the probability cloud describing the protons lags that for the lambdas of the same velocity, the correlation function then depends on the sign of the relative momentum in the direction defined by that of the displacement of the lambda and proton clouds. An example is illustrated in Fig. 3, where both sources are assumed to be characterized by a size of 4 fm, but are separated by Δz=1.5 fm or 3.0 fm. In Fig. 3 the difference of the correlation functions, $C_+(k) - C_-(k)$, is plotted against k where the transverse component of k is required to be less than 10 MeV/c. Here, C_+ refers to the correlation function constructed with the requirement that $k_z > 0$, while C_- is constructed with the opposite constraint.

A displacement Δz can result from a displacement in time, $\Delta\tau = \Delta z/v$, where v is the velocity of the Λp pair. The displacement direction, $\hat{z}$, is then defined by the direction of v, or that of the pair momentum relative to the source. Thus, if Λp correlations can be measured with an accuracy of a few percent at k~30 MeV/c, the conjecture that strange and non-strange baryons are emitted simultaneously can be addressed quantitatively.

One should remember that the residual interaction of the proton with the Coulomb field of the nuclear sources might distort the result. Unlike pp correlations, where both particles feel the identical force, only the proton experiences the Coulomb field. This issue has been previously considered in the context of pn correlations where the distortion was shown to be small for fast-moving pairs [7]. This effect should be smaller at RHIC where the excess charge at midrapidity is expected to be smaller than observed at SPS and AGS energies.

Finally, we make a brief note regarding $\Lambda\Lambda$ and $\bar{\Lambda}p$ correlations. In the view of our Λp results, we expect that the $\Lambda\Lambda$ strong interaction would also give sizeable correlations. These correlations are of great interest because of the predicted existence of a $\Lambda\Lambda$-like particle [8]. In conjunction with Λp, $\bar{\Lambda}p$ correlations may reveal valuable information on low energy $\bar{\Lambda}p$ annihilation cross sections which are presently unknown but indispensable in modeling certain aspects of heavy-ion collisions [9].

In summary, Λp correlations may provide a useful characterization of the space-time structure of relativistic heavy ion collisions should one be able to gather sufficient statistics. The lack of a relative Coulomb interaction allows the strong interaction to produce a large peak in the correlation function even for large sources, to which pp correlation loses its sensitivity. Furthermore, by binning according to the sign of the projected relative momentum, one might address the question of whether lambdas and protons are emitted simultaneously. However, the interpretation of the correlation function could benefit from a more precise parameterization of the Λp interaction.

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