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Possible effect of mixed phase and deconfinement upon spin correlations in the $\Lambda\bar{\Lambda}$ pairs generated in relativistic heavy-ion collisions

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Spin correlations for the $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs, generated in relativistic heavy ion collisions, and related angular correlations at the joint registration of space-parity nonconserving hadronic decays of two hyperons are theoretically analyzed. These correlations give important information about the character and mechanism of multiple processes, and the advantage of the $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ systems over other ones is conditioned by the fact that the P-odd decays $\Lambda \to p + \pi^-$ and $\bar{\Lambda} \to \bar{p} + \pi^+$ serve as effective analyzers of spin states of the Λ and $\bar{\Lambda}$ particles. The correlation tensor components can be derived by the method of "moments" – as a result of averaging the combinations of trigonometric functions of proton (antiproton) flight angles over the double angular distribution of flight directions for products of two decays. The properties of the "trace" T of the correlation tensor (a sum of three diagonal components), which determines the angular correlations as well as the relative fractions of the triplet states and singlet state of respective pairs, are discussed.

In the present report, spin correlations for two identical particles $(\Lambda\Lambda)$ and two non-identical particles $(\Lambda\bar{\Lambda})$ are generally considered from the viewpoint of the conventional model of one-particle sources. In the framework of this model, correlations vanish at enough large relative momenta. However, under these conditions – especially at ultrarelativistic energies – in the case of two non-identical particles $(\Lambda\bar{\Lambda})$ the two-particle annihilation sources (two-quark, i.e. quark–antiquark, and two-gluon ones) start playing a noticeable role and lead to the difference of the correlation tensor from zero. In particular, such a situation may arise, when the system passes through the "mixed phase" and – due to the multiple production of free quarks and gluons in the process of deconfinement of hadronic matter – the number of two-particle sources strongly increases.

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1. General structure of the spin density matrix of the pairs $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$

Spin correlations for $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs, generated in relativistic heavy-ion collisions, and respective angular correlations at joint registration of space-parity nonconserving hadronic decays of two hyperons provide important information on the character of multiple processes .

The spin density matrix of the $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs, just as the spin density matrix of two spin-1/2 particles in general, can be presented in the following form [1,2,3]:

$$\hat{\rho}^{(1,2)} = \frac{1}{4}\left[\hat{I}^{(1)}\otimes\hat{I}^{(2)} + (\hat{\sigma}^{(1)}\mathbf{P}_1)\otimes\hat{I}^{(2)} + \hat{I}^{(1)}\otimes(\hat{\sigma}^{(2)}\mathbf{P}_2) + \sum_{i=1}^{3}\sum_{k=1}^{3} T_{ik}\hat{\sigma}_i^{(1)}\otimes\hat{\sigma}_k^{(2)}\right]; \tag{1.1}$$

in doing so, $tr_{(1,2)}\hat{\rho}^{(1,2)} = 1$.

Here $\hat{I}$ is the two-row unit matrix, $\hat{\sigma}$ = ($\hat{\sigma}_x$, $\hat{\sigma}_y$, $\hat{\sigma}_z$) is the vector Pauli operator ($x, y, z \to 1, 2, 3$), $\mathbf{P}_1$ and $\mathbf{P}_2$ are the polarization vectors of the first and second particle ($\mathbf{P}_1 = \langle\hat{\sigma}^{(1)}\rangle$, $\mathbf{P}_2 = \langle\hat{\sigma}^{(2)}\rangle$), $T_{ik} = \langle\hat{\sigma}_i^{(1)}\otimes\hat{\sigma}_k^{(2)}\rangle$ are the correlation tensor components. In the general case $T_{ik} \neq P_{1i}\,P_{2k}$. The tensor with components $C_{ik} = T_{ik} - P_{1i}P_{2k}$ describes the spin correlations of two particles .

2. Spin correlations and angular correlations at joint registration of decays of two Λ particles into the channel $\Lambda \to p + \pi^-$

It is important to note that any decay of an unstable particle may serve as an analyzer of its spin state . In particular, for the decay $\Lambda \to p + \pi^-$ the normalized angular distribution takes the form:

$$\frac{d\,w(\mathbf{n})}{d\,\Omega_{\mathbf{n}}} = \frac{1}{4\,\pi}\,(1 + \alpha_\Lambda \mathbf{P}_\Lambda\,\mathbf{n}), \tag{2.1}$$

where $\mathbf{P}_\Lambda$ is the polarization vector of the Λ particle, $\mathbf{n}$ is the unit vector along the direction of proton momentum in the rest frame of the Λ particle, α_Λ is the coefficient of P-odd angular asymmetry ($\alpha_\Lambda = 0.642$). So, the decay $\Lambda \to p + \pi^-$ selects the projections of spin of the Λ particle onto the direction of proton momentum, and the analyzing power equals $\xi = \alpha_{\,\Lambda}\mathbf{n}$.

Now let us consider the double angular distribution of flight directions for protons formed in the decays of two Λ particles into the channel $\Lambda \to p + \pi^-$, normalized by unity (the analyzing powers are $\xi_1 = \alpha_\Lambda \mathbf{n}_1$, $\xi_2 = \alpha_\Lambda \mathbf{n}_2$). It is described by the following formula [2,3]:

$$\frac{d^2\,w(\mathbf{n}_1,\mathbf{n}_2)}{d\,\Omega_{\mathbf{n}_1}\,d\,\Omega_{\mathbf{n}_2}} = \frac{1}{16\,\pi^2}\left[1 + \alpha_\Lambda \mathbf{P}_1\,\mathbf{n}_1 + \alpha_\Lambda \mathbf{P}_2\,\mathbf{n}_2 + \alpha_\Lambda^2 \sum_{i=1}^{3}\sum_{k=1}^{3} T_{ik} n_{1i} n_{2k}\right], \tag{2.2}$$

where $\mathbf{P}_1$ and $\mathbf{P}_2$ are polarization vectors of the first and second Λ particle, T_{ik} are the correlation tensor components, $\mathbf{n}_1$ and $\mathbf{n}_2$ are unit vectors in the respective rest frames of the first and second Λ particle, defined in the common (unified) coordinate axes of the c.m. frame of the pair ($i, k = \{1, 2, 3\} = \{x, y, z\}$) .

The polarization parameters can be determined from the angular distribution of decay products by the method of moments [2,3] .

The angular correlation, integrated over all angles except the angle between the vectors $\mathbf{n}_1, \mathbf{n}_2$ and described by the formula [2,3,4,5]

$$d\,w(\cos\theta) = \frac{1}{2}\,(1+\frac{1}{3}\,\alpha_\Lambda^2 T\,\cos\theta)\sin\theta d\,\theta = \frac{1}{2}[1-\alpha_\Lambda^2\,(W_s-\frac{W_t}{3})\cos\theta]\sin\theta d\,\theta, \tag{2.3}$$

is determined only by the "trace" of the correlation tensor $T = W_t - 3W_s$ (W_s and W_t are relative fractions of the singlet state and triplet states, respectively), and it does not depend on the polarization vectors (single-particle states may be unpolarized).

3. Correlations at the joint registration of the decays $\Lambda \to p+\pi^-$ and $\bar\Lambda \to \bar p+\pi^+$

Due to CP invariance, the coefficients of P-odd angular asymmetry for the decays $\Lambda \to p+\pi^-$ and $\bar\Lambda \to \bar p+\pi^+$ have equal absolute values and opposite signs: $\alpha_{\bar\Lambda} = -\alpha_\Lambda = -0.642$. The double angular distribution for this case is as follows [2,3]:

$$\frac{d^2\,w(\mathbf{n}_1,\mathbf{n}_2)}{d\,\Omega_{\mathbf{n}_1}\,d\,\Omega_{\mathbf{n}_2}} = \frac{1}{16\,\pi^2}\Big[1+\alpha_\Lambda \mathbf{P}_\Lambda\,\mathbf{n}_1 - \alpha_\Lambda \mathbf{P}_{\bar\Lambda}\,\mathbf{n}_2 - \alpha_\Lambda^2\,\sum_{i=1}^{3}\sum_{k=1}^{3} T_{ik} n_{1i} n_{2k}\Big] \tag{3.1}$$

(here $-\alpha_\Lambda = +\alpha_{\bar\Lambda}$ and $-\alpha_\Lambda^2 = +\alpha_\Lambda\,\alpha_{\bar\Lambda}$) .

Thus, the angular correlation between the proton and antiproton momenta in the rest frames of the Λ and $\bar\Lambda$ particles is described by the expression:

$$d\,w(\cos\theta) = \frac{1}{2}\,(1-\frac{1}{3}\,\alpha_\Lambda^2 T\,\cos\theta)\sin\theta d\,\theta = \frac{1}{2}[1+\alpha_\Lambda^2\,(W_s-\frac{W_t}{3})\cos\theta]\sin\theta d\,\theta, \tag{3.2}$$

where θ is the angle between the proton and antiproton momenta .

4. Spin correlations at the generation of $\Lambda\bar\Lambda$ pairs in multiple processes

Further we will use the model of one-particle sources [6], which is the most adequate one in the case of collisions of relativistic ions .

As far as two Λ particles (identical particles) are concerned, the spin correlations and angular correlations at their decays were considered previously, within the model of one-particle sources, in the works [2,7] – taking into account Fermi statistics and final-state interaction (see also the detailed analysis in the paper [8]).

In the present report, we will be interested in spin correlations at the decays of $\Lambda\bar\Lambda$ pairs . In the framework of the model of independent one-particle sources, spin correlations in the $\Lambda\bar\Lambda$ system arise only on account of the difference between the interaction in the final triplet state ($S=1$) and the interaction in the final singlet state . At small relative momenta, the s-wave interaction plays the dominant role as before, but, contrary to the case of identical particles $(\Lambda\Lambda)$, in the case of non-identical particles $(\Lambda\bar\Lambda)$ the total spin may take both the values $S=1$ and $S=0$ at the orbital momentum $L=0$. In doing so, the interference effect, connected with quantum statistics, is absent .

If the sources emit unpolarized particles, then, in the case under consideration, the correlation function describing momentum-energy correlations has the following structure (in the c.m. frame of the $\Lambda\bar{\Lambda}$ pair):

$$R(\mathbf{k},\mathbf{v}) = 1 + \frac{3}{4}B_t^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}) + \frac{1}{4}B_s^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}). \tag{4.1}$$

The spin density matrix of the $\Lambda\bar{\Lambda}$ pair is given by the formula :

$$\hat{\rho}^{(\Lambda\bar{\Lambda})} = \hat{I}^{(1)} \otimes \hat{I}^{(2)} + \frac{B_t^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}) - B_s^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v})}{4\,R(\mathbf{k},\mathbf{v})}\,\hat{\sigma}^{(1)} \otimes \hat{\sigma}^{(2)}, \tag{4.2}$$

and the components of the correlation tensor are as follows:

$$T_{ik} = \frac{B_t^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}) - B_s^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v})}{4 + 3\,B_t^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}) + B_s^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v})}\,\delta_{ik}; \tag{4.3}$$

here the contributions of final-state triplet and singlet $\Lambda\bar{\Lambda}$ interaction are determined by the expressions obtained in the works [2,7] .

At sufficiently large values of k, one should expect that [7]:

$$B_s^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}) = 0, \qquad B_t^{(\Lambda\bar{\Lambda})}(\mathbf{k},\mathbf{v}) = 0.$$

In this case the angular correlations in the decays $\Lambda \to p + \pi^-$, $\bar{\Lambda} \to \bar{p} + \pi^+$, connected with the final-state interaction, are absent :

$$T_{ik} = 0, \quad T = 0.$$

5. Angular correlations in the decays $\Lambda \to p + \pi^-$ and $\bar{\Lambda} \to \bar{p} + \pi^+$ and the "mixed phase"

Thus, at sufficiently large relative momenta (for example, $k \gtrsim m_\pi$) one should expect that the angular correlations in the decays $\Lambda \to p + \pi^-$ and $\bar{\Lambda} \to \bar{p} + \pi^+$, connected with the interaction of the Λ and $\bar{\Lambda}$ hyperons in the final state (i.e. with one-particle sources) are absent . But, if at the considered energy the dynamical trajectory of the system passes through the so-called "mixed phase", then the two-particle sources, consisting of the free quark and antiquark , start playing a noticeable role . For example, the process $s\,\bar{s} \to \Lambda\bar{\Lambda}$ may be discussed .

In this process, the charge parity of the pairs $s\bar{s}$ and $\Lambda\bar{\Lambda}$ is equal to $C = (-1)^{L+S}$, where L is the orbital momentum and S is the total spin of the fermion and antifermion. Meantime, the CP parity of the fermion-antifermion pair is $CP = (-1)^{S+1}$.

In the case of one-gluon exchange, $CP = 1$, and then $S = 1$, i.e. the $\Lambda\bar{\Lambda}$ pair is generated in the triplet state; in doing so, the "trace" of the correlation tensor $T = 1$.

Even if the frames of one-gluon exchange are overstepped, the quarks s and $\bar{s}$, being ultrarelativistic, interact in the triplet state ($S = 1$) . In so doing, the primary CP parity $CP = 1$, and, due to the CP parity conservation, the $\Lambda\bar{\Lambda}$ pair is also produced in the triplet state. Let us denote the contribution of two-quark sources by x . Then, at large relative momenta we have:

$$T = x > 0.$$

Apart from the two-quark sources, there are also two-gluon sources being able to play a comparable role. Analogously with the two-photon process $\gamma\gamma \to e^+e^-$ [9], in this case the "trace" of the correlation tensor is described by the formula (the process $g\,g \to \Lambda\bar{\Lambda}$ is implied):

$$T = 1 - \frac{4\,(1-\beta^2)}{1+2\beta^2\,\sin^2\theta - \beta^4 - \beta^4\,\sin^4\theta}, \tag{5.1}$$

where β is the velocity of Λ (and $\bar{\Lambda}$) in the c.m. frame of the $\Lambda\bar{\Lambda}$ pair, θ is the angle between the momenta of one of the gluons and Λ in the c.m. frame (see [9]). At small β ($\beta \ll 1$) the $\Lambda\bar{\Lambda}$ pair is produced in the singlet state (total spin $S = 0$, $T = -3$), whereas at $\beta \approx 1$ – in the triplet state ($S = 1$, $T = 1$). Let us remark that at ultrarelativistic velocities β (i.e. at extremely large relative momenta of Λ and $\bar{\Lambda}$) both the two-quark and two-gluon mechanisms lead to the triplet state of the $\Lambda\bar{\Lambda}$ pair ($T = 1$).

6. Summary

So, it is surely advisable to investigate the spin correlations of $\Lambda\Lambda$ and $\Lambda\,\bar{\Lambda}$ pairs produced in relativistic heavy-ion collisions (see also, e.g., [8,10]) .

The spin correlations, as well as the momentum–energy ones, make it possible to determine the space–time characteristics of the multiple particle generation region . In doing so, the best way of studying the spin correlations is the method of angular correlations – method of moments.

Finally, it should be emphasized that, in the general case, the appearance of angular correlations in the decays $\Lambda \to p + \pi^-$ and $\bar{\Lambda} \to \bar{p} + \pi^+$ with the nonzero values of the “trace" of the correlation tensor T at large relative momenta of the Λ and $\bar{\Lambda}$ particles may testify to the passage of the system through the "mixed phase" [8,10] .

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