OPEN AND HIDDEN STRANGENESS IN HADRONIC SYSTEMS*

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We investigate production of ϕ mesons and Ξ baryons in nucleus–nucleus collisions. Reactions on strange particles acting as a catalyser are proposed to interpret the high observed ϕ yields in HADES experiments as well as the energy dependence of the widths of ϕ rapidity spectra in collisions at the SPS energies. It is argued that the enhancement of Ξ^- yield observed by HADES is even higher than originally reported, if effects of the experimental centrality trigger are taken into account. Cross sections for new hadronic processes that could produce Ξ^- are reviewed.

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Interesting information about strangeness production and fireball dynamics in heavy ion collisions is carried by ϕ mesons. The NA49 Collaboration found puzzling collision energy dependence of their rapidity spectra widths in Pb+Pb collisions at the CERN SPS [1]. The HADES Collaboration at the SIS machine of GSI Darmstadt, which investigates Ar+KCl collisions at bombarding energies of 1.76 A GeV, has found strong enhancement of ϕ production [2]. The same experiment has observed surprisingly high abundance of doubly strange Ξ^- baryon over Λ hyperons [3], which exceeds the predictions of the statistical model [4] as well as transport calculations [5]. In order to study strangeness enhancement, it is essential to know how it is distributed among all species and so a complete measurement of all species is needed; HADES did this [2,3,6,7]. Here we report on recently proposed catalytic ϕ meson production [8] which could help to explain the observations. We also discuss comments about new effective mechanisms of Ξ^- production.

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Traditionally, for baryon-rich systems the main contribution to ϕ yield was thought to be *OZI suppressed* reactions like $\pi N \to \phi N$ [9] and *strangeness coalescence* reactions $K\bar{K} \to \phi\rho$ and $K\Lambda \to \phi N$ [11]. A new type of *catalytic reactions*

$$\pi Y \to \phi Y\,, \qquad \bar{K}N \to \phi Y\,, \qquad Y = \Lambda,\, \Sigma\,,$$

was proposed in [8], in which only one rare strange reactant is needed and, furthermore, the OZI suppression is lifted thanks to the presence of a strange particle acting as a catalyser. Based on a simple hadronic effective theory we estimated and parameterized the cross sections of such processes to be typically of the order of 1–2 mb [10].

In order to see their efficiency, we set up a kinetic calculation assuming a simple parameterization for the time dependence of the net baryon density and temperature. Strangeness was taken into account perturbatively. In Fig. 1 (left panel) we compare the production rates of catalytic reactions with those of $\pi N \to \phi N$ processes. For reaction $a + b \to c + d$ its rate is determined as $R_{ab}^{cd} = \rho_a \rho_b \langle \sigma_{ab}^{cd} v_{ab} \rangle / (1 + \delta_{ab})$, where ρs are the densities of reactants and $\langle \sigma_{ab}^{cd} v_{ab} \rangle$ is the cross section multiplied by relative velocity and averaged over the distribution of velocities. The density evolution in that calculation corresponds roughly to collisions at beam energy of 6 A GeV with total fireball lifetime of 10 fm/c (for more details see [8,10]). We see that the contribution of catalytic reactions starts gradually as the catalysing strange hadrons are being produced and then becomes comparable to that of the usually assumed processes.

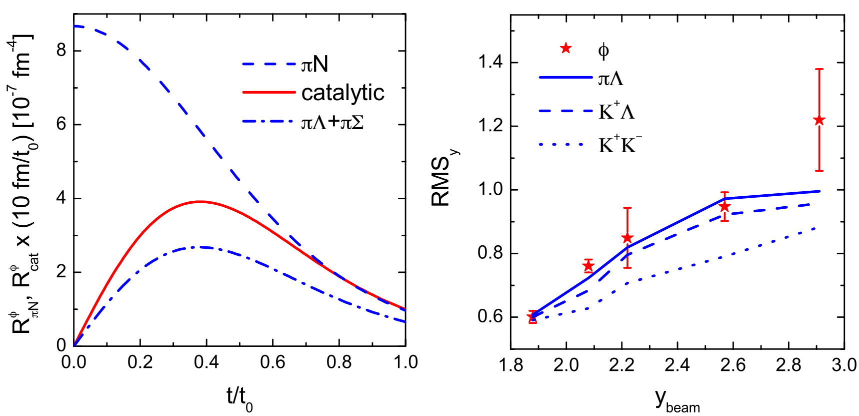

Fig. 1. Left panel: ϕ meson production rates. Solid line is the sum of all catalytic reactions, dash-dotted line the reactions on hyperons. Dashed line is the rate of the $\pi N \to \phi N$ reaction. Right panel: root mean square of the rapidity distributions of ϕs produced in Pb+Pb collisions *versus* the beam rapidity [1]. Lines show the distribution widths from reactions $\pi\Lambda \to \phi Y$, $K^+\Lambda \to \phi N$ and $K^+K^- \to \phi$.

Considering the rapidity distribution of ϕ mesons one basically assumes that it is given by the product of rapidity distributions of those species which produce ϕs, provided their rapidity distributions would not change in the course of the collision. The observed widths of ϕ rapidity distributions do not follow, however, from the product of kaon rapidity distributions, although kaon coalescence was supposedly the dominant process [11]. Instead, the reasonable description of the energy dependence of ϕ rapidity widths is obtained, if one combines mesons with Λ hyperons — like it would follow from the catalytic reactions. Deviation from such an interpretation observed only at the collision energy of 158 A GeV might indicate that here another mechanism of ϕ production sets in. This is an interesting observation in view of the currently running energy-scan programme and the search for the onset of deconfinement.

As measured by the HADES Collaboration [3] the yield of the doubly strange Ξ hyperons is dramatically enhanced in comparison to statistical model predictions. We have studied ratios of strange species with the constraint that the total density of all $S < 0$ hadrons is set by the measured number of K^+ mesons. In our calculation, strange quarks are distributed among hadrons according to the statistical model with temperature as a free parameter. In this treatment the density of species i is given as $\rho_i = \lambda_{\mathrm{S}}^{s_i} n_i(T, \mu_B)$, where n_i is the thermal density at the temperature T and chemical potential μ_B, and the strangeness fugacity λ_{S} is proportional to the density of strange quarks; s_i is strangeness of species i. Note that the cascade number depends quadratically on the density of strange quarks. This is important because the reported tenfold enhancement of Ξs [3] does not yet take into account the LVL1 trigger used by HADES to get rid of peripheral collisions. In the collisions selected by this trigger, the fireball volume is effectively larger than the volume averaged over minimum bias events. Consequently, the density of strange quarks is lower and the expected concentration of cascades is also lower. In summary, the observed enhancement of Ξ production is even stronger than reported originally, if the centrality selection is properly accounted for. We checked that this observation holds qualitatively even if the masses of the involved hadrons change in medium to the maximum possible extent. Therefore, one cannot exclude some mechanism of an out-of-equilibrium production of Ξ baryons in the nuclear collision.

Let us now review the processes, in which Ξ can be produced. Firstly, there are *strangeness creation* reactions $\bar{K}N \to K\Xi - 380\,\mathrm{MeV}$, $\pi\Sigma \to K\Xi - 480$ MeV, $\pi\Lambda \to K\Xi - 560$ MeV. They are endotermic, and their rates are strongly suppressed at temperatures $T \lesssim 100\,\mathrm{MeV}$ reachable at SIS energies. Secondly, there are exothermic *strangeness recombination* reactions. They can be anti-kaon-induced: $\overline{K}\Lambda(\Sigma) \to \Xi\pi + 154(232)\,\mathrm{MeV}$ with the cross sections calculated in [12] and routinely included in transport codes [5].

The other group or reactions, which have not been included so far in transport codes, are *double-hyperon processes* $\Lambda\Lambda \to \Xi N - 26\,\mathrm{MeV}$, $\Lambda\Sigma \to \Xi N + 52\,\mathrm{MeV}$, $\Sigma\Sigma \to \Xi N + 130\,\mathrm{MeV}$. At SIS energies the yields of hyperons are an order of magnitude higher than those of antikaons, so we expect higher contribution from the double-hyperon processes. The cross section of such Ξ^- production processes can be obtained from the cross sections of $\Xi^- p \to \Lambda\Lambda$ and $\Xi^0 p \to \Sigma^+\Lambda$ reactions calculated in [13] within the chiral effective field theory. We parametrize the matrix elements as

$$|M_{\Lambda\Lambda}|^2 = [3 + 12/(1 + 80\,x_1)]\ \mathrm{mb}\,, \qquad (1)$$

for $\Xi^- p \to \Lambda\Lambda$, where $x_1 = (\sqrt{s} - m_{\Xi^-} - m_p)/1\,\mathrm{GeV}$, and for $\Xi^0 p \to \Sigma^+\Lambda$

$$|M_{\Sigma\Lambda}|^2 = \left[5.5 + 36/(1 + 20\,x_2)^{1.2} + 32/(1 + 100\,x_2)^5\right]\ \mathrm{mb}\,, \qquad (2)$$

where $x_2 = (\sqrt{s} - m_{\Sigma^+} - m_\Lambda)/1\,\mathrm{GeV}$. Quality of these parameterizations is demonstrated in Fig. 2. Cross sections for the inverse reactions are calculated just by using proper pre-factors

$$\sigma_{\Lambda\Lambda\to\Xi^- p}(s) = (p_{p\Xi}/p_{\Lambda\Lambda})\,|M_{\Lambda\Lambda}|^2\,, \qquad \sigma_{\Sigma^+\Lambda\to\Xi^0 p}(s) = (p_{p\Xi}/p_{\Sigma\Lambda})\,|M_{\Sigma\Lambda}|^2\,, \qquad (3)$$

where $p_{ab}(\sqrt{s})$ is the CMS momentum of the pair of hadrons a and b with total energy $\sqrt{s}$. For the other isospin channels we have $\sigma_{\Lambda\Lambda\to\Xi^0 n} = \sigma_{\Lambda\Lambda\to\Xi^- p}$,

$$\begin{aligned} \sigma_{\Sigma^0\Lambda\to\Xi^- p} &= \tfrac{1}{2}\sigma_{\Sigma^+\Lambda\to\Xi^0 p}\,, \qquad \sigma_{\Sigma^0\Lambda\to\Xi^0 n} = \tfrac{1}{2}\sigma_{\Sigma^+\Lambda\to\Xi^0 p}\,, \\ \sigma_{\Sigma^-\Lambda\to\Xi^- n} &= \sigma_{\Sigma^+\Lambda\to\Xi^0 p}\,. \end{aligned}$$

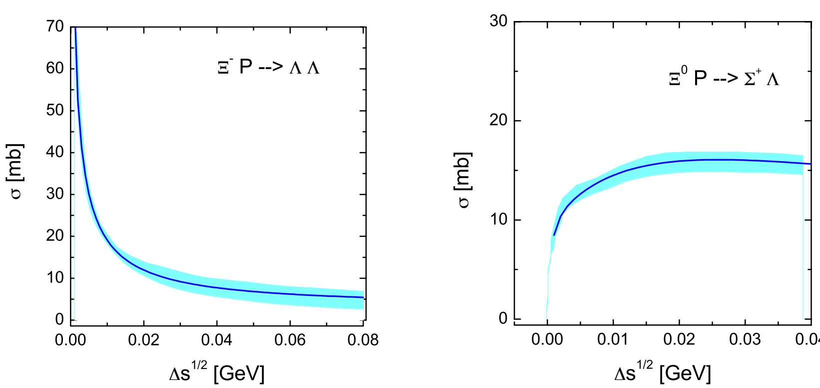

Fig. 2. The cross sections for the reactions $\Xi^- p \to \Lambda\Lambda$ and $\Xi^0 p \to \Sigma^+\Lambda$. Shadowed bands are calculations from [13]. Solid lines are the parameterizations (1) and (2).

Let us now turn back to reactions $\bar{K}Y \to \Xi\pi$. Their cross sections were calculated in a coupled-channels approach in [12]. The isospin-averaged cross sections are parameterized in [5] as

$$\sigma_{\overline{K}\Lambda\to\pi\Xi} = \frac{p_{\pi\Xi}}{4\,p_{\overline{K}\Lambda}}\,34.7\,\frac{s_{\overline{K}\Lambda}}{s}\,\mathrm{mb}\,, \tag{4}$$

$$\sigma_{\overline{K}\Sigma\to\pi\Xi} = \frac{p_{\pi\Xi}}{12\,p_{\overline{K}\Sigma}}\,318\,\left[1-\frac{s_{\overline{K}\Sigma}}{s}\right]^{0.6}\left[\frac{s_{\overline{K}\Sigma}}{s}\right]^{1.7}\mathrm{mb}\,, \tag{5}$$

where the symbol p_{ab} was introduced above, and the reaction threshold is $s_{\overline{K}Y} = (m_K + m_Y)^2$. The change of the cross section in medium due to a lowering kaon mass is usually taken into account [5, 14] by shifting the reaction threshold $\sigma^*(\sqrt{s}) = \sigma(\sqrt{s} + s_{\overline{K}Y}^{1/2} - s_{\overline{K}Y}^{*,1/2})$, where $s^*_{\overline{K}Y}$ is the reaction threshold with the in-medium particle masses. Doing so, one misses a potentially important effect. If kaon mass is lowered enough, the resonant process $\overline{K}Y \to \Xi^*(1530) \to \Xi\pi$ not included in [12] may become relevant. In Fig. 3 (left panel), we show that the reaction threshold crosses the resonance pole at the $\overline{K}$ potential $U_{K^-} \simeq -80\,\mathrm{MeV}$. The cross section of the resonant reaction can be simply added to the parameterizations (4) and (5). Overall structure of the cross section for the resonance process is given by

$$\sigma_{\mathrm{res}}(\sqrt{s}) = \left(2\,\pi/p_{\mathrm{in}}^2\right)\,\Gamma_{\mathrm{in}}\,\Gamma_{\mathrm{out}}\left[\left(\sqrt{s}-m_{\mathrm{res}}\right)^2 + \Gamma_{\mathrm{tot}}^2/4\right]^{-1}\,, \tag{6}$$

where Γ_{tot} is the total width of the resonance and Γ_{in} (Γ_{out}) is the partial width in the in(out)going channel. The partial widths for the decay of a $\frac{3}{2}^+$ resonance with rest energy $\sqrt{s}$ into a $\frac{1}{2}^+$ baryon with the mass m_B and 0^- meson with the mass m_M can be written (see *e.g.* page 310 in [15])

$$\Gamma_{MB}(\sqrt{s}) = \frac{V^2\,p^3}{12\,\pi\,\sqrt{s}}\left[\left(p_{MB}^2 + m_B^2\right)^{1/2} + m_B\right]\theta(\sqrt{s} - m_B - m_M)\,, \tag{7}$$

where V is the coupling constant of the order $O(m_\pi^{-2})$. From the measured value of the decay width $\Gamma(\Xi^* \to \Xi\pi) = 9\,\mathrm{MeV}$, we find $V_{\Xi^*\Xi\pi} = 1.315/m_\pi^2$. The SU(3) symmetry implies that $V_{\Xi^*\Lambda\bar{K}} \simeq V_{\Xi^*\Sigma\bar{K}} \simeq V_{\Xi^*\Xi\pi}$. In order to get isospin-averaged cross section for the Σ induced reactions, Eq. (6) is to be multiplied by factor 1/3. The total width of Ξ^* is given by the sum of all partial widths $\Gamma_{\mathrm{tot}}(\sqrt{s}) = \Gamma_{\pi\Xi}(\sqrt{s}) + \Gamma_{\bar{K}\Lambda}(\sqrt{s}) + \Gamma_{\bar{K}\Sigma}(\sqrt{s})$.

The resonant cross section for various values of the kaon potential is compared with the background cross section (4) in Fig. 3 (right panel). We conclude that for selected energies above the threshold the contribution of the resonant reaction may be significant.

The observed enhanced yields of ϕs and Ξs most likely indicate a non-equilibrium production mechanism. This may occur in an expanding fireball if the rates for annihilating given species cannot follow the fast drop of temperature.

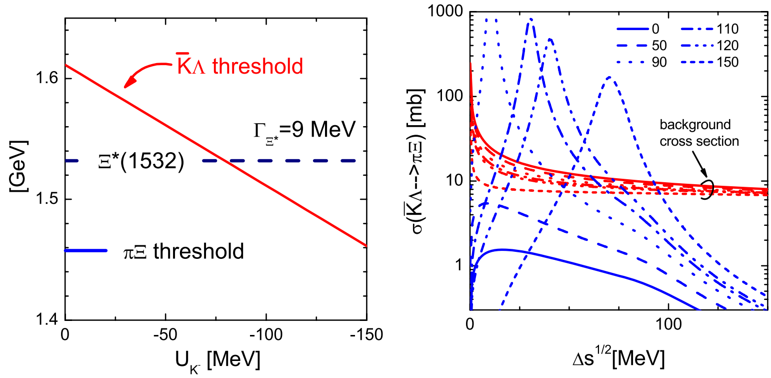

Fig. 3. Left: Threshold energy for $\overline{K}\Lambda$-induced reaction as a function of attractive kaon potential. The dashed line shows the position of the Ξ^* pole. Right: Resonant cross section (6) *versus* $\Delta s^{1/2} = s^{1/2} - m_\Lambda - m_K - U_{K^-}$; the indices show the values of the attractive antikaon potential $(-U)$ in MeV. For comparison background cross section (4) is also shown in the same figure.

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