Catalytic reactions in heavy-ion collisions

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We discuss a new type of reactions of a ϕ meson production on hyperons, $\pi Y \to \phi Y$ and anti-kaons $\bar{K} N \to \phi Y$. These reactions are not suppressed according to Okubo-Zweig-Iizuka rule and can be a new efficient source of ϕ mesons in a nucleus-nucleus collision. We discuss how these reactions can affect the centrality dependence and the rapidity distributions of the ϕ yield.

The study of ϕ meson production in different nucleus-nucleus collisions at various collision energies provides complementary information on collision dynamics and in particular on the evolution of the strange subsystem. Within the consitutent quark model the ϕ meson is dominantly a spin-one bound state of s and $\bar{s}$ quarks. Hence, hadronic interactions of ϕ mesons are suppressed due to the Okubo-Zweig-Iizuka rule, which, in the strict implementation, would forbid an interaction of a pure $(\bar{s}s)$ state with non-strange hadrons. Indeed, the OZI-forbidden reactions are typically orders of magnitude smaller than the OZI-allowed ones.

Since the OZI suppression weakens the ϕ production only by the ordinary hadronic matter and is lifted in the quark-gluon medium, the strong, order of magnitude, enhancement of the ϕ yield was proposed in [1] as a signal of the quark-gluon plasma formation. An enhancement of the ϕ yield was indeed observed experimentally at AGS and SPS energies albeit to a lesser degree [2, 3]. In [4] it was suggested that the main contribution to the ϕ yields at these energies would be given by the OZI-allowed process with *strangeness coalescence* $K\bar{K} \to \phi\rho$ and $K\Lambda \to \phi N$.

Surprisingly strong enhancement of the ϕ yield was observed at the beam energies about 2 GeV per nucleon [5, 6]. Such a large ϕ abundance cannot be described by the transport model [7], where ϕs are produced in reactions $BB \to BB\phi$ and $\pi B \to \phi B$ ($B = N, \Delta$) with the dominant contribution from pion-nucleon reactions. Note that the strangeness coalescence process could not contribute much to the ϕ yield at these energies since kaons have a long mean free path and most likely leave the fireball right after they are created.

In [8] we propose a new mechanism of the ϕ production — *the catalytic reactions* on strange particles

$$\pi Y \to \phi Y\,, \qquad \bar{K}N \to \phi Y\,, \qquad Y = \Lambda\,, \Sigma\,. \tag{1}$$

In contrast to the strangeness coalescence reaction, here the strangeness does not hide inside the ϕ's, but stays in the system and the presence of K mesons is unnecessary. The efficiency of these reactions should be compared with the process $\pi N \to \phi N$, which is found to be dominating in [9]. The reactions (1) are OZI allowed, so we win in cross sections compared to $\pi N \to \phi N$. We lose, however, in the smaller concentration of hyperons and anti-kaons compared to nucleons and pions.

The cross sections of reactions (1) were calculated in [8] according to tree-level diagrams (see Fig. 1) given by the effective Lagrangian of nucleons, hyperons and kaons, which incorporates the ϕ meson as a heavy Yang-Mills boson. Then, one coupling constant fixed by the $\phi \to K\bar{K}$ decay determines the coupling of ϕ to any strange hadron. The resulting isospin-averaged cross sections can be parameterized as

$$\sigma_{\pi Y \to \phi Y'}(s) = p_{\phi Y'}(s)\Big(a_{YY'} + b_{YY'}\frac{\Delta s^{1/2}}{1\ \mathrm{GeV}}\Big)\frac{\mathrm{mb}}{\mathrm{GeV}},$$

$$\sigma_{\bar{K}N \to \phi Y} = p_{\phi Y}(s)\frac{a_{KY} + b_{KY}\frac{\Delta s^{1/2}}{1\ \mathrm{GeV}}}{1 + d_{KY}\frac{\Delta s^{1/2}}{1\ \mathrm{GeV}}}\frac{\mathrm{mb}}{\mathrm{GeV}},$$

where $p_{\phi Y}(s)$ is center-of-mass momentum of the ϕ meson and hyperon. For the hyperon channels we have: $a_{\Lambda\Sigma} = 4.24$, $b_{\Lambda\Sigma} = 1.66$; $a_{\Sigma\Sigma} = 2.16$, $b_{\Sigma\Sigma} = 0.851$; $a_{\Sigma\Lambda} = 1.40$, $b_{\Sigma\Lambda} = 0.682$; and for the kaon channels: $a_{K\Lambda} \approx a_{K\Sigma} = 2.6$, $b_{K\Lambda} \approx b_{K\Sigma} = 1.2$, and $d_{K\Lambda} \approx d_{K\Sigma} = 2.0$

In order to estimate the efficiency of reactions with the ϕ production on hyperons and kaons, we model, first, the evolution of the strange subsystem in the course of a collision. We make two assumptions: (a) strangeness can be considered perturbatively; (b) the fireball matter is baryon-dominated. The first assumption allows us to introduce an effective parameterization for the time dependence of the fireball temperature and baryon density. We use the form of a scaling solution of hydrodynamic equations $T(t)/T_m = (\rho_B(t)/\rho_m)^{2/3} = (t^2/t_0^2 + 1)^{-\alpha}$, where T_m and ρ_m are the maximal temperature and density of the fireball, and t_0 is the typical time scale of the fireball expansion. In the baryon-dominated matter the particles carrying strange quarks, $\bar{K} = (K^-, \bar{K}^0)$, Λ, Σ, and heavier hyperons have short mean free path and remain in thermal equilibrium with pions,

nucleons and Δs till the fireball breaks up. So, the density of a hadron of type i with mass m_i is equal to $\rho_i(t) = \lambda_S^{s_i} \zeta_i e^{q_i \frac{\mu_B(t)}{T(t)}} m^2 T K_2(m/T)/2\pi^2$, where λ_S is the strangeness fugacity and s_i is the number of strange quarks in the hadron; μ_B is the baryon chemical potential and q_i is the baryon charge of the hadron. The degeneracy factor ζ_i is determined by the hadron's spin I_i and isospin T_i as $\zeta_i = (2 I_i + 1)(2 T_i + 1)$. We disregard the finite width of Δ's and treat them as stable particles with the mass $m_\Delta = 1232$ MeV. The baryon chemical potential $\mu_B(t)$ is determined by the equation $\rho_N(t) + \rho_\Delta(t) = \rho_B(t)$, where we neglect the contributions of hyperons, heavier resonances and anti-particles. The strangeness fugacity follows from the strangeness conservation relation: $\rho_{\bar{K}}(t) + \rho_\Lambda(t) + \rho_\Sigma(t) \approx \rho_K(t)$, where $\rho_K(t)$ is the number of produced kaons $K = (K^+, K^0)$ divided by the fireball volume. We do not assume that K mesons are in thermal in chemical equlibrium with other species since they have large mean free paths and can leave the fireball at some earlier stage of the collision. The evolution of ρ_K is described by the differential equation $\dot{\rho}_K(t) - \rho_K(t) \frac{\dot{\rho}_B(t)}{\rho_B(t)} = \mathcal{R}(T(t), \rho_B(t))$ with the initial condition $\rho_K(0) = 0$. The kaon production rate, $\mathcal{R}$, is determined by the processes with πN, $\pi \Delta$, NN, $\pi\pi$, and $N\Delta$ in the initial states; for the list of possible reaction channels and the corresponding cross sections see Ref. [10].

Now we are in position to analyze whether the catalytic reaction can be an efficient source of ϕ mesons compared to conventional ones. As a baseline we take the ϕ production rates in the $\pi N \rightarrow \phi N$ reactions $R_{\pi N}^\phi(t) = \kappa_{\pi N}^{\phi N} \rho_\pi \rho_N$. The transport coefficient $\kappa_{ab}^{cd} = \langle \sigma_{ab}^{cd} v_{ab} \rangle / (1 + \delta_{ab})$ is the cross section $\sigma_{ab}^{cd}(s)$ of the binary reaction $a + b \rightarrow c + d$ averaged over the momentum distributions of colliding particles with the particle relative velocity v_{ab}. We compare $R_{\pi N}^\phi$ with the catalytic reactions on hyperons $R_{\pi Y}^\phi = \sum_{\bar{Y}, Y = \Lambda, \Sigma} \kappa_{\pi Y}^{\phi \bar{Y}} \rho_\pi \rho_Y$ and on anti-kaons $R_{\bar{K} N}^\phi(t) = \left(\kappa_{\bar{K} N}^{\phi \Lambda} + \kappa_{\bar{K} N}^{\phi \Sigma} \right) \rho_{\bar{K}} \rho_N$. The rates of various processes are shown in Fig. 2 for the maximal temperature and density $T_m = 130$ MeV, $\rho_m = 5 \rho_0$, $\alpha = 0.3$, where $\rho_0 = 0.17 \, \text{fm}^{-3}$ is the nuclear saturation density. These parameters correspond roughly to a collision at beam energy 6 AGeV. The ϕ production in πN collisions (dashed line) starts, of course, at the very beginning and gradually falls off as the fireball cools down and expands. The rates of catalytic reactions increase initially (solid line) as more strange particles are produced, reach the maximum at $(0.3–0.4) t_0$ and drop off later. The rates become comparable for times $\gtrsim 0.6 t_0$. Note that the dominant contribution is given by reactions on hyperons (dash-dotted line). The rates in Fig. 2 correspond to the fireball expansion time $t_0 = 10$ fm. If the collision lasts longer then the curves for catalytic reactions

have to be scaled up by a factor $t_0/(10 \text{ fm})$, since the number of the strange particles is proportional to the expansion time. This will make the catalytic reactions efficient even at smaller temperatures. Our estimates show that the catalytic processes can contribute the ϕ production in heavy-ion collisions.

We discuss now the centrality dependence of the ϕ production. We will use the mean number of projectile participants, N_{pp}, as a measure for the initial volume of the fireball created in the collision, $V \propto N_{\text{pp}}$. If there is only one changing parameter with the unit of length as in the case of a symmetrical collision at the fixed collision energy, $l \sim V^{1/3} \propto N_{\text{pp}}^{1/3}$, the scaling properties of hydrodynamics imply that the collision time is of the order $t_0 \sim l/c \propto N_{\text{pp}}^{1/3}$ [11]. Then the number of produced ϕ mesons can be estimated as $N_\phi \sim a_{\text{conv}} N_{\text{pp}}^{4/3} + a_{\text{cat}} N_{\text{pp}}^{5/3}$. The term proportional to $N_{\text{pp}}^{4/3}$ is due to the conventional production reactions like $\pi N \rightarrow \phi N$, whereas the term proportional to $N_{\text{pp}}^{5/3}$ corresponds to the catalytic reactions [8]. For the experimental ratios in [2] we find $N_\phi/N_\pi \sim a\, n_{\text{pp}}^{1/3} + b\, n_{\text{pp}}^{2/3}$, and $N_\phi/N_{K^+} \sim a' + b'\, n_{\text{pp}}^{1/3}$, where $n_{\text{pp}} = N_{\text{pp}}/A$, a, a' and b, b' parameterize the relative strength of conventional and catalytic processes, and A is the number of nucleons in the colliding nuclei. In Fig. 3 we compare these parameterizations with the available data for AuAu collisions at 11.7 AGeV [2]. First, we adjust parameters a, a' and b, b' separately and obtain dashed and solid curves, respectively. The optimal fits are reached when both parameters are activated, dashed-dotted lines in Fig. 3. On the right panel in Fig. 3 we show the fit of the ϕ/N_{pp} ratio for InIn and PbPb collisions at 158 AGeV [12]. The data of InIn collisions can be better described with the account for the catalytic reactions.

The systematics of ϕ rapidity distributions in PbPb collisions at the SPS is reported in [3]. The distributions are given by the sum of two Gaussian functions of width σ placed symmetrically around mid-rapidity y_{beam} at distance a. The width of the distribution is characterized by the root mean square $\text{RMS}^2 = \sigma^2 + a^2$. Ref. [3] pointed out that the width of the ϕ meson distribution does not fit into the systematics for other mesons, increasing much faster with y_{beam}. It was emphasized in [3] that the steep rise of the ϕ distribution width cannot be explained by the hadronic process $K^+ K^- \rightarrow \phi$. We note that the rapidity distribution of hyperons increases much faster than those for mesons as the hyperons are dragged with nucleons to forward and backward rapidities. We assume now that the rapidity distributions of particles do not change after some initial stage when nuclei are passing through each other. The reaction kinematics is restricted mainly to the exchange of transverse momenta.

Then the rapidity distribution of ϕs produced in the reaction $1 + 2 \rightarrow \phi + X$ is roughly proportional to the product of rapidity distributions of colliding particle species 1 and 2. Using the parameters of K^+ and K^- from [13, 14] we obtain RMSs for the $K^+ K^- \rightarrow \phi$ reaction shown in Fig. 4 by dotted line. In contrast, the width of ϕ rapidity distributions from the reactions involving Λ particles, $\pi\Lambda \rightarrow \phi Y$ and $K^+\Lambda \rightarrow \phi N$ (solid and dashed lines) rises much faster and is comparable with the experimental results.

In conclusion, we proposed a new mechanism of ϕ meson production in nucleus-nucleus collisions—the catalytic reactions on strange particles (1). These reactions are OZI-allowed and their cross sections can be by an order of magnitude larger than the cross sections of conventional OZI-suppressed ϕ production reactions $\pi N \rightarrow \phi N$ and $N\Delta \rightarrow \phi N$, etc. We showed that the rates of ϕ production in the catalytic reactions can be competitive to or even exceed the conventional reactions. The catalytic reaction could affect the centrality dependence of the ϕ yield. Analyzing the ϕ rapidity distributions at SPS energies we find that the strong rise of the distribution width with the collision energy can be explained by the ϕ production in $\pi\Lambda$ and $K^+\Lambda$ collisions.

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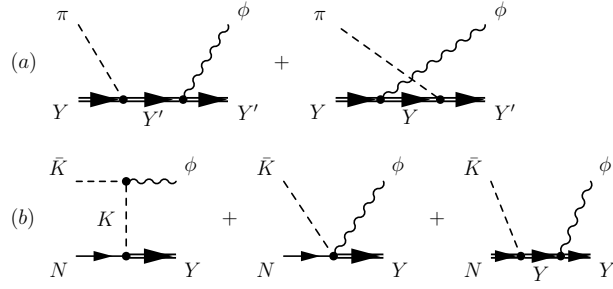14. C. Alt *et al.*, Phys. Rev. C **77**, 024903 (2008).

Figure 1. Diagrams contributing to: a) $\pi Y \to \phi Y$ reactions; b) $\bar{K}N \to \phi Y$ reactions.

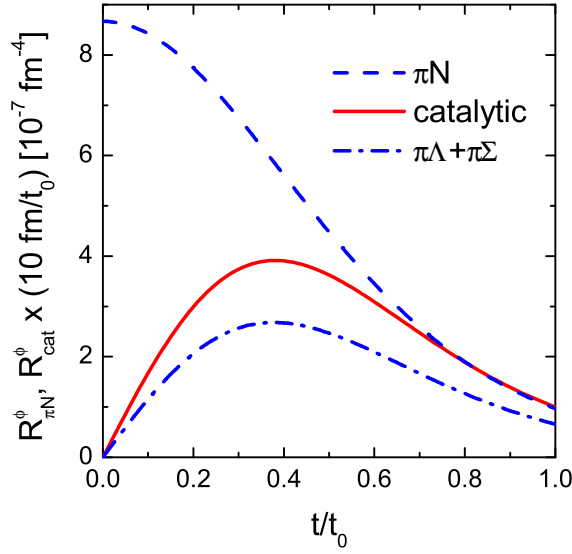**Figure 2.** ϕ meson production rates: solid line is the sum of all catalytic reactions, dash-dotted line the reactions on hyperons. Dashed line is the rate of the $\pi N \to \phi N$ reaction.
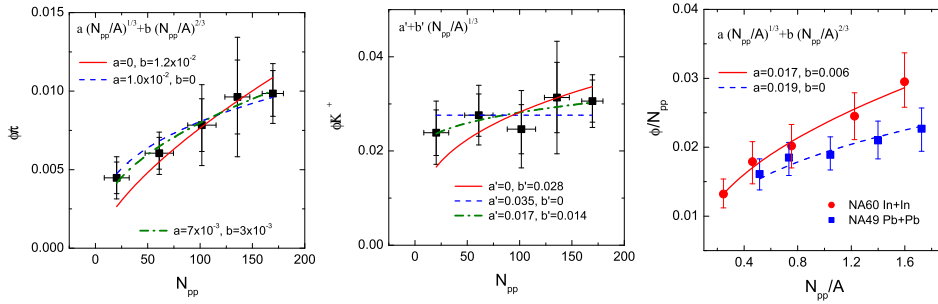

Figure 3. Centrality dependence of ratios ϕ/π (a) and ϕ/K^+ (b). Data points are for AuAu collisions at 11.7 AGeV [2]. (c) the ϕ/N_{pp} ratio for InIn and PbPb collisions at 158 AGeV, the data are from [12].
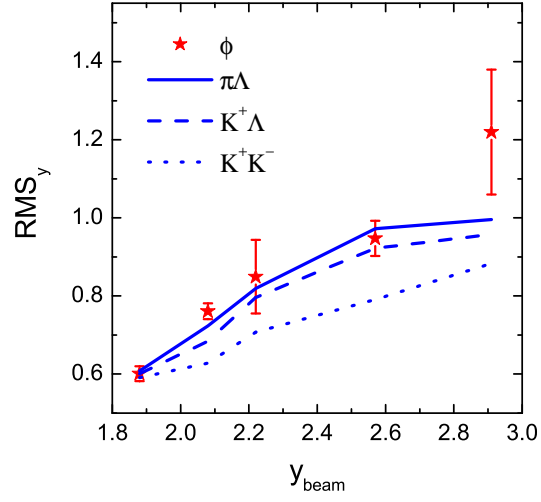
Figure 4. Root mean square of the rapidity distributions of ϕs produced in PbPb collisions versus the beam rapidity [3, 12]. Lines show the distribution widths from reactions $\pi\Lambda \to \phi Y$, $K^+\Lambda \to \phi N$ and $K^+ K^- \to \phi$.

FIGURE CAPTIONS

Fig. 1: Diagrams contributing to: a) $\pi Y \to \phi Y$ reactions; b) $\bar{K} N \to \phi Y$ reactions.

Fig. 2: 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.

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Fig. 4: Root mean square of the rapidity distributions of ϕs produced in PbPb collisions versus the beam rapidity [3, 12]. Lines show the distribution widths from reactions $\pi \Lambda \to \phi Y$, $K^+ \Lambda \to \phi N$ and $K^+ K^- \to \phi$.