Excessive double strange baryon production due to strangeness oscillation in p+A, A+A collisions

Peter Filip

Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, Bratislava 845 11, Slovakia
E-mail: fyziflip@savba.sk

Production of double strange $\Xi^-$ hyperons at sub-threshold energies has been observed by HADES experiment [1] to be unexpectedly enhanced in comparison to theoretical estimates. We suggest, that $K^0 \leftrightarrow \bar{K}^0$ oscillation of neutral kaons can be affected in very dense baryonic matter in a specific way, which may result in the oscillation length 5-10 fm. This allows for the strangeness violation process $(\bar{s}d) \rightarrow (s\bar{d})$ to occur in a very short time, within the volume of dense hadronic medium, and excessive double strange hyperons can be created via rescattering $\bar{K}^0 + (\Sigma, \Lambda) \rightarrow \Xi + \pi$ interactions. The significance of such processes is underestimated, if global strangeness conservation is assumed in $p+A$ and $A+A$ collisions at low energies.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

*Speaker.
†Support from ICHEP organizers and from Slovak Grant Agency VEGA (project 2/197/14) is acknowledged.
1. Introduction

The oscillation of neutral mesons ($K^0 \leftrightarrow \bar{K}^0$) is a beautiful quantum mechanical phenomenon, which allows us to study also the fundamental properties of nature (CP symmetry). $B_d^0 \leftrightarrow \bar{B}_d^0$ and $B_s^0 \leftrightarrow \bar{B}_s^0$ oscillations have been clearly observed as well [3], while $D^0$, $\bar{D}^0$ mesons containing only up-type quarks have been proved to oscillate only recently [4].

The period of $K^0 \leftrightarrow \bar{K}^0$ transitions (oscillation length $L_{osc}$) is determined by the mass difference $\Delta m_{K^0} = m(K^0) - m(\bar{K}^0)$ of eigenstates $K^0$ and $\bar{K}^0$ of the weak Hamiltonian. Measured values of $\Delta m_{K^0}, \Delta m_{\bar{K}^0}, \Delta m_{B_s^0}$, and $\Delta m_{D^0}$ mass differences in vacuum are (in $10^{10}$ s units): 0.529 ± 0.001, 0.95 ± 0.44, 51.0 ± 0.3, and 1776 ± 2, which gives [3] oscillation lengths $L_{osc} = \hbar / \Delta m$: 35 cm, ≈ 20 cm, 3.7 mm, and 0.11 mm. Standard Model explains these oscillations successfully by 2nd order flavour-changing transitions $(s\bar{u}) \leftrightarrow (\bar{s}d)$ and $(c\bar{d}) \leftrightarrow (\bar{c}u)$ and $(b\bar{s}) \leftrightarrow (\bar{b}d)$ taking place in the vacuum due to short-distance (box diagrams) and long-distance effects [3].

In the material medium (a regenerator), or in a dense nuclear matter, the value of $\Delta m_{K^0}$ mass difference of $K^0, \bar{K}^0$ eigenstates may become modified due to meson-baryon (repulsive) and antimeson-baryon (attractive) potentials [5]. Linear approximation (see Eq. 66 and 67 in [5])

$$m_{K^0}(\rho) = (1 + \alpha_K \rho / \rho_0) m_{K^0}^0$$

$$m_{\bar{K}^0}(\rho) = (1 - \alpha_{\bar{K}} \rho / \rho_0) m_{\bar{K}^0}^0$$

(1.1)

gives $m(K^0) - m(\bar{K}^0) \approx 80$ MeV at $\rho = \rho_0$ density, if values $\alpha_K \approx 0.05$ and $\alpha_{\bar{K}} \approx 0.12$ are used.

In this contribution we suggest $\Delta m_{K^0}$ mass difference in dense baryonic medium may become so large, that $(\bar{s} \rightarrow s)$ transition length $L_{osc} = \hbar / 2 \Delta m_{K^0}$ can be very short: 2 – 10 fm. This may allow for a single $(\bar{s}s)$ pair (created in the low-energy $p + A$ and $A + A$ collisions) to be sufficient for the production of double strange $\Xi^-(ssd)$ hyperons via process:

$$\begin{pmatrix} p+A \\ A+A \end{pmatrix} \rightarrow \begin{pmatrix} (\bar{s}d)K^0s \\ (sdu)\Lambda, \Sigma \end{pmatrix} \rightarrow \begin{pmatrix} (\bar{s}d)K^0s \\ \Lambda, \Sigma(sdu) \end{pmatrix} \rightarrow \Xi^- (ssd) + (ud)\pi^+$$

(1.2)

At high baryonic densities, $\bar{s}$ quarks preferentially hadronize into $K^0(d\bar{s})$ or $K^+(u\bar{s})$ mesons, while $s$ quarks are trapped into hyperons. When multiplicities of neutral $K^0(d\bar{s})$ and $\bar{K}^0(s\bar{d})$ mesons are very asymmetric (e.g. $N[K^0]/N[\bar{K}^0] \geq 100$), mesons $K^0(d\bar{s})$ may enhance $s$ quark population via fast $K^0 \rightarrow K^0$ transition. Excessive $\Xi^- (ssd)$ or $\Xi^0(ssu)$ hyperons may thus be created in $p + A$ and $A + A$ collisions at subthreshold energy [1] via rescattering process: $\bar{K}^0 + (\Sigma^0, \Lambda) \rightarrow \Xi + \pi$.

2. Neutral kaons in dense baryonic medium

In the vacuum (if CP violation effects $|\epsilon| \approx 2 \cdot 10^{-3}$ are neglected) the eigenstates $K^0_{1,2}$ of weak Hamiltonian $\mathbb{H}_w$ are: $K^0_{1,2} = (K^0 \pm \bar{K}^0) / \sqrt{2}$. In a medium, Hamiltonian $\mathbb{H}_w' = M' - \frac{i}{2} G'$ is

$$\mathbb{H}_w' = \begin{bmatrix} M_{11} + V_{K^0}(\rho) & M_{12} \\ M_{21} & M_{22} - \tilde{V}_{K^0}(\rho) \end{bmatrix} - i \frac{2}{\Gamma} \begin{bmatrix} \Gamma_{11} + \tilde{A}_{K^0}(\rho) & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} + \tilde{A}_{K^0}(\rho) \end{bmatrix}$$

(2.1)

and linear approximation (1.1) gives potentials $V_{K^0} = m_{K^0} \alpha_K (\rho / \rho_0)$ and $\tilde{V}_{K^0} = m_{K^0} \tilde{\alpha}_K (\rho / \rho_0)$. This means $V_{K^0} \approx 20$ MeV and $\tilde{V}_{K^0} \approx 60$ MeV at nuclear density $\rho \approx \rho_0 = 2 \cdot 10^{17}$ kg/m$^3$, for (momentum
averaged [5]) parameters $\alpha_K \approx 0.04$ and $\alpha_{\bar K} \approx 0.12$. Absorption coefficients $A_{K^0}, \bar A_{\bar K^0}$ in (2.1) are related to forward scattering amplitude difference $f_K(0) - \bar f_{\bar K}(0)$ of $K^0, \bar K^0$ mesons in medium [6].

Diagonalization of $2 \times 2$ non-hermitian Hamiltonian (2.1) with $M_{11} = M_{22} = 497$ MeV and $\Gamma_{11} = \Gamma_{22} = 3.7 \times 10^{-12}$ MeV (using $|\Gamma_{12}| = |\Gamma_{21}| \approx 3.48 \times 10^{-12}$ and $|M_{12}| = |M_{21}| \approx 1.74 \times 10^{-12}$) allows to obtain difference of $K_{1,2}^0$ eigenstate masses and decay widths in medium [7] as

$$\Delta \mu = \Delta m_{K^0} - \Delta m_{K^0} = \frac{i}{2} (\bar \Gamma_{K^0}^0 - \bar \Gamma_{K^0}^0) = \sqrt{4H_{12}H_{21} + (H_{22} - H_{11})^2} = \Delta m_{K^0} - \frac{i}{2} \Delta \Gamma_{K^0}. \quad (2.2)$$

Probabilities of $K^0 \leftrightarrow \bar K^0$ transitions are (using Eq. 9.7 and 9.8 from Ref. [7])

$$P[\bar K^0 \rightarrow K^0] = \left| \frac{q_H}{p_H} \right|^2 \left| g_-(\tau) \right|^2 (1 - \theta)^2, \quad P[K^0 \rightarrow \bar K^0] = \left| \frac{p_L}{q_L} \right|^2 \left| g_-(\tau) \right|^2 (1 - \theta)^2, \quad (2.3)$$

where the interference term

$$\left| g_-(\tau) \right|^2 = \frac{1}{4} \left[ e^{-\bar \Gamma_{K^0}^0} + e^{-\bar \Gamma_{K^0}^0} + 2 \cos[\Delta m_{K^0}(\tau) \cdot e^{-\bar \Gamma_{K^0}^0} + \bar \Gamma_{K^0}^0]/2 \right] \quad (2.4)$$

in (2.3) is multiplied by $|q_H/p_H| = |H_{22}/|\Delta \mu (1 - \theta)|$ quantity [7]. Conservation of CP symmetry gives $|q_H/p_H| = |p_L/q_L|$, and weak hamiltonian $H^\nu_0$ eigenvectors are: $K^0_L = p_H[K^0] + q_H[\bar K^0]$ and $K^0 = p_L[K^0] - q_L[\bar K^0]$. Consequently, one obtains for $K^0 \leftrightarrow \bar K^0$ transition probability

$$P[\bar K^0 \leftrightarrow K^0] = \frac{2H_{21}}{|\Delta \mu|^2} \left| g_-(\tau) \right|^2 = \frac{4|M_{21} - 2\bar \Gamma_{21}|^2}{|H_{22} - H_{11}|^2} \left| g_-(\tau) \right|^2 \approx S_\rho \left| g_-(\tau) \right|^2 \quad (2.5)$$

where $S_\rho$ is the suppression factor of $|\Delta S| = 2$ process $K^0(d \bar s) \leftrightarrow K^0(s \bar d)$ in the medium. For $K^0, \bar K^0 (497)$ pseudoscalar mesons at nuclear density $\rho \approx \rho_0$, one may expect $|H_{22} - H_{11}| \approx 100$ MeV. Values $|\Gamma_{12}| = |\Gamma_{21}| = 3.48 \times 10^{-12}$ and $|M_{12}| = |M_{21}| = 1.74 \times 10^{-12}$ MeV [7] then give enormous suppression factor $S_\rho \leq 10^{-26}$ for $K^0 \leftrightarrow \bar K^0$ oscillations in nuclear medium, in agreement with [8].

**Figure 1:** $K^{0*} \rightarrow \bar K^{0*}$ transition probability as a function of time $\tau$ obtained for density $\rho/\rho_0 = 1.2$.

**Figure 2:** Probability of $K^{0*} \rightarrow \bar K^{0*}$ oscillation as a function of time and baryonic density $\rho < 1.5\rho_0$.

However, for $K^{0*}(896)$ and $\bar K^{0*}(896)$ mesons, which may also form weak eigenstates [9] $K^{0*}_{L,S} = (K^{0*} \pm \bar K^{0*})/\sqrt{2}$, one obtains $S_\rho \approx 10^{-2}$ (see Figures 1 and 2), assuming $K^{0*}, \bar K^{0*}$ mesons share 33% of their decay products ($K^0 \rightarrow K^{0*}_{L,S} + \pi^0$ and $K^{0*} \rightarrow K^{0*}_{L,S} + \pi^0$). Indeed, one has [7]

$$\Gamma_{12} = \rho_c \langle K^{0*} | H''_{\pi^0} K^{0*}_S \pi^0 \rangle \langle K^{0*}_S \pi^0 | H''_{\pi^0} K^{0*} \rangle + \rho_c \langle K^{0*} | H''_{\pi^0} K^{0*}_L \pi^0 \rangle \langle K^{0*}_L \pi^0 | H''_{\pi^0} K^{0*} \rangle \quad (2.6)$$
which gives $\Gamma_{12} \approx 16\text{MeV}$, for widths $\Gamma(K^{0s} \rightarrow K^0_{2s} + \pi^0) = \Gamma(K^{0s} \rightarrow K^0_{0s} + \pi^0) = 8 + 8\text{MeV}$. Using $\Gamma_{12} = 16\text{MeV}$ and $\Gamma_{11} = \Gamma_{22} = \Gamma_{K^*} = 48\text{MeV}$ in the Hamiltonian for $K^{0s}$, $\bar{K}^{0s}$ mesons

$$\mathbf{H}_{K^{0s}} = \begin{bmatrix} 896 + V_{K^0}(\rho) & 1.7 \cdot 10^{-12} \\ 1.7 \cdot 10^{-12} & 896 - V_{K^0}(\rho) \end{bmatrix} - \frac{i}{2} \begin{pmatrix} 48 + A_{K^0} & 16 \cdot e^{i\xi} \\ 16 \cdot e^{-i\xi} & 48 + A_{K^0} \end{pmatrix}$$

(2.7)
suppression factor $S(\rho_B) \approx 10^{-2}$ is obtained in Eq.(2.5) for $\Delta V_{K^*} = 80\text{MeV}$ at density $\rho = \rho_0$. In Figures 3 and 4 we show $\Delta m_{K^*} = m(K^{0s}_{2s}) - m(K^{0s}_{0s})$ mass difference and $K^{0s} \rightarrow \bar{K}^{0s}$ transition length $L_{\bar{s} \rightarrow s}^{\tau_{osc}} = c \cdot \tau_{osc}/2$ evaluated for $K^{0s}$, $\bar{K}^{0s}$ mesons in baryonic matter using Hamiltonian (2.7).

**Figure 3:** Mass difference $\Delta m_{K^*} = m(K^{0s}_{2s}) - m(K^{0s}_{0s})$ of weak eigenstates $\mathcal{K}^{0s}_{2s}, \mathcal{K}^{0s}_{0s}$ in the nuclear medium.

**Figure 4:** Dependence of $K^{0s} \rightarrow \bar{K}^{0s}$ transition length $L_{\bar{s} \rightarrow s}^{\tau_{osc}} = \hbar c/2 \Delta m_{K^*}$ on baryonic density $\rho/\rho_0$.

### 3. Summary and conclusions

We have considered $(d\bar{s}) \leftrightarrow (d\bar{s})$ oscillations in dense nuclear matter. We suggest $K^{0s} \rightarrow \bar{K}^{0s}$ process may happen in $p + A$ or $A + A$ collisions [1] within time scale $(3-10\text{fm/c})$ with probability $\approx 1\%$. This may allow for the excessive $\Xi^-(ssd)$ hyperon production via $\bar{K}^0 + (\Sigma^0, A) \rightarrow \Xi + \pi$ reaction at sub-threshold energies, when single $(ss)$ pair is produced. If $N(K^{0s})/N(\bar{K}^{0s}) \geq 100$ condition is valid in $A + A$ collisions, $(\bar{s}/s)$ ratios may be modified due to $K^{0s} \rightarrow \bar{K}^{0s}$ processes. In agreement with Ref. [8] we find $K^{0s} \rightarrow \bar{K}^{0s}$ transitions in dense baryonic matter to be negligible.

Although fast oscillations of $K^0, B_s^0, B^0$ mesons in the nuclear medium are unlikely, a modification of $\Delta \hat{m}_K$ and $\Delta \hat{m}_B$ parameters in dense regenerators might be experimentally observable.

### References


