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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 Ξ^- 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 $\bar{K}^0 + (\Sigma^0, \Lambda) \rightarrow \Xi + \pi$ interactions. The significance of such processes is underestimated, if global strangeness conservation is assumed in $p+A$ and $A+A$ collisions at low energies.

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1. Introduction

The oscillation of neutral mesons ($K^0 \leftrightarrow \bar{K}^0$) is a beautiful quantum mechanical phenomenon, which allows [2] us to study also the fundamental properties of nature (CP symmetry). $B^0_d \leftrightarrow \bar{B}^0_d$ and $B^0_s \leftrightarrow \bar{B}^0_s$ 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 $\Delta m_{K^0} = m(K^0_2) - m(K^0_1)$ of eigenstates K^0_2 and K^0_1 of the weak $\mathbb{H}_w$ hamiltonian. Measured values of Δm_{K^0}, Δm_{D^0}, $\Delta m_{B^0_d}$, and $\Delta m_{B^0_s}$ mass differences *in vacuum* are (in $10^{10}\hbar/s$ units): 0.529 ± 0.001, 0.95 ± 0.44, 51.0 ± 0.3, and 1776 ± 2, which gives [3] oscillation lengths $L_{osc} = c\hbar/\Delta m$: 35cm, ≈ 20 cm, 3.7 mm, and 0.11 mm. Standard Model explains these oscillations succesfully by 2^{nd} order flavour-changing transitions $(s\bar{d}) \leftrightarrow (\bar{s}d)$ and $(c\bar{u}) \leftrightarrow (\bar{c}u)$ and $(b\bar{d}, \bar{s}) \leftrightarrow (\bar{b}d, s)$ 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 Δm_{K^0} mass difference of K^0_2, K^0_1 eigenstates may become modified due to meson-baryon (repulsive) and antimeson-baryon (attractive) potentials [5]. Linear approximation (see Eq. 66 and 67 in [5])

$$m_{K^0}(\rho) = (1 + \alpha_K \frac{\rho}{\rho_0}) m^{\rho=0}_{K^0} \quad ; \qquad m_{\bar{K}^0}(\rho) = (1 - \tilde{\alpha}_{\bar{K}} \frac{\rho}{\rho_0}) m^{\rho=0}_{\bar{K}^0} \,. \tag{1.1}$$

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

In this contribution we suggest Δm_{K^0} mass difference in dense baryonic medium may become so large, that $(\bar{s} \to s)$ transition length $L^{\bar{s} \to s} = c\hbar/2\Delta m_{K^0}$ can be very short: $2 - 10$ fm. This may allow for a *single* $(s\bar{s})$ 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:

$$\begin{bmatrix} p+A \\ A+A \end{bmatrix} \longrightarrow \binom{\bar{s}}{s} \begin{matrix} \nearrow \\ \searrow \end{matrix} \begin{matrix} (\bar{s}d)K^{0*} & \rightsquigarrow\rightsquigarrow & \bar{K}^{0*}(s\bar{d}) \\ & & \\ (sdu)\Lambda,\Sigma & \longrightarrow & \Lambda,\Sigma(sdu) \end{matrix} \begin{matrix} \searrow \\ \nearrow \end{matrix} \times \longrightarrow \Xi^-(sds) + (u\bar{d})\pi^+ \tag{1.2}$$

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. $N[K]/N[\bar{K}] \geq 100$), mesons $K^0(d\bar{s})$ may enhance s quark population via fast $K^0 \to \bar{K}^0$ 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: $\bar{K}^0 + (\Sigma^0, \Lambda) \to \Xi + \pi$.

2. Neutral kaons in dense baryonic medium

In the vacuum (if CP violation effects $|\varepsilon| \approx 2 \cdot 10^{-3}$ 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 $\mathbb{H}'_w = \mathbb{M}' - \frac{i}{2}\mathbb{G}'$ is

$$\mathbb{H}'_w = \begin{bmatrix} M_{11} + V_{K^0}(\rho) & M_{12} \\ M_{21} & M_{22} - \bar{V}_{\bar{K}^0}(\rho) \end{bmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} + A_{K^0}(\rho) & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} + \bar{A}_{\bar{K}^0}(\rho) \end{pmatrix} \tag{2.1}$$

and linear approximation (1.1) gives potentials $V_{K^0} = m_{K^0}\alpha_K(\rho/\rho_0)$ and $\bar{V}_{\bar{K}^0} = m_{\bar{K}^0}\tilde{\alpha}_{\bar{K}}(\rho/\rho_0)$. This means $V_{K^0} \approx 20$MeV and $\bar{V}_{\bar{K}^0} \approx 60$MeV at nuclear density $\rho \approx \rho_0 = 2 \cdot 10^{17}\,\mathrm{kg/m^3}$, for (momentum averaged [5]) parameters $\alpha_K \approx 0.04$ and $\tilde{\alpha}_{\bar{K}} \approx 0.12$. Absorption coeficients $A_{K^0}, \bar{A}_{\bar{K}^0}$ 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 2×2 non-hermitian Hamiltonian (2.1) with $M_{11} = M_{22} = 497\,\mathrm{MeV}$ and $\Gamma_{11} = \Gamma_{22} = 3.7 \cdot 10^{-12}\,\mathrm{MeV}$ (using $|\Gamma_{12}| = |\Gamma_{21}| \approx 3.48 \cdot 10^{-12}$ and $|M_{12}| = |M_{21}| \approx 1.74 \cdot 10^{-12}$) allows to obtain difference of $K^0_{1,2}$ eigenstate masses and decay widths in medium [7] as

$$\Delta\mu = \tilde{m}(K_2^0) - \tilde{m}(K_1^0) - \frac{i}{2}(\tilde{\Gamma}_{K_2^0} - \tilde{\Gamma}_{K_1^0}) = \sqrt{4H_{12}H_{21} + (H_{22} - H_{11})^2} = \Delta\tilde{m}_K - \frac{i}{2}\Delta\tilde{\Gamma}_K \,. \tag{2.2}$$

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

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

where the interference term

$$|g_-(\tau)|^2 = \frac{1}{4}\left[e^{-\tau\tilde{\Gamma}_{K_2^0}(\rho)} + e^{-\tau\tilde{\Gamma}_{K_1^0}(\rho)} - 2\cos[\Delta\tilde{m}_K(\rho)\tau] \cdot e^{-\tau[\tilde{\Gamma}_{K_2^0}(\rho) + \tilde{\Gamma}_{K_1^0}(\rho)]/2}\right] \tag{2.4}$$

in (2.3) is multiplied by $|q_H/p_H| = 2|H_{21}|/|\Delta\mu(1-\theta)|$ quantity [7]. Conservation of CP symmetry gives $|q_H/p_H| = |p_L/q_L|$, and weak hamiltonian $\mathbb{H}'_w$ eigenvectors are: $K_2^0 = p_H|K^0\rangle + q_H|\bar{K}^0\rangle$ and $K_1^0 = p_L|K^0\rangle - q_L|\bar{K}^0\rangle$. Consequently, one obtains for $K^0 \rightsquigarrow \bar{K}^0$ transition probability

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

where S_ρ is the suppression factor of $|\Delta S| = 2$ process $K^0(d\bar{s}) \rightsquigarrow \bar{K}^0(s\bar{d})$ in the medium. For $\bar{K}^0, K^0(497)$ pseudoscalar mesons at nuclear density $\rho \approx \rho^0$, one may expect $|H_{22} - H_{11}| \approx 100\,\mathrm{MeV}$. Values $|\Gamma_{12}| = |\Gamma_{21}| = 3.48 \cdot 10^{-12}$ and $|M_{12}| = |M_{21}| = 1.74 \cdot 10^{-12}\,\mathrm{MeV}$ [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].

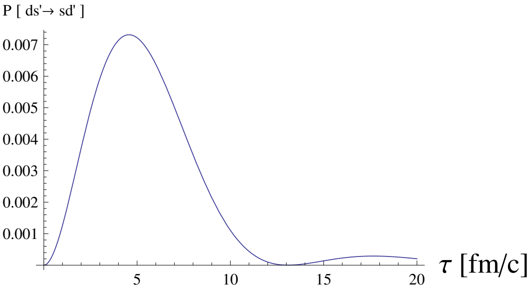

Figure 1: $K^{0*} \to \bar{K}^{0*}$ transition probability as a function of time τ obtained for density $\rho/\rho_0 = 1.2$.

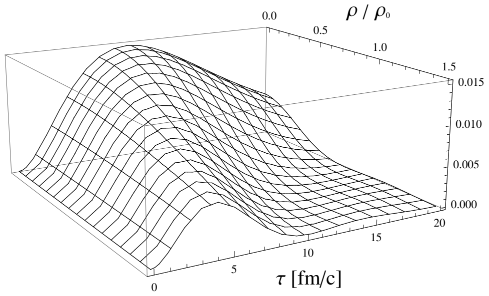

Figure 2: Probability of $K^{0*} \to \bar{K}^{0*}$ oscillation as a function of time and baryonic density $\rho < 1.5\rho_0$.

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 ($K^{0*} \to K^0_{S,L} + \pi^0$ and $\bar{K}^{0*} \to K^0_{S,L} + \pi^0$). Indeed, one has [7]

$$\Gamma_{12} = \rho_c \langle K^{0*}|H'_w|K_S^0\pi^0\rangle\langle K_S^0\pi^0|H'_w|\bar{K}^{0*}\rangle \;+\; \rho_c \langle K^{0*}|H'_w|K_L^0\pi^0\rangle\langle K_L^0\pi^0|H'_w|\bar{K}^{0*}\rangle \tag{2.6}$$

which gives $\Gamma_{12} \approx 16\,\text{MeV}$, for widths $\Gamma(K^{0*} \to K^0_{L,S} + \pi^0) = \Gamma(\bar{K}^{0*} \to K^0_{L,S} + \pi^0) = 8 + 8\,\text{MeV}$. Using $\Gamma_{12} = 16\,\text{MeV}$ and $\Gamma_{11} = \Gamma_{22} = \Gamma_{K^*} = 48\,\text{MeV}$ in the Hamiltonian for $K^{0*}, \bar{K}^{0*}$ mesons

$$\mathbb{H}'_{K^{0*}} = \begin{bmatrix} 896 + V_{K^0}(\rho) & 1.7 \cdot 10^{-12} \\ 1.7 \cdot 10^{-12} & 896 - \bar{V}_{\bar{K}^0}(\rho) \end{bmatrix} - \frac{i}{2} \begin{pmatrix} 48 + A_{K^0} & 16 \cdot e^{i\zeta} \\ 16 \cdot e^{-i\zeta} & 48 + \bar{A}_{\bar{K}^0} \end{pmatrix} \tag{2.7}$$

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 $\Delta m_{K^*} = m(K_2^{0*}) - m(K_1^{0*})$ mass difference and $K^{0*} \to \bar{K}^{0*}$ transition length $L^{\bar{s} \to s} = c \cdot \tau_{osc}/2$ evaluated for K^{0*}, $\bar{K}^{0*}$ mesons in baryonic matter using Hamiltonian (2.7).

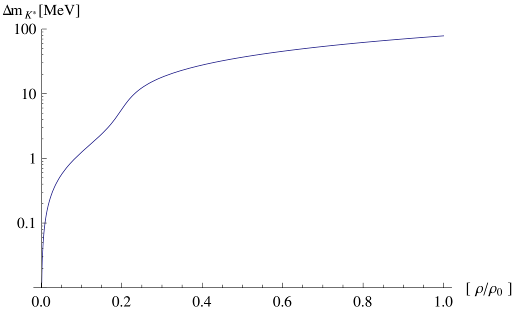

Figure 3: Mass difference $\Delta m_{K^*} = m(K_2^{0*}) - m(K_1^{0*})$ of weak eigenstates K_2^{0*}, K_1^{0*} in the nuclear medium.

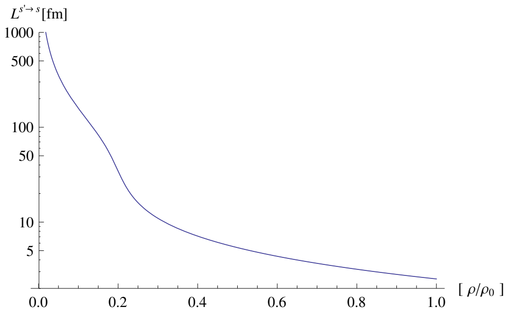

Figure 4: Dependence of $K^{0*} \to \bar{K}^{0*}$ transition length $L^{\bar{s} \to s} = \hbar c / 2\Delta m_{K^*}$ on baryonic density ρ/ρ_0.

3. Summary and conclusions

We have considered $(d\bar{s}) \leftrightarrow (\bar{d}s)$ oscillations in dense nuclear matter. We suggest $K^{0*} \to \bar{K}^{0*}$ 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 $\bar{K}^0 + (\Sigma^0, \Lambda) \to \Xi + \pi$ reaction at sub-threshold energies, when single $(s\bar{s})$ pair is produced. If $N(K^{0*})/N(\bar{K}^{0*}) \geq 100$ condition is valid in $A+A$ collisions, $(\bar{s}/s)$ ratios may be modified due to $K^{0*} \to \bar{K}^{0*}$ processes. In agreement with Ref. [8] we find $K^0 \to \bar{K}^0$ 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 $\Delta\tilde{m}_K$ and $\Delta\tilde{m}_B$ parameters in dense regenerators might be experimentally observable.

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