Flavour Oscillations in Dense Baryonic Matter

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Abstract. We suggest that fast neutral meson oscillations may occur in a dense baryonic matter, which can influence the balance of $s/\bar{s}$ quarks in the nucleus-nucleus and proton-nucleus interactions, if primordial multiplicities of neutral $K^0, \bar{K}^0$ mesons are sufficiently asymmetrical. The phenomenon can occur even if CP symmetry is fully conserved, and it may be responsible for the enhanced sub-threshold production of multi-strange hyperons observed in the low-energy A+A and p+A interactions.

1. Introduction

Strangeness conservation is usually assumed to take place in the strongly interacting matter created in nucleus-nucleus and proton-nucleus interactions [1]. This assumption is useful when baryonic density of the expanding QCD matter is negligible $\rho_B \approx 0$, or (naturally) in the vacuum, where net strangeness imbalance [2] develops at 10^{-3} level only due to CP symmetry violation.

In dense baryonic matter, however, the excess of baryons leads to the asymmetry in the population of $\bar{K}^0(\bar{d}s)/K^0(d\bar{s})$ mesons, since $\bar{s}$ antiquarks have little chance to become part of anti-baryons. Kaon multiplicity ratios $K^-(\bar{u}s)/K^+(u\bar{s}) \approx 10^{-2}$ are observed at low energy fixed-target experiments [3] and similar ratio $\bar{K}^0(\bar{d}s)/K^0(d\bar{s}) \approx 10^{-2}$ may be expected also for the primordial neutral kaons. When neutral kaons are reconstructed via $K^0_S \to \pi^+\pi^-$ decay channel, ratio $\bar{K}^0(\bar{d}s)/K^0(d\bar{s})$ is unobservable, while the ratio $K^{0*}(d\bar{s})/\bar{K}^{0*}(\bar{d}s)$ of vector mesons can be measured.

In this contribution we speculate about the possibility, that different in-medium potentials $V_K(\rho_B) \neq \bar{V}_{\bar{K}}(\rho_B)$ of neutral K^0, $\bar{K}^0$ mesons may result in the fast $(s\bar{d}) \rightsquigarrow (d\bar{s})$ and $(d\bar{s}) \rightsquigarrow (s\bar{d})$ transitions taking place in a dense baryonic matter. Due to the primordial excess of $(d\bar{s})$ mesons, the oscillations $(d\bar{s}) \leftrightarrow (s\bar{d})$ then result in the effective net strangeness non-conservation in A+A and p+A interactions, which can possibly explain the unexpected excess of s-quarks needed for the observed subthreshold production of multi-strange hyperons [4].

2. Neutral Kaon Oscillations in a Medium

Oscillations of neutral kaon states in the baryonic medium (regenerator) were studied in the pioneering experiment by Fitch et al. [5], in order to prove that interference of K^0_L and K^0_S meson states occurs, and CP violation is real. No modification of the mass difference $\Delta\tilde{m} = m(K^0_L) - m(K^0_S)$ inside the regenerator medium was expected [5], and this seems to be the assumption of all other experiments, where $K^0 \leftrightarrow \bar{K}^0$ oscillations were studied via strong interactions method [6].

However, in a dense baryonic matter, $K^0 \leftrightarrow \bar{K}^0$ oscillation length $\tau_{osc}^K = 2\pi\hbar/\Delta\tilde{m}$ can become shorter, due to larger mass difference $\Delta\tilde{m}$ of weak eigenstates $\tilde{K}_S^0$ and $\tilde{K}_L^0$ in the medium. Let us express Hamiltonian $\mathbb{H} = \mathbb{M} - \frac{i}{2}\mathbb{G}$ for the neutral kaon system [7] in medium as

$$\mathbb{H}' = \begin{bmatrix} M_{11} + V_{K^0}(\rho_B) & M_{12} \\ M_{21} & M_{22} + \bar{V}_{\bar{K}^0}(\rho_B) \end{bmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} + A_{K^0}(\rho_B) & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} + \bar{A}_{\bar{K}^0}(\rho_B) \end{pmatrix} \tag{1}$$

where potentials $V_{K^0}, V_{\bar{K}^0}$ and absorption coeficients $A_{K^0}, \bar{A}_{\bar{K}^0}$ are related to forward scattering amplitude difference $f_K(0) - \bar{f}_{\bar{K}}(0)$ of K mesons in medium. Let us assume linear dependence

$$V_{K^0}(\rho_B) = 20MeV[\,\rho_B\,/\rho_B^N] \quad ; \quad \bar{V}_{\bar{K}^0}(\rho_B) = -60MeV[\,\rho_B\,/\rho_B^N] \tag{2}$$

for V_{K^0} and $\bar{V}_{\bar{K}^0}$ potentials on density ρ_B up to the nuclear density value $\rho_B^N = 2.3{\cdot}10^{17}\mathrm{kg/m^3}$, in agreement with Eqs. 66, 67 in [8] (using values α_K=0.04 and $\alpha_{\bar{K}}$=−0.12 based on Figs. 3.1, 2.8, 2.5 in Ref.[8], with momentum dependence of $V_{K^+} \approx V_{K^0}$ and $\bar{V}_{K^-} \approx \bar{V}_{\bar{K}^0}$ potentials neglected). Diagonalization of Hamiltonian (1) with $M_{11} = M_{22} = 497\mathrm{MeV}$, and $\Gamma_{11} = \Gamma_{22} = 3.7 \cdot 10^{-12}$ (using $|\Gamma_{12}| = |\Gamma_{21}| = 3.48 \cdot 10^{-12}$ and $|M_{12}| = |M_{21}| = 1.74 \cdot 10^{-12}$) yields density-dependent mass difference $\Delta m(\rho)$ for $\tilde{K}_2^0, \tilde{K}_1^0$ eigenstates shown in Figure 1 (the absorption is neglected).

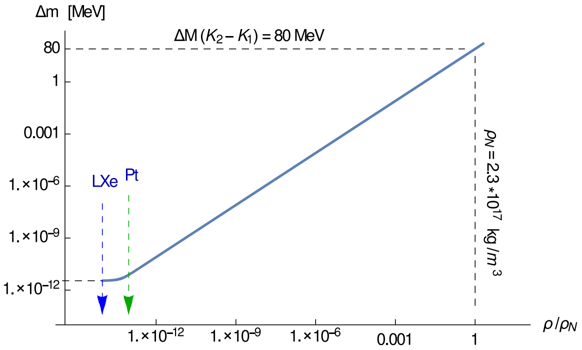

Figure 1. Mass difference of neutral kaon states in baryonic medium of density ρ/ρ_N.

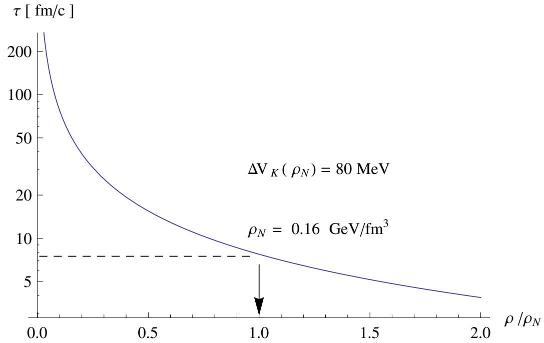

Figure 2. Oscillation time $\tau(\bar{s}d \to s\bar{d})$ in nuclear baryonic matter of density ρ/ρ_N.

Mass difference $\Delta\tilde{m}$ increases from its vacuum value $\Delta\tilde{m} = (3.48 \pm 0.01) \times 10^{-12}\mathrm{MeV}$ for densities larger than $\rho_{Fe} \approx 8\mathrm{g/cm^3}$. For W-Pt metals ($\rho \approx 21\mathrm{g/cm^3}$) the effect may be observable. However, measured forward scattering amplitudes $f_K(0), \bar{f}_{\bar{K}}(0)$ [9] should be used, instead of the rough linear approximation (2), to predict the magnitute of $\Delta\tilde{m}$ for dense metals.

3. Fast $d\bar{s} \leftrightarrow s\bar{d}$ Transitions in Dense Nuclear Medium

$K^0 \rightsquigarrow \bar{K}^0$ oscillation gives $\bar{s} \to s$ strangeness conversion length $\tau_{\bar{s}\to s} = \frac{1}{2}\tau_{osc} = \pi\hbar/\Delta\tilde{m}$, which for $\Delta\tilde{m} \approx 80\mathrm{MeV}$ (at nuclear density $\rho_B^N = 0.16\mathrm{GeV/fm^3}$) leads to $\tau_{\bar{s}\to s} \approx 7.5\mathrm{fm}/c$. This suggests, that neutral kaon oscillations (taking place in a dense baryonic medium) can potentially allow for $s \leftrightarrow \bar{s}$ conversion within time scales comparable to $p + A$ and $A + A$ interaction. Probability of $K^0 \leftrightarrow \bar{K}^0$ transition in the medium is [7] (CP symmetry means $|q_H/p_H|^2 = |p_L/q_L|^2$)

$$P[K^0 \rightsquigarrow \bar{K}^0] = \left|\frac{q_H}{p_H}\right|^2 |g_-(\tau)|^2 |(1-\theta)|^2 \quad ; \quad P[\bar{K}^0 \rightsquigarrow K^0] = \left|\frac{p_L}{q_L}\right|^2 |g_-(\tau)|^2 |(1-\theta)|^2 \tag{3}$$

where $|g_-(\tau)|^2 = \frac{1}{4}\left[e^{-\tau\Gamma_H} + e^{-\tau\Gamma_L} - 2\cos(\Delta\tilde{m}\tau)e^{-\tau(\Gamma_H+\Gamma_L)/2}\right]$, denoting $\tilde{K}_2^0 = p_H|K^0\rangle + q_H|\bar{K}^0\rangle$ and $\tilde{K}_1^0 = p_L|K^0\rangle - q_L|\bar{K}^0\rangle$ as eigenvectors of $\mathbb{H}'$. Since $|q_H/p_H| = 2|H_{21}|/|\Delta\mu(1-\theta)|$, where $\Delta\mu = \sqrt{4H_{12}H_{21} + (H_{22} - H_{11})^2}$ [7], parameter $(1{-}\theta)^2$ disappears in Eq.(3). For dense baryonic matter $4|H_{12}H_{21}| \ll |H_{22}-H_{11}|^2$, since $|H_{22}-H_{11}| = |(\bar{V}_{\bar{K}^0} - V_{K^0}) - \frac{i}{2}(\bar{A}_{\bar{K}} - A_K)|$ with CPT symmetry conserved, and consequently

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

where suppression factor $S(\rho_B) = |2H_{21}|^2/|\Delta V_K - \frac{i}{2}\Delta A_K|^2$. If our approximations are correct, transitions $\bar{s}d \leftrightarrow s\bar{d}$ can happen within time scale 10fm/c in nuclear matter, though being suppressed by factor $S(\rho_B) \approx 4|H_{21}|^2/(80\text{MeV})^2$.

For pseudoscalar $K^0(497)$ mesons (assuming dense medium does not influence M_{21}, Γ_{21} values originating from the weak interaction) one has $|H_{21}| \approx 2.5\times10^{-12}$MeV, and thus $K^0 \leftrightarrow \bar{K}^0$ transitions become irrelevant (negligible) with suppression factor $S(\rho_B) \approx 10^{-26}$.

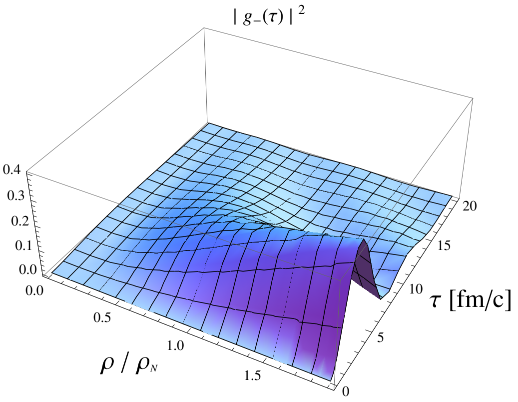

Figure 3. Interference term $|g_-(\tau)|^2$ for K^{0*}.

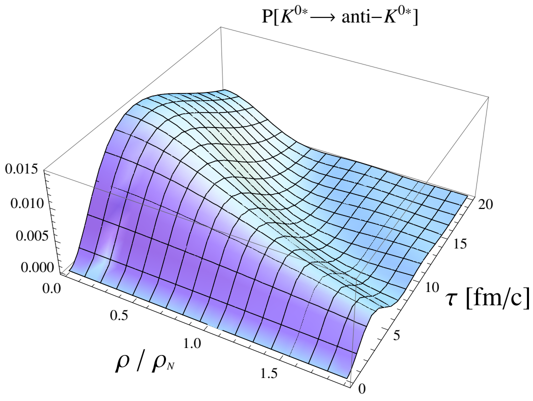

Figure 4. The probability $P[K^{0*} \to \bar{K}^{0*}]$.

However, the situation looks to be more promissing for $K^{0*}(896)$ vector mesons. Although $|M_{12}| \approx 10^{-12}$ remains to be small, value $\Gamma^*_{21} = \Gamma_{12} = \sum_n \rho^n_c \langle K^{0*}|H_w|f_n\rangle\langle f_n|H_w|\bar{K}^{0*}\rangle$ [7] may become much larger (in medium). For the upper estimate on Γ_{12} for $K^{0*}, \bar{K}^{0*}$ mesons, we write

$$\Gamma_{12} = \rho^S_c\langle K^{0*}|H_w|K^0_S\pi^0\rangle\langle K^0_S\pi^0|H_w|\bar{K}^{0*}\rangle + \rho^L_c\langle K^{0*}|H_w|K^0_L\pi^0\rangle\langle K^0_L\pi^0|H_w|\bar{K}^{0*}\rangle \tag{5}$$

Decay width of $K^{0*} \to K^0\pi^0 \to K^0_s\pi^0$ process is $\Gamma^{K^{o*}}_{S\pi^o} = (\frac{1}{2})48\text{MeV}/3 = 8\text{MeV}$, and the same applies to $K^{0*} \to K^0\pi^0 \to K^0_L\pi^0$ decay width: $\Gamma^{K^{o*}}_{L\pi^o} = 8\text{MeV}$. For anti-$K^{0*}$ decays we assume similarly: $\Gamma^{\bar{K}^{o*}}_{S\pi^o} = \Gamma^{\bar{K}^{o*}}_{L\pi^o} = 8\text{MeV}$ for $\bar{K}^{0*} \to \bar{K}^0\pi^0 \to K^0_{L,S}\pi^0$. Thus, we may expect $|\Gamma_{12}| \approx 16$MeV using Eq.(5), which makes the probability of $K^{0*} \leftrightarrow \bar{K}^{0*}$ oscillations significant. (Note, that quantum superposition of vector mesons $pK^{0*} + q\bar{K}^{0*}$ had been discussed by Littenberg [10].) Hamiltonian we have used for the system of $K^{0*}, \bar{K}^{0*}$ $(J=1)$ mesons was

$$\mathbb{H}'_{K^{0*}} = \begin{bmatrix} 896+V_{K^0}(\rho_B) & 1.7\cdot10^{-12} \\ 1.7\cdot10^{-12} & 896+\bar{V}_{\bar{K}^0}(\rho_B) \end{bmatrix} - \frac{i}{2}\begin{pmatrix} 48+A_{K^0} & 16\cdot e^{i\zeta} \\ 16\cdot e^{-i\zeta} & 48+\bar{A}_{\bar{K}^0} \end{pmatrix}. \tag{6}$$

and $S(\rho_B) \approx 10^{-2}$ suppression factor was obtained for $\Delta V_{K^*} = 80$MeV at nuclear density $\rho_B = 0.16\text{GeV/fm}^3$. If mass difference $\Delta\tilde{m}^* = \tilde{m}(K^{0*}_2) - \tilde{m}(K^{0*}_1)$ in the baryonic medium approaches $\Delta\tilde{m}^* \approx 80$MeV at $\rho_B = \rho^N_B$, we obtain $\tau(\bar{s}\to s) \approx 7$fm/c again. Figures 3 and 4 show the interference term

$$|g_-(\tau)|^2 = \frac{1}{4}\left[e^{-\tau\Gamma^*_H(\rho_B)} + e^{-\tau\Gamma^*_L(\rho_B)} - 2\cos(\Delta\tilde{m}^*(\rho_B)\tau)e^{-\tau[\Gamma^*_H(\rho_B)+\Gamma^*_L(\rho_B)]/2}\right] \tag{7}$$

and transition probability $P[K^{0*} \rightsquigarrow \bar{K}^{0*}]$ obtained as a function of time and density for $K^*(896)$. The oscillation $D^{0*} \leftrightarrow \bar{D}^{0*}$ in medium appeared to be negligible: $P[D^{0*} \rightsquigarrow \bar{D}^{0*}] \leq 10^{-7}$ for $\tau < 20$fm/c, due to upper bound $|\Gamma^{D^{o*}}_{12}| < 0.04$MeV, originating from $\Gamma_{tot}(D^{0*}) \approx 40$keV [11].

4. Subthreshold $\Xi^-(ssd)$ Production

Main motivation for the considerations presented here was to explain the excessive subthreshold production of double-strange hyperons $\Xi^-(ssd)$ observed by HADES experiment in Ar+KCl and p+Nb interactions [4]. Our hypothesis is depicted in diagram (8): at subthreshold energy, only one $(s\bar{s})$ pair is created, and s-quark becomes part of Λ or Σ hyperon, while $\bar{s}$ antiquark enters $(d\bar{s})$ bound state. The oscillation $(d\bar{s} \rightsquigarrow s\bar{d})$ in dense baryonic matter creates the second s quark (e.g. with probability 1%) needed for double-strange Ξ hyperons.

$$\begin{bmatrix} p+A \\ A+A \end{bmatrix} \longrightarrow \binom{\bar{s}}{s} \begin{array}{c}\nearrow\\ \\ \searrow\end{array} \begin{array}{ccc} (\bar{s}d)K^{0*} & \rightsquigarrow\rightsquigarrow & \bar{K}^{0*}(s\bar{d}) \\ & & \\ (sdu)\Lambda,\Sigma & \longrightarrow & \Lambda,\Sigma(sdu) \end{array} \begin{array}{c}\searrow\\ \\ \nearrow\end{array} \longrightarrow (ssd)\Xi^- + (u\bar{d})\pi^+ \tag{8}$$

Strangeness recombination reaction $\Lambda + \bar{K} \to \Xi + \pi$ allows then excessive Ξ hyperons to be produced. Rescattering simulation of p+A / A+A collisions may confirm or deny our suggestion.

5. Summary

We suggest, that fast strangeness oscillation $(\bar{s}d) \rightsquigarrow (s\bar{d})$ may occur in dense baryonic medium with small $P(\bar{s} \rightsquigarrow s) \approx 10^{-2}$ probability. This phenomenon is potentially capable to increase the total yield of $\bar{K}$ mesons, if condition $K^0/\bar{K}^0 > 100$ for primordial neutral kaon multiplicities is fulfilled. Excessive double-strange Ξ hyperon production may then take place at subthreshold energies via strangeness recombination reactions (a quantitative estimate is needed).

$D^{0*} \leftrightarrow \bar{D}^{0*}$ oscillation probability appears to be negligible ($P \leq 10^{-7}$), if $|\Gamma_{12}^{D^*}| < 0.04$MeV restriction is kept for dense baryonic medium. We assume $|\Gamma_{12}^{K^*}| \approx 16$MeV also for small baryonic densities, and therefore, $P[K^{0*} \rightsquigarrow \bar{K}^{0*}] \approx 10^{-2}$ is obtained even for $\rho_B \to 0$ (Figure 4).

Fast $K^{0*} \rightsquigarrow \bar{K}^{0*}$ oscillations might be directly observable, if K^{0*} and $\bar{K}^{0*}$ spectra were carefully measured at AGS energies. Since experimental data on K^* production were not published by AGS experiments, a precise measurement of $\bar{K}^{0*}$ production in $p+p$, $p+A$ and $A+A$ interactions by NA61/SHINE at low SPS energies, by NICA/MPD experiment, and possibly also by STAR fixed target or BES II program at RHIC, could clarify the situation.

Experimental verification of the in-medium change of $\Delta m(K_2^0 - K_1^0)$ mass difference in dense metals (W, Pt) would affirm our understanding of the neutral kaon physics [12] to be complete.

The readers should be aware of the recent publication [13] which is also attempting to explain the excessive Ξ^- hyperon production, and of publication [14] on neutral kaons in dense medium.

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[1] Tomášik B, Kolomeitsev E E 2016 *Eur. Phys. Jour.* A **52** 251
[2] Kabir P K 1970 *Phys. Rev.* D **2** 540; Dass G V, Sarma K V L, Kabir P K 1987 *Phys. Rev.* D **35** 1730
[3] Scheinast W, et al. 2006 *Phys. Rev. Lett.* **96** 072301; Agakishiev G, et al. 2009 *Phys. Rev.* C **80** 025209
[4] Agakishiev G, et al. 2009 *Phys. Rev. Lett.* **103** 132301; Agakishiev G, et al. 2015 *Phys. Rev. Lett.* **114** 212301
[5] Fitch V L, Roth R F, Russ J S, Vernon W 1965 *Phys. Rev. Lett.* **15** 73
[6] Camerini U, et al. 1962 *Phys. Rev.* **128** 362; Meisner G W, et al. 1966 *Phys. Rev. Lett.* **16** 278
[7] Branco G C, Lavoura L, Silva J P 1999 in book: *CP Violation*, Clarendon Press (Oxford)
[8] Hartnack C, et al. 2012 *Physics Reports* **510** 119
[9] Eberhard P H, Uchiyama F 1994 *Nucl. Inst. Meth. Phys. Res.* A **350** 144
[10] Littenberg L S 1980 *Phys. Rev.* D **21** 2027
[11] Nussinov S 1998 *Phys. Lett.* B **418** 383
[12] Angelopoulos A, et al. 2003 *Physics Reports* **374** 165
[13] Steinheimer J, Bleicher M 2016 *Jour. Phys. G: Nucl. Part. Phys.* **43** 015104
[14] Amelino-Camelia G, Kapusta J 1999 *Phys. Lett.* B **465** 291