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Article

Reactions Governing Strangeness Abundance in Primordial Universe

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Abstract: Strangeness flavor is abundant and in chemical equilibrium in the primordial Quark-Gluon Plasma(QGP) filling the early Universe. Upon hadronization near to $T = 150\,\text{MeV}$ one may think that relatively short lived massive strange hadrons decay rapidly and strangeness disappears. However, we show using detailed balance considerations for inverse decay reactions that the back reaction repopulate strangeness keeping it in chemical equilibrium at least to the time when strange antibaryons annihilate near $T \simeq$ 30-50 MeV. However, our present study is focused on the meson sector of the hadronic Universe. Specifically, we establish here the temperature range in which the expansion of the Universe becomes faster compared to the production processes which balance natural strangeness decay: In the temperature interval $33\,\text{MeV} < T < 20\,\text{MeV}$: $\mu^{\pm} + \nu_\mu \rightarrow K^{\pm}$, $\pi + \pi \rightarrow K$ and $l^- + l^+ \rightarrow \phi$ reactions in sequence become slower compared to the characteristic Hubble time.

Keywords: strangeness; primordial universe; cosmology

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1. Introduction

Nonequilibrium conditions in the early Universe are of general interest: their appearance is pre-requisite for the arrow of time dependent processes to take hold. Among the well studied cases is the Big Bang Nucleosynthesis[1–3] appearing in the temperature range $0.01 < T < 0.07\,\text{MeV}$, that is about 1000 times smaller temperature range compared to what will be considered here, $10 < T < 150\,\text{MeV}$. Many light isotopes, *e.g.* deuterium are ashes of this Universe era that are not fully burned. Their relative abundance can be relatively small, just like the case of even greater interest, the origin of non-vanishing baryon number in the Universe.

Baryogenesis is believed to occur at, or before the Universe underwent electroweak phase transition [1] at a temperature $T \simeq 130$ GeV, about 1000 times larger compared to temperature range we consider in this work. However, heavy bottom flavor decoupling near to deconfined quark-gluon plasma (QGP) transformation to hadron gas (HG) phase just at the upper range of our present consideration may offer alternate opportunity [4]. Complementing this work we explore here strange meson decay and production reactions that lead to strangeness flavor decoupling after formation of HG phase. We plan to return to the case of charm flavor in another research cycle. However, our finding that the strange meson decoupling occurs just below antibaryon decoupling and disappearance implies that we return to the case of strangeness including reactions involving (anti)hyperons.

We have studied before the freeze-out of hadrons in general driven by reaction $\pi^0 \Leftrightarrow \gamma + \gamma$ [5], and we compare with these results in this work. We considered the connection of the QGP phase with later stages of the Universe evolution [6], and explored in more detail the neutrino evolution, which relates to the question of the cosmic neutrino abundance [7], and free-streaming neutrino momentum distribution [8]. This work and its follow-up findings [9] could influence the speed of Universe expansion, a topic generating a lot of interest today [10,11].

The present work is, we believe, a first consideration of strangeness evolution in the Universe following on hadronization of QGP. We characterize Universe expansion dynamics during the epoch

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of interest $10 < T < 150\,\mathrm{MeV}$ and determine the characteristic Hubble time in Sect. 2. In Sect. 3 we present the key reactions and discuss their relative strength. In Sect. 4 we evaluate the dynamic rates employing detailed balance: the natural decay of particles concerned provides also the intrinsic strength of the inverse production reaction of interest. We outline consequences of our finding, and delimit related future research in Sect. 5.

2. Universe expansion

We evaluate the characteristic Hubble time $1/H$ as a function of temperature required as reference for the following results. In the Universe epoch of interest $10 < T < 150\,\mathrm{MeV}$ the Universe is radiation-dominated. This observation helps to relate the cosmological time to the ambient temperature. However, in this work all that matters is that we can express the Hubble expansion rate as a function of temperature. This is achieved remembering that the Hubble parameter can be written as [1]

$$H^2 = \frac{8\pi G_\mathrm{N}}{3}\rho_{tot}, \tag{1}$$

where G_N is the Newtonian constant of gravitation and ρ_{tot} is the energy density (here of for most part of relativistic 'radiation like' particle species) in the early Universe. In our calculation we include

$$\begin{aligned}
&\text{Photon}: \gamma\\
&\text{Neutrino}: \nu_e, \nu_\mu, \nu_\tau, \overline{\nu}_e, \overline{\nu}_\tau, \overline{\nu}_\mu\\
&\text{Charged lepton}: e^-, e^+, \mu^-, \mu^+\\
&\text{Hadron}: \pi^0, \pi^+, \pi^-.
\end{aligned} \tag{2}$$

Both muons and pions are not relativistic in the considered $10 < T < 150\,\mathrm{MeV}$ range. Their contribution to ρ_{tot} – we use their actual mass in the computation of their contribution to ρ_{tot} assuming chemical equilibrium: Muons are coupled through electromagnetic reactions $\mu^+ + \mu^- \Leftrightarrow \gamma + \gamma$ to the photon background and retain their chemical equilibrium down to below $T_\mu \simeq m_\mu/40 \simeq 2.6\,\mathrm{MeV}$. Because π-mesons are in thermal equilibrium [5], and are the lightest hadrons, they dominate hadronic contribution to the energy density in the strange particle disappearance temperature range $10 < T < 60\,\mathrm{MeV}$.

3. Strangeness creation and annihilation

Without further discussion we assume that before hadronization in the QGP epoch of temperature $T > 150\,\mathrm{MeV}$ the strangeness formation processes studied in laboratory [12] are fast enough to assure chemical equilibrium - hence the Universe undergoing a relatively slow on hadronic time scale phase transformation emerges from QGP near to chemical equilibrium abundance. In this transition the excess QGP entropy as compared to HG is absorbed in additional Universe comoving volume expansion while excess strangeness has time to reequilibrate into equilibrium HG abundance.

In this work we explore strange meson production and decay processes in the Universe following on QGP hadronization in the temperature interval $10 < T < 150\,\mathrm{MeV}$ range. The key reactions are illustrated in Fig. 1. We see here important strangeness abundance changing processes, including important 'hidden' $s\bar{s}$ components in η and ϕ. Particles $\pi, l^\pm, \gamma$ outside the blue boundary are all in thermal equilibrium in this temperature domain as already discussed, see also Ref. [5].

3.1. Available reaction rates

We introduce here the typical interaction rates relevant for the discussion of strangeness in the early Universe using the particle data group data tables [13]. We have

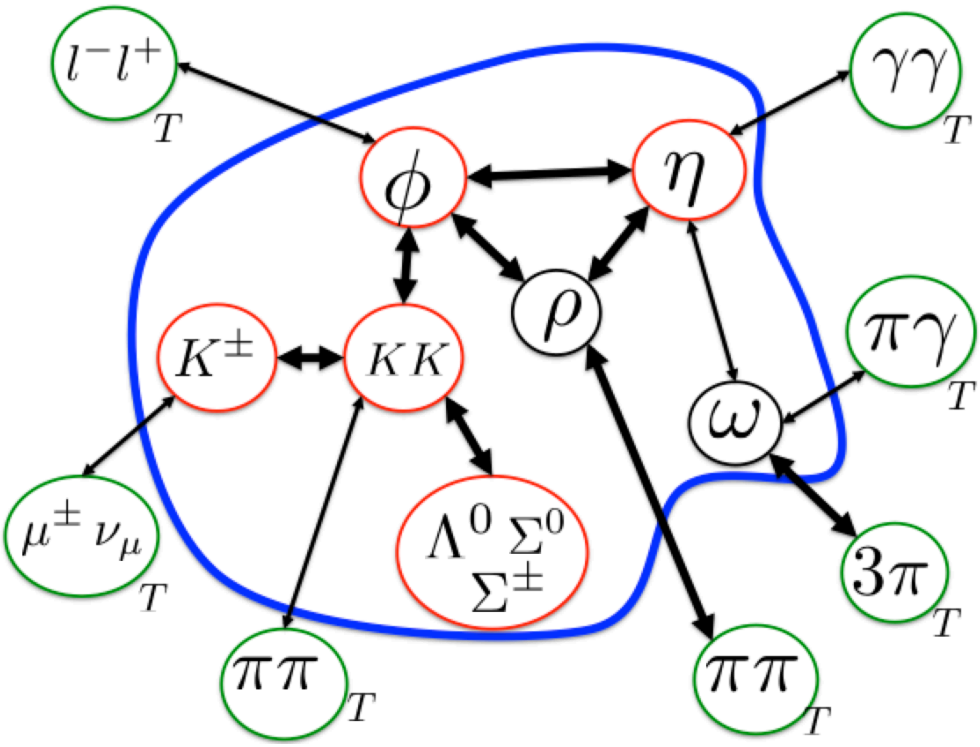

Figure 1. Principal strangeness abundance changing processes in the hadronic Universe $T < T_{\rm H} = 150\,\text{MeV}$. The blue boundary is drawn around hadronic particles expected to fall out of abundance equilibrium. The red circles within this domain represent strangeness-carrying mesons, black non-strange mesons of importance in creation of strangeness. The equilibrium (index T) heat bath of particles in green circles outside the blue domain contribute to meson forming reactions we study seen in the blue dynamical particle 'pot'.

- For ϕ meson, the partial decay rates are

$$\Gamma_{\phi\to KK} = 3.545\,\text{MeV}, \qquad \Gamma_{\phi\to\rho\pi} = 0.6535\,\text{MeV}, \tag{3}$$
$$\Gamma_{\phi\to\eta\gamma} = 0.0558\,\text{MeV}, \qquad \Gamma_{\phi\to ll} = 2.484\times10^{-3}\,\text{MeV}. \tag{4}$$

- For η meson, the partial decay rates are given by

$$\Gamma_{\eta\to\gamma\gamma} = 0.355\times10^{-3}\,\text{MeV}, \tag{5}$$
$$\Gamma_{\eta\to3\pi^0} = 0.516\times10^{-3}\,\text{MeV}, \qquad \Gamma_{\eta\to3\pi} = 0.368\times10^{-3}\,\text{MeV}, \tag{6}$$
$$\Gamma_{\omega\to\eta\gamma} = 3.905\times10^{-3}\,\text{MeV}, \qquad \Gamma_{\rho\to\eta\gamma} = 44.73\times10^{-3}\,\text{MeV}. \tag{7}$$

- For ρ meson, the decay rate is

$$\Gamma_{\rho\to\pi\pi} = 149.1\,\text{MeV}. \tag{8}$$

- For K meson, the decay rate for $K_S \to \pi+\pi$ and charge pion decay $K^\pm \to \mu^\pm\nu$ are given by

$$\Gamma_{K_S\to\pi\pi} = 7.350\times10^{-12}\,\text{MeV}, \tag{9}$$
$$\Gamma_{K^\pm\to\mu\nu} = 3.379\times10^{-14}\text{MeV}. \tag{10}$$

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- For hyperons Y, the decay rate is comparable to $\Gamma_{K_S \to \pi\pi}$. We postpone discussion pending more complete study of (anti)baryon component and note here

$$\Gamma_{Y \to N\pi} \approx 6.582 \times 10^{-12}\,\text{MeV}. \tag{11}$$

Based on these typical reaction rates, we can refocus attention on a smaller reaction system seen in Fig. 2.

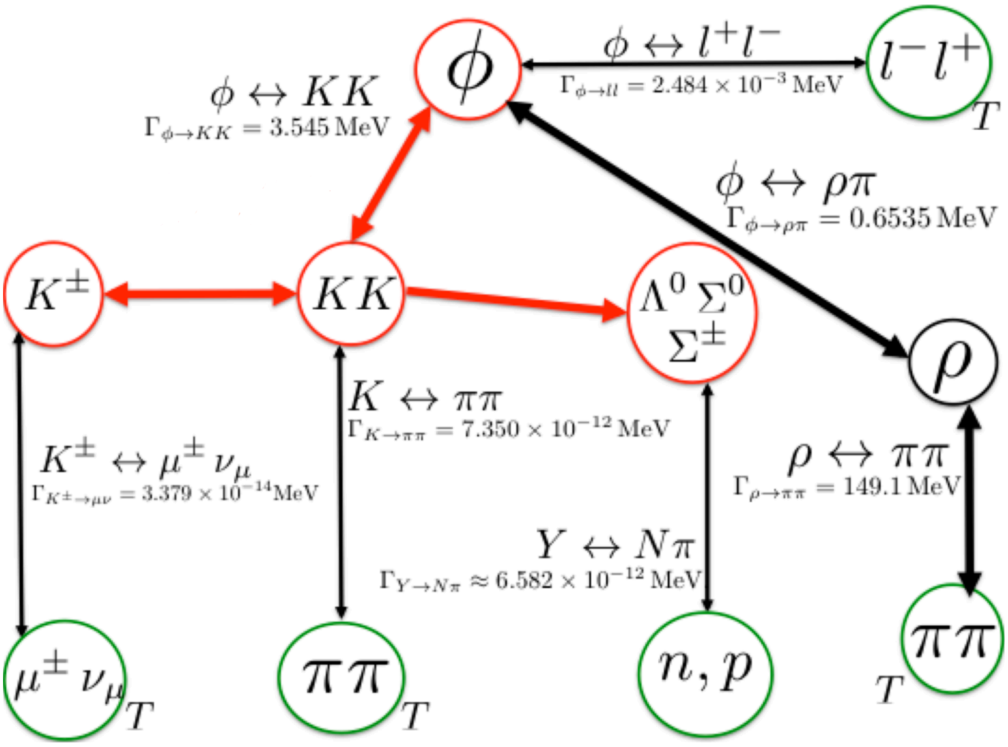

Figure 2. The strangeness abundances changing reactions in primordial Universe. The red circles show strangeness carrying hadronic particles; red thick lines denote effectively instantaneous reaction. Black thick lines show relatively strong hadronic reactions before strangeness is produced.

We note that:

- The strange quark abundance in early Universe is equal to the sum of strange baryons Λ^0, Σ^0, $\Sigma^\pm$ and strange mesons ϕ, K, $K^\pm$. We will see that in the early Universe the important source for creation of $\phi(s\bar{s})$ and $K(q\bar{s})\overline{K}(\bar{q}s)$ are given by $l^- + l^+ \to \phi$, $\rho + \pi \to \phi$, $\pi + \pi \to K, \overline{K}$, and $\mu^\pm + \nu \to K^\pm$.
- Reaction rate for $l^- + l^+ \to \phi$, $\pi + \pi \to K$, and $\mu^\pm + \nu \to K^\pm$ are relatively small compared to reaction $\rho + \pi \to \phi$. However, the thermal abundance of pions and leptons $\pi, l^\pm, \nu$ is relatively high compared to the more massive ρ. Therefore all these reactions compete with each other.
- The strong decay rate of $\phi \to K + K$ indicates that these particles ϕ and K are in relative chemical equilibrium.
- The strong strangeness exchange rates $K + N \to Y + \pi$ following on $\phi \to K + K$ with small decay rate of $K \to \pi + \pi$ and $Y \to N + \pi$ suggests the possibility that strangeness can accumulate in K meson and in Y hyperons resulting in strange baryon yields above chemical equilibrium yield, a topic of future study requiring consideration of baryon chemical potential considered negligible in the present study.

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4. Reaction rates

We now explore in more detail the conditions in which the nonequilibrium of strangeness arises. In order to study the strangeness nonequilibrium in the early Universe, we need to calculate the relevant dynamic reaction rates for strangeness production in detail.

4.1. Strangness and hadrons

The relevant interaction rates competing with Hubble time involving strongly interacting mesons are reactions $\pi+\pi \leftrightarrow K$, $\pi+\pi \leftrightarrow \rho$, $\rho+\pi \leftrightarrow \phi$, and $\mu^{\pm}+\nu \rightarrow K^{\pm}$. Our results are seen in Fig. 3, and we describe the methods used to obtain these results in the following.

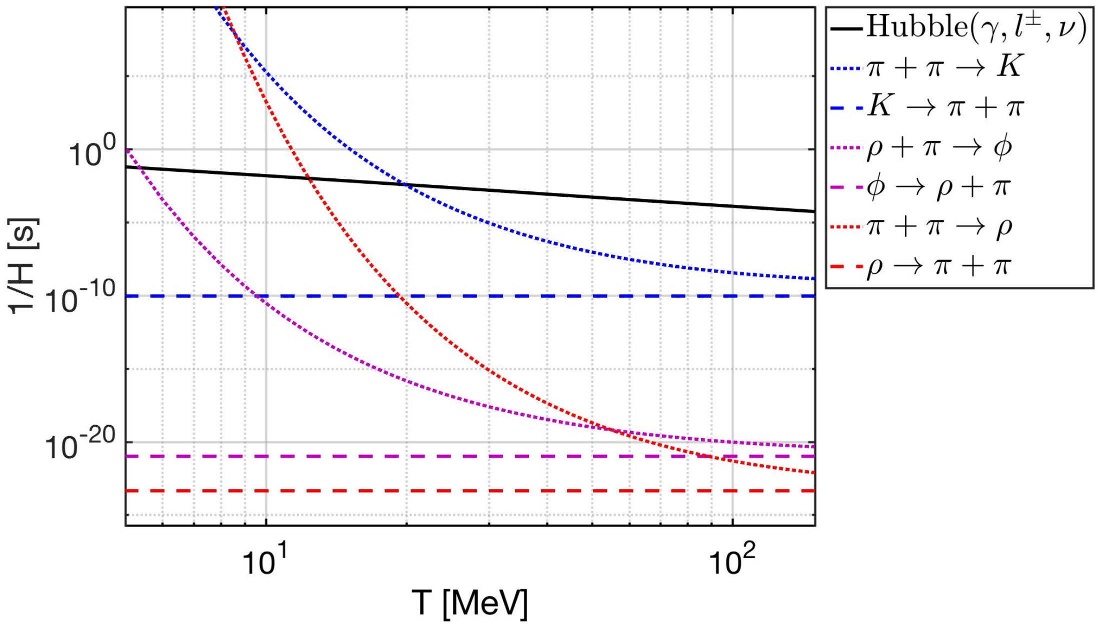

Figure 3. Hubble time $1/H$ (black line) as a function of temperature is compared to hadronic relaxation reaction times, see Eq. (19), for reactions $\pi+\pi \leftrightarrow K$(blue), $\pi+\pi \leftrightarrow \rho$ (red), $\rho\pi \leftrightarrow \phi$(purple). The horizontal dashed lines are the natural decay lifespans.

In general, the thermal reaction rate per time and volume for reaction $1+2 \rightarrow 3$ is given by [12,14]:

$$
\begin{aligned}
R_{12\rightarrow3} &= n_1\, n_2\, \langle\sigma v\rangle_{12\rightarrow3} \\
&= \frac{g_1 g_2}{32\pi^4}\,\frac{T}{1+I_{12}}\int_{m_3^2}^{\infty} ds\, \frac{\left[s-(m_1+m_2)^2\right]\left[s-(m_1-m_2)^2\right]}{\sqrt{s}}\,\sigma\, K_1(\sqrt{s}/T), \qquad (12)
\end{aligned}
$$

where the factor $1/(1+I_{12})$ is introduced to avoid double counting of indistinguishable particles, we have $I_{12}=1$ for identical particles, otherwise $I_{12}=0$. Many studies have shown that the hadronic reaction matrix element $|\mathcal{M}_{12\rightarrow3}|^2$ for hadronic reactions without resonance phenomenon is insensitive to changes of $\sqrt{s}$ in the considered energy range [12,14]. In this case, we assume that the transition amplitude $|\mathcal{M}_{12\rightarrow3}|^2$ is nearly constant in the energy range we consider, and the cross section σ can be written as

$$
\sigma = \frac{2\pi}{2\sqrt{\left[s-(m_1+m_2)^2\right]\left[s-(m_1-m_2)^2\right]}}\left(\frac{1}{g_1 g_2}\sum_{spin}|\mathcal{M}_{12\rightarrow3}|^2\right)\mathrm{IMS1(out)} \qquad (13)
$$

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where the one-particle invariant phase space is given by

$$\text{IMS1(out)} = \int d^4p_3\, \delta_0(p_3^2 - m_3^2)\, \delta^4(p_1 + p_2 - p_3) = \delta_0(s - m_3^2). \tag{14}$$

In this case, the thermal reaction rate per time and volume can be written as

$$\begin{aligned} R_{12\to3} &= \frac{1}{16\pi^3}\frac{T}{1+I}\sum_{spin}|\mathcal{M}_{12\to3}|^2\int_{m_3^2}^{\infty} ds \frac{\sqrt{[s-(m_1+m_2)^2]\,[s-(m_1-m_2)^2]}}{2\sqrt{s}}\delta_0(s-m_3^2)\,K_1(\sqrt{s}/T) \\ &= \frac{1}{16\pi^3}\frac{T}{1+I}\sum_{spin}|\mathcal{M}_{12\to3}|^2\frac{\sqrt{[m_3^2-(m_1+m_2)^2]\,[m_3^2-(m_1-m_2)^2]}}{2m_3}K_1(m_3/T). \end{aligned} \tag{15}$$

On the other hand, the vacuum decay rate for particle 3 can be written as

$$\frac{1}{\tau_3^0} = \frac{|p|}{8\pi\, m_3^2}\left(\frac{1}{1+I_{12}}\right)\left(\frac{1}{g_3}\sum_{spin}|\mathcal{M}_{12\to3}|^2\right), \tag{16}$$

$$|p| = \frac{1}{2m_3}\sqrt{m_1^4 + m_2^4 + m_3^4 - 2m_1^2m_2^2 - 2m_1^2m_3^2 - 2m_2^2m_3^2} \tag{17}$$

Hence, using the vacuum decay rate for the thermal reaction rate per unit time and volume can be written as

$$\begin{aligned} R_{12\to3} &= \frac{T}{16\pi^3}\frac{8\pi\, m_3^2}{|p|}\frac{g_3}{\tau_3^0}\frac{\sqrt{[m_3^2-(m_1+m_2)^2]\,[m_3^2-(m_1-m_2)^2]}}{2m_3}K_1(m_3/T) \\ &= \frac{g_3}{2\pi^2}\left(\frac{T^3}{\tau_3^0}\right)\left(\frac{m_3}{T}\right)^2 K_1(m_3/T). \end{aligned} \tag{18}$$

In order to compare the reaction time with Hubble time $1/H$, it is also convenient to define the relaxation time for the process $1 + 2 \longrightarrow 3$ as follows

$$\tau_{12\to3} \equiv \frac{dn_1/dY_1}{R_{12\to3}} = \frac{n_1^{eq}}{R_{12\to3}}, \quad n_1^{eq} = \frac{g_1}{2\pi^2}\int_{m_1}^{\infty} dE\, \frac{E\sqrt{E^2-m_1^2}}{\exp{(E/T)}\pm1}, \tag{19}$$

and the freeze-out temperature for the given reaction $1 + 2 \to 3$ can be estimated by considering the condition:

$$\tau_{12\to3} = 1/H. \tag{20}$$

4.2. Strangness and leptons, photons

The relevant interaction rates competing with Hubble time involving lepton background in the Universe are seen in Fig. 4. As an example, consider the reaction $K^\pm \leftrightarrow \mu^\pm + \nu_\mu$.. We have

- The decay modes of charged kaon $K^\pm$, we have

$$K^+ \longrightarrow \mu^+ + \nu_\mu, \quad K^- \longrightarrow \mu^- + \bar{\nu}_\mu, \tag{21}$$

  where the lifetime of $K^\pm$ is given by $\tau_{K^\pm} = 1.238 \times 10^{-8}$ sec and the mass $m_{K^\pm} = 493.677$ MeV. Hence the charged kaons in the cosmic plasma can be produced by the inverse of the decay processes, we have

$$\mu^+ + \nu_\mu \longrightarrow K^+, \quad \mu^- + \bar{\nu}_\mu \longrightarrow K^-. \tag{22}$$

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From Eq.(18) the thermal interaction rate per unit volume for the process $\mu^{\pm} + \nu \leftrightarrow K^{\pm}$ can be written as

$$R_{\mu\nu\leftrightarrow K^{\pm}} = \frac{g_{K^{\pm}}}{2\pi^2}\left(\frac{T^3}{\tau_{K^{\pm}}}\right)\left(\frac{m_{K^{\pm}}}{T}\right)^2 K_1(m_{K^{\pm}}/T). \tag{23}$$

With the thermal interaction rate per volume $R_{\mu\nu\leftrightarrow K^{\pm}}$, we can also define the equilibrium relaxation time for the process $\mu^{\pm} + \nu_\mu \rightarrow K^{\pm}$ as follow

$$\tau_{\mu\nu\rightarrow K^{\pm}} = \frac{n_\mu^{eq}}{R_{\mu\nu\leftrightarrow K^{\pm}}}, \qquad n_\mu^{eq} = \frac{g_\mu}{2\pi^2}\int_{m_\mu}^{\infty} dE\, \frac{E\sqrt{E^2 - m_\mu^2}}{\exp(E/T) + 1}. \tag{24}$$

In Fig.(4) we plot the interaction rate for $\mu^{\pm} + \nu_\mu \rightarrow K^{\pm}$(dark blue line) and compare to the Hubble expansion rate as a function of temperature.

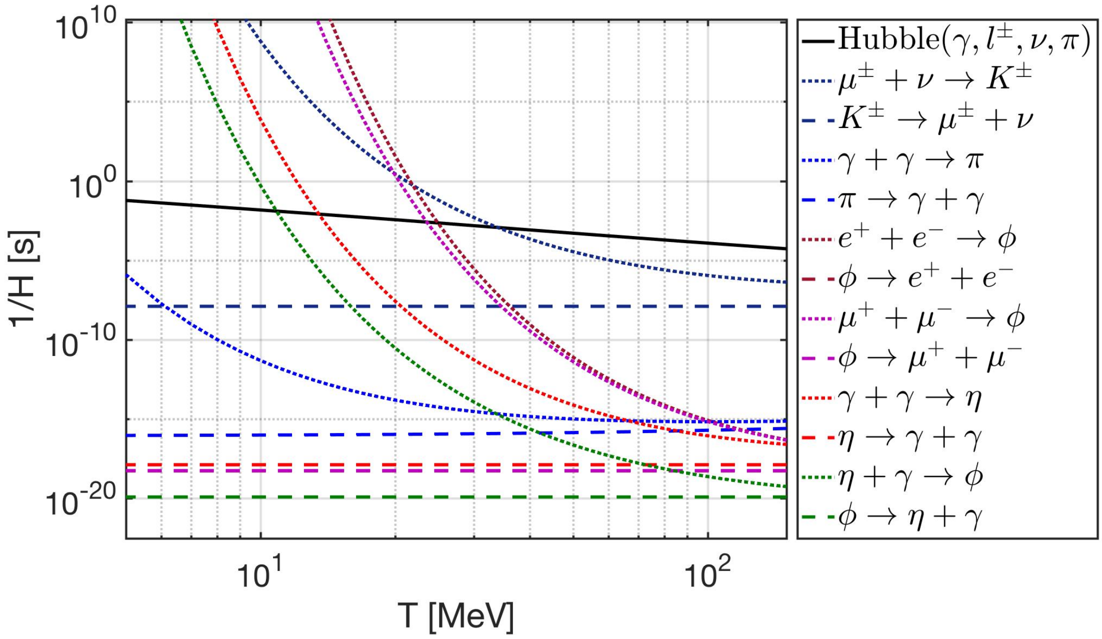

Figure 4. Hubble time $1/H$ (black line) as a function of temperature is compared to leptonic and photonic relaxation reaction times, see Eq. (19), for $\gamma + \gamma \leftrightarrow \pi$ (blue), $\gamma + \gamma \leftrightarrow \eta$ (red), $\eta + \gamma \leftrightarrow \phi$ (green), $l^{+} + l^{-} \leftrightarrow \phi$ (brown and purple), and $\mu^{\pm} + \nu_\mu \longrightarrow K^{\pm}$(dark blue line). The horizontal dashed lines are the natural decay lifespans.

The freeze-out condition

$$\tau_{\mu\nu\rightarrow K^{\pm}}(T_f) = 1/H(T_f) \tag{25}$$

where the relaxation reaction time $\mu^{\pm} + \nu_\mu \rightarrow K^{\pm}$ becomes slower compared to the Universe expansion and thus detailed balance in this reaction cannot be maintained is near $T_f^{K^{\pm}} = 33.90\,\mathrm{MeV}$.

If other strangeness production reactions did not exist, strangeness would disappear as the Universe cools below $T_f^{K^{\pm}} = 33.90\,\mathrm{MeV}$. However, using Eq. (18) and Eq. (19) we already evaluated the relaxation time for reactions: $\pi + \pi \leftrightarrow K$, $\pi + \pi \leftrightarrow \rho$, and $\rho + \pi \leftrightarrow \phi$ as functions of temperature in the early Universe as seen in Fig. 3. The intersection of characteristic reaction times with $1/H$ occurs for $\pi + \pi \rightarrow K$ at $T = 19.85\,\mathrm{MeV}$, for $\pi + \pi \rightarrow \rho$ at $T = 12.36\,\mathrm{MeV}$, and for $\rho + \pi \rightarrow \phi$ at $T = 5.36\,\mathrm{MeV}$.

Several other leptonic and photonic reactions of relevance are shown in Fig. 4. We see now the relaxation time for $\gamma+\gamma \leftrightarrow \pi$ (blue), $\gamma+\gamma \leftrightarrow \eta$ (red), $\eta+\gamma \leftrightarrow \phi$ (green), $l^+ + l^- \leftrightarrow \phi$ (brown and purple), and $\mu^\pm + \nu_\mu \to K^\pm$(dark blue line) as a function of temperature. We see that pions remain in equilibrium since $\gamma+\gamma \to \pi$ reactions are always faster compared to $1/H$. For the other reactions $\gamma+\gamma \to \eta$ reaction intersects $1/H$ at $T = 13.5\,\mathrm{MeV}$, $\eta+\gamma \to \phi$ at $T = 10.85\,\mathrm{MeV}$, $e^- + e^+ \to \phi$ at $T = 24.9\,\mathrm{MeV}$, $\mu^+ + \mu^- \to \phi$ at $T = 23.5\,\mathrm{MeV}$, and as noted before $\mu^\pm + \nu_\mu \to K^\pm$ at $T = 33.9\,\mathrm{MeV}$.

5. Discussion

In this work we focused our attention on reactions in which the particle number changes by one; that is a particle decays into two and is restored in two to one reactions in what one may call $1 \Leftrightarrow 2$ reaction process. For these the required reaction rates are obtainable from available decay rates as described here. These $1 \Leftrightarrow 2$ reactions in general dominate the processes we considered important at low temperature $T \ll m_\pi$ as the energy of two particles is converted into the heavier mass of just one particle.

In comparison the $2 \Leftrightarrow 2$ reactions have a significantly higher reaction threshold when strangeness is produced and thus certainly are negligible near to strangeness freeze-out condition and associated chemical nonequilibrium we are interested in. On the other hand, these reactions are important near to the QGP hadronization temperature $T \simeq 150\,\mathrm{MeV}$ and play an important part in the study of the evolution of strangeness in the HG phase emerging in QGP hadronization. However, there is no experimental scattering data available allowing the precise characterization of such reactions, instead one relies on theoretical concepts and models. For an introduction to this very different physics domain and detailed discussion of the here relevant reaction $KK \leftrightarrow \pi\pi$ we refer the reader to the Chapter 18 in Ref.[12].

In this work we also looked only at the meson sectors of strangeness and have established in the above discussion that a detailed study of chemical freeze-out and strangeness decoupling abundance in the early Universe requires use of the reaction rates we established in the domain $10 < T < 50\,\mathrm{MeV}$. We have shown that the first reactions to become slower compared to Hubble time $1/H$ for strange particles ϕ and K are $\mu^\pm + \nu_\mu \to K^\pm$, $\pi + \pi \to K$ and $l^- + l^+ \to \phi$ with reaction times crossing $1/H$ at $T = 33.9\,\mathrm{MeV}$, $T = 25\,\mathrm{MeV}$ and $T = 20\,\mathrm{MeV}$ respectively. Once these reactions decouple from the cosmic plasma, the corresponding detailed balance is broken and the inverse decay reactions are acting like a "hole" in the strangeness abundance "pot" due to this channel of strangeness decay in early Universe proceeding, but the reverse channel of strangeness production reaction being inhibited by in comparison fast Universe expansion.

However, there are many different channels of strangeness production and decay so the loss of one reaction channel does not end the strangeness abundance. As Universe expands, other strangeness producing reactions become relevant, for example $\gamma+\gamma \to \eta$ reaction intersects $1/H$ at $T = 13.5\,\mathrm{MeV}$, and $\eta + \gamma \to \phi$ at $T = 10.85\,\mathrm{MeV}$ thus when an η is produced we can always assume that a ϕ arises and thus considering the $\phi \Leftrightarrow K + K$ reactions this generates Kaons which can decay as now several strangeness decay paths exceed in speed the corresponding channel production rate.

This consideration demonstrates that when considering only meson content of the Universe and the cooling of the Universe reaches temperature around $T = 30\,\mathrm{MeV}$ strangeness will begin to progressively decouple from chemical equilibrium but remains in some (non-equilibrium) abundance. It is important to note that the decoupling is completed when we stop making strange hadrons (including hidden strangeness ϕ, η) near to $10\,\mathrm{MeV}$; we still keep creating ρ mesons down to $5\,\mathrm{MeV}$ but by now massive mesons are in a very, very low abundance and are not capable inducing further strangeness producing reactions.

However, mesons are not the only hadronic component in the Universe. There are also baryons and antibaryons and our domain of temperature where strangeness begins to decouple overlaps with the range in which baryons and antibaryons are expected to freeze-out at about $T = 40$-$50\,\mathrm{MeV}$ [1]. To be able to study antibaryon annihilation in a dynamical model we would need to include aside of ρ

also ω particle as one of the key antibaryon annihilation processes is $\bar{N} + N \Leftrightarrow \rho + \omega$, and if hyperons (strange baryons and antibaryons) are involved the K^* enters into this process.

This means that a quantitative study of strangeness freeze-out requires that a full account be given to strange hyperons and antihyperons which, as noted earlier, could enter into chemical nonequilibrium excess abundance given the peculiarity of the reactions explored. Ongoing production and annihilation processes of (anti)hyperons involving chemical nonequilibrium could be of greater interest in the context of baryogenesis.

We also note that in all above calculations we have considered kinetically equilibrated distribution described by the temperature T. This certainly applies to charged particles which are embedded in the cosmic background of a dense photon-electron-positron plasma. However, many of the reactions we considered involve neutral particles; here as an example consider the process $\pi^0 + \pi^0 \to K_S$, and many even more relevant reactions involving neutral strange baryon. A further study needs to establish the validity of the kinetic equilibrium hypothesis for neutral hadrons.

Another topic of interest and future exploration is noted in Fig. 3: At high T the reaction speed $\pi + \pi \leftrightarrow \rho$ (red in figure) is faster compared to $\rho\pi \leftrightarrow \phi$; thus the latter reaction draws on a near thermal equilibrium abundance of ρ. However, as the Universe cools the time constants reverse near $T \simeq 55\,\text{MeV}$: from now on all ρ created can convert faster to ϕ than they are resupplied, and ϕ will break out into kaons which populate hyperons as noted above. Such reaction chains create deviation of ρ abundance from equilibrium abundance.

Such chemical nonequilibrium in cascading reactions is not originating in the competition with the dynamics of Universe expansion, but in individual reaction rate competition arising within chain of evolution reactions due to the change in number of particles in detailed balance equation. This type of internal competition is also the mechanism that could distort the (anti)hyperon chemical abundance equilibrium as noted earlier. We note that these detailed balance considerations have been proposed as the origin of electron, positron decoupling in dense medium, see Refs.[15,16].

These considerations of future work demonstrate that a new and rich domain in the study of the Universe evolution has been opened by our present considerations. The primary conclusion and outcome of this first study of strangeness production mechanisms in the early Universe, following on QGP hadronization, is that the relevant temperature domains indicating non-trivial dynamics and freeze-out for (strange) mesons and strange (anti)baryon abundance are overlapping. Thus both baryon and strangeness chemical freeze-out have to be jointly explored in a dynamical model. The Universe in the range $20 \leq T \leq 60\,\text{MeV}$ is rich in physics phenomena involving strange mesons, (anti)baryons including (anti)hyperon abundances, which can enter into chemical nonequilibrium while undergoing successive freeze-out processes.

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