Strange hadron resonances as a signature of freeze-out dynamics

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We study the production and the observability of $\Lambda^*(1520)$, $K^*(892)$, and $\Sigma^*(1385)$, strange hadron resonances as function of the freeze-out conditions within the statistical model of hadron production. We obtain an estimate of how many decay products are rescattered in evolution towards thermal freeze-out following chemical freeze-out, and find that the resonance decay signal is strong enough to be detected. We show how a combined analysis of at least two resonances can be used to understand the chemical freeze-out temperature, and the time between chemical and thermal freeze-outs.

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Hadronic particle signatures of the formation of QGP phase in relativistic heavy ion collisions are most sensitive when the dense hadron matter fireball breakup is sudden. But final state particles could also emerge remembering relatively little about their primordial source, having been subject to rescattering in purely hadronic gas phase. Which reaction picture applies can have decisive influence on our understanding of the underlying physics, and thus we propose here a systematic method to experimentally make a distinction.

To address this question we consider strange hadron resonance abundances. At this time $\Lambda(1520)$ has been observed in heavy ion reactions at SPS energies following a suggestion that such a measurement was possible. SPS and RHIC experiments report measurement of the $K^*(892)$ signal, and RHIC has already measured both the $K^*$ and the $K^0$. In the SPS case, the $\Lambda(1520)$ abundance yield is about 2.5 times smaller than expectations based on the yield extrapolated from nucleon-nucleon reactions. This is to be compared with the enhancement by factor 2.5 of $\Lambda$-production in the same reaction in terms of the same comparison.

A possible explanation for this effective suppression by a factor 5, or more, is that the decay products ($\pi, \Lambda$) produced at a high chemical freeze-out temperature $T \simeq 175$ MeV have rescattered and thus their momenta did not allow to reconstruct this state in an invariant mass analysis. However, the observation of a strong $K^*$-yield signal contradicts this point of view, since the $K^*(892)$ decays faster ($\Gamma_{K^*} = 50.8 \pm 0.9$ MeV > $\Gamma_{\Lambda^*} = 15.6 \pm 1$ MeV). Therefore, $K^*(892)$ should be even more suppressed: a back of envelope calculation based on exponential population attenuation suggests that if the observable yield of $\Lambda(1520)$ is reduced by factor 5, the observable yield of $K^*(892)$ should be suppressed by a factor 10.

Another explanation is that the chemical freeze-out temperature which governs the production of these resonances in a thermal model is considerably lower, and hence rescattering of decay products is less significant. This is a point of view arising from a recent analysis of the hadronization process.

We explore the production, and the suppression of the observability of these resonances($K^*(892), \Lambda(1520)$), and also explore the (more difficult) measurement of the $\Sigma^*(1385)$ state as a further way of distinguishing between reaction scenarios. We will show in a quantitative analysis how these measurements can constrain both the chemical freeze-out temperature and the lifetime of the hadron interacting phase evolving between the chemical and the thermal freeze-out conditions.

The $\Sigma^*(1385)$ is expected to be produced in a thermal model more abundantly than $\Lambda^*(1520)$ in a hadronic fireball due to it’s high degeneracy factor and smaller mass. Because of its 3 times shorter lifetime ($\Gamma_{\Sigma^*} = 36-39$ MeV > $\Gamma_{\Lambda^*} = 15.6 \pm 1$ MeV), the $\Sigma^*$ signal is more strongly influenced by final state interactions than that of $\Lambda^*(1520)$. Like for $K^*(892)$, one would naively expect that the observable yield of $\Sigma^*$ should be suppressed by a factor 10.

We will first show that, in a fireball hadronizing according to the statistical model, the proportion of $\Lambda$ s and Kaons resulting from decays of the main resonances can be noticeably dependent on chemical freeze-out temperature. Hadrons produced directly from a medium at temperature ($T$) much lower than the particle mass (in all cases considered here) fill the available statistical phase space which has the relativistic Boltzmann distribution shape:

\[
\frac{d^2N}{dm^2TdY} \propto g \prod_{i=1}^{n} \lambda_i \gamma_i m_T \cosh(y) e^{-E/T} \tag{1}
\]

Here $g$ is the statistical degeneracy, $\lambda_i$ and $\gamma_i$ are the fugacity and equilibrium parameters of each valence quark, and $E$ is the energy. When the fireball is expanding at a relativistic speed, equation describes the energy distribution of an element of the fireball in a reference frame at rest with respect to the expansion (flow). However, in this paper we evaluate ratios of particles with similar masses, and interaction modes, often considered in full phase space. For this reasons to a good approximation, the flow effects largely cancel out. Similarly, for ratios of particles with the same valence quark composition, such as $\Sigma^*/\Lambda, \Lambda(1520)/\Lambda$ and, in the limit of $\lambda_u = \lambda_d$ (assumed hence forward), $K^*(892)/K^- (= K^*/K^+)$ the
chemical factors ($\lambda$’s and $\gamma$’s) cancel out between the two states compared.

We now include in the yields the descendents arising from resonance decays. In a decay of the type $R \rightarrow 1 + 2$ where a particle $R$ (mass $M$, transverse mass $m_T$, rapidity $Y$) into a particle 1 (mass $m_1$, transverse mass $m_{T1}$, rapidity $y_1$) and 2 (mass $m_2$), the distribution $d^2N_1/dm_{T1}^2dy_1$ can be obtained in terms of $d^2N_R/dm_T^2dy$ using the following transformation:

$$\frac{dN_1}{dm_{T1}^2dy_1} = \frac{g_rb^2}{4\pi p^*} \int_{Y_1}^{Y_1 + \Delta Y} dY \int_{M_{T1} - m_T}^{M_{T1} + m_T} dM \frac{d^2N_R}{dM_T^2dY}$$

$$J = \frac{\sqrt{E^* - m_T^2 c^2}}{\Delta Y}$$

Here $\Delta Y = Y - y$, $s$ is the combined invariant mass of all the decay products except 1, and $E^* = \frac{1}{2M}(M^2 - m^2 - m_1^2)$, $p^* = \sqrt{E^2 - m^2}$ are the energy and momentum of decay particle 1 in the resonances rest frame. $g_r$ accounts for a resonances degeneracy, while $b$ is the branching ratio of the considered decay channel.

A full justification for Eq. (3) is found in Refs. [9,10], where it is obtained by transforming the resonance distribution from its rest frame into the fireballs rest frame, and integrating over all the kinematically allowed values of rapidity and transverse mass. $J$ is the Jacobian of this transformation, with integration limits:

$$Y_\pm = y \pm \sinh^{-1}\left(\frac{p^*}{m_T}\right)$$

$$M_T^\pm = M \frac{E^* m_T \cosh(\Delta Y) \pm p_T \sqrt{p^2 - m_T^2 \sinh^2(\Delta Y)}}{m_T^2 \sinh^2(\Delta Y) + m^2}$$

Table I summarizes the dominant decay processes considered in our analysis and their parameters (Clebsch-Gordon coefficients have been used to estimate decays such as $(N^{*0} \rightarrow N^+\pi^-)/(N^{*0} \rightarrow N^0\pi^0)$).

| g | Reaction | $p^*$ (MeV) | branching ratio | visible? |
|---|----------|-------------|----------------|---------|
| 4 | $\Sigma^{*+}(1385) \rightarrow \Sigma^{0}\pi^+$ | 127 | $\approx 4\%$ | No |
| 8 | $\Sigma^{*+}(1385) \rightarrow \Lambda\pi$ | 208 | 88% | Yes |
| 4 | $\Sigma^{*+}(1385) \rightarrow \Lambda\pi^0$ | 208 | 88% | No |
| 2 | $\Sigma^0 \rightarrow \Lambda$ | 74 | 100% | No |
| 4 | $\Lambda(1520) \rightarrow NK$ | 244 | 45% | Yes |
| 3 | $K^{*+}(892) \rightarrow K^+\pi$ | 291 | $\approx 67\%$ | Yes |
| 3 | $K^{+}(1270) \rightarrow K\rho$ | 76 | 41% | No |
| 3 | $K^0(1270) \rightarrow K\pi$ | 301 | 16% | No |
| 6 | $K^{*+}(1400) \rightarrow K^{*+}(892)\pi$ | 301 | 100% | No |
| 6 | $K^{*+}(1400) \rightarrow K^*(892)\pi$ | 301 | 100% | No |
| 5 | $K^{*+}(1400) \rightarrow K^*(892)\pi,\pi$ | $\approx 400$ | 40% | No |
| 5 | $K^{*+}(1400) \rightarrow K^*(892)\pi,\pi$ | 622 | 50% | No |
| 1 | $K^{*+}(1400) \rightarrow K\pi$ | 622 | 100% | No |

In Fig. 1 we show the relative thermal production ratios at chemical freeze-out over the entire spectrum of rapidity and $m_T$ (solid lines) as well a central rapidity range defined by the $y - m_T$ region covered by the WA97 experiment ($|y| \leq 0.5$ in the center of mass frame) (dashed lines). The opportunity to measure the chemical freeze-out temperature by a measurement of the relative yields is apparent.

For example, at the lowest current estimates ($T \approx 100$ MeV) of the final break up temperature in 158A GeV SPS collisions 33% of $\Lambda$'s are actually primary $\Sigma^*$'s, the percentage rises to slightly more than 50% if chemical freeze-out occurs at $T = 190$ MeV. We recall that the CERN WA97 collaboration has measured hyperon yields to considerably greater precision than required to distinguish between these limiting cases [11], and the same is certainly expected of RHIC experiments such as STAR.

Considering the practical feasibility of such a measurement it should be noted that the decay $\Sigma^* \rightarrow \Lambda\pi$ would appear as a $\Lambda$-$\pi$ pair arriving from the central fireball. Experiments usually reconstruct $\Xi \rightarrow \Lambda\pi$ decays by finding the invariant mass of $\Lambda$-$\pi$ pairs with a common origin outside the collision, so a $\Sigma^*$ event would normally be discarded as a pair of unrelated particles coming directly from the fireball. An invariant mass analysis with resolution better than $\Sigma^*(1385)$ natural width (35 MeV) would be needed to distinguish it from from $\Xi(1321)$ and minimize the combinatoric background.

![FIG. 1. Temperature dependence of ratios of $\Sigma^*$, $K_0^*$ and $\Lambda(1520)$ to the total number of observed $K^*\Lambda$ s,$\Xi$s and $\Omega$ s. Branching ratios are included. Dashed lines show the result for a measurement at central rapidity $\Delta y = \pm 0.5$.](image)

The momentum of each particle in the $\Sigma^* \rightarrow \Lambda\pi$ pairs CoM (center of momentum) frame would be $\approx 208$ MeV/c, very close to the 211 MeV/c of the $\Omega \rightarrow \Lambda K$ decay. As Fig. 1 shows (top two solid/dashed lines), the potentially observable (i.e. produced) $\Sigma^*$'s should be more abundant than these two hyperons ($\Xi$,$\Omega$) at all considered hadronization temperatures. The chemical poten-
tials required to compute the two ratios $\Sigma^*/\Omega$, $\Sigma^*/\Xi$ in Fig. 3 were taken from [3].

The ratios of observed particles, however, can be considerably different from production ratios, since if the decay products rescat-ter before detection their identification by reconstructing their invariant mass will generally not be possible. While the lifetime of the $\Xi$ and $\Omega$ are large enough to ensure that only a negligible proportion of particles decay near enough to the fireball for rescattering to be a possibility, the lifetime of $K^{*0}$, $\Sigma^*$ and even $\Lambda(1520)$ is within the same order of magnitude of the fireballs dimensions i.e. $2R/c \simeq 1/\Gamma$. For this reason, a considerable number of decay products will undergo rescat-tering, and the estimation of this percentage is re-quired before any meaningful parameters are extracted from the data.

Note in Fig. 3 that the relative $\Sigma^*/\Xi$ signal is remark-ably independent (within 5% of Temperature. This feature arises because the $\Xi^*(1530)$ contribution cancels nearly exactly the thermal suppression of the $\Xi$ originating in the $\Xi - \Sigma^*$ mass difference. This effect could be used for a direct estimate of the $\Sigma^*$ lost through rescattering, even without knowledge of the freeze-out temperature, should the chemical parameters ($\lambda_1$ and $\gamma_1$) be known. A simple test of hadronization model consists in measurement of the ratio $\Sigma^*/\Xi$. If it is significantly smaller than unity, we should expect a re-equilibration mechanism to be present. Otherwise sudden hadronization applies.

We can go further in the use of the suppression of the considered resonances as a tool capable of estimating conditions at particle freeze-out. To do this we need to estimate the effect rescattering would have on the resonances signal. We formulate a simple model based on the width of the resonances in question and the decay products reactions within an expanding fireball of nuclear matter. While more realistic models, possibly involving event generators are needed for precise quantitative analysis, the model described below allows us to make a qualitative prediction and to verify the feasibility of the $\Sigma^*$ measurement.

We consider the decay of a generic resonance $N^*$

$$N^* \rightarrow p_1p_2,$$

in a gas of pions and nucleons. For the invariant mass of $N^*$ to be undetectable, it is assumed here that it is sufficient that either of the generic decay products $p_1$ or $p_2$ undergo one interaction. This interaction depends on the cross-section of the decay product with each particle in the fireball (pions, nucleons and antinucleons), the speed of each decay product relative to a typical fireball particle and the pion and nucleon density in the fireball (decreasing with time for a fireball constantly expanding with flow $v$).

This reaction rate is

$$P_1 = (\sigma_{1\pi}\rho_\pi + \sigma_{1N}\rho_N + \sigma_{1\Xi}\rho_\Xi)(\frac{R}{R + vt})^3(v),$$

and analogously for the second decay product ‘2’. Here, $\sigma$’s are the (energy averaged) interaction cross sections, the $\rho$’s are the densities, $R$ is the fireball radius at chemical hadronization, $(v)$ the velocity factor and $v$ is the space-average of the flow velocity.

To a good approximation, the thermal velocities in the fireball average out and $\langle v^2 \rangle_{1,2} = p^*\langle m_{1,2} \rangle$, here $p^*$ is as defined in Eq. (2). In addition to scattering and decay we also in principle can allow that $\Sigma^*$ and $\pi$ each have a probability of escaping the fireball. We have studied this effect and in this study of the measureability of the life-time of the interacting phase, such an escape probability is not relevant. The population equation describing the scattering loss abundance $(N_i)$ are, therefore:

$$\frac{dN_i}{dt} = \frac{1}{\tau} N_{Ni} - N_i P_i, \quad i = 1, 2$$

$$\frac{dN_{Ni}}{dt} = -\frac{1}{\tau} N_{Ni},$$

(5)

The required nucleon density $\rho_N$ is obtained in the a relativistic Boltzmann approximation:

$$\rho_N = \frac{g}{(2\pi\hbar c)^3} 4\pi m^2(\lambda_q\gamma_0)^3 K_2(mT),$$

(6)

where the $K_2(x)$ is the 2nd modified Bessel function. We consider the nucleons to have a mass of $\simeq 1$ GeV, and a degeneracy of 6, to take the p.n and the thermally suppressed but higher degeneracy $\Delta$ contributions into account in a first approximation. Considering the CERN/SPS environment we calibrate the fireball size $R$ to obtain the baryon multiplicity to be $\simeq 360$ within the volume, and we take $R = 8$ fm-145/T[MeV].

The temperature scaling of $R$ is chosen to assure that with the pion density computed in the massless particle limit, leading to

$$\rho_\pi = \frac{A\pi^2T^3}{90},$$

(7)

the entropy of the expanding system is conserved. The effective degeneracy $A$ is chosen to fix the entropy per baryon to be equal to the observed number of $\simeq 40$. We believe that this qualitative model of baryon and meson density has the right physical magnitude and scales correctly with variation of freeze-out temperature.

To estimate the average cross sections needed in Eq. (4) we recalled that the NA49 collaboration using the UrQMD event generator [12], has found that $\simeq 50\%$ of $\Lambda(1520)$ undergo rescattering after a time of 80 fm/c. In order to reproduce this result at $T \approx 160$ MeV, we took scattering cross sections shown in the top portion of table 1 based on Refs. [13,14]. It turns out that the cross section on nucleons and antinucleons are sufficient to make the fireball essentially opaque to one of the resonance decay products.
Figure 2 shows the dependence of the Λ(1520)/Λ, Σ∗/Λ and $K^{*0}(892)/K^{+}$ on the temperature and lifetime of the interacting phase. It is clear that, given a determination of the respective signals to a reasonable precision, a qualitative distinction between the high temperature chemical freeze-out scenario followed by a rescattering phase and the low temperature sudden hadronization scenario can be made. We also note that despite the shorter lifetime of the Σ∗ and higher pion interaction cross section, more Σ∗ decay products should be reconstructible than in the Λ∗(1520) case, at all but the highest temperatures under consideration.

Fig. 2 demonstrates the sensitivity of strange hadron resonance production to the interaction period in the hadron phase, i.e. the phase between the thermal and chemical freeze-out. What we learn from Fig. 2 is that while the suppression of one of these ratios considered has generally two interpretations, as it can mean either a low temperature chemical freeze-out or a long interacting phase with substantial rescattering, the comparison of two resonances with considerably different lifetimes can be used to constrain both the temperature of chemical freeze-out and the lifetime of the interacting phase.

We can reexpress the results presented in Fig. 2 representing one ratio against the other as is seen in Fig. 3 and attempt a first comparison with experiment. Combining the $K^{*0}/\pi^{+}$ results presented in [5] with earlier $K^{-}/\pi^{-}$ and $K^{+}/\pi^{+}$ results [14], it seems that the $K^{*0}/K^{+}$ ratio should be ≈ 0.2. Unless the Λ(1520)/Λ ratio will be considerably different than what is expected from [5], experimental measurement for SPS energies should be in the top left corner of the bottom portion of the Fig. 3, corresponding to a low chemical freeze-out temperature ($\approx 145$ MeV) and a short, if not negligible, time spend in the hadron re-interaction phase. Pending more experimental work, this evaluation serves only to demonstrate the functioning of the method we propose.

Table II. Scattering model parameters

| $\sigma_{\pi N}$ (mb) | $\sigma_{KN}$ | $\sigma_{\pi\pi}$ | $\sigma_{\pi K}$ | $\sigma_{NN}$ | $\sigma_{\pi K}$ |
|---------------------|--------------|------------------|-----------------|--------------|-----------------|
| 24                  | 20           | $X$              | 0.5 · $X$       | 24           | 50              |
| $\Gamma_{\Sigma^{*}}$ | $\Gamma_{\Lambda(1520)}$ | $\Gamma_{K^{*0}(892)}$ |
| 35 MeV              | 15.6 MeV     | 50 MeV           |

escape rate (fm$^{-3}$) negligible

| $\nu$ | R(fm) | $\mu_{K}$ |
|-------|-------|------------|
| 0.5   | 8.145/T MeV | 220 MeV |
| 11    |       |            |

The uncertain meson scattering cross sections (denoted in Table II for $\pi\pi$ by $X$ and for $\pi K$ by 0.5 · $X$) are therefore not material for the results we present. We quantitatively explored the range $1 < X < 100$ mb without seeing any significant change in our results. In the $\rho$ resonance region applicable at the conditions considered the value $X$ ≈ 70 mb is appropriate [14]. Remainder of Table II presents an overview of other parameters used in the model.
Should the $\Sigma^*/\Xi$ ratio become available along with a determination of $\lambda_i$ and $\gamma_i$, both the temperature and the lifetime can be inferred from the $\Sigma^*$ alone. Fig. 4 shows an analogous diagram to the one shown previously, but with the $\Sigma^*/(\text{all } \Lambda)$ on the horizontal axis and $\Sigma^*/(\text{all } \Xi)$ on the vertical. Since $\Sigma^*/(\text{all } \Xi)$ only depends on temperature by about 5%, see Fig. 1, the percentage of rescattered $\Sigma^*$ can be, to a good approximation, read off the vertical axis in Fig. 4.

![Fig. 3](image1.png)

**FIG. 3.** Dependence of the combined $\Lambda(1520)/(\text{all } \Lambda)$, $\Sigma^*(1385)/(\text{all } \Lambda)$, and $K^*(892)/(\text{all } K^-)$ signals on the chemical freeze-out temperature and interacting phase lifetime.

We have shown that a comparison of two or better three observable strange hadron resonance abundances, with different masses, widths and interaction modes of the decay products, can be used to estimate the currently uncertain hadron freeze-out behavior. We have chosen to consider strange hadrons as they have relatively narrow widths. A similar study of the lifespan between thermal and chemical freeze-outs, and chemical freeze-out temperature as parameters, can be undertaken with non-strange nucleon resonances. We believe that the experimental difficulties of such a measurement are much greater: the relative yield of resonances such as $N^*(1440)$, $\Delta(1230)$ compared to the nucleon is smaller than in case of strange baryons, the widths are much larger ($\Gamma_{N^*} \simeq 300 \text{ MeV}, \Gamma_\Delta = 120 \text{ MeV}$), and the final state nucleon has a greater scattering cross section in hadronic matter than the strangeness carrying hadron. Therefore the detectability of the non-strange baryon resonances in terms of an invariant mass analysis in the decay channels should be much smaller, except if a (very) sudden hadronization applies. Seen from that perspective, it will be interesting to see if the $\Delta(1230)$ state can be observed at all, as this would be suggesting that chemical and thermal freeze-out are indeed nearly coincident.

![Fig. 4](image2.png)

**FIG. 4.** Dependence of the combined $\Sigma^*/(\text{all } \Lambda)$ and $\Sigma^*/(\text{all } \Xi)$ signals on the chemical freeze-out temperature and interacting phase lifetime.

We believe that a detector capable of reconstructing $\Xi$ and $\Omega$ decays, with a narrower invariant mass resolution than the natural $\Sigma^*$-width (35 MeV) may be capable of measuring the $\Sigma^*$ signal by performing an invariant mass fit on $\Lambda-\pi$ pairs arriving directly from the fireball. Present day state of the art detectors such as STAR and NA57 should satisfy this criterion. We have shown that the $\Sigma^*/\Xi$ ratio is remarkably independent (within 5%) of freeze-out temperature and is greater than unity. A significantly depleted ratio would directly measure rescattering of hadrons after chemical freeze-out. Considering other ratios we learn from Fig. 2 that while the suppression of one of particle ratios considered is generally not able to allow resolution of the freeze-out properties, as it can mean either a low temperature chemical freeze-out or a long interacting phase with substantial rescattering, the comparison of two relative resonance yields with considerably different lifetimes can be used to constrain both the temperature of chemical freeze-out and the lifetime of the interacting phase. This is than qualitatively...
evaluated in Fig. 3.

We have shown in quantitative fashion how a measurement of the relative yields of $\Lambda(1520)$ and $K^*(892)$ with respect to the ground states $\Lambda$ and $K$ allows to constrain the chemical freeze-out temperature, and the lifetime of the intermediate evolution period ranging between thermal and chemical freeze-outs in relativistic heavy ion collisions, and hence to distinguish between sudden and staged hadronization scenarios. We have suggested that present experiments should be also able to detect the $\Sigma^*$ resonance, which when subject to the same analysis method offers a consistency check for the reaction mechanism considered.

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