# Strange Hadron Resonances and QGP Freeze-out

**G. Torrieri**[†] **and J. Rafelski**[†‡]

† Department of Physics, University of Arizona, Tucson, AZ 85721,
‡ CERN-Theory Division, 1211 Geneva 23, Switzerland

**Abstract.** We describe how the abundance and distribution of hyperon resonances can be used to probe freeze-out conditions. We demonstrate that resonance yields allow us to measure the time scales of chemical and thermal freeze-outs. This should permit a direct differentiation between the explosive sudden, and staged adiabatic freeze-out scenarios.

## 1. Possible hadronization scenarios

An important aspect in the study of heavy ion collisions is to determine the time scale governing hadron production and the duration of the decoupling (freeze-out) process. At present, there is no general consensus on the freeze-out time scale, and hence on how much observed particles "remember" about their primordial source. quark-gluon plasma (QGP) signals are visible in hadronic particles, when freeze-out is explosive, with sudden breakup of the fireball, and little interaction between the newly-formed particles [1, 2]. In principle the newly-formed hadrons could undergo a period of re-interaction in a hadronic gas phase. This re-interaction phase, the time scale of which can be hadron-specific, could significantly alter any considered QGP signal [3, 4, 5, 6].

The study of short-lived hyperon resonances produced in heavy ion collisions, either by direct observation [7, 8], or through their effect in observed heavy ion $m_T$ distributions [9], provides a very promising way to distinguish between these scenarios, since natural lifetime of hyperon resonances is generally shorter than the expected duration of the rescattering hadronic gas (HG) phase. Therefore, the resonances signal and distribution will be sensitive to the duration (or indeed the existence) of this HG phase. In particular, rescattering of resonance decay products should deplete the observable resonance signal, since short-lived resonances are detected by invariant mass reconstruction. A significant amount of rescattering would re-thermalize resonance decay products, which affects the resulting particle's $m_T$ distributions. This paper analyses existing resonance data, in an atempt to distinguish between the sudden and staged hadronization scenarios.

In next section 2 we look the spectra of hyperons and show that non-rethermalized resonance decays are much better agreeing with the observed $m_\perp$-shapes. We than study the directly observed strange hadron resonances in section 3. We describe the possibility of resonance quenching in subsection 3.1, and compare in a simple model of an opaque medium with the experimental results in subsection 3.2.

## 2. The role of resonances in fits

The precise $m_T$ spectra produced by the WA97 experiment [9] provided the first opportunity to test the sudden hadronization model. A necessary consequence of explosive hadronization is that chemical freeze-out, which fixes particle abundances, and thermal freeze-out, which fixes particle spectra, coincide. Hence, it should be possible to fit both normalisation and $m_T$ spectra for several particles, using the same temperature, flow and chemical potentials. The fitted parameters should also agree, within error bars, with the chemical fit parameters, obtained by using just particle ratios. Our simultaneous fit to normalized WA97 data was successful [10].

The sample of $K_s, \Lambda, \overline{\Lambda}, \Xi, \overline{\Xi}, \Omega + \overline{\Omega}$ (divided into four centrality bins) was fitted, using a single set of thermodynamic parameters for each bin, to a Cooper-Frye distribution [11],

$$\frac{dN}{m_T dm_T} = V \prod_i \lambda_i \gamma_i \int d\sigma_\mu p^\mu \Theta(d\sigma_\mu p^\mu) f(T, v, m_T). \tag{1}$$

Here V is the fireball volume (*i.e.*, an experiment-specific normalisation parameter), $\lambda_i, \gamma_i$ are the flavor fugacities and saturation parameters [2], $\sigma^\mu$ and $p^\mu$ are, respectively the 4-momentum and the freeze-out hypersurface, and $f(T, v, m_T)$ is the Lorentz-transformed Boltzmann distribution, dependent on temperature, flow and transverse mass.

In such an analysis [10], $T$ and the chemical parameters agreed, within the error bars, with earlier abundance fits [2], flow and volume increased with centrality, as expected for a thermalize expanding fireball, while the hadronization surface velocity was consistently close to the speed of light, in agreement with an explosive hadronization scenario. $\chi^2$ profiles showed a clear, statistically significant minimum in each of the quantities fitted.

The only systematic deviation between statistical hadronization model and data is present in the $\Omega$ spectrum. It's unusually large enhancement and anomalous slope are also interpreted as evidence for a staged freeze-out, with $\Omega$s freezing out earlier than other particles. However, as shown in [10], it is only the low momentum $\Omega$s that deviate significantly from the expected behavior in statistical hadronization. Such a low-momentum yield enhancement is explained by an additional QGP specific physical process, such as strange diquark correlations [2], or the formations of disoriented chiral condensates [12].

For the purpose of the study of the time scales in statistical hadronization an important direct constraint is provided by the prominence, in these fits, of resonance decay products. A non-negligible fraction of hyperons (more than half in case of the $\Lambda$) within the spectrum fitted are produced not directly, but through decay of produced resonances. Yields of heavy resonances are thermally suppressed because of their higher mass, but are typically enhanced by their higher spin and isospin degeneracy. If the resonance decays with an appreciable center of mass momentum (as is the case in all hyperon resonances, except $\Sigma^0 \to \Lambda\gamma$), the distribution of particles originating from decays differs considerably from a thermal distribution. Therefore, the shape of $m_\perp$ spectra which includes resonance decay products will depend on whether the decay products of short-lived resonances have had the opportunity to rethermalize or not. If the freeze-out is sudden, the observed spectra are a mixture of direct and decay shapes, and if there is a phase in which the particles produced during hadronization
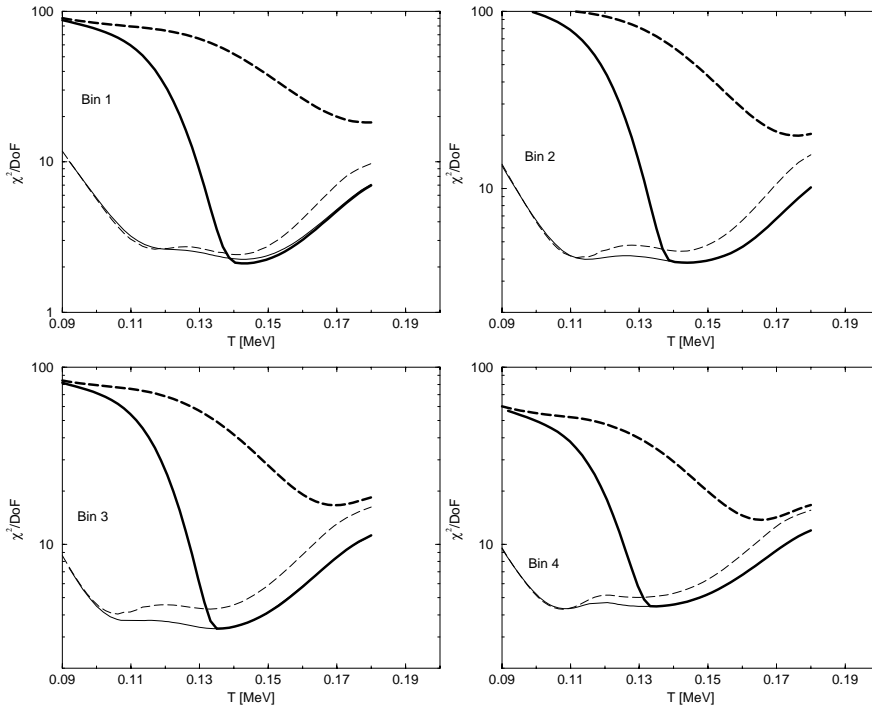
**Figure 1.** $\chi^2$ profiles of hyperon $m_\perp$ WA97 results, as function of temperature $T$. The four plots correspond to the WA97 centrality bins [9]. Solid lines are calculated assuming that the resonance decay products do not undergo rescattering, while dashed lines assume the decay products rethermalize. Thin lines show profiles calculated without enforcing the Bose Einstein condensation limit $\gamma_q^2 \le e^{\frac{m_\pi}{2T}}$, thick lines are obtained with this constraint enforced.

can undergo re-interaction, the spectrum observed is thermal, but expansion flow deformed.

In order to obtain a final particle spectrum from a thermal distribution of resonances, it is necessary to transform the decay products momenta from the resonance rest frame to the fireball rest frame, and integrate over the kinematically allowed momentum space. This procedure has been implemented in several ways by different authors ( [13, 14, 15] ); While numerically cumbersome, it requires no extra degrees of freedom within the fit.

The test for the reaction mechanism is obtained from the study of the $\chi^2$ distribution. A consistent lowering of $\chi^2$ once resonances are taken into account in a hyperons $m_T$ distribution confirms that resonance decay products emerge from the fireball unthermalized. In contrast, if resonance decay products re-thermalize, their effect will be a correction to normalisation (chemical potentials and volume) rather than slope parameters. In such a case, using the decay distributions [13, 14, 15], will not result in a better fit to the data.

Fig. 1 shows the temperature $\chi^2$ profiles (for the four WA97 centrality bins, with bin 4 being most central), calculated using the prescription in [13] to obtain decay spectra (solid lines) and assuming that resonance decay products rethermalize (dashed lines). These profiles are computed by minimising every parameter except

the temperature (flow, hadronization surface velocity and chemical potentials). Thin lines are results obtained allowing unphysical range of parameters, thick lines with the constraint on the light quark saturation parameter $\gamma_q$, corresponding to the condensation limit of the $\pi$: $\gamma_q^2 \leq e^{\frac{m_\pi}{2T}}$, where $m_\pi$ is the pion mass. The maximum value of $\gamma_q$ is prefered by the hadronizing high entropy QGP phase [2].

We see that the condensation constraint does not modify the value of the $\chi^2$ minimum for the solid lines (which correspond to non-thermalized resonance decay products), but greatly reduces it's ambiguity, and is ruling out a freeze-out temperature lower than $\approx 145$ MeV. As Fig. 1 shows comparing thick solid with the thick dashed lines, the hyperon $m_\perp$ fit strongly favours a scenario in which the decay products of resonances emerge from the fireball without re-interaction. If the condensation limit on $\gamma_q$ is not enforced (thin lines in 1), the $\chi^2$ is still consistently lowered by the inclusion of unrescattered resonances. On the other hand, once condensation limit is taken into account (thick lines), a model with thermalize resonance decay products statistically fails to describe the data: $\chi^2$ increases by a factor of 3, and the physically sensible minimum for thermal freeze-out disappears.

We therefore conclude that the WA97 $m_\perp$ data strongly favours a sudden hadronization scenario in which the hadrons emerging from the fireball without much re-interaction after freeze-out. However, a more direct way to measure the hadronization time scale is necessary in order to firmly confirm this result. We hope and expect that the experimental measurement of the resonance signal will prove useful in this regard.

## 3. Direct probes of sudden hadronization

### 3.1. First results on resonance yields

The resonance signal can be measured experimentally using invariant mass reconstruction. At present, the $K^{0*}$ has been observed by both NA49 [16] and STAR [7], and NA49 has also measured the $\Lambda(1520)$. It appears that while the $K^{0*}$ and $\overline{K^{*0}}$ are produced in the expected amounts, the $\Lambda(1520)$ yield is severely depleted. In fact, so far it has proven to be the only hyperon suppressed with respect to a proton-proton collision.

The observation of this suppression, by itself, has not been enough to settle the freeze-out time scale controversy. In principle such a suppression is welcome by both camps. The proponents of sudden freeze-out argue that freeze-out happens at a temperature considerably lower than that of the equilibrium QCD phase transition [1]. The yield N of a resonance of mass $m$ at temperature $T$ obeys,

$$N \propto m^2 T K_2(m/T) \propto (Tm)^{3/2} e^{m/T} , \tag{2}$$

here $K_2$ is the modified Bessel function. We see that heavy resonances such as the $\Lambda(1520)$ are more suppressed, since temperature is lower. The other camp notes that if one assumes a staged freeze-out, the suppression comes from rescattering of resonance decay products within HG phase. However, in this case it is difficult to see how the $K^*$ is not suppressed, especially considering it's larger width.

The actual situation is in our opinion more complicated [17]. The $\Lambda(1520)$ resonance is a D-wave of the ground $\Lambda$ (Isospin=1/2) state. It is therefore especially susceptible to in-medium mixing with the lower-mass hyperons (P-wave of the $\Sigma$, isospin $I = 3/2$ state), through reactions such as

$$\pi + \Lambda(1520) \to \Sigma^* \to \Lambda\pi, \Sigma\pi . \tag{3}$$

We therefore believe that other resonances will need to be measured in order to extract freeze-out information from their abundance. In particular, the non-suppression of $K^*$ s makes other P-wave resonances good candidates for investigation. The $\Sigma^*(1385)$ is the least massive resonance of this type, and for this reason, as well as it's other characteristics which we will explore in the next subsection, we regard it as a promising candidate.

### 3.2. Model and data comparison

Within statistical hadronization picture a particles yield depends on it's mass, the freeze-out temperature, and the chemical potentials corresponding to the particle's quantum numbers. If experimental acceptance does not cover the full $4\pi$ range, flow and hadronization surface velocity also need to be taken into account to determine the partial yields.

Since we are interested here primarily in the temperature, as well as the evolution subsequent to hadronization, it is indicative to pick an observable which is independent of as many of the above quantities as possible. To make chemical potentials cancel out, we can examine the ratio of the resonance to the "ground state" hyperon which contains the same valence quarks. For example, ratios such as $\Lambda(1520)/\Lambda$, $\Sigma^*/\Lambda$, $K^{*0}/K^-$ and $\overline{K^{*0}}/K^+$ are all independent of chemical potentials. Kaons require additional attention, because the $K^*$'s lifetime is too short for oscillation, but the $K_s$ does oscillate. Therefore, the observed $K^{*0}$ and the $K^0$ do not have the same valence quark composition. We also found that such ratios, and more generally, ratios of particles with comparable mass, are independent of flow and freeze-out surface geometry to a very good approximation.

To get a more quantitative estimate of how temperature and rescattering combine in fixing resonance ratios, a microscopic model that describes the rescattering of resonance decay products in a baryon-rich medium needs to be considered [18]. In such a model the probability of the resonance to decay in a hadron-rich medium, as well as the interaction cross-section between the decay products and the in-medium particles is allowed for. The number of reconstructible resonance decay products is obtained solving,

$$\frac{dN_i}{dt} = \Gamma N_{N^*} - N_i \Sigma_j \langle \sigma_{ij} \rangle \rho_{j0} \left(\frac{R_0}{R_0 + vt}\right)^3,$$
$$\frac{dN_{N^*}}{dt} = -\Gamma N_{N^*}. \tag{4}$$

Here $N^*$ and $N_i$ are, respectively, the resonance and decay product abundances, $\Gamma$ is the resonance width, $\rho_{j0}$ is the density of particle $j$ in the hadron gas at freeze-out and $\langle \sigma_{ij} \rangle$ is the thermally averaged interaction cross-section. Final observable yields of particle $i$ are given by integrating this model from chemical freeze-out (with a certain temperature) for an amount of time corresponding to the interacting system's lifetime.

Because of the rapid decrease in hadron density within the fireball due to flow (commonly estimated at around 0.5c), resonance ratios are extremely sensitive to the lifetime of the interacting phase compared to the resonances width. The chemical freeze-out temperature is also important, since it controls both the initial resonance abundance (through Eq. 2) and the initial density of the hadron gas.

The model is however remarkably insensitive to it's other parameters, such as the initial radius $R_0$ (which is also constrained by the entropy per baryon, $\approx 40$ in SPS experiments), and the cross-sections. In particular, we found that an order
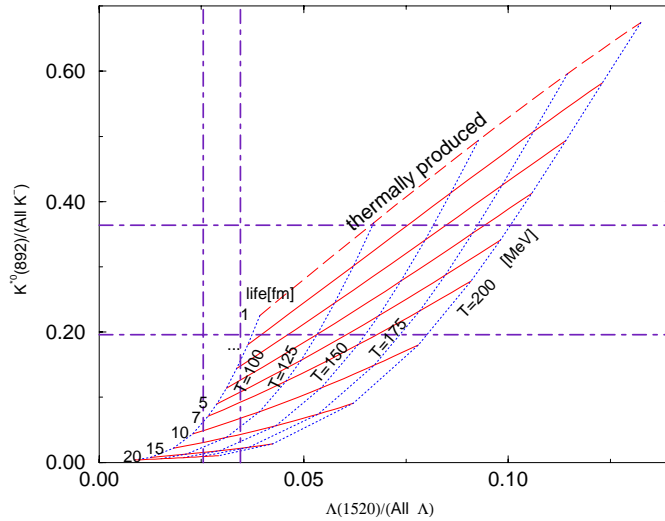
**Figure 2.** $K^*/K^-$ and $\Lambda(1520)/\Lambda$ ratios, shown as a function of each other, for a range of freeze-out temperatures and lifetimes. The dot-dashed lines represent current experimental boundaries protect[8]. The temperature and lifespan of freeze-out rescattering phase are shown.

of magnitude change in the interaction cross-sections will result in ratios changing by 30 %. For this reason, we believe that, while our model is very simplified (it neglects inelastic scattering and resonance creation within a hadron gas, and uses thermally averaged cross-sections), the results presented here are qualitatively correct, and serve as a good indication of how the interesting quantities may be extracted from experimental measurements.

We now turn to discuss the available experimental results. Fig. 2 gives the dependence of $K^*/K$ and $\Lambda(1520)/\Lambda$ on the chemical freeze-out temperature and the lifetime of the interacting hadron gas phase. It is apparent that these two quantities determine the ratios of two resonances of different masses and decay widths, as seen in the figure: an experimental point on a diagram such as Fig. 2 is just what is needed to distinguish between the explosive and gradual freeze-out scenarios.

The non-suppression of $K^*$, together with the very strong suppression of $\Lambda(1520)$, would seem to indicate instantaneous freeze-out with a temperature of less than 100 MeV. However, in obtaining this result $\Lambda(1520)$ quenching was neglected. If 50 % of the $\Lambda$ are quenched through reactions such as those in Eq. (3), existing data would be perfectly compatible with the sudden freeze-out picture, as we show in Fig. 3.

Observation of the $\Sigma^*(1385)$ yield should remove the uncertainty introduced by the quenching phenomenon. We have shown in [17], that the masses and lifetimes of the $K^*$ and $\Sigma^*(1385)$ combine to constrain the observed ratios to a very narrow yield band. Significant deviation from this band could be a strong sign of broadening of either of these two resonances. In addition, because of a coincidence between the masses of the $\Sigma^*$, the $\Xi$ and the availability of $\Xi^*(1530)$, the explicit dependence of the $\Sigma^*/\Xi$ ratio on temperature is very weak [18]. For this reason, if fugacities and saturation parameters of the light and strange quark are determined independently [19], comparison between $\Sigma^*(1385)$, $\Xi$ and $\Lambda$ should be sufficient to disentangle temperature and fireball lifetime conclusively.
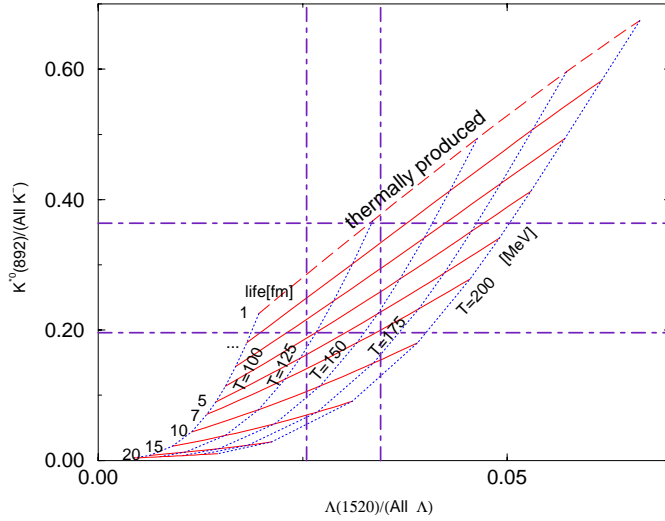
**Figure 3.** Same as Fig. 2, assuming half of the $\Lambda(1520)$ are quenched, and disappear from the observed particle sample.

We use these properties in Fig. 4, where we show how the $\Sigma^*/\Lambda$ and $\Sigma^*/\Xi$ ratios depend on the freeze-out temperature and lifetime. We see that lines corresponding to a given freeze-out temperature depend weakly on the details of the rescattering model. This makes the $\Sigma^*/\Xi$ ratio a probe of the hadronization temperature. A severely depleted $\Sigma^*/\Xi$ ratio, in the absence of evidence of broadening, would unambiguously signal a staged freeze out in which resonance decay products have ample opportunity to rescatter. The $\Sigma^*$ measurement could therefore distinguish between a scenario based on the explosive freeze-out from a super cooled QGP, and a high T chemical freeze-out, followed by a reinteraction period.

## 4. Conclusions

We have shown considering the statistical significance of different approaches to fit the $m_\perp$ spectra of WA97 experiment [9], that the strategy which does not allow for resonance products to rescatter is greatly favoured. To find this, we needed to limit the magnitude of the chemical quark-pair non-equilibrium to the maximum value compatible with the high entropy content, which is hadronizing. The $\chi^2$ minima are very pronounced and thus offer strong evidence for sudden mechanism of hadronization. This finding strongly supports the picture of suddenly hadronizing QGP as the source of these particles.

A more direct study of hadronization lifespan is derived from the observation of hyperon resonance yields. We have shown that combining results of several resonances allows to derive directly information on freeze-out temperature and duration. We have also argued that P-wave resonances are more suitable, than others, for this exercise, as they are less susceptible to in-medium modifications. Measurement of the $\Sigma^*(1385)$ yield, and it's ratio to hyperons such as the $\Lambda$ and the $\Xi$, has the potential of being just what is needed to unambiguously extract the freeze-out time scale and temperature from experimental heavy ion data.
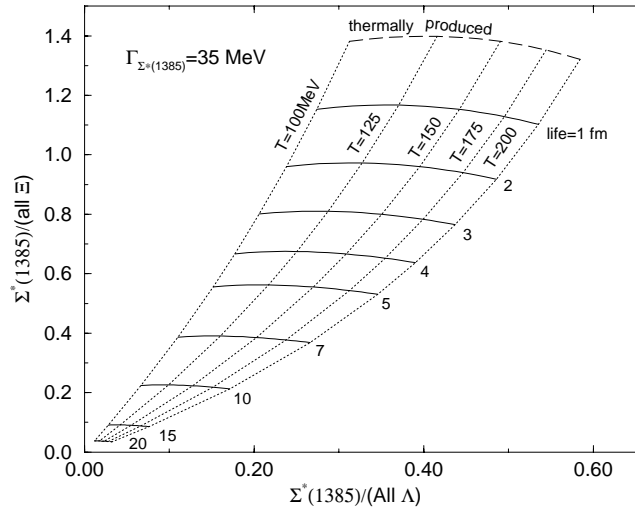
**Figure 4.** $\Sigma^*(1385)/\Lambda$ and $\Sigma^*(1385)/\Xi$, shown as a function of each other for a range of freeze-out temperatures and lifetimes. The chemical potentials used for this figure were taken from Ref. [2].

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