Freezeout of Resonances and Nuclear Fragments at RHIC

E.V. Shuryak

Department of Physics and Astronomy, SUNY at Stony Brook, NY 11794, USA

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Abstract. We quantify the conditions at which "composites", the resonances and bound states d, He\(^3\) are produced at RHIC. Using Hubble-like model for late stages, one can analytically solve the rate equations and also calculate the relevant optical depth factors. We calculate also the modification of \(\rho\) masse and width, and predict a radical shape change of \(\sigma\).

Keywords: high energy heavy ion collisions, resonance production, coalescence into nuclear fragments

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1. Introduction

This talks is based on two papers, one with Brown [1] and one ongoing work with Kolb [2], who will report a part of it related with late-time evolution here. Their common goal is to understand what are the conditions which determine the timing of production of observable resonances, and estimate at what conditions this happens. We have emphasized observable above because there are many resonances produced in the system but unobserved in the final invariant mass spectra because of rescattering of their decay products. The development of simple analytic model of the kinetics of resonance production/absorption, as well as evaluation of the “optical depth” integral.

An old but still important idea is “matter modification” of hadrons, providing the experimental test of the conditions in question. As such we discuss modification of the mass and shape of two classic \(\pi\pi\) resonances, \(\rho\) and \(\sigma\). Recent STAR observations of these effects are reproduced (for \(\rho\)) and predicted (for \(\sigma\)).

The issue of production of nuclear fragments is also an old one, at RHIC reduced to d, He\(^3\) and their antiparticles. In literature those are studied either by statistical or coalescence models, which left open many important issues. First of all, like resonances the observable fragments must escape all interactions with any particles in order to survive at the end. The second point is that this process is production-rate-limited, thus it can lead to non-thermal quasi-equilibria. Furthermore, new
element is the consistent evaluation of the 2-to-1 production rate itself in a recent work by Ioffe et al. [4].

2. The Optical Depth Factor

Let me start with the simplest pedagogical points about the observability of resonances and fragments, or “composites” as we may call them collectively, for brevity.

In the next section we will discuss rate equations which can be solved and determine the number of composites \( N(t) \) at time \( t \). The “observability condition” of a resonance can be written as

\[
\nu_{\text{visible}}(t) = \Gamma N(t) \exp \left( - \int_t^\infty \nu(t') \, dt' \right),
\]

where the l.h.s. is the production rate of visible resonances, \( \Gamma \) is the resonance decay width and the exponent is the optical depth factor containing integrated \( \nu(t) \), the combined scattering rate for all decay products. The \( N(t) \) decreases with time due to expansion and cooling, while the exponent changes from \( 0 \) at early time to \( 1 \) at late times: so the product naturally has a maximum at the time \( t_m \) such that

\[
\frac{1}{N(t_m)} \frac{dN(t_m)}{dt} + \nu(t_m) = 0.
\]

This condition means that for observable resonances the freezeout condition is different from that for stable particles and reads: the rate of their number change is equal to the absorption rate of all the decay products. For example, for \( \rho \) and \( \sigma \) we should not know their scattering rates but just that of two pions. Since for short-lived \( \rho \) and \( \sigma \) the first factor is close to overall expansion rate of matter at late time which follows from Hubble-like late-time regime \( d\log N(t_m)/dt \approx 3/t \), and the second is the same, we conclude that “visible” \( \rho \) and \( \sigma \) are produced at the same time.

The formation rate for a fragment made of \( A \) nucleons is made by some coalescence, and such rate is obviously proportional to nucleon density to that power, \( \sim (n_N(t))^A \). After it is produced, however, it still has very small probability to survive. Assuming that the destruction rate for a fragment \( \nu_A \approx A \nu_N \), where \( \nu_N \) is a scattering rate for one nucleon, one finds that for \( A \)-fragment the time distribution is approximately the \( A \)-th power of the same universal function

\[
n_{\text{fragments}}(t) \sim \left[ n_N(t) \exp \left( - \int_t^\infty \nu_N(t') \, dt' \right) \right]^A.
\]

So, the maximum of production of any visible fragment happens at the same time for all \( A \). Furthermore, the width of the distribution over production time decreases as \( A \) grows, as \( 1/\sqrt{A} \).