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Hadron yields and the phase diagram of strongly interacting matter

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Abstract

This paper presents a brief review of the interpretation of measurements of hadron yields in hadronic interactions within the framework of thermal models, over a broad energy range (from SIS to LHC energies, $\sqrt{s_{NN}} \simeq 2.5$ GeV–5 TeV). Recent experimental results and theoretical developments are reported, with an emphasis on topics discussed during the Quark Matter 2014 conference.

Keywords: Hadron yields; Thermal model; Statistical hadronization; LHC; Heavy ion

1. Introduction

It has been known since more than two decades that hadrons in high energy interactions are produced in approximate thermal and chemical equilibrium [1–4]. The relative abundances of light flavor hadrons are determined by a few thermal parameters and are, in the simplest case, approximately proportional to the Boltzmann factors. This is true with the only exception of strange particles, which deviate from the expected equilibrium abundance by a factor which depends on the strangeness content of the particle [5,6]. In central heavy ion collisions [3], strange particles were however found to follow the expected equilibrium distribution.[1]

[1] If 4π yields are considered instead of mid-rapidity dN/dy, a strangeness under-saturation factor of about 0.75 is still required at the SPS. Also note that the usage of mid-rapidity dN/dy at low energy is questionable, see for instance the discussion in [1,3].

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Measurements at different $\sqrt{s}$ revealed that the thermal fit parameters follow a smooth curve in the plane of temperature $T_{\rm ch}$ and baryochemical potential μ_B, the so-called "hadron freeze-out curve" [2,7]. For very high energy collisions, $\mu_B \to 0$ and the temperature extracted from a thermal analysis of the data ($T_{\rm ch} \sim$ 150–170 MeV) is found to be very close to the critical (crossover) temperature estimated in lattice QCD, $T_{\rm c} \in (143, 171)$ MeV [8]. Despite these observations, the profound meaning of the freeze-out curve [7,9–12] remains unclear and several key questions remain unanswered:

- What is the relation of the chemical freeze-out temperature to the QCD critical temperature?
- How is the equilibrium reached?
- What physics mechanisms drive the hadron freeze-out curve?

Recently, higher precision measurements revealed unexpected deviations from the thermal model expectations. The statistical model is an effective model (see e.g. the discussion in [13]) and the small deviations from the equilibrium picture may simply indicate that the precision of the data has become sufficient to reveal its limitations. Their study represents an opportunity for a better understanding of the underlying physics processes.

A qualitative summary of the parameters which control a thermal fit is given below for the non-expert reader. The interested reader should refer e.g. to [1,3,4] and references therein for a rigorous discussion.

The main parameters, describing particle production in equilibrium are:

- The temperature $T_{\rm ch}$ (constrained by ratios of particles with a large mass difference);
- The baryochemical potential μ_B (constrained by anti-baryon/baryon ratios, at LHC it is found $\mu_B \sim 0$);
- The volume V, which acts as a normalization parameter (constrained by the most precisely measured species, typically pions).

Deviations from (grand canonical) equilibrium can be incorporated through empirical under(over)-saturation parameters for strange, charm or light quarks (γ_s, γ_c and γ_q). The need for γ_s has already been discussed above. Another approach consists in the implementation of the "canonical suppression" mechanism (i.e. strangeness has to be conserved exactly and not on average) [6] on a smaller volume than the overall size of the system, determined by a "canonical radius" parameter, R_C. The parameter γ_c is introduced because charm can only be created in the initial phases of the collisions (it is too heavy to be created thermally) [15] and it is thus expected to be significantly out of equilibrium. While the usage of γ_s and γ_c is common to most implementations of the statistical model [3,16,17], γ_q is only found in the non-equilibrium model SHARE [4]. The physical picture in this model is that of an expanding, super-cooled quark–gluon plasma which undergoes a sudden hadronization without further re-interactions. The thermal parameters of the quark–gluon plasma are hence frozen, leading to out-of-equilibrium hadron abundances. From the point of view of the fit, γ_q allows the relative abundance of mesons and baryons to vary (as it is determined by the number of valence light quarks).

The selection of results presented in this paper reflects the author's bias, especially towards results presented during the Quark Matter 2014 conference. Due to space limitations, the list of references is also incomplete and subject to similar biases: preference is given to reviews and recent papers over the original literature.