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Going beyond the second virial coefficient in the hadron resonance gas model

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Abstract

We develop a novel formulation of the hadron resonance gas model which, besides a hard-core repulsion, explicitly accounts for the surface tension induced by the interaction between the particles. Such an equation of state allows us to go beyond the Van der Waals approximation for any number of different hard-core radii. A comparison with the Carnahan–Starling equation of state shows that the new model is valid for packing fractions 0.2–0.22, while the usual Van der Waals model is inapplicable at packing fractions above 0.1–0.11. Moreover, it is shown that the equation of state with induced surface tension is softer than the one of hard spheres and remains causal at higher particle densities. The great advantage of our model is that there are only two equations to be solved and neither their number nor their form depend on the values of the hard-core radii used for different hadronic resonances. Such an advantage leads to a significant mathematical simplification compared to other versions of truly multi-component hadron resonance gas models. Using this equation of state we obtain a high-quality fit of the ALICE hadron multiplicities measured at the center-of-mass energy 2.76 TeV per nucleon and we find that the dependence of χ^2/ndf on the temperature has a single global minimum in the traditional hadron resonance gas model with the multi-component hard-core repulsion. Also we find two local minima of χ^2/ndf in the model in which the proper volume

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of each hadron is proportional to its mass. However, it is shown that in the latter model a second local minimum located at higher temperatures always appears far above the limit of its applicability.

Keywords: Hadron resonance gas model; Hard-core repulsion; Induced surface tension

1. Introduction

During the last few years the hadron resonance gas model (HRGM) [1–4] became a precise and reliable tool to extract the parameters of chemical freeze-out (CFO) from the hadronic multiplicities measured in central nuclear collision. Nowadays the CFO is considered as a stage of heavy ion collisions, at which all particles do not interact with one another inelastically, so that the hadron multiplicities can change only via the decays. Furthermore, the HRGM is based on the assumption of a thermal and chemical equilibrium in the system and, hence, at CFO the hadron yields are completely defined by the equilibrium parameters, namely, the temperature T and the chemical potentials μ_B, μ_S and μ_{I3}, which correspond to the conservation of the baryonic charge, strangeness, and third isospin projection, respectively.

The traditional versions of the HRGM are basically the Van der Waals equation of state (EOS) which is formulated for all hadrons and hadronic resonances and which employs either one hard-core radius R for all hadrons, or at least two hard-core radii: one for mesons R_m and one for baryons R_B. However, a few main achievements in this field come from a formulation of the HRGM with multi-component hard-core repulsion (MHRGM) [2–5]. At the moment, the MHRGM contains at most five different hard-core radii: the pion hard-core radius R_π, the kaon hard-core radius R_K, the hard-core radius of Λ-(anti)hyperons in addition to the ones for other baryons R_B and for other mesons R_m. Having introduced four hard-core radii (no radius for Λ-(anti)hyperons) it was possible for the first time to describe the Strangeness Horn [2] with the highest quality $\chi^2/dof \simeq 7.3/14$ and at the same time to successfully fit 111 independent hadron multiplicities ratios measured from AGS ($\sqrt{s_{NN}} = 2.7$ GeV) to top RHIC ($\sqrt{s_{NN}} = 200$ GeV) collision energies with the fit quality $\chi^2/dof \simeq 1.16$, which was the best result at that time.

A couple of years later, taking into account one more global fitting parameter – namely the hard-core radius of Λ-(anti)hyperons, which turned out to be a very influential parameter – it was possible to decrease the value of χ^2/dof by about 20 percent and to reach the best fit quality of these data which is $\chi^2/dof \simeq 0.95$ [5]. Furthermore, the developed MHRGM allowed one to formulate the concept of separate CFOs of strange and non-strange hadrons [3,6], which naturally explains the apparent chemical non-equilibrium of strange charge in nucleus–nucleus collisions. And last but not least, a very high quality description of data allowed us to study the thermodynamics at CFO with very high confidence and to find the novel irregularities and signals of mixed-phase formation in nuclear collisions [4,7]. The recent discussion of other achievements and problems of HRGM can be found in Ref. [8].

In view of the future experiments at the NICA-JINR [9,10] and FAIR-GSI [11,12] accelerators we expect to obtain much more experimental data with a substantially higher accuracy. Evidently, these new data will, hopefully, allow us to experimentally study the second virial coefficients of the most abundant (or maybe even those of all measured) hadrons. For such a task a MHRGM with many hard-core radii should be formulated. However, since the existing MHRGM for N different hard-core radii requires the knowledge of a solution of N transcendental equations, a further increase of the number of hard-core radii (i.e., $N \sim 100$, corresponding to the various