

FEMTOSCOPIC MEASUREMENTS IN THE FRAME OF THEORETICAL MODELS*

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Collisions of heavy ions are very important source of information on structure of the most elementary matter components. Scientists develop experiments with heavy-ion collisions, which allow us to study the properties of strongly interacting nuclear matter at high energies. The main objective is to investigate a new state of matter — the Quark–Gluon Plasma (QGP). In this state, quarks are not combined into composite particles called hadrons, but they behave as free particles. Using femtoscopic methods, information about the space-time characteristics of the particle emitting source is obtained. From correlations of identical particles, it is possible to obtain size and shape of such a source. Phenomenological models *e.g.* EPOS, UrQMD and Therminator are dedicated to heavy-ion collisions. In this report, theoretical predictions of protons and antiprotons correlation functions from Au+Au collisions performed at $\sqrt{s_{NN}}$ of 7.7 GeV, 11.5 GeV, 39 GeV and 62.4 GeV from the STAR experiment program called Beam Energy Scan are presented.

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1. Introduction

The **Relativistic Heavy-Ion Collider** (RHIC) is one of the biggest colliders all over the world. In the RHIC complex, heavy-ion beams and high-energy beams of polarized protons are collided. A central goal of experiments at the RHIC (STAR and PHENIX) is to explore the phase diagram of Quantum Chromodynamics (QCD) at non-zero temperature and baryon chemical potential.

The **Solenoidal Tracker at RHIC** (STAR) has a comprehensive program — **Beam Energy Scan** (BES), which was launched in 2010. In BES, gold

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ions are collided with energies at $\sqrt{s_{NN}} = 7.7$ GeV, 11.5 GeV, 19.6 GeV, 27 GeV, 39 GeV and 62.4 GeV. The main objectives are search for: critical fluctuations (critical point) between cross-over area and 1st order phase transition, to signal 1st order phase transition between quark and hadron matter, to turn-off QGP signatures, which are observed at the top RHIC energies. The Phase I of the program ended in 2014 [1].

2. Models used in heavy-ion collision physics

In high-energy physics, many phenomenological models are used. They are frequently applied to examining the properties of matter in heavy-ion collisions. There are several groups of models: microscopic string models, macroscopic fluid dynamical- and thermal models [2].

Microscopic models, which are considered in this report, describe dynamic simulation of the collisions inspired by QCD. These models are based on description of individual particles, which are propagated through a cascade of collisions and decays. Examples of such models are UrQMD and EPOS.

2.1. EPOS model

EPOS consists on **E**nergy conserving quantum mechanical multiple scattering approach, based on **P**artons (parton ladders), **O**ff-shell remnants, and **S**plitting of parton ladders.

It is a string model based on the Gribov–Regge theory and the parton model [3]. Quantum Chromodynamics and Quantum Electrodynamics (QED) descriptions are included in EPOS. This model provides the recipe to calculate the cross-sections for the production of partons jets. It allows to choose the type (*e.g.* $p + p$, $d + N$, $N + N \dots$) and the energy of collision.

2.2. UrQMD model

The **U**ltra-**R**elativistic **Q**uantum **M**olecular **D**ynamics (UrQMD) model is a microscopic transport approach based on: stochastic binary scattering, color string formation resonance decay. This model uses Monte Carlo simulation and can be used to simulate nucleus–nucleus (*e.g.* Au+Au, Pb+Pb ...), nucleon–nucleus ($d + \text{Au}$) and nucleon–nucleon ($p + p$) collisions in relativistic energies available at Bevalac, SIS, AGS, SPS and RHIC [4].

The objectives of the UrQMD model are to understand the unusual physical phenomena such as: creation of dense hadronic matter at high temperatures and creation of mesonic matter and of antimatter.

2.3. Therminator generator

Thermal heavy-ion generator uses Monte Carlo methods to simulate collisions of relativistic heavy ions. It was created in order to study the production of particles in heavy-ion collisions at such experimental complexes as the SPS, RHIC or LHC. This generator implements thermal models of particle production, assuming single freeze-out, which means that chemical and thermal freeze-out happen at the same time.

3. Correlation function

The correlation function (CF) relies on information carried by particle produced during the collision. It is defined as a ratio of the probability of finding two particles with momentum \vec{p}_1 and \vec{p}_2 at the same time and place to the product of the probability of finding these particles separately — equation (1).

$$\text{CF}(\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1) P_1(\vec{p}_2)}. \quad (1)$$

4. Analysis

All protons and antiprotons correlation functions were built for three theoretical models — EPOS, UrQMD and Therminator, for four BES collision energies $\sqrt{s_{NN}} = 7.7$ GeV, 11.5 GeV, 39 GeV and 62.4 GeV. The number of analysed minimum bias collisions is 400 000 (for UrQMD), 500 000 (for EPOS) and 50 000 (for Therminator).

For obtained correlation functions, sizes of sources created during the collision were calculated. These values are presented in Table I and figure 1.

TABLE I

Sizes of the effective source for BES energies — $\sqrt{s_{NN}} = 7.7$ GeV, 11.5 GeV, 39 GeV and 62.4 GeV for all models (first value is radii for protons, second — antiprotons). Statistical uncertainties constitute $\sim 10\%$ of the determined values.

$\sqrt{s_{NN}}$ [GeV]	UrQMD	EPOS	Therminator
7.7	2.37±0.24/2.37±0.24	2.37±0.24/1.59±0.16	2.65±0.27/3.57±0.36
11.5	2.51±0.25/2.09±0.21	2.37±0.24/1.80±0.18	3.08±0.31/3.64±0.36
39	3.50±0.35/2.37±0.24	2.51±0.25/2.30±0.23	3.57±0.36/3.64±0.36
62.4	4.99±0.50/3.78±0.38	2.51±0.25/2.30±0.23	3.71±0.37/3.78±0.38

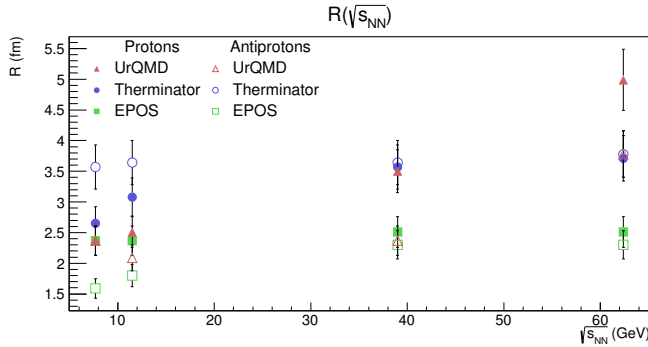


Fig. 1. Dependence of the radius of the source created during the collision with the energy and the model.

There is a clear energy dependence of the size of the source and the radii increase with $\sqrt{s_{NN}}$

$$R(62.4 \text{ GeV}) > R(39 \text{ GeV}) > R(11.5 \text{ GeV}) > R(7.7 \text{ GeV}).$$

The difference between protons and antiprotons radii that may be caused due to measurement of the total correlation function including residual correlations is also seen. An additional reason for these differences may be the increase of the baryon chemical potential with decrease of collision energy.

5. Summary

In this paper, there have been presented theoretical predictions of correlation functions of proton–proton and antiproton–antiproton in Au+Au collisions at $\sqrt{s_{NN}} = 7.7 \text{ GeV}$, 11.5 GeV , 39 GeV and 62.4 GeV for three heavy-ion collision models — EPOS, UrQMD and Therminator. The results show that the source size increase with energy of collisions but the differences between models are also visible.

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