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Isothermal compressibility of hadronic matter formed in relativistic nuclear collisions

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ABSTRACT

We present the first estimates of isothermal compressibility (k_{T}) of hadronic matter formed in relativistic nuclear collisions ($\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV to 2.76 TeV) using experimentally observed quantities. k_{T} is related to the fluctuation in particle multiplicity, temperature, and volume of the system formed in the collisions. Multiplicity fluctuations are obtained from the event-by-event distributions of charged particle multiplicities in narrow centrality bins. The dynamical components of the fluctuations are extracted by removing the contributions to the fluctuations from the number of participating nucleons. From the available experimental data, a constant value of k_{T} has been observed as a function of collision energy. The results are compared with calculations from UrQMD, AMPT, and EPOS event generators, and estimations of k_{T} are made for Pb–Pb collisions at the CERN Large Hadron Collider. A hadron resonance gas (HRG) model has been used to calculate k_{T} as a function of collision energy. Our results show a decrease in k_{T} at low collision energies to $\sqrt{s_{\mathrm{NN}}} \sim 20$ GeV, beyond which the k_{T} values remain almost constant.

1. Introduction

The determination of the thermodynamic state of matter formed in high-energy nuclear collisions is of great importance in understanding the behaviour of the matter formed at high temperature and/or energy density. A set of basic macroscopic quantities, such as temperature, pressure, volume, entropy, and energy density, as well as a set of response functions, including specific heat, compressibility and different susceptibilities define the thermodynamic properties of the system. These quantities are related by the equation of state (EOS), which on the other hand, governs the evolution of the system. One of the basic goals of calculating the thermodynamic quantities, such as the specific heat (c_v) and isothermal compressibility (k_{T}) is to obtain the EOS of the matter [1–7]. The c_v is the amount of energy per unit change in temperature and is related to the fluctuation in the temperature of the system [8,9]. The k_{T} describes the relative variation of the volume of a system due to a change in the pressure at constant temperature. Thus k_{T} is linked to density fluctuations and can be expressed in terms of the second derivative of the free energy with respect to the pressure. In a second order phase transition k_{T} is expected to show a singularity. The determination of k_{T} as well as c_v can elucidate the existence of a phase transition and its nature.

Heavy-ion collisions at ultra-relativistic energies produce matter at extreme conditions of energy density and temperature, where a phase transition from normal hadronic matter to a deconfined state of quark–gluon plasma (QGP) takes place. Lattice QCD calculations have affirmed a crossover transition at zero baryonic chemical potential (μ_{B}) [10,11]. On the other hand, QCD inspired phenomenological models [12–15] predict a first order phase transition at high μ_{B}. This suggests the possible existence of a QCD critical point where the first order transition terminates. The current focus of theoretical and experimental programs is to understand the nature of the phase transition and to locate the critical point by exploring multiple signatures. Since k_{T} is sensitive to the

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phase transition, its dependence on the μ_B or the collision energy provides one of the basic measurements on this subject.

Recently, collision energy dependence of c_v has been reported by analysing the event-by-event mean transverse momentum ($\langle p_T \rangle$) distributions [16]. In this approach, the $\langle p_T \rangle$ distributions in finite p_T ranges are converted to distributions of effective temperatures. The dynamical fluctuations in temperature are extracted by subtracting widths of the corresponding mixed event distributions.

In the present work, we have calculated the isothermal compressibility of matter formed in high energy collisions using experimentally observed quantities, as prescribed in Ref. [1]. This method uses the fluctuations of particle multiplicities produced in the central rapidity region. It may be noted that enhanced fluctuation of particle multiplicity had earlier been proposed as signatures of phase transition and critical point [17–21]. Thus the study of event-by-event multiplicity fluctuations and estimation of k_T are important for understanding the nature of matter at extreme conditions. The experimental data of event-by-event multiplicity fluctuations at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and Super Proton Synchrotron (SPS) of CERN have been used in combination with temperatures and volumes of the system at the chemical freeze-out to extract the values of k_T. These results are compared to that of three event generators and the hadron resonance gas (HRG) model. Our results provide important measures for the beam energy scan program of RHIC and the experiments at the CERN Large Hadron Collider (LHC), and gives guidance for experiments at the Facility for Antiproton and Ion Research (FAIR) at GSI and the Nuclotron-based Ion Collider facility (NICA) at JINR, Dubna.

2. Methodology

Isothermal compressibility is the measure of the relative change in volume with respect to change in pressure [1],

$$k_T|_{T,\langle N \rangle} = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)\Bigg|_{T,\langle N \rangle} \tag{1}$$

where V, T, P represent volume, temperature, and pressure of the system, respectively, and $\langle N \rangle$ stands for the mean yield of the particles. In the Grand Canonical Ensemble (GCE) framework, the variance (σ^2) of the number of particles (N) is directly related to isothermal compressibility [1,22], i.e.,

$$\sigma^2 = \frac{k_B T \langle N \rangle^2}{V} k_T, \tag{2}$$

where k_B is the Boltzmann constant. Charged particle multiplicity fluctuations have been characterised by the scaled variances of the multiplicity distributions, defined as

$$\omega_{ch} = \frac{\langle N_{ch}^2 \rangle - \langle N_{ch} \rangle^2}{\langle N_{ch} \rangle} = \frac{\sigma^2}{\mu} \tag{3}$$

where N_{ch} is the charged particle multiplicity per event, and $\mu = \langle N_{ch} \rangle$. Following the above two equations, we obtain

$$\omega_{ch} = \frac{k_B T \mu}{V} k_T, \tag{4}$$

which makes a connection between multiplicity fluctuation and k_T. This formalism, using GCE properties, may be applied to experimental measurements at mid-rapidity, as energy and conserved quantum numbers are exchanged with the rest of the system [23]. At the chemical freeze-out surface, the inelastic collisions cease, and thus the hadron multiplicities get frozen. While the ensemble average thermodynamic properties like the temperature and volume can be extracted from the mean hadron yields, k_T can be accessed through the measurements of the event-by-event multiplicity fluctuations.

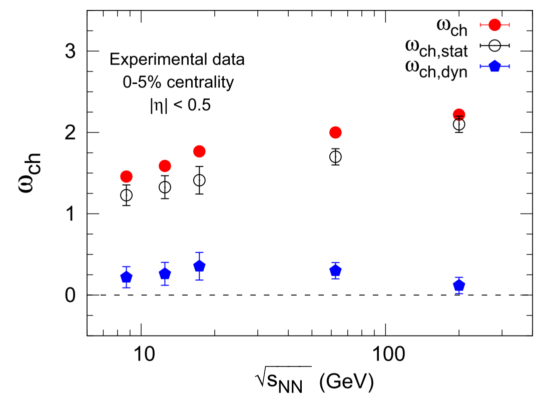

Fig. 1. Beam-energy dependence of scaled variances of multiplicity distributions (ω_{ch}) for central (0–5%) Au–Au (Pb–Pb) collisions from the available experimental data [22,24,26–30]. The statistical components of fluctuations ($\omega_{ch,stat}$) using the participant model calculations have been shown. The dynamical components of the fluctuations ($\omega_{ch,dyn}$) are obtained by subtracting the statistical components from the measured values.

3. Multiplicity fluctuations: experimental data

The multiplicity fluctuations have been measured for a range of collision energies by the E802 Collaboration [24] at BNL-AGS, WA98 [25], NA49 [26,27], NA61 [28,29] and CERES [30] experiments at CERN-SPS, and PHENIX experiment [22] at RHIC. The results of these measurements could not be compared directly because of differences in the kinematic acceptances and detection efficiencies. The experimental results are normally reported after correcting for detector efficiencies. But the acceptances in pseudorapidity (η) need not be the same for these experiments. The results from the experiments have been scaled to mid-rapidity so that these can be presented in the same footing [22,31]. Fig. 1 shows the values of ω_{ch} for $|\eta| < 0.5$ in central (0–5%) collisions as a function of the collision energy [31]. The solid circles represent experimental measurements. An increase in the scaled variances with the increase in collision energy has been observed from these data.

It is to be noted that the widths of the charged particle distributions and ω_{ch} get their contributions from several sources, some of which are of statistical in nature and the rest have dynamical origins. The dynamical components are connected to thermodynamics and have been used in the present work to extract k_T [1]. Thus an estimation of the statistical part is necessary to infer about the dynamical component of multiplicity fluctuations.

One of the major contributions to statistical fluctuations comes from the geometry of the collision, which includes variations in the impact parameter or the number of participating nucleons. In a participant model [18], the nucleus–nucleus collisions are treated as superposition of nucleon–nucleon interactions. Thus the fluctuation in multiplicity arises because of the fluctuation in number of participants (N_{part}) and the fluctuation in the number of particles produced per participant. In this formalism, based on Glauber type of initial conditions, ω_{ch} can be expressed as

$$\omega_{ch} = \omega_n + \langle n \rangle \omega_{N_{part}}, \tag{5}$$