Interferometry search for new forms of matter in A+A collisions

S.V. Akkelin[a], Yu.M. Sinyukov[a]

[a]Bogolyubov Institute for Theoretical Physics, Kiev 03143, Metrologichna 14b, Ukraine

A method allowing studies of the hadronic matter at the early evolution stage in A+A collisions is developed. It is based on an interferometry analysis of approximately conserved values such as the averaged phase-space density (APSD) and the specific entropy of thermal pions. The plateau found in the APSD behavior vs collision energy at SPS is associated, apparently, with the deconfinement phase transition at low SPS energies; a saturation of this quantity at the RHIC energies indicates the limiting Hagedorn temperature for hadronic matter.

1. INTRODUCTION

The goal of experiments with heavy ion collisions is to study the new forms of matter which can be created under an extreme conditions at the early stage of the evolution. The bulk of hadronic observables ("soft physics") are related, however, only to the very last period of the matter evolution, so called thermal or kinetic freeze-out - the end of the collective expansion of hadronic gas when the system decays. Our basic idea is to use the "conserved observables" which are specific functionals of spectra and correlation functions - integrals of motion. A structure of the integrals of motion, besides the trivial ones associated with energy, momentum and charges, depends on a scenario of the matter evolution. Our analysis is based on hydrodynamic picture of the chemically frozen evolution. Then the average phase-space density (APSD) and specific entropy of negative pions are approximately conserved values [1] which can be expressed through the observed spectra and interferometry radii irrespectively of unknown form of freeze-out (isothermal) hypersurface and transverse flows developed as it was proposed in Refs. [1,2]. Our aim is to study the properties of the matter at the hadronization stage at different energies of A+A collisions, from AGS to RHIC. For details of the analysis see Ref. [2].

2. THE APSD AND ENTROPY AS OBSERVABLES IN A+A COLLISIONS

The method is based on the standard approach for spectra formation that supposes that thermal freeze-out in expanding locally equilibrated system happens at some space-time hypersurface with uniform temperature T and particle number density n (or chemical potential μ). Then, within this approximation which is probably appropriate in some "boost-invariant" mid-rapidity interval, $\Delta y < 1$, the locally-equilibrium phase-space density of pions, totally averaged over the hypersurface of thermal freeze-out, $\sigma = \sigma_{th}$, and momentum except the longitudinal one (rapidity is fixed, e.g., $y = 0$) is the same as the totally averaged phase-space density in the static homogeneous Bose gas [1] and can be extracted directly from the experimental data in full accordance with the pioneer Bertsch idea [3]:

$$(2\pi)^3 \langle f(\sigma,y)\rangle_{y=0} = \frac{\int d^3p \overline{f}_{eq}^2}{\int d^3p \overline{f}_{eq}} = \kappa \frac{2\pi^{5/2} \int \left(\frac{1}{R_O R_S R_L} \left(\frac{d^2N}{2\pi m_T dm_T dy} \right)^2 \right) dm_T}{dN/dy}, \quad (1)$$

where $\overline{f}_{eq} \equiv (\exp(\beta(p_0 - \mu) - 1)^{-1}$, and β and μ coincide with the inverse of the temperature and chemical potential at the freeze-out hypersurface. The $\kappa = 1$ if one ignores the resonance decays. Here we neglect interferometry cross-terms since they are usually rather small in the mid-rapidity region for symmetric heavy ion central collisions at high energies.

Using the same approximation of the uniform freeze-out temperature and density we get the following expression for specific entropy in mid-rapidity:

$$\frac{dS/dy}{dN/dy} = \frac{\int d^3p \left[-\overline{f}_{eq} \ln \overline{f}_{eq} + (1+\overline{f}_{eq}) \ln(1+\overline{f}_{eq}) \right]}{\int d^3p \overline{f}_{eq}}. \quad (2)$$

The above ratio depends only on the two parameters: the temperature and chemical potential at freeze-out. The temperature can be obtained from the fit of the transverse spectra for different particle species and we will use the value $T = 120$ MeV as a typical "average value" for SPS and RHIC experiments. Another parameter, the chemical potential, we extract from an analysis of the APSD following to (1). The factor κ is accounting for a contribution of the short-lived resonances to the spectra and interferometry radii and absorbs also the effect of suppression of the correlation function due to the long-lived resonances [1]. Because of the chemical freeze-out a big part of pions, about a half, are produced by the short-lived resonances after thermal freeze-out. To estimate the thermal characteristics and "conserved observables" at the final stage of hydrodynamic evolution by means of Eqs. (1), (2) one needs to eliminate non-thermal contributions to the pion spectra and correlation functions from resonance decays at post freeze-out stage. To do this we use the results of Ref. [1] where a study of the corresponding contributions within hydrodynamic approach gives the values of parameter κ to be $\kappa = 0.65$ for SPS and $\kappa = 0.7$ for RHIC, if half of pions is produced by the resonances at post freeze-out stage. Then, from Eq. (1) one can extract the pion chemical potential at thermal freeze-out. This makes it possible to estimate the average phase-space density, the specific entropy and other thermal parameters of the system at the end of the hydrodynamic expansion.

3. THE ANALYSIS OF EXPERIMENTAL DATA AND THE RESULTS

To evaluate the APSD of negative pions by means of Eq. (1) we utilize the yields, transverse momentum spectra and interferometry radii of π^- at mid-rapidity measured in central heavy ions collisions by the E895 and E802 Collaborations for AGS energies [4,5], NA49 Collaboration for SPS CERN energies [6–8], STAR and PHENIX Collaborations for RHIC BNL energies [9–11]. Since the interferometry radii are measured by PHENIX Collaboration for $0 - 30$ % centrality events at $\sqrt{s_{NN}} = 200$ GeV [11], we increase the interferometry volume measured by PHENIX Collaboration at this c.m. energy by a factor of 1.215 to get the interferometry volume corresponding to the most central $0-5$ %

centrality bin in accordance with N_{part} dependence of the Bertsch-Pratt radius parameters found in Ref. [11].

The results for the APSD at mid-rapidity for *all* negative pions ($\kappa = 1$) at the AGS, SPS, RHIC energies are presented in Fig. 1. The APSD of negative *thermal* pions ($\kappa = 0.65$ for SPS and $\kappa = 0.7$ for RHIC energies respectively) are used then to extract the chemical potentials μ of them at thermal freeze-out at different SPS and RHIC energies, and after that to calculate the specific entropies, $s = \frac{dS/dy}{dN/dy}$ (2), and the entropies, $\frac{dS}{dy} = s * \frac{dN}{dy}$, of negative thermal pions. The entropies dS/dy of negative thermal pions are demonstrated in Fig. 2, where the values at the RHIC energies are mean values of STAR and PHENIX data. In Fig. 3 we present, in addition to Fig. 2, the rapidity densities, dN^{π^-}/dy, of *all* negative pions at mid-rapidity in central nucleus-nucleus collisions for the AGS, SPS and RHIC energies. The lines in Fig. 3 represent the logarithmic law of energy dependence for negative pion multiplicities: $a \log_{10}(\sqrt{s_{NN}}/b)$, where $a = 160(230)$, $b = 1.91$ GeV (3 GeV) for solid (dashed) lines respectively.

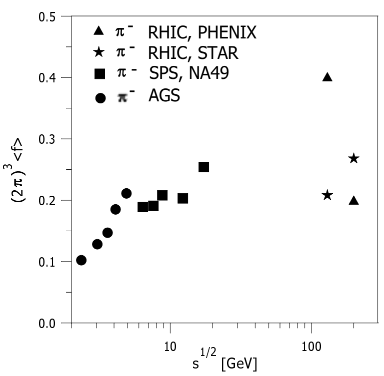

Figure 1. The average phase-space density of all negative pions at mid-rapidity, $(2\pi)^3 \langle f(y) \rangle$, (circles, squares, stars and triangles) as function of c.m. energy per nucleon in heavy ion central collisions.

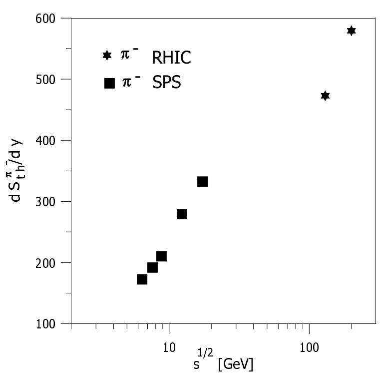

Figure 2. The rapidity density of entropy for negative thermal pions, $dS_{th}^{\pi^-}/dy$, (squares and stars) as function of c.m. energy per nucleon in heavy ion central collisions.

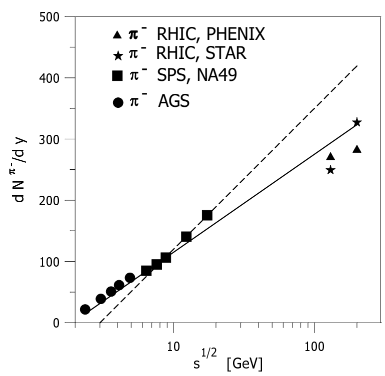

Figure 3. The rapidity density of negative pions, dN^{π^-}/dy, as function of c.m. energy per nucleon in heavy ion central collisions.

4. CONCLUSIONS

A behavior of the pion APSD vs collision energy has a plateau at low SPS energies that indicates, apparently, the transformation of initial energy to non-hadronic forms of matter at SPS; a saturation of that quantity at the RHIC energies can be treated as an existence of the limiting Hagedorn temperature of hadronic matter, or maximal temperature of deconfinement T_c. A behavior of the entropy of thermal pions and measured pion multiplicities in central rapidity region vs energy demonstrates an anomalously high slope of an increase of the pion entropy/multiplicities at SPS energies compared to what takes place at the AGS and RHIC energies. This additional growth could be, probably, a manifestation of the QCD critical end point (CEP). The observed phenomenon can be caused by the dissipative effects that usually accompany phase transitions, such as an increase of the bulk viscosity [12], and also by peculiarities of pionic decays of σ mesons and other resonances with masses that are reduced, as compare to its vacuum values, in vicinity of the QCD CEP [13]. At the RHIC energies there is no anomalous rise of pion entropy/multiplicities, apparently, because the crossover transition takes place far from the CEP and no additional degrees of freedom appear at that scale of energies: quarks and gluons were liberated at previous energy scale.

ACKNOWLEDGMENTS

The research described in this publication was made possible in part by Award No. UKP1-2613-KV-04 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF) and by NATO Collaborative Linkage Grant No. PST.CLG.980086. Research carried out within the scope of the ERG (GDRE): Heavy ions at ultrarelativistic energies - a European Research Group comprising IN2P3/CNRS, EMN, Universite de Nantes, Warsaw University of Technology, JINR Dubna, ITEP Moscow and Bogolyubov Institute for Theoretical Physics NAS of Ukraine.

REFERENCES

1. S.V. Akkelin, Yu.M. Sinyukov, Phys. Rev. C 70 (2004) 064901.
2. S.V. Akkelin, Yu.M. Sinyukov, arXiv: nucl-th/0505045.
3. G.F. Bertsch, Phys. Rev. Lett. 72 (1994) 2349; 77 (1996) 789.
4. J.L. Klay *et al.* (The E895 Collaboration), Phys. Rev. C 68 (2003) 054905; M.A. Lisa for the E895 Collaboration, Nucl. Phys. A 661 (1999) 444c.
5. Y. Akiba for the E802 Collaboration, Nucl. Phys. A 610 (1996) 139c; L. Ahle *et al.* (The E802 Collaboration), Phys. Rev. C 66 (2002) 054906.
6. S.V. Afanasiev *et al.* (The NA49 Collaboration), Phys. Rev. C 66 (2002) 054902.
7. M. Gazdzicki *et al.* (The NA49 Collaboration), J. Phys. G 30 (2004) S701; C. Blume *et al.* (for the NA49 Collaboration), J. Phys. G 31 (2005) S685.
8. S. Kniege *et al.* (The NA49 Collaboration), J. Phys. G 30 (2004) S1073.
9. C. Adler *et al.* (The STAR Collaboration), Phys. Rev. Lett. 87 (2001) 082301; J. Adams *et al.* (The STAR Collaboration), arXiv: nucl-ex/0311017; J. Adams *et al.* (The STAR Collaboration), Phys. Rev. Lett. 92 (2004) 112301; J. Adams *et al.* (The STAR Collaboration), Phys. Rev. C 71 (2005) 044906.
10. K. Adcox *et al.* (The PHENIX Collaboration), Phys. Rev. Lett. 88 (2002) 192302; K. Adcox *et al.* (The PHENIX Collaboration), Phys. Rev. C 69 (2004) 024904; S.S. Adler *et al.* (The PHENIX Collaboration), Phys. Rev. C 69 (2004) 034909.
11. S.S. Adler *et al.* (The PHENIX Collaboration), Phys. Rev. Lett. 93 (2004) 152302.
12. P. Danielewicz, M. Gyulassy, Phys. Rev. D 31 (1985) 53.
13. M. Stephanov, K. Rajagopal, E. Shuryak, Phys. Rev. Lett. 81 (1998) 4816; E. Shuryak, arXiv: hep-ph/0504048.