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PREDICTIONS ON SOME POSSIBLE PHASE TRANSITIONS IN AU-AU NUCLEAR CENTRAL COLLISIONS IN CBM EXPERIMENT AT FAIR-GSI

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Abstract. In this work, we present numerical calculations for the excitation function of the antiparticle to particle ratio for the 6-25 A GeV energy interval, which have a predictive character for the CBM experiment at FAIR-GSI. For two energy intervals, plateau shapes are observed, in contrast to the general tendency of the antiparticle to particle ratio growth with energy increase, which may suggest the emergence of the mixed phase for a fraction of time. The results of our calculations are in good agreement with the results from other papers based on experimental data (AGS, HADES). In the analysis of the systematic dependence of $\frac{K^-}{K^+}$ on the $\frac{\bar{p}}{p}$ ratios, quasi-coincidences or "points returns" for two, three consecutive energies appear, which may suggest possible phase transitions in the newly formed nuclear matter in relativistic heavy ion collisions.

1. INTRODUCTION

The Compressed Baryonic Matter (CBM) experiment at Facility for Antiproton and Ion Research (FAIR)-GSI is motivated by the study of the equation of state specific to nuclear matter, and by the search of phase transitions, its program being compatible with that of RHIC and LHC, but for larger baryonic densities.

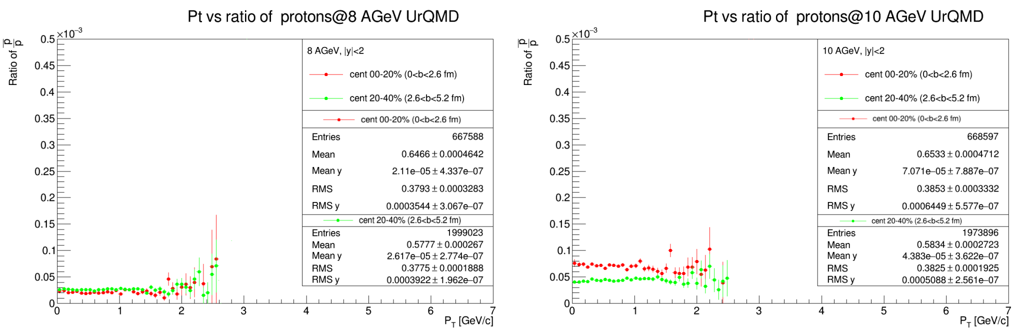
The excitation function of the antiparticle to particle ratio can be used for the study of exotic states (the existence of density isomers) and phase transitions in nuclear matter formed in heavy ions nuclear collisions. In this study based on antiparticle to particle ratios, we show numerical calculations for the 6-25 A GeV energy range in Au-Au central collisions, where we have identified local tendencies of equalities or quasi-decreases in the ratio values of $\frac{K^-}{K^+}$ and $\frac{\bar{p}}{p}$, in energy sequences compatible with SIS100 and SIS300. Our calculations have a predictive character for possible phase transitions in the newly formed nuclear matter in Au-Au central collisions, for the CBM experiment.

The analyzes in this article were performed using the UrQMD 3.3 generator, integrated in the YaPT system [1], with t = 200 fm/c, the state equation being defined by the cascade mode, and the number of events set to 100.000. We compared the results with some predictions of the thermal model, and we notice in the case of systematic dependence of the $\frac{K^-}{K^+}$ to $\frac{\bar{p}}{p}$ ratios some deviations, seen as points returns corresponding to some values, quasi-coincidence values for two to four neighboring energies or even plateau shapes.

In the numerical calculations two rapidities ($0 < y < 0.8$ and $0.5 < y < 1.4$) are highlighted, for which the fluctuations of the antiparticle to particle ratio excitation functions can suggest some possible phase transitions in two energy intervals: 10 -13 A GeV (in some cases 9-13 A GeV) and 18-21 A GeV. Thus, the value of the ratio $\frac{K^-}{K^+}$ is greater for the second centrality, 20-40% ($2.6 < b \leq 5.2$ fm), and we find plateau forms which contrast with general trends showing an increasing ratio with the energy increase [2] and which may indicate the emergence of a possible mixed phase.

2. RESULTS AND DISCUSSIONS

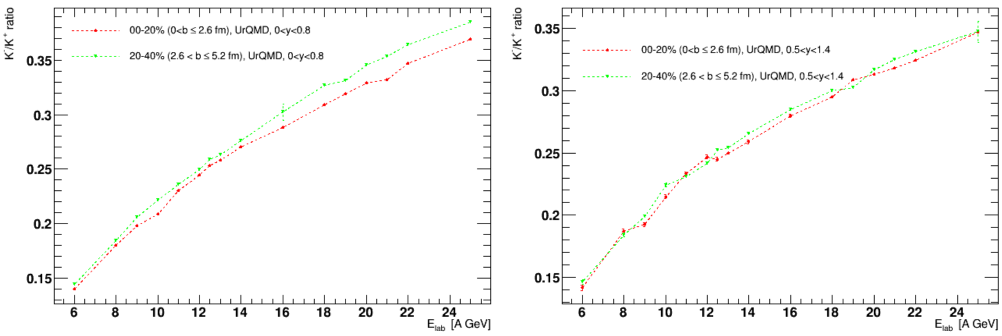
First of all, we draw attention to a change in the value of the $\frac{\bar{p}}{p}$ ratio ($|y| < 2$) at 8 A GeV and 10 A GeV, which we call "centralities order change", understood by the fact that the value of the ratio calculated for a centrality increases relative to the value of the ratio for the other centrality (Fig. 1). By detailing this result, we notice that $\frac{\bar{p}}{p}$ ratio at 8 A GeV is higher for 20-40% centrality than for 0-20% centrality, and only above 8.5 A GeV one can see the change, that is the $\frac{\bar{p}}{p}$ ratio value at 0-20% ($0 < b \leq 2.6$ fm) becoming larger.



(a) (b)

Fig. 1 – The transverse momentum distribution which is dependent on the $\frac{\bar{p}}{p}$ ratio, for two centralities and different energies: a) 8 A GeV; b) 10 A GeV

We see this "centralities order change" again in a faster succession in the 10-13 A GeV and 18-21 A GeV energy ranges for the $\frac{K^-}{K^+}$ and $\frac{\bar{p}}{p}$ ratios, where we observe plateau shapes, but we will return to it later (see Figs. 2, 3). This, in general, suggests a large variation in the density of nuclear matter newly created in heavy ion collisions, and a collision centrality dependence. On the whole of the results, we acknowledge an interesting fact: for the antiparticle-particle ratio distributions, for $0.5 < y < 1.4$ and $0 < y < 0.8$ (Fig. 2 a, b and Fig. 3 a), one can notice that for the second centrality, 20-40% ($2.6 < b \leq 5.2$ fm), the $\frac{K^-}{K+}$ ratio is many times higher than that for the 0-20%.

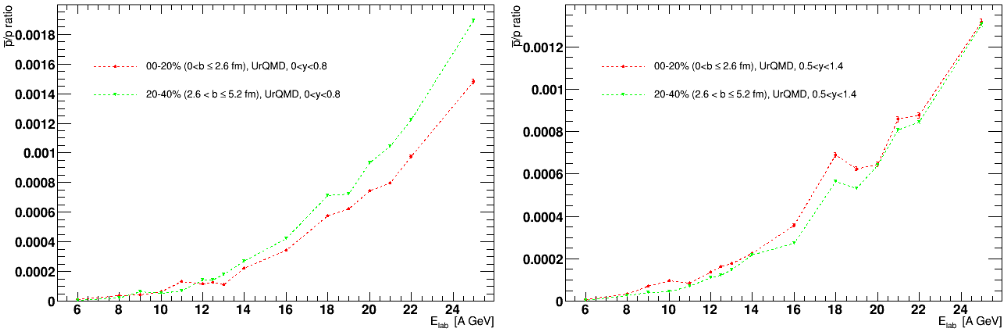


(a) (b)

Fig. 2 – $\frac{K^-}{K+}$ ratio distribution for two centralities, considering different collision energies and two rapidities: a) $0 < y < 0.8$; b) $0.5 < y < 1.4$

To explain this behavior, we can consider an increase of K^- number related to the resonances formation and their hard decays [3, 4]. The KaoS - HADES [5] experiment, for energies between 2 A GeV and 3 A GeV, indicates a ratio of $\frac{K^-}{K+}$ higher with increasing centrality of the collision. One explanation would also be the increasing of $\frac{K^-}{K+}$, linked to a greater production of K^-, which was connected with negative kaon effective mass reduction due to the increased amplitude for the strangeness exchange channel [6]. Other data [7] suggest a higher significant weight, by approximately 20% for the K^- production, which comes from Φ decays. ”Centralities order change” becomes much more pronounced in the 10-13 A GeV and 18-21 A GeV intervals, where the most interesting results come in, namely particle ratio values equalities - stopping of ratio excitation function - that may suggest a mixed phase for a fraction of time.

In the procedure of our calculations, we noticed a quasi-decrease (plateau) of the ratio for 11 and 13 A GeV (*e.g.* $\frac{\bar{p}}{p}$, $0 < y < 0.8$, 0-20% - Fig. 3 a), working with a step of 2 A GeV for calculating the antiparticle-particle ratio, but during the ”occurrence” of the calculation results - as we suggested above - we were motivated to investigate 1 A GeV intervals for excitation function and even 0.5 A GeV, such to see the formation or ”kind” of the plateau. As a conclusion of the first results discussed so far, we repeat here a recently reported issue [8]: the calculations lead to the idea that hidden fluctuations can be lost if we work with big energy steps for the



(a) (b)

Fig. 3 – $\frac{\bar{p}}{p}$ ratio distribution for two centralities, considering different collision energies and two rapidities: a) $0 < y < 0.8$; b) $0.5 < y < 1.4$

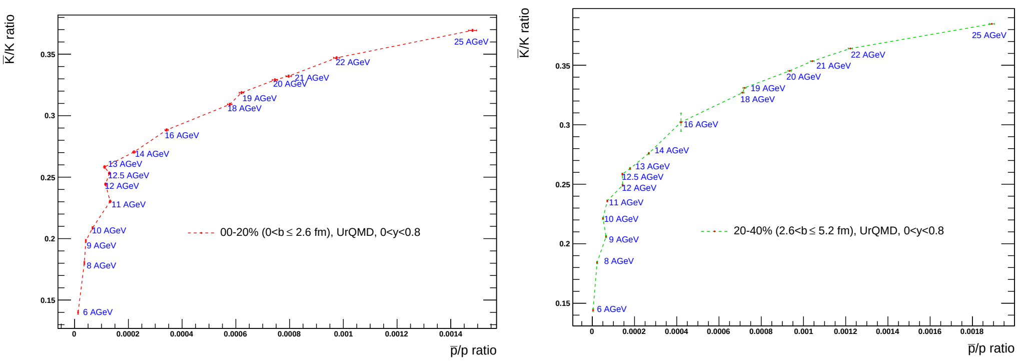
statistical models, according to which antiparticle-particle ratios would have a linear distribution with increasing energy and constant values with centrality variations, until 30 A GeV, and then follow an exponential growth with increasing energies.

Otherwise, the results for the two specified energy ranges (with plateau forms) suggesting the existence of the mixed phase, are in good agreement with the results of the ”Generalized Shock Adiabat Model” (GSAM), compared with the AGS (Au-Au) and SPS (Pb-Pb) data for regions with anomalous thermodynamic properties, as is the case with first-order phase transition and rapid cross-over [9–11]. The results in the reference [9] suggest the formation of the mixed phase based on the calculations of pion/baryon and entropy/baryon ratios in the energy range 6.9 – 11.6 A GeV. According to these studies, the mixed phase of quark-gluon plasma (QGP) - hadron gas is described as a state for which, at high baryon densities, the adiabatic compressibility of QCD matter does not decrease with increasing pressure, because the less dense phase can be compressed into the denser phase, this being an example of anomalous behavior [9].

The results of the calculations presented in this article are also similiar to the results of the numerical calculations of [12], which predict the formation of the mixed phase between $4.2 < \sqrt{s_{NN}} < 4.87$ GeV ($E_{lab} \approx$ 8 - 11 A GeV). These are based on the compatibility assessments, with the help of QDD (quality of data description) of models that explicitly predict QGP formation (Core-Corona [13], PHSD [14], Quark Combination (QuarkComb) [15], 3-Fluid dynamics (3FD) [16]) or Hadronic gas models (HSD [17], SHM [18], RQMD 2.1 [19], UrQMD 1.3 [20]) to the data of AGS and SPS experiments for Au-Au and Pb-Pb collisions respectively.

If we return to the ”centralities order change” for our results in the 10-13 A GeV

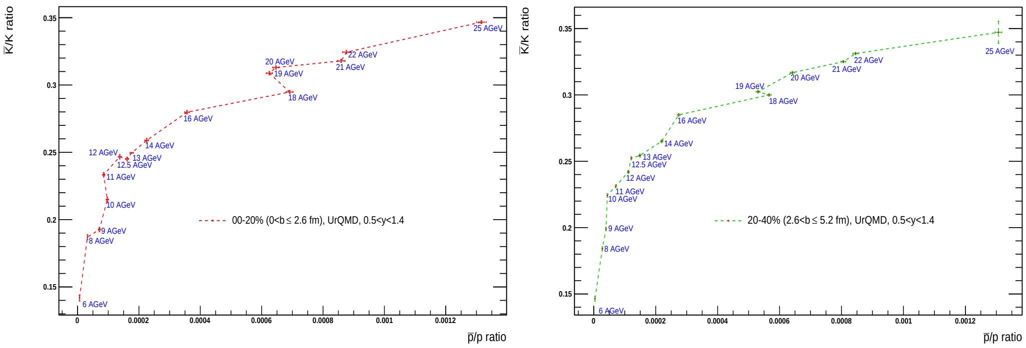
(9-13 A GeV) and 18-21 A GeV intervals - with the occurrence of plateau shapes, even with alternating pattern - where the change is made faster, an interpretation of the results with the above characteristics could be related to the competition between antiparticle-particle production potential and particle production by resonance decays or increasing the amplitude of the strangeness exchange channel, assuming also a balancing between the gradients of the two energy densities of the QGP - hadronic gas system, one which is closer to the mixed phase - QGP boundary, and the other which is ”softer”, towards the resonant hadronic gas. The balancing between the two energy densities discussed is mediated by a pre-equilibrium transition. This transition occurring before the possible deconfinement (QGP onset) due to the increase in color field intensity, resulting in strong interactions of gluonic fields (intense string overlaps, high energy density), will be conserved after QGP production, so it will intermediate the compression of QCD matter - both partonic and hadronic - inside mixed phase region. We believe that the identification of mixed phases has a greater significance than that attributed so far by some authors, in searching for the critical point. It has to occur in several energy intervals and a good characterization of the emergence map of the mixed phase series can lead to a good description of the critical point closeness, although it remains a difficulty to fully characterize the mixed phase [8, 9]. The results of the numerical calculations made and presented in this article, compared to the references [9, 12], suggest two mixed phases up to 30 A GeV, and one assumes it near 40 A GeV in preliminary results, but this does not make the purpose of this study, since it deals mostly with SIS100 specific energies.



(a) (b)

Fig. 4 – The dependence of the $\frac{K^-}{K^+}$ ratio to the $\frac{\bar{p}}{p}$ ratio, for two centralities at $0 < y < 0.8$: a) 0-20%; b) 20-40%

For the second energies interval (18-21 A GeV) wich might suggest the exis-



(a) (b)

Fig. 5 – The dependence of the $\frac{K-}{K+}$ ratio to the $\frac{\bar{p}}{p}$ ratio, for two centralities at $0.5 < y < 1.4$: a) 0-20%; b) 20-40%

tence of mixed phase the ratio values for antikaons-kaons are equal, but also for antiprotons-protons, this repetitive plateau phenomenon showing a good correlation between the two ratio species, at exactly the same 18-19 A GeV sequence, for both rapidities, especially for the second centrality. There is also a $\frac{\bar{p}}{p}$ ratio value strong increase at 18 A GeV energy, for both discussed centralities, at $0.5 < y < 1.4$ (Fig. 3 b).

If we do the systematic dependence of the $\frac{K-}{K+}$ to $\frac{\bar{p}}{p}$ ratio (see Fig. 4, Fig. 5), trying a comparison with the predictions of the thermal model, we observe some deviations in the form of value turns (Fig. 4 a, Fig. 5 a,b), quasi-coincidence of values for two successive energies (18, 19 A GeV - Fig. 4 b, Fig. 5 b) and even plateaus (Fig. 5 a) which may suggest possible phase transitions in the energies intervals discussed so far.

3. CONCLUSIONS

The analysis of the numerical results presented in this article leads to the conclusions presented below.

First of all, we have for exactly 18-19 A GeV energies sequence the same plateau phenomenon for the antikaons/kaons ratios, and the antiprotons/protons ratios, which indicate a repetitive phenomenon, especially for the second centrality (Fig. 2, Fig. 3). Then there are rapid changes in the increase of the ratio values for one centrality with respect to the other, correlated with the alternative plateau forms (suggesting the mixed phase), specific to the two discussed centralities (Fig. 2 b, Fig. 3 a).

The results of the numerical calculations for the 6-25 A GeV energies interval thus have a predictive character for the CBM experiment, and they are consistent with other results based on experimental data [5, 9, 12], but we advert to the emergence of the mixed phase for the 10-13 A GeV (9-13 A GeV) and 18-21 A GeV energies ranges, for a fraction of time. These phase transition suggestions can also be seen from the plateau shapes, value turns, and coincident points by systematically analyzing the dependence of the $\frac{K^-}{K^+}$ and $\frac{\bar{p}}{p}$ ratio values (Fig. 4, Fig. 5).

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