arXiv:hep-ph/0404125 v1 15 Apr 2004

Relativistic Nucleus-Nucleus Collisions: A Connection between the Strangeness-Maximum at $\sqrt{s} \approx 7$ GeV and the QCD Critical Endpoint from Lattice Studies

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Abstract

A steep maximum occurs in the Wroblewski ratio between strange and non-strange quarks created in central nucleus-nucleus collisions, of about A=200, at the lower SPS energy $\sqrt{s} \approx 7$ GeV. By analyzing hadronic multiplicities within the grand canonical statistical hadronization model this maximum is shown to occur at a baryochemical potential of about 450 MeV. In comparison, recent QCD lattice calculations at finite baryochemical potential suggest a steep maximum of the light quark susceptibility, to occur at similar μ_B, indicative of "critical fluctuation" expected to occur at or near the QCD critical endpoint. This endpoint hat not been firmly pinned down but should occur in the 300 MeV $< \mu_B^c <$ 700 MeV interval. It is argued that central collisions within the low SPS energy range should exhibit a turning point between compression/heating, and expansion/cooling at energy density, temperature and μ_B close to the suspected critical point. Whereas from top SPS to RHIC energy the primordial dynamics create a turning point far above in ϵ and T, and far below in μ_B. And at lower AGS energies the dynamical trajectory stays below the phase boundary. Thus, the observed sharp strangeness maximum might coincide with the critical $\sqrt{s}$ at which the dynamics settles at, or near the QCD endpoint.

Bulk hadron production systematics in central nucleus-nucleus collisions at relativistic energy is, overall, well reproduced by a statistical Hagedorn hadronic freeze-out model. A grand canonical version of this model captures the various hadronic species multiplicities, per collision event, from pions to omega hyperons, in terms of a few universal parameters that describe the dynamical stage in which the emerging hadronic matter decays to a quasi-classical gas of free resonances and hadrons [1, 2, 3]. The grand canonical parameters are temperature T, volume V and chemical potential μ. They capture a snapshot of the fireball expansion within the narrow time interval surrounding hadronic chemical freeze-out, which thus appears to populate the hadron/resonance mass and quantum number spectrum, predominantly, by phase space weight [4, 5] thus creating an apparent thermal equilibrium state prevailing in the produced hadron-resonance-population. This chemical equilibrium instantaneously decouples from fireball expansion surviving further (near isentropic) processes. It can thus be retrieved from the finally observed hadronic multiplicities, by state of the art grand canonical model analysis. This analysis succeeds from AGS, via SPS, to RHIC energy [1, 2, 3, 5].

Statistical model analysis is also applicable to elementary collisions, $p + p$, $p+\overline{p}$, and e^+e^- annihilation as was shown by Hagedorn [6] and, more recently, by Becattini and Collaborators [7, 8]. The canonical version of ensemble analysis is applicable here. Mutatis mutandis the same hadrochemical equilibrium feature is being attested, emphasizing the statement that the apparent equilibrium does not arise from a thermodynamical inelastic rescattering cascade toward equilibrium - there is essentially none in elementary processes - but should stem directly from the QCD hadronization process occuring under phase space dominance [4, 5].

The crucial difference between elementary and central nucleus-nucleus resides, in statistical model view, in a transition from canonical to grand canonical order in the ensuing decoupled hadronic state. This transition was studied by Cleymans, Tounsi, Redlich et al. [9]. Its main feature is strangeness enhancement.Comparing the strange to non-strange hadron multiplicities in elementary, and in central nucleus-nucleus collisions at similar energy, one observes an increase of the singly strange hyperons and mesons, relative to pions, of about 2-4, and corresponding higher relative enhancements of multiply strange hyperons [10, 11, 12], ranging up to order-of-magnitude enhancement. In the terminology of Hagedorn statistical models, strangeness is suppressed in the small system, canonical case, of elementary collisions (due to the dictate of local strangeness conservation in a small "fireball" volume), whereas it approaches flavour equipartition in large fireballs due to the occurence of quantum number conservation, on average only, over a large volume - as reflected by the **global** chemical potential featured by the grand canonical ensemble: "strangeness enhancement" occurs as the fading-away of canonical constraints.

From statistical model analysis we obtain a more general view of strangeness relative to non-strangeness production than is provided by considering individual strange to non-strange production ratios, like K/π, Ω/π etc., from $p+p$ to central A+A. The model quantifies strange to non-strange hadron/resonance production by means of Wroblewski quark counting at hadronic freeze-out [13]. It determines the so-called Wroblewski-ratio,

$$\lambda_s = \frac{2(<s> + <\overline{s}>)}{<u> + <\overline{u}> + <d> + <\overline{d}>} \tag{1}$$

which quantifies the overall strangeness to non-strangeness ratio at hadronic freeze-out. Strangeness enhancement (i.e. removal of strangeness suppression in elementary collisions) is quantified, by such an analysis, to proceed from $\lambda_s \approx$0.25 in elementary collisions, to $\lambda \approx 0.45$ in central nucleus-nucleus collisions [2, 3].

Now we turn to the point of the present study. From a recent energy scan conducted at the SPS by NA49, studying hadron multiplicities from $\sqrt{s}$=7 to 17 GeV, a steep maximum was observed [14] in the K^+/π and Λ/π ratios in central Pb+Pb collisions, as shown in Figs.1 and 2. As the K^+ and Λ channels carry most of the total $<s> + <\overline{s}>$ content, this experimental result indicates a kind of "singularity" in the strange to non-strange production ratio, from AGS

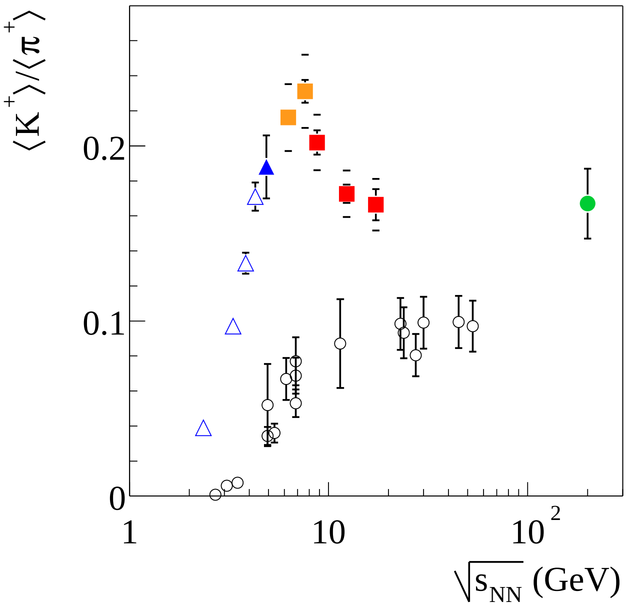

Figure 1: Energy dependence of $< K^+ > / < \pi^+ >$ ratio for central Pb+Pb (Au+Au) collisions (upper points) and p+p interactions (lower points).

to RHIC energy. It appears to be unlikely that state of the art hadronic or partonic quasi-classical microscopic transport models should exhibit such non-smooth behaviour which is also absent in $p + p$ collisions. In order to generalize the new NA49 data, away from consideration of individual channel strange to non-strange multiplicities, Becattini et al. [3] analyzed the $\sqrt{s}$ dependence of the Wroblewski-parameter λ_s in the grand canonical statistical hadronization model. Their result is shown in Fig.3 which gives λ_s as a function of the chemical potential μ_B. From top AGS energy (at $\mu_B \approx 550$ MeV) to RHIC energy ($\mu_B \leq 50$ MeV) one perceives an average λ_s of about 0.45 ± 0.08 whereas a steep excursion is seen, to $\lambda_s = 0.6 \pm 0.1$, at μ_B=440 MeV. This point corresponds to the steep maxima observed in Figs.1 and 2, to occur at SPS fixed target energy of 30 GeV/A in central Pb+Pb collisions, corresponding to $\sqrt{s}$=7.3 GeV. The steep singularity of the NA49 K^+/π and Λ/π ratios at this $\sqrt{s}$ thus reflects in a maximum of the Wroblewski λ_s, derived from grand canonical analysis. For the sake of clarity we state here that the latter analysis just takes note, in a snapshot at hadronic freeze-out (to a decoherent hadron/resonance gas) of the general multiplicity order prevailing at the instant of hadronization. The observed λ_s maximum should, therefore, present a hint that hadronization at $\sqrt{s} \approx 7$ GeV should occur under influences, absent at energies above and below. Moreover, NA49 has shown recently [15] that the event-by-event fluctuation of the ratio $(K^+ + K^-)/(\pi^+ +$

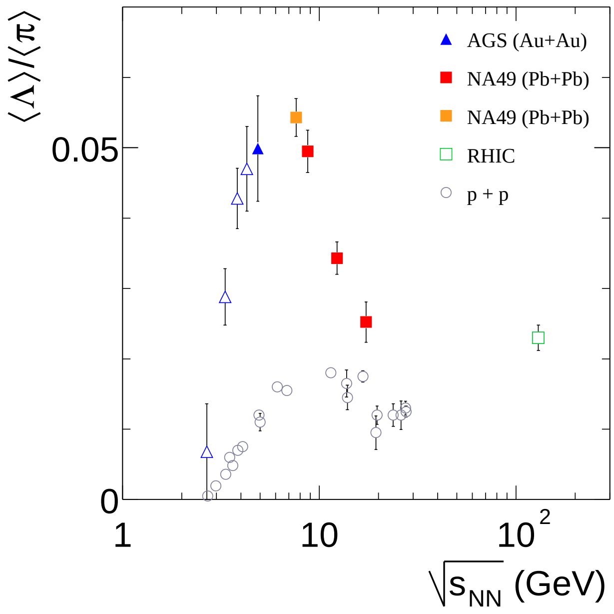

Figure 2: Energy dependence of the $< \Lambda > / < \pi >$ ($< \pi >= 1.5 \, (< \pi^- > + < \pi^+ >)$) ratio for central Pb+Pb (Au+Au) collisions (upper points) and p+p interactions (lower points).

π^-) measured in central Pb+Pb collisions increases steeply toward $\sqrt{s} = 7$ GeV whereas it was formerly found [16] to amount to be below 4%, at top SPS energy, $\sqrt{s} = 17.3$ GeV.

We thus propose that the dynamical trajectory of central Pb+Pb collisions comes close to the critical point of QCD, at or near $\sqrt{s} = 7$ GeV. This point has been expected to occur on the line in the T, μ_B plane which describes the boundary between the hadronic and partonic QCD phases [17]. Along that line the phase transition is expected to be a crossover at $\mu_B < \mu_B^c$, become second order at $\mu_B = \mu_B^c$, and first order for $\mu_B > \mu_B^c$. At $\mu_B = \mu_B^c$ and T = T$_c$ we thus expect phenomena analogous to critical opalescence. Recent QCD lattice calculations succeeded in an extrapolation to finite chemical potential [18, 19], thus making a first prediction for the phase boundary line and, in particular, the critical point - albeit with considerable uncertainty as was discussed by Redlich at QM04 [20]. This uncertainty stems, firstly, from the uncertainty in the extrapolation to finite μ_B but, secondly, from the unphysical (high) strange quark mass employed in these lattice calculations which, at present, place the critical point somewhere in the interval 500 MeV $< \mu_B^c \leq$ 700 MeV. Redlich argued that it should move to considerably lower μ_b once the s-mass can be chosen closer to the physical quark mass [20]. This expectation was substantiated by recent lattice calculations which show that the critical point might move downward in

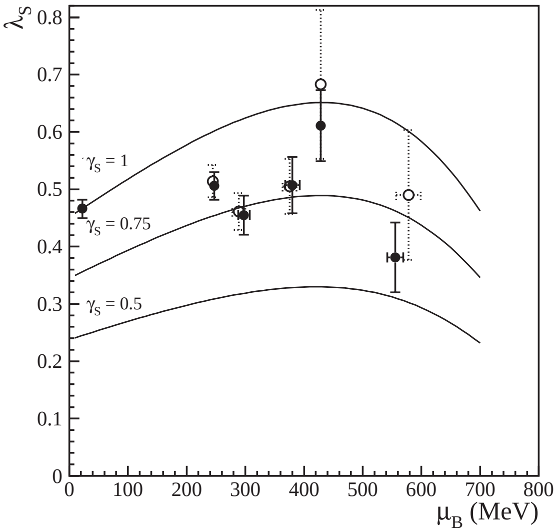

Figure 3: Dependence of the λ_s parameter on baryochemical potential extracted from the fits to hadron multiplicities in central Pb+Pb (Au+Au) collisions at AGS, SPS and RHIC energies. The lines show the dependence expected for different values of the γ_s parameter.

μ_B once more realistic quark masses are employed [21]. From Fig.3 we see that the strangeness maximum at $\sqrt{s} = 7$ GeV corresponds to $\mu_B \approx 440$ MeV and thus quite close to the expected μ_B^c position. Furthermore the energy density at the phase boundary is estimated by lattice QCD to be rather low [22] ($\epsilon \leq 1$ GeV/fm^3).

Central collisions of heavy nuclei at SPS energy exhibit a general cycle of initial compression and heating which is followed by a maximum energy density stage which then turns into expansion and cooling [23]. The quantities characterizing the overall system dynamics, such as volume and energy-entropy density etc. change very rapidly except during the high density stage which acts analogous to a classical turning point. Also it is only during this stage that relaxation times can be of comparable magnitude to the system evolution time scales (like volume-doubling etc.). One can thus begin only here treating the system dynamical evolution in terms of energy density, temperature and chemical potential - thus defining a dynamical trajectory in the T, μ_B plane. Only if this turning point coincides closely with the QCD critical endpoint one could expect to observe substantial critical phenomena. Now it is well known that the maximum energy density in central collisions of mass 200 nuclei amounts (Bjorken estimate) to above 2 GeV/fm^3 at top SPS [24], and to about 5 GeV/fm^3 at RHIC [25] energies, thus overshooting, by far, the critical QCD energy density. The system will thus cross the phase coexistence line, upon re-expansion, whilst already undergoing rapid expansion. Furthermore, the chemical potential is certainly well below 300 MeV at the time of hadronization.The evolution will thus miss the critical point at top SPS, and RHIC energies; and at much lower AGS energies the dynamics falls into the $\mu_B \geq$500 MeV domain but the energy might not suffice to reach the phase boundary. In summary we may indeed expect that the dynamical evolution reaches its energy density plateau phase near the expected critical point (i.e. at energy density just below or at 1 GeV/fm^3, and at μ_B between 300 and 500 MeV) somewhere in between maximum AGS and minimum SPS energy.

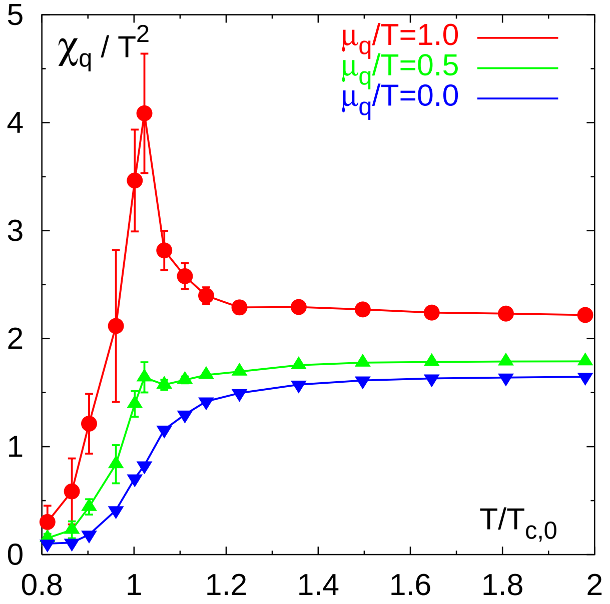

Figure 4: The quark number susceptibility calculated within lattice QCD as function of temperature (relative to transition temperature) for different values of quark chemical potential.

We now turn to the final point of our line of argument by returning to the lattice results [19, 20] at finite μ_B. They see a steep maximum of the quark number susceptibility

$$\chi_{u,d} \equiv T^2 (\frac{d^2}{d(\mu/T)^2} \frac{p}{T^4}) \tag{2}$$

occuring at T=T$_c$= 150 MeV and $\mu_B = 3\mu_Q$=3 T = 450 MeV. We reproduce the Bielefeld-Swansea results in Fig.4 which also shows the calculations for $\mu_B =$ 225 MeV and $\mu_B = 0$ (essentially corresponding to top SPS and RHIC energies, respectively). The latter exhibit no susceptibility peak but a smooth transition from T < T_c to T > T_c. As $\chi_{u,d}$ can also be written as

$$\chi_q = T^2(\frac{\delta}{\delta(\mu_{u/T})} + \frac{\delta}{\delta(\mu_{d/T})})\,\frac{n_u + n_d}{T^3} \tag{3}$$

we see that the peak in the susceptibility implies a maximum fluctuation of the quark number densities n_u and n_d. We interpret this result as an indication of critical fluctuation occuring in the vicinity of the critical endpoint implicitly present in this calculation. Directly at μ^c the susceptibility would diverge. The critical point in this calculation must thus be near $\mu_B = 450$ MeV and T = 150 MeV. This, in turn, is very close to the parameters of the grand canonical model at the strangeness maximum, $\sqrt{s} = 7$ GeV (Fig.3).

As to the relation between the susceptibility maximum of lattice QCD and the strangeness maximum observed by NA49 (at which the Wroblewski parameter λ_s exhibits an anomaly), Gavai and Gupta [26] have suggested the relationship

$$\lambda_s = \frac{2\chi_s}{\chi_u + \chi_d} \tag{4}$$

which appears to offer a direct link. In fact they obtain $\lambda_s = 0.48$ from a lattice calculation at zero μ_b: closely coinciding with the value observed at top SPS and RHIC energy (Fig.3). Unfortunately, though, their result refers to $\mu_b = 0$, and the Bielefeld-Swansea calculations at finite μ_b [19] are in two-flavour QCD only. A prediction for χ_s at $\mu_B \approx 450$ MeV, or, more generally, a full three-flavour lattice treatment of the vicinity of the critical point is required to finally assess the line of argument of the present note. If proven correct we would encounter, here, the first **direct** reflection of QCD in nucleus-nucleus collision data.

The author acknowledges stimulative discussions with F. Becattini, R. V. Gavai, F. Karsch and K. Redlich.

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