STRANGE PARTICLES FROM HADRONIC COLLISIONS

Johann Rafelski
Department of Physics
University of Arizona
Tucson, AZ 85721
USA

ABSTRACT

The properties of the quark gluon plasma fireballs as created in central inelastic interactions of high energy Oxygen and Sulphur nuclei and in 4 GeV/c $\bar{p}$-annihilation with heavy nuclei are studied. Production of strange baryons and antibaryons from quark gluon matter created in these reactions is discussed.

Overview: Hot and dense nuclear matter in its quark gluon form has attracted much attention over the past decade. Experimental results involving collisions of heavy nuclei reported at this meeting indicate that we are creating the desired conditions permitting to study this new form of matter. An unexpected degree of inelasticity is found and the transverse energy generated in central collisions increased roughly as $A_p^{2/3}$ and not as A_p [1,2], which would be the case if the individual nucleon-nucleon collisions were largely independent from each other. Consequently, and in agreement with interpretations of earlier experiments involving proton - nucleus collisions [3] one is lead to believe that nearly complete geometric nuclear stopping prevails. This in turn points to the formation of a dense and hot fireball with the baryon number originating from both the projectile and target nuclei [4], which I will interpret in terms of quark gluon matter. I discuss subsequently what this implies for the predictions [5] of strange baryon and antibaryon abundances, the key observables of this new form of matter. The qualitative results presented are in good agreement with the first data from the CERN experiments NA35, NA36 and WA85, in that enhancement of strange antibaryons in the 'hot' central fireball is expected, while in the 'cold' target fragmentation region enhancement of strange baryon abundances results. Aside from the nuclear collisions, antiproton annihilations can be used to form quark matter and recent work on strange particle production in these reactions is also surveyed. The observed enhancement of strange baryons is found to be of the same origin as the enhancement expected in the target rapidity region for nuclear collisions.

Fireball rapidity: Should a fireball of the projectile and target nuclei be formed, than simple kinematic considerations lead to a relation between the projectile and fireball rapidities, $y=\cos\tau$, in terms of projectile and participating target nucleons A. For a large Lorentz factor τ: $y_f=\frac{1}{2}y_p-\frac{1}{4}\ln(A_t/A_p)$. Assuming that the projectile collides with all matter in the central tube it hits on impact in the heavy nucleus, the mean number of participants from the target nucleus is: $A_t=1.5A_T^{1/3}A_p^{2/3}$, which gives $A_t=55$ for ($A_p=16$, $A_T=197$ for a gold target), and hence $y_f=2.4$. For $A_p=32$ y_f is 0.1 units higher, since the system approaches the symmetric limit $A_p= A_t$. The number of target participants is found to be somewhat higher (=88). Counting the projectile participants we thus expect 1.67 times more baryons in the central fireball created by Sulphur as compared to Oxygen and correspondingly 1.6 - 1.7 times higher transverse energy.

However, the number of participating baryons and therefore the fireball rapidity has a geometric distribution towards the symmetric case involving similar numbers of participants from projectile and target: in asymmetric collisions this case arises when the projectile hits off the center of the target. Hence we should anticipate that in the ensemble of so called central collisions we have a distribution of participants A_t from the target which in consequence spreads the y_f to a distribution with width $\sim\ln(A_t/A_p)$.

Energy contents: The lost rapidity of the projectile particles becomes the internal excitation of the nuclear fireball. To obtain the mean fireball energy (mass) we hence equate the total laboratory energy of the fireball with the total available energy (neglecting the small rest energy of the participating target)

$$\int dM/dy \cosh y \, dy = m_N A_p \tau_p \qquad (1)$$

Assuming the rapidity density of a massless (quark-gluon) gas, i.e.

$$N^{-1}dN/dy = M^{-1}dM/dy = 0.5/\cosh^2(y-y_f), \qquad (2)$$

we find

$$M_f = m_N A_p \tau_p / (\pi/2 \cosh y_f) , \qquad (3)$$

where $M_f = \int dM/dy\, dy$. In the above equation the important factor $\pi/2$, characteristic of the distribution (2) has to be replaced by $\exp(\Gamma/4)$ for a Gaussian distribution; taking a δ-distribution this factor is unity. Assuming the 'average' case of 55 target participants in the central collision of Oxygen on a heavy target with ±200 nucleons we find M_f= 372 GeV and the 71 baryonic participants initially have E/b = 5.22 GeV. For A_p= 32 the average central collision leads to 120 baryonic participants. The energy of the fireball derived from eq.(3) is now 652 GeV, which is 1.75 times the oxygen value. The energy per baryon, however, is 5.43 GeV, nearly the same as before. Hence the spectra of secondary particles should be rather similar, since each carries a similar energy content. However, the greater energy content available in the collision is reflected in the absolute charged particle multiplicity, total transverse energy etc. These quantities should all scale with a factor 1.6 - 1.7 . As we have seen, this scaling laws arise from the hypothesis of complete nuclear stopping.

Initial conditions of the QGP-fireball and its evolution: Under the hypothesis that the hadronic fireball has been created in form of QGP we can use the observed pion abundance in order to determine the entropy content of the fireball [8] and to determine its properties from the QGP equations of state. Each pion at $T>m_\pi$ carries away 4 units of entropy, each baryon $2.5 + m_N/T$. Recently released data [6] on rapidity distribution of negatively charged particles, mostly pions, created in the central collisions show a peaked distribution with y_f at 2.4 - 2.5 . The π^- and all charged particle yield has also been given [7] for the O-Au collisions with central trigger: $\langle n^-\rangle=124\pm2$ and $\langle n_c\rangle=286\pm4$. Only 83% ± 5% of the negative particle multiplicity is in the T = 153 MeV component [6], which I associate with central π^-.Thus the central fireball $\langle\pi^-\rangle$ multiplicity is $\langle n_{\pi^-}\rangle=103\pm4$. Accounting for the expected fireball neutron to proton ratio of 1.37 I find $\langle n_{\pi^+}\rangle=92\pm4$, and the average $\langle n_\pi\rangle/3=\langle n_{\pi^0}\rangle=97$. Taking the baryon multiplicity 71 for the central hot fireball $\langle n_\pi\rangle/b=4.1$, at the hadronization point, leading to S/b = 25.5 . This is the entropy of the hadronic gas. Since the hadronization process of the hot and entropy rich QGP is not strongly entropy generating, the entropy of the quark gluon plasma will be similar.

Given the initial conditions, viz E/b=O(6 GeV) and S/b=O(25) we can find the initial values of T and μ_b in the QGP phase, using the perturbative QCD equations of state with a choice of parameters: $\alpha_s = 0.6$, $B^{1/4}$=170 MeV^4. The result is T=220 MeV, μ_b=450 MeV, ϵ=2.5 GeV/fm^3, n/n_o=2.5 . The isentropic evolution of the QGP to the phase transition temperature leaves the ratio $\mu_b/T = 0.69\cdot3$ constant, as shown in Fig. 1. We note in the Figure the evolution for S/b = 25 and 20 . The energy density 1 GeV/fm^3 is reached at a temperature of 180 MeV, and the range of T considered is just that recorded by the WA80 collaboration for the neutral pions [9]. Varying α_s and B by ±30% and ±40% , respectively, leads to ±15% variations in the initial values of μ and T. This sensitivity indicates that we can measure the key QCD parameters in nuclear reactions, once we understood their entropy and energy contents.

Strangeness separation: We notice in Fig. 1 that the evolution of the fireball proceeds completely in the regime of parameters T, μ_b which favor retention of antistrange quarks in the plasma and emission of strange quarks. Thus heavy ion collisions at SPS energies create conditions favorable to the enrichment of antistrange quarks in the hot plasma phase, while emitting into the hadronic gas envelope strange quarks [10,11]. The curve shown separating the T,μ_b regions with differing strangeness separation property has been computed [12] as proposed in Ref. 11. The physical consequence of these considerations is that at the hadronization of the quark gluon plasma, the numerous $\bar{s}$-quarks which have been separated from the s-quarks will form strange antibaryons, which are thus comparatively enriched in comparison to strange baryons (this occurs only in the rapidity region of the central fireball). For 'cold' quark matter, S/b < 10, we anticipate that the s-quarks remain in the quark matter, while $\bar{s}$-quarks are radiated before hadronization mostly as Kaons. The remaining strange and baryon rich quark matter than hadronizes, forming lambdas, while the production of kaons is avoided at low T and relatively high μ, since the hadronic gas phase is than entropy richer than the quark gluon plasma phase [13]. Thus in the target fragmentation region we expect lambda enhancement. As this discussion shows, it is interesting to measure as function of rapidity the abundance of strange and antistrange baryons. Should the strangeness separation effects prevail, than the target rapidity region should contain an enhancement of 'cold' strange baryons, while the fireball rapidity region should contain an enhancement of 'hot' strange antibaryons.

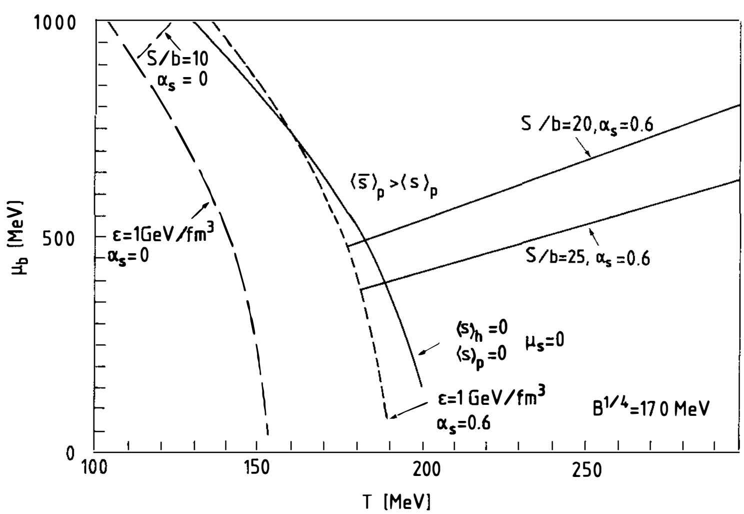

Fig. 1: The T,μ_b-in QGP: straight lines- entropy per baryon 20 and 25; dashed curves- energy density 1 GeV/fm^3 for α_s = 0 and 0.6; almost in coincident with solid curve- boundary for anti strangeness enrichment region.

Strange baryons in antiproton annihilations: Many of the phenomena just discussed seem to have been already observed in a recent experiment [14] on strange particle production in 4 GeV/c antiproton annihilations on Ta. Indeed, these results can be successfully interpreted [15] if quark gluon plasma formation is assumed along with the same reaction model as described above: antiprotons annihilate and deposit energy in the forward cone of nuclear matter within the target nucleus. Thus a fireball of nuclear matter containing the annihilation and projectile kinetic energy will be formed, with baryon number being O(10). The observed spectra and total abundance of lambda particles is consistent with the hypothesis that (super cooled) quark matter phase has been formed at rather modest temperature $T < 60$ MeV. It should be noted that attempts to describe these data in terms of individual hadronic reactions have not been successful [16]. The rapidity distribution of lambdas emitted from the fireball is centered around a mean value which depends now more sensitively on the number of target participants. The rapidity spectrum is in agreement with the hypothesis of a $y_f=0.25$ fireball at a mean temperature T=100 MeV . The number of target participants ($A_t= 13$) fixes as before the energy per baryon in the fireball, E/b = 1.32 GeV. The overall yield of lambdas originating from the nuclear fireball region is found not only to be unusually large, but also to be 2.4 times greater than that of kaons (here K_s). In usual $p\bar{p}$- annihilations the opposite is true with the K_s yield being 3.6 times greater. Similarly, the total strangeness cross section σ_s as found from the data presented in the Ref. 14 is twice the $A^{2/3}$-scaled $p\bar{p}$ result: 257 compared to 136 mb.

Cold quark matter: The observed velocity (rapidity) of the fireball implies that the Tantalum nucleus is transversed in 10^{-22} sec. This constrain on the fireball lifetime induces the hot matter to seek a point of relative stability, which would be at the minimum of the energy per baryon curve for a given entropy per baryon. Using as before the perturbative QCD equations of state for the energy per baryon, we seek the temperature of quark matter at which as function of baryon density a minimum appears in the energy per baryon expected for the fireball, 1.32 GeV. Taking the value of the QCD parameters to be same as before I find T=53 MeV, μ_b=1200 MeV ($n/n_0=2.75$, $\epsilon=0.5$ GeV/fm^3, S/b=4). Variation of α_s in the range 0.5 - 0.7 and of B within a factor two leave these results unchanged, in particular so when an increased value of α_s is associated with a reduced value of B, as required for consistency with other QCD and hadronic spectra studies. For strange quark mass of 170 MeV the equilibrium ratio of strangeness to baryon number is 1/250, but this value depends sensitively on T and may be as large as 1/50 . Note that the 'hot' component at T ~ 100 MeV arises now due to the reheating occurring in the transition to the hadronic gas. However, as it is probably the state of lower entropy compared to an isolated ball of hadronic gas at the same energy and baryon number, it is rather stable with respect to the global transition to the hadronic gas phase, decaying by successive reactions.

In support of the quark matter formation hypothesis in this annihilation reaction is: The observation that alone the annihilation mechanism generates about 25 units of entropy, half of what we require in the associated quark fireball. As mentioned, there is both a strong s-quark and lambda anomaly in that these cross sections are much greater than expected. Because strangeness is produced efficiently in the quark gluon plasma [5] such high abundance can be expected. In the quark matter phase the strangeness production time constant is 3 10^{-22} sec at T = 60 MeV. This time is of similar magnitude as the estimate for the fireball to transverse the nucleus and hence we can expect chemical equilibrium of strange quark abundance in the cold quark matter fireball. Statistical equilibrium abundance of strangeness, <s> = (0.004 - 0.02)·b (in dependance on the Temperature of quark matter), where $b \sim 2A^{1/3}$, leads to strangeness production cross section: $A\cdot(1.2\ \mathrm{fm})^2\cdot(0.04 - .016)$ = 84 - 210 mb. As is the case with nuclear collisions, the anomalous abundance of strangeness could arise in the hadronic gas fireball if it 'cooks' for an unusually long time. Against this interpretation speaks the fact that there is no sign of the anomaly in the C-Ta collisions at similar energy [17]. The fact that the s-anomaly occurs only in the annihilation reaction favors strongly the quark matter interpretation.

Summary: I have shown that in view of recent experiments it is consistent and indeed rather compelling to consider the formation of quark matter in various hadronic reactions with nuclei. In particular I have discussed the expected abundances of strange baryons and antibaryons in 'cold' and 'hot' quark matter.

REFERENCES

1. Lectures at this meeting (Rencontres des Moriond 1988) by the experimental collaborations: NA34, NA35, WA80.
2. W. Heck et al, GSI-88-08, January 1988, 'Study of the Energy Flow in O-Nucleus Collisions at 60 and 200 GeV/Nucleon', see in particular Fig. 12 .
3. H.E. Miettinen and P.M. Stevenson, Phys. Lett. B199 (1987) 591.
4. J. Rafelski and A. Schnabel, Phys. Letters B in press; J. Rafelski and A. Schnabel, 'Physical Properties of Quark Gluon Plasma at CERN SPS', UCT/TP preprint 81/1987; J. Rafelski, Lecture at the Quark Matter 1987 meeting in Nordkirchen, W. Germany, August 1987.
5. J. Rafelski, in Proceedings of Rencontres des Moriond 1987, Editions Frontieres 1988, and references therein.
6. H. Ströbele et al, GSI-88-07, January 1988, 'Negative Particle Production in Nuclear Collisions at 60 and 200 GeV/nucleon'.
7. NA35 Collaboration, A. Bamberger et al, GSI-88-09, January 1988, 'Charged Particle Multiplicities and Interaction Cross Sections in High Energy Nuclear Collisions'.
8. N.K. Glendenning and J. Rafelski, Phys. Rev. C31 (1985) 823.
9. WA80 Collaboration, R. Albrecht et al, GSI-87-82, December 1987, 'Photon and Neutral Pion Distributions in 60 and 200 A GeV O + Nucleus and p+Nucleus Reactions'.
10. C. Greiner, Diploma Thesis, Frankfurt/M 1988; Phys. Rev. Lett. 58 (1987) 1825 .
11. J. Rafelski, Phys. Lett. B190 (1987) 167.
12. A. Schnabel and J. Rafelski, to be published.
13. A. Schnabel, PhD Thesis 1988.
14. K. Miyano, Y. Noguchi, M. Fukawa, E. Kohriki, F. Ochiai, T. Sato, A. Suzuki, K. Takahashi, Y. Yoshimura, N. Fujiwara, S. Noguchi, S. Yamashita and A. Ono, Phys. Rev. Lett. 53 (1984) 1725 and 'Neutral Strange Particle Productions and Inelastic Cross Section in p+Ta Reaction at 4 GeV/c', KEK Preprint 87-160 February 1988).
15. J. Rafelski, 'Quark Gluon Plasma in 4 GeV/c Antiproton Annihilations an Nuclei', Submitted to Phys. Lett. B
16. C.M. Ko and R.Yuan, Phys. Lett. B192 (1987) 31 .
17. V.D. Toneev, H. Schulz, K.K. Gudima and G. Röpke, Sov. J. Part. Nucl. 17 (1986) 485 [Fiz. Elem. Chastits At. Yadra 17 (1986) 1093] and references therein. See in particular page 511.