PRINT-93-0344 (MINNESOTA)
Fermilab Library
0 1160 0023588 1

REACTION DYNAMICS OF ULTRA-RELATIVISTIC HEAVY ION COLLISIONS WITHIN THE PARTON CASCADE MODEL

K. GEIGER
School of Physics and Astronomy
116 Church St S.E.
University of Minnesota
Minneapolis, MN 55455, U.S.A.

ABSTRACT

The chemical composition of the hot and dense parton matter formed in the central region of ultra-relativistic heavy ion collisions is studied for the case of $Au + Au$ collisions at RHIC energy using the parton cascade model. It is shown that within this framework, which is based on current understanding of semi-hard and hard interactions in QCD including the emission and absorption of soft partons, a chemical equilibration between the gluons and the quarks cannot be achieved. The gluons and u, d, s and c quarks all rapidly approach kinetic equilibrium with a common temperature. The gluons also subsequently achieve chemical equilibrium, but the light quarks only reach about 60% of their ideal chemical equilibrium densities. It is demonstrated that the baryon density in the central region is small relative to the total parton density, with an associated ratio of baryon chemical potential to temperature of 0.35, slowly decreasing with time.

1. Introduction

One of the major goals of the experimental programs at the future heavy ion colliders, the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), is to detect evidence for the predicted QCD phase transition to a QGP. Of particular interest is the question whether the QCD phase, as established shortly after the initial nuclear contact through the materialization of partons, lasts long enough to evolve into a thermally *and* chemically equilibrated plasma of quark-gluon matter [1]. Therefore it is essential to learn about the time scales associated with the development of the matter from the first instant of collision, via a pre-equilibrium stage, towards a QGP. Furthermore, an understanding of the pre-equilibrium dynamics and the characteristic properties of a realistic QGP in terms of the gluon and quark

composition is inevitable for finding unambiguous signatures that can be identified with the experimental particle detectors. The theoretical approach that I would like to advocate here to study these issues, is to follow the system of interacting partons in complete phase-space and time during the first few fm/c and to extract the degree of kinetic and chemical equilibration of the parton system.

2. The parton cascade model

The model framework for the analysis is provided by the parton cascade model. The specific aspects of this model are presented in detail in Refs. [2,3,4]. The general concept of the approach can be briefly summarized as follows. In the parton cascade model ultra-relativistic nuclear collisions are described as the time evolution of the partons' phase-space distributions. The space-time development is formulated within renormalization group improved QCD perturbation theory, embedded in the framework of relativistic transport theory. The dynamics of the dissipative processes during the early stage of the nuclear reactions is simulated as the evolution of multiple internetted parton cascades associated with quark and gluon interactions. Each cascade is an arbitrarily complicated composition of elementary $2 \rightarrow 2$ parton-parton 'collisions', $1 \rightarrow 2$ parton 'decays' and $2 \rightarrow 1$ 'fusion' processes [3]. Therefore the model incorporates the possibility of detailed balance with respect to the various interaction processes - a feature which is essential when addressing the question of thermal and chemical equilibration. At the end of the perturbative QCD phase the hadronization is modelled as a recombination of the final state partons to form color singlet clusters, followed by the fragmentation of these clusters into observable hadronic states [4].

3. Results

To study the space-time evolution of the partons with focus on their thermodynamics and relative chemical admixtures in ultra-relativistic heavy ion collisions I will concentrate on the illustrative case of central $Au+Au$ collisions at RHIC energy $\sqrt{s} =$ 200 A GeV (A=197). The following results were obtained by simulating these reactions within the parton cascade model. The microscopic dynamics of the partons is described in terms of the *proper time* τ, taken to be $\tau = \mathrm{sign}(t-t_0(s))\sqrt{(t-t_0(s))^2 - z^2}$, where t is the center-of-mass time and $t_0(s)$ is its value at the moment of maximum overlap of the colliding nuclei ($t_0 \simeq 0.8$ fm for $\sqrt{s} = 200$ A GeV) [3] and z is the beam axis with the center-of-mass at $z = 0$. Furthermore, I define the *central collision region*, for $\tau \geq 0$, as a cylindrical expanding volume bounded by $|\eta| \leq 1$ and $|\vec{r}_\perp| \leq 5$ fm, where η is the ordinary space-time rapidity and $\vec{r}_\perp$ the transverse coordinate perpendicular to the beam axis. This central collision region is discretized into thin slabs of $\Delta z = 0.05$ fm, in which the parton distributions are extracted at various times. From these, the thermodynamic quantities (temperature, number densities, etc.) are evaluated in the local rest frame of each slab.

3.1. Kinetic equilibration in the central region

In Fig. 1 the time development of the partons' momentum distributions in the central region (15) of $Au + Au$ collisions at $\sqrt{s} = 200$ A GeV with zero impact is displayed, individually for gluons and the various quark flavors. Plotted are the invariant distributions $(1/\bar{n}_a)d\bar{n}_a/d^3p(\tau)$ versus $p \equiv |\vec{p}|$, which were obtained from the actual parton distributions for each species a (gluons g and quarks plus antiquarks u, d, s, c), averaged over the spatial volume defined before. Note that the histograms are scaled by powers of 10 for better presentation. The sequence of plots demonstrate that the partons indeed rapidly approach kinetic equilibrium in the central region, as is reflected by the increasingly thermal shape. The highly non-thermal initial momentum distribution [4] of the partons in the incoming nuclei first develops a power-law shape characteristic for the harder primary parton collisions and the associated (mini)jet production. With progressing time this QCD power-law tail flattens out and the exponential slope at lower momentum ($p \lesssim 3$ GeV), which is already visible at $\tau = 0.2$ fm, becomes steeper, indicating the decrease in the effective temperature of the system.

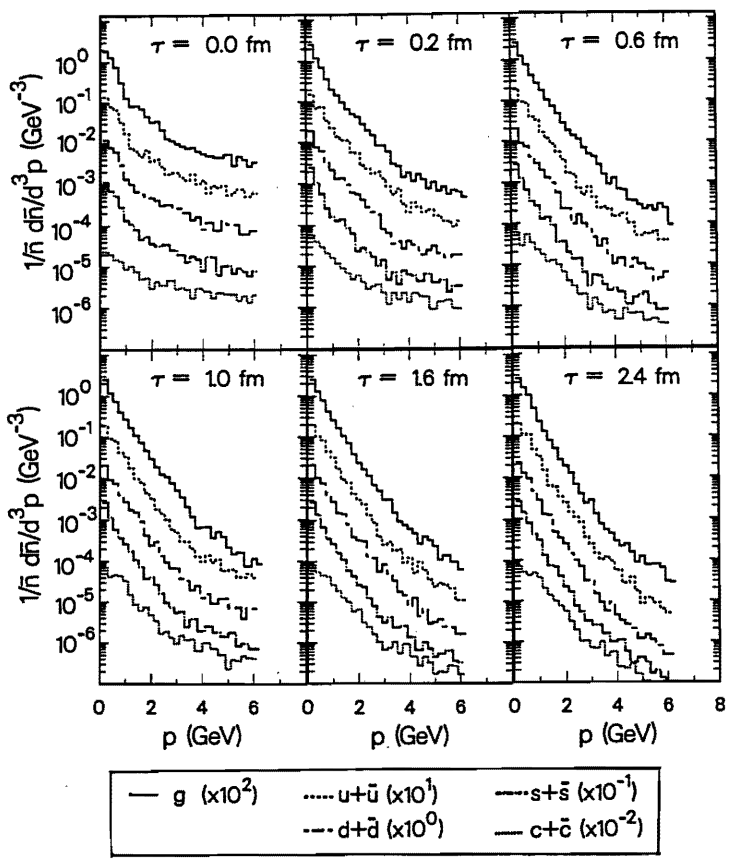

Fig. 1: Time development of the partons' momentum distributions (normalized and scaled by powers of 10) in central $Au + Au$ collisions at $\sqrt{s} = 200$ A GeV, from the moment of maximum nuclear overlap ($\tau = 0$ fm) to the end of the calculation ($\tau = 2.4$ fm).

Fig. 2 summarizes the thermodynamic properties of the system of partons implied by the time evolution of the phase-space distributions. Shown are the pressure p, the number density n, energy density ε and entropy density s, as well as the associated temperature $T \equiv 4/3\,(\varepsilon/s)$ as functions of the proper time τ in the local rest frame of the matter (the curves are interpolations of the data points to guide the eye). The time dependence of the quantities n, p, ε, s and T may be parametrized in terms of negative powers of τ/τ_0 with the parameter $\tau_0 = 0.05$ fm: $n(\tau) = 565$ fm^{-3} $(\tau/\tau_0)^{-0.90}$, $p(\tau) = 580$ GeV fm^{-3} $(\tau/\tau_0)^{-1.25}$, $\varepsilon(\tau) = 1300$ GeV fm^{-3} $(\tau/\tau_0)^{-1.15}$, $s(\tau) = 1800$ fm^{-3} $(\tau/\tau_0)^{-0.85}$, and $T(\tau) = 950$ MeV $(\tau/\tau_0)^{-0.3}$.

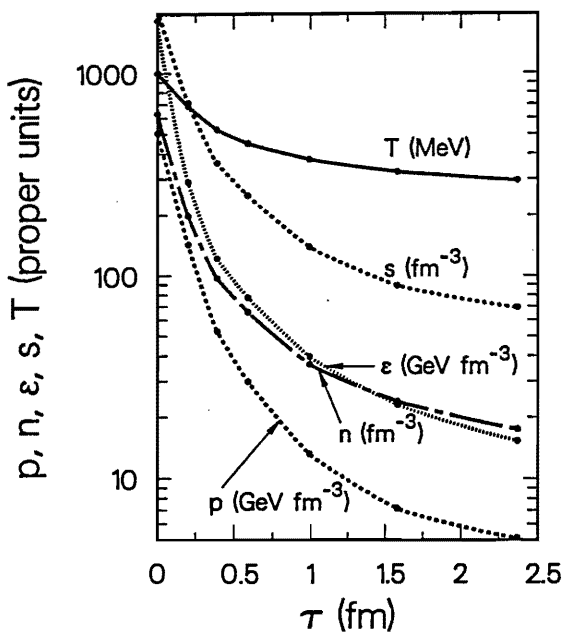

Fig. 2: Pressure p, particle density n, energy density ε, entropy s and associated temperature T of the parton system in the central collision region of $Au + Au$ collisions at $\sqrt{s} = 200$ A GeV as a function of proper time τ.

3.2. Chemical equilibration among gluons and quarks

As an objective measure to estimate the degree of chemical equilibration among the partons I will compare the actual parton number densities n and energy densities ε with the equilibrium densities $n^{(eq)}$ and $\varepsilon^{(eq)}$ for a perfectly equilibrated gas of non-interacting, massless partons at the same temperature (for details see Ref. [5]). To do so, I require the same space-time evolution pattern for both. Furthermore, I make use the resulting fact of the calculations that transverse expansion effects of the matter can be neglected at least during the first few fm [3,5]. Then all the thermodynamic quantities can be expressed as functions of the proper time τ only: $n(\tau, \vec{r}_\perp) = n(\tau)$, $p(\tau, \vec{r}_\perp) = p(\tau)$, $T(\tau, \vec{r}_\perp) = T(\tau)$, etc..

Fig. 3 displays, as a function of time τ, the ratios of the total densities n and ε in the central region, resulting from the parton cascade simulation, to the correspond-

ing equilibrium densities at temperature $T = T(\tau)$ and zero chemical potentials μ_a, $\rho^{(n)}(\tau) = n(\tau)/n^{(eq)}(T, \mu_a = 0)$ and $\rho^{(\varepsilon)}(\tau) = \varepsilon(\tau)/\varepsilon^{(eq)}(T, \mu_a = 0)$. Both $\rho^{(n)}$ and $\rho^{(\varepsilon)}$ reach unity (dotted line) after about $\tau \simeq 1$ fm, indicating that the actual particle and energy densities of the system as a whole show effectively the properties of an equilibrated parton gas [5]. Consistent with that is the time dependence of the dimensionless ratio $(\varepsilon/n)^{3/4}$, which approaches the value of an ideal gas of gluons and quarks with $N_f = 3 - 4$ quark flavors. However, this behavior is predominantly dictated by the gluon distributions and that the contributions of quarks and antiquarks to the total density are significantly below the values required for an ideal mixture among the various parton species. An indication for the establishment of a perfect chemical mixture would be that the ratios $\rho^{(n)}$ and $\rho^{(\varepsilon)}$ tend to unity for gluons and each quark flavor *individually.*

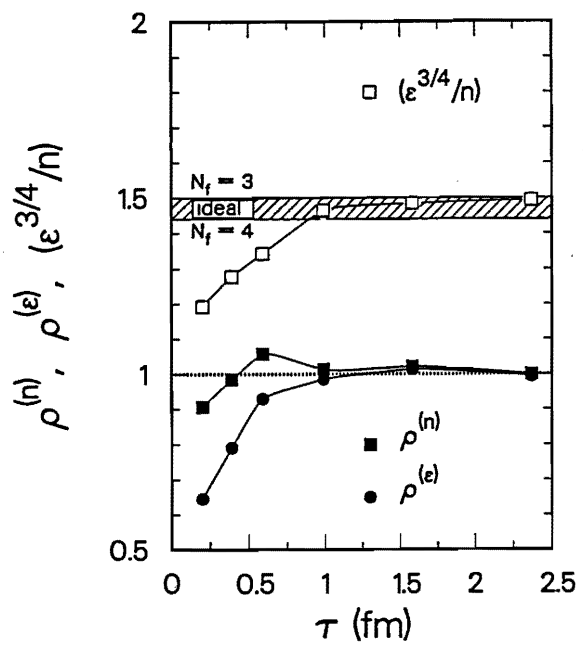

Fig. 3: Time evolution of the ratios $\rho^{(n)}$ and $\rho^{(\varepsilon)}$, for the actual parton densities n and ε to the corresponding ideal equilibrium densities $n^{(eq)}$, respectively $\varepsilon^{(eq)}$ in the central collision region of $Au + Au$ collisions at $\sqrt{s} = 200$ A GeV.

To see how close the parton system comes to a complete chemical equilibrium, one has to compare separately for each species a the actual densities n_a and ε_a with the equilibrium densities $n_a^{(eq)}$ and $\varepsilon_a^{(eq)}$. To do so, I will take into account the fact that the momentum distributions of the parton species are rather distinct due to the difference in their masses and the frequency of their interactions [5]. One can parametrize this distinctive property of the partons' momentum distributions by replacing the effective temperature T of the system as a whole with species-dependent 'temperatures' T_a: $T(\tau) \longrightarrow T_a(\tau) = c_a(\tau)^{-1} \langle E_a \rangle(\tau)$, where $\langle E_a \rangle = \varepsilon_a/n_a$ is the average energy per particle of type a in the local restframe of the matter, and $c_g(\tau) \simeq 2.70$, $c_q \simeq$

3.15. Next, I consider the ratios $\rho_a^{(n)}(\tau) = n_a(\tau)/n_a^{(eq)}(T_a, \mu_a = 0)$ and $\rho_a^{(\varepsilon)}(\tau) = \varepsilon_a(\tau)/\varepsilon_a^{(eq)}(T_a, \mu_a = 0)$ for each parton species $a = g, u, d, s, c$ seperately. Fig. 4 shows these ratios as functions of time τ. It is obvious that the system of partons can *not* establish perfect chemical equilibrium with proper admixtures of gluons and quarks, although, as implied by Fig. 3, it exhibits the thermodynamic behaviour of an ideal parton gas. The gluon density n_g, which rapidly increases and reaches its maximum around $\tau = 0.5$ fm, approaches to within 10% of its equilibrium value at about $\tau = 1.2$ fm. The densities of light quarks plus antiquarks, $n_q + n_{\bar{q}}$, build up only to about 60% of their equilibrium densities. The heavier quarks s and c achieve even less. An analogeous conclusion holds for ε_g, $\varepsilon_q + \varepsilon_{\bar{q}}$ and $\varepsilon_q - \varepsilon_{\bar{q}}$.

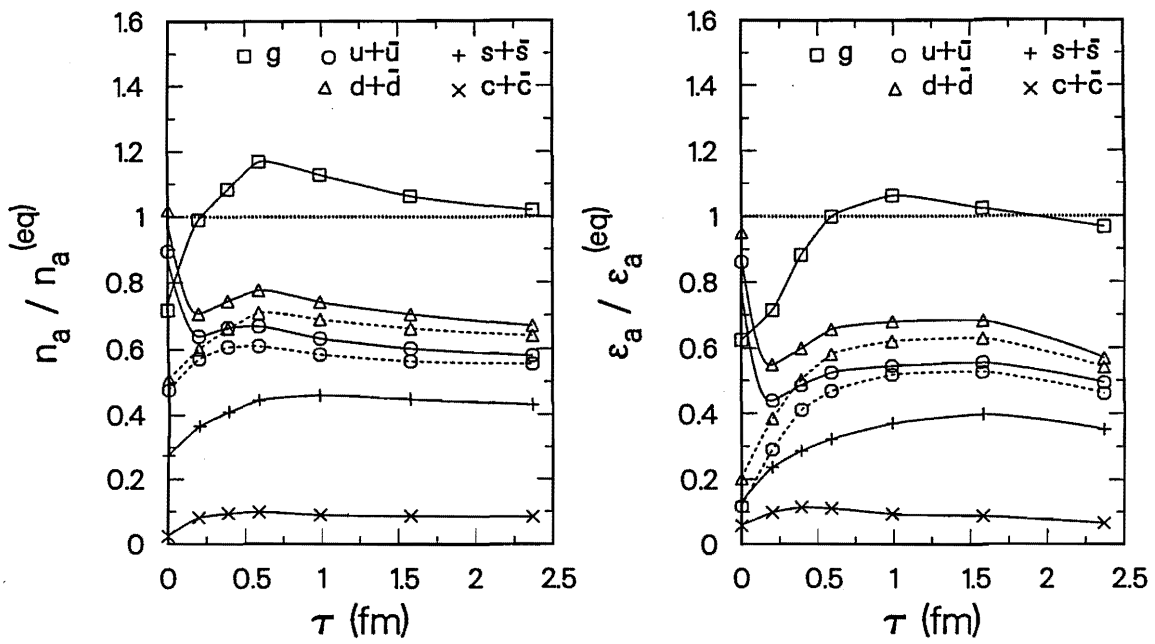

Fig. 4: Time development of the ratios $\rho_a^{(n)}$ and $\rho_a^{(\varepsilon)}$, measuring the deviation of the actual particle and energy densities from their equilibrium values for gluons ($a = g$) and quarks plus antiquarks ($a = u, d, s, c$) seperately.

The dominance of the production of secondary gluons via $gg \to gg$, $gq \to gq$, as well as $g \to gg$ and $q \to qg$ [5], gives rise to a fast build up of $\rho_g(\tau)$ which overshoots its equilibrium value. It bends over as the phase-space density reaches its maximum and gluon fusion (absorption) processes $gg \to q$, $qg \to q$ become significant. The further decrease of $\rho_g(\tau)$ is then mainly due to the diffusion of the quanta as the volume expands and the gluon density dilutes. The production of secondary quarks and antiquarks, on the other hand, does not occur fast and intense enough to ensure an approach to chemical equilibrium because both type of proceses, the conversion of virtual initial state quarks to real excitations through $qg \to qg$, $qq' \to qq'$, and, the production of new $q\bar{q}$ pairs through $gg \to gg$, $q\bar{q} \to q'\bar{q}'$, $g \to q\bar{q}$ are insufficiently frequent to compete with the dilution of the central densities as the plasma expands.

3.3. Baryon density evolution

Finally I would like to address the question of how the baryon density evolves in space-time. It is usually assumed that its magnitude in the central region is neglegiable, so that this region of phase-space can be considered as baryon-free. As it turns out, this is indeed a good approximation. The total baryon number of the system associated with the baryon content of the incoming nuclei must be conserved throughout the reaction. On the parton level, this translates to a constant total number of quarks minus antiquarks, with a surplus of $6A$ quarks in AA collisions (3 per nucleon). However, the local baryon density $n^{(B)}$ is space-time dependent and determined by the dynamics ofg the partons. With the calculated densities n_a and $n_{\bar{a}}$ $(a = u, d)$ and the associated temperature T, resulting from the parton cascade simulation, one readily can estimate the time evolution of the baryon density and of the corresponding baryon chemical potential $\mu_a^{(B)}$ [5]. Fig. 5 (a) shows the absolute magnitudes of $\mu_a^{(B)}$ as a function of proiper time τ. It is about equal for both u and d quarks and decreases rapidly from $\mu_{u(d)}^{(B)} \simeq 400\,(500)$ MeV at $\tau = 0$ to about $\mu_{u(d)}^{(B)} \simeq 40\,(50)$ MeV at $\tau = 2.4$ fm. Thus, the total $\mu^{(B)} = \mu_u^{(B)} + \mu_d^{(B)}$ amounts to roughly 90 MeV. Fig. 5 (b) displays the dimensionless ratios $\mu_a^{(B)}/T$ for u and d quarks seperately, which at first relax fast (within $\simeq 0.5$ fm) and then decrease slowly to values of $\simeq 0.15 - 0.2$ at $\tau = 2.4$ fm, or $\mu^{(B)}/T \simeq 0.35$. The spatial distribution of $\mu^{(B)}$ along the z-axis at $\tau = 2.4$ fm turns out to be rather homogeneous in magnitude throughout the range $|z| \lesssim 1.8$ fm.

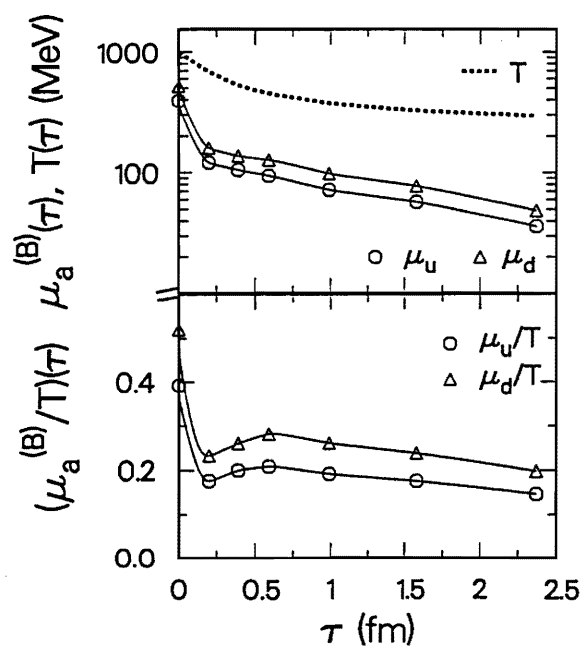

Fig. 5: (a) Baryon chemical potentials $\mu_a^{(B)}$ for $a = u, d$ as a function of time τ in the central region of $Au + Au$ collisions at $\sqrt{s} = 200$ A GeV. The dashed line shows for reference the temperature of the system (c.f. Fig. 2). (b)Corresponding time development of the dimensionless ratio $\mu_a^{(B)}/T$ for u and d quarks.

4. Conclusions

Within the framework of the parton cascade model, I have studied the composition of the parton matter formed in central $Au + Au$ collisions at RHIC energies $\sqrt{s} = 200$ A GeV. The results from simulations of these reactions imply a rapid thermalization of the partons' phase-space distributions in the central collision region and the formation of a very hot and dense state of parton matter. Within this scenario I analyzed the 'chemistry' of partons in terms of the contributions of gluons and the different quark flavors to the particle and energy densities. The essential results can be summarized as follows:

(i) The matter formed in the central region (with space-time rapidity $|\eta| \leq 1$) is essentially a hot gluon plasma rather than a quark-gluon plasma, with an effective temperature close to 1 GeV shortly after the moment of maximum nuclear overlap ($\tau = 0$). The dynamics is clearly dominated by the gluons.

(ii) As the system expands and cools, the gluon density reaches its equilibrium value around $\tau \approx 2$ fm. The densities of quarks and antiquarks always stay well below the gluon density and cannot build up to the full equilibrium values required for an ideal chemical mixture of gluons and quarks.The time for chemical equilibration of the quarks is too long to compete with the dilution of the densities due to expansion and cooling.

(iii) The baryon density in the central region, associated with the valence quarks, turns out to be generally small relative to the total parton density. The basic reasons for this are: first, the valence quarks have a harder initial momentum distribution than the gluons and seaquarks, and second, the total parton density increases rapidly due to the intense materialization of initially virtual partons and the copious production of additional particles, whereas the baryon density is quickly diluted in the central region and resides mostly in the receding beam fronts. The central baryon density amounts to less than 10 % of the total parton density, which translates into an estimate of the associated baryon chemical potential $\mu^{(B)} \simeq 90$ MeV at $\tau = 2.4$ fm, or $\mu^{(B)} \simeq 0.35\,T$.

5. References

[1] See e.g. *Quark Matter '91, Proceedings of the Ninth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions*, Gatlinburg, TN, U.S.A., 1991, [*Nucl. Phys.* **A 525**, 1c (1992).

[2] K. Geiger and B. Müller, *Nucl. Phys.* **B 369**, 600 (1992).

[3] K. Geiger, *Phys. Rev.* **D46**, 4965 (1992); *ibid* 4986.

[4] K. Geiger, *Phys. Rev.* **D47**, 133 (1993).

[5] K. Geiger and J. Kapusta, UMSI Preprint 1/93 (1993), to appear in Phys. Rev. **D**.