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RESTORATION OF CHIRAL SYMMETRY IN NUCLEUS–NUCLEUS COLLISIONS AROUND 10 GeV/u*

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Using hadron phase-space distributions obtained with the quark-gluon string model, we have studied [1] the modification of the quark condensate $\langle\bar{q}q\rangle$ in relativistic nucleus-nucleus collisions and estimated the 4-volume, where the ratio of $\langle\bar{q}q\rangle$ over its vacuum value $\langle\bar{q}q\rangle_0$ is small ($0.1 \lesssim \langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0 \lesssim 0.3$) and the scalar baryon density exceeds its value for normal nuclear density by 50%. As a function of beam energy this 4-volume rises sharply in the region 1 GeV $\lesssim E_{\rm lab}/A \lesssim$ 4 GeV and decreases at higher energies. Based on this estimate it is concluded that moderate beam energies on the order of 10 GeV/u are favourable for studying the restoration of chiral symmetry in baryon-rich matter. At higher energies chiral symmetry restoration is dominated by mesons. Therefore a dedicated machine in the energy regime around 10 GeV/u is needed to study chiral symmetry restoration in baryon-rich matter. Such studies would be complementary to those at SPS-, RHIC- and LHC-energies on meson-dominated chiral-symmetry restoration.

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1. Introduction and basic equations

In vacuum the chiral symmetry of QCD is spontaneously broken and the quark condensate $\langle\bar{q}q\rangle$, which is an order parameter of the chiral phase transition, is non-zero. In hadronic matter, the quark condensate is reduced, implying a partial restoration of chiral symmetry, while in quark-gluon matter, beyond the deconfinement transition, one expects chiral symmetry to be restored and consequently the quark condensate to vanish. The leading

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density and temperature dependence of the condensate has been studied in static (equilibrium) systems [2, 3]. In this contribution I briefly report on an estimate [1] of the quark condensate in an inherently dynamic system, *i.e.* in a relativistic nucleus-nucleus collision. The results are relevant in the discussion of a suitable accelerator for studying chiral restoration, *e.g.* a synchrotron/storage ring (S/SR) at GSI which may supply heavy-ion beams up to 30 GeV/u.

The quark condensate, and in particular its modification in matter, is not directly accessible in experiment. However, if the in-medium properties of hadrons are closely related to the quark condensate [4, 5], the observation of changes in these properties may open an indirect way of exploring the restoration of chiral symmetry in dense matter. Fig. 1 shows the dependence of the quark condensate on the variables T and ρ as obtained in the selfconsistent mean-field approximation of the Nambu–Jona-Lasinio model [6].

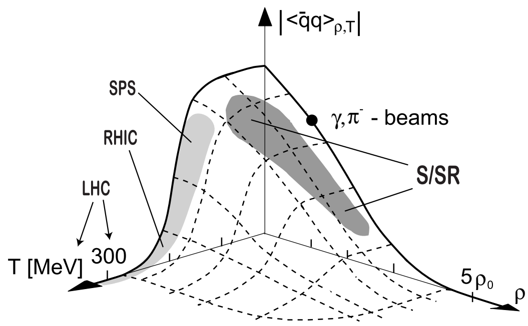

Fig. 1. The quark condensate as function of baryon density ρ and temperature T within the Nambu–Jona-Lasinio model [6]. The dot indicates the position for normal nuclear matter density and the shaded areas the regions, where experiments at different heavy-ion accelerators are expected to test the (partial) restoration of chiral symmetry (*cf.* the discussion in section 4)

The low-density and low-temperature behaviour of $\langle \bar{q}q \rangle$ is governed by relations of the form [2, 3],

$$\frac{\langle \bar{q}q \rangle}{\langle \bar{q}q \rangle_0} = 1 - \sum_h \frac{\sigma_h \rho_h^s}{f_\pi^2 m_\pi^2}\,, \tag{1}$$

where the sum runs over the hadron species h. Here σ_h denotes the σ-commutator of the hadron, ρ_h^s the corresponding scalar density of non-interacting particles, $f_\pi = 94$ MeV the pion decay constant and m_π the pion mass.

At low temperatures and zero net baryon density, the modification of the quark condensate in Eq. (1) is dominated by pions and yield a reduction quadratic in the temperature T. This T-dependence is not significantly altered by higher-order loop corrections [2, 7] and also in agreement with lattice QCD calculations, *cf.* [8].

For nuclear matter at zero temperature and low baryon density ρ, the leading term in Eq. (1) is given by a gas of non-interacting nucleons and yields a reduction linear in ρ such that $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ takes the value 0.7 at normal nuclear matter density $\rho_0 = 0.16$ fm^{-3}. Terms of higher order in the density have been estimated in relativistic Brueckner-Hartree-Fock calculations using realistic nucleon-nucleon interactions (*cf. e.g.* [9]). Qualitatively these calculations show that, for densities higher than $1.5\rho_0$, the condensate seems to stay at a value of about 40 % of its vacuum value. However, the role of higher-order effects is rather unsettled and results of saturation already at 80% for normal nuclear density have been obtained, *cf.* [10]. Because of these uncertainties in the ρ-dependence of the quark condensate, measurements on chiral restoration at large baryon densities are of particular interest.

While it may be possible to describe the late stages of nucleus-nucleus collisions approximately with equilibrium thermodynamics this is clearly not possible for the early stages. The non-equilibrium character of nucleus-nucleus collisions can be taken into account by evaluating the scalar densities in Eq. (1) from the phase-space densities, which are obtained in simulations of the collisions and, in general, are different from equilibrium distributions.

2. Qualitative consideration of heavy-ion collisions

In contrast to equilibrium systems, where the quark condensate has been studied so far, very fast changes are encountered in relativistic nucleus-nucleus collisions, characteristic times being on the order of 10 fm/c. The typical time τ for the quark condensate to respond to changes of the medium has not been studied so far. However, one would expect this time to be governed by the mass of the lightest scalar meson and thus to be of the same order as typical hadronic times, *i.e.* $\tau \lesssim 1$ fm/c. In this exploratory calculation [1] we have assumed that the response of the condensate is instantaneous, except for produced particles, whose contribution to the quark condensate is taken into account only after a (proper) time $\tau_f = 1$ fm/c for formation.

Since $\langle\bar{q}q\rangle$ is a Lorentz scalar the condensate in the interior of a moving nucleus equals the condensate in a nucleus at rest, *i.e.*, it is reduced by about 1/3 from its vacuum value. This means that when two nuclei pass through each other without interacting, the quark condensate in the overlap region is reduced by the amount corresponding to nuclear matter at $\rho = 2\rho_0$, *i.e.*, by about 2/3. On the other hand, Lorentz contraction of the volume leads to a velocity dependent enhancement of the baryon density $2\gamma\rho_0$, where

$\gamma = 1/\sqrt{1-v^2}$ and v is the velocity of the nucleus. At AGS energies this purely kinematical effect without any dynamical compression yields a baryon density of $(5-6)\rho_0$, while at CERN energies one finds about $20\rho_0$. Similarly, also the energy density is strongly enhanced due to Lorentz contraction of the collision volume. This trivial Lorentz contraction, which is responsible for the bulk of the very large baryon and energy densities found in simulations of heavy-ion collisions at ultra-relativistic energies, does not, however, affect the quark condensate. Consequently, the baryon density is not a suitable measure for the restoration of chiral symmetry in such collisions.

We note that when the finite sizes of the hadrons is taken seriously, one arrives at similar conclusions. The relevant quantity, which determines the quark condensate of such a system is not the number density but the volume fraction which is not occupied by hadrons [11]. In the spirit of the chiral bag model it is assumed that the interior of a nucleon is in the chirally symmetric phase, and consequently that the quark condensate is effectively zero there. Thus, each nucleon represents a small volume, where the chiral symmetry is locally restored, and the average value of the condensate in nuclear matter is proportional to the fraction of the volume which is unoccupied. By identifying the coefficient of the term linear in density with that given by Eq. (1), one finds for the volume of a nucleon at rest $v_N = \sigma_N / f_\pi^2 m_\pi^2$, which implies $R_N = 0.8$ fm. Now consider a moving nucleus composed of finite-size nucleons. Since all volumes, that of the nucleus and those of the nucleons, are Lorentz contracted by the same factor, the fraction of the volume which is not occupied is a Lorentz invariant. On the other hand, a nucleon, which is stopped in a nucleus-nucleus collision, recovers its rest volume. Consequently, stopping leads to an increase in the occupied fraction of the Lorentz contracted interaction volume, and hence to a decrease of $|\langle \bar{q}q \rangle|$. The occupied fraction is increased further by the produced hadrons. In this way the time-dependent magnitude of the quark condensate in nucleus-nucleus collisions depends sensitively on the collision dynamics, in particular on stopping and particle production rates.

3. The quark condensate in central Au+Au collisions

In order to describe the collisions in a realistic way, we employ the Quark-Gluon String Model (QGSM) [12], which is based on the string phenomenology of hadronic interactions. The general experimental characteristics of relativistic nucleus-nucleus collisions are well reproduced over a large range of beam energies from SIS [13], to AGS [14] and SPS energies [12,15]. Thus, we expect that the model describes the space-time evolution of such collisions sufficiently well.

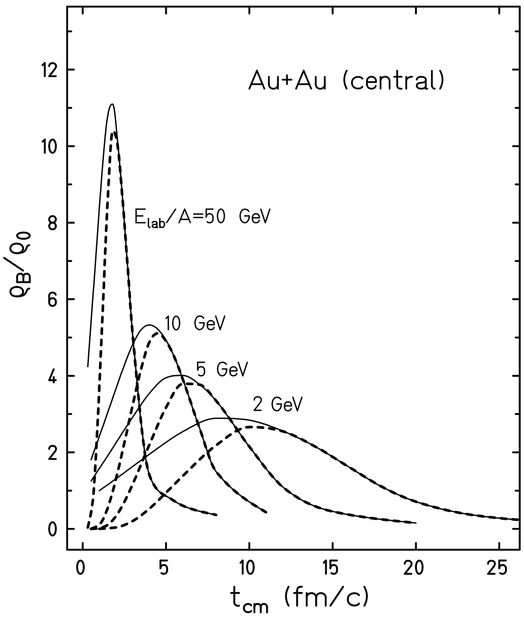

Fig. 2. Time evolution of the central baryon density in head-on Au+Au collisions for beam energies 2 GeV $\leq E_{\rm lab}/A \leq$ 50 GeV. The solid lines correspond to all baryons while the dashed lines are for the participants only, which have suffered at least one collision.

In Fig. 2 we show the time evolution of the central baryon density for head-on Au+Au collisions at beam energies from $E_{\rm lab}/A$ = 2 GeV up to 50 GeV. The total central baryon density increases rapidly reaching a maximum shortly after the point of maximum overlap. Subsequently, the density decreases rapidly with time. A comparison of the total and participant densities shows that even near the maximum not all nucleons in the center have experienced a collision. Nevertheless, both definitions of the density imply that very large baryon densities are reached at high beam energies. However, as we argued above, these densities result to a large extent from Lorentz contraction and hence, are not immediately relevant for the restoration of chiral symmetry and associated medium effects.

We compute the quark condensate by adapting Eq. (1) to the transport model (*cf.* [1] for details) and incorporate the higher-order effects from the baryons by limiting their contribution to $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ to less than 0.6. The resulting time evolution of the quark condensate in the center of the interaction region is shown in Fig. 3. For beam energies beyond 4 GeV, the ratio $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ becomes negative for some time during the collision. Obviously, the low-density approximation is no longer valid when this happens.

However, if we trust our approximation down to a certain positive value r for $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$, we obtain the correct time interval for the quark condensate being below that value.

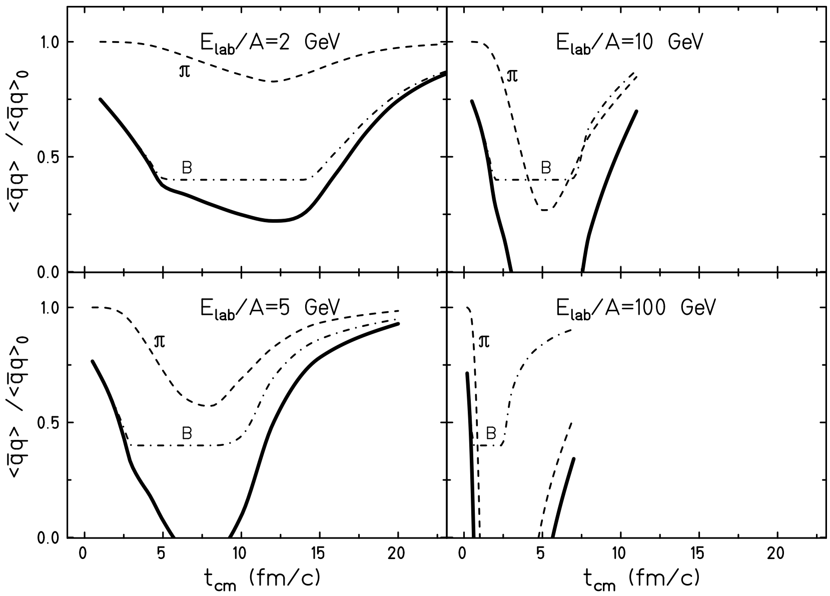

Fig. 3. Time evolution of the central quark condensate (solid lines) in head-on Au+Au collisions for $E_{\mathrm{lab}}/A = 2$, 5, 10, 100 GeV. The contribution from baryons (dash-dotted lines) and pions (dotted lines) are shown separately.

At a beam energy of $E_{\mathrm{lab}}/A = 2$ GeV the pion density remains relatively small, and hence the main reduction of $|\langle\bar{q}q\rangle|$ is due to baryons which in our simulation reach densities of $3\rho_0$ (see Fig. 1). At higher energies, the pion contribution becomes gradually more important. At $E_{\mathrm{lab}}/A = 50$ GeV and above the reduction of $|\langle\bar{q}q\rangle|$ is dominated by pions and other mesons. At SIS energies and partially also at AGS energies, the reduction of the quark condensate is essentially due to the baryons, while at ultra-relativistic energies the meson contribution dominates.

In general, we expect that signals from the partial restoration of chiral symmetry should depend not only on the time but also on the volume, where the quark condensate is small. In order to have an effect as large as possible, the time should be as long as possible, and – in order to minimize unwanted surface effects – the volume should be as big as possible. We choose a relatively simple quantity that accounts for both time and volume, *i.e.* the 4-volume

$$\Omega_r = \int \mathrm{d}^3x\,\mathrm{d}t\ \Theta\left(r - \frac{\langle\bar{q}q\rangle(x,t)}{\langle\bar{q}q\rangle_0}\right)\,, \tag{2}$$

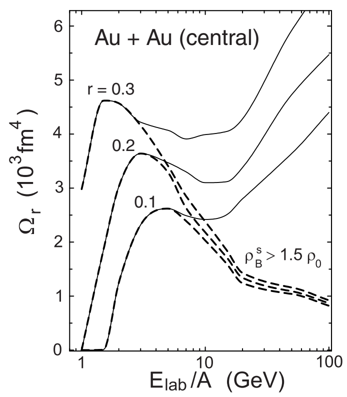

Fig. 4. The invariant 4-volume Ω_r, defined by Eq. (2) where $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ drops below $r = 0.1, 0.2$ and 0.3 as function of beam energy. If in addition the scalar baryon density is required to be larger than $1.5\rho_0$, the dashed curves are obtained.

where Θ denotes the Heaviside function. Thus Ω_r is the integral over all 4-volume elements, where $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ is less than r. It can be regarded as a typical measure for the intensity of a signal from chiral restoration in a heavy-ion collision.

The 4-volume Ω_r is shown by the solid lines in Fig. 4 as function of the bombarding energy for different values of r. Depending on the value of r we find a sharp increase at a threshold energy of $(1 - 4)$ GeV/u, a plateau in an intermediate energy range up to ≈ 20 GeV/u and a monotonous increase towards larger energies. According to Fig. 3 the threshold and plateau regions are associated with high baryon densities, while the rise at high energies is due largely to meson degrees of freedom. We point out that the saturation of the baryon contribution, introduced to account for higher-order effects, plays a crucial role only at low energies, but does not affect the 4-volume appreciably at beam energies $\gtrsim 3$ GeV/u.

In order to obtain a quantitative characterization of the different regimes we also show the 4-volume, where $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ is small with the additional constraint that the scalar density of baryons is larger than $1.5\rho_0$ (dashed lines in Fig. 4). This 4-volume exhibits a maximum, which – depending on the value of r – lies in the range $(2 - 8)$ GeV/u, and then decreases as the energy is increased. The decrease with increasing beam energy is a result of the increasing expansion velocity, which leads to a faster dilution of the baryon density for larger values of $E_{\rm lab}$ (*cf.* Figs. 2 and 3). On the other hand, the growth of the meson contribution to the 4-volume at high energies is due to a high rate for meson production, which compensates for the fast expansion and implies that a dense meson gas exists over a relatively long time in an expanding interaction volume.

4. Discussion and conclusions

We have argued that the quark condensate is better suited than the baryon density as a measure for chiral restoration in simulations of relativistic nucleus-nucleus collisions. The condensate is directly related to the spontaneous breaking of chiral symmetry, since it is an order parameter for this transition. Furthermore, it is not influenced by trivial Lorentz contraction and accounts for both baryons and mesons in a natural way.

We have estimated the quark condensate in relativistic nucleus-nucleus collisions and have calculated the 4-volume, where the condensate is small. However, the quark condensate is not a direct observable and the relative weight of time and volume depends on the signal under consideration. Because of this uncertainty, the following discussion based on the 4-volume should be taken with some care.

We find that the invariant 4-volume, where the condensate is small, increases rapidly at $E_{\rm lab}/A = (1-4)$ GeV, levels off at intermediate energies and increases for beam energies beyond $\approx$ 20 GeV. This behaviour is due to an interplay between meson and baryon contributions to the quark condensate. For baryon-rich matter, the 4-volume decreases at high energies with increasing beam energy, giving rise to a maximum at fairly low beam energies.

Although for a given probe the optimal beam energy may differ, experimental signals of chiral symmetry restoration are expected to exhibit a characteristic threshold behaviour corresponding to the sharp rise of the 4-volume. All in all, our results indicate that the conditions reached in nucleus-nucleus collisions at moderate beam energies, *i.e.* 2 GeV$\lesssim E_{\rm lab}/A \lesssim$ 20 GeV, are favourable for exploring the restoration of chiral symmetry in baryon-rich matter.

For probes that rely on high baryon densities, the optimal conditions are probably reached at beam energies around 10 GeV/u. In this connection we like to point out that the in-medium modifications invoked in interpretations of the low-mass lepton-pairs in ultra-relativistic nucleus-nucleus collisions at the SPS [16, 17] depend mainly on high baryon densities [18–20]. For such medium effects the dashed curves in Fig. 4 and the baryon time scales of Fig. 3 are relevant. Consequently, if such a model is correct, one expects an even more pronounced enhancement of lepton pairs at lower beam energies, say $E_{\rm lab}/A \approx$ 10 GeV, where chiral restoration is accompanied by high baryon densities.

The strong variation of the 4-volume with beam energy suggests to measure excitation functions in relatively small steps between 2 GeV/u and 20 GeV/u. This could be done with a dedicated accelerator, like the Synchrotron/Storage Ring (S/SR) which is under discussion at GSI.

Let me finally come back to Fig. 1. This figure has frequently been used to discuss the areas in the (T,ρ)-plane, which can be studied with a given accelerator. Often this has been done by just looking at the regions for the maximum of baryon and energy densities. This has caused errornous conclusions on the potential of different accelerators. From our studies of the 4-volume, which is some measure for the strength of signals from chiral restoration in heavy-ion collisions, we conclude that experiments at SPS, RHIC and LHC probe the chiral restoration for essentially baryon-free matter. In the 4-volume the large baryon densities, which are reached for small time intervals are not relevant. I conclude that information about chiral restoration in baryon-rich matter (denoted by the shaded area for S/SR) can only be obtained from experiments at beam energies 2 GeV $\lesssim E_{\mathrm{lab}}/A \lesssim$ 20 GeV.

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