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The physics of heavy ion collisions

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Summary. — A theoretical introduction to the physics of the quark-gluon plasma is given, together with a critical discussion of current experimental observables needed to observe it and study its properties.

PACS 12.38.Mh – Quark-gluon plasma.
PACS 25.75.Nq – Quark deconfinement, quark-gluon plasma production and phase transitions.
PACS 21.65.Qr – Quark matter.

1. – Theoretical introduction

The Quantum-Chromodynamics (QCD) is the theory describing the interactions between quarks and gluons, the elementary constituents of all hadronic particles. The running coupling constant of QCD, $\alpha_s(Q)$, is small when the exchanged momentum Q is large ($Q \gg \Lambda_{\rm QCD} \simeq 0.3$–$0.5\,\rm GeV$, corresponding to an interaction distance of the order $r \simeq 1/Q \ll 1\,\rm fm$) thus allowing a perturbative treatment of hard interactions: in this regime, the QCD theoretical predictions have been found in good agreement with experimental results([1]). In the other limit, when Q is small, α_s becomes larger: the perturbative techniques are no longer applicable.

In the perturbative regime, the relevant degrees of freedom are the elementary particles (quarks and gluons) inside the hadrons, while in the non-perturbative case the hadrons participate in the interactions as a whole.

If we imagine to compress a hadronic gas until the hadrons start to overlap, eventually we reach a state in which each quark finds within its immediate vicinity a considerable number of other quarks. It has no way to identify which of these had been its partners in a specific hadron at some previous state of lower density. Beyond a certain point, the

([1]) Actually, in all processes governed by strong interaction there are non-perturbative ingredients, like the parton distribution functions. However they are believed to be universal so that, once they have been measured in one particular experiment, they can be applied to all other processes thus giving genuine predictions.

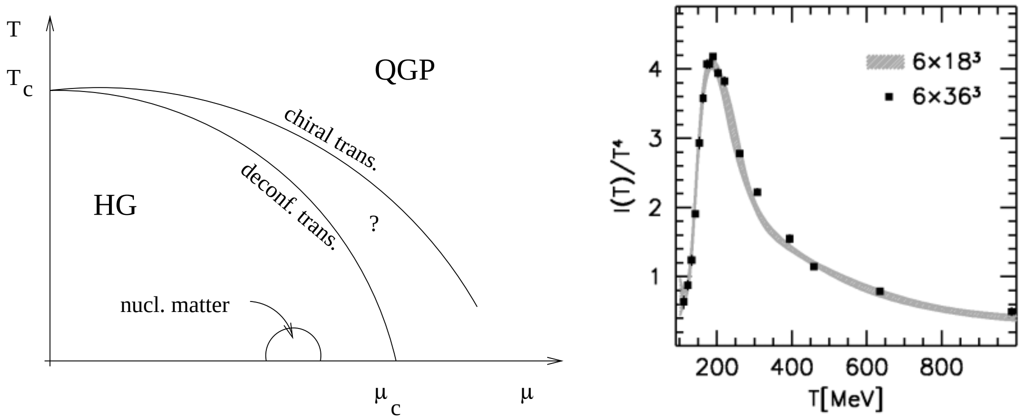

Fig. 1. – Left: the phase diagram in the (T, μ)-plane. Right: the interaction measure [1].

concept of a hadron thus loses its meaning, and we are quite naturally led from hadronic matter to a system whose basic constituents are unbound quarks.

In confined matter the constituents are color-neutral $q\bar{q}$ or qqq states of hadronic size (radius $\sim 1\,\mathrm{fm}$). The quarks inside a hadron polarize the surrounding gluonic medium; the resulting gluon cloud around each quark provides it with a dynamically generated effective mass of about 300 MeV. In an ideal version of QCD, with massless quarks in the Lagrangian, this corresponds to spontaneous chiral symmetry breaking. In a more realistic description, where the quarks have small current mass, the chiral symmetry is explicitly broken, nevertheless the interactions provide the quarks with larger effective masses. However it can be shown, as a simple exercise, that thermal fluctuations reduce the mass of the constituent quark, thus restoring chiral symmetry if the system temperature is high enough. In this condition, the gluon cloud surrounding the quark is dissolved, and the quark is weakly interacting (in the sense that the coupling constant α_s is small, but the interactions are always described by QCD, *i.e.* "strong" interactions!) with the rest of the system.

We thus intuitively conclude that, by "heating" or "compressing", a hadron gas undergoes a phase transition toward a state in which partons are no longer confined into colorless hadrons but they form a medium of color-charged constituents (color deconfinement). Hadronic matter thus shows two transitions, deconfinement and chiral symmetry restoration. In the (T, μ)-plane (μ is the chemical potential, related to baryon density), the phase diagram has approximately the form shown in fig. 1(left), with the hadron gas (HG) at low temperature and density, and the quark-gluon plasma (QGP) at high T and/or high μ.

This intuitive argument can be quantitatively studied from first principle with Lattice QCD, by identifying two suitable order parameters for the two transitions. In the case of the deconfinement transition, the proper order parameter is the average value of the Polyakov loop [2]: $\langle L \rangle \propto \exp[-F_{q\bar{q}}(T)/T]$, where $F_{q\bar{q}}(T)$ is the free energy of a static (*i.e.* infinitively massive) $q\bar{q}$ pair at infinite separation. In a confining medium, $F_{q\bar{q}}$ diverges and $\langle L \rangle = 0$, while in a deconfined phase $F_{q\bar{q}}$ is finite and therefore $\langle L \rangle \neq 0$. In the more realistic case in which $q\bar{q}$ have a finite mass, in the hadronic phase $\langle L \rangle$ is very small but not exactly zero.

The order parameter for the chiral transition is the chiral condensate: $\chi(T) = \langle \psi\bar{\psi} \rangle \sim M_q$, which measures the dynamically generated ("constituent") quark mass M_q. At high temperature this mass melts, so that $\chi(T) = 0$, while at low temperature $\chi(T) \neq 0$ signals the breaking of chiral symmetry. In the past years, intensive lattice studies have shown that for vanishing baryon density (*i.e.* $\mu = 0$), deconfinement and chiral symmetry restoration occur at the same (critical) temperature $T_c \simeq 175\,\mathrm{MeV}$, in other words, these two transitions coincide [3]. It is not clear that this coincidence will occur also at finite μ, since the numerical studies are technically much more difficult.

Lattice calculations show also that, above the onset of deconfinement, the interactions between deconfined quarks and gluons are not weak at all: in fact in the region $T_c \leq T < 5T_c$ the QGP is strongly interacting. This can be seen from the "interaction measure" $I(T) = (\varepsilon - 3p)/T^4$ (ε is the energy density, p the pressure), shown in fig. 1(right), which is exactly zero for an ideal gas of relativistic, non-interacting particles.

2. – Experimental signatures

It is natural to look for an experimental confirmation of these theoretical results. In the last 25–30 years, an intensive program of high-energy heavy-ion collisions has been carried out at BNL (AGS,RHIC) and CERN (SPS,LHC) with the aim of producing a state of color-deconfined matter in the laboratory. A real nuclear collision is a very complicated process, undergoing several stages, from an out-of-equilibrium initial state (colliding nucleons and primary particles), going through thermalization, equilibration to the final state of decay particles observed in the detector.

The equilibrated QGP is hotter than its environment (the vacuum) and hence emits radiation through quark-gluon interactions and quark-antiquark annihilation which produce real and virtual photons, respectively, and these will leave the medium without further strong interaction. They can thus provide information about the state of the medium when they were formed, *i.e.* about the hot QGP [4]. The difficulty is that they can be formed at all evolution stages of the medium, even in the hadronic phase, and so one has to find a way to identify hot thermal electromagnetic radiation. If this can be achieved, such radiation provides a thermometer for the medium.

Another interesting observable is the enhancement of strange quark production. It is known that in electron-positron and hadron-hadron collision, the production of strange quarks is suppressed with respect to lighter u and d quarks because of its large mass, but in the QGP the chiral restoration should remove this suppression. The strangeness enhancement is then predicted to be a signature QGP formation [5]. These phenomenon has been indeed observed: the ratio of newly produced s quarks to u and d quarks, given by the Wroblewski ratio

$$\lambda_s = \frac{\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}\,,$$

increases by a factor 2 going from elementary to heavy ion collisions, as shown in fig. 2(left).

The thermal and statistical equilibrium of the matter produced in a nuclear collision should manifest itself in some collective behavior measurable in the final particles. In a non-central nucleus-nucleus collision, with impact parameter b, the distribution of the longitudinal and transverse momentum of final particles can be parametrized as a function of the azimuthal angle ϕ as [6]

$$\frac{\mathrm{d}N}{p_t \mathrm{d}p_t \mathrm{d}p_z \mathrm{d}\phi} \propto \frac{\mathrm{d}N}{p_t \mathrm{d}p_t \mathrm{d}p_z}\Big(1 + 2v_2(p_T, b)\cos 2\phi\Big)\,.$$

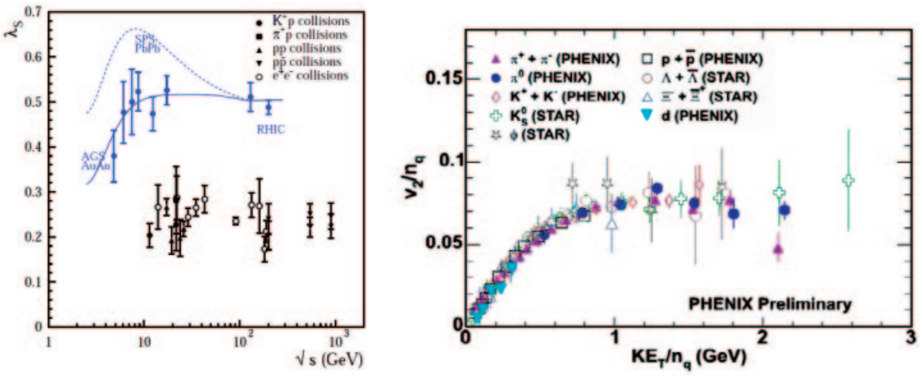

Fig. 2. – Left: the Wroblwewski ratio in elementary and heavy ion collisions (from [7]). Right: the "elliptic flow" coefficient v_2 divided by the number of valence quarks for identified particles in Au-Au collisions at RHIC [8].

The coefficient v_2 as measured in Au-Au collision at RHIC energies in identified particle spectra shows a remarkable scaling with the number n_q of valence quarks ($n_q = 2$ for mesons, 3 for baryons), as shown in fig. 2(right): this can be naturally explained by assuming that the collective motion has been generated at the quark level, *i.e.* before the formation of hadrons.

Alternative tools are obtained by testing the medium with external probes, *i.e.* with probes produced in the first stages of the nucleus-nucleus collision, before the thermalization and formation of QGP. A popular example is the suppression of the J/ψ: it is a strongly bound meson (the dissociation energy, *i.e.* the gap between the J/ψ mass and twice the mass of the lightest charmed meson is about 600 MeV), therefore its inelastic cross-section with colorless hadrons is very small, while in the deconfined phase it melts

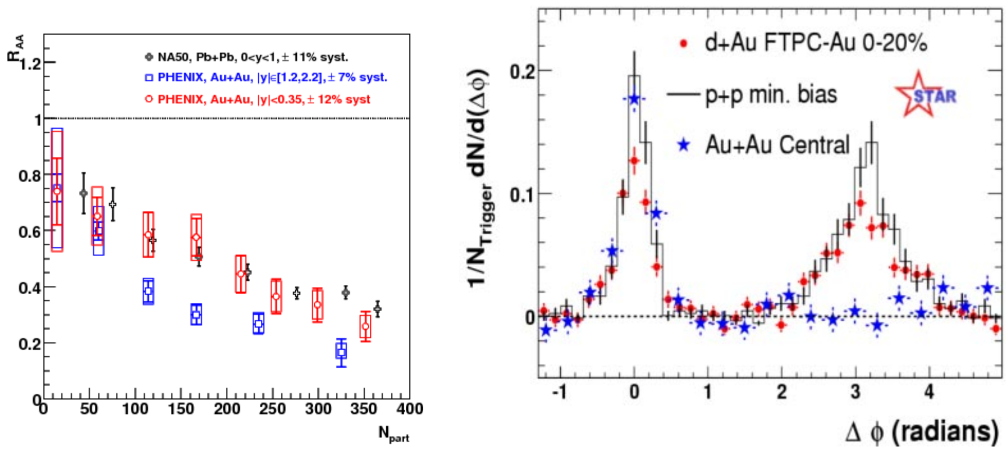

Fig. 3. – Left: J/ψ nuclear modification factors at SPS and RHIC as a function of the number of participants [9]. Right: high-p_T particle correlations at RHIC energies [10].

for the color screening [11]. In the past twenty years there has been a long debate on the suppression of J/ψ's at SPS: it became clear that some of the observed suppression was due to interactions between the pre-resonant $c\bar{c}$ state with the nucleons in the colliding nuclei, but after this contribution has been separated it was evident that in central Pb-Pb collisions at SPS there was an anomalous suppression [12]. Some attempts were made to explain this behavior with interactions of the J/ψ with the final state hadrons (comovers), without assuming QGP formation. Subsequently, the PHENIX Collaboration found in Au-Au collisions at RHIC energies a comparable suppression: in fig. 3(left) the nuclear modification factor R_{AA} is plotted. It is defined as: $R_{AA} = \frac{\mathrm{d}N_\psi^{AA}}{\mathrm{d}p_T}/[N_{\mathrm{coll}}\frac{\mathrm{d}N_\psi^{pp}}{\mathrm{d}p_T}]$, and it is the number of observed J/ψ's in an Au-Au collision rescaled to an equivalent number of proton-proton collisions. In the absence of nuclear effects, this number should be exactly 1. The fact that R_{AA} at RHIC is comparable with the one measured at SPS makes very difficult to support comover absorption, since the number (and, therefore, the density) of produced particles is much higher and consequently the suppression should be stronger.

Like the J/ψ's, high-p_T jets are produced in the initial stages of the nuclear reaction. They are fast colored partons passing through the medium: if such a medium is deconfined, they lose a large fraction of their energy; if the medium is confined, they hadronize and lose a smaller amount of energy. An attenuation of jets thus indicates the presence of a dense, deconfined medium. This is seen in high-p_T particle correlations at RHIC, plotted in fig. 3(right): in proton-proton and deuteron-Au collision a clear back-to-back correlation is present. In central Au-Au collision, on the other hand, only a parton emitted near the surface and moving towards the exterior of the medium can reach the detector; the opposite parton has to traverse the dense medium and therefore it is absorbed.

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