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The quark-gluon medium (micro- and macro-QCD)

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Abstract

The properties of the quark-gluon medium observed in high energy nucleus-nucleus collisions are discussed. The main experimental facts about these collisions are briefly described and compared with data about proton-proton collisions. Both microscopic and macroscopic approaches to their description are reviewed. The chromodynamics of the quark-gluon medium at high energies is mainly considered. The energy loss of partons moving in this medium is treated. The principal conclusion is that the medium possesses some collective properties which are crucial for understanding the experimental observations.

Keywords: QCD, Hydrodynamics

1. Introduction

The topic of *the quark-gluon medium* is so widely spread nowadays that it can not be squeezed into a single lecture. That is why I mostly concentrate on general ideas about the evolution of the quark-gluon medium in high energy heavy ion collisions and on those properties of the medium which are revealed by the energy losses of partons moving in it. They are described by the chromodynamics of the quark-gluon medium which is of the main concern in this lecture. It ascribes quarks and gluons as elementary objects (partons) responsible for the interaction. The goal is to confront experimental data and theoretical ideas about the properties of the quark-gluon medium formed in high energy collisions of hadrons and nuclei (for recent review see [1]).

General "consensus" is achieved concerning the types of processes observed in pp-collisions and their description. They are split into the two groups: SOFT (low p_T) processes, where one uses phenomenology, notion of clusters, multiperipheral models, BFKL equations; and HARD (large p_T) processes, where one considers pQCD, jets production and their evolution, DGLAP equations.

Highly coherent parton configurations and strong internal fields become especially important for the matter in collision. By colliding two heavy nuclei at ultrarelativistic energies one expects to get a hot and dense internally colored medium. It should exhibit some collective properties not seen at static conditions.

2. The main experimental findings

Nowadays, high energy experimental data are obtained at the following accelerators: Tevatron ($p\bar{p}$, $\sqrt{s} \leq 1.96$ TeV); RHIC (pp and ions (up to Au+Au), $\sqrt{s} \leq 200$A GeV); LHC (pp, $\sqrt{s} = 0.9$; 2.36; 7; planned 14 TeV; and

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Pb+Pb, $\sqrt{s} = 2.76$A TeV; planned 5.5A TeV).

The very first question addressed is the difference in AA and pp processes at high energies. The following characteristics were studied:

1.Ratio of particle spectra in AA and pp

$$R_{AA}(y, p_T; b) = \frac{d^2N_{AA}/dydp_T}{N_{part}d^2N_{pp}/dydp_T} \tag{1}$$

shows that $R_{AA} \approx 0.2$ at high $p_T > 4$ GeV which indicates jet quenching (both at RHIC and LHC) and leads to conclusion that AA are not reducible to pp.

2. Correlations: two-, three-particle; jets; BE-HBT; ridge; double-humped distributions... They reveal, e.g., collective flows: v_2 - elliptic (azimuthal) flow induced by the liquid pressure

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{dyp_Tdp_T}(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]) \tag{2}$$

3. Enhancement: hadrocomposition changes (e.g., strangeness, p/π, quarkonia ...)

These facts lead to CONCLUSION: The quark-gluon medium is formed (plasma, liquid).

Many important features were observed in 7 TeV pp-collisions at LHC. For example, particle density in pp (already at 2.36 TeV) becomes comparable to that of AA at RHIC; the size of the interaction region at high multiplicities becomes comparable to that of AA at RHIC (as found from Bose-Einstein correlations), and, most spectacular, ridge was observed in high multiplicity pp at 7 TeV. It raises the question whether this is the signature of the quark-gluon medium formed even in pp. No definite answer was found yet.

3. From partons and fields to the quark-gluon medium

The evolution of quark-gluon fields at the initial stages of collisions is described by microscopic QCD. Later, due to some instabilities the collective properties of this system develop and a quark-gluon matter is formed. At this stage its properties (in particular, propagation of partons through it) should be describable both by micro- and macro-QCD.

At the very beginning, the two Lorentz-contracted sheets with transverse partonic fields (called the Color Glass Condensate - CGC) collide. Soon afterwards they transform into a system of longitudinal fields in color flux tubes localized in the transverse plane and stretching between the valence color degrees of freedom. It is called Glasma. This evolution is described by the JIMWLK-equation [2] obtained from micro-QCD. It preceeds the next stage where the matter with collective properties is formed (possibly, after some instabilities). It is named the Quark-Gluon Plasma (QGP). At the final stage it hadronizes producing final particles.

The mechanical and thermodynamical properties of QGP are studied by comparison of experimental data with theoretical results obtained in the framework of the QCD-inspired hydrodynamics briefly discussed in part 4 of the lecture.

The energy loss of partons in the quark-gluon medium is the main source of experimental information about its properties during the QGP stage. As in electrodynamics, it may be separated in the two categories.

The loss due to the change of the velocity vector of a parton such as elastic scattering, bremsstrahlung and synchrotron radiation is usually treated microscopically. All these phenomena result from the *short-range* response of the parton to the impact of the matter fields. Elastic scattering does change the parton energy due to the recoil effect and deflects it and thus changes the energy flow in the initial direction. At high energies it is less probable than the emission of gluons (bremsstrahlung) during the nearby collisions with the matter constituents. The medium structure imposes some conditions on the coherence properties of the radiation process and on the effective radiation length (in analogy to the Ter-Mikhaelyan and Landau-Pomeranchuk effects in electrodynamics). In general, the intensity of the radiation depends on the relation on the path length of the parton in the medium, its mean free path (defined by the distance between the scattering centers and by cross sections) and the formation length of emitted radiation. The synchrotron radiation of gluons induced by the curvature of parton trajectory in chromomagnetic fields may become important for strong enough fields. Namely these processes are considered in part 5 of the lecture.

Principally different source of energy losses is connected with the medium polarization by the propagating parton. This is the collective response of the medium related to the non-perturbative *long-range* interconnection of its