Phase Diagram of Quantum Chromodynamics

2 CFU

Teaching staff

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Office: room 326, DFA

Reception hours: 15:00-17:00, Monday and Wednesday

Program of the course:

This course aims at teaching the most important aspects of the phase diagram of Quantum Chromodynamics (QCD), namely studying QCD at finite temperature and baryon chemical potential. QCD is the theory of strong interactions, which are described in terms of quarks and gluons. The expected phase diagram of QCD is quite rich. At low temperature and baryon density there is the *confinement phase*, in which the relevant degrees of freedom are the hadrons (mesons, baryons and possibly glueballs); this phase is characterized by the spontaneous breaking of chiral symmetry, and the static potential between one quark and one antiquark contains a linearly rising term describing confinement. The latter implies that it is not possible, in these conditions, to observe an isolated quark. On the other hand, at very high temperature, of the order of 10^{12} Kelvin, a transition to a new phase is expected, in which (roughly speaking) chiral symmetry is approximately restored and deconfinement takes place. This new phase could be called the deconfinement phase. Since in the new phase quarks and gluons are expected to be the relevant degrees of freedom due to deconfinement, this new phase is baptized *quark-gluon plasma*. Similarly, phase transitions are expected to occur at finite baryon density, as large as those probably present in compact stellar objects. In this case one talks about *quark matter*, and several phase transitions can occur, involving both a normal quark matter phase and a color superconductive one. The latter could be characterized by many phases, among them one in which a locking between color and flavor symmetries occurs in the case of QCD with three dynamical flavors (u, d and s quarks) and that could provide a continuity between the hadron and the quark matter phases.

The present course is a theoretical one. However, several applications to compact stars and nuclear collisions will be presented; consequently, PhD students in astrophysics or nuclear physics might find interest in the topics discussed here. Moreover, since the course focuses on the phases and phase transitions in QCD, the course might be of interest to all the PhD students who study statistical mechanics and/or superconductivity and are interested in learning how the phase transitions occur in a strongly interacting system. Even more, the QCD phase diagram and the existence of phase transitions in QCD are the very reason why high energy nuclear collisions are run in experiments at LHC, hence the course might find the interest of experimentalist PhD students whose work is related to the quark-gluon plasma produced at LHC.

The course is planned to be of 2 credits.

Plan of the course

Quantum Chromodynamics: quick reminder on gauge theories, SU(3) gauge theory and QCD, asymptotic freedom (2 hours)

Color confinement and chiral symmetry breaking: how spontaneous breaking of chiral symmetry appears from the hadron spectrum, chiral condensate, confining potential, effective models for the strong interactions at finite temperature and baryon density (2 hours)

QCD phase transitions at finite temperature: Chiral symmetry restoration and deconfinement at finite temperature, QCD thermodynamics, quark-gluon plasma, heavy ion collisions (4 hours)

QCD at large baryon density: critical endpoint of the QCD phase diagram, effective description of QCD at high density, color superconductivity, Debye screening and Meissner effect in high density QCD, applications to the physics of neutron stars, QCD axions in hot and dense quark matter (6 hours)

Bibliography:

Scientific papers and slides provided by the teacher

E. J. Weinberg, *Classical Solutions in Quantum Field Theory: Solitons and Instantons in High Energy Physics*, Cambridge University Press (2015)

M. E. Peskin and D. V Schroeder, *An Introduction to Quantum Field Theory*, CRC Press (2019)

J. I. Kapusta and C. Gale, *Finite Temperature Field Theory: Principles and Applications*, Cambridge University Press (2023)