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Properties of hot and dense matter from relativistic heavy ion collisions

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ABSTRACT

We review the progress achieved in extracting the properties of hot and dense matter from relativistic heavy ion collisions at the relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory and the large hadron collider (LHC) at CERN. We focus on bulk properties of the medium, in particular the evidence for thermalization, aspects of the equation of state, transport properties, as well as fluctuations and correlations. We also discuss the in-medium properties of hadrons with light and heavy quarks, and measurements of dileptons and quarkonia. This review is dedicated to the memory of Gerald E. Brown.

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1. Introduction

Soon after the discovery of QCD [1], and following the realization that QCD exhibits asymptotic freedom [2,3], it was recognized that QCD implies the existence of a new high temperature phase of weakly interacting quarks and gluons, termed the quark–gluon plasma [4–6]. The idea of a limiting temperature for hadronic matter predates the discovery of QCD, and a quantitative prediction $T \simeq 170$ MeV was obtained in the statistical bootstrap model of Hagedorn [7]. The existence of a new phase was confirmed in the first calculations using the lattice formulation of QCD, initially for pure $SU(2)$ gauge theory [8–11].

These results inspired the community to explore the possibility to create and study the quark–gluon plasma by colliding heavy nuclei at high energy, see for example [12]. Early ideas of creating thermodynamically equilibrated matter in high energy hadronic collisions go back to Fermi [13], Landau [14], and Hagedorn [7]. The idea of colliding $U + U$ at the CERN ISR was considered, but not pursued, in the late 1960s. The subject received “subtle stimulation” [15] from a workshop on “GeV/ nucleon collisions of heavy ions” at Bear Mountain, New York [16]. A meeting on ultra-relativistic heavy ion physics was convened in Berkeley in 1979 [17], which spawned a series of Quark Matter conferences that continue to this day.

An experimental relativistic heavy ion program began at the Bevalac facility at Lawrence Berkeley National Laboratory in the mid nineteen-seventies, initially motivated by the study of compressed nuclear matter and the search for “abnormal” states of matter, such as pion condensed matter or Lee–Wick matter [18,19]. These experiments discovered a number of collective phenomena [20], such as hydrodynamic flow, that are still being studied today. Exploratory experiments in the highly relativistic regime, initially carried out with rather small nuclei, began at the Brookhaven AGS and the CERN SPS accelerator in 1986. These experiments confirmed that a significant amount of energy is being deposited at mid-rapidity. It was also found that the observed particle yields are well described by the Hagedorn inspired hadron resonance model [21,22]. There were already some surprises, such as an unexpected enhancement of low mass lepton pairs [23].

The availability of Pb beams at the SPS, and the beginning of the collider era at the dedicated Relativistic Heavy Ion Collider (RHIC) at Brookhaven, mark the beginning of the current era in relativistic heavy ion physics. A wealth of phenomena were discovered, many of them surprising. At CERN this includes the observation of anomalous J/ψ suppression [24], the enhanced, compared to pp collisions, production of strange hadrons [25], as well as a low-mass enhancement coupled with the disappearance of the rho-peak in dilepton measurements [26].

The central discoveries at RHIC are the observation of a large azimuthal asymmetry, known as elliptic flow v_2, in the particle yields [27], as well as a strong suppression of high energy jets and heavy quarks [28]. The observed elliptic flow was consistent with predictions from ideal hydrodynamics, which was puzzling, since one expected to find a weakly interacting quark–gluon plasma, which should not exhibit fluid dynamic behavior. Further analysis of this effect, together with the large opacity of the QGP implied by the jet quenching data, forced a paradigm shift. In particular, it was argued that, instead of the originally anticipated weakly coupled system of quarks and gluons, the experiments had discovered a strongly interacting quark–gluon plasma (sQGP) [29–32].

These experimental advances were accompanied by important theoretical developments and breakthroughs. For example it was realized that by using methods developed in string theory, the holographic duality between gravitational theories in warped higher dimensional space–time and gauge theories in flat space on its boundary, one could study certain strongly interacting theories [33]. Using these techniques it was shown that theories that can be realized using holographic dualities saturate a lower bound on the shear viscosity over entropy density ratio [34]. In addition, inspired by the RHIC data,