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Ultrarelativistic heavy ion collisions: the first billion seconds

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Abstract

I first review the early history of the ultrarelativistic heavy ion program, starting with the 1974 Bear Mountain Workshop, and the 1983 Aurora meeting of the U.S. Nuclear Science Committtee, just one billion seconds ago, which laid out the initial science goals of an ultrarelativistic collider. The primary goal, to discover the properties of nuclear matter at the highest energy densities, included finding new states of matter – the quark-gluon plasma primarily – and to use collisions to open a new window on related problems of matter in cosmology, neutron stars, supernovae, and elsewhere. To bring out how the study of heavy ions and hot, dense matter in QCD has been fulfilling these goals, I concentrate on a few topics, the phase diagram of matter in QCD, and connections of heavy ion physics to cold atoms, cosmology, and neutron stars.

Keywords: Ultrarelativistic heavy ion collisions, QCD phase diagram of dense matter, ultracold atoms, neutron stars

1. Introduction

Serious planning for the first ultrarelativistic heavy ion collider, RHIC, began in the summer of 1983, just about 10^9 seconds before the QM2015 conference, whence the title of this talk. I would like first to review the early history of the ultrarelativistic heavy ion program, to ask what we had in mind when planning and building RHIC, and incorporating heavy ions collisions into the LHC; what were the scientific motivations; and to what extent have we shed light on the scientific issues and succeeded in fulfilling the promises of the program. Much of this history was documented in the talk I prepared for the Quark Matter conference at Stony Brook in 2001 [1], so I will briefly recap the significant developments. Since a non-trivial part of the justification for the program was its promise of making connections with other fields of physics, I would like also to touch on connections that have and are still being made.

The early 1974 Workshop at Bear Mountain, just north of New York City, on *BeV/nucleon collisions of heavy ions,* was a pivotal event in the conception of heavy ion physics [2], since after this workshop physicists began to take seriously the possibility of using heavy ion collisions as a tool to study the properties of matter under extreme conditions of high energy and baryon densities, to ask whether was there a "nuclear world quite different from the one we have learned to accept as familiar and stable?" After some three decades of experiment which have successfully seen and continue to explore this *terra incognita*. we can answer this question very positively. The question asked by T. D. Lee at the meeting – could one see the restoration of broken symmetries, and create abnormal states of nuclear matter at high density in collisions – foreshadowed restoration of broken chiral symmetry at high densities, albeit in the context of nucleons rather than quarks.

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The Bear Mountain Workshop took place at the end of the period in which understanding of the basic structure of matter in terms of quarks was put on a firm footing, especially with the development of asymptotic freedom in 1973 [3]. Although quark matter was proposed as early as 1970 by Itoh in neutron stars and by Carruthers in 1973 [4], nuclear physicists at the time were more comfortable with hadronic based pictures of high densities, e.g., the Hagedorn resonance gas [5] and the Walecka model [6]. The first mention of a deconfinement transition in dense matter was by Collins and Perry [7], who suggested that matter is a "quark soup" at high densities, and then by Cabbibo and Parisi [8].

The 1970's saw considerable interest in developing facilities for heavy ion experiment among U.S., European, and Japanese physicists [9]. The Bevalac, which grew out of the Berkeley Bevatron, dates back to the early 1970's and was a principle training ground for subsequent European heavy ion research. The AGS fixed target program at Brookhaven (BNL) was conceived at the time of Bear Mountain, and initiated in Jan. 1983, first with ^{16}O beams, and then with Si and Au; experiments started in Oct. 1986 and dwindled down in the early 2000's after the start of RHIC physics. In addition, in the late 1970's the Institute for Nuclear Studies in Tokyo began developing the Numatron to accelerate ions as heavy as uranium up to energies of 1.3 GeV/A; unfortunately the machine was never approved for construction.

The first glimmer of RHIC traces back to the open meeting of the U.S. Nuclear Science Advisory Committee (NSAC)) held at Wells College in Aurora, N.Y. in July 1983, a meeting to help decide on the next major facility for nuclear physics in the U.S. On the first day of this meeting the U.S. high energy community, meeting independently in Washington, decided to abandon the Colliding Beam Accelerator (or Isabelle, named after accelerator physicist J. Blewett's sailboat) being built at Brookhaven (BNL) in favor of the 200 GeV per nucleon Desertron, or SSC, itself cancelled in 1993. This decision presented our NSAC subcommittee on extreme states of nuclear matter [16] with an irresistible opportunity to build a relativistic heavy ion collider in the forlorn CBA tunnel, an idea J.D. Bjorken had first proposed informally at Fermilab in March 1983. The committee's arguments, which I presented, met with wide acceptance in Aurora. A proposal on the table for a Variable Energy Nuclear Synchrotron, or VENUS, fixed target machine at LBL, with energy up to 20 GeV/A, was abandoned. Thus did RHIC enter the conceptual stage.

As we argued, the main goal for such a collider would be to discover the properties of extended nuclear matter at the highest densities. What are the gross features of its phase diagram, its equation of state and its entropy? What are its dynamical properties, its excitations, and collective modes? How does it transport conserved quantities – energy-momentum, baryons, etc.? How does it stop hadronic and quark projectiles, and how does it dissipate energy? How does it emit particles? A "frontier opportunity" would be "discovering new states of matter, including a quark-gluon plasma." Making a quark-gluon plasma was a goal, but not *the* goal. The 1983 NSAC Long Range Plan [17] later summarized the scientific questions as, "What is the nature of nuclear matter at energy densities comparable to those of the early universe?" "What are the new phenomena and physics associated with the simultaneous collision of hundreds of nucleons at relativistic energies?" It stressed that the most outstanding opportunity opened by an ultrarelativistic heavy ion collider is "the creation of extended regions of nuclear matter at energy densities beyond those ever created in the laboratory over volumes far exceeding those excited in elementary particle experiments and surpassed only in the early universe."

Promised connections to other fields included, as we noted in Aurora, using heavy ion collisions to learn about QCD – which at the time was still under the wing of high energy physics – to see the deconfinement transition and determine its order, to see chiral symmetry restoration, and as well to learn the behavior of QCD at large distances. Collisions, it was hoped, might tell us about matter in the deep interiors of neutron stars, the nature of nuclear matter in supernovae; the role of the QCD confinement transition in cosmology – e.g., possible production of black holes of order 0.01 solar masses in a first order phase transition – and give insights into cosmic ray physics. One would have a new arena to study many-body effects familiar in condensed matter, e.g, quasiparticles, broken symmetry states and their restoration.

Immediately after the Aurora meeting, BNL assembled a task force to set the design parameters of the new machine. The choice of maximum beam energy, 100 GeV/A, within the constraints of the tunnel design, was driven by Bjorken's suggestion of producing jets that would propagate through and thus probe the collision volume. The importance of being able to vary the beam energy as well as the projectiles, e.g., to run light projectiles on heavy targets (as is now being effectively employed), in order to see the onset of