Chapter 12
Begin of the Search for the Quark-Gluon Plasma

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Abstract LBL has been the cradle where relativistic heavy ion physics began, and where the Hagedorn Statistical Model was first connected to relativistic heavy ion physics. The early program of research at the Bevalac and its development into an international program at CERN, paying tribute to the seminal effort by Howel Pugh, is described.

12.1 The Beginning

Bevalac and ISR

By the early 1970s the Lawrence Berkeley Laboratory (LBL, now LBNL—Lawrence Berkeley National Laboratory) became the leading force in the nascent field of relativistic heavy ion physics, with the Bevalac providing beams of relativistic heavy ions for fixed target experiments. At that time very little was known about quark-gluon plasma. The word "quark" does not even appear in any document related to the Bevalac. Experimental interest was focused on ultra dense nuclear matter proposed by Lee and Wick and on the related possibility to create a pion condensate. Instead, abundant hot particle production was observed which entailed interest in Hagedorn's physics, see Chap. 13.

It was generally agreed that in the near future more energetic nuclear beams would be used in the search for new physics. Quarks soon came onto the menu of these new plans. The potential of relativistic heavy ion collisions became fully apparent and very important to the nuclear physics community. These collisions required at least ten times higher center of mass (CM) energy than was available at the Berkeley Bevalac, which at that time was the world's highest energy heavy ion machine. Several laboratories in the world showed interest in this program.

CERN had instrumental capability and interest at the time and became the first center of this new physics. At CERN, the synergy of nuclear physics and

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high-energy physics was a key factor in these rapid developments. This synergy was entirely absent in other places, where particle physics did not have the Hagedorian soft hadron physics tradition.

The path to the heavy ion physics program at CERN was, however, not easy.

In 1975, Howel Pugh (then at the University of Maryland) was advocating putting nuclear beams into the CERN Intersecting Storage Rings (ISR) to reach ten times the Bevalac CM energy, so that experiments could investigate the hypothetical quark deconfinement matter. The ISR, a proton-proton collider, could accelerate nuclear beams at about CM energy of 30 GeV per nucleon pair for light nuclei and about 12 GeV for the typical case of the heavier ones (Au, Pb, U).

The experimental program involving nuclear collisions at ISR was limited to alpha particles (^{4}He), not for lack of interest, see also Chap. 28, but because no appropriate heavy ion source was as yet available at CERN. Howel Pugh and James Symons of LBL became involved in the ^{4}He program. Results were, however, rather disappointing as also the experimental capabilities were limited, and, ^{4}He was simply too light a nucleus to demonstrate collective fireball-like effects at even the top ISR energy.

When the ISR was set to be closed in 1983, the future of the heavy ion program at CERN became uncertain. These early initiatives, however, in the end and with the help of the CERN DG Herwig Schopper (1981–1988), paved the way for a strong SPS Heavy Ion Program at CERN in the coming decades, see Chap. 29.

SPS and RHIC Programs Take Shape

In 1979 Howel Pugh arrived at LBL to assume the post of Bevalac Scientific Research Director. He was attracted by the unique physics opportunities of the Bevalac, with which he was familiar from regularly attending Bevalac Program Advisory Committee meetings in his capacity as an NSF official. He saw LBL as the best place to push the ultra-relativistic heavy ion physics program forward to higher collision energies.

The next years were marked by a vigorous development of several proposals at LBL, all meant to reach the higher energies required for the formation of quark-gluon plasma. They began to appear on the agendas of the various committees. Howel Pugh was the principal author of the VENUS (Variable Energy Nuclear Synchrotron) proposal, which envisioned a large synchrotron plus stretcher ring that would fill LBL's entire hillside. This facility was never built, but the VENUS proposal served as the prototype for the future RHIC collider concept.

The next development, also led by Howel Pugh, was the TEVALAC, a fixed target program which would increase the energy of the Bevalac. This idea followed somewhat similar proposals, which had been in discussion at CERN since 1973. Finally Howel turned his attention to the design of the "Mini-Collider", which would take the heavy ion beams from the Bevalac and collide them in a circular accelerator. In a way it was a stepping-stone for future projects at RHIC and LHC. If it had been funded, this “Mini-Collider” would have been the shortest path to the discovery of QGP.

During this period, CERN moved forward as well. The next step, after ISR, was establishing the heavy ion program to the SPS, a proton synchrotron that would provide nuclear beams at 20 GeV CM energy. In 1984 a heavy ion CERN high energy SPS scientific program was approved. External resources needed to be found to generate the required heavy ion beams and to realize the multi-purpose usage of PS-SPS synchrotron as both, LEP injector and heavy ion accelerator. GSI and LBL agreed to build a special heavy ion injector for the CERN synchrotron. LBL was to build the novel RFQ pre-accelerator. Howel Pugh was the driving force behind LBL participation in the SPS program.

At the same time, the availability of the half-built and abandoned ISABELLE *pp* collider civil structure at BNL generated a strong push for the development of a heavy ion collider there. This project replaced the heavy ion options considered at LBL. However, the decision to start with heavy ions afresh at BNL meant that one had to develop heavy ion beam transfer line to the AGS, train a new generation of experts, and carry out within this new environment the collider technology development of what ultimately became RHIC and its experiments. All this was going to take much precious time—gambling that SPS energy was too low to matter in the search for, and discovery of, the new phase of matter, quark-gluon plasma.

12.2 Quark-Gluon Plasma Discovered

New Instrumentation

Moving to the higher energies required not only new accelerators but also new, modern, high-capability detectors. Howel Pugh proposed using a time projection chamber electronic detector (TPC) and recognized that such modern detectors would make a large difference for the Bevalac experiments. A TPC for heavy collisions was a new and quite revolutionary concept at the time and many were skeptical that this could be done. It had the advantage of allowing a 3-dimensional analysis of complex heavy ion collisions.

Pugh with three LBL collaborators (G. Odyniec, G. Rai and P. Seidel) provided all the necessary calculations and simulations (“EOS: A Time Projection Chamber for the Study of nucleus-nucleus collisions at the Bevalac”, LBL-22314, UC-34C). He named this new detector EOS TPC (after Equation Of State, but also after the Greek goddess of the dawn). Working on this project was the most exhilarating experience available to a young physicist. We were astonished by the amount of “impossible” or “unsolvable” problems we encountered. They seemed like brick walls, but, in fact, they were only temporary. Under Howel’s direction we were able to overcome each of them.

EOS TPC was built in LBL under H. Wieman’s leadership, and installed in 1991 into the HISS magnet to be used in the Bevalac heavy ion program. It was a tremendous success and the credit goes to Howel Pugh's vision of the program necessary to pursue the physics of heavy ion collisions. The EOS TPC opened a totally new way of analyzing data and was a precursor for the future CERN SPS-NA49 TPC, BNL RHIC-STAR TPC and CERN LHC-ALICE TPC.

One can say that this contribution was the preeminent legacy of Howel Pugh in the field of relativistic heavy ion physics.

Experiments

The BNL-RHIC did not become operational for many years. In the interim, from 1986 to 1993, LBL teams worked at CERN SPS in the experiments NA35, NA36 and WA80. The initial success of these experiments catalyzed a wider group of new international CERN experiments. The earlier beams consisted of Oxygen (^{16}O) and Sulfur (^{32}S) nuclei, which are rather light. They were not massive enough to assure QGP formation and the CERN Heavy Ion Program needed to proceed to a mass 200 nuclei. An injector complex for Lead ions (^{208}Pb) was completed in 1994. For these beams a totally new TPC experiment, NA 49, based on the LBL experience with the EOS TPC, was built. There was also a highly developed spectrometer facility, the Ω-spectrometer that was readied to take data, see Chap. 15. CERN had a wide and diverse relativistic heavy ion physics program.

In the mid-1990s the early results from this successful program, including the NA35/49 experiment in which I participated, indicated most interesting changes in the energy dependence of hadron production, particularly hadrons containing strange quarks, in Pb+Pb collisions, see Chap. 11. Within the statistical model, which was extensively developed by Rolf Hagedorn and his collaborators, the observed changes could be interpreted as the onset of the deconfinement of the phase transition to the quark-gluon plasma state.

In a locally thermalized fireball of particles created in the collisions, the apparent temperature is related to the thermal motion of the particles and their collective expansion velocity. From the composition of hadrons resulting from the decay of the fireball, the temperature at which the transition takes place can be estimated to be below $T \simeq 1.8 \times 10^{12}\,\mathrm{K} = 155\,\mathrm{MeV}$, a value near to the limiting temperature, i.e. the temperature where hadronic matter dissolves into quark matter. Introduced earlier by Rolf Hagedorn, the limiting temperature following from the exponential slope of the mass spectrum is $T_{\mathrm{H}} \simeq 155$–$160\,\mathrm{MeV}$, see Chap. 21.

This observation of the QGP formation at SPS in strange particle production, see Chaps. 11 and 15, was followed by strong and irrefutable results confirming the quark-gluon plasma in heavy ion collisions at the higher RHIC energies, see Chap. 14, and the present day results at yet much higher energies at the LHC agree.