arXiv:nucl-th/0002042 16 Feb 2000

January 31, 2000

Evidence for a New State of Matter: An Assessment of the Results from the CERN Lead Beam Programme

Ulrich Heinz and Maurice Jacob
Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland

The year 1994 marked the beginning of the CERN lead beam programme. A beam of 33 TeV (or 160 GeV per nucleon) lead ions from the SPS now extends the CERN relativistic heavy ion programme, started in the mid eighties, to the heaviest naturally occurring nuclei. A run with lead beam of 40 GeV per nucleon in fall of 1999 complemented the program towards lower energies. Seven large experiments participate in the lead beam program, measuring many different aspects of lead-lead and lead-gold collision events: NA44, NA45/CERES, NA49, NA50, NA52/NEWMASS, WA97/NA57, and WA98. Some of these experiments use multipurpose detectors to measure simultaneously and correlate several of the more abundant observables. Others are dedicated experiments to detect rare signatures with high statistics. This coordinated effort using several complementing experiments has proven very successful. The present document summarizes the most important results from this program at the dawn of the RHIC era: soon the relativistic heavy ion collider at BNL will allow to study gold-gold collisions at 10 times higher collision energies.

Physicists have long thought that a new state of matter could be reached if the short range repulsive forces between nucleons could be overcome and if squeezed nucleons would merge into one another. Present theoretical ideas provide a more precise picture for this new state of matter: it should be a quark-gluon plasma (QGP), in which quarks and gluons, the fundamental constituents of matter, are no longer confined within the dimensions of the nucleon, but free to move around over a volume in which a high enough temperature and/or density prevails. This plasma also exhibits the so-called “chiral symmetry” which in normal nuclear matter is spontaneously broken, resulting in effective quark masses which are much larger than the actual masses. For the transition temperature to this new state, lattice QCD calculations give values between 140 and 180 MeV, corresponding to an energy density in the neighborhood of 1 GeV/fm^3, or seven times that of nuclear matter. Temperatures and energy densities above these values existed in the early universe during the first few microseconds after the Big Bang.

It has been expected that in high energy collisions between heavy nuclei sufficiently high energy densities could be reached such that this new state of matter would be formed. Quarks and gluons would then freely roam within the volume of the fireball created by the collision. The individual quark and gluon energies would be typical of a system at very high temperature (above 200 MeV) even if the system should not have enough time to fully thermalize. Positive identification of the quark-gluon plasma state in relativistic heavy ion collisions is, however, extremely difficult. If created, the QGP state would have only a very transient existence. Due to color confinement, a well-known property of strong interactions at low energies, single quarks and gluons cannot escape from the collision – they must always combine to color-neutral hadrons before being able to travel to the detector. This process is called “hadronization”. Thus, regardless of whether or not QGP is formed in the initial stage, the collision fireball later turns into a system of hadrons. In a head-on lead-lead collision at the SPS about 2500 particles are created (NA49) of which more than 99.9% are hadrons. Evidence for or against formation of an initial state of deconfined quarks and gluons at the SPS thus must be extracted from a careful and quantitative analysis of the observed final state.

A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.

The evidence for this new state of matter is based on a multitude of different observations. Many hadronic observables show a strong nonlinear dependence on the number of nucleons which participate in the collision. Models based on hadronic interaction mechanisms have consistently failed to simultaneously explain the wealth of accumulated data. On the other hand, the data exhibit many of the predicted signatures for a quark-gluon plasma. Even if a full characterization of the initial collision stage is presently not yet possible, the data provide strong evidence that it consists of deconfined quarks and gluons.

We emphasize that the evidence collected so far is “indirect” since it stems from the measurement of particles which have undergone significant reinteractions between the early collision stages and their final observation. Still, they retain enough memory of the initial quark-gluon state to provide evidence for its formation, like the grin of the Cheshire Cat in Alice in Wonderland which remains even after the cat has disappeared. It is expected that the present “proof by circumstantial evidence” for the existence of a quark-gluon plasma in high energy heavy ion collisions will be further substantiated by more direct measurements (e.g. electromagnetic signals which are emitted directly from the quarks in the QGP) which will become possible at the much higher collision energies and fireball temperatures provided by RHIC at Brookhaven and later the LHC at CERN.

In the following the most important experimental findings and their interpretation are described in more detail:

Hadrons are strongly interacting particles. In nuclear collisions, after being first created, they undergo many secondary interactions before escaping from the collision "fireball". When they are finally set free, the fireball volume has expanded by about a factor 30–50; this information can be extracted from two-particle correlations between identical hadrons by a method called "Bose-Einstein interferometry" (NA44, NA49, WA98). At this point, the relative abundances and momentum distributions of the hadrons still contain important memories of the dense early collision stage which can be extracted by a comprehensive analysis of the hadronic final state. More than 20 different hadron species, including a few small anti-nuclei (anti-deuteron, anti-helium), have been measured by the seven experiments (NA44, NA45, NA49, NA50, NA52, WA97, WA98). A combined analysis of their momentum distributions and two-particle correlations shows that, at the point where they stop interacting and "freeze out", the fireball is in a state of tremendous explosion, with expansion velocities exceeding half the speed of light, and very close to local thermal equilibrium at a temperature of about 100-120 MeV. This characteristic feature gave rise to the name "Little Bang". The observed explosion calls for strong pressure in the earlier collision stages. Recently measured anisotropies in the angular distribution of the momenta perpendicular to the beam direction (NA49, NA45, WA98) indicate that the pressure was built up quickly, pointing to intense rescattering in the early collision stages.

An earlier glimpse of the expanding system is provided by a measurement of correlated electron-positron pairs, also called dileptons (NA45). These data show that in sulphur-gold and lead-gold collisions the expected peak from the rho (ρ) vector meson (a particle which can decay into dileptons even before freeze-out) is completely smeared out. Simultaneously, NA45 finds in lead-gold collisions an excess of dileptons in the mass region between 250 and 700 MeV, by about a factor 3 above expectations from hadron decays scaled from proton-nucleon to lead-gold collisions. Theory explains this by a broadening of the ρ's spectral function, resulting from scattering among pions and nucleons in a very dense hadronic fireball, just below the critical energy density for quark-gluon plasma formation. The ρ meson mixes with its partner under chiral symmetry transformations, signalling the onset of chiral symmetry restoration as matter becomes denser and denser.

The theoretical analysis of the measured hadron abundances (NA44, NA45, NA49, NA50, NA52, WA97, WA98) shows that they reflect a state of "chemical equilibrium" at a temperature of about 170 MeV. This points to an even earlier stage of the collision. In fact, such temperatures (corresponding to an energy density of about 1 GeV/fm^3) are the highest allowed ones before, according to lattice QCD, hadrons should dissolve into quarks and gluons. The observations are explained by assuming that at this temperature the hadrons were formed by a statistical hadronization process from a pre-existing quark-gluon system. Theoretical studies showed that at CERN energies subsequent interactions among the hadrons, while causing pressure and driving the expansion and cooling of the fireball, are very ineffective in changing the abundance ratios. This is why, after accounting for the decay of unstable resonances, the finally measured hadron yields reflects rather accurately the conditions at the quark-hadron transition.

A particularly striking aspect of this apparent “chemical equilibrium” at the quark-hadron transition temperature is the observed enhancement, relative to proton-induced collisions, of hadrons containing strange quarks. Globally, when normalized to the number of participating nucleons, this enhancement corresponds to a factor 2 (NA49), but hadrons containing more than one strange quark are enhanced much more strongly (WA97, NA49, NA50), up to a factor 15 for the Omega (Ω) hyperon and its antiparticle (WA97)! Lead-lead collisions are thus qualitatively different from a superposition of independent nucleon-nucleon collisions. That the relative enhancement is found to *increase* with the strange quark content of the produced hadrons contradicts predictions from hadronic rescattering models where secondary production of multi-strange (anti)baryons is hindered by high mass thresholds and low cross sections. Since the hadron abundances appear to be frozen in at the point of hadron formation, this enhancement signals a new and faster strangeness-producing process *before or during* hadronization, involving intense rescattering among quarks and gluons. This effect was predicted about 20 years ago as a quark-gluon plasma signature, resulting from a combination of large gluon densities and a small strange quark mass in this color deconfined, chirally symmetric state. Experimentally it is found not only in lead-lead collisions, but even in central sulphur-nucleus collisions, with target nuclei ranging from sulphur to lead (NA35, WA85, WA94). This is consistent with estimates of initial energy densities above the critical value of 1 GeV/fm^3 even in those collisions.

Evidence for the formation of a transient quark-gluon phase without color confinement is further provided by the observed suppression of the charmonium states J/ψ, χ_c, and ψ' (NA50). These particles contain charmed quarks and antiquarks (c and $\bar{c}$) which are so heavy that they can only be produced at the very beginning when the constituents of the colliding nuclei still have their full energy. As one varies the size of the colliding nuclei and the centrality of the collision one finds, after subtracting the expected absorption effects from final state interactions between the $c\bar{c}$ pair and the nucleons of the interpenetrating nuclei, a succession of suppression patterns: The most weakly bound state, ψ', is suppressed already in sulphur-uranium collisions (NA38), the intermediate χ_c seems to disappear quite suddenly in semi-central lead-lead collisions, and in the most central lead-lead collisions an additional reduction of the J/ψ yield indicates that now also the strongly bound J/ψ ground state itself is significantly suppressed (NA50). The observation of χ_c suppression is indirect, via its 30-40% contribution to the measured J/ψ yield which is expected from scaling proton-proton measurements. Charmonium suppression was predicted 15 years ago as a consequence of color screening in a quark-gluon plasma which should keep the charmed quark-antiquark pairs from binding to each other. According to this prediction, suppressing the J/ψ requires temperatures which are about 30% above the color deconfinement temperature, or energy densities of about 3 GeV/fm^3. This agrees with estimates of the initial energy densities reached in central lead-lead collisions, based on calorimetry or on a back-extrapolation from the freeze-out stage to the timei before expansion started. It was tried to reproduce the data by assuming that the charmonia are destroyed solely by final state interactions with surrounding hadrons; none of these attempts can account for the shape of the centrality dependence of the observed suppression. On the other hand, the interpretation of this pattern in terms of color screening by deconfined quarks and gluons leads to the prediction of a similar suppression pattern at RHIC in much smaller nuclei; this prediction will soon be tested.

In spite of its many facets the resulting picture is simple: the two colliding nuclei deposit energy into the reaction zone which materializes in the form of quarks and gluons which strongly interact with each other. This early, very dense state (energy density about 3–4 GeV/fm^3, mean particle momenta corresponding to $T \approx 240$ MeV) suppresses the formation of charmonia, enhances strangeness and begins to drive the expansion of the fireball. Subsequently, the "plasma" cools down and becomes more dilute. At an energy density of 1 GeV/fm^3 ($T \approx 170$ MeV) the quarks and gluons hadronize and the final hadron abundances are fixed. At an energy density of order 50 MeV/fm^3 ($T = 100$–120 MeV) the hadrons stop interacting, and the fireball freezes out. At this point it expands with more than half the light velocity.

This does not happen only in a few "special" collision events, but essentially in *every* lead-lead collision: characteristic observables, like the average transverse momentum of produced particles or the kaon/pion ratio, show only the statistically expected fluctuations in a thermalized ensemble, around average values which are the same in all collisions (NA49). Since the kaon/pion ratio is essentially fixed at the point of hadronization, this indicates the absence of long-range correlations like those expected in a fully-developed thermodynamic phase transition. A better theoretical understanding of the phase-transition dynamics might emerge from these observations. The short-range character suggests similarities with the transition found in high-T_c superconductivity.

"Direct" observation of the quark-gluon plasma may be possible via electromagnetic radiation emitted by the quarks during the hot initial stage. Searches for this radiation were performed at the SPS (WA98, NA45, NA50) but are difficult due to high backgrounds from other sources. For sulphur-gold collisions WA80 and NA45 established that not more than 5% of the observed photons are emitted directly. For lead-lead collisions WA98 have reported indications for a significant direct photon contribution. Preliminary data from NA45 are consistent with this finding, but so far not statistically significant. NA50 has seen an excess by about a factor 2 in the dimuon spectrum in the mass region between the ϕ and J/ψ vector mesons. The predicted electromagnetic radiation rates at the above mentioned temperatures are marginal for detection. While under these conditions it is a great experimental achievement to have obtained positive evidence for a signal, its connection with the predicted "thermal plasma radiation" is not yet firmly established.

This is expected to change at the higher collision energies provided by RHIC and

LHC. The much higher initial temperatures (up to nearly 1000 MeV for lead-lead collisions at the LHC have been predicted) and longer plasma lifetimes should facilitate the direct observation of the plasma radiation and lead to the production of additional heavy charm quarks by gluon-gluon scattering in the QGP phase. The much higher initial energy densities which can be reached at RHIC and LHC give us more time until the quarks and gluons rehadronize, thus allowing for a quantitative characterization of the quark-gluon plasma and detailed studies of its early tharmalization processes and dynamical evolution. Finally, the higher collision energies allow for the production of jets with large transverse momenta, whose leading quarks can be used as "hard penetrating probes" within the quark-gluon plasma. At RHIC a set of four large detectors, with complementary goals and capabilities, ensures that all experimental aspects of ultrarelativistic heavy ion collisions are optimally covered. The ability of the collider to simultaneously accelerate and collide nuclei of different sizes and energies promises a complete understanding of systematic trends as one proceeds from proton-proton via proton-nucleus to gold-gold collisions. As in solid state physics, where the knowledge of the basic interaction Lagrangian (QED) does not permit to reliably predict many bulk properties and where the detailed understanding of the latter is usually driven by experiment, we expect that such a systematic experimental study of strongly interacting matter will eventually lead to a quantitative understanding of "bulk QCD". We are looking forward to these far-reaching opportunities provided by RHIC and LHC.

Key references to the experimental data:

NA44 Collaboration:

H. Beker et al., "M_T-dependence of boson interferometry in heavy ion collisions at the CERN SPS", Physical Review Letters **74** (1995) 3340-3343

I.G. Bearden et al., "Collective expansion in high-energy heavy ion collisions", Physical Review Letters **78** (1997) 2080-2083

I.G. Bearden et al., "Strange meson enhancement in Pb-Pb collisions", Physics Letters B **471** (1999) 6-12

NA45/CERES Collaboration:

G. Agakichiev et al., "Low-mass e^+e^- pair production in 158 A GeV Pb-Au collisions at the CERN SPS, its dependence on multiplicity and transverse momentum", Physics Letters B **422** (1998) 405-412

B. Lenkeit et al., "New results on low-mass lepton pair production in Pb-Au collisions at 158 GeV/c per nucleon", Nuclear Physics A **654** (1999) 627c-630c

B. Lenkeit et al., "Recent results from Pb-Au collisions at 158 GeV/c per nucleon obtained with the CERES spectrometer", Nuclear Physics A **661** (1999) 23c-32c

NA49 Collaboration:

T. Alber et al., "Transverse energy production in ^{208}Pb+Pb collisions at 158 GeV per nucleon", Physical Review Letters **75** (1995) 3814-3817

H. Appelshäuser et al., “Hadronic expansion dynamics in central Pb+Pb collisions at 158 GeV per nucleon”, European Physical Journal C **2** (1998) 661-670

F. Sikler et al., “Hadron production in nuclear collisions from the NA49 experiment at 158 GeV/$c \cdot A$”, Nuclear Physics A **661** (1999) 45c-54c

NA50 Collaboration:

M.C. Abreu et al., “Anomalous J/ψ suppression in Pb-Pb interactions at 158 GeV/c per nucleon”, Physics Letters B **410** (1997) 337-343

M.C. Abreu et al., “Observation of a threshold effect in the anomalous J/ψ suppression”, Physics Letters B **450** (1999) 456-466

M.C. Abreu et al., “Evidence for deconfinement of quarks and gluons from the J/ψ suppression pattern measured in Pb-Pb collisions at the CERN-SPS”, CERN-EP-2000-013, submitted to Physics Letters B

NA52/NEWMASS Collaboration:

R. Klingenberg et al., “Strangelet search and antinuclei production studies in Pb+Pb collisions”, Nuclear Physics A **610** (1996) 306c-316c

G. Ambrosini et al., “Baryon and antibaryon production in Pb-Pb collisions at 158 A GeV/c”, Physics Letters B **417** (1998) 202-210

G. Ambrosini et al., “Impact parameter dependence of $K^{\pm}, p, \overline{p}, d$ and $\overline{d}$ production in fixed target Pb + Pb collisions at 158 GeV per nucleon”, New Journal of Physics **1** (1999) 22.1-22.23

WA97/NA57 Collaborations:

E. Andersen et al., “Strangeness enhancement at mid-rapidity in Pb-Pb collisions at 158 A GeV/c”, Physics Letters B **449** (1999) 401-406

F. Antinori et al., “Production of strange and multistrange hadrons in nucleus-nucleus collisions at the SPS”, Nuclear Physics A **661** (1999) 130c-139c

F. Antinori et al., “Transverse mass spectra of strange and multistrange particles in Pb-Pb collisions at 158 A GeV/c”, CERN-EP-2000-001, submitted to European Physical Journal C

WA98 Collaboration:

R. Albrecht et al., “Limits on the production of direct photons in 200 A GeV ^{32}S+Au collisions”, Physical Review Letters **76** (1996) 3506-3509

M.M. Aggarwal et al., “Centrality dependence of neutral pion production in 158 A GeV ^{208}Pb+^{208}Pb collisions, Physical Review Letters **81** (1998) 4087-4091; **84** (2000) 578-579(E)

M.M. Aggarwal et al., “Freeze-out parameters in central 158 A GeV ^{208}Pb+^{208}Pb collisions”, Physical Review Letters **83** (1999) 926-930