Experiments with Lead Projectiles of 33 TeV Total Energy at the CERN SPS

1. The scientific goal: creating an extended "quark-gluon- plasma" state of strongly interacting matter

Our current understanding of the strong interaction, one of the four basic forces of nature, is based on Quantum Chromodynamics (QCD). This theory describes how quarks interact by exchanging gluons, and helps to describe the structures of bound aggregates of two or three quarks that we call hadrons (pions, kaons, protons, neutrons ...) which are held together by the strong force. QCD is designed in analogy to the well proven theory of elementary electromagnetic interactions: quantum electrodynamics (QED). This theory describes how ordinary charged particles interact by exchanging photons, thus explaining the corresponding bound aggregates which range from atoms and molecules to extended solid materials, and are held together by the electromagnetic force. Our familiar, cold world consists of such objects, with basic QED structure. An interesting further realm of QED structures, beyond cold objects, is presented by the electromagnetic plasma states governing stellar interiors at high energy density. With increasing temperature, the medium becomes more and more ionized: electrons lose their binding to individual atoms or molecules. In the extreme case, of a white dwarf burned-out star, the electrons completely decouple from the atomic nuclei forming a continuous Fermi liquid. The properties of white dwarfs are governed by this electron plasma which is a perfect conductor even though the initial constituents of the star were perfectly neutral atoms. In modern terminology, the electrons are completely **deconfined** in this plasma from their low temperature atomic bound states.

It is one of the remaining open problems of strong interaction QCD to clarify whether the formal analogy between QED and QCD, proven to exist as far as the corresponding cold objects (atoms and hadrons) are concerned, extends to finite temperature behaviour. Does a deconfined (colour conducting) continuous QCD plasma state exist? This is not merely a formality - assessing behaviour fully analogous to QED would satisfy the desire to show that such gauge theories are, universally, the last word concerning the fundamental interactions. Additional emphasis is placed on the demonstration of plasma existence, stemming from two further considerations:

a) Whereas deconfinement of electrons in a QED plasma is based on well understood ionization processes, the confinement-deconfinement phenomena of colour carrying objects (quarks and gluons) are not well understood in current QCD. Ionizing a neutral atom results in a free electron that moves away into the vacuum unrestricted. The analogous ionization reaction of a colour-carrying quark from its colour neutral hadron bound state into the vacuum does not exist. Individual colour carrying objects exhibit a "horror vacui" and, thus, do not quite conform to our naive expectations concerning elementary particles, the expectation being that they can be set "free" in vacuum, like photons, electrons, neutrinos. The deconfinement process of quarks can only take place in a medium of extremely high energy density which is already full, by definition, of other virtual coloured objects, i.e. quark- antiquark pairs and gluons. Such medium could not be created until now, so we do not know whether it really exists.

b) However, during the very early stages of cosmological expansion, standard astrophysics theory insists that a deconfined plasma must have existed. It is of prime importance for big bang dynamics to know the critical energy density, the specific heat, temperature etc. of the plasma. Upon expansion cooling it should have decayed in a phase transition to a confinement situation: our familiar protons and neutrons, or hadrons, in general, of which matter consists since that early big bang time. This occurred after a few microseconds since the initial cosmic bang. Can we recreate this phase transition?

In the terrestrial laboratory the only conceivable avenue toward creating a volume of sufficient size, energy density and life time could be to bombard heavy nuclei head-on at ultra-relativistic energy. This violent collision might create, for a short instant of time, a "fireball" reaction volume that allows to generate the plasma state . To this end, Lead nuclei (^{208}Pb) are accelerated at CERN since 1994 to an energy of 158 GeV per nucleon in the projectile, i.e. to about 33 TeV total energy. This involved a newly built special injector accelerator along with the synchrotron-chain BOOSTER, PS, SPS. At the Brookhaven AGS, similarly heavy Gold projectiles are available since 1993 but it is the special point of the ten times higher CERN energy that one can be confident here (based on former experiments with lighter nuclear projectiles) to reach the necessary energy density, of several GeV per cubic fermi of reaction volume, where we expect from QCD to create a plasma.

2. Signals of Plasma Formation in Pb-Pb Collisions

How do we imagine the dynamical evolution of a high energy, head-on collision of heavy nuclei? In the centre of mass frame, two Lorenz-contracted discs filled with nucleons interpenetrate. In the initial phase of microscopic nucleon collisions, these QCD bound states (of three valence quarks, virtual "sea" quark-antiquark pairs, and gluons) get disrupted and spread out over phase space. These processes create a pre-equilibrium state of partons which still possess a preferential momentum orientation along the beam direction. Partonic rescattering will, in the next stage, bring the reaction volume closer to a thermal distribution, with an approximate equipartition of momentum orientation, and also approaching a flavour equipartition among the three light quark species, up, down and strange. The energy density being high enough, this state may settle into the equilibrium plasma state of quarks and gluons which is the desired object: a deconfined, continuous QCD high temperature state, if this state really exists! At an energy density of several GeV per cubic fermi, this phase will expand and cool until the phase transition point is reached where the partons recombine into hadrons. It would be nice now to see all newly born hadrons going directly into the detector from the phase transition point. However, nature has put an obstacle into the way of such a direct observation of the phase transition products: the spatial hadron density is very high still, the new hadrons will keep interacting until further expansion dilution finally sets them free to escape into empty space. The interesting parts of this overall evolution, i.e. the passage from a hypothetical plasma state to its characteristic phase transition into hadrons, is thus shrouded both by a preceding incomprehensible pre-equilibrium partonic phase, and by a subsequent hadronic rescattering phase. A decade of intense theoretical work has been devoted to the question of how to define suitable observable features that might pin down the transient plasma, and its phase transition by hadronization. Two major avenues of experimental approach have emerged:

a) Look at observables that get established during the initial phase (partonic pre- equilibrium to hypothetical plasma state). The intuitively most straight-forward observable would consist in the intense photon "black body" emission from the hot plasma state. Photons would escape from the fireball without significant rescattering from the developing high density hadron phase. Likewise, the thermal plasma state should radiate lepton pairs which also encounter no strong interaction with the hadronic fireball. A further, more intricate signal of early evolution is contained in the production rate of the charmed mesons J/Ψ and $\Psi^{'}$. At the relatively low energy of SPS-Pb+Pb collisions, such bound states of a charm-anti-charm $c\bar{c}$ quark-antiquark pair can be only created during the initial phase, of microscopic nucleon-nucleon collisions at beam energy. Later on, as the system spreads out in momentum space, the production rates of such mesons fall off dramatically. Thus, if the reaction volume passed through a plasma phase, the initially created, emerging Ψ and $\Psi^{'}$ states would get dissolved in the plasma, along with all other initial hadronic states. A suppression of final J/Ψ and Ψ' yields would result. We thus expect to see production of enhanced photon and dilepton yields, along with suppression of charmonium meson production.

b) Look at the hadrons produced in the secondary phase of dynamics: from plasma to hadronization to final hadron emission. Theory suggests that the relative production rates of various hadronic species (from pions to kaons, antiprotons, Omegas etc.) should preserve a memory, retaining the characteristics of the "parent" plasma phase. In particular, strange quark-antiquark pairs should be preferentially produced in the plasma phase which, ideally, approaches equipartition among the initial up/down quarks and newly created strange quarks. This enhanced strangeness content of the collision volume should survive hadronic rescattering because strange quarks decay by long life-time, weak interaction processes only. Furthermore, a reaction volume of high strangeness content may emit "strangelets", i.e. hadronic states of unusual flavour composition. The concept arises of a "hadronic thermometer": measure all the yields and yield ratios of hadronic species from the light pions up to the heavy, strange Omega hyperons. This set of data then fixes the temperature and energy density prevailing at the birthplace of the hadronic population. From our above arguments, the hadrons emerge from the hadronization phase of the quark-gluon population in the fireball - just like in the gigantic Big Bang fireball. The mini-bang would thus fix the critical parameters (T_c

the critical temperature, and ϵ_c the critical energy density) of the QCD phase transition between partons (quarks and gluons) and hadrons.

This hadron thermometer idea resembles the experience with our air that are commonplace to us: at room temperature the air consists mostly of molecular O_2 and H_2 with very little monoatomic O and N. The population ratios $[O]:[O_2]$ and $[N]:[N_2]$ are similar thermometer variables: they increase with the energy density or temperature. At the SPS we use the $[K]:[\pi]$ or the $[\Omega]:[\pi]$ ratios, instead.

A further analogy to commonplace classical physics is employed by the hadron spectrometers to gain information about the nature of the parton-hadron phase transformation (is it first or second order, does it involve a large latent heat jump, etc.). In explosives one distinguishes different types of phase transition, deflagration, detonation etc., by the patterns in which they emit the explosion gases into space - either uniformly or in "blast waves" or in directed shock fronts. The QCD analogies of such emission patterns are looked at in so-called 4π hadron spectrometers which cover simultaneously all directions of hadron emission from the fireball to pin down the complete picture of the explosive phase transition. It consists of the individual trajectories of several thousand emitted hadrons: a formidable instrumental task.

3. The Lead-Beam Experiments at CERN

The Lead (^{208}Pb) SPS beam facility is in operation since 1994. No single, universal experiment could be constructed with state of the art detector technology that would cover all of the potential signals of plasma creation, enumerated above. For example, the detection of photons and of J/Ψ mesons each require a highly specialized experiment technique and layout, preventing simultaneous observation of pion correlation or strange particle production because the corresponding instrumentation would be, logically and topographically, in the way of the instrumentation required for the former observables. This feature of mutually contradictory optimal layouts is characteristic of all such "fixed target" experiments, conducted with extracted synchrotron beams hitting a stationary target. We note in passing that universal, comprehensive experiments can be constructed with considerably higher compatibility at colliding beam facilities such as RHIC at BNL (starting up in 2000) and LHC at

CERN (planned for 2005).

It is, therefore, not surprising to see seven major experiments (and a multitude of smaller experiments employing nuclear emulsion track recording techniques) devoted to investigate the various physics quantities, of interest in the analysis of ultra-relativistic Lead on Lead-collisions. These major experiments are, at first sight, complementary to each other but they still provide for a certain overlap in their coverage of relevant observables, such that most of the expected results can be cross-chequed. Furthermore all experiments provide for instrumentation capable of selecting central, head-on collisions of Pb projectiles which obviously offer the most favourable conditions to create a high energy density "fireball". All experiments will thus report results referring to a common class of collision events.

For the sake of orientation of the outside observer a brief description follows of the major experiments. Note that the CERN code names for the experiments refer to the two major external beam systems of the SPS, the West Area (Meyrin) and the North Area (Prevessin). "NA49" thus refers to the 49th experiment conducted in the North Area since its construction in 1976, "WA98" indicating the 98th experiment conducted in the West Area. Note also that this numbering convention does not imply that of the order of 150 independent, newly constructed experiments have by now been conducted with external SPS beams. Many experiments were re-coded in the passage of time according to their stepwise evolution toward redefined physics goals. In line with such adaptation/recycling strategies of rejuvenating experimental gear toward new purposes, we encounter several key experiments in the Pb beam programme that have seen a previous trajectory in elementary particle physics, whereas other experiments were newly constructed specifically for nuclear beam physics.

NA44: Superconducting magnetic spectrometer identifying various hadrons, in particular pion and kaon pairs to investigate their Bose-Einstein correlation in momentum space (now disassembled).

NA45: Double-layer large acceptance Ring Imaging Cerenkov (RICH) detector system measuring electron-positron pair spectra to identify effects on hadron masses and decays due to emission from the plasma state, or the dense hadronic state right at the plasma-hadron transition.

NA49: Large acceptance multihadron magnetic spectrometer with four Time Projection Chambers (TPC), Time of Flight (TOF) and calorimetry identifying charged hadrons as well as neutral strange particles to investigate hadronic signals of plasma formation down to the level of single events, and do hadron "thermometry".

NA50: Magnetic spectrometer to measure $\mu^+\mu^-$ pairs, investigating the predicted Ψ, Ψ' suppression and analyzing muon pair spectra to identify emission from the plasma state.

NA52: High charge resolution magnetic, time of flight spectrometer measuring composite antinuclei and nuclei and searching for "strangelets" (hadrons containing more than 3 valence quarks and a high fraction of strange quarks).

WA97: Medium acceptance magnetic spectrometer with wire chambers and RICH counter containing a telescope of high granularity silicon pixel detectors, measuring strange baryons and antibaryons up to the Ω to look for the plasma effect on strangeness production rates (now NA57).

WA98: Large acceptance photon-hadron calorimeter/spectrometer with Pb-glass photon calorimeter, photon number detector, charged hadron tracking and time of flight, identifying direct photons, π^0, η and charged hadrons, investigating direct emission of plasma black body radiation, as well as hadronic observables (now disassembled).