DECONFINED MATTER CREATED AT CERN:

ANOMALOUS J/ψ SUPPRESSION OBSERVED BY EXPERIMENT NA50 *

The theory of strong interactions, Quantum Chromodynamics (QCD), predicts a phase transition from ordinary hadronic matter to a "deconfined" state of unbound quarks and gluons, the quark-gluon plasma (QGP). The QGP is the cosmological ancestor of usual nuclear matter. It filled the Universe at very early times, some microseconds after the Big Bang, before the birth of elementary particles.

Just as normal matter, the QGP is made of colored quarks and gluons, the well-known basic constituents described by QCD in the framework of the Standard Model. In the normal state of hadronic matter, these are bound to make mesons and baryons. When the density of such matter is increased more and more, the presence of many quarks and gluons very close to each other causes the binding potential to become weakened by screening. As a consequence, the quarks and gluons are liberated and in this *deconfined state of matter* are able to move freely like electrons in a conventional plasma.

The phase transition from hadronic matter to the QGP is predicted to occur for extreme temperatures and energy densities. Searching for experimental evidence for its existence, several groups of physicists have been looking since 1986 for possible indications from the very high density matter which is created in ultrarelativistic heavy ion collisions. Up to now, the most favorable experimental conditions were found at CERN; Brookhaven National Laboratory will take over when the new RHIC facility starts operation this year.

Getting clear and unambiguous experimental evidence for QGP formation is a difficult task. The main problem is that even if the QGP is produced in a laboratory experiment, it is an extremely short-lived state with a lifetime of some 10^{-23}s, which quickly turns back to normal matter through the inverse hadronization phase transition. Any characteristic signature will therefore be detectable only if it is present in the early phase and keeps its memory of the state at that time. In particular, it has to survive the hadronization transition without being wiped out by subsequent strong interactions. For that reason, heavy hadrons produced in the early stages of the collision can be considered as the most sensitive probes for experimental QGP identification [1].

Fourteen years ago, in 1986, T. Matsui and H. Satz predicted that J/ψ production would be suppressed if QGP was formed [2]. Their argument was that the initially formed $c\bar{c}$ pair, a charm quark and its antiquark, would in a QGP medium be unable to form a J/ψ resonance because of the screening of the confining potential.

Some months later, the experiment NA38 started at CERN an extensive experimental program studying charmonium production on different targets with incident 450 GeV/c protons, and with the newly available oxygen and sulphur ions accelerated to 200 GeV per nucleon. The apparatus was able to detect, with a special 18 meters long spectrometer, the muon pairs produced by interactions of an incident beam on a fixed target and to identify their physical origin: these pairs could originate from a J/ψ decaying into two muons or from quark-antiquark annihilation into dileptons, known as Drell-Yan production. The detector was also able to measure, on an event by event basis, the transverse energy produced in the reaction; this provides an estimate of the centrality of the interaction, which in turn determines the energy density of the collision.

This set of measurements shows that the resulting J/ψ production suffers normal absorption by nuclear matter along its path through the interacting nuclei. Such nuclear absorption leads to a well-known smoothly increasing suppression determined by comparing J/ψ production in proton-proton collisions with that in proton-nucleus interactions, far away from any possible conditions for QGP formation. This "normal suppression" agrees perfectly with the experimental results over the whole range from proton-proton collisions to the most central sulphur-uranium reactions in which conditions could in principle be close to those required for QGP production.

In 1994, after several years of technical efforts and construction, CERN accelerated Pb ion beams up to 158 GeV per nucleon. For the first time, really heavy ions could be used with an overall energy of more than 3 TeV available to heat and compress the interaction volume. Conditions to form a QGP were now much better than with lighter ions like sulphur, because of the much larger volumes and numbers of participating nucleons involved. These features favour thermalization of the medium and increase the lifetime of a possible QGP.

Experiment NA38 was upgraded to cope with the high radiation levels and multiplicities induced by Pb-Pb reactions. The detector of this new experiment, renamed NA50, was carefully tuned and fully understood during the data taking period of 1994. The first preliminary results, based on the data collected in 1995, were reported in March 1996 at the "Rencontres de Moriond". A more elaborate version was presented at the end of May at the International Quark Matter Conference 1996 in Heidelberg. The results show that the reference measurement, Drell-Yan events, are produced according to their normal expected rate from proton-proton up to Pb-Pb reactions. On the other hand, the production of the J/ψ resonance in Pb-Pb reactions was quite a surprise. In the most peripheral collisions, the J/ψ is produced normally, in accord with the nuclear absorption already observed with protons on nuclei and with lighter ions beams. But when the centrality increases, the J/ψ production was in clear disagreement with this normal behaviour. It became significantly lower and, for the most central interactions, it amounted to only one half of the value expected from the extrapolation of normal nuclear suppression. This "anomalous J/ψ suppression" [3] was confirmed with much higher accuracy by a new set of data collected in 1996. The new results [4] show moreover that the anomalous suppression only appears for impact parameter values lower than 8 fm, corresponding to an energy density higher than 2.2 GeV/fm^3. Finally, the most recent results [5] of a specific study based on data collected in 1998 prove without ambiguity that the deviation from normal nuclear absorption increases with decreasing impact parameter, a crucial feature for the interpretation of the physics underlying the experimental observations.

Figure 1 summarizes the experimental results. It shows the detailed pattern of the anomalous J/ψ suppression observed from measurements on Pb-Pb interactions. It also shows the normal suppression pattern as deduced from similar studies of experiment NA38 on collisions with lighter incident ions. The results strongly suggest that there is an onset of a new physical process for energy densities higher than 2.2 GeV/fm^3. On one hand, the J/ψ production rate exhibits a sudden departure from the nuclear absorption regime and on the other hand, the deviation from this regime increases steadily with increasing energy density. These two features are incompatible with explanations based on conventional hadronic physics mechanisms, as can be seen in Fig. 2. They can be naturally understood in the framework of charmonia melting due to QGP production, where a stepwise pattern is expected: the fingerprint of deconfinement predicted fourteen years ago by Matsui and Satz has finally been observed.

References

[1] An introduction to colour deconfinement and the use of charmonium production as a probe can be found in "Colour deconfinement in hot and dense matter". Talk given by H. Satz at CRIS'96. CRIS'96 Proceedings, Preprint CERN-TH/96-172 or hep-ph/9611366.

[2] J/ψ suppression by quark-gluon plasma formation.
T. Matsui and H. Satz, Phys. Lett. 178 B (1986) 416.

[3] Anomalous J/ψ suppression in Pb-Pb interactions at 158 GeV/c per nucleon.
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[4] Observation of a threshold effect in the anomalous J/ψ suppression.
Phys. Lett. B450 (1999) 456.

[5] Evidence for deconfinement of quarks and gluons at the CERN SPS.
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* More information on the NA50 experiment can be found on the Web site **www.cern.ch/NA50/**

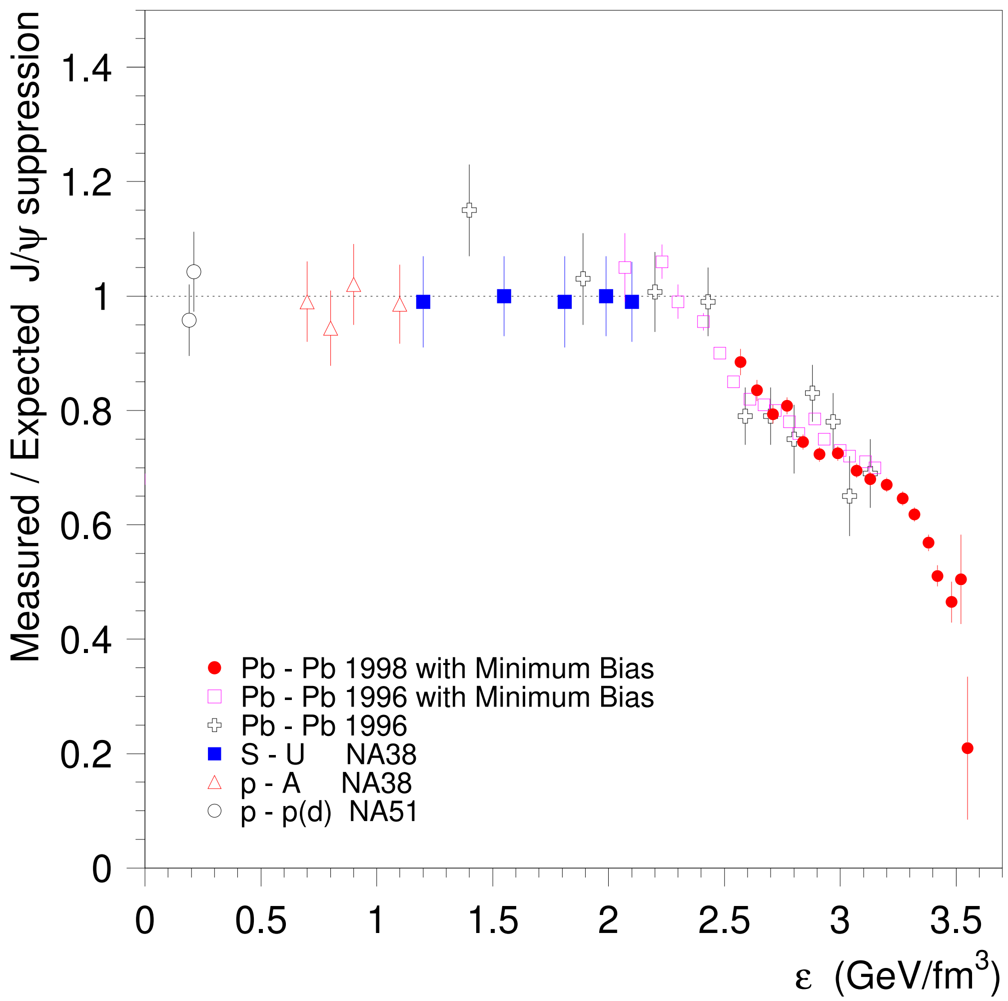

Figure 1: The J/ψ anomalous suppression as a function of the energy density reached in the collision. Suppression is obtained from the measured cross-sections divided by the values expected from nuclear absorption. The latter are deduced from a fit to measurements on interactions of incident protons with various targets (open circles and triangles) and on S-U collisions (closed black squares). As can be seen from the figure, in Pb-Pb interactions J/ψ is suppressed normally, i.e. according to pure nuclear absorption, for energy densities lower than $2.2\,\mathrm{GeV/fm^3}$. For higher density values, a peculiar abnormal suppression pattern is observed, as can be expected from charmonium melting due to deconfinement.

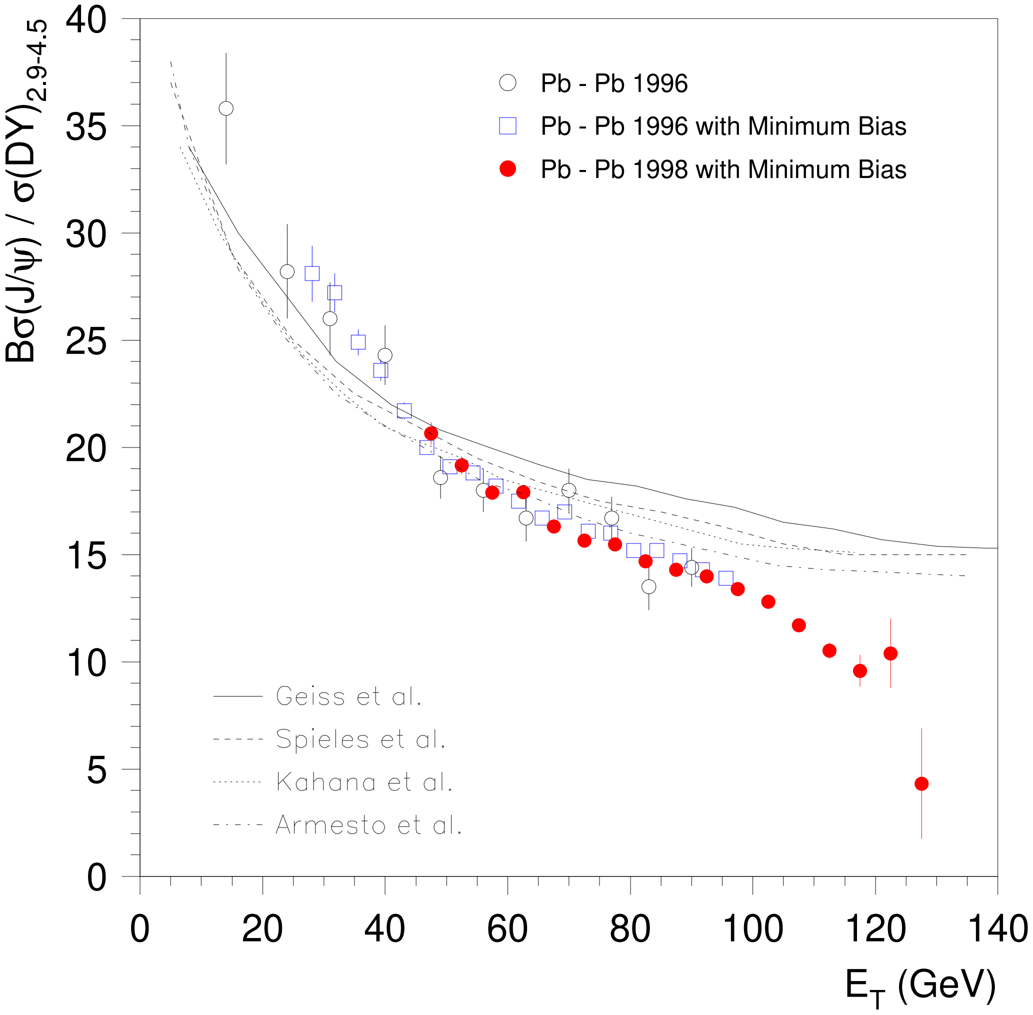

Figure 2: Comparison between the NA50 Pb-Pb data and several conventional calculations of J/ψ suppression. This figure, taken from Ref. 5, clearly shows that the presently available conventional scenarios are excluded by the data.