CHARMONIUM SUPPRESSION IN PB-PB COLLISIONS AND QUARK-GLUON DECONFINEMENT

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for the NA50 Collaboration

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An anomalous charmonium suppression in central Pb-Pb collisions at 158 GeV/c per nucleon was observed in the NA50 experiment at CERN. The ratio of the J/ψ production cross section to the Drell-Yan cross section measured for several lighter colliding systems extending from p-p to S-U exhibits the exponential decrease due to ordinary absorption of the J/ψ in nuclear matter. For Pb-Pb interactions the experimental data agree with this ordinary absorption curve only for the most peripheral collisions. By increasing the centrality of the interaction, a threshold effect is observed for the onset of the anomalous suppression. The experimental data agree well with the predictions of a quark-gluon phase transition formed during the collision and with the interpretation of charmonium suppression due to Debye color screening in a deconfined plasma.

1 Introduction

Although the existence of a deconfinement state of quarks and gluons or quark-gluon plasma is predicted by non-perturbative lattice calculations [1], only the experimental observations of this new state of matter could provide the real values of critical temperature and energy density of phase transition. An extensive search of the new physical phenomena by collisions of high energy lead ions with nuclear targets was performed in CERN experiments during last years. Several experimental observables sensitive to quark-gluon plasma formations were tested.

In particular the NA50 experiment extends to lead-lead collisions the early study of charmonium states production in the NA38 experiment made with protons and light ions like sulphur and oxygen. The physical justification of the NA50 experiment was based on the prediction of Matsui and Satz [2] on a suppression of charmonium production in case of quark-gluon plasma formation during heavy ion collisions due to Debye color screening of the binding potential between c and $\overline{c}$ quarks preventing to form charmonia states.

As a reference process for comparison of charmonium production cross section with different projectiles and target nuclei the yield of Drell-Yan dimuons was chosen. It was found that the Drell-Yan cross section is proportional to the product of numbers of nucleons in colliding nuclei $\sigma(DY) \sim A \cdot B$. Therefore one can assume that the Drell-Yan process in nucleus-nucleus collisions proceeds through nucleon-nucleon interactions.

On the other hand in the NA38 experiment with light nuclei projectiles [3] the deviation of the J/ψ production cross section from a $A \cdot B$ dependence was observed. A decrease of the charmonium production cross section compared to the Drell-Yan cross section for heavier colliding nuclei was accounted for by nuclear absorption of the $c\overline{c}$ pair before it forms the J/ψ state [4]. This ordinary suppression could be described by one parameter - the absorption cross section $\sigma_{abs} = 6.1 \pm 0.7$ mb [5].

The first experimental data on Pb-Pb obtained by NA50 in 1995 [5] exibit a strong departure from this smooth behaviour. The value of the J/ψ production cross section in Pb-Pb collisions was found to be by a factor 0.77 ± 0.04 below the one expected from the extrapolation of the ordinary absorption dependence established from the p-A and S-U data. This effect of anomalous charmonium suppression increased for more central collisions. The centrality of the collision was determined by the measurement of the neutral transverse energy E_T with an electromagnetic calorimeter. The most central collisions correspond to $E_T > 100$ GeV.

In 1996 new high statistical measurements were made by increasing the target thickness [6]. A detailed study of the centrality dependence was possible, and it was shown that the charmonium production cross section for low E_T, i.d. for the most peripheral collisions could be described by the ordinary absorption curve. The statistical accuracy of the experimental results was considerably increased by using as a reference process the minimum bias events. The procedure of minimum bias analysis is described in detail in [6]. The data obtained in 1996 have shown unambiguously that a threshold suppression effect was observed at $E_T \sim 40$ GeV corresponding to an impact parameter of about 8 fm.

However a comparision made for the high E_T value of the (thin target) 1995 data and the (thick target) 1996 data has revealed some excess for the latter sample of events. This distortion is due to reinteractions of spectator fragments in the thick target, about 30% of an interaction length. Some secondary peripheral collisions with larger cross sections ratio could be erroneously taken as more central collisions without reinteraction. Therefore the experiment in 1998 was performed with one thin target [7]. The result is in perfect agreement with the 1995 data. The review of charmonium suppression in Pb-Pb collisions obtained in the three running periods is presented in this report.

2 Experimental installation

The main detector of the NA50 installation is a dimuon spectrometer equipped with tracking wire chambers, trigger scintillator detectors, a hadron absorber with a preabsorber made of BeO [5]. Additional detectors were used specifically designed to cope with the high radiation level, the huge multiplicities and the background induced by incident Pb ions: a beam hodoscope and several antihalo detectors. A set of quartz counters located near each piece of the segmented target was used to determine the vertex of the interaction and reject events where spectator fragments produce a second interaction in a downstream subtarget.

The centrality of the collisions is determined by three detectors: an electromagnetic calorimeter, a multiplicity detector and a zero degree calorimeter.

For the extraction of the J/ψ and ψ' yield from the muon pair invariant mass spectra, the contributions from different processes were taken into account: combinatorial background originating from uncorrelated pion and kaon decays, open charm and Drell-Yan production.

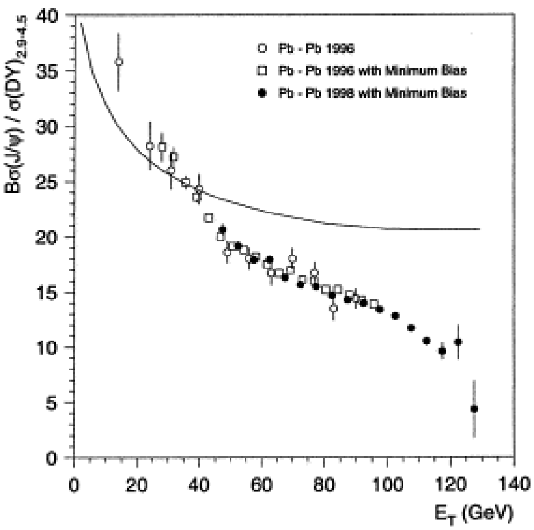

Figure 1. σ_ψ/σ_{DY} ratio as a function of E_T, obtained with the standard and minimum bias analyses of the 1996 and 1998 data samples. The curve represents the J/ψ suppression due to the ordinary nuclear absorption.

3 Results from the NA50 experiment

A detailed investigation of the anomalous charmonium suppression in Pb-Pb collision is the main goal of the NA50 experiment. The results obtained up to now are presented in Figs. 1, 2, 3. The ratio of the measured cross section for J/ψ production to the Drell-Yan cross section as a function of the neutral transverse energy E_T is shown in Fig. 1. Results with better statistics and more E_T bins have been obtained using the minimum bias events, and calculating with the Glauber model the ratio of Drell-Yan to minimum bias yield. They are normalized to the standard analysis results in the E_T interval between 50 and 75 GeV. The most central data of the 1996 sample for $E_T > 100$ GeV are not shown due to systematics effects due to reinteractions within the thick target.

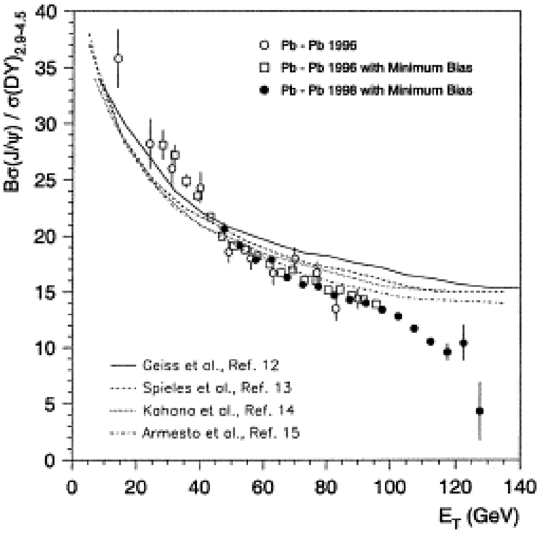

Figure 2. Comparison between our data and several conventional calculations of J/ψ suppression.

The solid line, shown in Fig.1, corresponds to the extrapolation of the ordinary nuclear absorption curve obtained from proton-nuclei and light nuclei collision systems studied by the NA38 and NA51 collaborations [3]. A clear onset of the sudden drop near $E_T = 40$ GeV is seen. This anomalous threshold effect first observed by the NA50 collaboration in 1995 is confirmed by results obtained with the high statistics data in 1996. No conventional models could represent this sharp threshold effect with increasing centrality of collision.

The data of the 1998 experimental run are shown in Fig. 1 for $E_T > 40$ GeV since for lower E_T the contribution from Pb interactions on air is too big as compared to the thin target used. It was found with the special empty target run that this background is negligible for the events with E_T above 40 GeV. The 1998 data show a second drop in the J/ψ suppression pattern at E_T around 90 GeV.

By increasing the centrality of the collision a steady decrease of the ratio of the J/ψ to Drell-Yan cross section is observed. This centrality dependence is in clear disagreement with several hadronic models which assume that the charmonia states are absorbed by interactions with comoving hadrons [8-11]. All these models predict a smooth decrease of the J/ψ production cross section from p-p to Pb-Pb collisions, tending to a saturation of the J/ψ suppression in the most central collisions. The comparision is presented in Fig. 2.

On the contrary, the centrality dependence of the anomalous J/ψ suppression measured in the NA50 experiment agrees with the pattern expected in the framework of production of a deconfined state of quarks and gluons [12].

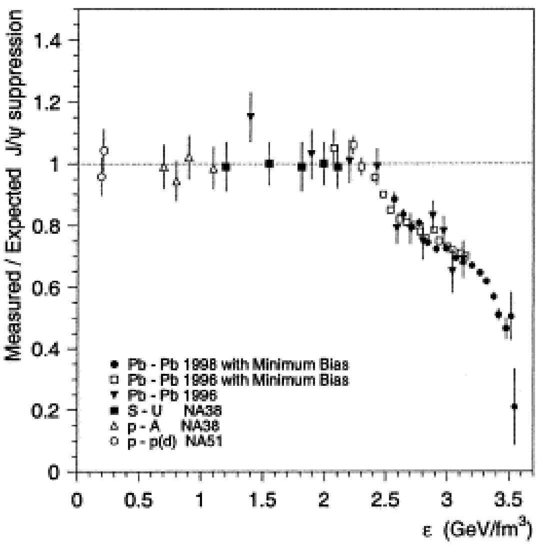

Figure 3. Measured J/ψ production yields, normalized to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. Results are shown as a function of the energy density reached in the collision.

The threshold effect and the anomalous charmonium suppression pattern are illustrated in Fig.3, where the ratio of the J/ψ production yield to the expected one due to only ordinary nuclear absorption is plotted as a function of the energy density reached in the nucleus- nucleus collision. In this plot are compared the data for different colliding systems from the NA38 and NA50 experiments. The energy density was computed according to Bjoken's model [13]. It reaches the value 3.5 GeV/fm^3 for the most central Pb-Pb collisions and is in accordance with other experimental estimates and with cascade model calculations. The two drops observed in the charmonium production cross section seen in Fig.3 at energy densities around 2.3 and 3.1 GeV/fm^3 could be understood as due to the successive melting of first the more loosely bound state χ_c and then the J/ψ charmonium states. The fraction of J/ψ produced by χ_c radiative decay is not known. For p-A collision this fraction is about 30-40 %.

4 Conclusions

The combined results of the NA38 and NA50 experiments clearly show a two step-wise charmonium suppression pattern at high energy densities with no visible saturation for the most central collisions. This observation exclude the presently available models of J/ψ suppression based on the interaction of charmonium with surrounding hadronic confined matter. On the contrary the step-wise behaviour of charmonium suppression is easily understood as a result of Debye color screening if quark-gluon plasma is produced during the collisions. Therefore, the experimental study of charmonium suppression performed by the NA50 collaboration provides evidence for the deconfinement of quarks and gluons in central Pb-Pb collisions at SPS energy.

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