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Heavy-ion collisions

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Abstract. This is a short summary of the systematics observed in various heavy-ion experiments at CERN SPS energies.

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1. Introduction

Interest in heavy-ion collisions is due to the possibility of being able to identify the QCD phase transition in such collisions. Recall that the transition temperature, $T_c \approx 150$ MeV. It is expected that temperatures reached in heavy-ion collisions do not exceed $2T_c$. Then thermal signatures are imposed on particle spectra for momenta (or energies) less than half a GeV. This is the reason why most of the experimental activity centres on soft phenomenology. In a few special cases there is a 'transducer' which allows us to see the effect of such small temperatures at much higher scales.

Since this is a summary of present data for people outside the field, most references are to data. The few references to papers by phenomenologists are either to the authors of the major paper on a topic, or to those who have analysed the consistency of data.

2. Soft hadrons

First, let me ask what is the evidence for any kind of non-trivial effect on soft spectra in heavy-ion collisions? The answer depends, of course, on what a 'trivial' effect is. Since there is no computable theory for soft hadron production, the answer is model dependent. Recently, Jeon and Kapusta have defined such a trivial extrapolation by considering nucleus–nucleus collisions as a linear combination of p + p collisions [1]. The idea is that the prediction of such a model should be considered to be a trivial scaling. They find that most spectra seen at CERN SPS energies in heavy-ion collisions are trivial. Their results for proton spectra are shown in figure 1. Similar results are obtained for other hadrons. Other extrapolations of soft hadronic spectra from p + p to heavy-ion collisions exist in the form of Monte Carlo codes [2]. These also give similar results.

There have been other interesting proposals in the realm of soft hadrons, such as disoriented chiral condensates [5]. There is no experimental evidence for this as yet [6].

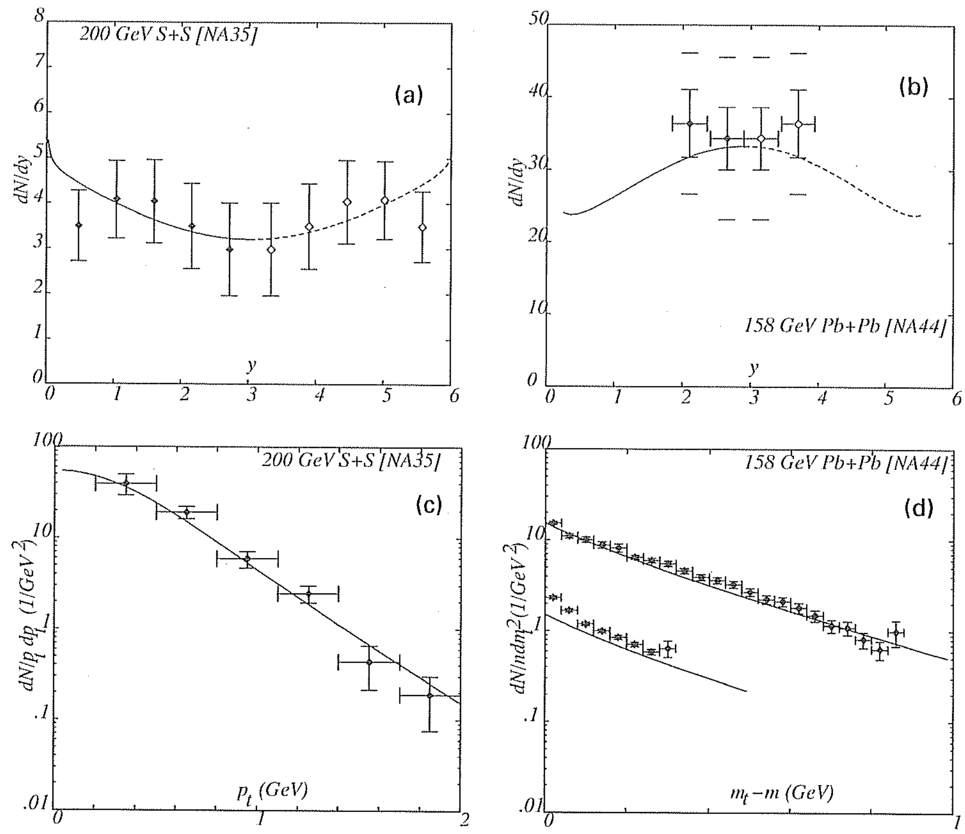

Figure 1. Rapidity and p_t (or $m_t = \sqrt{p_t^2 + m^2}$) distributions of protons for different energies and ions. The lines are the predictions from [1].

The only possible discrepancy here is in strange particle yields. Based on the extrapolations of [1, 2], it would seem that strange mesons and baryons are produced more frequently in S + S and Pb + Pb collisions, than a simple extrapolation from p + p would warrant. In particular, the ratio of observed K^+/π^+ over all angles (4π) is enhanced by almost a factor of two over the corresponding values in p + p collisions. Singly strange baryons (Λ) are also enhanced, but less than doubly or triply strange baryons (Ξ and Ω respectively). For more on the experimental status of strangeness enhancement, see [3].

A first attempt has been made to explain these excesses; appropriately by using the simplest possible model of a hadron gas in thermal equilibrium [4]. It turns out that the data prefer a freeze-out temperature of about 180 MeV and require a strong departure from chemical equilibrium. Understanding this will be a task for the future. None of this data gives any clear and direct evidence for or against the QCD phase transition.

3. Photons, dileptons and jets

Earlier disagreements between different soft-photon experiments now stand resolved. It seems that the photon spectrum in heavy-ion collisions is a simple extrapolation of that seen in p + p collisions [7]. Low mass dileptons seem to indicate an enhanced ϕ meson production [8], in line with other observations of strangeness enhancement. At higher masses, the continuum spectrum of dileptons is a trivial extrapolation of that from p + p collisions.

There are no measurements of jets at present, although there is a 'transducer' in jet phenomenology that boosts the effects of the temperature scale into a momentum scale orders of magnitude higher. This is the Bose enhancement of soft gluon radiation from a jet moving in a hot medium [9].

4. Quarkonium suppression

I turn now to quarkonium suppression where a simple 'transducer' shifts the energy scale of the temperature, about 300 MeV, to the scale of hard QCD, about 3 to 10 GeV. when the difference of the J/ψ mass and the minimum invariant mass of two D mesons is of the order of the temperature reached in the heavy ion collision (or higher) one would expect the J/ψ to dissolve. The mass of the J/ψ is the transducer, since this disappearance is seen as the vanishing of a bump in the dimuon cross section at the mass of the J/ψ. The J/ψ vanishes at T_c; other quarkonia vanish slightly below or above [10].

Some time ago, it was claimed that the J/ψ cross section seen in Pb + Pb collisions at the SPS was suppressed more than an extrapolation from light-ion data would indicate [11]. As shown in figure 2, this statement is true only very naively. The best fit line to the beam/target dependence of the cross section indeed lies above the Pb + Pb data. However, this line is fitted to data and therefore the slope has errors. Within 2σ errors in the fitted line, there is no J/ψ suppression [12].

It has been claimed that this analysis is too naive because it neglects systematic errors in experiments. It turns out that the experimental analysis is as naive, in exactly the same way. The error in the fitted line that is quoted in [12] is exactly the same as that quoted in the experimental paper [11]!

Experimentalists often like to plot the same data in a different way. The x-axis is changed to a model dependent quantity called the path length of the J/ψ in a medium, L. This quantity is derived from more direct observables. The claimed suppression is even more dramatically seen in this plot. However, the story does not change. While the central fitted line does seem to indicate a suppression, this disappears at the 4σ level [13].

A prayer to the gods of beam time allocation: the significance of the result on J/ψ suppression is not going to improve significantly by running the Pb + Pb point longer. It is more important to reduce the primary uncertainty – that of the extrapolation from light ions. This can be done only by improving the statistics of the light ion data.

With recent improvements in the theory of heavy quarkonium formation [14], it becomes possible to predict a new effect in the thermal suppression of J/ψ. It turns out that such a thermal suppression should come coupled with a major change in the angular distribution of the decay dileptons [15].

In general, the angular distribution of these dileptons can be parametrised as $1+\alpha\cos\theta$, where θ is the Collins–Soper angle. The parameter α is measured to be close to zero in proton–proton and light ion collisions. This is due to a compensation of the angular distributions in directly produced J/ψ and those produced through radiative decays of χ_c.

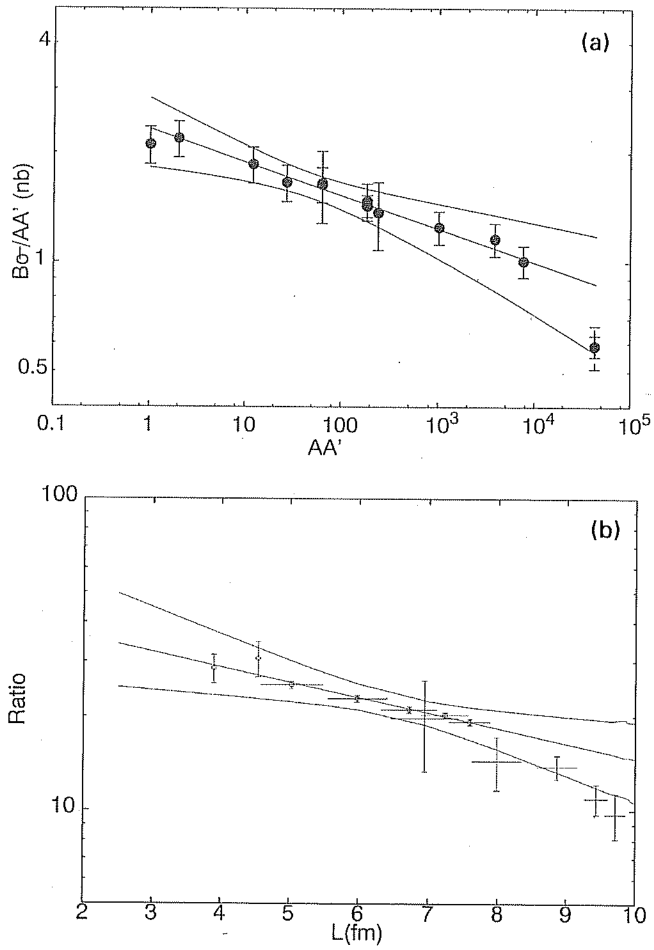

Figure 2. The data on light and heavy ion induced cross sections for J/ψ production [11] and the extrapolation from light ion data to Pb+Pb. On the left is the extrapolation in terms of the product of the nuclear masses (the best fit and the 2σ band are shown; the last point is the Pb+Pb point). On the right is the extrapolation in terms of the path length traversed by the J/ψ (the best fit and the 4σ line are shown; the last five points are for Pb+Pb with different impact parameters).

In a hot environment, the χ states would dissolve, leaving a non-trivial value of α, as shown in figure 3.

5. Conclusion

The only present experimental result which can possibly be interpreted as a signal of the quark-gluon plasma is the NA50 observation of J/ψ suppression. However, the present evidence for this is weak; it is at best a 3σ result. It is important to improve the confidence level of this result by improving the accuracy of the measurement of this cross section in

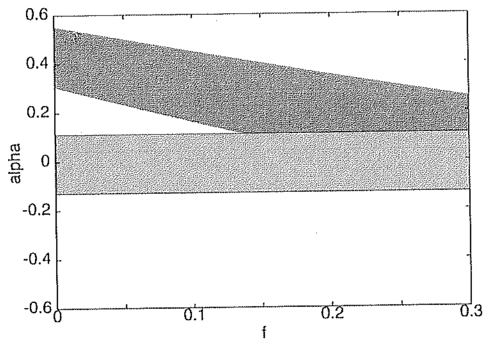

Figure 3. The value of α in heavy-ion collisions as the fraction f of J/ψ coming from χ_c decays decreases. The horizontal band is 1σ band of the present measurement. The other band is 1σ limit of the expected change when χ_c is suppressed.

p + nucleus collisions. It is also necessary to look beyond the total cross section at the angular distribution.

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