PARTICLE RAPIDITY DENSITY AND COLLECTIVE PHENOMENA IN HEAVY ION COLLISIONS

R. UGOCCIONI* AND J. DIAS DE DEUS
CENTRA and Departamento de Física (I.S.T.)
Av. Rovisco Pais, 1049-001 Lisboa, Portugal

We analyse recent results on charged particle pseudo-rapidity densities from RHIC in the framework of the Dual String Model, in particular when including string fusion. The model, in a simple way, agrees with all the existing data and is consistent with the presence of the percolation transition to the Quark-Gluon Plasma already at the CERN-SPS. It leads to strict saturation of the particle (pseudo-)rapidity density, normalised to the number of participant nucleons, as that number increases. Asymptotically, as $\sqrt{s} \to \infty$, with the number of participants fixed, this density approaches again nucleon-nucleon density. A comparison with recent WA98 data is presented.

The dependence of measurable quantities like charged particle density, transverse energy and J/ψ production rate on the number $N_{\rm part}$ of participant nucleons in high energy heavy ion collisions is extremely important both for a better understanding of the initial conditions in the evolution of newly created dense matter and because it provides the information for discriminating among different models.[1,2,3,4,5,6] In this contribution we analyse such quantities in the framework of the Dual String Model (DSM).

We start by building nucleus-nucleus collisions as resulting from superposition of nucleon-nucleon collisions, in the way it is done in the Glauber model approach and its generalisations: in the DSM, i.e., the Dual Parton Model[7] with the inclusion of strings,[8] the valence quarks of the nucleon produce particles, via strings, only once —this is the wounded nucleon model case— and production is proportional to the number N_A of participant nucleons. As the energy and N_A increase the role of sea quarks and gluons increases, they interact and produce, again via strings, particles, and the number of collisions ν becomes the relevant parameter. One should notice that multiple inelastic scattering may occur either internally within a given nucleon-nucleon collision or externally involving interactions with different nucleons.

Following Ref. 9, and taking into account the above basic properties, we

* *Present address: Dipartimento di Fisica Teorica, via Giuria 1, 10125 Torino, Italy*

now write an expression for the particle pseudo-rapidity density,

$$\left.\frac{dN}{dy}\right|_{N_A N_A} = N_A \left[2 + 2(k-1)\alpha\right] h + (\nu_{N_A} - N_A) 2k\alpha h, \qquad (1)$$

where h is the height of the valence-valence rapidity plateau, α is the relative weight of the sea-sea (including gluons) plateau and k is the average number of string pairs per collision. Elementary multi-scattering arguments[9] give $\nu_{N_A} = N_A^{4/3}$. However, as we mentioned above, the diagram corresponding to sea-sea scattering can be iterated with $k \geq 1$ being, in general, a function of energy. The number of nucleon-nucleon collisions is, of course, $N_A + (\nu_{N_A} - N_A) = \nu_{N_A}$, and the number of strings is $N_s = N_A \left[2 + 2(k-1)\right] + (\nu_{N_A} - N_A) 2k = 2k\nu_{N_A}$. The first term on the right-hand side of Eq. (1) is just a sum over nucleon-nucleon scattering contributions (including internal parton multiple scattering) and we can thus write

$$\left.\frac{dN}{dy}\right|_{N_A N_A} = \left.\frac{dN}{dy}\right|_{pp} N_A + (\nu_{N_A} - N_A) 2k\alpha h \qquad (2)$$

If external multiple scattering is absent, by putting $\nu_{N_A} = N_A$, one obtains the wounded nucleon model limit; if $k \gg 1$ we obtain the limit in which multiple scattering dominates.

In Fig. 1, together with the PHOBOS data, we have presented the quantity $\frac{1}{N_A} \left.\frac{dN}{dy}\right|_{N_A N_A}$ as function of the c.m. energy $\sqrt{s}$ for the wounded nucleon model limit—solid line—and the multiple scattering dominance limit—dotted line. Assuming that h and α are energy independent (constant plateaus), the energy dependence of $dN/dy|_{pp}$, obtained from a parametrisation of experimental data,[6] fixes the energy dependence of k. We find $\alpha = 0.05$ and $h = 0.75$.

In the DSM, strings may interact by fusing[14,15] in the transverse plane of interaction thus modifying the number and the distributions of produced particles: in particular, due to the vector nature of the colour charge, a cluster of m strings will emit fewer particles that m separate strings.[16]

The number of strings coming from nucleon multiple scattering —the second term in Eq. (1)—is $N_A(N_A^{1/3} - 1)2k$ and they occupy the transverse interaction area S_{N_A}, which, for central collisions, is approximately given by $S_{N_A} \simeq \pi \left(1.14 N_A^{1/3}\right)^2$, such that the dimensionless transverse density parameter η is

$$\eta = \left(\frac{r_s}{1.14}\right)^2 2k N_A^{1/3} (N_A^{1/3} - 1), \qquad (3)$$

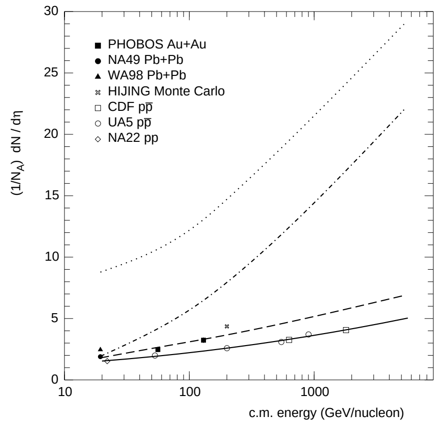

Figure 1. Pseudo-rapidity density normalised per participant pair as a function of c.m. energy. The lines give predictions for the wounded nucleon model (solid line), the pure multicollision approach (dotted line), and the Dual String Model, without fusion Eq. (2) (dash-dotted line) and with fusion Eq. (4) (dashed line). AA points are taken from Ref. 2,3,5, pp and $p\bar{p}$ from Ref. 10,11,12,13

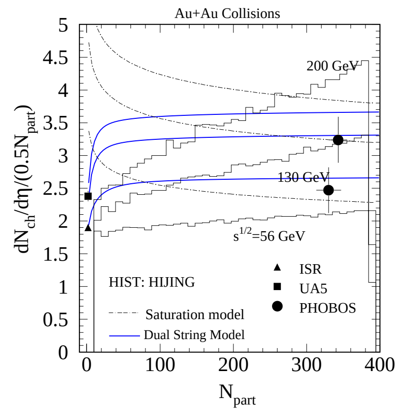

Figure 2. Central charged particle rapidity density per participating pair as a function of the number of participants. Results of HIJING (histograms), EKRT predictions (dot-dashed lines) and DSM predictions (solid lines) for central Au+Au collisions at $\sqrt{s} = 56, 130, 200$ AGeV. Also shown are results from pp and $p\bar{p}$ collisions and PHOBOS data (Everything in the figure except the DSM curves is taken from Ref. 5.)

where $r_s \simeq 0.2$ fm is the string transverse section radius. Note that η increases with N_A and, via k, also with $\sqrt{s}$.

When fusion occurs, Eq. (2) becomes[6]

$$\frac{1}{N_A}\frac{dN}{dy}\bigg|_{N_A N_A} = \frac{dN}{dy}\bigg|_{pp} + F(\eta)(N_A^{1/3} - 1)2k\alpha h, \tag{4}$$

where $F(\eta)$ is the particle production reduction factor,[17]

$$F(\eta) \simeq \sqrt{\frac{1 - e^{-\eta}}{\eta}}. \tag{5}$$

It can now easily be shown[18] that the DSM with fusion predicts saturation of the particle rapidity densities per participant pair of nucleons as N_A increases. This prediction is compared to other models[5,19,20] in figure 2 and to experimental data from WA98[3] in figure 3.

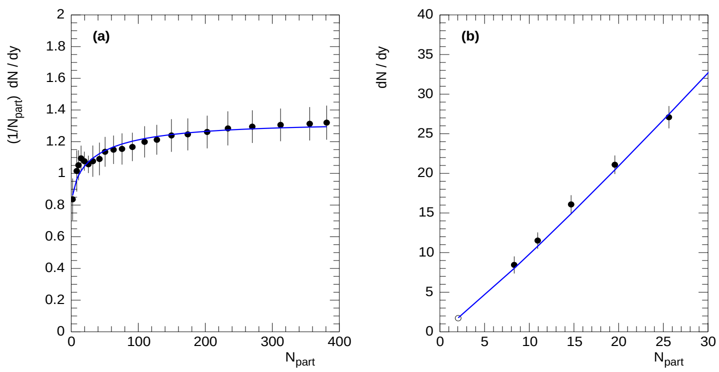

Figure 3. **(a)** Charged particle density per participant nucleon versus the number of participants; **(b)** absolute charged particle density versus the number of participants. The data from WA98[3] refer to 158A GeV Pb+Pb collisions (filled circles), the open circle refers to pp collisions[21]; the solid line results from Eq. (4) with $\alpha = 0.11$ and $h = 0.77$.

Furthermore, it is to be noted that the predictions for particle densities in central Pb+Pb collisions of the DSM without fusion and of the DSM with fusion are very different at $\sqrt{s} = 200$ AGeV (RHIC) and at $\sqrt{s} = 5.5$ ATeV (LHC) as can be seen in the following table:

c.m. energy	200 AGeV	5.5 ATeV
without fusion	1500	4400
with fusion	700	1400

Of course this model is essentially soft. The parameters of the elementary collision densities, h and α, were assumed constant, all the energy dependence being attributed to the parameter k, the average number of string pairs per elementary collision. If h and α are allowed to grow with energy, as a result, for instance, of semi-hard effects, the parameter k may then have a slower increase than the one obtained here.

Finally, one should consider the idea that string fusion eventually leads to a situation of percolation[14,15] with the formation of extended regions of colour freedom, with the features of the expected Quark-Gluon Plasma. Indeed the parameter η at the CERN-SPS has the value $\eta \approx 1.8$, larger than the critical density ($\eta_c \approx 1.12 \div 1.17$) which means that percolation transition is already taking place at $\sqrt{s} = 20$ AGeV, even allowing for non-uniform matter distribution in the nucleus ($\eta_c \approx 1.5$);[22] this result is valid even with $k = 1$. The observed anomalous J/ψ suppression[23] may then be a signature of the percolation transition to the Quark-Gluon Plasma.[14,15]

Indeed, in our simple approach,[15] J/ψ and Drell-Yan production are treated as rare events: this implies that their ratio is given by the product of two functions, one describing absorption of J/ψ (which we assume as usual to be exponential in the amount of matter longitudinally traversed), the other describing J/ψ ($c\bar{c}$) suppression due to Debye screening. If we take the drastic position that the latter is 100% effective if there is percolation, and ineffective otherwise, then screening is described by the probability of non-percolation, which can be parametrised as

$$P_{\text{non-perc}}(\eta) = \left[1 + \exp\left(\frac{\eta - \eta_c}{a_c}\right)\right]^{-1}, \tag{6}$$

with a_c a parameter linked to the finite size of the nuclear system. Thus we see that the onset of the phase transition is characterised by a change in the curvature of the J/ψ over D.Y. ratio from positive (during absorption) to negative. This however is only a qualitative description: a quantitative one should probably take into account more details of the process (e.g., geometry varying with impact parameter, resonances, ...).

In conclusion, the DSM is a model with two components, the valence-valence component and the sea-sea component, the sea-sea component increasing its importance with energy and number of participants. This is somewhat similar to the HIJING Monte Carlo model, with soft and hard components. On the other hand, with fusion the DSM behaves, for large N_A, similarly to the EKRT model, but with strict saturation of the particle density per participant nucleon. However, in the original EKRT model the saturation criterion in the transverse plane is stronger than in case of fusion of strings. Here, saturation in the interaction area is asymptotic (when $\eta \to \infty$) while in the EKRT model it occurs at finite density. This causes the decrease of the particle density with N_A in the EKRT original model.

Probably different explanations, such as the ones based on string fusion, parton saturation, parton shadowing, are in some sense dual and refer to the same underlying physics.[9] What is becoming clear is that saturation of particle density puts strong constraints in models, and limits the rise of the (pseudo-)rapidity plateau at RHIC and LHC.

Acknowledgements

R.U. gratefully acknowledges the financial support of the Fundação Ciência e Tecnologia via the "Sub-Programa Ciência e Tecnologia do 2^o Quadro Comunitário de Apoio."

References

1. M. Gyulassy, these proceedings.
2. B.B. Back et al., PHOBOS Collaboration, Phys. Rev. Lett. **85**, 3100 (2000).
3. M.M. Aggarwal et al., WA98 Collaboration, preprint nucl-ex/0008004, (WA98/CERN).
4. C. Lourenço, talk given at the Heavy Ion Day meeting in Lisbon, Portugal, April 2000.
5. X.-N. Wang and M. Gyulassy, preprint nucl-th/0008014.
6. J. Dias de Deus and R. Ugoccioni, Phys. Lett. B **491**, 253 (2000).
7. A. Capella, U.P. Sukhatme, C.I. Tan and J. Trân Thanh Vân, Physics Reports **236**, 225 (1994).
8. N.S. Amelin, M.A. Braun and C. Pajares, Phys. Lett. B **306**, 312 (1993); N.S. Amelin, M.A. Braun and C. Pajares, Z. Phys. C **63**, 507 (1994).
9. N. Armesto and C. Pajares, Int. J. Mod. Phys. A **15**, 2019 (2000).
10. M. Adamus et al., NA22 Collaboration, Z. Phys. C **37**, 215 (1988).
11. G.J. Alner et al., UA5 Collaboration, Physics Reports **154**, 247 (1987).
12. R.E. Ansorge et al., UA5 Collaboration, Z. Phys. C **43**, 357 (1989).
13. F. Abe et al., CDF Collaboration, Phys. Rev. D **41**, 2330 (1990).
14. N. Armesto, M.A. Braun, E.G. Ferreiro and C. Pajares, Phys. Rev. Lett. **77**, 3736 (1996); M. Nardi and H. Satz, Phys. Lett. B **442**, 14 (1998).
15. J. Dias de Deus, R. Ugoccioni and A. Rodrigues, Eur. Phys. J. C **16**, 537 (2000).
16. T.S. Biro, H.B. Nielsen and J. Knoll, Nucl. Phys. B **245**, 449 (1984).
17. M.A. Braun and C. Pajares, Eur. Phys. J. C **16**, 349 (2000).
18. J. Dias de Deus and R. Ugoccioni, Phys. Lett. B **494**, 53 (2000).
19. K.J. Eskola, K. Kajantie, P.V. Ruuskanen and K. Tuominen, Nucl. Phys. B **570**, 379 (2000).
20. K.J. Eskola, K. Kajantie and K. Tuominen, preprint JYFL-3700 and HIP-2000-45/TH (hep-ph/0009246), Univ. of Jyväskylä and Univ. of Helsinki.
21. C. De Marzo et al., Phys. Rev. D **26**, 1019 (1982).
22. A. Rodrigues, R. Ugoccioni and J. Dias de Deus, Phys. Lett. B **458**, 402 (1999).
23. M.C. Abreu et al., NA50 Collaboration, Phys. Lett. B **477**, 28 (2000).