COMPARISON BETWEEN DATA FROM ULTRARELATIVISTIC HEAVY-ION COLLISIONS AND A GEOMETRICAL MODEL BASED ON LOCAL ENERGY AND MOMENTUM CONSERVATION*

Łukasz Rozpłochowski

Faculty of Physics, Astronomy and Applied Computer Science
Jagiellonian University
Łojasiewicza 11, 30-348 Kraków, Poland

(Received April 14, 2020)

During ultrarelativistic heavy-ion collisions, an extraordinary state of matter, the Quark–Gluon Plasma, is produced. The main aim of this work was to investigate the properties of a new model of the nucleus+nucleus collisions at high energy, and its applicability. This model, called further "the fire-streak model", is based on the geometry of the collision and local energy and momentum conservation. The reactions studied so far are the Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 17.3$ GeV and $\sqrt{s_{\rm NN}} = 8.8$ GeV. Comparing results from the model to experimental data collected by the NA49 experiment at the CERN SPS, we obtain a good agreement. The second main subject of the investigation was the application of the model to the nucleon+nucleon $(N+N)$ collisions and the relation between the Pb+Pb and $N+N$ collisions (experimental data were collected by NA49 as well as NA61/SHINE) at the same energy. Obtained results show that if we consider the change in the overall energy balance between the Pb+Pb and the $N+N$ system (included by baryon stopping and strangeness enhancement), it is possible to extend our approach to $N+N$ reactions.

DOI:10.5506/APhysPolBSupp.13.893

1. Introduction

The simplest way of presenting the ultrarelativistic heavy-ion collision is to think about two nuclei observed in the center of mass, and (because of the high velocity) contracted in the longitudinal direction. These nuclei collide producing hot and dense matter in a state of the Quark–Gluon Plasma, where quarks and gluons constitute a kind of "liquid" in the volume of the plasma. Subsequently, the system cools down, hadronizes and finally

* Presented at the 45$^{\rm th}$ Congress of Polish Physicists, Kraków, September 13–18, 2019.

undergoes a freeze-out, when emitted hadrons no longer interact with each other. Then the particles (like π mesons) are detected by the experimental setup. Data collected in this way are our only available knowledge about these collisions. In general, the evolution of the system in space and time is unknown.

The fire-streak model constitutes an attempt to understand what is happening in the heavy-ion collision, especially in the Pb+Pb collision. The model as presented in Refs. [1, 2] has been formulated by Szczurek and developed by Rybicki and Kiełbowicz. However, it should be stated that a similar idea, generally known under the name of the "fire-streak model", has been known in the field since 1971, Refs. [3–8]. For this reason, in the present document, we keep the word "fire-streak" for "historical consistency", but it should be underlined that differences between the two approaches are evident. More on this subject can be found in Ref. [9].

This paper is a short summary of the author's master thesis, see Ref. [10]. Further details are also given in Refs. [1, 2].

2. The fire-streak model

The fire-streak model is based on a very simple geometrical idea and local energy and momentum conservation. In this model, we think about nuclei not as groups of nucleons, but as three-dimensional mass and charge distributions. As shown in Fig. 1, these three-dimensional distributions (nuclei) are divided into "bricks" in the plane perpendicular to the beam axis. The transverse size of the brick is equal to 1×1 fm^2. The b marked in the figure is the impact parameter and decides which brick from one nucleus will collide with a brick from the opposite nucleus. We can calculate the energy and momentum of each brick. After colliding, bricks "stick together" and create a new object called the fire-streak. As we know energy and momentum for each brick, we can calculate the energy and momentum for the fire-streak.

The last important feature of the model is the fragmentation function. We assume that at the end, all fire-streaks are fragmenting into the particles. We postulate an analytical function which decides how many π^- are created and what is their rapidity. This fragmentation function for a single fire-streak is

$$\frac{\mathrm{d}n}{\mathrm{d}y}(y) = A\,(E_s^* - m_s)\,\exp\left(\frac{\left[(y-y_s)^2+\epsilon^2\right]^{r/2}}{r\sigma_y^r}\right), \qquad (1)$$

where E_s^* is the total energy of a single fire-streak in its own c.m.s. frame, m_s is the sum of brick masses before the collision, y_s is the rapidity of the fire-streak in the collision c.m.s. and four parameters A, ϵ, r, and σ_y are

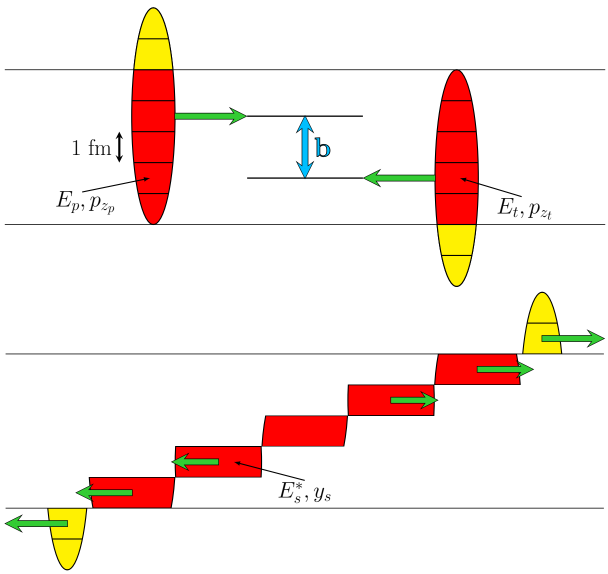
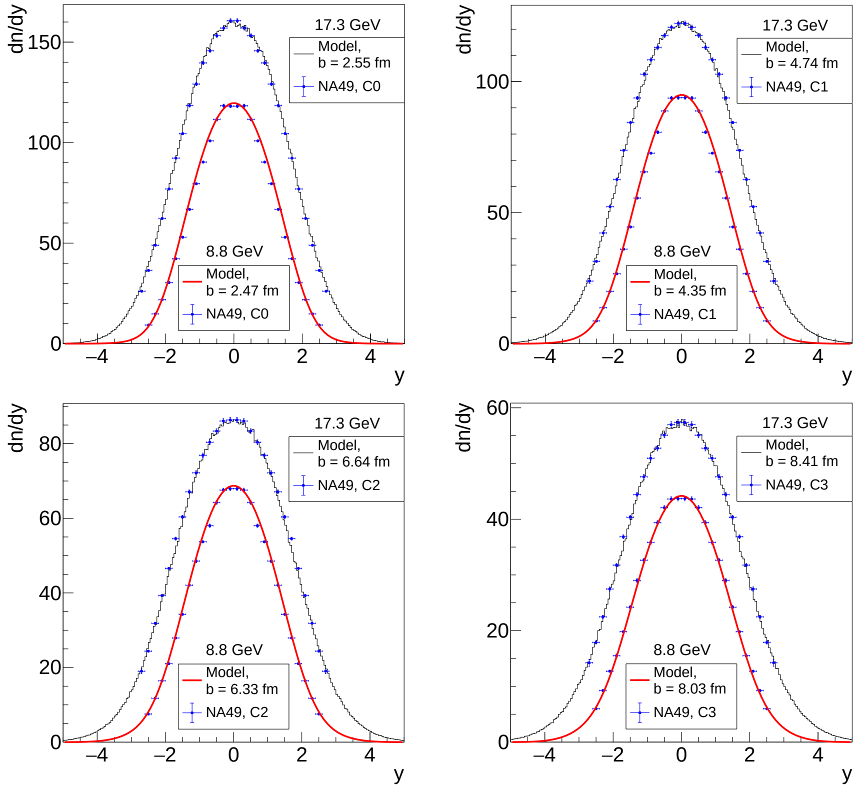


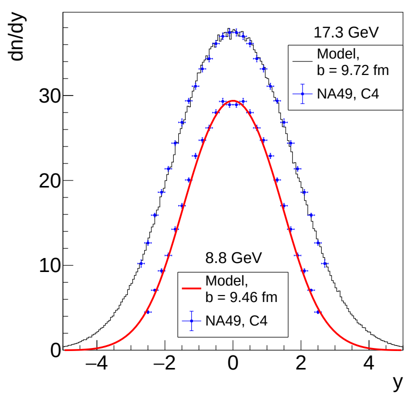
Fig. 1. The fire-streak model, before and after the nucleus–nucleus collision. Two "bricks" from opposite nuclei collide and "stick together", creating the fire-streak.

fitted to the experimental data. It needs to be emphasized that equation (1) describes the rapidity distribution of pions created from a single fire-streak. To obtain the rapidity distribution of all pions in the collision, it should be summed over all the fire-streaks.

3. Results

Figure 2 presents all the results obtained so far for the fire-streak model for Pb+Pb collisions at two energies. Higher, black histograms (published in Ref. [1]) present the model compared with experimental data for $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV and lower, red curves (from my M.Sc. Thesis Ref. [10]) present the model compared with data at $\sqrt{s_{\mathrm{NN}}} = 8.8$ GeV. The model is compared to rapidity distributions of negatively charged π mesons (blue points) collected by the NA49 experiment from Ref. [11]. Each of the five subfigures corresponds to one experimental centrality class ($C0$, $C1$ ...). The impact parameter b, which was obtained in the Glauber simulation to correspond to each centrality class, is in the legend of Fig. 2. In Ref. [1], the authors found good agreement between data and the model for $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV. The values of parameters for the fragmentation functions (Eq. (1)) are listed in the last subfigure of Fig. 2.





parameters	energy [A GeV]	
	8.8	17.3
$\langle A\rangle$	0.17366	0.05598
ϵ	2.20	0.01
r	4.60	2.55
σ_y	1.800	1.475

Fig. 2. (Color online) Lower, red curves represent a model for $\sqrt{s_{\rm NN}} = 8.8$ GeV compared to experimental π^- rapidity distributions (blue points with error bars) for Pb+Pb collisions. Higher, black histograms, comes from Ref. [1], and shows the fire-streak model for higher energy equal to $\sqrt{s_{\rm NN}} = 17.3$ GeV. All experimental data come from Ref. [11]. The sets of parameters of the fragmentation function for each energy are shown in the table. The five panels correspond to five centrality classes, from central to peripheral collisions.

The goodness of the model is usually described by the χ^2 value with respect to number degrees of freedom (χ^2/n.d.f.). For the study presented here a correct estimate of χ^2/n.d.f. is quite difficult to obtain due to the very strong dominance of systematic over statistical errors in the experimental data [11]. The systematic error has different components including, *e.g.*, a sizeable centrality measurement uncertainty which directly affects the normalization in the comparison data/model. Consequently, our present tentative estimates give values of χ^2/n.d.f. differing by more than two orders of magnitude with and without the inclusion of the systematic errors (from ~ 1 to ~ 300). Consequently, a final quantitative estimate of χ^2/n.d.f. is still to be provided in the near future.

The model is applied to the "simpler" reaction, which is the nucleon–nucleon ($N+N$) collision at the same energies as for Pb+Pb collisions and the result is shown in Fig. 3. The solid and dashed curves are the very same fragmentation functions that were used in the Pb+Pb reaction for each energy respectively. These curves are multiplied by factors 0.812 (for 17.3 GeV) and 0.85 (for 8.8 GeV) to match them to the data (grey/red

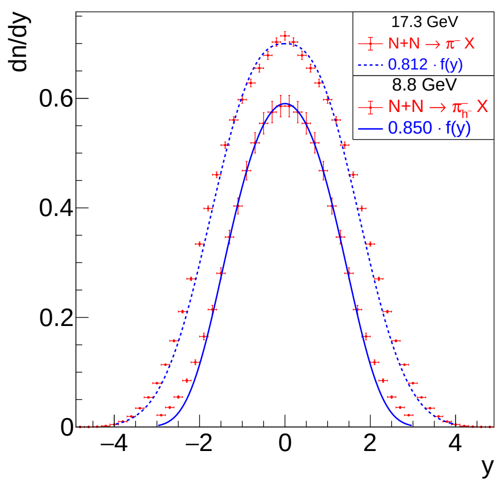


Fig. 3. (Color online) The grey/red data points correspond to the mixture of $p+p$, $n+p$, $p+n$, and $n+n$ collisions estimated from NA49 and NA61/SHINE experimental $p+p$ data [12, 13] using isospin symmetry in order to match the isospin content of Pb+Pb reactions as described in Refs. [2, 10]. The dashed line represents our model for $N+N$ collisions at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV (published in Ref. [2]). The solid curve shows our model for $N+N$ collisions at $\sqrt{s_{\mathrm{NN}}} = 8.8$ GeV. Both curves correspond to single fire-streak fragmentation functions ($f(y)$ in the legend) obtained from Pb+Pb collisions at the same energy and multiplied by factors described in the text resulting from our calculation of energy balance in $N+N$ and Pb+Pb reactions.

points). This means a change of normalization, which emerges from the change in the energy balance (energy repartition) between different particle types in the two reactions. The factors 0.812 and 0.85 are obtained from experimental data in an (essentially) model-independent way (as is shown in Ref. [2]).

4. Summary

The fire-streak model is a very simple model of the ultrarelativistic heavy-ion collision based on the geometry of the reaction and conservation laws. This model is working for Pb+Pb collisions at energy $\sqrt{s_{\rm NN}} = 8.8$ GeV as well as for $\sqrt{s_{\rm NN}} = 17.3$ GeV. It appears possible to apply our model to the "simpler" $N + N$ collision. After estimating the changes in the energy balance, between Pb+Pb and $N + N$ reactions, we can apply the fragmentation function from Pb+Pb collisions to the $N + N$ reaction. This suggests that the Pb+Pb collision is well-described by a superposition of multiple fire-streaks, while in the $N + N$ collision, there is only a single fire-streak (because of the size of "bricks" of the order of 1×1 fm^2). The accuracy of the estimation of the energy balance is about 4% at $\sqrt{s_{\rm NN}} = 17.3$ GeV and 2–4% at $\sqrt{s_{\rm NN}} = 8.8$ GeV.

This work was supported by the National Science Centre, Poland (NCN) (grant No. 2014/14/E/ST2/00018).

REFERENCES

[1] A. Szczurek, M. Kiełbowicz, A. Rybicki, *Phys. Rev. C* **95**, 024908 (2017).
[2] A. Rybicki *et al.*, *Phys. Rev. C* **99**, 024908 (2019).
[3] W.D. Myers, *Nucl. Phys. A* **296**, 177 (1978).
[4] R. Hagedorn, «Thermodynamics of strong interaction», Technical Report CERN-71-12, 1971.
[5] J. Gosset, J.I. Kapusta, G.D. Westfall, *Phys. Rev. C* **18**, 844 (1978).
[6] V.K. Magas, L.P. Csernai, D.D. Strottman, *Phys. Rev. C* **64**, 014901 (2001).
[7] V. Magas, L. Csernai, D. Strottman, *Nucl. Phys. A* **712**, 167 (2002).
[8] I.N. Mishustin, J.I. Kapusta, *Phys. Rev. Lett.* **88**, 112501 (2002).
[9] A. Rybicki, *Acta Phys. Pol. B Proc. Suppl.* **13**, 659 (2020), this issue.
[10] Ł. Rozpłochowski, «The influence of energy and momentum conservation on particle production in nuclear collisions», Master's Thesis, Jagiellonian University, 2019.
[11] T. Anticic *et al.*, *Phys. Rev. C* **86**, 054903 (2012).
[12] C. Alt *et al.*, *Eur. Phys. J. C* **45**, 343 (2006).
[13] A. Aduszkiewicz *et al.*, *Eur. Phys. J. C* **77**, 671 (2017).