# Influence of the partonic Pauli blocking on the hadronic final state in relativistic nucleus-nucleus collisions

Ben-Hao Sa[1,2,3] and A. Bonasera[2,*]
[1]China Institute of Atomic Energy, P.O. Box 275 (18), Beijing, 102413, China
[2]Laboratorio Nazionale del Sud, Istituto Nazionale Di Fisica Nucleare, Via S. Sofia 44, I-95123 Catania, Italy
[3]Institute of Theoretical Physics, Academy Sciences, Beijing, 100080, China
(Received 11 February 2003; revised manuscript received 6 July 2004; published 28 September 2004)

A simple transport model for ultra-relativistic nucleus-nucleus collisions is proposed to investigate the effect of Pauli blocking, in the transition from the hadron phase to parton phase, on the hadronic final state. A boost invariant study of the Pauli blocking is implemented in the Monte Carlo simulation for the first time. It turns out that this partonic Pauli effect on the final hadron multiplicity in a nucleus-nucleus collision is negligible at SPS energy, around two percent at RHIC energy, but reaching ten percent at LHC energy. The higher reaction energy the stronger is the partonic Pauli effect.

DOI: 10.1103/PhysRevC.70.034904 PACS number(s): 25.75.−q, 12.38.Mh, 24.10.Lx

Pauli blocking plays an important role in the nucleus-nucleus collisions at low and intermediate energies as the available phase space volume is quite small [1–5]. Since the available momentum phase space is huge and more than 95% produced particles are bosons in the ultra-relativistic nucleus-nucleus collisions the role of the Pauli effect is ignored usually. Although pions, kaons, etc. are not influenced by the Pauli principle, their precursors, *u*, *d*, and *s* quarks and their antiquarks, do really have all the influences of Pauli blocking if a Quark-Gluon Plasma (QGP) is formed and survives long enough in a limited region of phase space. Thus, it is worth studying the effect of partonic Pauli blocking on the hadronic final state in ultra-relativistic nucleus-nucleus collisions.

To our knowledge the quantum statistic effect in ultra-relativistic heavy ion collisions was really implemented in studying the boson enhancement in pion transverse momentum [6] and was also considered formally in the parton transport equation [7]. It should be emphasized that a great effort was made in [7] in the field of parton cascade model after the pioneering study of Ref. [8]. However, the partonic Pauli blocking effect was not really implemented in the Monte Carlo simulation of currently available parton cascade models [9–13].

In this paper a simple transport model for ultra-relativistic nucleus-nucleus collisions is proposed investigating the effect of Pauli blocking at the parton initial stage on the hadronic final state. The partonic Pauli blocking is implemented boost invariantly for the first time in the Monte Carlo simulation. The amount of this Pauli effect on the particle multiplicity is negligible at SPS energy, around two percent at RHIC energy, but reaching ten percent at LHC energy, due to the increased number of produced partons with increasing beam energy.

The parton cascade model for ultra-relativistic heavy ion collision is generally composed of the parton initial state, the parton evolution, the hadronization, and the hadron evolution. However, the models in [11,13] lack the last two parts at present, for instance. The partonic Pauli blocking, of course, plays a role only in the former two parts. As a first step the proposed simple transport model is used in investigating mainly the Pauli blocking effect in the generation of the parton initial state according to the hadronic distributions at the highest density stage.

There are two ways to create the parton initial state. In [9,10,13] the parton initial state was composed of partons from the mini-jets production in nucleus-nucleus collision. However, the gluons from the HIJING multiple mini-jet generator [14] was only considered in [9,10]. The parton initial state in [11,12] was created via probability distributions first for the spatial and momentum coordinates of nucleons in the colliding nuclei and then for the flavor, spatial and momenta coordinates of partons in the nucleons. Our simple transport model follows the former way, however, both the quarks (antiquarks) and gluons from our multiple mini-jet generator (see below) are considered.

Our multiple mini-jet generator for an ultra-relativistic nucleus-nucleus collision is based on PYTHIA [15] which is a well known event generator for hadron-hadron collisions. In our multiple mini-jet generator the radial position of a nucleon in the colliding nucleus *A* (indicating the atomic number of this nucleus as well) is sampled randomly from a Woods-Saxon distribution. Each nucleon is given a beam momentum in the *z* direction and zero initial momenta in the *x* and *y* directions (the Fermi motion is neglected). The Lorentz contraction is taken into account after the initialization of nucleons. A distance of closest approach for each colliding nucleon pair along their straight line trajectory is calculated together with its collision time under the requirement that the above distance must be less than or equal to $\sqrt{\sigma_{tot}/\pi}$. Here $\sigma_{tot}$ refers to the total cross section assumed to be equal to 50 mb for Au+Au collisions at $\sqrt{s_{nn}}$=200 GeV and 40 and 100 mb for Pb+Pb collisions at $\sqrt{s_{nn}}$=17.3 and 5500 GeV [16], respectively. The nucleon-nucleon collision list is then constructed. The calculations above were first performed in the cm frame of the colliding nucleon pair and then boosted to the cm or Lab. frame of the nucleus-nucleus system for a

*Electronic address: sabh@iris.ciae.ac.cn; bonasera@lns.infn.it

 

TABLE I. Particle yield in nucleous-nucleus collission at relativistic energies.

| | $Pb+Pb$ | | | $Au+Au$ | | | $Pb+Pb$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\sqrt{s_{nn}}=5500$ GeV 10% most central | | | $\sqrt{s_{nn}}=200$ GeV 5% most central | | | $\sqrt{s_{nn}}=17.3$ GeV 5% most central | | |
| Particle | $w/o$ Pauli | $w$ Pauli | $1-w/w/o$ | $w/o$ pauli | $w$ pauli | $1-w/w/o$ | $w/o$ Pauli | $w$ Pauli | $1-w/w/o$ |
| $\pi^+$ | 7282 | 6624 | 0.0904 | 1352 | 1324 | 0.0207 | 427.6 | 424.9 | 0.00631 |
| $\pi^-$ | 7298 | 6640 | 0.0907 | 1368 | 1339 | 0.0212 | 440.9 | 437.4 | 0.00794 |
| $K^+$ | 855.2 | 781.0 | 0.0868 | 161.8 | 159.0 | 0.0173 | 52.30 | 51.89 | 0.00784 |
| $K^-$ | 818.6 | 745.6 | 0.0892 | 127.9 | 125.6 | 0.0180 | 26.20 | 26.82 | -0.0237 |
| $N_{ch}$ | 17475 | 15974 | 0.0859 | 3266 | 3236 | 0.00919 | 1102 | 1096 | 0.00544 |

colliding or fixed target experiment, respectively.

A nucleon-nucleon collision with the smallest collision time is selected from the collision list performing the first collision. This nucleon-nucleon collision, if its $\sqrt{s_{nn}}$ is larger than a threshold for running PYTHIA (~5 GeV, extrapolated from a default value of 10 GeV) is modeled by PYTHIA with string fragmentation switched off; thus the produced particles are quark pairs, diquark pairs and gluons. Otherwise, the nucleon-nucleon collision is treated as a usual two body collision [17]. The diquark (anti-diquark) is then split into quarks (antiquarks) randomly as in [13] and the gluon into the quark pair randomly as well. It is simply assumed that in the splitting of diquarks (anti-diquarks) and/or gluons, the first daughter parton takes the mother's three coordinates, the other is arranged around the first one to within 0.5 fm in each directions randomly, and both daughter partons have same time component as their mother. Here the mass of the diquark (anti-diquark), the quark (antiquark), and the gluon is the same as those in JETSET [15]. The produced partons propagate along a straight line trajectory similarly to the nucleons. However, the parton interaction is neglected for the moment; thus partons do not collide and possibly create new partons. After a nucleon-nucleon collision both the particle list and the nucleon-nucleon collision list are updated. In updating the collision list, one removes the collision pairs involving any partner of the colliding nucleon pair from the collision list first. Subsequently, one adds all possible collision pairs composed of one nucleon from the colliding nucleon pair (renewed after the scattering) and another one in the particle list. The next nucleon-nucleon collision is selected from the updated collision list and the processes above are repeated until the nucleon-nucleon collision list is empty.

For each parton $i$ among $N_{new}$ partons produced in the current nucleon-nucleon collision a judgment must be performed to calculate its unblocking probability, $p_{unb}(i)$ (see below). If the product of unblocking probabilities of $N_{new}$ produced partons,

$$P_{unb} = \prod_{i=1}^{N_{new}} p_{unb}(i) \tag{1}$$

satisfies

$$P_{unb} \leqslant \xi, \tag{2}$$

where $\xi$ is a random number, the current nucleon-nucleon collision is blocked and thrown away. Another nucleon-nucleon collision is selected from the nucleon-nucleon collision list and the processes above are repeated.

In the heavy-ion collision at low and intermediate energies the Pauli effect was treated boost uninvariantly [1–5]. We introduce a method of boost invariant Pauli blocking in the Monte Carlo simulation for the first time. To calculate $p_{unb}(i)$ we first select the partons with the same flavor as parton $i$ from both the $N_{new}$ partons and the particle list formed before the current nucleon-nucleon collision. That is, there are two components of the Pauli effect: one is stemming from the partons generated in the current nucleon-nucleon collision and another one from partons generated in the previous nucleon-nucleon collisions. If the total number of partons picked above is denoted by $N_{pick}$ we boost all of $N_{pick}$ partons to the rest frame of parton $i$ to be consistent with the method of distance of closest approach used above. Two three-dimensional cubes: one in coordinate space with size $\Delta_r$ and the other in momentum space with size $\Delta_p$, are defined at $i$ (as the origin). The product of these two cubes, which is an invariant scalar [18], is assumed to be $h^3$ with values of $\Delta_r$ and $\Delta_p$ equal to 1 fm and 1.24 GeV$/c$, respectively. We have verified that the final result is insensitive to the change of the value of $\Delta_r$ and/or $\Delta_p$ around 1 fm and/or 1.24 GeV$/c$ to within 20%. If the six-dimensional cell spanned between partons $i$ and $j$ $(j \in N_{pick})$, $|x_{ij}\times y_{ij}\times z_{ij} \times p_{x,j}\times p_{y,j}\times p_{z,j}|$ (invariant scalar), is within $(\Delta_r\times\Delta_p)^3$, i.e. the conditions

$$|x_{ij}| \leqslant \Delta_r/2,\ |y_{ij}| \leqslant \Delta_r/2, |z_{ij}| \leqslant \Delta_r/2, \tag{3}$$

$$|p_{x,j}| \leqslant \Delta_p/2,\ |p_{y,j}| \leqslant \Delta_p/2,\ |p_{z,j}| \leqslant \Delta_p/2, \tag{4}$$

are satisfied simultaneously, the occupation number of parton with flavor as parton $i$, $N_{occu}(i)$, is increased by one. The $x_{ij}$ and $p_{x,j}$ in the above equations, respectively, are the $x$ component of the coordinate distance between $i$ and $j$ and of the momentum of $j$ in the rest frame of $i$ $(i \in N_{new})$ for instance. Thus the occupation probability of parton with flavor as parton $i$ and with a given color and spin (assuming equal probability for each color and spin) is

$$p_{occu}(i) = N_{occu}(i)/g, \tag{5}$$

where $g=6$ is the spin and color degeneracies of the quark and/or antiquark with a given flavor (identified as $u$, $d$, and $s$). The unblocking probability of parton $i$ is then

$$p_{unb}(i) = 1 - p_{occu}(i). \tag{6}$$

The above parton system is then hadronized by JETSET (LUND fragmentation) [15] after the nucleon-nucleon collision ceased (freeze-out) and the hadronic final state is the consequence (i.e., the hadron rescattering is not included for the moment). One investigates the partonic Pauli blocking in the generation of initial parton state effects on the hadronic final state in nucleus-nucleus collisions by comparing the simulations using the simple transport model with partonic Pauli blocking algorithm turned on (later referred to as with Pauli or "w Pauli") to the ones with Pauli off (later referred to as without Pauli or "w/o Pauli").

For a $p+p$ collision the simple transport model without Pauli is nearly the default PYTHIA and the PYTHIA model has been well tested in the elementary $e^+e^-$ collisions mainly. We test it here in the central $p+p$ collisions at $\sqrt{s}=200$ and 17.3 GeV. The charged multiplicity in the region of $|\eta| \leqslant 2.5$ and $p_t > 0.15$ GeV/$c$ is, respectively, 19.1 and 8.15 in the calculations of the simple transport model without Pauli. The corresponding UA1 $p+\bar{p}$ data is, respectively, 21.0 and 10.5 after correction for a "minimum bias" trigger [19]. The simple transport model with Pauli has also to be fitted in a $p+p$ collision at $\sqrt{s}=200$ and 17.3 GeV reaching the same charged multiplicity as in the simple transport model without Pauli by adjusting the parameters $a$ and $b$ in the LUND string fragmentation function [15] from the default values of 0.3 and 0.58 GeV$^{-2}$ to 0.4 and 0.52 and 0.45 and 0.56, respectively. In the string fragmentation the produced hadrons take a fraction of $z$ from the light-cone momentum of the fragmenting string and the remnant $1-z$ string fragments further. The variable $z$ is sampled according to the LUND string fragmentation function. The larger $a$ and/or the smaller $b$ the less $z$ and thus the more particle multiplicity. Since there is no experimental data for the $p+p$ $(p+\bar{p})$ collision at $\sqrt{s}=5500$ GeV, we adjust the $a$ and $b$ parameters from default values to 0.53 and 0.53 in the calculation of the simple transport model with Pauli for a $p+p$ collision at $\sqrt{s}=5500$ GeV such that the charged multiplicity is equal to the ones (86.4) in the calculation of the simple transport model without Pauli. The above fixed simple transport model with Pauli and the simple transport model without Pauli (default $a$ and $b$ parameters) are then used in the simulations of Au+Au and Pb+Pb collisions at $\sqrt{s}=200$ and 17.3 and 5500 GeV, respectively, to investigate the partonic Pauli effect.

In Table I the particle multiplicity in 5% most central Au+Au collisions at $\sqrt{s_{nn}}=200$ GeV and Pb+Pb collisions at $\sqrt{s_{nn}}=17.3$ GeV (5% most central) and 5500 GeV (10% most central) in the simple transport model calculations both with and without Pauli blocking is given. The fractional change of the particle multiplicity in the calculations with Pauli relative to the ones without Pauli is given in the table as well. One sees in Table I that the partonic Pauli effect on the final hadron multiplicity in a nucleus-nucleus collision is negligible at SPS energy, around two percent at RHIC energy, but reaching ten percent at LHC energy. The higher reaction energy the stronger the Pauli effect because of the increasing number of produced partons and of the competition between the partonic Pauli blocking, which decreases the pion production, and the fragmentation, which benefits the low $p_T$ pions.

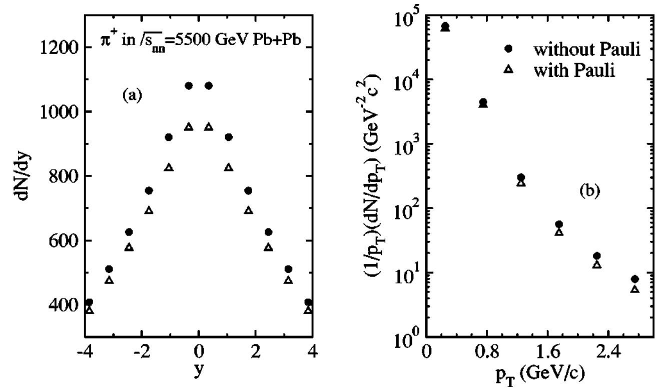


FIG. 1. Rapidity [panel (a)] and transverse momentum [panel (b)] distributions of $\pi^+$ in Pb+Pb collisions at $\sqrt{s_{nn}}=5500$ GeV.

The rapidity and transverse momentum distributions of $\pi^+$ and $K^+$ in Pb+Pb collisions at $\sqrt{s_{nn}}=5500$ GeV are given, respectively, in Figs. 1 and 2 from both with and without Pauli blocking simple transport model calculations. The discrepancy between the distribution in the calculations with Pauli and the distribution in calculations without Pauli is visible for both the rapidity and transverse momentum distributions, especially in the former.

In summary, a simple transport model for ultra-relativistic nucleus-nucleus collisions is proposed studying the partonic Pauli blocking in the parton initial state on the hadronic final state. A boost invariant study of the Pauli effect is implemented in the Monte Carlo simulation for the first time. It turned out that this partonic Pauli blocking effect on the final hadron multiplicity is negligible in nucleus-nucleus collisions at SPS energy, around two percent at RHIC energy, but reaching ten percent at LHC energy, i.e., the higher beam

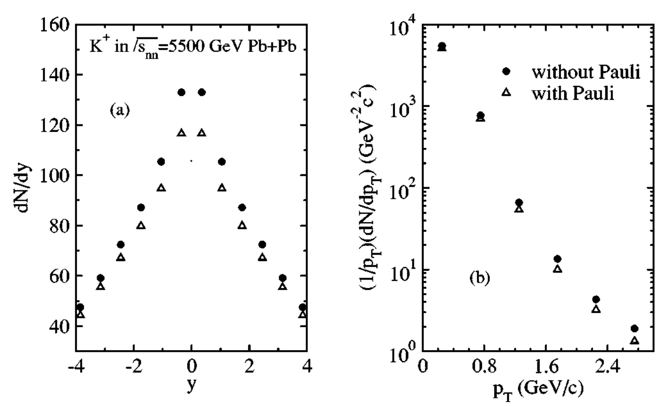


FIG. 2. Rapidity [panel (a)] and transverse momentum [panel (b)] distributions of $K^+$ in Pb+Pb collisions at $\sqrt{s_{nn}}=5500$ GeV.

energy the stronger is the partonic Pauli effect. Of course, our result is a rough estimation since both the parton interaction and the hadron rescattering are neglected. Further investigations are required.

Finally, the financial support from NSFC (10135030, and 10075035) in China and INFN and Department of Physics, University of Catania in Italy (where this study was begun) are acknowledged.

[1] J. Cugnon, T. Mitzulani, and J. Meulen, Nucl. Phys. **A352**, 505 (1981); J. Cugnon, C. Volant, and S. Vuillier, *ibid.* **620**, 475 (1997).
[2] G. F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).
[3] J. Aichelin, Phys. Rep. **202**, 233 (1991).
[4] A. Bonasera, F. Gulminelli, and J. Molitoris, Phys. Rep. **243**, 1 (1994).
[5] Bn-H. Sa, Ri-H. Wang, Xo-Z. Zhang, Yu-Mg. Zheng, and Zg-D. Lu, Phys. Rev. C **50**, 2614 (1994).
[6] G. M. Welke and G. F. Bertsch, Phys. Rev. C **45**, 1403 (1992).
[7] K. Geiger and B. Müller, Nucl. Phys. B **369**, 600 (1992); K. Geiger, Phys. Rep. **258**, 237 (1995).
[8] D. Boal, Phys. Rev. C **33**, 2206 (1986).
[9] B. Zhang, Comput. Phys. Commun. **109**, 193 (1998); B. Zhang, C. M. Ko, B. A. Li, and Z. W. Lin, Phys. Rev. C **61**, 067901 (2000).
[10] D. Molnár and M. Gyulassy, Phys. Rev. C **62**, 054907 (2000); Nucl. Phys. **A697**, 495 (2002).
[11] V. Börchers, J. Meyer, S. Gieseke, G. Martens, and C. C. Noack, Phys. Rev. C **62**, 064903 (2000).
[12] S. A. Bass, B. Müller, and D. K. Srivastava, Phys. Rev. Lett. **91**, 052302 (2003).
[13] Zhe Xu and C. Greiner (private communication).
[14] M. Gyulassy and X.-N. Wang, Comput. Phys. Commun. **83**, 307 (1994).
[15] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).
[16] Particle Data Group, Phys. Rev. D **66**, 010001 (2002).
[17] B.-H. Sa, A. Tai, H. Wang, and F.-H. Liu, Phys. Rev. C **59**, 2728 (1999); B.-H. Sa and A. Tai, *ibid.* **62**, 044905 (2000).
[18] L. P. Csernai, *Introduction to Relativistic Heavy Ion Collisions* (Wiley, New York, 1994).
[19] C. Albajar *et al.*, Nucl. Phys. B **335**, 261 (1990).