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Limiting Fragmentation and ϕ Meson Production at RHIC*

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Abstract: The PHOBOS's limiting fragmentation etc. three empirical scaling rules for charged multiplicity in Au+Au collisions at RHIC are investigated by a hadron and string cascade model LUCIAE. Similar studies are performed for the ϕ meson exploring its production mechanism via comparing with the charged multiplicity. The LUCIAE results for charged multiplicity are compatible with PHOBOS observations. However, for the ϕ meson the three empirical scaling rules are either kept only or kept better in the LUCIAE calculations without reduction mechanism of the s quark suppression extra introduced for the strangeness in LUCIAE model. These results seem indicating a universal production mechanism for charged particle and ϕ meson in string fragmentation regime. It is discussed that the PHOBOS's empirical scaling rules are model dependent indeed.

Key words: limiting fragmentation; energy dependence of charged particle; participant pair scaling; π meson; LUCIAE model

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The ansatz of limiting fragmentation, i.e. the number of particles produced in high energy elementary and/or nuclear collisions by the wounded projectile nucleons should be independent of the details of the target, projectile, and beam energy, was introduced very early[1]. It was employed later in the fragment production in intermediate energy heavy ion collisions. Recently, the BRAHMS and PHOBOS collaborations revealed sequentially the evidence of limiting fragmentation in shifted pseudorapidity density distribution of charged particle per participant pair in Au+Au collisions at RHIC energies[2,3]. Meanwhile, the PHOBOS collaboration reported even other two empirical scaling rules: a striking similarity between Au+Au and e^+e^- collisions in the energy dependence of charged particle production and the approximate participant pair scaling of the charged particle production[4]. These empirical observations may suggest a universal mechanism of particle production in strong interaction system controlled mainly by the available energy, $\sqrt{s_{nn}}$, and challenge theorists to an explanation.

On the other hand, there was evidence that the ϕ meson production may be distinguishable from the charged particle[5,6]. In addition, the ϕ meson is not only a promising signature for the QGP formation but also a good probe studying the reaction dynamics at early stage[7—9]. It is worthy to investigate above three empirical scaling rules

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for ϕ meson exploring its production mechanism via comparison with charged particle.

To this end, a hadron and string cascade model, LUCIAE[10], is employed studying the limiting fragmentation etc. three empirical scaling rules both for charged particle and the ϕ meson in Au+Au collisions at RHIC energies in this letter. The three empirical scaling rules are reproduced fairly well for charged particle. A discussion is given for the ϕ meson production mechanism in string fragmentation regime. It is pointed out that since the PHOBOS observations rely strongly on the definition and calculation of the number of participant nucleons and the PHOBOS's $\langle N_{part} \rangle$ was extracted based on HIJING[11], the three empirical scaling rules are model dependent indeed.

Table 1　The charged multiplicity ($|\eta| \leqslant 4.7$) in 6% most central Au+Au collisions

$\sqrt{s_{nn}}$ /GeV	PHOBOS[1]	LUCIAE (d.)[2]	LUCIAE (m.)[3]	a	b	STAR (dN_ϕ/dy)	LUCIAE (dN_ϕ/dy)
19.6	1 670±100	1 466	1 572	0.5	0.38		
130	4 020±200	4 779	4 191	0.05	1.16	5.73±1.06[4]	5.08 (6.51[5])
200	4 810±240	5 949	4 964	0.02	1.46	7.20±0.40[6]	8.02 (10.2)

1. from [3]; 2. default a and b parameters; 3. modified a and b parameters; 4. $-0.5<y<0.5$ taken from [30]; 5. with default a and b parameters; 6. $-0.5<y<0.5$ taken from [9].

The LUCIAE model[10] is based on FRITIOF[12]. FRITIOF is an incoherent hadron multiple scattering and string fragmentation model where the nucleus-nucleus collision is depicted simply as a superposition of nucleon-nucleon collisions. What characterizes LUCIAE beyond FRITIOF are the follows: First of all, the rescattering among the participant and spectator nucleons and the produced particles from string fragmentation are generally taken into account[13]. Secondly, the collective effect in gluon emission of string is considered by firecracker model[14]. Thirdly, a phenomenological mechanism for the reduction of s quark suppression in the string fragmentation is introduced[15]. Fourth, the nuclear shadowing effect[16] is taken into account. As the ϕ meson does not interact strongly with hadronic matter[7-9, 17-20], we neglect it in this work for the moment.

The LUCIAE model reproduced fairly well the experimental data of the charged multiplicity[10,15,21] and the enhanced production of strange baryons (Λ, Ξ, and Ω)[15,22] and ϕ meson[21] in nucleus-nucleus collisions at SPS energy. However, the LUCIAE model overestimates the charged multiplicity, for instance, nearly a factor of 1.2 in Au+Au collisions at RHIC energy because some energy dependent physics may not well represent in LUCIAE model.

Recently an energy dependent modification of the jet fragmentation function accounting for the energy dependence of parton energy loss was proposed in pQCD studies of eA and AA collisions[23-25]. On the other hand, in Refs. [26—28] the string fragmentation function in transport model has been considered to be modified in the dense string environment at early stage of the relativistic nucleus-nucleus collisions. Following Refs. [26—28] we assume that the default a and b parameters in LUND string fragmentation function[29] are suitable for Pb+Pb collisions at SPS energies. However, for Au+Au collisions at $\sqrt{s_{nn}} = 19.6$, 56, 130, 200 GeV we first adjust roughly the a and b parameters to the experimental charged multiplicity[3]. The fitted a and b parameters are then employed to investigate the three empirical scaling rules both for the charged particle and ϕ meson in above Au+Au collisions.

In the LUCIAE calculations for Pb+Pb and Au+Au collisions at SPS and RHIC energies the

centrality, rapidity (pseudorapidity), and p_t cuts are the same as that in the corresponding experiments, respectively. As an example, in Tab. 1 the data of charged multiplicity ($|\eta| \leqslant 4.7$) in 6% most central Au + Au collisions at $\sqrt{s_{nn}} = 19.6$, 130, and 200 GeV (taken from Ref. [3]) are given together with the corresponding LUCIAE results and the fitted a and b values. In the LUCIAE results the "d." and "m." in bracket refer to the LUCIAE calculation with default ($a=0.3$ and $b=0.58$) and modified a and b parameters, respectively. The STAR data of ϕ meson rapidity density ($-0.5<y<0.5$) in Au + Au collisions at $\sqrt{s_{nn}} = 130$ and 200 GeV (taken from Refs. [30] and [9]) and the corresponding LUCIAE results are given in last two columns.

In Fig. 1 the experimental limiting fragmentation behavior of the charged particle in Au + Au collisions at $\sqrt{s_{nn}} = 19.6$, 130, and 200 GeV[3] is compared with the corresponding LUCIAE results. The upper and lower panels in Fig. 1 are, respectively, for 0%—6% and 35%—40% most central collisions. In Fig. 1 the circles, triangles, and squares are, respectively, for $\sqrt{s_{nn}}=200$, 130, and 19.6 GeV and the full and open labels are for PHOBOS data and LUCIAE results, respectively. The shifted pseudorapidity η' is equal to $\eta - y_{beam}$ where y_{beam} refers to the beam rapidity (assuming similar value for the pseudorapidity and rapidity variables[2]). One sees in Fig. 1 that the LUCIAE model reproduces fairly well the experimental limiting fragmentation of charged particle in 6% most central collisions. However, in 35%—40% central collisions the LUCIAE results are systematically lower than the PHOBOS observations in the region $\eta' > -1.0$. That may attribute to the fact that the discrepancy in $\langle N_{part} \rangle$ among models (PHOBOS's $\langle N_{part} \rangle$ was extracted based on HIJING model[11]) is increased with the decrease of centrality[31]. The PHOBOS's $\langle N_{part} \rangle$ is visibly lower than LUCIAE in 35%—40% central collisions indeed.

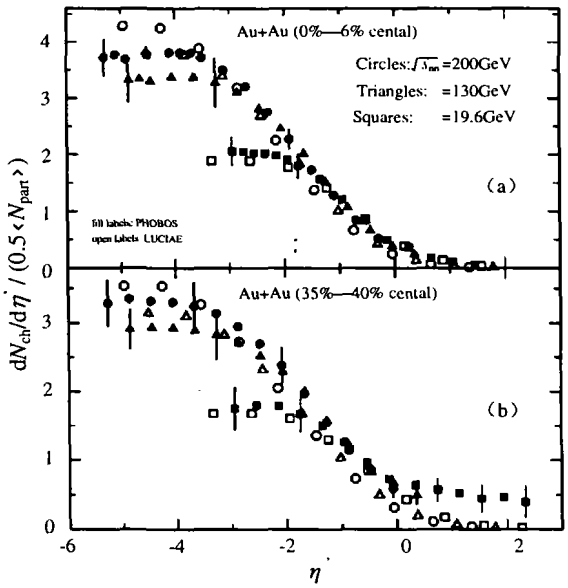

Fig. 1 Shifted pseudorapidity density distribution of the charged particle per participant pair in 6% (upper panel) and 35% − 40% (lower panel) most central Au+Au collisions at $\sqrt{s_{nn}} = 19.6$, 130, 200 GeV.

Given in upper panel of Fig. 2 is the shifted pseudorapidity density distributions per participant pair of ϕ meson in 0%—6% most central Au+Au collisions at, respectively, $\sqrt{s_{nn}} = 200$, 130, and 19.6 GeV (circles, triangles, and squares) from LUCIAE. Since in LUCIAE model a mechanism for the reduction of s quark suppression in the string fragmentation was extra introduced for strangeness thus the corresponding LUCIAE results without this mechanism is plotted in lower panel. Comparing the lower panel with upper panel we see that the limiting fragmentation is kept in a wider η' region in the LUCIAE calculations without reduction of s quark suppression than with ones.

The data of total charged multiplicity per participant pair in 7%, 7%, and 5% most central Pb +Pb collisions at 40, 80, and 158 A GeV (open circles, taken from Ref. [4]) and in 6% most central Au+Au collisions at $\sqrt{s_{nn}}=19.6$, 56, 130, and 200 GeV (full circles, taken from Ref. [4]) are plotted as function of $\sqrt{s_{nn}}$ in Fig. 3. In Fig. 3 the full and open triangles are the corresponding re-

sults from LUCIAE calculation with and without the reduction of s quark suppression, respectively. The LUCIAE results for ϕ meson are given by full and open squares (scaled by 100) for, respectively, with and without the reduction of s quark suppression. Fig. 3 turns out that the LUCIAE model fairly

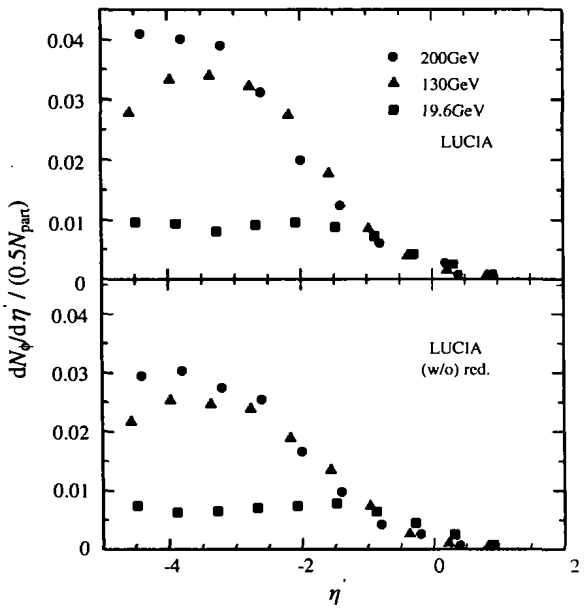

Fig. 2 Shifted pseudorapidity density distribution of ϕ meson per participant pair in 6% most center Au+Au collisions at $\sqrt{s_{nn}}$ = 19.6, 130, 200 GeV from LUCIAE calculations with (upper panel) and without (lower panel) reduction of s quark suppression

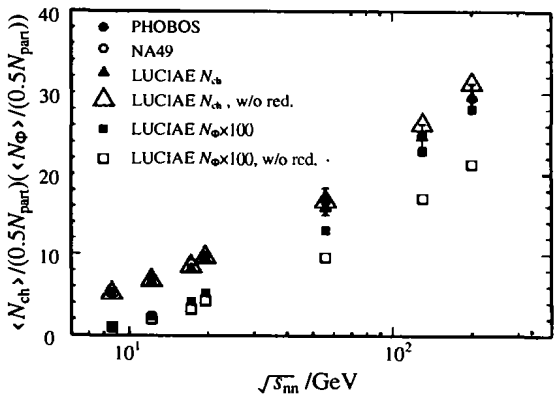

Fig. 3 Charged multiplicity (ϕ meson yield) per participant pair in Pb+Pb and Au+Au collisions at SPS and RHIC energies as a function of $\sqrt{s_{nn}}$.

reproduces the experimental $\sqrt{s_{nn}}$ dependence of the charged multiplicity per participant pair in Pb+Pb and Au+Au collisions at SPS and RHIC energies. For ϕ meson, only the LUCIAE calculations without the reduction of s quark suppression depend on $\sqrt{s_{nn}}$ in nearly the same way as the charged particle.

In the left panel of Fig. 4 the PHOBOS observation of approximate $\langle N_{part}\rangle$ scaling for total charged multiplicity in Au+Au collisions at $\sqrt{s_{nn}}$ = 200 GeV[4] is given by full circle with error bar. The corresponding LUCIAE results with and without reduction of s quark suppression are given by full and open triangles. Full and open squares are the results of ϕ meson from LUCIAE calculations with and without the reduction of s quark suppression, respectively. One sees in left panel that the ϕ meson yields per participant pair from LUCIAE calculations without the reduction of s quark suppression parallel to the corresponding charged multiplicity better than ones from LUCIAE calculations with the reduction of s quark suppression. The left panel shows also that for charged particle although the LUCIAE results are compatible with PHOBOS data within error bar, but the LUCIAE results violate $\langle N_{part}\rangle$ scaling stronger than PHOBOS data. That may attribute to the discrepancy in $\langle N_{part}\rangle$ definition and calculation between PHOBOS and LUCIAE model as mentioned in Ref. [31]. To this end, in right panel we compare the PHOBOS data to the results (open triangles for $\langle N_{ch}\rangle$ and open squares for $\langle N_\phi\rangle$) from a calculation where $\langle N_{ch}\rangle(\langle N_\phi\rangle)$ is from LUCIAE but the $\langle N_{part}\rangle$ from PHOBOS[3] (corresponding to the same percentile of the total cross section as in LUCIAE calculation). The full triangles and full squares in right panel are the same as that in left panel. We see in right panel that using a single value of $\langle N_{ch}\rangle$ ($\langle N_\phi\rangle$) from LUCIAE but dividing it by $\langle N_{part}\rangle$ from deferent calculation, one from PHOBOS and the other from LUCIAE, the resulted $\langle N_{ch}\rangle/(0.5\langle N_{part}\rangle)(\langle N_\phi\rangle/(0.5\langle N_{part}\rangle))$ depends on $\langle N_{part}\rangle$ in different way. Thus the above PHOBOS observation is model dependent indeed.

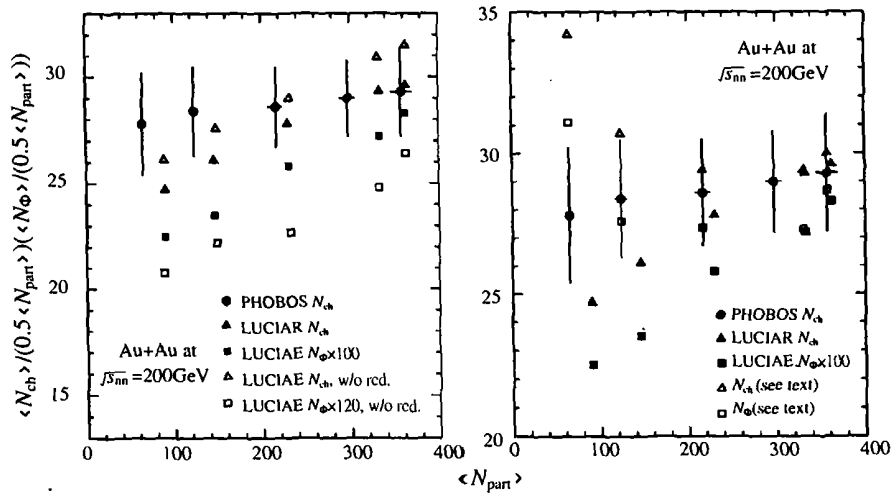

Fig. 4 The $\langle N_{part}\rangle$ scaling of total charged multiplicity (ϕ meson yield) per participant pair in Au+Au collisions at $\sqrt{s_{nn}}$=200 GeV.

In summary, we have modified the LUND string fragmentation function that its a and b parameters are first adjusted roughly to the experimental data of charged multiplicity in Au+Au collisions at RHIC energies[3, 4]. The fitted a and b parameters are then employed to study the three empirical scaling rules for both the charged multiplicity and the ϕ meson. It is turned out that the three empirical observations for the charged multiplicity[3, 4] could be fairly reproduced by the LUCIAE model. However, for ϕ meson it is either kept only or kept better in the LUCIAE calculation without the reduction mechanism of s quark suppression. It seems an evidence that the ϕ meson production may not distinguish from the charged particle in string fragmentation regime, except the mechanism of the reduction of s quark suppression extra introduced for the strangeness in LUCIAE model. Because the PHOBOS observations rely strongly on the number of participant nucleon and PHOBOS's $\langle N_{part}\rangle$ is extracted based on HIJING[11], the PHOBOS's three empirical scaling rules are model dependent.

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在 RHIC 的极限碎裂和 φ 介子产生*

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摘　要：利用强子和串级联模型 LUCIAE 研究了 PHOBOS 的极限碎裂等以及在 PHIC 进行的 Au＋Au 碰撞中带电粒子多重性的经验标度规律. 对 φ 介子的产生机制也通过与带电粒子多重性的比较进行类似的研究. 结果似乎表明在串级碎裂模型中带电粒子和 φ 介子有共同的产生机制. 还讨论了 PHOBOS 经验标度规律的模型依赖性.

关 键 词：极限碎裂；带电粒子的能量依赖；参加对标度；π 介子；LUCIAE 模型

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