"Wounded" quarks and diquarks in high energy collisions

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Particle production in Au-Au, Cu-Cu, d-Au, and p-p collisions at 200 GeV c.m. energy are analyzed in the wounded quark-diquark model. Existing data are well reproduced. Emission functions of wounded and unwounded constituents are determined. Implications for the collective evolution of the system are discussed.

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I. INTRODUCTION

It is now well established that the idea of a "wounded" source of particles [1] turned out rather useful in description of particle production from nuclear targets [2]. It seems therefore interesting to verify to what extent the recent high energy data confirm this hypothesis and what are its consequences for the evolution of the system created in heavy ion collisions at high energy. This is the subject of the present paper.

A wounded source, by definition, emits a fixed density of particles, independently of the number of collisions it underwent inside the nucleus. To understand the physical meaning of this concept, let us recall the original argument leading to this idea.

The idea can be understood if one observes that the process of particle production is not instantaneous. This was first noted (and the consequences for scattering at high energies derived) by Landau and Pomeranchuk [3]. A simplified version of the argument can be presented as follows.

Consider a particle created in a high-energy collision. In the reference frame where the longitudinal momentum of this particle vanishes, the minimal time necessary for its creation is $t_0 \geqslant 1/m_t$ where $m_t = \sqrt{m^2 + p_t^2}$ is its energy. Consider now the "laboratory" frame where the target nucleus is at rest. In this frame the particle in question acquires some longitudinal momentum, the time is multiplied by the Lorentz factor, and we have

$$t = \gamma t_0 \geqslant \frac{E}{m_t^2} = \frac{\cosh y_{\text{lab}}}{m_t}, \qquad (1)$$

where E is the energy of the particle. Consequently, the uncertainty of the distance from the collision point to that at which the particle is created (i.e., the resolving power of the longitudinal distance) is

$$l = vt \geqslant \frac{\sinh y_{\text{lab}}}{m_t}. \qquad (2)$$

When this distance is longer than the size of the nucleus, $Z(b)$, at a given impact parameter, i.e., when the rapidity of the produced particle is large enough, the particle cannot resolve individual collisions and therefore it is natural to admit that its creation may be insensitive to the number of collisions of the source. This is the origin of the idea of

wounded sources and it is clear that it makes sense only when one considers production of particles with the laboratory rapidity exceeding that determined by the condition $l \geqslant Z(b)$. But at small laboratory rapidities particle production from a fast-moving source is anyway expected to be small (if not negligible). Therefore the concept of the wounded source can be applied in practice in the whole rapidity region.

It was recently shown [4] that the idea of wounded constituents of the nucleon can successfully explain the centrality dependence of particle production at $\eta = 0$ in Au-Au collisions at RHIC [5]. Assuming that high energy interactions of nucleons are dominated by independent interactions of its two constituents, a quark and a diquark (each one producing the same particle density), it was possible to explain the small momentum transfer elastic pp and πp scattering [6] as well as energy and centrality dependence of particle production in Au-Au collisions at the same time.[1]

Encouraged by these results, in the present paper we extend the analysis to rapidities in a wide range beyond the central region using data on particle production in p-p, d-Au, Au-Au, and Cu-Cu collisions at 200 GeV c.m. energy.

Our main conclusion is that the data are in reasonable agreement with the wounded quark-diquark model in a wide range of rapidities excluding, however, the narrow target and projectile fragmentation regions. In the fragmentation regions two additional contributions could be identified:

(i) First, it is necessary to account for the decay products of the constituents which did not interact ("unwounded") but belong to a wounded nucleon. Since such constituents are colored, they have to decay into observable particles.

(ii) One also has to take into account particle production by secondary interactions of particles produced by the projectile inside the nucleus. Since, as already explained, the fast particles (in the rest frame of the nucleus) are produced outside the nucleus, the secondary interaction may only produce particles which are slow in the rest frame of the nucleus.

In the next section we present a general formulation of the model. The d-Au collisions are discussed in Sec. III and the nucleus-nucleus collisions in Sec. IV. Our conclusions

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[1]Other efforts in this direction can be found in [7].

are listed in the last section where also some comments are
included.

II. GENERAL FORMULATION OF THE MODEL

In the central rapidity region the model predicts that the
density of particles produced in collision of nucleus A with
nucleus B is given by [4]

$$\frac{dN_{AB}(y)}{dy} \equiv \rho_{AB}(y) = w_B^{(c)} F_B(y) + w_A^{(c)} F_A(y), \qquad (3)$$

where $w_{A,B}^{(c)}$ is the number of wounded constituents (quarks and
diquarks) in the nucleus $A(B)$, whereas F_A and F_B are particle
densities emitted by one wounded quark or diquark in the
nucleus A and B, respectively. Evaluation of $w^{(c)}$ for various
processes considered in this paper is given in the Appendix.

In the c.m. system we have, of course,

$$F_B(y) = F_A(-y) \equiv F(y), \qquad (4)$$

where from now on, y shall always denote rapidity in the c.m.
frame.

As explained in the Introduction, to extend the description
to the region close to the maximal and minimal rapidities, it is
necessary to take into account at least two other contributions
to particle production. Taking this into account, Eq. (3) is
modified into

$$\rho_{AB}(y) = w_B^{(c)} F(y) + w_A^{(c)} F(-y) + \bar{w}_B^{(c)} U(y) + \bar{w}_A^{(c)} U(-y)$$
$$+ C_B(y) + C_A(-y), \qquad (5)$$

where $U(y) \equiv U_B(y) = U_A(-y)$ represents the contribution
from the decay of one unwounded constituent (but belonging
to a wounded nucleon) and $\bar{w}_{A,B}^{(c)}$ is the number of unwounded
constituents in the nucleus $A(B)$. It can be simply determined
using our assumption that each nucleon consists of two active
constituents (a quark and a diquark)

$$w_{A,B}^{(c)} + \bar{w}_{A,B}^{(c)} = 2w_{A,B}, \qquad (6)$$

where $w_{A,B}$ is the number of wounded nucleons in the nucleus
$A(B)$.

The terms C_A and C_B represent the "intranuclear cascade",
i.e., the contribution from secondary interactions of particles
created inside the nucleus.

The contributions U_A and C_A are expected to be significant
only at y close to $-Y$ (the c.m. rapidity of the nucleon in
nucleus A). Similarly the U_B and C_B are expected to be
significant only at y close to Y.

In nucleon-nucleon collisions, the "cascade" contribution
is absent and we obtain

$$\rho_{NN}(y) = w_N^{(c)} [F(y) + F(-y)] + \bar{w}_N^{(c)} [U(y) + U(-y)], \quad (7)$$

where from the analysis of elastic pp data we have found [4]
that $w_N^{(c)} = 1.187$. Following Eq. (6) we obtain $\bar{w}_N^{(c)} = 0.813$.

The two equations (5) and (7) describe the relation between
particle production in nucleon-nucleon, nucleon-nucleus, and
nucleus-nucleus collisions implied by the model. They de-
scribe the data in terms of three unknown functions. Since these
functions have a well defined physical meaning, the important
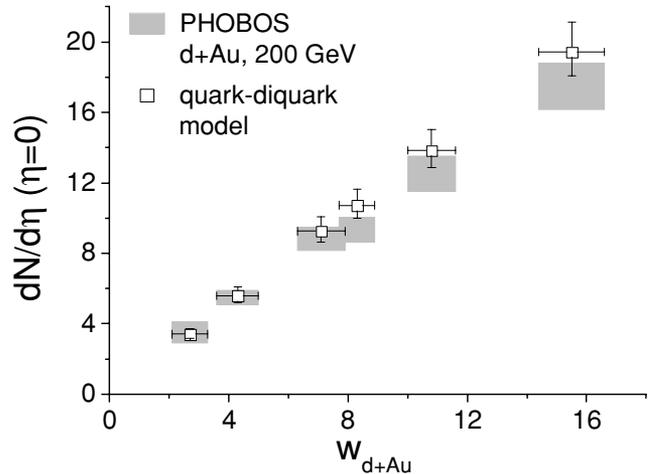
FIG. 1. Wounded quark-diquark model compared with the midra-
pidity d-Au data from PHOBOS Collaboration.

result of our investigation is not only to verify the validity of
Eqs. (5) and (7) but also determination of the emission function
of a wounded constituent $F(y)$, the decay distribution of an
unwounded constituent $U(y)$ and the "cascade" contribution
$C(y)$.

III. d-Au COLLISION

The PHOBOS data on charged particle production in d-Au
collisions at $\sqrt{s} = 200$ GeV [8] cover the c.m. pseudorapidity
range $|\eta| \leqslant 5.3$.

The first step is to check if the data are consistent with
the model at $\eta = 0$, where the simple formula [implied by
Eqs. (3) and (7)]

$$\rho_{d-Au}(0) = \rho_{NN}(0) \frac{w_{Au}^{(c)} + w_d^{(c)}}{2w_N^{(c)}} \qquad (8)$$

holds with $\rho_{NN}(0)$ being the density of particles produced in
a single pp collision at $\eta = 0$. In the further calculations we
take $\rho_{NN}(0) = 2.31^{+0.2}_{-0.16}$ [9]. In Fig. 1 $dN_{d-Au}/d\eta$ at $\eta = 0$ is
plotted versus $w_{d+Au} = w_{Au} + w_d$ (number of wounded nu-
cleons in both colliding nuclei) and compared with the model
prediction (8). One sees that, within substantial experimental
errors, the data are consistent with the model.[2] It is also seen,
however, that the data for most central collisions are somewhat
below the results given by Eq. (8).

To investigate the rapidity region outside $y = 0$, we first
ignore the "intranuclear cascade" contributions C_d and C_{Au}.
This simplification allows to investigate the data in terms of
only two functions: $F(y) \equiv F_d(y) = F_{Au}(-y)$ and $U(y) \equiv
U_d(y) = U_{Au}(-y)$, being the densities of particles produced
from one wounded or unwounded constituent, respectively.
This condition is well justified for the deuteron since the
intranuclear cascade in this case is negligible. On the other

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[2]The errors in model prediction reflect the inaccuracy in the pp
data, i.e., $\rho_{NN}(0)$.
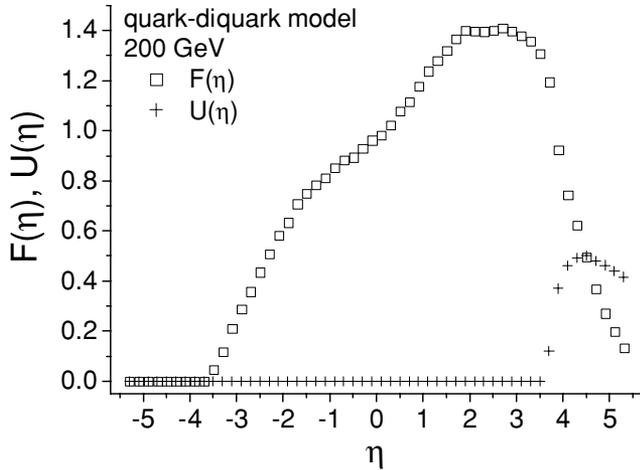
FIG. 2. The densities of particles produced from one constituent at $\sqrt{s} = 200$ GeV. Squares: wounded, $F(\eta)$; Crosses: unwounded, $U(\eta)$.

hand, we expect a discrepancy in the Au fragmentation region. This discrepancy provides a measure of the effect.

We construct $F(\eta)$ and $U(\eta)$ using the PHOBOS d-Au data [8]. First, to avoid propagation of the slight difference between the model and the data observed at $\eta = 0$ (c.f. Fig. 1), we adjust data to the model at this point, multiplying at each rapidity by a constant (for each centrality) factor $\rho^{th}_{d-Au}(0)/\rho^{exp}_{d-Au}(0)$. This allows to discuss the shape of the distributions in rapidity independently of the absolute normalization (which is also consistent with the model, as seen in Fig. 1).

Next we verified that in the pseudorapidity range $|\eta| \leqslant 3.5$ the contribution from the decay of unwounded constituents is not necessary for description of data and thus one can take $U(\eta) = 0$. It means that the data in this region can be described solely in terms of wounded constituents. This was confirmed by analyzing the data on the deuteron side ($0 \leqslant \eta \leqslant 5.3$) in terms of three functions: $F_d(\eta) = F(\eta)$, $F_{Au}(\eta) = F(-\eta)$ and $U_d(\eta) = U(\eta)$. From this analysis we have also found that $F_{Au}(\eta) = 0$ for $\eta > 3.5$.

Using these findings and the 20–40% centrality PHOBOS data[3] it was possible to determine $F(\eta)$ for $|\eta| \leqslant 3.5$. For $\eta > 3.5$ we used the 20–40% and 40–60% centrality PHOBOS data to obtain both $F(\eta)$ and $U(\eta)$.

In Fig. 2 the functions $F(\eta)$ and $U(\eta)$ are shown. One sees that, as expected [10–12], $U(\eta)$ is confined to the region close to the maximal rapidity. One also observes that $F(\eta)$ is negligible for $\eta \leqslant -3.7$.

Using these $F(\eta)$ and $U(\eta)$ one could evaluate the predictions of the model for all centralities and in the full rapidity range. The results are compared to the PHOBOS [8] and STAR [13] data in Fig. 3. One sees that the agreement is satisfactory for $\eta \geqslant -4$. The discrepancy for $\eta < -4$ can be attributed to the additional "cascade" contribution which is expected in the Au fragmentation region. Large errors do not
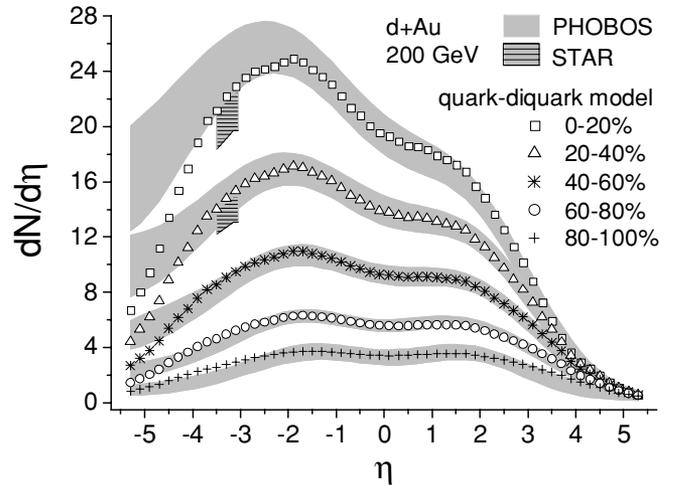
FIG. 3. Wounded quark-diquark model compared to d-Au data from the PHOBOS and STAR Collaborations. The data are normalized to the model prediction at $\eta = 0$. One sees a generally good agreement except in the Au fragmentation region where the contribution from secondary interactions inside the target apparently becomes important.

allow us, unfortunately, to perform a more quantitative analysis of this phenomenon.

All in all, the results presented in Fig. 3 show that the model describes correctly the data.

Since the functions F and U are now determined, it is possible to construct the model prediction for pp collisions. In Fig. 4 this is confronted with preliminary pp PHOBOS data [9]. We see that the agreement is very good. For comparison we also present the prediction of the model without contribution from unwounded constituents. It appears that this contribution is indeed needed.

We feel that this result indicates that the physics of particle production in pp and d-Au collisions is basically the same
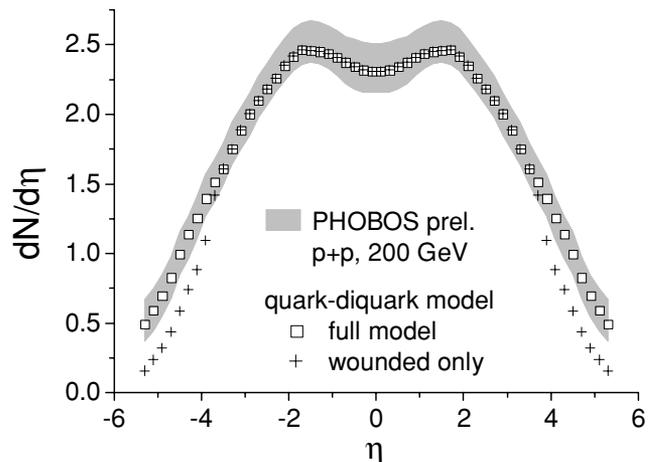
FIG. 4. Wounded quark-diquark model compared with the preliminary pp PHOBOS data. For comparison we also present the prediction without contribution from unwounded constituents. One sees that it is necessary to account for the data.

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[3]For the $\eta < 0$ one observes a certain difference between the STAR and PHOBOS data for 0–20% centrality. Therefore we preferred to take the 20–40% centrality where this difference is much smaller.
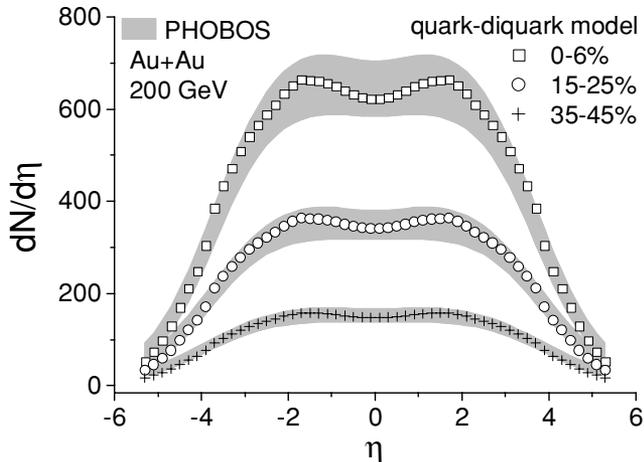
FIG. 5. Wounded quark-diquark model compared with the Au-Au data from PHOBOS Collaboration.

(apart from the trivial difference in the form of intranuclear cascade).

It may be interesting at this point to speculate about the possible mechanism which may lead to the results for $F(\eta)$ and $U(\eta)$ shown in Fig. 2. The very broad rapidity distribution of particles emitted by the wounded source suggests a colour-exchange mechanism. The simplest possibility is the multigluon exchange between the projectile and target (every gluon exchange changes the color of the source and thus may lead to particle production). Since every constituent consists of many partons and since the probability of exchanging a gluon between two partons does not depend on their rapidity difference (gluon is a particle of spin 1), one may fairly easily obtain a rather broad rapidity distribution of the produced particles. As discussed in [14,15] this picture can naturally accommodate the asymmetric shape of $F(\eta)$ (the shoulder seen at $\eta = -1$ is, most likely, the kinematic effect related to the transformation from rapidity to pseudorapidity). On the other hand, particle production from the unwounded source can be understood as resulting from the decay of a string spanned between the wounded and unwounded constituent. The details of this picture and its derivation from fundamental theory represents an interesting problem which, however, goes beyond the scope of the present investigation.

IV. Au-Au AND Cu-Cu COLLISIONS

In Fig. 5 we compare the predictions of the wounded quark-diquark model with the PHOBOS data [5] in Au-Au collisions. This observation shows that the intranuclear cascade is not effective for central nucleus-nucleus collisions,[4] thus suggesting that the secondary interactions in the nucleus lead to particle production mainly if they happen on the spectator nucleons. It would be interesting to investigate this point in more detail when more precise data are available.

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[4] A closer look shows that there is some indication of discrepancy in the fragmentation region in case of most peripheral collisions.
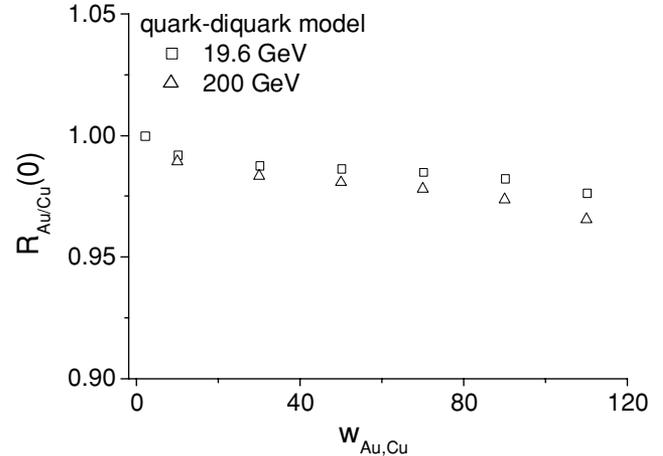
FIG. 6. The ratio of density of particles produced at midrapidity in Au-Au collisions to that produced in Cu-Cu collisions at the same number of wounded nucleons. For comparison we also present the results at 19.6 GeV c.m.

The values of the numbers of wounded constituents for various centralities are given in the Appendix.

We have found in the previous section that $F(\eta)$, the contribution form wounded constituents, largely dominates the spectrum in the region $|\eta| \leqslant 4.5$. It then follows from Eq. (5) that, for symmetric nucleus-nucleus collisions, the ratio of particle densities produced by various nuclei must be a constant, independent of η. Indeed, we have

$$R_{\text{Au/Cu}}(\eta) \equiv \frac{\rho_{\text{AuAu}}(\eta)}{\rho_{\text{CuCu}}(\eta)} = \frac{w_{\text{Au}}^{(c)}}{w_{\text{Cu}}^{(c)}} = R_{\text{Au/Cu}}(0). \qquad (9)$$

This consequence of the model is known to be very well satisfied by Au-Au and Cu-Cu data [16].

In Fig. 6 $R_{\text{Au/Cu}}(0)$ evaluated from the model is shown versus the number of wounded nucleons (the same for Au and Cu). One sees that it is very close to 1, also in agreement with data [16].

V. CONCLUSIONS AND COMMENTS

Our conclusions can be formulated as follows.

(i) We have compared the wounded quark-diquark model with the PHOBOS data on particle production in p-p, d-Au, Cu-Cu, and Au-Au collisions at 200 GeV c.m. energy in the full range of rapidity. The shape of the rapidity distribution is well reconstructed. The overall normalization of the d-Au data is not described so well, although it is consistent with the model within the (still rather large) experimental uncertainties.

(ii) The particle emission function from one wounded constituent is determined. Its most important features are (a) a large maximum in the forward direction; (b) a significant fraction of particles emitted in the backward hemisphere; (c) strong suppression of particle emission in the target fragmentation region.

(iii) Particle emission from unwounded constituents contributes only to the fragmentation region of the projectile.

(iv) Particle production from secondary interactions inside the nucleus are confined to its fragmentation region, in agreement with theoretical expectations. These secondary interactions seem to have stronger effect on particle production in nucleon-nucleus than in the central nucleus-nucleus collisions.

(v) For the good agreement of the model with data it was crucial to accept that each wounded constituent emits the same density of particles. This somewhat surprising result indicates that intensity of particle emission is mainly determined by the color content of the source (the color content of quark and diquark are the same). This suggests the color-exchange models as a possible mechanism responsible for particle production, in harmony with the discussion at the end of Sec. III.

The following comments are in order.

(i) Contrary to the common prejudice, good agreement of the wounded constituent model with Au-Au and Cu-Cu data is *not* in contradiction with the collective phenomena observed in heavy ion collisions. It only shows that in all hadronic collisions *the early stage* of the particle production process can be understood as a superposition of contributions from hadronic constituents. This does not preclude further collective evolution of the system which obviously must be more visible in the system produced in collision of two heavy nuclei than, e.g., in nucleon-nucleon collision.

(ii) The wounded constituent picture has, however, important consequences for the properties of the hot matter created in heavy ion collisions. First of all, it implies that most of the entropy must be produced already at the very early stage of the collision. It also implies rather early equilibration in transverse direction, presumably already at the level of nucleon-nucleon collisions [17–19]. Finally, the absence of the visible effects of the longitudinal pressure in Au-Au collisions (which would modify somewhat the rapidity distribution) suggests that the early evolution of the plasma may be dominated by the purely *transverse* hydrodynamic expansion while the longitudinal evolution is described by free-streaming. This possibility (which solves the "problem of early equilibration") was investigated recently [20] and shown to be in agreement with data on elliptic flow. One may thus consider our result as an indirect confirmation of the hypothesis formulated in [20].

(iii) The model describes particle production in nucleon-nucleon collisions as emission from two (left- and right-moving) sources, both populating most of the available phase-space. This picture suggests presence of specific long-range, forward-backward correlations. It would be interesting to study these correlations in more detail.

(iv) In the present investigation we have entirely neglected the possible dependence on transverse mass, thus implicitly assuming that m_t distributions do not vary significantly with the varying centrality of the collision.

This is approximately correct for the bulk of created particles (mostly pions at small transverse momentum) but it would be certainly interesting to investigate limits of the wounded constituent model at higher transverse momenta and for heavy particles.

(v) The model provides a natural qualitative explanation of the "stopping" of a high-energy nucleon in a collision with the heavy nucleus [21]. Indeed, since the contribution from an unwounded constituent dominates the very end of rapidity phase-space and since the number of unwounded constituents in the nucleon passing through a nucleus is smaller than that in a nucleon-nucleon collision, one expects less high-energy nucleons in the former case. A quantitative estimate of this effect may provide information about the momentum distribution of the constituents (quark and diquark) inside the nucleon.

APPENDIX: ESTIMATE OF THE NUMBER OF WOUNDED CONSTITUENTS

A. Au-Au

Evaluation of the number of wounded quarks and diquarks $w_{\rm Au}^{(c)}$ in Au-Au collision is described in detail in [4]. For the three centralities, 0–6%, 15–25%, and 35–45%, presented in Fig. 5 we obtain $w_{\rm Au}^{(c)} = 320, 175$, and 76, respectively. The number of unwounded constituents is determined from Eq. (6) with the values $2w_{\rm Au}$ taken from [5] ($2w_{\rm Au} = 344$, 200, and 93, respectively). The same procedure is used for Cu-Cu collisions.

B. *d*-Au

Evaluation of the number of wounded quarks and diquarks in the *d*-Au system is somewhat more complicated. First we assume that each wounded nucleon in Au is hit only once,[5] so the number of wounded constituents in Au is given by $w_{\rm Au}^{(c)} = w_{\rm Au} w_N^{(c)}$, where $w_{\rm Au}$ is the number of wounded nucleons in Au (provided by the PHOBOS Collaboration [8]) and $w_N^{(c)} = 1.187$ [4].

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[5]This is a good approximation since there is no significant difference between the number of wounded nucleons in Au and the number of collisions [8].

To estimate the number of wounded quarks and diquarks in the deuteron let us first consider the nucleon-nucleus collision.

The average number of wounded quarks $w_{N,k}^{(q)}$ in the nucleon which underwent k inelastic collisions is given by the straightforward counting of probabilities

$$w_{N,k}^{(q)} = 1 - (1 - p_q)^k, \tag{A1}$$

where p_q is the probability for a quark to interact in a single pp collision. In [4] we have found that $p_q \approx w_N^{(c)}/3 = 0.395$. One can write analogous formula for $w_{N,k}^{(\text{diq})}$, i.e., number of wounded diquarks in the nucleon which underwent k inelastic collisions.

Thus, the number of wounded constituents (quarks and diquarks) in the nucleon which underwent k inelastic collisions is

$$w_{N,k}^{(c)} = 2 - (1 - p_q)^k - (1 - p_{\text{diq}})^k, \tag{A2}$$

where p_{diq} is the probability for a diquark to interact in a single pp collision and $p_{\text{diq}} \approx 2p_q = 0.79$.

For the average number $\langle k \rangle$ of collisions per one wounded nucleon in deuteron we take $\langle k \rangle = n_{\text{coll}}/w_d$, using the values of n_{coll} (number of collisions) and w_d (number of wounded nucleons in deuteron) given by the PHOBOS Collaboration [8].

Replacing in Eq. (A2) k by $\langle k \rangle$ we obtain[6] $w_{N,\langle k \rangle}^{(c)}$ and, finally, the number of wounded constituents $w_d^{(c)}$ in deuteron for a given n_{coll} and w_d reads

$$w_d^{(c)} = w_d w_{N,\langle k \rangle}^{(c)}. \tag{A3}$$

This procedure gives $w_d^{(c)} = 3.95, 3.66, 3.1, 2.3, 1.6$ for 0–20%, 20–40%, 40–60%, 60–80%, and 80–100% centrality, respectively.

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[6]We have verified that for the Glauber distribution the error induced by replacing k by $\langle k \rangle$ does not change the results significantly.

[1] A. Bialas, M. Bleszynski, and W. Czyz, Nucl. Phys. **B111**, 461 (1976); A. Bialas, W. Czyz, and W. Furmanski, Acta Phys. Pol. B **8**, 585 (1977).

[2] See, e.g., W. Busza, Acta Phys. Pol. B **35**, 2873 (2004).

[3] L. Landau and I. Pomeranchuk, Dokl. Akad. Nauk **92**, 535 (1953); **92**, 735 (1953); L. Stodolsky, Proceedings of VI ICMD, Rutherford Lab., 1975, p. 577.

[4] A. Bialas and A. Bzdak, Phys. Lett. **B649**, 263 (2007).

[5] B. B. Back *et al.* (PHOBOS Collaboration), Phys. Rev. C **65**, 061901(R) (2002); **70**, 021902(R) (2004); **74**, 021901(R) (2006).

[6] A. Bialas and A. Bzdak, Acta Phys. Pol. B **38**, 159 (2007); A. Bzdak, Acta Phys. Pol. B **38**, 2665 (2007).

[7] R. Nouicer, AIP Conf. Proc. **828**, 11 (2006); S. Eremin and S. Voloshin, Phys. Rev. C **67**, 064905 (2003); P. K. Netrakanti, and B. Mohanty, *ibid.* **70**, 027901 (2004); B. De and S. Bhattacharyya, *ibid.* **71**, 024903 (2005); E. K. G. Sarkisyan and A. S. Sakharov, AIP Conf. Proc. **828**, 35 (2006); arXiv: hep-ph/0410324.

[8] B. B. Back *et al.* (PHOBOS Collaboration), Phys. Rev. C **72**, 031901(R) (2005).

[9] R. Nouicer *et al.* (PHOBOS Collaboration), J. Phys. G **30**, s1133 (2004), arXiv: nucl-ex/0403033.

[10] A. Bialas and E. Bialas, Phys. Rev. D **20**, 2854 (1979).

[11] A. Dar and F. Takagi, Phys. Rev. Lett. **44**, 768 (1980).

[12] A. Bialas, W. Czyz, and L. Lesniak, Phys. Rev. D **25**, 2328 (1982).

[13] B. I. Abelev *et al.* (STAR Collaboration), arXiv: nucl-ex/0703016.

[14] A. Bialas and M. Jezabek, Phys. Lett. **B590**, 233 (2004).

[15] A. Bialas and W. Czyz, Acta Phys. Pol. B **36**, 905 (2005).

[16] see Fig. 5 in G. Roland *et al.* (PHOBOS Collaboration), Nucl. Phys. **A774**, 113 (2006).

[17] F. Becattini, Z. Phys. C **69**, 485 (1996).

[18] A. Bialas, Phys. Lett. **B466**, 301 (1999).

[19] S. Steinke and J. Rafelski, J. Phys. G **32**, 455 (2006).

[20] A. Bialas, M. Chojnacki, and W. Florkowski, arXiv: 0708.1076; M. Chojnacki and W. Florkowski, arXiv: 0710.5871.

[21] W. Busza and A. Goldhaber, Phys. Lett. **B139**, 235 (1984).