WOUNDED-QUARK EMISSION FUNCTION IN ASYMMETRIC HEAVY-ION COLLISIONS

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The wounded-nucleon and -quark models (WNM, WQM) are compared using d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The shape of the wounded-quark emission function seems to be universal for different centralities, in contrast to the wounded-nucleon emission function. Predictions for $dN_{ch}/d\eta$ distributions for various centrality classes in $p+Al$, $p+Au$, $d+Au$, and $^3He+Au$ collisions are presented and compared to recent PHENIX results.

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1. Introduction

The wounded-nucleon and -quark models (WNM, WQM), among others, are frequently used [1–14] to describe soft particle production in relativistic heavy-ion collisions. In WNM, nucleus–nucleus collision is considered as multiple nucleon–nucleon interactions [1]. Any nucleon from one nucleus colliding inelastically with at least one nucleon from another nucleus is called a “wounded” nucleon and is assumed to populate charged particles independently of the number of collisions it undergoes. On the other hand, in WQM, it is postulated that a heavy-ion collision consists of quark–quark interactions [2]. By analogy, the wounded quarks produce particles independently of the number of collisions.

Deuteron–gold ($d+Au$) collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the PHOBOS Collaboration at the Relativistic Heavy Ion Collider (RHIC) [15] were used to compare both models. The wounded-source emission functions $F(\eta)$ (pseudorapidity single particle density originating from one wounded source) for different centralities were extracted using the PHOBOS data and our Monte Carlo Glauber simulations.

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2. Two models

As described in detail in Ref. [16], WNM and WQM were taken into consideration. In both cases, the charged particle multiplicity distribution is given by

\[
\frac{dN_{\text{ch}}}{d\eta} = w_L F(\eta) + w_R F(-\eta),
\]

where in the wounded-nucleon (-quark) model, \( F(\eta) \) is the wounded-nucleon (-quark) emission function, \( w_L \) and \( w_R \) are the average numbers of the left-going and the right-going wounded nucleons (quarks), respectively. If \( w_L \neq w_R \), the wounded-source emission function can be extracted separately for each centrality

\[
F(\eta) = \frac{1}{2} \left[ \frac{N(\eta) + N(-\eta)}{w_L + w_R} + \frac{N(\eta) - N(-\eta)}{w_L - w_R} \right],
\]

where \( N(\eta) := \frac{dN_{\text{ch}}}{d\eta} \) is taken from the PHOBOS measurement on \( d+Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV [15].

In our Monte Carlo Glauber simulation, the positions of nucleons in the gold nucleus are drawn according to the Woods–Saxon distribution [17, 18], whereas in the deuteron, the proton’s position is taken from the Hulthen distribution and the neutron is placed opposite to the proton [17, 19]. Two nucleons collide if a transverse distance, \( d \), between them is \( d \leq \sqrt{\sigma_{nn}/\pi} \). The inelastic nucleon–nucleon cross section \( \sigma_{nn} = 41 \) mb corresponds to \( \sqrt{s_{NN}} = 200 \) GeV [17].

Wounded nucleons populate particles according to a negative binomial distribution (NBD) with \( \langle n \rangle = 5 \) and \( k = 1 \) [20], where \( k \) measures the deviation from the Poisson distribution. For each centrality bin, \( w_L \) and \( w_R \), were calculated to complete Eq. (2).

In WQM, the positions of three constituent quarks around the center of each nucleon were drawn using \( g(\vec{r}) = g_0 \exp(-r/a) \), where \( a = r_p/\sqrt{12} \) with \( r_p = 0.81 \) fm being the proton’s radius [6, 21].

Quarks collide if \( d \leq \sqrt{\sigma_{qq}/\pi} \), where \( \sigma_{qq} \) is the inelastic quark–quark cross section. We took \( \sigma_{qq} \approx 7 \) mb to reproduce \( \sigma_{nn} = 41 \) mb [16]. Each wounded quark emits charged particles according to NBD with \( k_q = k_p/1.3 \) and \( \langle n_q \rangle = \langle n_p \rangle/1.3 \), where \( k_p = 1 \) and \( \langle n_p \rangle = 5 \) are the parameters of NBD used in our WNM calculations.

\[\text{Quarks are shifted so that their center of mass is the center of a nucleon and we actually used } \tilde{g}(\vec{r}) = g_0 \exp(-C r/a). \text{ } C = 0.82 \text{ was determined by the trial and error method.}\]
3. Results

Using Eq. (2), the wounded-nucleon emission function was extracted for different centrality bins and is shown in Fig. 1 (left)\(^2\). Apparently, the shape of \( F(\eta) \) is different for various centralities.

![Fig. 1. The wounded-nucleon (left) and -quark (right) emission functions extracted from PHOBOS \( d+Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV. For clarity, the uncertainty bars are shown only for a limited number of points.](image)

The extracted wounded-quark emission function, shown in Fig. 1 (right), is virtually universal for different centrality classes, see Ref. [16] for details. This observation was also verified recently in Ref. [22]. This could imply that the soft particle production in \( d+Au \) collisions is better described by WQM rather than WNM. Note that the wounded-quark emission function is physically meaningful for \(|\eta| \leq 3\) because in the fragmentation regions, other effects should be taken into account, \( e.g. \) contributions from unwounded quarks (within wounded nucleons) [5].

These results encouraged us to make predictions for \( p+Al, p+Au, d+Au, \) and \(^3\)He+Au collisions at the same energy for various centralities (as requested by the PHENIX Collaboration). We assumed that the wounded-quark emission function \( F(\eta) \) is universal also for various asymmetric systems at the same energy. Then, we determined \( w_L \) and \( w_R \) for each centrality class and using Eq. (1) we computed \( dN_{ch}/d\eta \) distributions for all colliding systems. The minimum-bias wounded-quark emission function \( F(\eta) \) has been used. The results are presented in Fig. 2. A very recent paper by the PHENIX Collaboration shows that the wounded-quark model with its universal wounded-quark emission function can reasonably well describe all measured asymmetric collisions [23].

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\(^2\) The errors represent the systematic uncertainties of \( N(\eta) \). Thus, they are not expected to influence the shape of \( F(\eta) \).
4. Conclusions

To summarize, we argued that the wounded-quark emission function has a universal shape for various centrality classes (within uncertainties) in the range of $|\eta| \leq 3$, whereas the wounded-nucleon emission function differs across centralities [16]. The latest PHENIX results show that just one common wounded-quark emission function can successfully describe different systems ($p+\text{Al}$, $p+\text{Au}$, $d+\text{Au}$, and $^{3}\text{He}+\text{Au}$) at $\sqrt{s_{NN}} = 200$ GeV as our predictions are in reasonably good agreement with their measurement [23]. It suggests that the considered heavy-ion collisions and soft particle production are quite well described by the wounded-quark model. As a next step, we plan to take unwounded quarks from wounded nucleons into account for regions $|\eta| > 3$ and also to study larger colliding systems such as $\text{Au}+\text{Au}$ or $\text{Cu}+\text{Cu}$. For further research, it would be valuable to study event-by-event fluctuations of $F(\eta)$ as well as to verify the model at different energies.
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