Chromoelectric flux tubes and the transverse-momentum distribution in high-energy nucleus-nucleus collisions

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Transverse-momentum distribution of quark-antiquark pairs created—through tunneling—from chromoelectric flux tubes of an arbitrary field strength spanned between two arbitrary color charges is computed and its properties discussed. It is also argued that such nonelementary flux tubes may be responsible for large-$p_\perp$ tails recently observed in nucleus-nucleus collisions at energies $\gtrsim 100$ GeV per nucleon, and for shorter $q\bar{q}$ formation times favoring appearance of $q\bar{q}$ plasma.

Recently, a model for particle production based on a decay of a $q\bar{q}$ chromoelectric flux tube through tunneling of another $q\bar{q}$ pair was proposed and discussed.[1–3] In this model, the flux tube is approximated by a uniform chromoelectric field and the process of $q\bar{q}$ pair production is treated as a tunneling effect in analogy with Schwinger's treatment of e^+e^- creation in a uniform external electric field.[4] In Refs. 1–4, the mutual interaction of the emerging pair was neglected. It was pointed out in Ref. 5 that while this assumption is perfectly justified in QED, in the case of QCD the energy of the mutual interaction E_{int} is of the same order as the energy of the quarks in the external chromoelectric field and thus can hardly be neglected. Furthermore, it was shown in Ref. 5 how to calculate, with the mutual interaction of the emerging pair included, the decay probability of the $q\bar{q}$ tube formed in the process of e^+e^- annihilation into hadrons (such tubes shall be called elementary henceforth). It was observed in Ref. 5 that the mutual $q\bar{q}$ interaction energy E_{int} is uniquely determined by the string tension σ and is equal to

$$E_{\text{int}}=2\sigma r \ , \tag{1}$$

where $2r$ is the distance between q and $\bar{q}$. The string tension is related to the quark charge g and the chromoelectric field strength ϵ by the formula[1–5]

$$\sigma=\tfrac{1}{4}g\epsilon \ . \tag{2}$$

It is worth noticing that σ given by Eq. (2) is by a factor of 2 smaller than the σ obtained for the static flux tube which is confined by an external pressure B (Ref. 6).

In the present note, we generalize the results of Ref. 5 to describe the decay of a flux tube with an arbitrary chromoelectric field $\mathscr{E}$ spanned between two color charges of size G (not necessarily equal to g). We feel that such nonelementary flux tubes can be formed in collisions of two heavy nuclei at high energies and thus this generalization may be of some practical interest. In particular, we show that this effect may possibly account for the anomalous two-component structure of the transverse-momentum distributions observed recently in nucleus-nucleus collisions at energies exceeding 100 GeV/nucleon by the Japanese-American cooperative emulsion experiment (JACEE).[7]

We write the energy balance for the tunneling $q\bar{q}$ pair as

$$2(p_L{}^2(r)+p_\perp{}^2+m^2)^{1/2}-g\mathscr{E}\,r+\tfrac{1}{2}g\epsilon r=0 \ . \tag{3}$$

Here, r is the longitudinal distance of the quark (antiquark) from the point $r=0$ from which the components of the pair start to receed from each other under the influence of the external field $\mathscr{E}$ of the nonelementary tube in which the tunneling pair is originally embedded. p_L is the longitudinal and $p_\perp$ the transverse momentum of the quark (antiquark). $-g\mathscr{E}\,r$ is the energy gained by the pair pulled apart by the field $\mathscr{E}$, and $\frac{1}{2}g\epsilon r=2\sigma r$ is the mutual interaction of the $q\bar{q}$ pair at the distance r. The right-hand side of Eq. (3) is the energy of the vacuum from which the pair is being created.

Following Ref. 5 we get for the action

$$J=2\int_0^\tau |p_L(r)|dr=\tfrac{1}{2}\pi E_\perp\tau=\frac{\pi E_\perp{}^2}{g(\mathscr{E}-\frac{1}{2}\epsilon)} \ , \tag{4a}$$

where $E_\perp{}^2=p_\perp{}^2+m^2$ and

$$\tau=\frac{E_\perp}{\frac{1}{2}g(\mathscr{E}-\frac{1}{2}\epsilon)} \tag{4b}$$

is the distance at which the virtual pair becomes real (i.e., $p_L=0$). Thus, τ can be interpreted as a formation zone (formation time) of the $q\bar{q}$ pair. Equation (4a) represents the required generalization of Eq. (6) from Ref. 5. Indeed, for the elementary tube $\mathscr{E}=\epsilon$, and we recover Eq. (6) of Ref. 5. On the other hand, when $\mathscr{E}\gg\epsilon$, we can neglect the $q\bar{q}$ interaction and we get Eq. (9) of Ref. 1.

The formula (4a) implies for the tunneling probability, in the field $\mathscr{E}$ of the tube, of a virtual pair into a real pair with each component having transverse momentum $p_\perp$ and mass m:

$$P(E_\perp)=|e^{-J}|^2=e^{-\pi E_\perp\tau}=\exp\left(-\frac{\pi E_\perp{}^2}{\frac{1}{2}g(\mathscr{E}-\frac{1}{2}\epsilon)}\right) \ . \tag{5}$$

Following Refs. 1 and 5, we obtain for the transverse-

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momentum distribution

$$\frac{dN(p_\perp)}{d^2p_\perp} \propto \ln[1-P(E_\perp)] = \sum_{n=1}^{\infty} \frac{1}{n} e^{-n\pi E_\perp \tau}$$
$$\approx e^{-\pi E_\perp \tau} = \exp\left[-\frac{\pi(p_\perp{}^2+m^2)}{\frac{1}{2}g(\mathscr{E}-\frac{1}{2}\epsilon)}\right] . \quad (6)$$

In Eq. (6), the product $g\epsilon$ is approximately determined by the experimental $p_\perp$ distribution observed in e^+e^- annihilation into hadrons (as we already noted in this case $\mathscr{E}=\epsilon$). It is thus seen from Eq. (6) that for a nonelementary chromoelectric tube, the value of the field strength $\mathscr{E}$ determines the transverse-momentum distribution. As is argued further on, such nonelementary chromoelectric flux tubes may possibly show up in some complicated hadronic interactions, in particular, in collisions of heavy nuclei at high energies.[8] It seems interesting therefore to discuss the consequences of Eq. (6) for different values of $\mathscr{E}$.

Consider first large field strengths $\mathscr{E} > \epsilon$. For such strong tubes, formula (6) implies broader (than in the case of elementary tubes) $p_\perp$ distribution and increased probability of tunneling into channels with two heavy quarks. Thus, one expects a relative enhancement of production of strange particles. Furthermore, in this case one may expect an increase of multiplicity because creation of one $q\bar{q}$ pair is not sufficient to break the tube. Indeed, from Gauss's law we have[1,5]

$$\mathscr{E} a = \tfrac{1}{2} G \ , \quad (7)$$

where a is the area of the cross section of the tube and G is the color charge at its end points. To break the tube, a pair of color charges $\bar{G}G$ must be introduced and such a pair can only be made from several elementary $q\bar{q}$ pairs. Thus, we see that the formation of a nonelementary tube with $\mathscr{E} > \epsilon$ should be signaled by observation of a simultaneous increase of $p_\perp$, m, and multiplicities of produced particles. It is amusing to note that the same effects were proposed as a signature for formation of quark-gluon plasma in collisions of heavy nuclei.[10]

For small $\epsilon > \mathscr{E} > \frac{1}{2}\epsilon$, we expect smaller (than in the case of elementary tubes) $p_\perp$ and an additional suppression of strange particles.[11] Finally, for $\mathscr{E} < \frac{1}{2}\epsilon$, the tube becomes stable against $q\bar{q}$ tunneling.

The last point we want to discuss is a possibility of formation of a very strong chromoelectric field in collisions of heavy nuclei at high energies. The additive quark model[12] and the dual parton model[13] of such collisions are rather suggestive in this respect. In the quark model, an existence of rather complicated multiquark configurations exchanging color was suggested in Ref. 12 as a generalization of the quark model of hadron-hadron[9] and hadron-nucleus[14] collisions. In this model, some tubes (called strings in Ref. 12) may be attached to several wounded quarks. This effect may lead to larger field strengths, depending on the total color charge of the quarks and the transverse cross section of the tube—according to Gauss's law (7).

In the dual parton model,[13] only elementary tubes are assumed. Nevertheless it seems likely that, due to the large density of the tubes in central nucleus-nucleus collisions, some of them shall coalesce into more composite (nonelementary) objects.

We thus conclude that popular models of particle production in hadronic collisions suggest possibilities of formation of nonelementary chromoelectric flux tubes in collisions of heavy ions at high energies.[15] Their effects should be particularly enhanced in events with large multiplicities. In this context, it is remarkable that large-$p_\perp$ tails were indeed observed recently in individual high-multiplicity nucleus-nucleus collisions by the JACEE collaboration.[7] It is therefore not unlikely that these observations indicate presence of flux tubes with large chromoelectric field strengths $\mathscr{E}$. This suggestion is strengthened further by the fact that in the same experiment such a phenomenon is not observed in proton-nucleus collisions. This is indeed expected in the quark model[15] because the tubes are always attached to just one quark of the incident proton.

It was recently suggested[17] that the observation of high transverse momenta in collisions of two heavy nuclei can be explained through a formation of a quark-gluon plasma. As we already noted, the signatures for formation of a strong chromoelectric field and of a quark-gluon plasma are conspicuously similar. We feel that a clear two-component structure seen in the events of Ref. 7 favors the interpretation advocated in the present note, i.e., the existence of regions with exceptionally strong chromoelectric field formed locally in the impact parameter plane. It requires, however, further investigations to settle the matter and to establish possible relations between the two descriptions. At this point it is interesting to note that (4b) implies that for a large field strength $\mathscr{E}$ the formation zone of $q\bar{q}$ pair is smaller than for elementary tubes. Consequently, the energy density is in this case very likely much higher than in ordinary collisions[17] and thus formation of the quark-gluon plasma much easier.

It was also suggested recently[18] that the broadening of the $p_\perp$ distribution in nucleus-nucleus collisions may be a simple consequence of the already established relation[19] between multiplicity and average $p_\perp$. While, as shown in Ref. 18, this approach can account for increase of the average value of $p_\perp$, it remains to be seen whether it can also explain the two-component structure of the $p_\perp$ spectrum of the events of Ref. 7.

To summarize, we suggest that in central collisions of heavy ions at high energies, a chromoelectric field much stronger than that created in e^+e^- annihilation may be formed locally in some regions of the impact parameter plane. Such field fluctuations can be detected by (a) increased multiplicity, (b) two-component structure of $p_\perp$ distributions showing large-$p_\perp$ tails, and (c) the enhanced production of strange particles.

It is not unlikely that these fluctuations of the field may also be important in formation of the quark-gluon plasma (e.g., by significant shortening of the plasma formation time) and thus that the two phenomena are not unrelated.

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