Anomalous Soft Photons associated with Hadron Production in String Fragmentation

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Abstract.

The bosonized QCD2+QED2 system for quarks with two flavors contains QCD2 and QED2 bound states, with an isoscalar photon at about 25 MeV and an isovector (I=1,I_3=0) photon at about 44 MeV. Consequently, when a quark and an antiquark at the two ends of a string pulls apart from each other at high energies, hadrons and soft photons will be produced simultaneously in the fragmentation of the string. The production of the QED2 soft photons in association with hadrons may explain the anomalous soft photon data in hadron-hadron collisions and e^+-e^- annihilations at high energies.

Keywords: String fragmentation, soft photon production, hadron production
PACS: 11.10.Kk 11.15.Tk 13.66.-a 24.85.+p

INTRODUCTION

Anomalous soft photons are low-p_T photons (p_T<60 MeV) produced in excess of what is expected from electromagnetic bremsstrahlung. They are found to possess the following interesting properties:

1. Anomalous soft photons are produced in K^+p [1]-[3], π^-p [4, 5], π^+p [2, 3], and pp [6] collisions, and in e^+e^- annihilations [7]-[10] at high energies. They occur only in association with hadron production. They are absent in e^++ $e^-$$\to$$Z^0$$\to$ μ^++ μ^- in which there is no hadron production [7, 8].
2. The transverse momenta of the anomalous soft photons are found to be in groups, at approximately 5, 15, and 50 MeV [6, 9, 11].
3. The soft photon yield is proportional to the hadron particle yield [9].
4. The soft photons are associated more with neutral hadron production than with charged hadron production [9].

Previously, many different theoretical models have been put forth to explain the phenomenon [12]. However, a complete understanding is still lacking.

We note that in the flux tube environment, both color charge oscillations and electric charge oscillations are quantized, and the system contains QCD2 and QED2 bound states. We would like to propose that these bound hadron and soft photon states will be produced simultaneously in the process of string fragmentation, when a quark pulls away from an antiquark at high energies. The production of these soft photons in association with the production of hadrons may explain the anomalous soft photon phenomenon [11].

APPROXIMATE COMPACTIFICATION OF QCD4+QED4 INTO QCD2+QED2

To investigate the simultaneous production of QCD and QED quanta, we consider the U(3) group that is the union of the color SU(3) and the electromagnetic U(1) subgroups with coupling constants g_f^α that depend on the U(3) generator index α and the quark favor f in QCD4+QED4,

$$g_u^{\{1,..,8\}} = g_d^{\{1,..,8\}} = g_{\rm QCD4}, \ \ \text{for QCD}, \tag{1}$$

$$g_u^0 = -e_u = -Q_u e, \ \ g_d^0 = -e_d = -Q_d e, \ \text{for QED}, \tag{2}$$

where $Q_u = 2/3$, and $Q_d = -1/3$. In high energy particle production processes, the dominance of the longitudinal motion of the leading quark and antiquark and the presence of transverse confinement lead to the formation of a flux tube that can be approximated as a string. As shown in [11], the dynamics of the system of quarks and gauge fields in QCD4+QED4 can then be approximately compactified into the dynamics of QCD2+QED2, in which quarks acquire a transverse mass m_T that encodes the information of the flux tube radius R_T [11]. The coupling constants in 2D and 4D space-time are then related approximately by [11]

$$g_{\rm 2D}^2 \sim \frac{g_{\rm 4D}^2}{\pi R_T^2}. \tag{3}$$

For QCD and QED states, the isospin symmetry remains a good symmetry for QCD but not for QED. The four (I,I_3) QED states split apart. We study only neutral I_3=0 bound states: the isoscalar $(I$=0,I_3=0) state and the isovector $(I$=1,I_3=0) state, in the strong coupling limit in which $|g_{\rm QCD2}|>>m_T$.

BOUND STATES IN QCD2+QED2

The best method to search for bound states is by bosonization [13]. We use non-Abelian bosonization [14] for U(3) interactions, and Abelian bosonization for flavor degrees of freedom. The bosonization program consists of introducing boson fields to describe elements of the U(3) group and showing subsequently that these boson fields lead to stable boson states with finite or zero masses. Not all degrees of freedom available to the bosonization technique in U(3) will lead to good boson states with these desirable properties. We therefore search for stable bosons by varying only the amplitude of the boson field in color space, keeping the orientation in color space fixed [11]. This means that we limit the U(3) generator index α in Eqs. (1) and (2) to be $\alpha = 0$ and 1.

From bosonization we find that QCD2+QED2 contains bound boson states because gauge field oscillations lead to quark color and electric charge density oscillations, and through the Maxwell equations the quark color and electric charge density oscillations in turn lead to gauge field oscillations. The self-consistency of gauge field oscillations and the induced quark charge density oscillations lead to an equation of motion for the gauge field oscillations in the form of a Klein-Gordon equation characterized by isospin-dependent masses [13, 15].

As shown in [11], the mass square $(M_I^\alpha)^2$ of the stable boson in QCD2+QED2 for a state with quantum numbers (I,I_3=0) is given by

$$(M_I^\alpha)^2 = \left(\frac{g_{u(2D)}^\alpha + (-1)^I g_{d(2D)}^\alpha}{\sqrt{2\pi}} \right)^2 + \frac{2}{3-\alpha} e^\gamma m_T \mu, \quad (4)$$

where the index α=0 corresponds to QED2, α=1 corresponds to QCD2, γ=0.5772 is the Euler constant, and μ is the mass scale for the interaction in question.

HADRON AND PHOTON MASSES IN QCD2+QED2 WITH TWO FLAVORS

For QCD2 and QED2 in the flux tube, the coupling constants are related to the 4D constants as given in Eq. (3) by

$$g_{\rm QCD2}^2 \sim \frac{4\alpha_s}{R_T^2}, \ \text{and}\ e_{\rm QED2}^2 \sim \frac{4\alpha}{R_T^2}, \quad (5)$$

where α_s=$g_{\rm QCD4}^2/4\pi$ and α=$e_{\rm QED4}^2/4\pi$=1/137. The flux tube radius R_T can be determined from the root-mean-squared transverse momentum of produced hadrons as

$$R_T \sim \frac{1}{\sqrt{\langle p_T^2 \rangle_\pi}}. \quad (6)$$

The measurement of the π^0 spectra in Z^0 hadronic decay gives $\sqrt{\langle p_T^2\rangle_\pi}$=0.56 GeV in the reaction plane [16] and thus the flux tube has a radius R_T~0.35 fm. For the strong coupling constant at this energy, we shall take $\alpha_s = 0.316$, which leads from Eq. (5) to the string tension coefficient b=$g_{\rm QCD2}^2/2$=0.2 GeV^2 [18, 19].

With these coupling constants and Eq. (4), the QCD2 and QED2 boson masses can be determined as shown in Table I. In the massless quark limit, the QCD2 isovector hadron state is massless and lies lower than the isoscalar hadron state at 505 MeV, whereas the ordering is opposite for the QED2 states, with an isoscalar photon at 12.8 MeV and an isovector I_3=0 photon at 38.4 MeV.

TABLE 1. Meson and photon masses with I_3=0 in a tube

		QCD2	QED2
Coupling Constant (MeV)		$g_{\rm QCD2}$=632.5	$e_{\rm QED2}$=96
massless quarks	I=0	504.6 MeV	12.8 MeV
	I=1	0	38.4 MeV
μ=m_T=400 MeV	I=0	734.6 MeV	
	I=1	533.8 MeV	
m_T= 400 MeV	I=0		25.3 MeV
μ=m_q=1 MeV	I=1		44.1 MeV

The value of m_T can be estimated from $\sqrt{\langle p_T^2\rangle_\pi}$. Because a pion is a quark-antiquark composite, we obtain the quark transverse mass m_T=$\sqrt{\langle p_T^2\rangle_\pi/2}$=0.4 GeV.

The mass scale μ depends on the bosonization of the scalar density, which diverges in perturbation theory and has to be renormalized and renormal-ordered again in an interacting theory [13]. The mass scale μ therefore depends on the interaction. For QCD2, the strong confining interaction dominates and leads to transverse confinement with a quark transverse mass m_T. It is reasonable to take the mass scale μ in QCD2 to be the same m_T characterizing the flux tube transverse confinement. This μ value gives a QCD2 isovector hadron mass of 0.534 GeV and isoscalar hadron mass of 0.735 GeV (Table I) that agree approximately with the observed average isovector hadron transverse mass $m_{\pi T}$=0.577 GeV and isoscalar hadron transverse mass $m_{\eta T}$~0.824 MeV.

For QED2, we envisage that the scalar density $\bar\psi\psi$ that diverges in perturbation theory has to be renormalized in a free theory in which the quarks are characterized by the quark current masses. The appropriate mass scale μ for QED2 is therefore the quark current masses, of order 1 MeV. The values of the QED2 boson masses obtained with m_T=0.4 GeV and μ=1 MeV are given in Table I, which gives an isoscalar photon of about 25 MeV and an isovector photon of about 44 MeV, in approximate agreement with observed soft photon p_T spectra at approximately 15 and 50 MeV in [6, 9, 11], except for the groups of soft photons with p_T~5 MeV whose origin remains unknown.

SIMULTANEOUS PRODUCTION OF QED2 PHOTONS AND QCD2 HADRONS

In hadron-hadron collisions and e^+-e^- annihilations at high energies, a string is formed between a quark and an antiquark (or diquark). When the quark and the antiquark pull apart from each other in the string fragmentation process, the QCD vacuum is so polarized that hadrons are produced by the strong QCD field, with the rapidity distribution of the produced hadrons in the form of a plateau, as discussed by Casher, Kogut and Susskind [17], and analyzed phenomenologically in [18, 19].

The receding quark and antiquark as well as quarks in the vacuum also carry electric charges and they interact with electromagnetic interactions. Simultaneous with the QCD interaction and the production of QCD hadrons, the quark and the antiquark generate a strong electric field between them in the flux tube that can produce QED photons, if they are stable bosons of the QCD2+QED2 system.

QCD2 hadrons and massive QED2 photons have been found to be stable quanta in the QCD2+QED2 system. The isoscalar photon mass $M^{\gamma}_{I=0}$ is about 25 MeV and the isovector I_3=0 photon mass $M^{\gamma}_{I=1}$ is about 44 MeV for a flux tube of radius of 0.35 fm. The same receding quark and antiquark source will produce both QCD2 hadrons and QED2 photons simultaneously. The production process corresponds to the excitation of the QCD2+QED2 vacuum due to the color and electric charge oscillations generated during the string fragmentation process.

The simultaneous production of hadrons and photons explains why anomalous photons are present only in association with hadron production. As the source and the production mechanism of both hadrons and photons are the same, the number of produced hadrons and QED2 photons are therefore proportional to each other, on an event-by-event basis, as observed by the DELPHI Collaboration [9].

We envisage that after a massive QED2 photon is produced it emerges from the interacting region to the outside non-interacting region, with an adiabatic expansion of the flux tube. The massive QED2 photon will evolve into a massless QED4 photon adiabatically, with the photon mass in QED2 turning into the transverse momentum in QED4. We therefore expect that a produced isoscalar photon will lead to a photon with an average transverse momentum of about 25 MeV, and an isovector I_3=0 photon with an average transverse momentum of about 44 MeV. These transverse momenta fall within the domain of soft photon transverse momenta observed in Z^0 hadronic decay [9] and hadron-hadron collisions [6].

The present model predicts that the isoscalar photon mass is lower than the isovector photon mass. Consequently, the production of isoscalar photons is more likely than isovector photons. In contrast, the QCD isoscalar meson mass is greater than the isovector meson mass, the production of isoscalar mesons is less likely than that of isovector mesons. As a consequence, the ratio $N^{\gamma}/N_{\rm neutral}$ is much greater than the ratio $N^{\gamma}/N_{\rm charged}$, as observed by the DELPHI Collaboration [9].

In conclusion, in the flux tube string-like environment formed after a high-energy hadron-hadron collision or e^+-e^- annihilation, the QCD2+QED2 system contains stable QCD2 hadrons and QED2 photons. These bosons will be produced simultaneously when a quark pulls away from an antiquark (or diquark) at high energies during the fragmentation of the string. They may lead to the anomalous soft photons observed in hadron-hadron collisions and e^+e^- annihilations at high energies.

ACKNOWLEDGMENTS

The research was sponsored by the Office of Nuclear Physics, U.S. Department of Energy.

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