CERN-TH.5747/90

COLD QUARK-GLUON PLASMA AS SOURCE OF
VERY SOFT PHOTONS IN HIGH ENERGY COLLISIONS

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ABSTRACT

We present a qualitative discussion and a detailed model calculation of very soft photon production by globs of cold quark-gluon plasma, a mechanism proposed in ref.[1] as part of a possible common explanation of various "ultrasoft" effects observed in high energy collisions. We successfully compare the model with published data and discuss its extrapolation to ongoing experiments.

CERN-TH.5747/90
May 1990

1. In a recent publication [1], one of us proposed that three "ultrasoft" effects observed experimentally in high energy multiparticle production could find a common explanation in the formation, in the final phase of QCD parton showers, of dense globs of cold quark-gluon plasma (CQGP). Such globs could be composed of a few dozens QCD partons (quarks, antiquarks and gluons) with negligible virtualities and very low momenta in the glob restframe (mean value $\bar{p} \lesssim 50 \text{ MeV}/c$). Although such CQGP is necessarily far from thermal equilibrium, its hadronization must be very slow because it requires the recombination of many partons per final pion. Thus, a CQGP glob of diameter D_G should have a lifetime λ_{D_G} with $\lambda \gtrsim 1$ ($\hbar=c=1$). By the uncertainty principle D_G must be $\gtrsim 1/\bar{p}$, i.e. $D_G \gtrsim 4 \text{ fm}$ if $\bar{p} = 50 \text{ MeV}/c$.

Among the ultrasoft effects considered in [1], the simplest one to discuss is the production by CQGP partons of direct photons with low transverse momenta ($p_T \lesssim 50 \text{ MeV}/c$). This is the subject of the present Letter. As discussed in [2], it seems very difficult to explain the ultrasoft photon production by standard mechanisms. A "pion liquid" approach was recently proposed by Shuryak [3]. For experimental guidance we use the results of ref.[4] on K^+p collisions at 70 GeV/c beam momentum, the only ultrasoft data published so far in definitive form. More experimental data, especially on "elementary" collisions (hadron-hadron, lepton-hadron, e^+e^- annihilation), are certainly needed before reliable conclusions can be drawn. We therefore give a qualitative analysis of the problem before presenting the results of concrete model calculations. Our main conclusion will be that the CQGP glob mechanism of [1] can reproduce the data of [4] if the glob is almost at rest in the collision restframe.

2. We consider a CQGP glob of mass $M_G \sim 1 \text{ GeV}$ composed of $N_p \sim 40$ partons with mean momentum $\bar{p} \sim M_G/N_p$. We first do not distinguish between gluons (g), quarks (q) and antiquarks ($\bar{q}$), and we denote by S the appropriate average of the product (relative velocity) $\times$ (cross section) for parton-parton photoproduction (these simplifications are lifted in our model calculations). We write D_G^3 for the volume of the glob and λ_{D_G} for its lifetime. The average number

of photons produced by the glob within its lifetime is then of order

$$n_\gamma^G \sim \lambda_{D_G} D_G^{-3} S N_p(N_p-1)/2 \sim \lambda S N_p^2/2D_G^2 \quad (1)$$

If N_G is the average number of such globs produced in a collision, our rough estimate for the average number of supersoft photons per collision is given by

$$n_\gamma^{\text{coll}} \sim N_G n_\gamma^G \quad (2)$$

Since the CQGP glob is supposed to form at the end of a QCD parton shower involving high virtualities and therefore small space dimensions (well below 1 fm), we expect the product $\bar{p} D_G$ to have the minimum value compatible with the uncertainty relation. With $\bar{p} N_p \sim M_G$ eq.(1) then becomes

$$n_\gamma^G \sim \lambda S M_G^2/2 \quad (3)$$

The absence of $\bar{p}$ and N_p in this estimate is only apparent; S depends on $\bar{p}$ (and also on the gluon/quark ratio in the glob, see below). A glob mass $M_G \sim 1 \text{ GeV}$ has been suggested in [1] as a reasonable choice, and the calculations reported below give S values of millibarn order or somewhat smaller. For $S \sim 0.8 \text{ mb}$ eq.(3) gives

$$n_\gamma^G \sim \lambda \quad (4)$$

Hence, for a short glob lifetime ($\lambda \sim 1$), each glob emits about one ultrasoft photon and N_G is comparable to the observed n_γ^{coll} (from ref.[4]) one estimates $n_\gamma^{\text{coll}} \sim 0.5$. For long glob lifetimes, each glob emits on the average several photons. If the observed n_γ^{coll} is $\lesssim 1$, this means that bursts of several ultrasoft photons are produced by a minority of collisions (a kind of intermittency in time if one looks at the photons coming from a succession of events). Such an effect is apparently not observed in [4]. This does not necessarily imply a short glob lifetime, however, because $S M_G^2$ may well be smaller than the value 2 used in the above estimates.

3. To perform detailed calculations, we choose the glob mass M_G , the number of gluons, and equal numbers for u and d quarks and antiquarks (CQGP globs originate from gluons in the QCD cascade and their heavy flavour content is expected to be very low). For

the parton momenta we simply adopt relativistic phase space distributions with mass zero for gluons and 10 MeV for quarks. The cross sections for $q\bar{q} \rightarrow q\bar{q}$, $q\bar{q} \rightarrow q\bar{q}$ and $q\bar{q} \rightarrow g\bar{g}$ are calculated in lowest QED and QCD order. We took $\alpha_s = 0.5$ for the strong coupling constant (it simply enters as a multiplicative factor). We are fully aware that the use of lowest order perturbative QCD is a very crude approximation at our low $\bar{p}$ values; in fact we expect that higher order QCD effects would tend to reduce the cross sections because they would correct for the many channels without photons. The average number n_g^G of photons emitted by the glob is given by the covariant expression

$$n_g^G = k(M_G^2) \frac{t}{V} \sum_i \sum_j \int_{i \leq j} [(p_i \cdot p_j)^2 - m_i^2 m_j^2]^{1/2} (E_i E_j)^{-1} \cdot \sigma_{ij}(s_{ij}) \delta(\sum_k p_k - p) \prod_k d^3 p_k / E_k \quad (5)$$

where $k(M_G^2)$ is the phase space normalization constant

$$\{k(M_G^2)\}^{-1} = \int d(\sum_k p_k - p) \prod_k d^3 p_k / E_k \quad (6)$$

In eqs.(5,6) P , t and V denote the 4-momentum ($P^2 = M_G^2$), lifetime and volume of the glob ($t = \lambda D_G$ and $V = D_G^3$ in the glob restframe). The indexed symbols refer to 4-momenta, energies and masses of partons. The invariant energy squared of a 2-parton system is denoted as s_{ij} , and σ_{ij} is the photon production cross section in a head-on collision of partons i and j .

The cross sections of $q\bar{q} \rightarrow q\bar{q}$ and $q\bar{q} \rightarrow g\bar{g}$ were averaged over colours of initial partons and summed over those of final partons. Our formulae differ from those of ref.[5] only by inclusion of non-zero quark masses.

To calculate the distribution of photons in $x = 2p_L/s^{1/2}$ or p_T , the appropriate delta functions should be inserted under the integration sign of eq.(5) and the cross section for the subprocess should be replaced by the corresponding differential quantity. For example, for obtaining the distribution in x one makes the replacement

$$\sigma_{ij} \rightarrow (2)^{-1} \int d\sigma_{ij}/dt_{ij} \delta[x - x(t_{ij}, \phi_{ij}, p_i, p_j)] dt_{ij} d\phi_{ij} \quad (7)$$

where t_{ij} is the 4-momentum transferred in an elementary collision, and ϕ_{ij} is the azimuthal angle of the photon in the two-parton restframe. For comparison with the data of ref.[4], differential cross sections are calculated by multiplying the photon number densities by the K_p^+ inelastic cross section at 70 GeV/c beam momentum (16.06 + 0.14 mb).

Our calculations are done by Monte Carlo integration, replacing the delta function in (7) by step functions for finite bins, and obtaining the distribution in histogram form. We have used Jadach's Monte Carlo generator for relativistic phase space [6]. The shapes of the x - and p_T -distributions are determined by our model, the absolute normalization involves the combination of free parameters

$$F = \lambda D_G^{-2} N_G \quad (8)$$

4. The histograms of figs. 1 and 2 have been calculated with $F = 0.01 \text{ fm}^{-2}$ for a glob of mass $M_G = 1 \text{ GeV}$ composed of $N_p = 40$ partons, half of them gluons (this corresponds to $\lambda N_G \gtrsim 0.64$ since $D_G \gtrsim N_p/M_G = 8 \text{ fm}$; the parameter S of eq.(1) was found to be 0.7 mb). We have given the glob a gaussian rapidity distribution of width $\langle y_G \rangle^{1/2} = 0.6$ around $y_G = 0$ in the overall c.m. frame, and an exponential $p_{T,G}^2$ distribution with $\langle p_{T,G} \rangle = 0.3 \text{ GeV}/c$. The effect of these glob distributions on the photon spectra of figs. 1 and 2 is small compared to a glob at rest in the c.m. frame. After proper adjustments of F , the photon spectra are remarkably insensitive to a reduction of the quark mass to 5 MeV (F becomes 0.0045 fm^{-2}), to changes of the gluon/quark number ratio at constant N_G and N_p (F varies from 0.005 to 0.028 fm^{-2} when the number of gluons is changed from zero to 32), and to changes of M_G and N_p at constant $\bar{p} \sim M_G/N_p$ ($F = 0.004 \text{ fm}^{-2}$ for $M_G = 1.5 \text{ GeV}$ and $N_p = 60$ with 30 gluons). An increase of $\bar{p}$ of course widens the photon spectra.

Figs. 1 and 2 show that the ultrasoft photon distributions of [4] can be accounted for qualitatively by our CQGP mechanism under

the assumption that the glob is almost at rest in the c.m. frame of the collision. This may be an acceptable assumption at the relatively low c.m. energy of 11.5 GeV at which the data of [4] were taken, but a growing spread in the rapidity of the glob is unavoidable at higher energies. Also a weak broadening of the p_T distribution is expected.

At present, two CERN experiments, WA83 and NA34, are investigating very soft photon production in hadronic collisions, and the HELIOS/SOPHY Collaboration (NA34) has published preliminary data for p-Be and p-Al collisions at 450 GeV/c beam momentum [7]. To extrapolate our model from 70 GeV/c K^+p to higher energy hadron-hadron reactions, we propose the following simple assumptions:

- i) leave unchanged the glob parameters M_G , N_p , gluon/quark number ratio, D_G , λ , $\langle p_{T,G} \rangle$;
- ii) scale N_G and F proportionally to the mean multiplicity;
- iii) scale $\langle y_G^2 \rangle^{1/2}$ proportionally to the maximum c.m. rapidity, i.e. as $\log(\text{c.m. energy})$;
- iv) use the new inelastic cross section as indicated after eq.(7).

Since we deal with non-perturbative QCD effects, we have no proper justification for these assumptions; it will be for experiment to confirm them or give guidance for their improvement.

Applying these rules to 450 GeV/c pp collisions, we obtained the full histogram of fig.3 for the p_T -spectrum of photons produced with c.m. rapidity y in a unit interval centered at $y=0$. The rapidity spread of the glob is $\langle y_G^2 \rangle^{1/2} = 0.83$. For comparison the dashed histogram gives the same spectrum for $\langle y_G^2 \rangle^{1/2} = 0.2$.

The case of collisions involving nuclei is bound to be more complicated in view of the difficulty to predict how the nuclear environment could affect the large CQGP glob ($D_G \gtrsim 8$ fm from the uncertainty relation). Nevertheless, with reference to the NA34 experiment [7], we feel that for a light nucleus as beryllium the main correction to the pp prediction at the same energy should be the increased inelastic cross section (rule iv).

5. In conclusion, we have shown through a qualitative discussion and a model calculation what are the characteristics of the direct photon spectra resulting from the CQGP mechanism proposed in [1]. Their comparison with the data of [4] is encouraging with the glob parameters considered in [1]. We stress again, however, that new experiments will be essential for further progress. Regarding theoretical work, the main unsolved problem concerns the hadronization of CQGP globs, which is bound to be very different from the string fragmentation and cluster hadronization schemes used in the familiar QCD parton shower models. In particular, we expect the glob hadronization to be very slow for $\bar{p} \lesssim 30$ MeV/c but to get much faster if $\bar{p}$ grows to 100 MeV/c or more. For such larger mean parton momenta, the production of soft photons by the glob should be strongly reduced.

We would like to dedicate this paper to Yves Goldschmidt-Clermont who, before his untimely death, devoted so much work and thought to the experiment of ref.[4] and to the further search for ultrasoft photon effects. We acknowledge valuable discussions with M. Spyropoulou-Stassinaki, W. Beusch, C. Fabjan, U. Goerlach, E. Quercigh and P. Sonderegger.

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FIGURE CAPTIONS

Fig.1: The experimental x-spectrum of ultrasoft photons produced in K^+p collisions at 70 GeV/c with the inner bremsstrahlung curve [4], compared to our model calculations without (full histogram) and with (dashed histogram) the cut $E_\gamma(\text{lab}) > m_{\pi^0}/2$ which was applied to the experimental data and the bremsstrahlung calculation [4].

Fig.2: Same as fig.1, but p_T -spectrum.

Fig.3: The photon p_T -spectrum at mid-rapidity in pp collisions at 450 GeV/c, model calculations with $\langle y_G^2 \rangle^{1/2} = 0.83$ (full histogram) and 0.2 (dashed histogram).

- Figure 2 -

- Figure 3 -