Ring-like events: Cherenkov gluons or Mach waves?

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Abstract

Similar to electromagnetic forces, strong interactions might induce such collective effects as Cherenkov and Mach waves. Their conical structure would be responsible for specific ring-like events. The theoretical and experimental arguments in favor of these phenomena are discussed and their most important features are described.

1 Introduction

Cherenkov photons and Mach shock waves are wellknown collective effects in physics. Both have the similar origin - wave radiation by a body moving with speed exceeding the wave velocity \( c_w \), i.e. the phase velocity. For Cherenkov photons, to be emitted by a charged particle moving with the velocity \( v \), the phase velocity of light in a medium must be less than \( v \). For Mach waves, this is the velocity of sound. If \( z \)-axis is chosen along the body propagation, then in both cases emission in an infinite medium at rest is directed along the cone with the polar angle \( \theta \) defined by the condition

\[
\cos \theta = \frac{c_w}{v}.
\]

For Cherenkov photons \( c_w = c/n \) where \( n \) is the index of refraction, for Mach waves \( c_w = c_s \) where \( c_s \) is the sound velocity in the medium. These are collective effects determined by the presence of the medium. The wave fronts have a conical shape with an opening angle \( \theta_f \) with respect to the direction of body (particle) motion given by \( \theta_f = \frac{\pi}{2} - \theta \). Photons are emitted perpendicular to the wave front. Rings of light in Cherenkov detectors are used to measure \( v \). Emission of Cherenkov photons is due to the polarization of atoms induced by a beam of charged particles. Mach shock waves are characterized by the pressure variation. Both effects are consequences of electromagnetic forces acting in the medium.

Are there analogues of these effects for strong interactions? Many indications in favor of it exist but further studies are necessary. Here one should rely on quantum chromodynamics (QCD) with quarks and gluons acting as partons in high energy interactions. Almost massless quarks with spin 1/2 and massless vector gluons recall electrons and photons but color forces between them with self-interaction of gluons lead to such new properties as asymptotic freedom and confinement.
2 Cherenkov gluons

The intuitive picture which comes to mind is to consider the impinging partner in \(hh, hA, AA\) collisions as a bunch of partons passing through a hadronic medium. A target hadron or nucleus can be treated as a nuclear slab with a definite index of nuclear refraction. The analogue to Cherenkov photons would be Cherenkov gluons emitted by a parton entering this hadronic medium. The notion of Cherenkov gluons was proposed long time ago [1, 2] and experimental indications in favor of this effect appearing from time to time are quite extensive [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

2.1 The nuclear index of refraction

The necessary condition for this effect is the excess of the real part of the index of refraction over 1. In electrodynamics, the index of refraction \(n\) is related to the forward scattering amplitude of photons in a medium \(F(\omega)\) as

\[
n(\omega) = 1 + \Delta n = 1 + \frac{2\pi N}{\omega^2} F(\omega). \tag{2}
\]

Here \(\omega\) is the photon frequency, \(N\) is the density of the scatterers (inhomogeneities) of the medium. The amplitude \(F(\omega)\) is normalized by the optical theorem

\[
\text{Im} F(\omega) = \frac{\omega}{4\pi} \sigma(\omega), \tag{3}
\]

where \(\sigma(\omega)\) is the total cross section of photon interaction in the medium.

In what follows, we use the rest system of one of the colliding hadrons or nuclei in analogy with classical situation of charged particles passing through Cherenkov detectors.

If the formula (2) is applicable in QCD, one should use the forward scattering amplitude of gluons \(F_g(\omega)\) in a hadronic medium as well as the density of partons. The latest one is related to the structure functions. It is more difficult to say something about \(F_g(\omega)\).

To provide some estimates, it was proposed [1] to come back to pre-QCD times. At those days, nucleons and pions were considered as elementary entities with pions being the quanta of radiation. Namely in this way the ideas about nuclear Cherenkov effect were first promoted [19, 20, 21, 22, 23, 24, 25, 26, 27]. No discussion of the nuclear index of refraction was attempted at that time. It was ad hoc assumed that the necessary condition can be somehow satisfied. The purpose was to explain main mechanism of particle production by this effect. It has failed.

If considered in the rest system of the target, the density of scatterers inside a nucleus would be approximately given by the inverse volume of a nucleon, i.e. \(N \approx \frac{3m^3_\pi}{4\pi}\) (\(m_\pi\) is the pion mass). Thus

\[
\text{Re} n(\omega) = 1 + n_R(\omega) = 1 + \frac{3m^3_\pi}{8\pi\omega} \sigma(\omega) \rho(\omega), \tag{4}
\]

where \(\rho(\omega) = \text{Re} F/\text{Im} F\) and now \(F(\omega)\) \((\sigma(\omega))\) is the pion-nucleon amplitude (cross section). The necessary condition\(^1\) is fulfilled if \(\text{Re} F > 0\) (or \(\rho > 0\)).

It is known from experiment that there are two energy regions where real parts of hadronic forward scattering amplitudes become positive. At low energies, it happens in

\(^1\)More precisely, as seen from Eq. (1) the necessary condition should read \(\Delta n_R > 1/2\gamma^2\) with \(\gamma\) being \(\gamma\)-factor of the impinging partner.
a half of any resonance shaped as $F(\omega) \propto (\omega - \omega_0 + i\Gamma/2)^{-1}$ so that at $\omega > \omega_0$ one gets $\text{Re}F(\omega)_{\text{max}} = \Gamma^{-1}$ and

$$\Delta n_R^h = \frac{3m_\pi^3}{2\omega^2\Gamma}.$$  (5)

Here $\omega_r$ is the pion energy required to produce a resonance. It can be of the order of $m_\pi$. Since the widths $\Gamma$ are of the order of hundred MeV for known resonances, $\Delta n_R^h$ can be of the order of 1.

At high energies, according to experimental data on $pp$ and $\pi p$ amplitudes, $\rho(\omega)$ also becomes positive above some threshold, which is quite high ($\omega_{th} > 70$ GeV, typically). Here the value of $\Delta n_R$ is very small $[1][2]$, increases above the threshold and then decreases at large $\omega$ as

$$\Delta n_R^h(\omega) \approx \frac{a}{\omega},$$  (6)

where $a \approx 2 \cdot 10^{-3}$ GeV at $\rho \approx 0.1$ as follows from experiment and Eq. (4). The dispersion relations show that real parts of other hadron amplitudes also become positive. The index $h$ refers to high energy hadrons.

One can speculate that approximately the same estimates should be valid for gluons as carriers of strong forces if this feature is common for all hadronic reactions. Then they can be used to get some insight into the characteristics of the collective conical flow of parton jets initiated by a primary parton piercing through a nuclear slab. In principle, one should consider the index of refraction for initial parton (quark or gluon) as well. However, since its energy is extremely high, then $\Delta n$ becomes very close to 0 according to (5).

The nuclear index of refraction was recently discussed in connection with Cherenkov gluons in [28][29].

Partons able to emit gluons with energies above the mentioned threshold and those which can emit only "resonance" gluons are treated separately below.

### 2.2 Very high energy jets

First, let consider the forward moving jet produced by an initial parton. In the target rest system it has very high energy if cosmic rays or Tevatron, RHIC, LHC energies\(^2\) are considered. The emitted gluons can be also very energetic. For would be infinite hadronic medium and gluons with energies above the threshold one gets from (1) and (6) the cone angle

$$\theta_\infty = \sqrt{2\Delta n_R^h(\omega)} = \sqrt{\frac{3m_\pi^3}{4\pi\omega^2} \sigma(\omega)\rho(\omega)}.$$  (7)

However, the size of hadronic targets is very small $l \approx A^{1/3}/m_\pi$ where $A$ is the atomic number of a nucleus. The color currents appear only inside the target during the collision. Partons are confined and color neutralized outside it. If, following I. Tamm [30], one considers emission by a current acting only at the finite length $l$ and separates its part proportional to $\Delta n_R$ that is typical for Cherenkov radiation, the following distribution is obtained [2]

$$\frac{1}{\sigma} \frac{d\sigma}{d\omega dz} = \frac{4\alpha_sC_F\Delta n_R^h}{\pi} f(z),$$  (8)

\(^2\)Note that LHC energies correspond to $10^{17}$ eV in the target rest system while the threshold energy $\omega_{th}$ is about $10^{13}$ eV.
where
\[ f(z) = \frac{\sin z}{z} \left[ \frac{\sin z}{z} - \cos z \right], \]  
(9)

\[ z = \frac{\omega l \theta^2}{4} = \frac{p_t l \theta}{4} < \pi. \]  
(10)

The function \( f(z) \) has a maximum at
\[ \theta = \sqrt{\frac{2\pi}{\omega l}}. \]  
(11)

and the width
\[ \Delta(\ln \theta) < 0.4 - 0.5. \]  
(12)

The conical flow appears at smaller angle (11) compared to \( \theta_{\infty} \) (7). But this angle is much larger than the bremsstrahlung angles \( \theta_{bs} \propto 1/E \) (\( E \) is the energy of the initial parton).

The transverse momenta are large.
\[ p_t = \sqrt{\frac{2\pi \omega}{l}}. \]  
(13)

They are in GeV-region for \( \omega > \omega_{th} \).

The crucial parameter which differs the finite length emission from the infinite one is \( \omega l \Delta n_R/2 \). The formula (7) is valid for
\[ \omega l \Delta n_R/2 \gg 1. \]  
(14)

For estimates of \( \Delta n_R \) given by Eq. (10) one gets the opposite condition \( \omega l \Delta n_R/2 \ll 1 \) for all realistic \( l \). That is why the condition (11) arises.

Let us notice that the imaginary part of the index of refraction describes the attenuation of the created flow. For a plane wave \( e^{ikr} \) it is given by a factor \( \exp[-\omega r \text{Im}(\omega)] = \exp[-3m_2^2 \sigma r/8\pi] \) which damps it down at distances by the order of magnitude larger than 1 Fm, i.e. our treatment should be valid practically for all nuclei.

The primary parton creates a forward moving jet which would correspond in the above classical model to the term not vanishing at \( \Delta n_R \rightarrow 0 \) and omitted in the calculations. It can not be treated by this model but QCD works quite well in describing such jets. Namely this jet initiates the conical flow. The microscopic mechanism of this effect is the collective excitation and polarization of colored partons in the medium by a forward moving parent with subsequent coherent directed emission of color radiation.

The cone angle for high energy gluons in the rest system of target \( n \) is rather small (\( \theta \ll 1 \)) because \( \omega \gg l^{-1} \). However, being transformed to c.m.s. of colliding nuclei, where RHIC experiments are done, the angles become large, and, moreover, the cones can exchange by hemispheres. This is the general relativistic effect of ”medium” motion. The approximate estimates given in [2] indicate that for \( pp \)-collisions this effect could be noticed at rather large c.m.s. angles about \( 60^\circ - 70^\circ \), i.e. at quite small pseudorapidities \( |\eta| \approx 0.3 - 0.5 \). To get more precise estimates, some additional assumptions are necessary.

According to (11), this angle is smaller for nucleus collisions. For two nuclei colliding, two humps in the pseudorapidity distribution must appear. It follows from Eq. (11) that the cone angle is proportional to \( l^{-1/2} \), i.e. to \( A^{-1/6} \). It becomes smaller for larger nuclei. In the pseudorapidity plot this corresponds to the shift of humps by \( \frac{1}{6} \ln A \) that is close to 1 for largest nuclei compared to nucleon. Since any of the colliding nuclei can be treated
as a target or as a bunch of partons, two cones in the opposite hemispheres in c.m.s. may be observed. They are symmetrical for identical nuclei. Especially interesting is the difference between predictions for different nuclei. If a light nucleus collides with a heavy one, forward and backward cones have different angles according to the above comment. For larger \(l\) this dependence becomes slower and \(\theta\) approaches \(\theta_\infty\) so that no such effect exists if \(\Delta n_R\) or \(l\) are so large that the condition (14) is satisfied.

The important corollary of Eq. (6) is that a high energy gluon can also emit Cherenkov gluons due to self-interaction of gluons. The phase velocity of emitted gluon must be smaller than the phase velocity of initial one. This is fulfilled if \(\Delta n_R(\omega)\) decreases with \(\omega\) (see (6)). In this case secondary Cherenkov rings around the direction of emitted Cherenkov gluon can be detected, in principle.

Very high energy partons can also emit rather soft Cherenkov gluons corresponding to resonance regions for hadrons. The emission angle in the target rest system is rather large for forward moving jets in accordance with (1) and (5). One can try to detect this effect only in the fixed target experiments. It results in two peaks in the deep forward and backward fragmentation regions of the pseudorapidity distribution. These peaks are unobservable in collider experiments because particles are captured inside the accelerator ring. For "resonance" gluons and large nuclei, the condition (14) can be satisfied. Then the emission angle is defined by

\[
\cos \theta_r \approx \frac{1}{1 + \Delta n_R^r}
\]

and does not depend on \(l\).

### 2.3 Moderate energy jets

Instead of producing the forward moving energetic jet, the primary parton can in some cases create secondary jets with lower energies. This can be either the result of its hard high-\(p_t\) scattering or of production of a new aside moving jet similar to the gluon jet in three-jet events in \(e^+e^-\)-annihilation. Kinematics of these two processes is different, in general. If the energy of a secondary jet is below the high energy threshold \(\omega_{th}\) for positivity of \(\Delta n_R(\omega)\), then only low energy gluons relevant for production of hadron resonances can be emitted. The above estimates of \(\Delta n_R^r\) show that the parameter \(\omega l \Delta n_R^r/2\) is of the order of 1. The cone angle becomes large even in the target rest system (see (15)). The attenuation of such gluons is quite strong because \(\text{Im}\Delta n_R^r\) is of the order of 1. They can produce resonances. Therefore, one can speculate that such moderate energy jets would be accompanied by ring regions with some excess of resonances forming a kind of "resonance gas" for a short time. This effect is pronounced only in the special narrow energy bands of corresponding wings of resonances. The attempts to define these bands were done in [27, 31, 32] without referring to the parton structure of particles. For large values of \(\Delta n_R^r\) the transition radiation induced by the target edges can also become important.

### 2.4 Conclusion on Cherenkov gluons

Thus, one can expect to observe two (high and low energy) components of Cherenkov gluons if Eq. (2) is applicable in QCD and the data on real parts of hadronic amplitudes are used.

High energy Cherenkov gluons can be emitted by the primary impinging parton at small polar angles in the target rest system given by Eq. (11). Each gluon would produce
a jet. These jets should form the ring with “jetty” substructure (spots) in the azimuthal plane perpendicular to the direction of the primary parton. At very high energies the number of Cherenkov gluons can be large and they form a ring in a single event. If one or few gluons are emitted in an event, the rings can be detected only in high statistics experiments as peaks of the pseudorapidity distribution. The emission angle becomes quite large in the system where the target moves towards the impinging parton (collider experiments). The transverse momenta of particles inside the ring can be somewhat enhanced.

For low energy Cherenkov gluons corresponding to resonance regions, the emission angle is large even in the target rest system, i.e., in the fixed target experiments. In the collider (c.m.s.) system it would correspond to extremely large polar angles for forward moving initial parton and effect is not observable. The effect can be observed only for transversally moving partons or, may be, in collisions of protons with heavy nuclei. The enhancement of resonance production can influence the $\pi/p$ ratio inside the rings compared to outer regions. Almost monochromatic pions would dominate, if resonance motion and confinement effects do not spoil it for such low energies.

Small values of $\Delta n_R > 0$ in the high energy region and narrow energy bands in which $\Delta n_R > 0$ at low energies imply that the probability of the process is not very high and it should be carefully chosen from large background due to more ordinary processes.

### 3 Mach waves

Any quark-gluon jet created by a high energy parton can become a source of another collective conical flow which has macroscopic analogue known as Mach shock waves. Since the jet propagates with the speed of light it can be considered as a supersonically moving body. Therefore the large perturbations of matter are created and give rise to shock waves. They would induce particle radiation at Mach angle $\theta_M$ with the jet direction in the target rest system

$$\cos \theta_M = \frac{c_s}{c}.$$  \hspace{1cm} (16)

The cone of the front of the shock wave has the angle $\theta_f = \frac{\pi}{2} - \theta_M$. Thus, at the microscopic level, the cone of particles should be produced. Now, everything depends on how one treats the hadronic medium and whether sound waves can propagate in it. Unfortunately, our knowledge of this medium is still not complete enough to answer these questions. In various models and at different conditions, its states range from quite dilute cold nuclear matter and nuclear Fermi liquid to quark-gluon condensate (CGC), quark-gluon plasma (QGP), strongly interacting quark-gluon plasma (sQGP), ”resonance gas” and dense quark-gluon liquid (QGL). The Mach angle does not depend on jet energy but depends on the state of matter. For weak waves in the mixed phase state the speed of sound is negligibly small $c_s \approx 0$. The lattice calculations show that the speed of sound can be still rather small $c_s^2 \approx 0.15c^2$. For ”resonance gas” it was estimated equal to $c_s^2 \approx 0.2c^2$. For ultrarelativistic equation of state it should be $c_s^2 = \frac{1}{5}c^2$. For sQGP the value $c_s^2 = \frac{2}{3}c^2$ may be chosen. For plasma with strong vector (gluon!) interaction the shock waves are strong and have larger speeds $c_s \approx c$, i.e. the situation approaches the conditions for high energy Cherenkov gluons.

The cone angles are quite large (60° if $c_s = 0.5c$) in the rest system of the target. Mach cones produced by forward jets initiated by primary partons are reversed to large pseudorapidities in the backward hemisphere, when transformed to c.m.s. of colliding
nuclei. For RHIC energies, they escape in accelerator pipes unobserved (see Section 5). This effect, however, can be detected in fixed target experiments or for transversally moving jets (in c.m.s.) similarly to low energy Cherenkov gluons.

4 Experimental data

The most important feature of both effects is the cone of particles (or subjets) at the definite angle to the direction of propagation of initiating it parton (or jet). If this direction is chosen as $z$-axis, then there should be maximum in pseudorapidity ($\eta = -\ln \tan \theta/2$) distribution of particles for a corresponding event or a set of events. Two colliding nuclei must give rise to two peaks. Namely such maxima observed in the cosmic rays event at energy $10^{16}$ eV [3] (Fig. 1) initiated the idea about Cherenkov gluons [1]. When the two-dimensional distribution of particles was considered in the azimuthal plane (called as target diagram in cosmic rays experiments), this event revealed two (forward and backward in c.m.s.) densely populated ring-like regions within narrow interval of polar angles but widely distributed in azimuthal angles. Therefore such events were called as ring-like events.

Approximately at the same time the similar event with two peaks was observed at $10^{13}$ eV [6]. Some events with one peak were shown even earlier [4, 5]. Individual events with a prominent ring-like structure were also found at accelerator energies [7, 8]. Especially impressive is the event [8] with peak in the pseudorapidity distribution $dn/d\eta = 100$ within narrow interval $\delta \eta = 0.1$ that 60 times exceeds the average density (Fig. 2). As usually, for individual events, it is unclear whether they reveal some dynamical mechanism or are rare statistical fluctuations even though it has been estimated that probability of these fluctuations is extremely low.

The experimental data on high multiplicity hadron collisions with high statistics at energies of hundreds GeV became available only in 1980s. It would be naive to expect to observe the peaks at these energies immediately because the background from ordinary processes is huge. One had to select events by some criteria which would favor observation of subjets, i.e. groups of particles quite dense on the pseudorapidity plot and well separated from other groups. One can hope that the effect is more clearly seen with such a choice and the background is less strong. This program was applied to $pp$-interactions in fixed target experiments at 205 and 360 GeV [9] and later to $\pi p$ and $Kp$ interactions [12]. The pseudorapidity distributions of the centers of dense isolated groups (which were interpreted as jets) possess the peaks at $\eta_c = \pm 0.3$, i.e. at $\theta_{c.m.s.} \approx 70^o$ and $110^o$ (Fig. 3). No such effect is seen in Fritiof 1.6 events.

Apart from considering the distribution of centers of dense isolated groups one can analyze the azimuthal structure [10, 15, 18] plotting the sum of squared differences of azimuthal angles of two neighboring particles in the investigated groups. It must be different for purely stochastic particle production, for jet-like mechanism and for ring-like events. Observed distributions also favor presence of ring-like events in interactions Pb-emulsion (Ag, Br) at 158 GeV and Au-emulsion at 11.6 GeV. Events with this azimuthal parameter favoring ring-like structure show pronounced two-hump property of the pseudorapidity distribution.

A new method of pattern recognition in event-by-event analysis of two-dimensional correlations in individual high multiplicity events using wavelets [44] was applied to the shown above cosmic rays event [13] and to fixed target PbPb interactions at 158 GeV [17]. The ring-like structure in the target diagram of some events was found with radii...
corresponding to the maxima in pseudorapidity distribution. Fig. 4 demonstrates how
correlations at some scale are distributed in the azimuthal plane of one of PbPb events at
158 GeV. The dark regions forming jetty rings correspond to correlated groups of particles
(jets).

Some low-energy data on AA-interactions showed similar surprising irregularities as
well [11, 16]. In principle, the positive values of Δn_R in one of the resonance wings could
be blamed for them.

A new approach to search for ring-like events at RHIC and LHC energies was recently
proposed in [45]. HIJING model has been used to get inclusive pseudorapidity distribution
for 3500 central (b=0) collisions (AuAu at √s = 200A GeV and PbPb at √s = 5500A
GeV). Then the spikes in individual HIJING events exceeding this distribution by more
than one or two standard deviations are separated and the distribution of their centers is
plotted. They are considered as purely statistical fluctuations or jets produced at hard
scattering. Therefore this distribution is rather smooth. If experimental data show some
peaks at definite pseudorapidity values over this background, this can be an indication
on a new collective effect not considered in HIJING.

The above data concerned mostly either individual cosmic rays events or low-statistics
nucleus-emulsion interactions. The high statistics data were available only for hadron-
hadron interactions at relatively low energies and asked for some special selection in the
primary data as discussed above. Gluons emitted by forward moving jets were searched
for. The recent high-statistics data on AA-interactions from RHIC allow to search for new
peculiar features using a special trigger [46]. Instead of evolution of a primary forward
moving jet, the process of creation of two oppositely moving jets by a primary parton was
chosen. These moderate energy jets originate at some point inside the target nucleus and
move transversally to the initial parton, i.e. in the azimuthal plane. This shows that they
are produced in high-p_t head-on collisions of two partons belonging to the colliding nuclei.
Surely, the choice of this quite rare process with high transferred momentum drastically
reduces the statistics. It is compensated by a good trigger provided by the jet which passes
only the thin layer of matter near the edge of the nucleus. Therefore one can select these
events and study the effects induced by its companion jet piercing through the larger part
of the nucleus in the opposite direction. The trigger jet produces the particle flow near
φ = 0 and the companion jet - near φ = π. These peaks are clearly seen in pp-collisions.
However, in AuAu collisions the distribution near φ = π is double-peaked one with a
minimum at φ = π (see Fig. 5). This can be explained as a result of cone radiation. Since
the companion jet moves in the same azimuthal plane where the observation is done, the
cone is cut by the plane which contains its vertical. Therefore two peaks along the two
cut sides of the cone are detected. They add to the usual companion jet radiation which
moves at φ = π and can be considered here as background. If the cone were cut by the
plane perpendicular to its vertical, i.e. to the direction of propagation of the companion
jet, as it was done for primary jets, one would see the ring-like structure of these events.
It is interesting to perform measurements in the plane perpendicular to the cone vertical
and to see directly the ring-like structure.

This effect is interpreted in [40] as Mach waves moving with the speed c_s = 0.33c.
It is claimed in [40] that this value of c_s can be obtained for RHIC as a time-weighted
average of several stages of nuclear matter: QGP, mixed phase and "resonance gas". The
c.m.s. system of RHIC coincides with the "laboratory system" of the transversally moving
companion jet. The angle θ_M ≈ 70° is quite large.

Let us note that the typical energies of the companion jets are about 5-20 GeV which
are much below the energy of a primary parton at RHIC if considered in the target rest frame. They are also below those energies where $\Delta n_R$ becomes positive at high energies in hadron collisions. However, namely for resonances $\Delta n'_R$ becomes positive and rather large according to [3]. This would provide quite large angles for Cherenkov gluons in this energy range as well. The angle $70^\circ$ corresponds to $\Delta n'_R = 2$ according to Eq. (15).

One is tempted to conclude that spikes of the pseudorapidity distributions at large c.m.s. angles and peaks for companion jets observed at RHIC are initiated by jets with high and moderate energies, correspondingly, if treated as Cherenkov gluons. Any jet created with the same energy in fixed target experiments should give rise to the similar effect. It is surprising that the peaks at large angles in the target system were not observed earlier for forward moving jets in those fixed target experiments, where the conditions similar to RHIC (jets with energies about 10 GeV inside a nucleus at rest) were achieved.

5 Specifics of collective hadronic events

Theoretically, Cherenkov and Mach waves are different because they are transverse and longitudinal excitations, correspondingly. However, it is not easy to reveal this feature in experiment. Their common feature is the cone of radiation. It must result in two humps of the one-dimensional pseudorapidity distribution and in ring-like structure of two-dimensional plots. They have been observed. Cherenkov and Mach waves could differ by their most prominent characteristics, the emission angle [11]. From above discussion one sees that the sound velocity can range from very low values for weak waves to $c$ for strong waves. The phase velocity of gluons would be close to $c$ at high energies and several times less at low energies if above estimates applied. Thus there is strong overlap in these numbers and further properties must be studied.

Each high energy gluon would produce a jet. If the number of emitted Cherenkov gluons in a single event is not large, this event would not have the ring-like structure but jets preferring the angle [11]. For Mach waves, the ring-like structure must appear in any individual event until we treat them in a classical way and do not speak about phonons, plasmons (strongly interacting!?!) etc. Specific dependence of the emission angle on atomic number could differ these two mechanisms.

The enhanced transverse momenta could be a signature for high energy Cherenkov gluons. The latest D0 data [17] on jet transverse momenta up to 510 GeV in $pp$-interactions at $\sqrt{s} = 1.96$ TeV have been successfully fitted by QCD. Thus the enhancement should be a purely nuclear effect. This conclusion would agree with RHIC data but indirectly differs from results of [3].

Gluons differ from photons by self-coupling. Therefore, a high energy Cherenkov gluon can emit its own secondary gluon. If well separated as 3-jet events in $e^+e^-$-annihilation, both can give rise to ring-like structures in the planes perpendicular to their directions. (Two gluons producing smoke-rings!) However, the intensity of this secondary effect must be very low if the initial effect is not strong enough and would require the special trigger. Low energy Cherenkov gluons can be efficient in producing resonances. This would change the pion momentum spectrum and $\pi/p$ ratio in the rings more densely populated with resonances compared to outside regions.

Eq. (11) defines the emission angle in the target system. The forward moving jet meets the backward moving flow of partons in c.m.s.. The medium motion relative to any jet can be easily accounted and characteristics in different coordinate systems calculated.
In particular, if the forward moving parton produces Mach waves at \( c_s = 0.33c \) which generate massless partons, the emission angle in the RHIC system differs from 180° less than by 1°:

\[
\theta_{c.m.s.} = \pi - \frac{1}{\gamma} \left( \frac{c + c_s}{c - c_s} \right)^{1/2} \approx 180° - 0.8°.
\]

(17)

The difference from \( \pi \) is even less for massive particles. This angle is of the order of bremsstrahlung angles in the deep fragmentation region. Thus, the effect can not be observed. (It flies in the tube!)

The situation is not completely clear for aside moving jets. One can find out from the shift of the cone whether the medium motion is important. The symmetrical positions of peaks at RHIC energies favor the conclusion that the medium is as a whole at rest for transverse jets. However, there exists more exotic possibility that the matter is not equilibrated and partons still remember their initial directions with two flows moving in opposite directions like in the superfluid liquid even though the center of mass is at rest. The cone angle will be changed. In statistical physics, this state of matter asks for the second virial coefficient becoming negative and particles paired. In QCD, the analogous effect of negative cumulant moments \[48, 49, 50\] can be related to the similar phenomenon with many-parton clustering in place of two-particle pairing.

6 Conclusion

There are some indications from experiment on coherent collective effects in hadronic matter which result in the so-called ring-like events. They can be explained as cones formed either by Cherenkov gluons or by Mach shock waves. Cherenkov and Mach waves have similar origin but correspond to propagation of transverse and longitudinal excitations in a medium, correspondingly. High-multiplicity central nuclei collisions are preferred for their search because of larger number of participating partons even though the background increases also.

Two peaks of the pseudorapidity distribution positioned in accordance with Eq. (11) provide most important signature of ring-like events in one-dimensional plots. Two-dimensional plots in the plane perpendicular to the motion of initiating jet must have ring-like structure. More detailed characteristics of these events are necessary to make definite choice. In particular, energy and A-dependences of this effect as well as resonance contents and transverse momentum behavior must be studied. More direct proof of the ring-like structure in high statistics experiments is necessary, e.g., the analysis of RHIC events in the plane perpendicular to the companion jet direction, i.e. to the cone vertical. The observation of ring-like structure induced by secondary gluons would be very important. One can hope to get the value of the nuclear index of refraction and/or the sound velocity in nuclear matter from the cone angle. This can lead us to the proper equation of state of the nuclear matter.

Anyway, there is no doubt that study of these events will provide us with deeper knowledge of properties of quark matter at extreme energies.

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Figure 1: The pseudorapidity distribution of produced particles in the stratospheric event at $10^{16}$ eV has two pronounced peaks.
Figure 2: The pseudorapidity distribution of NA22-event [8] with extremely high peak.
Figure 3: The pseudorapidity distribution of the centers of dense isolated groups in $pp$-interactions at 360 GeV [9] shows some excess over background at $|\eta_c| \approx 0.3$. 
Figure 4: The two-dimensional ($\eta - \phi$) plot of the wavelet coefficients at scale $j = 5$ obtained from analysis of PbPb event at 158 GeV [17]. Dark regions denote large values of wavelet coefficients, i.e. strongly correlated groups of particles. The ring regions $1.8 < \eta < 2.3$ and $2.7 < \eta < 3.0$ correspond to peaks of the pseudorapidity distribution $\eta = 2.5$ is equivalent to c.m.s. angle $\pi/2$. The dots indicate particle positions. The empty space near the center is due to the limited acceptance of the detector.
Figure 5: The $\phi$-distribution of particles produced by trigger and companion jets at RHIC \cite{46} shows two peaks in $pp$ and three peaks in AuAu-collisions.
