I. M. Dremin. *Hadronic analogs of Cherenkov, transition, and bremsstrahlung radiation.* Effects analogous to well-known electrodynamic phenomena such as Cherenkov, transition, and bremsstrahlung radiation are found to occur in the physics of strong interactions. The first two are connected with the presence of a medium and the last can occur even when there is only one scatterer. Formally, the nature of the effect is determined by the quantity βn ($\beta = v/c$, v is the velocity of the radiator, and n is the refractive index of the medium). When $\beta n > 1$ we have the Vavilov-Cherenkov effect; a change in n produces the transition radiation, and a change in the velocity vector gives rise to bremsstrahlung.

For radiation of frequency ω, the refractive index of a medium is related to the (forward) scattering amplitude $F(\omega)$ as follows:

$$n(\omega) = 1 + \frac{2\pi N}{\omega^2} F(\omega), \tag{1}$$

where N is the density of scattering targets in the medium. The real part of the forward-scattering amplitude is positive for all hadrons at energies of a few hundred MeV. According to (1), this means that a hadron colliding with a hadronic medium" (a nucleus or another hadron) can radiate secondary hadrons by analogy with the emission of Cherenkov radiation in electrodynamics[1].

The analogy with electrodynamics is strengthened further if we consider the emission of gluons by quarks[1)] (the constituents of the hadron), since the properties of gluons and quarks are respectively similar to the properties of photons and electrons. The behavior of the hadronic scattering amplitudes suggests that $\Delta n \equiv n - 1$ is positive for the constituents of hadrons i.e., quarks and gluons, as well. The characteristic features of the hadronic case are that[1] Δn is small ($\lesssim 10^{-6}$) and decreases with increasing frequency ω as ω^{-1}, and that the size of the hadronic target is limited, i.e., $l \sim m_\pi^{-1}$ (m_π is the pion mass), so that $\omega l \Delta n \ll 1$ (although $\omega l \gg 1$). This, in turn, means that a rigorous separation of radiation into different types is difficult to achieve. This becomes clear if we consider the emission of radiation by a current that appears and disappears instantaneously as it traverses a path of length l in a medium. This problem was first solved by Tamm[2] in 1939. The total intensity of radiation emitted at frequency $\omega \gg E$ (E is the primary energy) is given by

$$\frac{d^2 I}{d\omega\, d\Omega} = 4\alpha_c c_F \theta^2 \sin^2\left[\frac{1}{4}\omega l(\theta^2 - 2\Delta n)\right][\pi^2 \omega(\theta^2 - 2\Delta n)^2]^{-1}, \tag{2}$$

[1)]Both the quark and the gluon finally transform into jets of hadrons traveling in the direction of emission of the parton that initiates them.

which is valid for angles $\theta^2 \ll 1$ and where $\Delta n \ll 1$, $|v| \approx 1$ has been taken into account. Instead of the fine structure constant α, this expression involves the chromodynamic constant α_c ($c_F = 4/3$), since we are considering radiation by a color current.

The radiation described by (2) has the characteristic angular distribution, namely, it takes the form of a halo around the current emitting it. In other words, gluon jets of given energy ω are emitted by the quark preferentially at a particular polar angle to its direction of motion. This angle is given by

$$\theta_J \approx \sqrt{\frac{2\pi}{\omega l}}. \tag{3}$$

which is appreciably greater than the usual angles of the order of m/E, i.e., the jets have high transverse momenta:

$$p_\perp \approx \omega\theta_J \approx \sqrt{\frac{2\pi\omega}{l}}. \tag{4}$$

As the energy increases, the radiation intensity rises as the square of the logarithm of primary energy.

The Cherenkov emission of gluons, which is due to the properties of the hadronic medium, can be separated from the resultant emission if we consider the term linear in Δn in the expansion of (2). It also forms a halo (at practically the same angle (3)). The fact that Δn is small ensures that the higher order terms are negligible, so that the hadronic transition radiation, which is expected to be quadratic in Δn, should also be negligible.

Thus, if the hadron (or nucleus) is looked upon as a hadronic medium of size $l \sim m_\pi^{-1}$ with refractive index n, the emission of gluon jets, which is analogous to Cherenkov radiation should give rise to a hadronic halo around the primary quark jet with intensity proportional to $\Delta n \equiv n - 1$.

We now ask the natural question: what physical significance can be attached to the medium-independent emission given by (2) with $\Delta n = 0$.

In fact, this is typical bremsstrahlung associated with sudden velocity changes at the beginning and the end of the path in this problem. Do such "current discontinuities" occur in real physical situations? If, for the sake of simplicity, we consider the case of e^+e^- annihilation into hadrons, there are no color currents initially, but they appear instantaneously at the point of interaction and then decay because of screening by confining forces. However, since the size of the nucleus (regarded as the "medium") is known, but the mechanism responsible for screening is not clear, we cannot uniquely describe how and where the compensation of the color current actually occurs. It is possible that the phenomenon of screening of the color current as a result of confinement leads to a new scale of length that is different from the usual hadronic dimensions used above in the discussion of Cherenkov radiation for which only the size of the hadronic medium is important. It is qualitatively clear that these lengths should be smaller than the corresponding lengths in electrodynamics, so that gluon bremsstrahlung should be emitted at greater angles than the usual electromagnetic radiation.[1,3,4]

The increase in the angles and transverse momenta as the size of the segment from which the radiation is collected is reduced, can readily be demonstrated by considering the example of successive scattering of an electron by two scatterers whose separation can be varied.[4] As this separation is increased, the emitted intensity increases (initially in proportion to the square of the length) whereas the emission angle decreases. The emission cone of radiation originating on the segment between the two scatterers can be observed if its interference with the radiation from the ends of the trajectory is small. This can be achieved not only by large-angle scattering in the above problem, but also by suppressing the emisson from the ends of the trajectory (for example, by using waveguides[2)]).

In the hadron case, one would expect that the confinement of quarks and gluons is analogous to the screening of the field of an electron in the interior of a waveguide, and therefore the emission from the extreme ends of the trajectory of the quark can be neglected because the color of the quark is neutralized in the initial and final hadrons, but may manifest itself in the interaction process. Consequently, this type of hadronic emission should appear with sufficiently high transverse momenta.

Individual events with the required ring structure of the target diagram (i.e., enhanced hadron density within a ring in the azimuthal plane) have been seen in cosmic rays. Detailed analysis of accelerator data (especially at colliding-beam energies) will be necessary before final conclusions can be drawn.

To summarize, we may say that the finite size of nuclear targets and the phenomenon of quark and gluon confinement should ensure that the gluon jets that are emitted by analog with the emission of classical bremsstrahlung and Cherenkov radiation should emerge at appreciably greater angles than in the electromagnetic case. At high energies, each energetic jet should be surrounded by a halo of jets of lower energy. The size of the halo is a measure of the effective length of the source, and its intensity is an indication of the mechanism responsible for the emission. Experimental studies of such multiple creation events should produce important information on the physics of hadrons.

[1] I. M. Dremin, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 152 (1979) [JETP Lett. **30**, 140 (1979)]; Yad. Fiz. **33**, 1357 (1981) [Sov. J. Nucl. Phys. **33**, 726 (1981)].
[2] I. E. Tamm, J. Phys. (USSR) **1**, 439 (1939).
[3] S. Frautschi and A. Krzywicki, Z. Phys., **1**, No. 1 (1979).
[4] I. M. Dremin, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 617 (1981) [JETP Lett. **34**, 594 (1981)].

[2)] In this case the radiation can also be referred to as transition radiation if the latter is taken to include also radiation due to a change in the boundary conditions in the problem of a uniformly moving charge.