Coherent hadron radiation at extremely high energies

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During the interaction of extremely high energy ($E_{lab} \gtrsim 10$ TeV) hadrons a hadron radiation can appear, similar to the Vavilov-Cerenkov radiation in the case of electromagnetic fields. The process exhibits an energy-threshold character. The emitted particles with a given energy are concentrated near some polar angle and possess high transverse momentums (at least several GeV/sec).

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In 1973 I. E. Tamm and I.M. Frank showed theoretically that "an electron, moving in a medium, radiates light even during uniform motion only if its velocity exceeds the velocity of light in this medium"[1] and in this way explained the Vavilov-Cerenkov effect.

A hadron, passing through a nuclear-active medium (nucleus or nucleon), can also emit coherent hadron radiation (primarily pions) when its velocity exceeds the velocity of radiation in the medium.[1)] For this to occur it is necessary, first of all, that the real part of the index of refraction of radiation in the medium be greater than one within some frequency region. The index of refraction $n(\omega)$ is related to the amplitude of the forward elastic scattering $f(\omega)$ of the radiation quanta by the particles of the medium by the formula[3]

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

where ω is the frequency of the radiation, ν is the density of the scatterers (inhomogeneities) of the medim, and the amplitude $f(\omega)$ is normalized by the condition

$$\mathrm{Im} f(\omega) = \frac{\omega}{4\pi} \sigma(\omega). \tag{2}$$

Here $\sigma(\omega)$ is the total cross section of the interaction of the radiation with the particles of the medium.

Noting that in the case being considered the quantity ν is determined by the size of the hadrons $\nu \approx 3m_\pi^3/4\pi$ (m_π is the pion mass) and introducing $\rho(\omega) = \mathrm{Re}\, f(\omega)/\mathrm{Im} f(\omega)$, we have:

$$\mathrm{Re}\, n(\omega) \equiv 1 + \Delta n_R(\omega) = 1 + \frac{3m_\pi^3}{8\pi\omega} \sigma(\omega)\rho(\omega). \tag{3}$$

It is known from experiment[4] that $\rho(\omega)$ becomes positive for $\pi^- p$ scattering when $\omega \gtrsim \omega_n \approx 70$ GeV. Other hadron-hadron processes possess a similar "threshold" property [for pp, pn, pd interactions $\rho(\omega) > 0$ for $\omega \gtrsim 330$ GeV].

Since adequately detailed experimental data now only exist for the pp interactions, Fig. 1 shows the behavior of $\Delta n_R(\omega)$ in the case when $\sigma_{pp}(\omega)$ and $\rho_{pp}(\omega)$ are

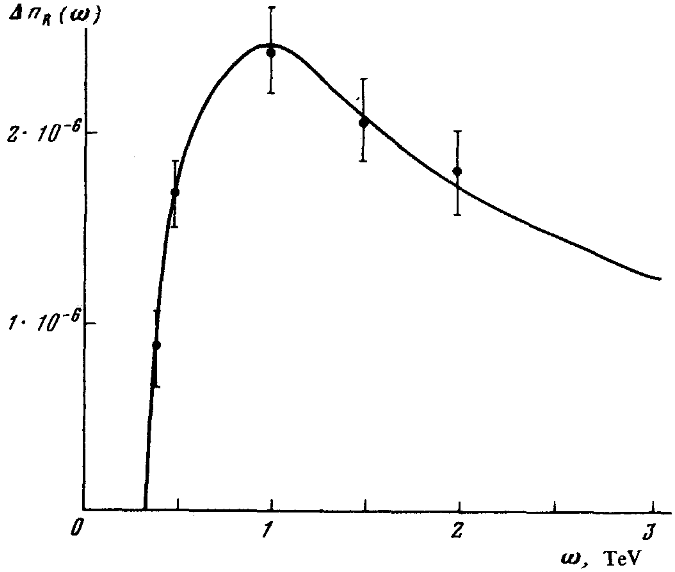

FIG. 1. The function $\Delta n_R(\omega)$ for pp interactions in accordance with Eq. (3). Points—experiment, curve—result of calculation from dispersion relations.

introduced into Eq. (3). The results of calculations of $\rho(\omega)$ from the dispersion relations, obtained for other hadron processes, agree well with the existing experiment and therefore provide a basis for expecting that the qualitative character of the behavior of $\Delta n_R(\omega)$ for the interactions of different hadrons will not be fundamentally different from that shown in Fig. 1. Within an accuracy of logarithmic factors the quantity $\sigma(\omega)\rho(\omega)$ in Eq. (3) can be assumed to be constant as $\omega \to \infty$, i.e., $\Delta n_R(\omega)$ decreases as ω^{-1}. This means that the index of refraction of a bombarding hadron with an energy much greater than 1 TeV can be assumed to be equal to one, considering only the index of refraction to be different from one (although comparatively small) for its radiation, having an appreciably lower energy. The most important aspect is the presence of a reaction threshold—the process can generally not proceed if the energy of the primary particle is not sufficient to emit radiation quanta with energies of hundreds of GeV.

For uniform motion of the source the emitted waves have identical phases at the angle (in the laboratory coordinate system)[1]:

$$\cos\theta_0 = \frac{1}{\beta n} \quad \text{or} \quad \theta_0 \approx \sqrt{2\Delta n_R(\omega)} = \sqrt{\frac{3m_\pi^3}{4\pi\omega}\sigma(\omega)\rho(\omega)}, \tag{4}$$

i.e., $\theta_0 \lesssim 2\times 10^{-3}$ for the $\Delta n_R(\omega)$ in the figure.[2)] It is interesting that at a fixed angle radiation is possible at two frequencies, the values of which converge as one approaches the maximum angle, as determined from the maximum of the $\Delta n_R(\omega)$ curve.

The transverse momentum of a particle, emitted at the angle θ_0, is equal to

$$p_\perp = \omega\theta_0 = \sqrt{\frac{3m_\pi^3}{4\pi}\omega\sigma(\omega)\rho(\omega)}\ , \tag{5}$$

i.e., it increases approximately as $\omega^{1/2}$ as $\omega \to \infty$.

The phase shift of the radiation waves over a length $l \sim m_\pi^{-1}$ is equal to[5]

$$\Delta\phi = -\frac{\omega}{2m_\pi}(\theta^2 - 2\Delta n_R(\omega))\ . \tag{6}$$

From this, in particular, we obtain (4) by assuming $\Delta\phi = 0$. The coherency condition $|\Delta\phi| \lesssim \pi$ is satisfied up to angles of the order of $\theta_k \sim (2\pi m_\pi/\omega)^{1/2}$, appreciably greater than θ_0, but still decreasing equally as $\omega^{-1/2}$ with an increase in ω. The radiation should travel into a cone of angles $\theta < \theta_k$.

All the radiation properties described above follow only from the coherency condition. But, however, the location of the intensity maximum, for example, within the radiation cone is strongly dependent on the dynamics of weak interactions.

We obtain estimates of the characteristics of the secondary particles by assuming the following picture for the process. The interaction of colliding hadrons can be considered as the passage of quarks, carrying colored charge, through a quark-gluon medium. If the radiation condition (4) is satisfied in this medium, then the quarks will emit gluons, which are then converted into the particles observed in the experiment due to the action of the containment mechanism. As usual, we will assume that the kinematic characteristics of the secondary particles are determined by the initial step in the production of high-energy gluons, and the subsequent action of the containment mechanism is important only for the quantum numbers and the multiplicity, but it does not exert any appreciable influence on the kinematic properties of the process.

Since gluons are massless vector particles, by ignoring their self-action we can consider the entire process to be approximately analogous to the emission of photons by electrons in a medium and can use the Vavilov–Čerenkov radiation formulas for estimates by replacing the fine structure constant with the chromodynamic constant α_c (which is here of the order of one and therefore it must be remembered that higher orders with respect to this constant can be important).

The radiation for uniform motion along a finite segment of length l and with instantaneous acceleration at the beginning and end of this segment was calculated in Ref. 6. The angular and energy distributions of the number of gluons N_g are given by the formula (for $1 \sim m_\pi^{-1}$):

$$\frac{dN_g}{d(\cos\theta)d\omega} = \frac{8a_c}{\pi\omega}\theta^2 \frac{\sin^2\left[\frac{\omega}{2m_\pi}(\theta^2 - 2\Delta n_k(\omega))\right]}{[\theta^2 - 2\Delta n_R(\omega)]^2} \tag{7}$$

This formula is easily obtained from Eqs. (7.6)–(7.9) of Ref. 6 if it is considered that in our case the quantities θ, Δn_R, m_π/ω and $1-\beta$ are much smaller than one. Here, unfortunately, it is impossible to distinguish between the "faster than light" radiation and the radiation due to acceleration since the quantity Δn_R is very small and the radiation path $\sim m_\pi^{-1}$ is small enough $(\omega \Delta n_R / m_\pi < 1)$. Nevertheless, restrictions on the total radiation, of course, also mean restrictions at the same time on the effect we are looking for.

It is not hard to see that all the gluons will be concentrated inside a ring if the products of their decay are detected in the plane perpendicular to the direction of the primary particle since the number of gluons at small angles $\theta \ll \theta_0$ increases as $dN_g/d(\cos\theta) \sim \theta^2$, and for $\theta \sim \theta_k$ it decreases with an increase in angle as $dN_g/d(\cos\theta) \sim \theta^{-2}$. This can be observed very simply in the experiment in terms of the presence of a peak in the pseudovelocity distribution $\eta = -\log\tan\theta$ in this region of angles.

The energy spectrum of the gluon radiation will be of the type $d\omega/\omega$ for large ω. This distinguishes it from the plateau of the form $dN \sim d\omega$ in the case of the Vavilov–Čerenkov effect. This is due to the fact that $dN \sim \Delta n_R d\omega$ for small Δn_R and in the first case $\Delta n_R \sim \omega^{-1}$, whereas in the second case $\Delta n_R \approx$const.

It is easy to see from the indicated distributions that the total number of gluons increases approximately logarithmically with an increase in the primary particle energy.

The actual role and the ability to observe the effect are due to the fact that the extremely small factor $\Delta n_R \sim 10^{-6}$ is compensated to a large extent by the large factor ω/m_π. A more precise estimate requires detailed assumptions about the mechanism of the process.

The following conclusions can be drawn from what has been presented above: 1) the process can occur when the energy of the primary hadron is appreciably greater than 1 TeV and the energies of the emitted pions are greater than 100 GeV. Coherent hadron radiation can most probably be observed at energies starting with tens (or even hundreds) of TeV if its intensity proves to be sufficiently high. 2) If the energy of the emitted pion is $\omega \sim 1$ TeV, then the emission angle is $\theta_0 \sim 2 \times 10^{-3}$ and the transverse momentum is $p_T \gtrsim 2$ GeV.

Thus, coherent hadron radiation occurs with large transverse momentums, where the background from the usual processes is comparatively low, and it can be responsible for the fact that the average transverse momentum increases with an increase in the primary particle energy, as indicated by many cosmic ray data.[7] 3) In an accelerator of oppositely directed protons with an enegy of 400×400 GeV this radiation should be detected at angles of tens of degrees and should travel in two symmetrical cones (in the front and rear hemispheres). 4) In the data, obtained in cosmic rays, the rear cone can be transformed into a second, broader ring, enclosing the smaller radius ring, by means of the Lorentz transformations. On the average the energy of the particles in the outer ring should be less than the energies in the inner ring (approximately inversely proportional to the radius). The primary particle energy can be estimated from the mutual position of the rings, and the point of interaction can be found from their radii (see Ref. 8).

In conclusion, it would be desirable to emphasize again that here we have been dealing with the possibility of the appearance of a new effect in hadron interactions at extremely high energies, leading to an increase in the fraction of particles with high transverse momentums and without touching upon the basic mechanism for the production of particles with low transverse momentums.

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[1)]Attention for a long time has been directed at this possibility[2]; however, a lack of arguments in favor of the fact that the index of refraction exceeds one has undermined the trust in such a mechanism for producing particles, the properties of which, moreover, were determined by a nearly arbitrary choice of the frequency dependence of the index of refraction, and therefore this work has not been pursued further.

[2)]Terms of the order of m_π/ω and ω/E_0 and ω/E_0 are ignored everywhere compared with unity and it is taken into consideration that $\theta \ll 1$ and $\Delta n_R \ll 1$.

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