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Mixed optical Cherenkov–Bremsstrahlung radiation in vicinity of the Cherenkov cone from relativistic heavy ions: Unusual dependence of the angular distribution width on the radiator thickness

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A B S T R A C T

The Cherenkov radiation (ChR) angular distribution is usually described by the Tamm–Frank (TF) theory, which assumes that relativistic charged particle moves uniformly and rectilinearly in the optically transparent radiator. According to the TF theory, the full width at half maximum (FWHM) of the ChR angular distribution inversely depends on the radiator thickness. In the case of relativistic heavy ions (RHI) a slowing-down in the radiator may sufficiently change the angular distribution of optical radiation in vicinity of the Cherenkov cone, since there appears a mixed ChR–Bremsstrahlung radiation. As a result, there occurs a drastic transformation of the FWHM of optical radiation angular distribution in dependence on the radiator thickness: from inversely proportional (TF theory) to the linearly proportional one. In our paper we present the first analysis of this transformation taking account of the gradual velocity decrease of RHI penetrating through a radiator.

1. Introduction

The Cherenkov radiation (ChR) is widely used in the threshold detectors in experimental high-energy particle physics. The characteristics of ChR (the number of photons, emission angle, etc.) according to the standard Tamm–Frank theory [1] are usually calculated assuming that relativistic charged particle moves uniformly and rectilinearly in the optically transparent radiator and emission (optical range) appears at the well-known Cherenkov angle. According to the Tamm–Frank theory, the full width at half maximum (FWHM) of the ChR angular distribution inversely depends on the radiator thickness.

Several reasons such as multiple scattering [2] and slowing-down may break this ideal character of particle motion in the matter and cause deviations in angular distributions of ChR. In the case of relativistic heavy ions (RHI), the multiple scattering is negligible (for reasonable radiator thickness) and the effect of slowing-down due to ionization energy loss becomes the main reason, which can influence the ChR.

RHI slowing-down in the radiator material leads to a significant velocity decrease in the RHI energy region about 100–1000 MeV/u, as a result – the Cherenkov emission angle changes and the ChR spectral and angular distributions become broadened with a specific diffraction-like structure [3–7]. The first theoretical prediction of this feature of ChR from RHI was done in [8]. Later, several experiments [9–11] on ChR from RHI performed at GSI (Darmstadt, Germany) showed the sufficient discrepancy between the Tamm–Frank theory [1] and experimental data on angular distributions of ChR from 900 MeV/u Au RHI in a LiF radiator. In [3–5] we developed new theory, which allows to calculate the ChR spectral and angular distributions taking the most correct account of RHI slowing-down. As a result, in [7] the data of these earlier GSI experiments were successfully explained. In view of such interesting and bright effect connected with influence of RHI slowing-down on ChR it is interesting to pay attention on the process of transformation of the Tamm–Frank theory valid for the particle's uniform and rectilinear motion into the new one which takes into account the gradual velocity decrease of a particle penetrating through a radiator. This transformation was not yet studied in detail.

Strictly speaking, the terminology in this field requires some modifications: from ChR with slowing down to maybe more deeper one – mixed ChR and Bremsstrahlung radiation.

Some comments are necessary for understanding a problem. The first version of the theory of optical radiation from uniformly and infinitely time moving charge in an optically transparent radiator suggested by Tamm and Frank does not contain the thickness. In order to introduce the finite the radiator thickness, some modifications have been suggested (see, e.g. in [12]).

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The formulae suggested for a finite-size radiator are widely used to calculate the real characteristics of the Cherenkov radiation in the finite size radiator. The broadening of the angular distribution in a finite-size radiator is important since it leads to the loss of the part of the photons due to reflection/transmission on the back borders in a large scale Cherenkov detectors. To compare: the Tamm–Frank theory predicts delta-like angular distribution – so that the reflection and transmission can be easily calculated and detector design is easy to perform.

Speaking on optical radiation from RHI, we may say on the mixed type of radiation: Cherenkov and Bremsstrahlung radiation and probably Transition radiation. The last one appears only at entrance and exit into/out of the radiator and one can suggest its intensity is much less than the intensity of mixed – Cherenkov–Bremsstrahlung radiation, which is collected from the whole path in a radiator.

If we exclude the RHI slowing down, we get ordinary Cherenkov radiation in a finite-size target [12]. If we exclude optics (refraction index = 1), we get the bremsstrahlung from RHI with very small intensity due to its huge mass. If we take into account both optics and slowing-down (deceleration), there appear mixed (or combined radiation) Cherenkov–Bremsstrahlung radiation, the properties of which we will investigate in vicinity of the Cherenkov cone.

In some aspects, the situation which we consider in our paper remains the so-called synchrotron-Cherenkov radiation from cosmic particles in the Earth atmosphere. This and some similar problems (not for RHI) are considered in [13] dedicated to the very deep theoretical analysis of different aspects of radiation, including the Tamm problem.

In this paper we present the first analysis of the Cherenkov–Bremsstrahlung radiation angular distribution FWHM dependence on the radiator thickness L and show how $\sim 1/L$ dependence transforms into linear $\sim L$ dependence, if the slowing-down of RHI is taken into account. We concentrate on solid Cherenkov radiators, in view of very recent experiments [14,15].

2. Qualitative consideration

To analyze the transformation from $1/L$ to L dependence of FWHM let us start form the basic formula for spectral-angular distribution of radiation intensity from charged particle in a matter [14]:

$$\frac{dW}{d\hbar\omega d\Omega} = \frac{Z^2\omega^2\sqrt{\varepsilon}}{137\, 4\pi^2 c^2}\left|\left[\mathbf{n}\times[\mathbf{n}\times\mathbf{I}]\right]\right|^2, \tag{1}$$

$$\mathbf{I} = \int_0^T \mathbf{v}(t)\exp\left[i\omega\left(t-\sqrt{\varepsilon}\frac{\mathbf{n}\cdot\mathbf{r}(t)}{c}\right)\right]dt. \tag{2}$$

Here Z – is the particle charge, $\omega = 2\pi c/\lambda$ is the radiation frequency, c – is the speed of light in vacuum, $\sqrt{\varepsilon}$ – is the radiator refractive index depending on the radiation wavelength λ, $\mathbf{r}(t), \mathbf{v}(t)$ – are the particle trajectory and velocity respectively, $\mathbf{n}$ – is the unit vector determining the radiation direction, and T stands for penetration time through a radiator.

The formula (1) is derived in the frame of the classical radiation theory (finding fields in the wave zone, the Pointing vector and thus the flux of electromagnetic energy – or intensity of radiation).

The Tamm–Frank theory [1] based on Eq. (2) (constant velocity $\mathbf{v}(t) = const$) predicts an inverse dependence of the ChR angular distribution width (FWHM) on the radiator thickness L:

$$\Delta\theta_{TF} = \frac{\lambda}{\sqrt{\varepsilon}L}. \tag{3}$$

If one takes into account the RHI slowing-down in a radiator, instead of the equation (3) there appears a new one:

$$\Delta\theta_{stopping} = \frac{1}{\gamma_0^3\beta_0^2Mc^2}\frac{1}{\sqrt{(\sqrt{\varepsilon}\beta_0)^2-1}}S(E_0)L. \tag{4}$$

Here, $\gamma_0 = 1/\sqrt{1-\beta_0^2}$, $\beta_0 = v_0/c$, v_0 and E_0 – are the RHI initial velocity and energy, M – is the RHI mass, $S(E_0) = -dE/dx$ – is the radiator's stopping power.

The equation (4) was obtained assuming that in a thin radiator [8]:

$$\frac{1}{v_L} = \frac{1}{v_0} - \frac{\varsigma}{v_0^2}L, \tag{5}$$

where v_0, v_L – are the RHI velocities at entrance and exit of the radiator respectively, and

$$\varsigma = \left(\frac{dv(z)}{dz}\right)\bigg|_{z=0} = -\frac{c^2}{\gamma_0^3 v_0 Mc^2}S(E_0). \tag{6}$$

As it follows from Eq. (4), the FWHM ($\Delta\theta_{stopping}$) of the Cherenkov–Bremsstrahlung radiation angular distribution from RHI linearly depends on the radiator thickness L.

One may suggest that the real Cherenkov–Bremsstrahlung radiation angular distribution width from RHI is a sum of two terms: the width of the Tamm–Frank distribution plus the width that appears in the case of stopping:

$$\Delta\theta \cong \Delta\theta_{TF} + \Delta\theta_{stopping} \cong \alpha\cdot\frac{1}{L} + \beta\cdot L. \tag{7}$$

If so, the Eq. (7) determines the transition from Tamm–Frank distribution to the more realistic one, and it happens at radiator thickness

$$L_{\min} = \sqrt{\frac{\lambda}{\sqrt{\varepsilon}K}}, \tag{8}$$

which corresponds to the minimum of the Eq. (7). Here,

$$K = \frac{1}{\gamma_0^3\beta_0^2Mc^2}\frac{1}{\sqrt{(\sqrt{\varepsilon}\beta_0)^2-1}}S(E_0).$$

To comment: Eq. (8) contains the non-trivial dependence of $L_{\min}$ on several parameters – radiation wavelength λ, refraction index $\sqrt{\varepsilon}$ and RHI energy E_0.

The FWHM of the Cherenkov–Bremsstrahlung radiation angular distribution as a function of radiator thickness L calculated using the Eq. (7) for different RHI energies and radiation wavelengths is shown below in the Fig. 1. The minimum value of the Cherenkov–Bremsstrahlung angular distribution width for curves a–c is in accordance with the Eq. (8).

The Eq. (8) is only a simple naive estimation of $L_{\min}$. It is difficult to derive the general analytical formula for $L_{\min}$, since one needs to know real values of $\mathbf{r}(t)$ and $\mathbf{v}(t)$ inside a radiator taking account of RHI slowing-down. Therefore, in the next section we consider the L-dependence of the shape and width of the Cherenkov–Bremsstrahlung radiation from RHI by means of numerical calculations using the Eq. (1).

3. Numerical calculations: L-dependence of the Cherenkov–Bremsstrahlung angular distributions shape and FWHM

The Cherenkov–Bremsstrahlung angular distributions of RHI taking account of their slowing-down in a radiator are calculated using the Eqs. (1)–(2). To obtain exact values of RHI velocity and coordinate $\mathbf{r}(t), \mathbf{v}(t)$ in a radiator taking account of slowing-down,