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PRODUCTION OF e^+e^--PAIRS ON LINEAR COLLIDERS DUE TO THE UNRUH EFFECT

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ՈՒՆՐՈՒԻ ԷՖԵԿՏԻ ՀԵՏԵՎԱՆՔՈՎ e^+e^--ԶՈՒՅԳԵՐԻ ԱՌԱՋԱՑՈՒՄԸ ԳԾԱՅԻՆ ԿՈԼԱՅԴԵՐՆԵՐԻ ՎՐԱ

Քննարկված է վակուումային ֆլուկտուացիաների հետևանքով արագացվող կոորդինատների համակարգերում «ջերմային էֆեկտների» հանդես գալը։ Հաշված են Ունրուի մեխանիզմով գծային կոլայդերների վրա առաջացած ֆոտոնների և e^+e^- զույգերի լրիվ թիվը, ինչպես նաև համապատասխան էներգիայի կորուստները։

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1. Introduction

Recently it has been shown [1-4] that due to the Unruh effect [5-7], when a charged particle is accelerated in an external field or in the result of collision with other particle, a new type of radiation, called Unruh radiation, is produced. In short, the physics of this phenomenon consists in the following. According to the Unruh effect any particle moving with acceleration a' in its instantaneous rest frame (IRF) finds itself in a bath of black body thermal radiation with a temperature $T=a'/2\pi k$ where k is the Boltzman constant, $\hbar=c=1$. The scattering of these Planck photons on the charged particle in IRF results in the fact that observer in the laboratory frame (LF) can detect a real radiation which is called Unruh radiation. In the case of relatively low values of a' and T, when the photon energy in IRF $\omega' \ll m$ it takes place Thomson scattering. In this case as it is shown in [1] the integral radiation intensity is $I_{unr} \sim a'^4$, and it becomes higher than the intensity of the Larmor radiation $I_{larm} \sim a'^2$, when $a' \gtrsim 3.10^{33} cm/s^2$.

For higher values of a' or T, when the condition $\omega \ll m$ is not satisfied in IRF, it take place Compton scattering. The works [2,3] are devoted to the calculation of the corresponding Unruh radiation produced when a high energy electron passes through external or crystallographic fields or through laser or electron bunch fields. It is shown that for realistic conditions the particle energy losses due to the Unruh radiation is smaller than the losses conditioned by the synchrotron radiation (beamstrahlung). Therefore the terrestrial observation of the Unruh effect by detecting the Unruh radiation is not realistic just as by other suggested methods [8,9].

On the other hand as it is mentioned in [1,2] when $\omega > 4m$ the process of e^+e^--pair production can take place via the reaction $\gamma e \to e e^+ e^-$ where γ is a Planck photon in IRF and e is an electron undergoing large acceleration. Looking for a new process for detecting the Unruh effect this work is devoted to the investigation of the e^+e^--pair production on linear colliders by Unruh mechanism.

In general the pair production due to the Unruh effect during bunch-bunch collisions can proceed through the following three processes which correspond to the already known processes considered for the linear colliders (see, for instance, [10]).

a) The double process when during bunch-bunch collision an Unruh radiation photon γ_{unr} produces e^+e^--pair incoherently on separate particles of the remained part ($\sim 1/2$) of the oncoming bunch, $\gamma e \to e e^+ e^-$. This process is analogous to that considered in [11,12].

b) The double process when during bunch-bunch collision an Unruh radiation photon produces coherently a e^+e^--pair in the collective field H of the remained part of the oncoming bunch, $\gamma H \to He^+e^-$. This is the analogous of [13].

c) The above-discussed new process of the additional e^+e^--pair production by thermal photon of the the Unruh effect on the electron accelerated in the field of the oncoming bunch (analogous to [14]).

In this work we shall consider only the process c) since it can be shown that the energy losses due to the process c) dominates the other losses.

Before proceeding let us note that the synchrotron radiation parameter $Y=\gamma H/H_0$ ($\gamma=E/m$ is the particle Lorentz factor, H is the external magnetic field, $H_0=m^2/e=1.44\ 10^{13}$g is the so called critical field) is determined by the bunch's parameters

$$Y = \frac{5\gamma r_0^2 N}{6\alpha\sigma_z\sigma_y(1+R)} \tag{1}$$

where $\sigma_{x,y,z}$ are the sizes of the Gauss bunches of N particle, $R=\sigma_x/\sigma_y$, $\alpha=1/137$ and $r_0=e^2/m$ is the classical electron radius. Using the expressions [3] $a'=\gamma eH/m=Ym$, the results of our calculations are given as function of kT which is connected with H or Y with relations:

$$kT=e\gamma H/2\pi m=Ym/2\pi$$

$$kT(\mathrm{MeV})=1.84\ 10^{-15}\gamma H(\mathrm{gauss})=8.12\ 10^{-2}Y. \tag{2}$$

2.The Total Number of Photons and e^+e^--Pairs Produced by Unruh Mechanism

One can obtain the total number of photons under consideration by integrating the spectra given in the work [3]. However such a way of calculation is not reasonable, especially, in the case of e^+e^--pairs when the necessary differential cross sections are not available. Therefore, we shall use the invariance property of the total cross sections (number of the events).

According to the Unruh mechanism the number of the real photons and e^+e^--pairs produced by thermal photons with energy in the interval $\omega_1', \omega_1'+d\omega_1'$ in unit time in IRF is equal to

$$\frac{dn_{\gamma,e^+e^-}}{dt'\,d\omega_1'} = \frac{dn_{pl}}{d\omega_1'}\,\sigma_{\gamma,e^+e^-}(\omega_1') \qquad (3)$$

where

$$\frac{dn_{pl}}{d\omega_1'} = \frac{1}{\pi^2}\,\frac{\omega_1'^2}{\exp(\omega_1'/kT) - 1} \qquad (3')$$

is the thermal radiation photon spectrum of the Unruh effect, $\sigma_{\gamma,e^+e^-}(\omega_1)$ are the cross sections of the processes $\gamma e \to e\gamma$ and $\gamma e \to e e^+e^-$ (see [15,16]), taking into account the angular isotropy of the radiation in IRF. Integrating (3) over ω_1' (or over $k=\omega/m$ from $k=0$ or $k=4$) we obtain the total numbers of produced photons and pair per unit length in LF ($dl=\gamma dt'$):

$$\frac{dN_{\gamma,e^+e^-}}{dl} = \frac{1.756\ 10^{30}}{\gamma}\int_{0,4}^{\infty}\frac{k^2 dk}{\exp(km/kT) - 1}\,\sigma_{\gamma,e^+e^-}(k) \qquad (4)$$

where according to [15,16]

$$\sigma_{\gamma}(k)=\frac{\pi r_0^2}{k}\left[\left(1-\frac{2}{k}-\frac{2}{k^2}\right)\ln(1+2k)+\frac{1}{2}+\frac{4}{k}-\frac{1}{2(1+2k)^2}\right], \qquad (5)$$

$$\sigma_{e^+e^-}(k)=(F_{BH}+F_{\beta}+F_{BG})(1-\Delta) \qquad \text{for} \quad 4 < k < 16,$$

$$\sigma_{e^+e^-}(k)=F_{BH}+F_{B}+F_{BG} \qquad \text{for} \quad 16 < k < 100,$$

$$\sigma_{e^+e^-}(k)=F_{BH}+F_{B} \qquad \text{for} \quad 100 < k < 10000,$$

$$\sigma_{e^+e^-}(k)=F_{BH} \qquad \text{for} \quad k > 10000,$$

$$F_{BH}=\alpha r_o^2\left[\frac{28}{9}\ln(2k)-\frac{218}{27}\right],$$

$$F_{B}=-\frac{\alpha r_o^2}{k}\left[\frac{4}{3}(\ln 2k)^3-3(\ln 2k)^2+6.84\ln 2k-21.51\right],$$

$$F_{BG}=\frac{\alpha r_o^2}{k^2}\left[\frac{8}{3}(\ln 2k)^3-\left(4-\frac{1}{k}\right)(\ln 2k)^2-\frac{1}{18}\left(168+\frac{106}{k}+\frac{49}{k^2}\right)(\ln 2k)-11.8-\frac{16.8}{k}-\frac{0.27}{k^2}\right],$$

and Δ is the Mork's correction which in this work is approximated by polynom.

In Fig. 1 it is given the dependence of $\gamma dN/dl$ on kT(MeV) calculated for beamstrahlung (curve 1) and for radiation (curve2) and pairs (curve3) produced by Unruh mechanism. As it is seen after multiplying by γ the curves are independent of γ. One can estimate the corresponding yield for any collider in the following way. Coming out from the collider's parameters one determines the value of Υ and kT using the expressions (1) and (2). Then in order to obtain the number of particles produced during one collision of the oncoming bunches, it is necessary to multiply the corresponding values of $\gamma dN/dl$ by the bunch length and divide over γ.

As it is seen from Fig.1 at low values of kT or Υ the total number of the beamstrahlung photons exceeds the number of all other particles; in the region kT=25-80 MeV the Unruh radiation dominates, while for kT>80 MeV the number of the Unruh e^+e^--pairs is greater than the number of other particles.

Here it is necessary to note that for the same value of kT quite different spectral distributions correspond to these three types of particle production. The differential spectra of the Unruh radiation are compared with the well known beamstrahlung spectra in the work [3]. What concerns the differential spectra of the Unruh e^+e^--pairs it will be difficult to calculate such spectra because of the very complicated form of the expressions for the differential cross section of the process $\gamma e \rightarrow e e^+ e^-$-pairs. In the next section we assume that in IRF the Planck photons give their total energy to the produced e^+e^--pairs and estimate the energy carried away by the e^+e^--pairs. Some difficulties connected with this assumption are discussed in the last section.

3. Energy Carried away by Photons and Pairs due to Unruh Effect

The corresponding calculations have been carried out by a Monte Carlo program schematically shown in Fig.2. After introducing the bunch parameters, such as γ, kT etc, for the given electron number k the subprogram PLANK composed with the help of the expression (3') determines the thermal photon energy ω'_1 in IRF using random number. For the given ω'_1 the subprograms SCOMPT and SPAIR composed with the help of the expressions (5) calculate the total absorption coefficients. Then the length λ_j of the electron range before the j-th interaction is determined. If the summary electron range S_{i+1} is greater than the bunch length, S_0 in IRF the program takes the following (k+1)-th electron, otherwise with the help of the ratio R of the Compton and pair production total cross sections the program determines the interaction type.

If an e^+e^--pair is produced the photon angle θ_1' is determined using the isotropy of the thermal radiation in IRF. The values,ω_1',θ_1' and γ allow to determine the photon energy ω_1 in LF using Lorentz transformations. Here it is assumed that the energy ω_1 is completely transferred to the produced pair and the fraction $x_p=\omega_1/E_e$ of the pair energy is determined.In such a way the distributions $dN_{e^+e^-}/dx_p$ are calculated for various values of kT.

If a Compton scattering takes place then the subprogram COMPT composed with the help of the Klein-Nishina differential cross section calculates the energy ω_2' of the scattered photon in IRF. Then the angle θ_2' is determined. The values ω_2',θ_2' and γ allow to calculate the energy ω_2 of the emitted photon in LF and obtain the distributions dN_γ/dx_γ where $x_\gamma=\omega_2/E_e$. Finally for the given kT, γ etc, the program determines the fractions δ_γ and $\delta_{e^+e^-}$ of the energy carried away by Unruh photons and e^+e^--pairs per unit bunch length.

Let us note that the above described Monte Carlo calculations are adequate to the analytical-numerical calculations [3]; they are transparent and allow to take easily into account multiple processes. Moreover they allow to estimate the processes a) and b) discussed in the introduction;it appeared that the processes a) and b) give negligible contribution compared with the other processes.

Fig. 3 shows the dependence of $\gamma\delta$ upon kT(MeV) for beamstrahlung (curve 1),as well as for Unruh radiation and pairs (curve 3) computed with the help of the above described Monte Carlo program. As it is well known (see [10]) designing a linear collider one usually chooses such machine parameters which provide a value of the fractional energy losses due to the beamstrahlung $\delta_L = \frac{\delta L}{\gamma} < 0.1-0.2$ (L is the bunch length) in order to have a satisfactory energy resolution of the colliding beams. Then coming out from this constraint one estimates the number of the produced background e^+e^--pairs which may hit the poles of magnets and create background for the experimental arrangements. As it follows from Fig.3 at high values of kT (or Y) the fractional energy losses due to the Unruh radiation and pairs exceed the corresponding beamstrahlung value making , in principle, the direct observation of the Unruh effect possible at high values of kT when performing other type experiments is impossible.

4. Discussion

At present it is accepted by many physicists (see also the opposite point of view [17]) that the zero fluctuations of the vacuum quantum field result in thermal effects in the accelerated frames. These effects may manifest themselves also in inertial frames, say in LF, just as the Hawking effect which occurs in the strong gravitational fields of the black holes may be observed as a decrease of black holes mass.The main difficulty lies in the fact that the effects are very weak to be observed in usual conditions. Of course, it is too early to describe the details of the experimental observation, however, it is reasonable to discuss some theoretical approximations and difficulties.

First, it is necessary to discuss the "seeming violation" of the energy conservation law. Indeed, the energy spectra of the Unruh radiation given in the work [3] and the energies carried away by the e^+e^--pairs due to the Unruh mechanism calculated in this work exceed the energies of the separate electrons in the bunches (x_γ, $x_p > 1$). Mathematically this fact is the consequence of the applied method of calculation when in IRF a thermal photon with energy higher than the electron mass is scattered (or produces e^+e^--pair). As a result of Lorentz transformation the energy of the scattered photon (or of the produced pair) may become higher than the energy of a single electron of the bunch which seems violates the energy conservation. However, this is not true, since the thermal photon is"created" due to the acceleration of an individual electron in the field of the whole oncoming bunches electrons. So that as a result of coherent effect the scattered radiation photon (or the produced pair) can have energy higher than the energy of an individual electron. The situation is similar to the case of pair production in the field of a nucleus with Z greater than Z_{crit} when the same question arises: where does the pair energy come from?

It is worth to remember that in this work it is assumed that the primary electron undergoes a constant acceleration which results in some misunderstanding even in the case of usual radiation (see [18]).We do not take into account the inhomogeneity and the edge effects of the bunch field which is done for beamstrahlung and usual pair creation in the works [19] and [20], respectively.

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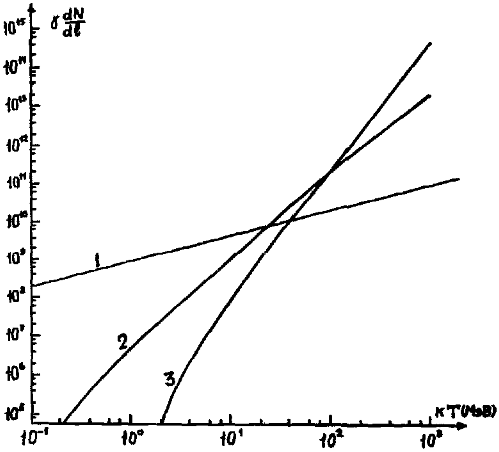

Fig.1 The dependence of $\gamma dN/dl$ on kT(MeV) for radiation (curve 2) and e^+e^--pair production (curve 3) due to the Unruh mechanism as well as for beamstrahlung (curve 1) coinciding with the results of the work [21].

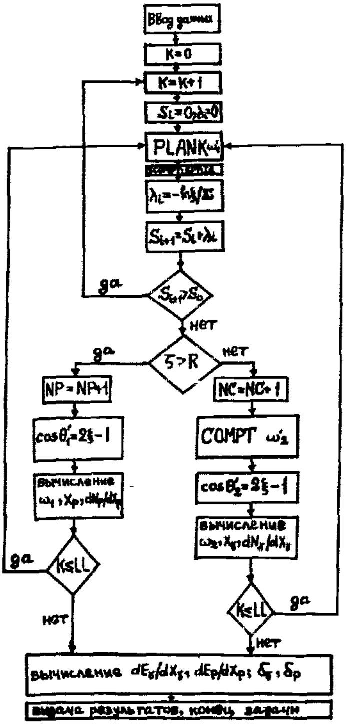

Fig.2 The scheme of the Monte Carlo Calculations

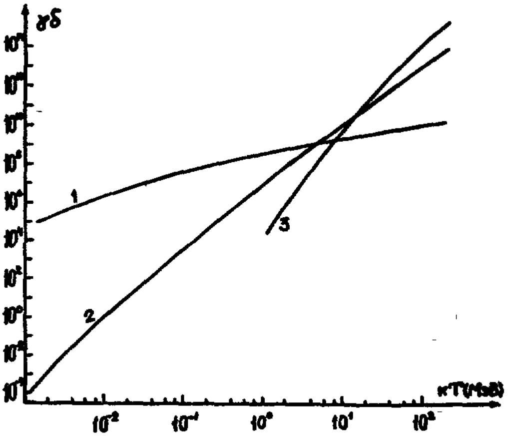

Fig.3 The dependence of the product $\gamma\delta$ (δ is the fractional energy carried away by the produced particles per unit bunch length) upon kT(MeV) for radiation (curve 2) and e^+e^--pair production (curve 3) due to the Unruh mechanism as well as for beamstrahlung (curve 1) coinciding with the results of the work [21].

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