# New Quantum Effect: Emission of Cosmic $X$– or $\gamma$–rays by Moving Unstable Particles at Late Times

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**Abstract.** A quantum effect induced by the late time properties of decaying states is discussed and its possible observational consequences are analyzed. It is shown that charged unstable particles as well as neutral unstable particles with non–zero magnetic moment which were able to survive sufficiently long may emit electromagnetic radiation. The nonclassical behavior of unstable particles at late times when deviations of the decay law from the exponential form begin to dominate is a source of the mechanism responsible for this effect. Analyzing the transition times region between exponential and non-exponential form of the survival amplitude it is found that at this time region the instantaneous energy of the unstable particle can take very large values, much larger than the energy of this state at times from the exponential time region. Results obtained for the model considered suggest that this new purely quantum mechanical effect may be responsible for causing unstable particles produced by astrophysical sources and moving with relativistic velocities to emit electromagnetic–, $X$– or $\gamma$–rays at some time intervals from the transition time regions.

## 1 Introduction

Theoretical predictions of deviations from the exponential form of the decay law at suitably long times resulted in increasing interest in studies of long time properties of unstable states. The predicted effect is almost negligible small and therefore very difficult to its confirmations in laboratory experiments. On the other hand, numbers of created unstable particles during some astrophysical processes are so large that some of them can survive up to times $t$ at which the survival probability depending on $t$ transforms from the exponential form into the inverse power–like form. Here we show at this time region a new quantum effect can be observed: A very rapid fluctuations of the instantaneous energy of unstable particles can take place. These fluctuations of the instantaneous energy should manifest itself as fluctuations of the velocity of the particle. Based on results presented in [1] we present in this talk some new results and we show that this effect may cause unstable particles to emit electromagnetic radiation of a very wide spectrum: from radio frequencies through $X$–rays to $\gamma$–rays of very high energies and that the astrophysical processes are the place where this effect should be observed.

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## 2 On unstable states

Studying properties of unstable states $|\phi\rangle \in \mathcal{H}$ (where $\mathcal{H}$ is the Hilbert space of states of the considered system) one usually starts from an analysis of their survival probability. The survival probability (the decay law), $\mathcal{P}_\phi(t)$ of an unstable state $|\phi\rangle$ decaying in vacuum is given by the following relation

$$\mathcal{P}_\phi(t) = |a(t)|^2, \tag{1}$$

where $a(t)$ is the probability amplitude of finding the system at the time $t$ in the initial state $|\phi\rangle$ prepared at time $t_0 = 0$,

$$a(t) = \langle\phi|\phi(t)\rangle. \tag{2}$$

and $|\phi(t)\rangle$ is the solution of the Schrödinger equation for the initial condition $|\phi(0)\rangle = |\phi\rangle$:

$$i\hbar\frac{\partial}{\partial t}|\phi(t)\rangle = H|\phi(t)\rangle, \tag{3}$$

where $H$ denotes the total self–adjoint Hamiltonian for the system considered.

From the literature it is known that the amplitude $a(t)$, and thus the decay law $\mathcal{P}_\phi(t)$ of the unstable state $|\phi\rangle$, are completely determined by the density of the energy distribution $\omega(\mathcal{E})$ for the system in this state [2]

$$a(t) = \int_{Spec.(H)} \omega(\mathcal{E})\, e^{-\frac{i}{\hbar}\,\mathcal{E}\,t}\, d\mathcal{E}. \tag{4}$$

where $\omega(\mathcal{E}) \geq 0$ and $a(0) = 1$.

Khalfin in [3] assuming that the spectrum of $H$ must be bounded from below, ($Spec.(H) = [E_{min}, \infty)$ and $E_{min} > -\infty$), and using the Paley–Wiener Theorem [4] proved that in the case of unstable states there must be $|a(t)| \;\geq\; A\, \exp\,[-b\,t^q]$, for $|t| \to \infty$. Here $A > 0$, $b > 0$ and $0 < q < 1$. Therefore the decay law $\mathcal{P}_\phi(t)$ of unstable states decaying in the vacuum, (1), can not be described by an exponential function of time $t$ if time $t$ is suitably long, $t \to \infty$, and that for these lengths of time $\mathcal{P}_\phi(t)$ tends to zero as $t \to \infty$ more slowly than any exponential function of $t$. This effect was confirmed in experiment described in the Rothe paper [5], where the experimental evidence of deviations from the exponential decay law at long times was reported. In the light of the result of Rothe's group the following problem seems to be important: If (and how) deviations from the exponential decay law at long times affect the energy of the unstable state and its decay rate at this time region.

Analysis of late times properties of unstable states becomes easier if to express $a(t)$ in the following form

$$a(t) = a_{exp}(t) + a_{lt}(t), \tag{5}$$

where $a_{exp}(t)$ is the exponential part of $a(t)$, that is $a_{exp}(t) = N\,\exp\,[-i\frac{t}{\hbar}(E_\phi^0 - \frac{i}{2}\,\Gamma_\phi^0)]$, ($E_\phi^0$ is the energy of the system in the state $|\phi\rangle$ measured at the canonical decay times, i.e. when $\mathcal{P}_\phi(t)$ has the exponential form, $\Gamma_\phi^0$ is the decay width, $N$ is the normalization constant), and $a_{lt}(t)$ is the late time non–exponential part of $a(t)$. From the literature it is known that the characteristic feature of survival probabilities $\mathcal{P}_\phi(t)$ is the presence of sharp and frequent fluctuations at the transition times region, when contributions from $|a_{exp}(t)|^2$ and $|a_{lt}(t)|^2$ into $\mathcal{P}_\phi(t)$ are comparable and that the amplitude $a_{lt}(t)$ and thus the probability $\mathcal{P}_\phi(t)$ exhibits inverse power–law behavior at the late time region for times $t$ much later than the crossover time $T$. The crossover time $T$ can be found by solving the following equation,

$$|a_{exp}(t)|^2 = |a_{lt}(t)|^2. \tag{6}$$

In general $T \gg \tau_\phi$, where $\tau_\phi = \hbar/\Gamma_\phi^0$ is the lifetime of $\phi$. Formulae for $T$ depend on the model considered (i.e. on $\omega(E)$) in general). A typical form of the decay curves, that is the form of the non–decay probability $\mathcal{P}_\phi(t)$ as a function of time $t$ is presented in Figs (1), (2). The results of calculations

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presented in these Figures were obtained for the Breit–Wigner energy distribution function, $\omega(E) \equiv \omega_{BW}(E)$, where

$$\omega_{BW}(E) \stackrel{\text{def}}{=} \frac{N}{2\pi}\Theta(E - E_{min})\frac{\Gamma_{\phi}^{0}}{(E - E_{\phi}^{0})^2 + (\frac{\Gamma_{\phi}^{0}}{2})^2}, \tag{7}$$

and $\Theta(E)$ is the unit step function. The cross–over time $T$ is a function of the parameter

$$s_0 \stackrel{\text{def}}{=} \frac{E_{\phi}^{0} - E_{min}}{\Gamma_{\phi}^{0}}. \tag{8}$$

The larger $s_0$ the larger $T$ (see Figs (1), (2)).

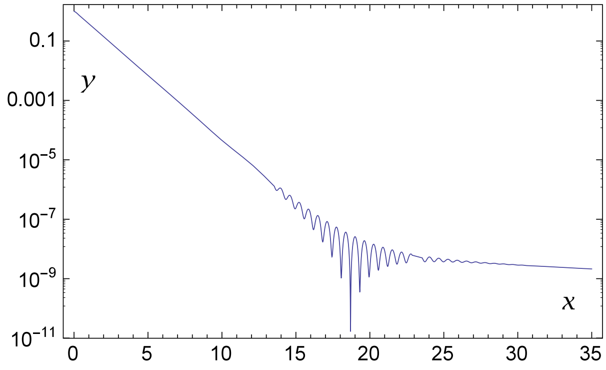


**Figure 1.** The general, typical form of the decay curve $\mathcal{P}_{\phi}(t)$: The case $s_0 = 10$. Axes: $y = \mathcal{P}_{\phi}(t)$ — the logarithmic scale; $x = t/\tau_{\phi}$ — the time is measured in lifetimes.

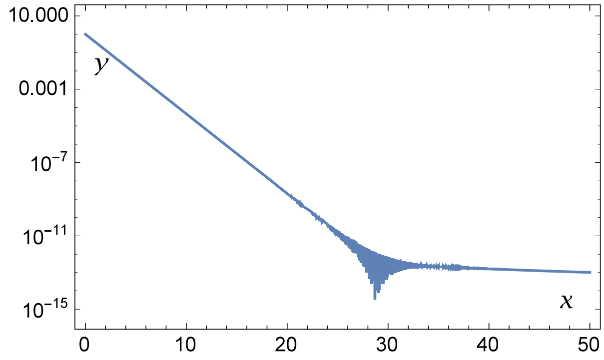


**Figure 2.** The same as in Fig (1) for the case $s_0 = 100$.

Fluctuations of $\mathcal{P}_{\phi}(t)$ at the transition times region, $t \sim T$, which one can see in Figs (1), (2), can be explained as follows: Using decomposition (5) one finds that

$$\mathcal{P}_{\phi}(t) = |a_{exp}(t)|^2 + 2\Re\,[a_{exp}(t)\,a_{lt}^{*}(t)] + |a_{lt}(t)|^2. \tag{9}$$

At times $t \sim T$ the dominating term in this decomposition of $\mathcal{P}_{\phi}(t)$ is the interference term $2\Re\,[a_{exp}(t)\,a_{lt}^{*}(t)]$ which is the source of the large fluctuations of $\mathcal{P}_{\phi}(t)$ mentioned.

## 3 Energy of unstable states

We need know properties of the energy of unstable states at late times. In the general case the energy and the decay rate of the system in the state $|\phi\rangle$ under considerations, (to be more precise the instantaneous energy and the instantaneous decay rate), can be found using the following relations (for details see [6–9]).

$$\mathcal{E}_\phi \equiv \mathcal{E}_\phi(t) = \Re\,(h_\phi(t)), \quad \gamma_\phi \equiv \gamma_\phi(t) = -\,2\,\Im\,(h_\phi(t)), \tag{10}$$

where $\Re\,(z)$ and $\Im\,(z)$ denote the real and imaginary parts of $z$ respectively and $h_\phi(t)$ denotes the "effective Hamiltonian" for the one–dimensional subspace of states $\mathcal{H}_{||}$ spanned by the normalized vector $|\phi\rangle$,

$$h_\phi(t) \stackrel{\text{def}}{=} i\hbar\,\frac{\partial a(t)}{\partial t}\,\frac{1}{a(t)}, \tag{11}$$

or equivalently

$$h_\phi(t) \equiv \frac{\langle\phi|H|\phi(t)\rangle}{\langle\phi|\phi(t)\rangle}. \tag{12}$$

We have $\mathcal{E}_\phi(t) \simeq E_\phi^0$ and $\varGamma_\phi(t) \simeq \varGamma_\phi^0$ at the canonical decay times. At asymptotically late times there is [1, 6, 8, 10]

$$\mathcal{E}_\phi(t) \;\simeq\; E_{min} + \frac{c_2}{t^2} + \frac{c_4}{t^4}\ldots, \quad (\text{for } t \gg T), \tag{13}$$

$$\varGamma_\phi(t) \;\simeq\; \frac{c_1}{t} + \frac{c_3}{t^3} + \ldots \quad (\text{for } t \gg T), \tag{14}$$

where $c_i = c_i^*$, $i = 1, 2, \ldots$, ($c_1 > 0$ and the sign of $c_i$ for $i \geq 2$ depends on the model considered), so $\lim_{t\to\infty} \mathcal{E}_\phi(t) = E_{min}$ and $\lim_{t\to\infty} \varGamma_\phi(t) = 0$. Results (13) and (14) are rigorous.

The basic physical factor forcing the amplitude $a(t)$ to exhibit inverse power law behavior at $t \gg T$ is the boundedness from below of $\sigma(H)$. This means that if this condition is satisfied and $\int_{-\infty}^{+\infty} \omega(E)\,dE \;\equiv\; \int_{E_{min}}^{+\infty} \omega(E)\,dE \;<\; \infty$, then all properties of $a(t)$, including the form of the time–dependence at times $t \gg T$, are the mathematical consequence of them both. The same applies by (11) to the properties of $h_\phi(t)$ and concerns the asymptotic form of $h_\phi(t)$ and thus of $\mathcal{E}_\phi(t)$ and $\varGamma_\phi(t)$ at $t \gg T$.

Starting from relations (2), (4), (11) and assuming the form of $\omega(E)$ and performing all necessary calculations numerically one can find $\mathcal{E}_\phi(t)$ for all times $t$ including times $t \gg T$. A typical behavior of the instantaneous energy $\mathcal{E}_\phi(t)$ at the transition time region is presented in Figs (3), (4) and (5). In these Figures the function $\kappa(t)$ is defined as follows

$$\kappa(t) = \frac{\mathcal{E}_\phi(t) - E_{min}}{E_\phi^0 - E_{min}}, \tag{15}$$

and all calculations were performed for the Breit–Wigner energy distribution function (7).

One can see in Figs (1), (2) that the characteristic feature decay curves is the presence of sharp and frequent oscillations at the transition times region. This means that derivatives of the amplitude $a(t)$ may reach extremely large values for some times from the transition time region and the modulus of these derivatives is much larger than the modulus of $a(t)$, which is very small for these times. This explains why in this time region the real and imaginary parts of $h_\phi(t) \equiv \mathcal{E}_\phi(t) - \frac{i}{2}\,\gamma_\phi(t)$, which can be expressed by the relation (11), ie. by a large derivative of $a(t)$ divided by a very small $a(t)$, reach values much larger than the energy $E_\phi^0$ of the the unstable state measured at times for which the decay curve has the exponential form.

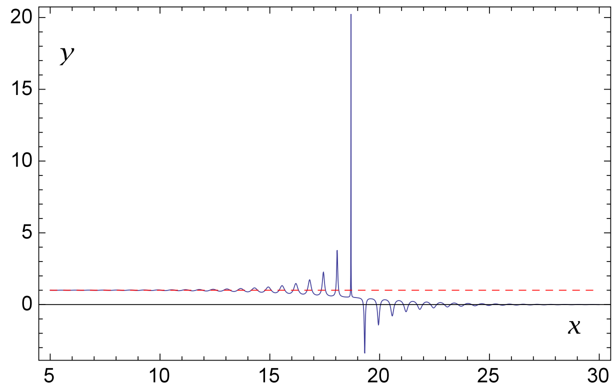


**Figure 3.** The instantaneous energy $\mathcal{E}_\phi(t)$ in the transitions time region: The case $s_0 = 10$. Axes: $y = \kappa(t)$, $x = t/\tau_\phi$ — the time is measured in lifetimes. The dashed line denotes the case $\kappa(t) = 1$, that is $\mathcal{E}_\phi(t) = E^0_\phi$.

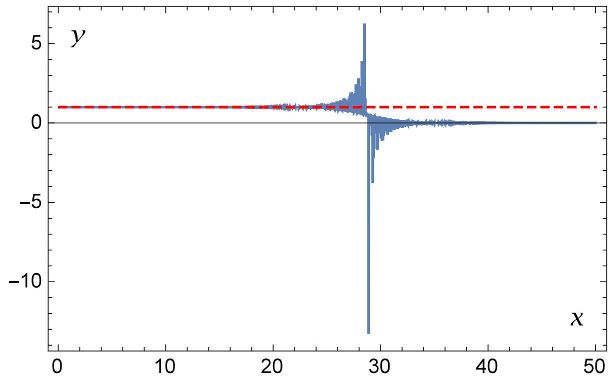


**Figure 4.** The same as in Fig (3) for the case $s_0 = 100$.

## 4 Some observable effects

Note that from the point of view of a frame of reference in which the time evolution of the unstable system was calculated the Rothe experiment as well as the picture presented in Figs (1), (2) and (3), (4), (5) refer to the rest coordinate system of the unstable system considered.

Properties of the ratio $\kappa(t)$ taking place for some time intervals mean that the instantaneous energy $\mathcal{E}_\phi(t)$ at these time intervals differs from the energy $E^0_\phi$ measured at times from the exponential decay time region (i.e. at the canonical decay times). The relation (12) explains why such an effect can occur. Indeed, if to rewrite the numerator of the righthand side of (12) as follows,

$$\langle\phi|H|\phi(t)\rangle \equiv \langle\phi|H|\phi\rangle\, a(t) + \langle\phi|H|\phi(t)\rangle_\perp, \tag{16}$$

where $|\phi(t)\rangle_\perp = Q|\phi(t)\rangle$, $Q = \mathbb{I} - P$ is the projector onto the subspace od decay products, $P = |\phi\rangle\langle\phi|$ and $\langle\phi|\phi(t)\rangle_\perp = 0$, then one can see that there is a permanent contribution of decay products described by $|\phi(t)\rangle_\perp$ to the energy of the unstable state considered. The intensity of this contribution depends

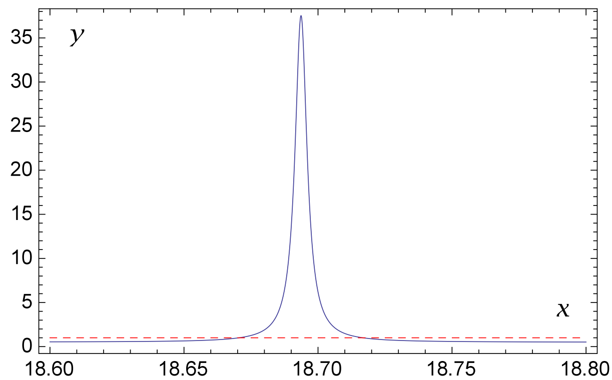


**Figure 5.** The highest local maximum of the instantaneous energy $\mathcal{E}_\phi(t)$ presented in Fig. (3). Axes: $y = \kappa(t)$, $x = t/\tau_\phi$ — the time is measured in lifetimes. The dashed line corresponds to the case $\kappa(t) = 1$, or $\mathcal{E}_\phi(t) = E^0_\phi$.

on time $t$. This contribution into the instantaneous energy is practically constant in time at canonical decay times whereas at the transition times, when $t \sim T$, it is fluctuating function of time and the amplitude of these fluctuations may be significant. What is more relations (12) and (16) allow one to proof that in the case of unstable states $\Re\,[h_\phi(t)] \neq const$. Using these relations one obtains that

$$h_\phi(t) = \langle\phi|H|\phi\rangle + \frac{\langle\phi|H|\phi(t)\rangle_\perp}{a(t)}. \tag{17}$$

From this relation one can see that $h_\phi(0) = \langle\phi|H|\phi\rangle$ if the matrix elements $\langle\phi|H|\phi\rangle$ exists. It is because $|\phi(t = 0)\rangle_\perp = 0$ and $a(t = 0) = 1$. Now if to assume that for $0 \leq t_1 \neq t_2$ there is $\Re\,[h_\phi(0)] = \Re\,[h_\phi(t_1)] = \Re\,[h_\phi(t_2)] = const$ then one immediately conclude that $\Re\,[h_\phi(t)] = \langle\phi|H|\phi\rangle$ for any $t \geq 0$. Unfortunately such an observation contradicts implications of (17): From this relation it follows that $\Re\,[\frac{\langle\phi|H|\phi(t)\rangle_\perp}{a(t)}] \neq 0$ for $t > 0$ and thus $\Re\,[h_\phi(t > 0)] \neq \langle\phi|H|\phi\rangle \equiv \Re\,[h_\phi(0)]$ which shows that $\Re\,[h_\phi(t)] \equiv \mathcal{E}_\phi(t)$ can not be constant in time.

Astronomical observations provide information that there are sources of unstable particles in space that emit them with relativistic or ultra–relativistic velocities in relation to an external observer so many of these particles move in space with ultra high energies. Thus one meets the following problem: What effects can be observed by an external observer when the unstable particle, say $\phi$, which survived up to the transition times region, $t \sim T$, or longer is moving with a relativistic velocity in relation to this observer. The distance $d$ from the source reached by this particle is of order $d \sim d_T$, where $d_T = v^\phi \cdot T'$ and $T' = \gamma T$, $\gamma \equiv \gamma(v^\phi) = (\sqrt{1-\beta^2})^{-1}$, $\beta = v^\phi/c$, $v^\phi$ is the velocity of the particle $\phi$. (For simplicity we assume that there is a frame of reference common for the source and observer both and that they do not move with respect to this frame of reference). So, in the case of moving particles created in astrophysical processes one should consider the effect shown in Figs (3), (4) together with the fact that the particle gains extremely huge energy, $W^\phi$, which should be conserved.

Let us consider the case when the unstable particle under considerations has a constant momentum $\vec{p}$, $|\vec{p}| = p > 0$. Next, let us assume for simplicity that $\vec{v} = (v_1, 0, 0) \equiv (v^\phi, 0, 0)$ then there is $\vec{p} = (p, 0, 0)$. Now, let $\Lambda_p$ be the Lorentz transformation from the reference frame $O$, where the momentum of unstable particle considered is zero, $\vec{p} = 0$, into the frame $O'$ where the momentum of this particle is $\vec{p} \equiv (p, 0, 0) \neq 0$ or, equivalently, where its velocity $\vec{v}^\phi$ equals $\vec{v}^\phi = \vec{v}^\phi_p \equiv \vec{p}/m\gamma$, and let

$E$ be the energy of the particle in the reference frame $O$ and $E'$ be the energy of the moving particle and having the momentum $\vec{p} \neq 0$. In this case the corresponding 4–vectors are: $\wp = (E/c, 0, 0, 0) \in O$ and $\wp' = (E'/c, p, 0, 0) = \Lambda_p \wp \in O'$. There is $\wp' \cdot \wp' \equiv (\Lambda_p \wp) \cdot (\Lambda_p \wp) = \wp \cdot \wp$ in Minkowski space, which is an effect of the Lorentz invariance. (Here the dot "$\cdot$" denotes the scalar product in Minkowski space). Hence, in our case: $\wp' \cdot \wp' \equiv (E'/c)^2 - p^2 = (E/c)^2$ because $\wp \cdot \wp \equiv (E/c)^2$ and thus $(E')^2 = c^2 p^2 + E^2$. There is $p \equiv \frac{E}{c} \gamma \beta$ in the case of a free particle. Therefore $c^2 p^2 + E^2 \equiv E^2 \gamma^2 \beta^2 + E^2 = E^2 (1 + \beta^2 \gamma^2) \equiv E^2 \gamma^2$. The last relation means that the energy, $E'$, of moving particles equals

$$E' = \sqrt{E^2 + c^2 p^2} \equiv E \gamma \stackrel{\text{def}}{=} W^{\phi}. \tag{18}$$

So in the case of the instantaneous energy, $\mathcal{E}_{\phi}(t)$ considered in previous Sections we can write that

$$W^{\phi} \equiv \mathcal{E}_{\phi}(t_k) \gamma_k = W^{\phi}(t_k), \tag{19}$$

at the instant $t_k$ (where $\gamma_k = \gamma(t_k)$.

We have $\mathcal{E}_{\phi}(t) \equiv E^0_{\phi}$ at canonical decay times. Thus, $W^{\phi} \equiv E^0_{\phi} \gamma$, at these times (where $\gamma = \gamma(t \sim \tau_{\phi})$) and at times $t \gg \tau_{\phi},\ t \sim T$ we have $\mathcal{E}_{\phi}(t) \neq E^0_{\phi}$. Now denoting by $W^{\phi}_1$ the energy of the moving particle at the canonical decay times, by $W^{\phi}_2$ the energy of the particle at transition times and by $W^{\phi}_3$ the energy at asymptotically late times (here simply $W^{\phi}_i = W^{\phi}(t_i)$, $i = 1, 2, 3$) and taking into account the principle of conservation of energy, we can conclude that

$$W^{\phi}_1 = W^{\phi}_2 = W^{\phi}_3. \tag{20}$$

The most useful relation follows from (20) for $t_1 \ll T'$ and $t_2 \sim T'$, (where $T' = \gamma T$): $W^{\phi}_1 \equiv E^0_{\phi} \gamma = W^{\phi}_2$, or the equivalent one,

$$E^0_{\phi} \gamma_1 \equiv \mathcal{E}_{\phi}(t_2) \gamma(t_2). \tag{21}$$

It is convenient to rewrite the last relation as follows,

$$\gamma_1 = \frac{\mathcal{E}_{\phi}(t_2)}{E^0_{\phi}} \gamma(t_2). \tag{22}$$

The ratio $\frac{\mathcal{E}_{\phi}(t_2)}{E^0_{\phi}}$ can be extracted from Figs (3), (4), (5):

$$\frac{\mathcal{E}_{\phi}(t)}{E^0_{\phi}} = 1 + (\kappa(t) - 1) \frac{E^0_{\phi} - E_{min}}{E^0_{\phi}}. \tag{23}$$

Thus if $\kappa(t) \neq 1$ then $\gamma_2 \neq \gamma_1$, which means that $v^{\phi}_2 \neq v^{\phi}_1$ or that $a_{average} = \frac{v^{\phi}_2 - v^{\phi}_1}{t_2 - t_1} \neq 0$. So, the moving charged unstable particle $\phi$ has to emit electromagnetic radiation at the transition time region. The same concerns neutral unstable particles with non–zero magnetic moment. The energy of the electromagnetic radiation emitted by such a charged particle in a unit of time can be found using the Larmor formula:

$$P = \frac{1}{6\pi\epsilon_0} \frac{q^2 \dot{v^{\phi}}^2}{c^2} \gamma^6, \tag{24}$$

where $P$ is total radiation power, $q$ is the electric charge, $\epsilon_0$ – permittivity for free space. There is an analogy in classical physics of the effect described above: A conservation of the angular momentum and a pirouette like effect.

## 5 Some estimations

From the results presented in Figs (3), (5) one can find coordinates of, e.g., the highest maximum: $(x_{mx}, y_{mx}) = (18.69, 37.68)$. They allow one to find that $\kappa(t_{mx}) = y_{mx} = 37.68$. Coordinates of points of the intersection of this maximum with the straight line $y = 1$ are equal: $(x_1, y_1) = (18.67, 1.0)$ and $(x_2, y_2) = (18.72, 1.0)$. Thus $\Delta x = x_2 - x_1 = 0.05$. (Here $x = t/\tau_\phi$), and this $\Delta x$ allows one to find $\Delta t = t_{mx} - t_1$. Let us consider now $\mu$ meson as an example. In such a case: $E_\mu^0 - E_{min} = m_{\mu^\pm} - (m_e + m_{\bar{\nu}_e} + m_{\nu_\mu}) \simeq 105$ [MeV], ($\tau_\mu = 2,198 \times 10^{-6}$[s] and the crossover time equals: $T^\mu \simeq 165\tau_\mu = 0,37 \times 10^{-3}$[s], [1]). Using these data one finds the relation of $\gamma(t_1)$ with $\gamma(t_{mx})$ and using this relation one can extract $\Delta v^\mu$. Next using such obtained $\Delta v^\mu$ and $\Delta t = t_{mx} - t_1$ extracted from Fig (5) one can use the Larmor formula (24) and to calculate the total radiation power $P$. The result is $P \sim 0.84$ [keV/s].

Astrophysical and cosmological processes in which extremely huge numbers of unstable particles are created seem to be a possibility for the above discussed effect to become manifest. The fact is that the probability $\mathcal{P}_\phi(t) = |a(t)|^2$ that an unstable particle $\phi$ survives up to time $t \sim T$ is extremely small. According to estimations of the luminosity of some $\gamma$–rays sources the energy emitted by these sources can even reach a value of order $10^{52}$ [erg/s], and it is only a part of the total energy produced there. If to consider a source emitting energy $10^{50}$ [erg/s] then, eg., an emission of $\mathcal{N}_0 \simeq 6.25 \times 10^{47}$ [1/s] particles of energy $10^{18}$ [eV] is energetically allowed. The same source can emit $\mathcal{N}_0 \simeq 6.25{\times}10^{56}$ [1/s] particles of energy $10^9$ [eV] and so on.

Within the model considered in this talk the cross–over time $T$ is given by the following approximate relation (valid for $E_\phi^0/\varGamma_\phi^0 \gg 1$),

$$\varGamma_\phi^0\, T \equiv \frac{T}{\tau_\phi} \;\sim\; 2\,\ln\Big[2\pi\Big(\frac{E_\phi^0 - E_{min}}{\varGamma_\phi^0}\Big)^2\Big], \tag{25}$$

(see, eg. [6, 8, 11]). As it was mentioned, e.g. in [12], a typical value of the ratio $(E_\phi^0 - E_{min})/\varGamma_\phi^0$ is $(E_\phi^0 - E_{min})/\varGamma_\phi^0 \geq O(10^3 - 10^6)$. Taking $(E_\phi^0 - E_{min})/\varGamma_\phi^0 = 10^6$ one obtains from (25) that $\mathcal{N}_\phi(T) \equiv \mathcal{P}_\phi(T)\,\mathcal{N}_0 \sim 2.53{\times}10^{-26}\,\mathcal{N}_0$. So there are $\mathcal{N}_\phi(T) \sim 14{\times}10^{21}$ particles per second of energy $W^\phi = 10^{18}$ [eV] or $\mathcal{N}_\phi(T) \sim 14 \times 10^{30}$ particles of energy $W^\phi = 10^9$ [eV] in the case of the considered example and $T$ calculated using (25).

## 6 Conclusions

Analyzing properties of evolving in time unstable states we found that their instantaneous energy, $\mathcal{E}_\phi(t)$, can not be constant in time and fluctuates with the increasing amplitude. The amplitude of these fluctuations is negligible small at canonical decay time and it grows up to the transition time region, where it becomes significant. In the case of moving unstable particles these fluctuations at the transition time region, $t \sim T$, (where $T$ is the crossover time — see (6) and (25)), cause fluctuations of the velocity of these particles at this time region, which forces the charged particles to emit electromagnetic radiation. This observation is valid also in the case of moving neutral unstable particles with a non–zero magnetic moment: They have to emit electromagnetic radiation in the transition time region too. This means that ultra relativistic unstable charged particles or unstable particles with non–zero magnetic moment can emit $X$– or $\gamma$–rays in this time region. A chance to observe this effect in the Earth laboratories is rather very small. On the other hand astrophysical sources are able to create such numbers $\mathcal{N}_0$ of unstable particles that sufficiently large number $\mathcal{N}_\phi(T) \gg 1$ of them has to survive up to times $T$, and therefore they have to emit electromagnetic radiation at this time region. Hence there is a chance to observe this effect analyzing the data of astronomical observations. The expected spectrum of this radiation can be very wide: From radio frequencies up to $\gamma$–rays.

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## References

[1] K. Urbanowski and K. Raczyńska, Phys. Letters, **B 731**, 236, (2014) (*Preprint* 1303.6975 [astro–ph.HE])
[2] S. Krylov and V. A. Fock, Zh. Eksp. Teor. Fiz., **17**, 93, (1947).
[3] L. A. Khalfin, Zh. Eksp. Teor. Fiz., **33**, 1371, (1957); [Sov. Phys. – JETP, **6**, 1053, (1958)].
[4] R. E. A. C. Paley and N. Wiener, *Fourier transforms in the complex domain*, (New York: American Mathematical Society, 1934)
[5] C. Rothe, S. I. Hintschich and A. P. Monkman, Phys. Rev. Lett., **96** 163601, (2006).
[6] K. Urbanowski, Cent. Eur. J. Phys., **7** 696, (2009).
[7] K. Urbanowski, International Journal of Modern Physics, **A 6** 1051, (1991).
[8] K. Urbanowski, European Physical Journal, **D 54** 25, (2009).
[9] F. Giraldi, Eur. Phys. J., **D 69**: 5 (2015).
[10] K. Urbanowski, Physical Review Letters, **107** 209001, (2011).
[11] K. Urbanowski, European Physical journal **C 58**, 151, (2008).
[12] L. M. Krauss and J. Dent, Phys. Rev. Lett., **100**, 171301, (2008).