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EMISSION OF COMPOSITE PARTICLES IN A CONSTANT ELECTRIC FIELD

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The spectrum of emission of a composite particle with one degree of freedom in a constant electric field is obtained in the paper. The effectiveness of emission of such particle is compared with the structureless particle having the same parameters. The power of emission of composite particle is several digits more than that of a structureless particle. The dependence of the main characteristics of the emission spectrum on the parameters of the composite particle is discussed.
KEY WORDS: composite particle, spectrum of emission, constant electric field, internal degrees of freedom

ИЗЛУЧЕНИЕ КОМПОЗИТНОЙ ЧАСТИЦЫ В ПОСТОЯННОМ ЭЛЕКТРИЧЕСКОМ ПОЛЕ

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В работе получен спектр излучения композитной частицы с одной заряженной внутренней степенью свободы в постоянном электрическом поле. Проведено сравнение эффективности излучения такой частицей с бесструктурной, обладающей такими же параметрами. Мощность излучения композитной частицы превышает на несколько порядков мощность излучения бесструктурной. Обсуждается зависимость основных характеристик спектра излучения от параметров композитной частицы.
КЛЮЧЕВЫЕ СЛОВА: композитной частицы, спектра излучения, постоянное электрическое поле, внутренние степени свободы

ВИПРОМІНЮВАННЯ КОМПОЗИТНОЇ ЧАСТИНКИ В ПОСТІЙНОМУ ЕЛЕКТРИЧНОМУ ПОЛІ

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У роботі отримано спектр випромінювання композитної частинки з одним зарядженим внутрішнім ступенем свободи в постійному електричному полі. Проведено порівняння ефективності випромінювання такою частинкою з безструктурної, що володіє такими ж параметрами. Потужність випромінювання композитної частки перевищує на кілька порядків потужність випромінювання безструктурної. Обговорюється залежність основних характеристик спектра випромінювання від параметрів композитної частинки.
КЛЮЧОВІ СЛОВА: композитна частинка, спектр випромінювання, постійне електричне поле, внутрішні ступені свободи.

As nanotechnologies make constant progress, it becomes important to study systems with small number of degrees of freedom. There is a number of reasons for it. Firstly, from general point of view, every particle has finite dimensions and, respectively, degrees of freedom. That's why abstract idea about particles as point objects has certain restrictions. Finding out the influence of size finitude and internal degrees of freedom upon the particles behaviour is an important direction of studies. Secondly, the tendencies to miniaturization of different mechanisms and to creation of robots and nanorobots lets one experimentally implemented systems with a small number of internal degrees of freedom. In a sense, multifunctional nanomechanisms must have a small, but sufficient for chaotic modes to arise, number of internal degrees of freedom. The presence of chaotic mode enables various rearrangements of functioning modes and, in fact, embodies multifunctionality. The reason of multifunctionality in the presence of chaos is connected with possibility to rearrange modes of movement without changing the device itself, in particular, periodic movements. Such possibility is defined by the presence of countable number of unstable periodic orbits in the chaotic region of phase space. That's why, using special technique of control, one can rearrange the frequency of periodic movements and, in that way, influence the frequency of emission. As the simplest among such devices, we can regard molecules of rotaxanes and "nanopeapods" [5-7]. It is of great importance to find out how efficiently such a system will emit. To prove the efficiency of emission, one can limit oneself to a simple model of composite particle with one internal degree of freedom and, respectively, one period of movement. In this case, the above-mentioned possibility to rearrange the frequencies is absent, but the quality character and properties of emission will be the same. To be more precise, as it is shown below, the frequencies rearrangement does appear in this case, but according to a different mechanism. In our paper, we concentrate exactly upon the efficiency and emission properties of such a system, which can be regarded as a converter of constant electric field into electromagnetic radiation. It is the study of such systems that we discuss in our paper.

In the paper, the spectrum of emission is obtained for a composite particle with one charged internal degree of freedom in the constant electric field. The dependence of the main characteristic of this emission spectrum upon the parameters of the composite particle is discussed. The possibility to control the emission frequency by changing the value of the electric field is shown. A considerable efficiency of such particle emission is found out compared to the emission of a structureless one with the same characteristic parameters. The emission power of the composite one exceeds the emission power of a structureless one by several digits.

The general aim is an investigation the properties of the radiation of a structurally complex charged particle, which has internal degrees of freedom.

THE EMISSION OF A CHARGED COMPOSITE PARTICLE

Let us consider the emission arising when a charged composite particle is moving in the constant electric field. By a charged composite particle we mean a particle consisting of a neutral shell and a charged internal particle (Fig. 1). The internal particle moves freely, absolutely elastically colliding with the shell. Though the structure of such a particle is rather simple, the results can be easily generalized for more complicated cases.

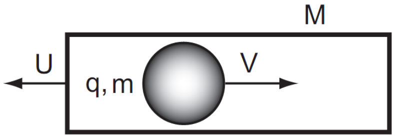

Fig.1. The structure scheme of composite particle moving in constant electric field E . The internal particle with the charge q has mass m . The shell is neutral with mass M . The velocity of the shell is lettered as U , and that of the internal particle – as V .

The movement of the composite particle with the charged internal particle in the constant electric field has been thoroughly studied in. Is is found out that such particles can be in two different modes of movement. In the first mode, the internal particle periodically collides with only one wall of the shell, and in the other mode – with both walls alternately. It is important to note that in both cases the movement is periodic. In the first case the velocity of the internal particle in the moments of collision with the shell t_n is described by a simple formula:

$$V_n = n\frac{2m}{m+M}(U_0 - V_0) + V_0 .$$

The typical graph of shell and the internal particle velocity dependence upon time is shown in Fig.2. The oscillation period is defined by the relation [8]:

$$\tau = \frac{2m}{qE}(U - V) ,$$

here $U - V$ is the difference of velocities of the shell and the internal particle in the moment of their collision, E is the electric field strength, and q is the charge of the internal particle.

Considering the movement of the charged internal particle in detail, one can notice that it is the composition of uniformly accelerated movement and periodic collisions with the neutral shell. So, the total emission of the composite particle consists of the deceleration emission and the emission of uniformly accelerated charge. The interference of these components will cause an emission with a special spectrum to arise.

In nonrelativistic case, the emission of the charge, moving with acceleration into a solid angle at a certain frequency is described by a simple formula:

$$\frac{dI(\omega)}{d\Omega} = \frac{q^2}{4\pi^2 c^2}\sin^2\theta \left|\int \dot{v} e^{i\omega t} dt\right|^2 .$$

The angle θ is counted off the direction of the charge movement. The angular dependence $\sin^2\theta$ is characteristic for the emission of a charge moving with nonrelativistic velocity. Such dependence means that the emission mostly takes place into a plane, which is perpendicular to the direction of the particle movement. Since we limit ourselves to the case of nonrelativistic velocities, then in order to obtain the spectral dependence it is enough to make a Fourier transform of the particle acceleration $\dot{v}(t)$.

Let us consider the spectral distribution of emission for a composite particle emission moving in the constant electric filed during the time T. Taking into account that the acceleration of the internal particle has a periodic component with a period τ, it is convenient to choose the general time of the movement multiple of this period duration $T = N\tau$. One can imagine the movement of the internal particle as uniformly accelerated movement with consecutive strikes. So the dependence of the acceleration on time has the following form:

$$\dot{v}(t) = a + \sum_{n=0}^{N} \Delta v \delta(t - t_n),$$

with Δv being the leap of velocity of the internal particle after collision with the shell, and $t_n = n\tau$. Using Fourier transform $a(t) = \dot{v}(t)$, we obtain the emission spectrum of the composite particle:

$$\frac{dI(\omega)}{d\Omega} = \frac{q^2}{4\pi^2 c^2} \sin^2\theta \left| \int_0^T a e^{i\omega t} dt + \Delta v \sum_{n=0}^{N} e^{i\omega t_n} \right|^2.$$

The first summand corresponds to the emission of the particle with uniformly accelerated motion. As it was discussed, e.g. in, such emission is difficult to observe. Really, at $T \to \infty$ the spectrum of the uniformly accelerated particle emission changes into δ-function.

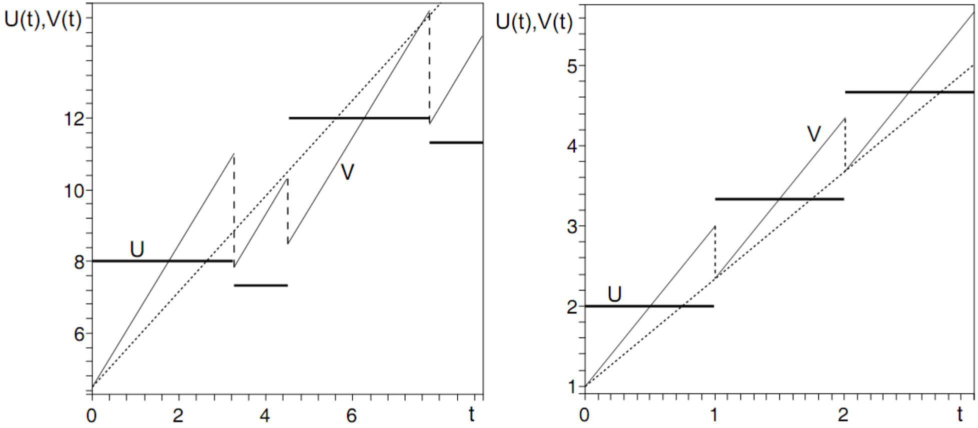

Fig.2. A typical example of dependence of the shell velocity U and the charged internal particle velocity V on time. The left graph corresponds to the movement mode with the internal particle colliding with both walls of the shell. The right one concerns the mode with the internal particle colliding with only one wall of the shell. The dashed line shows, for comparison, the movement of a structureless particle with mass $M + m$ and charge q.

In other words, such an emission will be concentrated on very low frequencies. So, this component may be not considered. The contributions of separate collisions of the internal particle with the c shell can be easily summed up, since the collisions take place between the same lapses of time $t_n = n\tau$. As a result, the spectrum of the emission takes the form:

$$\frac{dI(\omega)}{d\Omega} = \frac{q^2 \sin^2\theta}{4\pi^2 c^3} \left(\frac{2M(U_0 - V_0)}{M + m} \right)^2 \frac{\sin^2 N\omega\tau / 2}{\sin^2 \omega\tau / 2}.$$

The graph of a typical emission spectrum is shown in Fig.3. It is easy to see that the maximum value of the emission power is achieved at frequencies multiple by $\omega = \frac{\Omega_0}{2} = \frac{\pi}{\tau} = \frac{\pi q E}{2m(U_0 - V_0)}$ and at these frequencies it is $\frac{q^2 \sin^2\theta}{4\pi^2 c^2} N^2$. The characteristic width of the peaks $\Delta\omega$ is also easy to evaluate, and it coincides with $\Delta\omega \approx \frac{\pi}{\tau N}$.

So, the spectrum turns out to be concentrated on the main frequency of internal particle collisions with the shell and on the frequencies multiple to it. In the formula obtained, the amplitude of the peaks on multiple harmonic components is constant with frequency increase. A similar problem is observed also at obtaining of deceleration emission spectrum and at a separate collision. The solution of this problem is trimming the spectrum at a certain frequency. For a separate collision, the value of this frequency is defined by the characteristic time of colliding of the shell and the internal particle τ_{coll} . So, in the case of charged composite particle the linear spectrum of the emission is also trimmed for the same reason at frequency $\omega_{max} \sim 1/\tau_{coll}$. Being aware of the spectral emission of the composite particle, let us calculate the average power of composite particle emission:

$$P_{comp} = \frac{2q^2}{3\pi c^3}\left(\frac{\Delta v}{\tau_{col}}\right)^2 \frac{\tau_{col}}{\tau} = \frac{2q^2}{3\pi c^3}(a_{col})^2\frac{\tau_{col}}{\tau}.$$

a_{col} being the acceleration of the internal particle at the collision with the shell. To compare how many times the composite particle is more effective emitter compared to a structureless particle, it is enough to compare the power obtained with the full power of the emitted structureless particle with mass $m+M$ and charge q in the electric field E .This power is easy to obtain by means of the well-known Larmor formula:

$$P_{solid} = \frac{2q^2}{3c^3}\dot{v}^2 = \frac{2q^2}{3c^3}\left(\frac{qE}{m+M}\right)^2.$$

Comparing the emission powers obtained, one can evaluate the efficiency of composite particle emission compared with that of a structureless one. Really, they are related as

$$\eta = \frac{P_{comp}}{P_{solid}} = \frac{2a_{col}^2(U_0 - V_0)}{\pi(qE/m)\tau_{col}} \sim \frac{\tau}{\tau_{col}}.$$

Moreover, taking into account that the internal particle velocity change during the time of collision is comparable to its change during the time between the collisions, the efficiency can be evaluated in a simple correlation:

$$\eta \sim \frac{\tau}{\tau_{col}}.$$

The time of collision of internal particle with the shell is usually very small compared to the time between separate strikes upon the walls. So the composite particle, as an emitter, turns out several digits more efficient than a structureless particle.

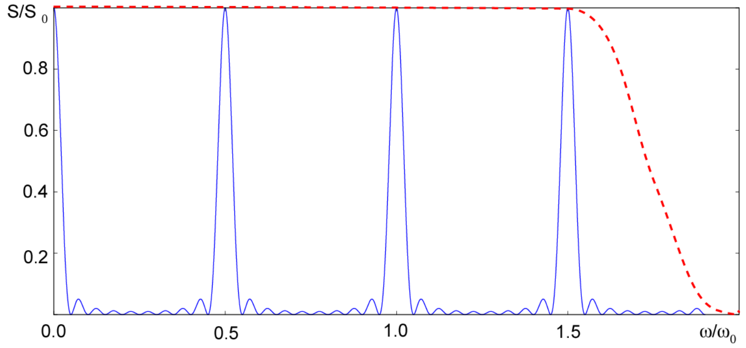

Fig.3. A typical emission power spectrum of a charged composite particle.
Here $\Omega_0 = \frac{2\pi}{\tau}$ is the frequency of colliding of internal particle and the shell.

Let us now discuss the influence of the medium on the emission of such systems from the qualitative point of view. It should be noted that such influence is rather easy to take into account. Let us explain it on the most realistic case of shell friction on the medium. If the energy passed to the shell at collision with the internal degree of freedom is less than the energy spent on the friction during the period of movement, which corresponds to the case of low friction, the average tempo of shell acceleration will reduce, but in all the rest the character of composite particle movement and its emission will be preserved. The friction increased, the movement mode arises with the average velocity of shell movement is preserved, the movement of internal degree of freedom is preserved qualitatively. Even at bigger friction when the average velocity of the shell movement becomes arbitrary small, the periodicity of the internal degree of freedom movement is preserved and so the character of such system emission s preserved qualitatively. In this case, the spectrum of emission and the rest of its characteristics are easy to obtain, making the shell mass tend to infinity $M \to \infty$.

Back to the dependence of the period upon characteristic parameters of composite particle, one should note the easiness of controlling the emission spectrum of a composite particle by changing the value of the electric field. In this sense, the system we have considered has an extra advantage, its frequency can be chosen in the range needed for the observation by choosing in the right way the value of the field or masses of external and internal degrees of freedom. In its turn, it enables passing more complicated information with the use of frequency modulation. Besides, such a particle can be used as a detecting device of constant electric fields.

In a more complicated case, the collisions of the internal particle alternately with both walls of the shell the resulting formula for the spectrum is supplemented by a multiplier corresponding to the interference between the collisions with the front and the rear walls. It is natural that this multiplier does not depend upon the frequency. Thus, the form of the power spectrum is the same in a more complicated case as well.

CONCLUSION

In the conclusion it is worth mentioning that the results obtained in the paper predict the characteristic properties of emission of structurally complicated particle with charged internal degrees of freedom when it moves in an constant electric field. Such a system can be regarded as a kind on nanoantenna. The presence of interaction between internal and external degrees of freedom is important for it. In a certain case, the properties of such emission carry information about the internal structure of a structurally complicated particle. Taking into account that with body size reducing, the number of internal degrees of freedom is decreased, one should expect the arising of such effects in nanoparticles of general nature.

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