Библиографический список

1. *Mohr P.J., Taylor B.N.* CODATE recommended values of the fundamental physics constants. 2000 // Rev. Mod. Phys. 2000. Vol. 72, № 2. P. 5496–5499.

2. *Бойкова Н.А., Тюхтяев Ю.Н., Фаустов Р.Н.* О вкладах порядка $\alpha^6 \ln(m_2/m_1)$ в тонкий сдвиг S-уровней энергии мюония // Ядерная физика. 1998. Т. 61, № 5. С. 866–870.

3. *Fulton T., Martin P.C.* Two-body system in quantum electrodynamics. Energy levels of positronium // Phys. Rev. 1954. Vol. 95, № 3. P. 811–822.

4. *Grotch H., Yennie D.R.* Effective potential model for calculating nuclear corrections to the energy levels of hydrogen // Rev. Mod. Phys.1969. Vol. 41, № 2. P. 350–374.

5. *Нюнько Н.Е., Тюхтяев Ю.Н., Фаустов Р.Н.* Влияние движения ядра на тонкую структуру водорода / Сообщение ОИЯИ Р2-7493. Саратов, 1973. 16 с.

6. *Doncheski M., Grotch H., Erickson G.W.* Pure recoil corrections to the Lamb shift in hydrogenic atoms // Phys. Rev. 1991 Vol. 43, № 5. P. 2152–2170.

7. *Salpeter E.E., Bethe H.A.* Relativistic equation for bound state problems // Phys. Rev. 1951. Vol. 84, № 6. P. 1232–1242.

8. *Khriplovich I.B., Milstein A.I., Yelkhovsky A.S.* Corrections of $(\alpha^6 \ln\alpha)$ in two-body QED problem // Phys. Lett. B. 1992. Vol. 282. P. 237–242.

9. *Fell R.N.* Order $\alpha^4 \ln\alpha^{-1} f_{RYD}$. Corrections to the n=1 and n=2. Energy levels of positronium // Phys. Rev. Lett. 1992. Vol. 68. P. 25–28.

10. *Khriplovich I.B., Milstein A.I., Yelkhovsky A.S.* Logarifmic corrections in the two–body QED problem // Physica Scripta. 1993. Vol. 146. P. 252–260.

11. *Fell R.N.* Corrections of $(\alpha^6 \ln\alpha)$ / Preprint BUM 01742. Massachusetts, 1992.

12. *Fell R.N., Khriplovich I.B., Milstein A.I., Yelkhovsky A.S.* On the recoil corrections in hydrogen // Phys. Lett. A. 1993. Vol. 181. P. 172–174.

УДК 535.343.9; 530.145

ABSORPTION AS AN INDICATION OF VACUUM e^+–e^- PAIR CREATION IN A STRONG NONSTATIONARY ELECTRIC FIELD

D.B. Blaschke[a,b,c], S.V. Ilyine[d], G. Röpke[c], S.A. Smolyansky[d]

[a] Institute of Theoretical Physics, University of Wrocław, 50–204 Wrocław, Poland
[b] Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
[c] Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
[d] Saratov State University, RU-410026 Saratov, Russia
E-mail: isv–new@mail.ru

We discuss the high frequency conductivity and absorption coefficient of an electron – positron plasma (EPP) created from the vacuum in a strong nonstationary electric field (nonstationary Schwinger mechanism). It is shown that the basic contribution here is due to vacuum polarization effects. For subcritical linearly polarised fields, we obtain the general expression for the induced conductivity and the absorption coefficient, which is investigated in a wide range of frequencies from the optical to the γ-ray region.

Key words: electron-positron plasma; Schwinger mechanism; vacuum creation; X-ray laser; quasiparticle; optical properties.

Поглощение как Индикатор Вакуумного Рождения e^+–e^- Пар в Сильных Нестационарных Электрических Полях

Д.Б. Бляшке, С.В. Ильин, Г. Рёпке, С.А. Смолянский

Обсуждаются коэффициенты высокочастотной проводимости и поглощения электрон-позитронной плазы, рождающейся из вакуума в сильных нестационарных электрических полях (нестационарный механизм Швингера). Показано, что основной вклад обусловлен вакуумными поляризационными эффектами. Для субкритических линейно поляризованных полей, получены основные выражения для индуцированной проводимости и коэффициента поглощения, которые исследованы в широком диапазоне частот.

Ключевые слова: электрон-позитронная плазма, механизм Швингера, вакуумное рождение, ренгеновский лазер, квазичастица, оптические свойства.

1. Introduction

The formation of a relativistic EPP created from the vacuum under the action of an ultrashort optical laser pulse is one of the topics of modern fundamental physics and forthcoming experimental efforts [1,2]. It has been estimated that a zetawatt laser with intensity 10^{28} W/cm^2 could be built. That would allow to approach the Schwinger limit of the electric field for electron-positron pair creation $E_c = m^2/e = 1.3 \times \times 10^{16}$V/cm. Vacuum creation of light mesons becomes also possible for such subcritical fields [3]. It is discussed as one of the perspectives at the X-ray laser [4,5]. Thus the experimental observation of vacuum EPP has become an actual problem. Some of the observable effects have been discussed before in the literature, see, e. g., Ref. [6,7].

In the present work, we avoid to detail methods of the generation of acoherent quasiclassical time dependent electric field and rather focus on the discussion of the optical properties of the created EPP. We use a kinetic approach for the description of vacuum particle creation [8,9] and investigate the absorption of the EPP in the case of subcritical electric fields $E/E_c \ll 1$, which justifies to limit ourselves to the low density approximation only. It is shown that the basic contribution to the induced conductivity stems from the vacuum polarization effects in the external field. The general expression for the induced conductivity and absorption coefficient is obtained and investigated in detail in two ranges of the adiabaticity parameter corresponding to the optical and γ-ray regions. The absorption of a weak probe signal sent through the high density region in the focus of the acting strong electric field can be considered in the present formalism too.

2. The basic equations

We start from the collisionless kinetic equation for the description of vacuum EPP creation due to a spatially homogeneous, time dependent electric field of the linear polarization with the field strength $\vec{E}(0,0,E(t))$ [8,9].

$$\dot{f}(\vec{p},t)=\frac{1}{2}\Delta(\vec{p},t)\int\limits_{t_0}^{t} dt'\Delta(\vec{p},t')\left[1-f(\vec{p},t)\right]\cos\theta(\vec{p},t,t'), \qquad (1)$$

where

$$\Delta(\vec{p},t)=\frac{eE(t)\varepsilon(\vec{p})}{\varepsilon^2(\vec{p},t)}, \qquad (2) \qquad\qquad \theta(p,t,t')=2\int\limits_{t'}^{t} d\tau\,\varepsilon(\vec{p},\tau), \qquad (3)$$

$$\varepsilon(p,t)=\sqrt{\varepsilon_\perp^2(\vec{p})+\left(p_\parallel-eA(t)\right)^2}, \quad \varepsilon_\perp=\sqrt{m^2+p_\perp^2}. \qquad (4)$$

Here, $E(t)=-\dot{A}(t)$, and $f(\vec{p},t)$ is the time dependent distribution function of EPP quasiparticles generated from the vacuum during the period of the field action. For the investigation of the optical properties of the EPP droplet it is important to consider the structure of the total current

$$j(t)=j_{cond}(t)+j_{pol}(t), \qquad (5)$$

where the conduction and the vacuum polarisation currents are equal to $\left(\int_p = \int d^3p\,(2\pi)^{-3}\right)$

$$j_{cond}=4e\int_p \frac{p_\parallel}{\varepsilon(\vec{p},t)}\,f(\vec{p},t), \qquad (6)$$

$$j_{pol}=2e\int_p \frac{\varepsilon_\perp}{\varepsilon(\vec{p},t)}\,u(\vec{p},t), \qquad (7)$$

where $u(\vec{p},t)$ is the vacuum polarization function,

$$u(\vec{p},t)=\int\limits_{t_0}^{t} dt'\Delta(\vec{p},t')\left[1-f(\vec{p},t)\right]\cos\theta(\vec{p},t,t'). \qquad (8)$$

We will use below the low density approximation, $f(\vec{p},t) \ll 1$. From Eqs. (1) and (8) follows that

$$f(\vec{p},t)=\frac{1}{4}\left|\int\limits_{t_0}^{t} dt'\Delta(\vec{p},t')\exp\left(i\theta(\vec{p},t,t')\right)\right|^2, \qquad (9)$$

$$u(\vec{p},t)=\int\limits_{t_0}^{t} dt'\Delta(\vec{p},t')\cos\theta(\vec{p},t,t'). \qquad (10)$$

This approximation corresponds to the assumption of the weakness of the external field with the characteristic strength E_0, i. e.

$$E_0/E_c \ll 1. \qquad (11)$$

Below it is assumed that the external, linearly polarized field is a harmonic one with the frequency ν,

$$E(t)=E_0\cos\nu t, \qquad A(t)=-(E_0/\nu)\cos\nu t. \qquad (12)$$

The considered theory is characterized also by the adiabaticity parameter γ, which defined as [10]

$$\frac{1}{\gamma}=\frac{eE_0}{\nu m}=\frac{E_0 m}{E_c \nu}. \qquad (13)$$

Given the condition (11), there are two limiting situations: the case of low (optical) frequencies $m/\nu \gg 1$, where $\gamma \ll 1$ and the case of γ – ray frequencies $\nu \sim m$, where $\gamma \gg 1$.

Our aim is an estimation of the effectiveness of the quasiparticle EPP creation by means of optical methods of registration. As the first step, we intend to construct the theory of electromagnetic field absorption by the generated quasiparticale EPP. We are guided here by the deep analogy with the Bloch theory of electron – hole interaction with an electromagnetic field in solid stats physics (see, e. g., Ref. [11]).

Below we restrict ourselves to the case of a spatially homogeneous system, and define the absorption coefficient as the ratio of the spectral power densities of the instantaneous absorbed and incoming energies, i. e.

$$\alpha(\omega)=Q(\omega)/w(\omega), \qquad (14)$$

where $Q(\omega)$ and $w(\omega)$ are the Fourier transforms of the corresponding energy functions

$$Q(t)=\vec{j}(t)\vec{E}(t),\quad w(t)=E^2(t)/4\pi, \tag{15}$$

with the conservation law $\dot{w}(t)=-Q(t)$.

Thus, the next problem is the determination of the components of the conductivity tensor components corresponding to the chosen symmetry of the system.

3. Absorption coefficient

The relative orders of the distribution function (9) and the function of vacuum polarization (10) are defined by the amplitude (2), for which approximately holds $\Delta \sim \Delta^{(1)} \sim E_0 / E_c$, so that

$$f \sim f^{(2)} \sim (E_0 / E\,)^2,\quad u \sim u^{(1)} \sim (E_0 / E_1). \tag{16}$$

However, the function $f^{(2)}$ can be an even one with respect to $p_\parallel$ and thus does not give a contribution to the conductivity current (6). Hence, the leading approximation for the conductivity and polarization currents will be

$$j_{cond} \sim j_{cond}^{(2\div3)},\qquad j_{pol} \sim j_{pol}^{(1)} \tag{17}$$

(the uncertainty in the order of the leading approximation of the conductivity current j_{cond} stems from the of the field in the one particle energy $\varepsilon(\vec{p},t)$ (4) and the phase (3), see below). In any case, the polarization current gives the basic contribution in the total current,

$$j \approx j_{pol} \approx j_{pol}^{(1)} \tag{18}$$

if $j_{pol}^{(1)} \neq 0$.

Below the absorption coefficient will be investigated for the two asymptotic ranges of the adiabaticity parameter (13) where analytic results can be obtained.

Case of the high frequency region: $\nu \le m$, $\gamma >> 1$. A considerable simplification is reached here as the field influence in the one particle energy (4) can be neglected,

$$\varepsilon\,(\vec{p},t) \to \varepsilon\,(p)=\sqrt{m^2+p^2}. \tag{19}$$

Then it follows from Eqs. (7), (10), (18) and (19) that

$$j_o = 2e^2 \int_p \frac{\varepsilon_\perp^2}{\varepsilon_0^3} \int_{t_0}^{t} dt'\, E(t')\cos\left[2\varepsilon_0(t-t')\right]. \tag{20}$$

The structure of this expression allows to extract the vacuum polarization contribution to the conductivity. The generalized Ohm law in a nonstationary medium is [12]

$$j_i(t)=\int_{-\infty}^{t} dt'\sigma_{ij}(t-t',t')\,E_j(t'). \tag{21}$$

The conductivity tensor $\sigma_{ij}(t-t',t')$ depends on two times: the first argument $t-t'$ takes into account the retardation effects while the second one t' corresponds to the nonstationary state of the medium induced by the influence of an external field. In the considered linear approximation (20), nonstationary medium effects are absent and hence Eq. (21) transforms to

$$j(t)=\int_{-\infty}^{t} dt'\sigma(t-t')\,E(t'), \tag{22}$$

where we accounted for the presence of one field polarization only.

The comparison of Eqs. (20) and (22) leads to the following result for the polarization conductivity $(t_0 \to -\infty)$

$$\sigma(t)=2e^2 \int_p \frac{\varepsilon_\perp^2}{\varepsilon_0^3}\cos(2\varepsilon_0 t). \tag{23}$$

The angular integration here gives the result

$$\sigma(t)=\frac{2e^2}{3\pi^2}\int_{2m}^{\infty}\frac{dx}{x^2}\sqrt{x^2/4-m^2}\,\times \\ \times\left(2m^2+x^2/4\right)\cos xt. \tag{24}$$

Finally, performing the Fourier transformation, we obtain a result for the frequency dependent conductivity which is in full analogy with the Bloch theory of electromagnetic wave interaction (in the dipole approximation) with free carriers in a semiconductor [10],

$$\sigma(\omega)=\frac{e^2}{24\pi^2}\sqrt{\omega^2-4m^2}\,\times \\ \times\left(1+8m^2/\omega^2\right)\,\theta(\omega-2m). \tag{25}$$

The main prediction of this result is the threshold $\omega = 2m$ in the frequency dependence of the polarization conductivity.

Now it is easy to find the connection between the conductivity (25) and the absorption coefficient (14). From Eq. (22) follows

$$j(\omega)=\sigma(\omega)E(\omega), \tag{26}$$

and for the spectral densities of the energies (15) we obtain

$$Q(\omega)=\int d\omega'\sigma(\omega')E(\omega')E(\omega-\omega'), \tag{27}$$

$$w(\omega)=\frac{1}{4\pi}\int d\omega'\,E(\omega')E(\omega-\omega'). \tag{28}$$

Let us apply these formulas to a monochromatic signal (12), where

$$E(\omega)=\frac{1}{2}E_0\,[\delta(\omega-\nu)+\delta(\omega+\nu)], \tag{29}$$

so that

$$Q(\omega)=\pi\, w_0\,\sigma_0(\nu)[\delta(\omega)+\delta(\omega-2\nu)], \tag{30}$$

$$w(\omega)=\frac{1}{4}w_0\,[2\delta(\omega)+\delta(\omega-2\nu)], \qquad (31)$$

were $w_0=E_0^2/4\pi$. Disregarding the static parts of these relations and comparing the spectral densities at the frequency $\omega=2\nu$, we obtain for the absorption coefficient the result

$$\alpha(\nu)=4\pi\,\sigma(\nu). \qquad (32)$$

Thus, in the applied approximation, the EPP will absorb the energy of an external field starting with the threshold frequency $\nu=m$ (in Eq. (25) $\omega=2\nu$(!), which corresponds to a two-photon process, see Eq. (30)). Otherwise, the EPP is optically transparent up to the pair creation region. It is worth noting, that this effect is rather large $\sim e^2$ and it can be expected that the absorption at $\nu<m$ will appear in some higher order as, e. g., $O(e^4)$.

The optical region. Let us write the general expression for the polarization conductivity, that follows from Eqs. (7), (10) in the low density approximation

$$\sigma_{pol}(t,t')=2e^2\int_p \frac{\varepsilon_\perp^2}{\varepsilon_p(p)}\left\{\varepsilon_\perp^2+\left[p_\parallel+e\left(A(t)-A(t')\right)\right]^2\right\}^{-1}\times$$
$$\times\cos 2\int\limits_{t'}^{t}d\tau\left\{\varepsilon_\perp^2+\left[p_\parallel+e\left(A(t)-A(t')\right)\right]^2\right\}^{1/2}. \qquad (33)$$

Here a substitution was used, which makes explicit the dependence on $\varepsilon_0(p)$ defined by Eq. (19).

In the high frequency region ($\nu\le m$, $\gamma>>1$). Eq. (33) leads to the results (25), (32) again. The case of the «optical» region ($\nu<<m, \gamma>>1$), after using the averaging procedure over harmonics of the laser field, leads to the result

$$\sigma_{pol}(\omega)=\frac{e^2}{\pi^3}J_0^2\left(\frac{2eE_0}{\nu^2}\right)\int\limits_0^\infty dp\,\frac{p^2\left(\varepsilon_0^2-p^2/3\right)}{\varepsilon_0\left(\varepsilon_0^2+e^2E_0^2/\nu^2\right)}\left\{\frac{4e^2E_0^2}{\nu^2}-\left(\omega-2\varepsilon_0\right)^2\right\}^{-1/2}, \qquad (34)$$

were $J_0(x)$ is modified Bessel function. This result is valid under the condition

$$\omega<\frac{2eE_0}{\nu}-2m\approx 2m\gamma, \qquad (35)$$

that is fulfilled certainly in the considered range. The corresponding absorption is defined by Eq. (32). The presence of two frequencies ν and ω has a simple meaning: the frequency ω is the response frequency of the polarized vacuum under the influence of the monochromatic laser field which has the frequency ν. These frequencies are identified in Eq. (32).

Let us remark, that the response of the EPP with respect to a weak probe signal with a linear polarization collinear with the basic strong electric field can be considered also in the framework of the present formalism. For this aim it is sufficient to consider the bichromatic signal with the electric field

$$E(t)=E_0\cos\nu\,t+E_1\cos\nu_1 t \qquad (36)$$

were E_0, ν correspond to the basic high intensity field and E_1, ν_1 to the probe laser.

4. Summary

The results of the work can be summarized as follows. In the case of subcritical fields (11), it was shown, that the absorption coefficient is defined mainly by the vacuum polarization effect in Eq. (18). A general expression (33) was obtained for the induced polarization conductivity, which is valid for all values of the adiabaticity parameter (13). Eq. (33) was investigated analytically in two asymptotic cases: $\gamma<<1$ (the high frequency limit, Eqs. (25), (32)) and $\gamma>>1$ (the low frequency (optical, x-ray) region, Eqs. (32),(34)). These results have preliminary character and require a more detailed investigation.

The condition (11) of the field weakness is in need of joint consideration with the quasipartical condition [13]

$$E>>E_{cl}=\nu^2. \qquad (37)$$

Thus, the electric field should be satisfy to the double inequality

$$E_{cl}=eE_c(\nu/m)^2<<E<<E_c. \qquad (38)$$

These conditions are fulfilled well in the region $\nu<<m$. The high frequency limit $\nu\sim m$ is the upper bound of validity of requirement (38).

We thank A. V. Prozorkevich for the useful remarks.

References

1. *Tajima T., Mourou G.A.* Zettawatt lasers and their applicayions in ultrastrong-field physics // Phys. Rev. ST Accel. Beams. 2002. Vol. 5. P. 031301.

2. *Tajima T., Mourou G.A., Bulanov S.V.* Optics in the relativistic regime // Rev. Mod. Phys. 2006. Vol. 78. P. 309.

3. *Kuznetsova I., Habs D., Rafelski J.* Pion and muon production in electron-positron photon plasma // arXiv:0803.01588.

4. *Ringwald A.* Pair production from vacuum at the focus of an X-ray free electron laser // Phys. Lett. 2001. Vol. B510. P. 107.

5. *Alkofer R., Hecht M.B., Roberts C.D. Schmidt S.M., Vinnik D.V.* Pair creation and an X-ray free electron laser // Phys. Rev. Lett. 2001. Vol. 87. P. 193902.

6. *Heinzl T., Liesfeld B., Amthor K.-U., Schwoeren H., Sauerbrey R., Wipf A.* On the observation of vacuum birefrugence // Opt. Commun. 2006. Vol. 267. P. 318.

7. *Di Piazza A., Hatsagortsyan K.Z., Keitel C.H.* Light diffraction by a strong standing electromagnetic wave // Phys. Lett. 2006. Vol. 97. P. 083603.

8. *Schmidt S.M., Blaschke D., Röpke D., Smolyansky S.A., Prozorkevich A.V., Toneev V.D.* A quantum kinetic eqation for partical production in the schwinger mechanism // Jntern. J. Mod. Phys. 1998. Vol. E7. P. 709.

9. *Pervushin V.N., Skokov V.V., Reichel A.V. Smolyansky S.A., Prozorkevich A.V.* The kinetic description of vacuum particle creation in the oscillator represettotion // Ibid. 2005. Vol. A20. P. 5689.

10. *Popov V.S.* Multiphoton atom ionizationin a field of ultrashort laser puls // JETP. 2001. Vol. 120. P. 315.

11. *Haug H., Koch S.W.* Quantum theory of the optical and electronic propeties of semiconductors. London: World Scientific Publ. Co., 2004.

12. *Pustovalov V.V., Silin V.P.* Nonlinear theory of waves interacyion in plasma // Trudy FIAN im. P.N. Lebedeva. 1972. Vol. 61. P. 42.

13. *Berestetskii V.B., Lifshitz E.M., Pitaevskii L.P.* Quantum electrodynamics. Oxford: Pergamon Press, 1982.

УДК 535 (092)

РАЗВИТИЕ ПРЕДСТАВЛЕНИЙ О ПРИРОДЕ ЗРЕНИЯ ОТ ЛЕОНАРДО ДА ВИНЧИ ДО ТОМАСА ЮНГА

Б. А. Медведев, А. А. Кудряшова

Саратовский государственный университет,
кафедра общей физики
E-mail: bmedvedev@yandex.ru

В контексте проблем, связанных с гуманизацией и гуманитаризацией физического образования, включая философские и дидактические вопросы повышения творческого потенциала молодых исследователей в области физиологической и физической оптики, представлено развитие взглядов на природу зрения в трудах Леонардо да Винчи, Исаака Ньютона и Томаса Юнга.

Ключевые слова: история физики, творцы физической оптики, природа зрения.

Development of Ideas about Nature of Sight froм Leonardo da Vinci to Thomas Young

B. A. Medvedev, A. A. Kudryashova

In the context in the problems, connected with humanization and humanitarization of physical formation, including philosophical and didactic questions of an increase in the creative potential of young researchers in the field of physiological and physical optics, is represented the development of views on nature of sight in the works of Leonardo da Vinci, Isaac Newton and Thomas Young.

Key words: history of physics, creators of physical optics, nature of the sight.

> Истинная наука – та, которую опыт заставил пройти сквозь чувства и наложил молчание на языки спорщиков и которая не питает сновидениями своих исследователей, но всегда от первых истинных и ведомых начал продвигается постепенно и при помощи истинных заключений к цели…
>
> *Леонардо да Винчи*

Введение

Более 70% информации об окружающем нас мире мы получаем посредством зрения, и лишение этого дара представляется для человека большой трагедией. Именно по этому актуальность развития представлений о природе зрения и интенсификации оптических и медико-биологических исследований в области физиологической оптики не вызывает сомнения. Тем не менее в связи с темой нашей работы, вынесенной в заголовок, мы начинаем нашу статью с вопросов: Зачем физику, точную, не терпящую отступлений от правил науку, рассматривать в философском контексте? В чём польза рассуждений о её истории? Не затем ли, ответим мы, чтобы вспомнить: «Истина так нежна, что чуть только отступил от неё, впадаешь в заблуждение; но и заблуждение это так тонко, что стоит только немного отклониться от него, и оказываешься в истине» (Блез Паскаль). Цена заблуждений и ошибок в истории физики высока настолько, что современный исследователь должен помнить: он всегда на границе познания, его мышление не должно страдать «догматом непогрешимости». С другой стороны, его не может не интересовать фундаментальный вопрос о том, кто делает открытия. Почему Галилей и Ньютон, Больцман и Максвелл, Планк и Резерфорд, Бор и Эйнштейн, Гейзенберг и Шредингер, Де Бройль, Дирак и Паули и, наконец, Пригожин? Почему именно им было дано привести к смене научных парадигм и изменению физической картины мира?