Applied Physics Institute

National Academy of Sciences of Ukraine

(Sumy, Ukraine)

VERIFICATION OF QUANTUM ELECTRODYNAMICS IN THE STRONG PULSED LASER FIELD (PHELIX LASER) AND STRONG MAGNETIC FIELD

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September 26, 2014, Kharkov

Department of QED of Strong Fields

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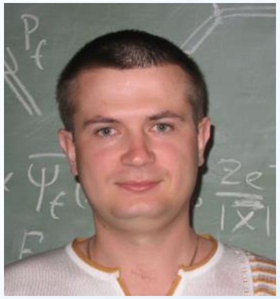


Dr. Lysenko O.B.   Dr. Denisenko O.I.   Dr. Starodub S.S.   Dr. Nedoreshta V.N.   Dr. Padusenko E.A.

THE MAIN RESEARCH:

- QED in the intense laser fields
- Interaction of laser radiation with electrons and ions
- Amplification laser radiation in the QED processes

Laboratory of Applied Methods of Field Theory

**Kholodov R., Kravchenko S., Kul`ment`ev A., Novak O.,
Lul`chenko S., Vechirka V., Ostapovich D., Khelemelya A., Dyachenko M.**

THE MAIN RESEARCH:

- **QED in strong magnetic field**
- **Electron cooling theory**

Letter of collaboration with SPARC

Agreement of collaboration
between Stored Particles Atomic Physics Research Collaboration (SPARC)
at Facility for Antiproton and Ion Research (FAIR) project
and the Institute of Applied Physics,
National Academy of Sciences of Ukraine

Hereby both parties have entered into an Agreement of collaboration free of any monetary obligations concerning investigation of processes of quantum electrodynamics (QED) in strong external fields for the FAIR project.

The collaboration expects scientific data exchange, joint academic meetings, co-publications, mutual academics visits, joint post-graduate study.

Within the Agreement of collaboration the Parties are planning the joint works as follows:

- investigation of resonant and non-resonant processes of quantum electrodynamics (QED) of the first and the second order on the fine structure constant in strong impulse field of laser (PHELIX), namely, the processes of scattering of electrons by nuclei (by electrons, by positrons, by mu-mesons); the processes of spontaneous bremsstrahlung, photo-production of electron-positron pair at a nuclear field and the Compton scattering of photons by electrons;
- investigation of QED processes of the first and the second order on the fine structure constant in bi-chromatic strong laser field, namely study of interference effect related to the most probable radiation and absorption of combination frequency photons by electrons;
- investigation of the QED phenomena at relativistic heavy ions collisions, electron-positron pair creation, in particular;
- investigation of resonant and non-resonant QED processes in strong magnetic field between colliding nuclei, in particular, electron-positron pair production, photon polarization shift, etc.

Date: 16.11.2012

Spokersperson of Stored Particles Atomic Physics Research Collaboration
Prof. Reinhold Schuch

Director of the Institute of Applied Physics, NAS of Ukraine
Academician of NAS of Ukraine
Prof. Volodymyr Yu. Storizhko

Within the Agreement of collaboration the Parties are planning the joint works as follows:

- **investigation of resonant and non-resonant processes of QED in the strong pulsed laser field (PHELIX),** пamely, the processes of scattering of electrons by nuclei (by electrons, by positrons, by mu-mesons); the processes of spontaneous bremsstrahlung, photo-production of electron-positron pair at a nuclear field, the Compton scattering of photons by electrons and others.

- **investigation of QED processes in the bi-chromatic strong pulsed laser field,** namely study of parametric interference effect related to the most probable radiation and absorption of the combination frequency photons by electrons;

- **investigation of resonant and non-resonant QED processes in strong magnetic field between colliding nuclei**, in particular, electron-positron pair production, photon polarization shift, etc.

The Main Physical Parameters of QED Effects in a Pulsed Light Field

Born approximation:

the interaction of an electron and a positron with a nucleus is considered in the first order of the perturbation theory

$$\frac{v}{c} \gg Z\alpha = \frac{Z}{137} \qquad (1)$$

The classical relativistically invariant parameter:

the ratio of a work of a field at the wavelength to the electron rest energy

$$\eta_0 = \frac{eF_0\lambda\!\!\!^{-}}{mc^2} \qquad (2)$$

The Bunkin-Fedorov multiphoton quantum parameter:

the ratio of a work done by a field within space, passing by an electron during the characteristic time of wave oscillation, to the energy of a wave photon

$$\gamma_0 = \eta_0 \frac{mcv}{\hbar\omega} \qquad (3)$$

The range of moderately strong fields

in which these parameters satisfy the conditions:

$$\eta_0 \ll 1, \quad \gamma_0 \gtrsim 1 \qquad (4)$$

$$\left(10^5 \div 10^6\right)\text{V/cm} \lesssim F_0 << \left(10^{10} \div 10^{11}\right)\text{V/cm} \qquad (5)$$

Model of a Quasi-Monochromatic Field

We will consider an external electromagnetic pulse in the form of a plane elliptically polarized wave that propagates along the z axis with the 4-potential

$$A(\varphi) = A_0 \cdot g\left(\frac{\varphi}{\omega\tau}\right) \cdot \left(e_x \cos\varphi + \delta \cdot e_y \sin\varphi\right), \quad A_0 = \frac{cF_0}{\omega}, \tag{6}$$

The function g is the envelope of the potential. We will require that it has to be equal to the unity at the pulse center, g(0) = 1, and decrease exponentially $g \to 0$ when $|\varphi| >> \omega\tau$.

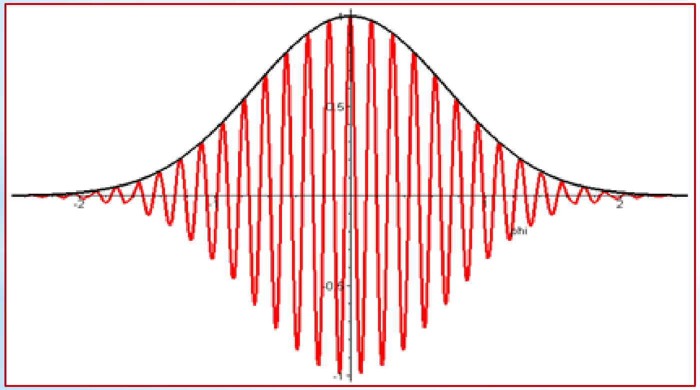


Fig.1 Quasi-monochromatic field

$$\varphi = \omega t - \mathbf{kr} = \omega\left(t - \frac{z}{c}\right), \qquad e_{x,y} = \left(0, \mathbf{e}_{x,y}\right) \tag{7}$$

$$\omega\tau \gg 1 \tag{8}$$

In the range of optical frequencies, the characteristic pulse duration τ can be even tens of femtoseconds and, consequently, condition (8) is met for most present-day powerful pulsed lasers.

The main parameters of PHELIX laser system

	Long pulse	Short pulse
Pulse duration	0.7–20 ns	0.4–20 ps
Energy	0.3–1 kJ	120 J
Max intensity	10^{16} W/cm^2	10^{20} W/cm^2
Repetition rate at maximum power	1 shot every 90 min	1 shot every 90 min
Intensity contrast	50 dB	60 dB

Resonant QED processes in the pulsed laser field

Nonresonant QED processes in the pulsed laser field

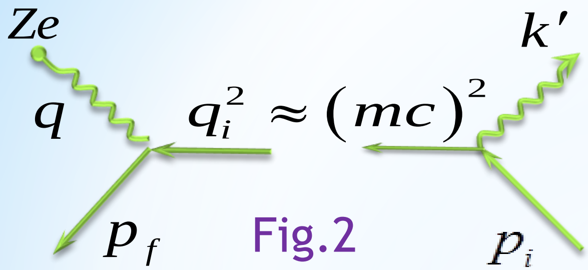


Fig.2

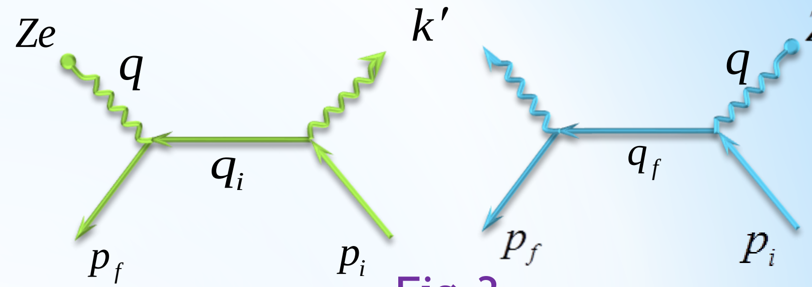


Fig.3

$$\beta = \frac{\left(q_i^2 - m^2c^2\right)}{4\left(kq_i\right)}\left(\omega\tau\right) \lesssim 1 \qquad (9)$$

$$\beta = \frac{\left(q_i^2 - m^2c^2\right)}{4\left(kq_i\right)}\left(\omega\tau\right) >> 1 \qquad (10)$$

$$d\sigma_{res} \sim P_{res} \cdot d\sigma_s \cdot dW^{(1)} \qquad (11)$$

$$P_{res} \sim \left(\omega\tau\right)^2 \exp\left(-\beta^2/2\right) \cdot \left(\frac{\tau}{2T}\right) \int_{-T/\tau}^{T/\tau} d\phi \cdot \left|\operatorname{erf}\left(\phi + \frac{i\beta}{2}\right) + 1\right|^2 \qquad (12)$$

$$\Gamma_R \sim \alpha \eta_0^2 \frac{\sigma_c\left(q_i\right)}{\sigma_T} \cdot \frac{\left(kq_i\right)}{mc} \qquad (13)$$

$$\beta << 1 \Rightarrow P_{res} \sim \frac{1}{\left(q_i^2 - m^2c^2\right)^2 + 4\left(mc\right)^2 \Gamma_\tau^2} \cdot \qquad (14)$$

$$\Gamma_\tau \sim \frac{\left(kq_i\right)}{mc}\left(\frac{1}{\omega\tau}\right) \qquad (15)$$

$$\Gamma_\tau \gtrsim \Gamma_R \qquad (16)$$

Following processes of QED in the pulsed laser field ($I \sim 10^{15} \div 10^{17}\ \mathrm{W/cm^2}$) were studied

- Electron scattering on a nucleus in the pulsed laser field: $e + Ze \to e' + Ze + n\omega$
- Resonant and nonresonant electron–positron pair photoproduction on a nucleus in the pulsed laser field:

$$\gamma + Ze \to e^- + e^+ + Ze + n\omega, \quad n = n_1 + n_2, \quad n_{1,2} = \pm 1, \pm 2, \pm 3, \dots$$

- Resonant and nonresonant spontaneous bremsstrahlung of an electron scattered by a nucleus in the pulsed laser field:

$$e + Ze + n_1\omega \to e' + \gamma + Ze + n_2\omega$$

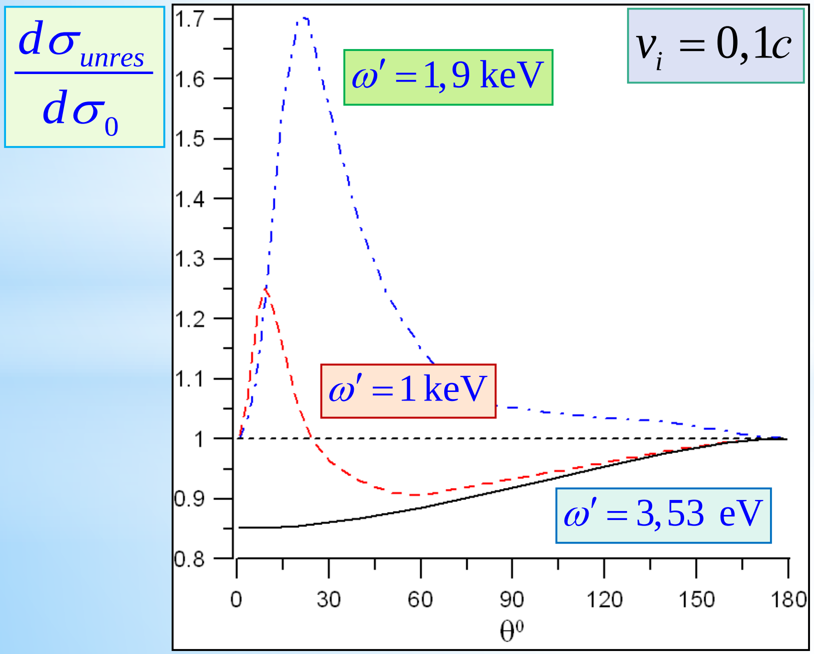


Fig.4

$\omega = 2.35\,\mathrm{eV}$, $\tau = 1.5\,\mathrm{ps}$, $F_0 = 6 \cdot 10^9\ \mathrm{V/cm}$

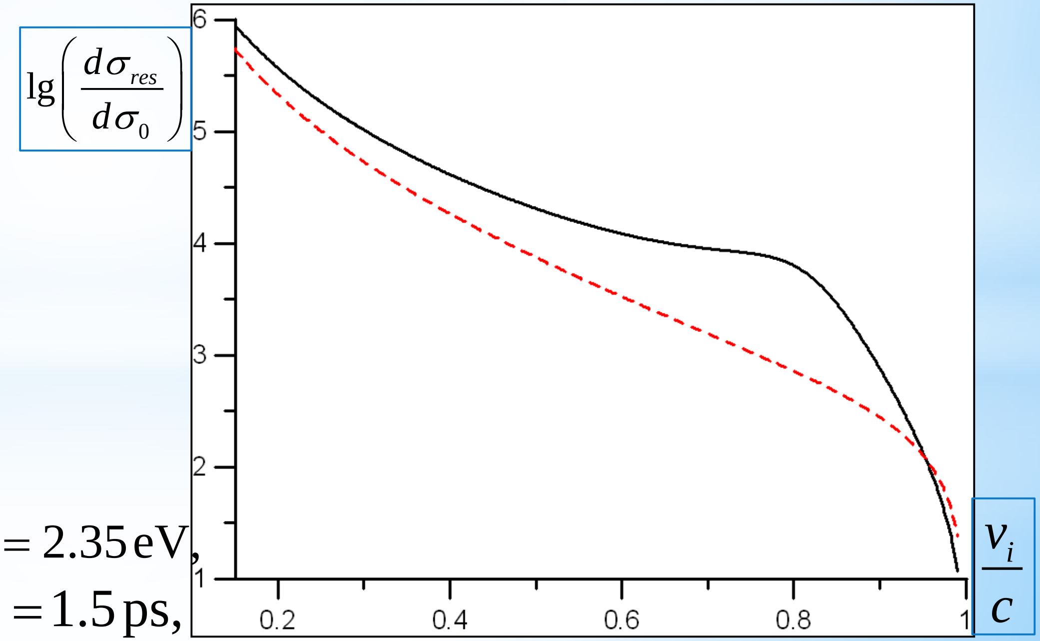


Fig.5

Following processes of QED in the pulsed laser field ($I \sim 10^{15} \div 10^{17}$ W/cm^2) were studied

- Muon Pair Production in Electron–Positron Annihilation in the laser field:

$$e^- + e^+ + n_1\omega \to \mu^- + \mu^+ + n_2\omega$$

- Resonant and nonresonant scattering of a lepton by a lepton (electron-electron, electron-positron, electron-muon) in the pulsed laser field:

$$l_1 + l_2 + n_1\omega \to l_1' + l_2' + n_2\omega, \quad n_{1,2} = \pm1, \pm2, \pm3, \ldots$$

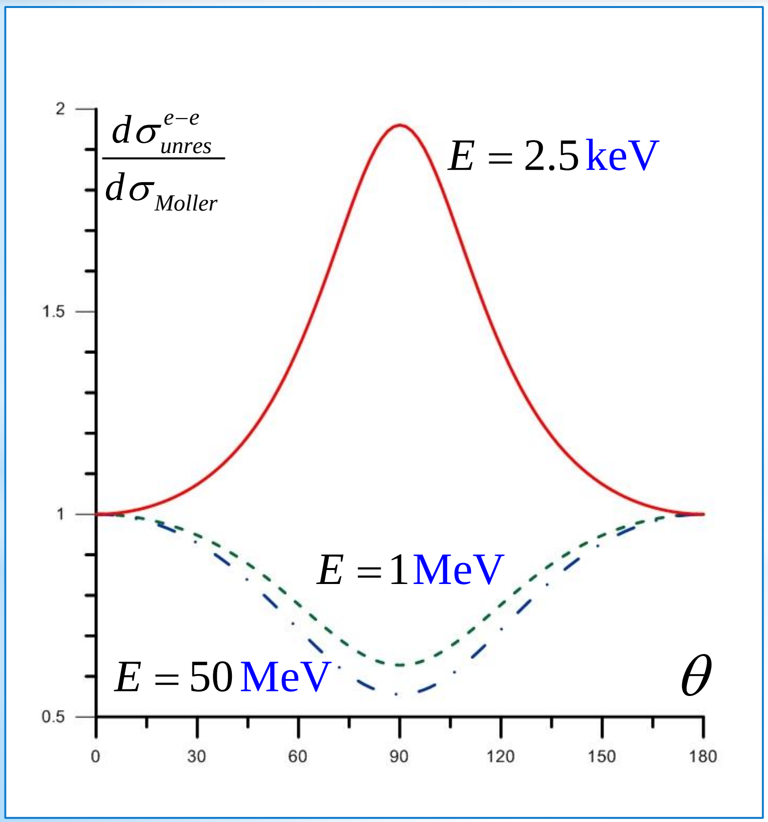


Fig.6

$\omega = 2.35$ eV, $\tau = 1.5$ ps, $F_0 = 6 \cdot 10^9$ V/cm

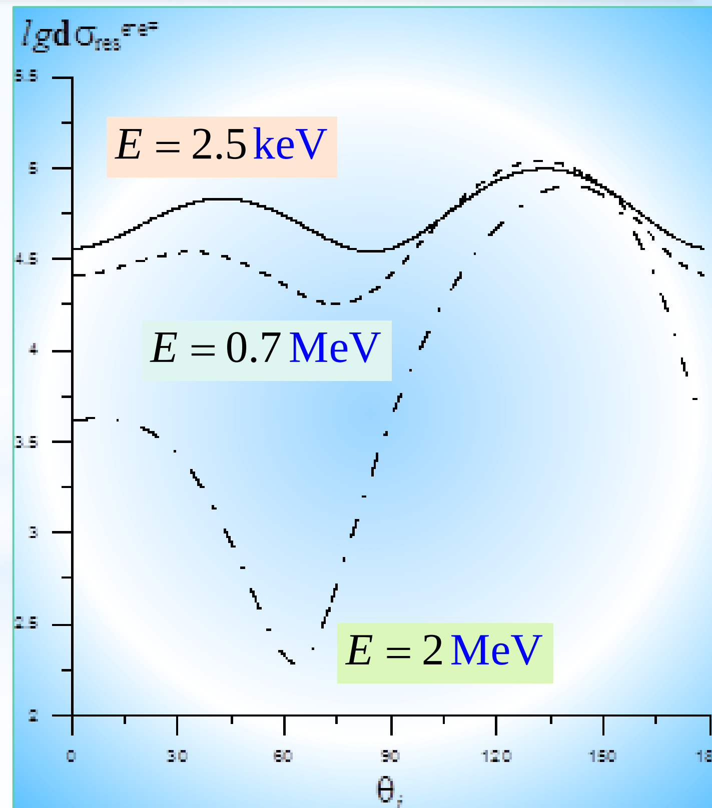


Fig.7

Following processes of QED in the pulsed laser field ($I \sim 10^{15} \div 10^{17}\ \mathrm{W/cm^2}$) were studied

- Two-photon emission by an electron in the strong laser field:

$$e^- + n_1\omega \to e'^- + \gamma_1 + \gamma_2 + n_2\omega$$

- Resonant and nonresonant two-photon production an electron-positron pair in the strong pulsed laser field:

$$\gamma_1 + \gamma_2 \to e^- + e^+ + (n_1 + n_2)\omega$$

- Resonant and nonresonant scattering of photon by electron (Compton Effect) in the strong pulsed laser field:

$$\gamma + e^- + n_1\omega \to \gamma' + e'^- + n_2\omega$$

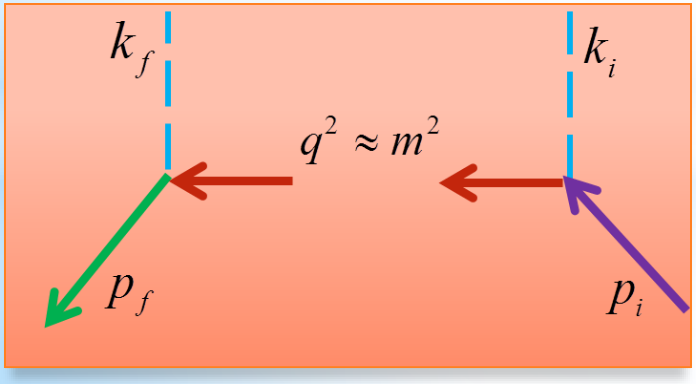


Fig.8

$$\left|1 - \frac{\omega_i}{\omega_{i,\mathrm{res}}}\right| \sim \frac{1}{\omega\tau} \ll 1 \qquad (17)$$

$$\frac{W_{fi}^{\mathrm{res}}}{\mathrm{W}_{\mathrm{Compt}}} \approx \frac{\tau}{T} P_{\mathrm{res}} \ \beta \cdot R(u, \tilde{u}_1) \gtrsim 10^3 \qquad (18)$$

Attraction Effect of Nuclei and the Same Charged Particles in the Strong Pulsed Laser Field

- **Attraction Effect of Electrons in the Strong Pulsed Laser Field**
- **Attraction Effect of Hydrogen ions in the Strong Pulsed Laser Field**
- **Attraction Effect of Uranium nuclei in the Strong Pulsed Laser Field**

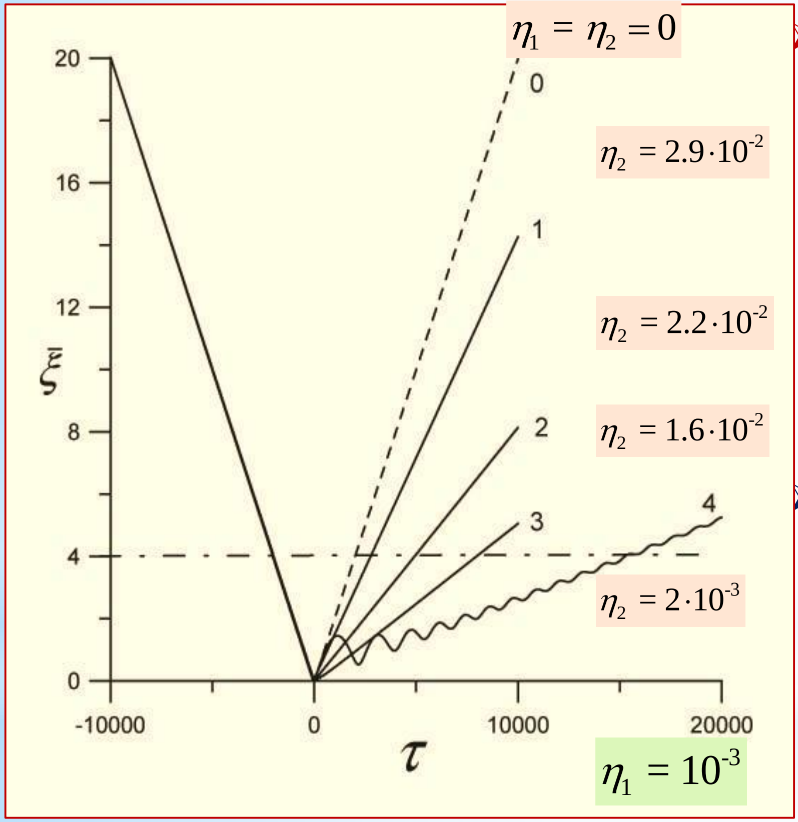


Fig. 9 The average relative distance between nuclei vs. time τ for various values of the nuclei oscillation velocity in the second wave.

- The effect of an attraction of the same charged nonrelativistic uranium nuclei in the strong pulsed laser field is predicted. Effective force of interaction becomes an attractive force and uranium nuclei move away from each other much more slowly. As a result the pulsed laser field can slow down backward motion of nuclei in 7 times.

- The given effect is caused by magnetic interaction of the currents related to the relative motion of the same charged nuclei.

Amplification of an electromagnetic field in the electrons scattering by ions in the moderate-strong field

- **The gain coefficient in the scattering of electrons by ions in an elliptically polarized light wave is theoretically studied in the general relativistic case.**
- **The anomalous amplification effect in the moderate-strong electromagnetic field is predicted. This effect results in to increase of the electric-field strength up to three orders of magnitude.**

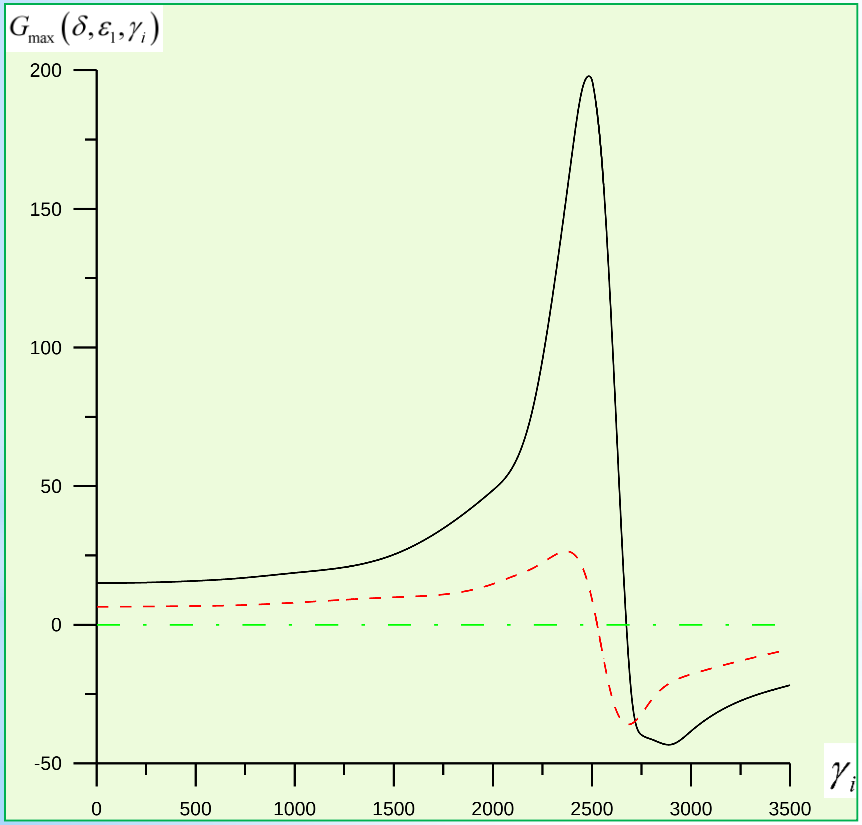


Fig.10

$$E_f - E_i + n\cdot\hbar\omega = 0, \quad n = \pm1, \pm2, \ldots \qquad (19)$$

$$\mu = \mu_* \cdot \left(\frac{mc}{|\mathbf{p}_i|}\right)^3 \cdot G(\theta_i, \delta, \varepsilon_1, \gamma_i) \quad \left(\frac{1}{\text{cm}}\right) \qquad (20)$$

$$\mu_* = 16\pi^2 Z^2 n_i n_e r_e^3 \lambda\!\!\!^{-}{}^2 \qquad (21)$$

Nonreletivistic energies

The anomalous amplification effect

$$\mu_{\max} = \mu_* \cdot \left(\frac{c}{v_i}\right)^3 \cdot G_{\max} \qquad (22)$$

Ultrarelativistic electron energies:

$$E_i >> mc^2,\ \theta_i = \measuredangle(\mathbf{k}, \mathbf{p}_i) << 1$$

$$\mu = 16\mu_* \cdot \left(\frac{E_i}{mc^2}\right)^3 \cdot G' \qquad (23)$$

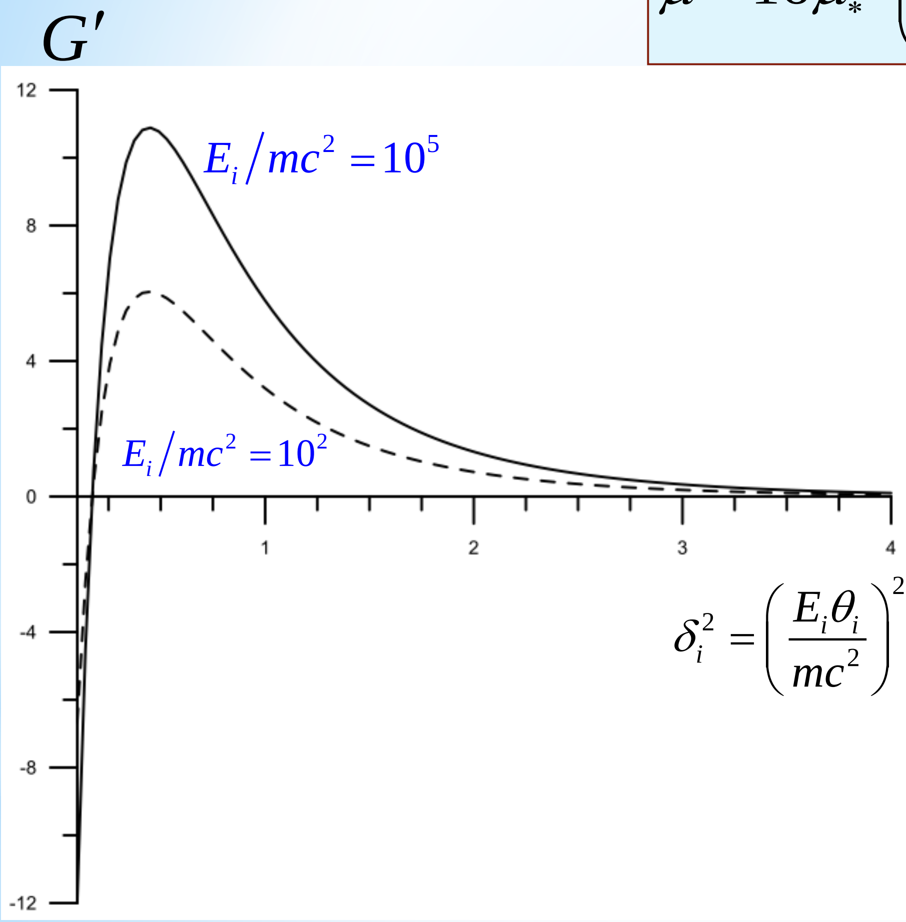


Fig. 11 Plots of the function G' versus the parameter δ_i^2 for ultrarelativistic electrons

It is shown that the gain coefficient for ultrarelativistic electron energies depends on the energy as a cubic power of energy and can be significantly large.

As a result, the gain coefficient can increase up to quantities of order

$$\mu \sim (1 \div 10)\ \text{cm}^{-1} \qquad (24)$$

for electron energies

$$E_i \sim 10 \div 20\ \text{GeV} \qquad (25)$$

Coherent Effects of QED Processes in a Multifrequency Laser Field

Following theories were created :

- The relativistic theory of electron scattering on a nucleus in **a multifrequency laser field**
- The relativistic theory of the emission of a spontaneous photon by an electron in **a multifrequency laser field**
- The relativistic theory of formation of an electron-positron pair by a photon in **a multifrequency laser field**
- The relativistic theory of spontaneous bremsstrahlung of an electron scattered by a nucleus in **two-frequency laser field**
- The relativistic theory of the electron–positron pair photoproduction on a nucleus in **two-frequency laser field**

There are two essentially different kinematic fields of scattering: noninterference region and interference region

$$d\sigma_{n_1 n_2} \sim \left| I_{n_1 n_2} \right|^2 \cdot d\sigma_0, \quad E_f - E_i + n_1 \cdot \hbar\omega_1 + n_2 \cdot \hbar\omega_2 = 0 \qquad (26)$$

Parametric interference effect of QED processes in a Multifrequency Laser Field

In noninterference kinematics the electrons emit and absorb photons of both waves independently from each other

$$d\sigma_{n_1 n_2} = J_{n_1}^2(\gamma_1)\cdot J_{n_2}^2(\gamma_2)\cdot d\sigma_0, \quad \gamma_{1,2} \sim \eta_{1,2}\frac{mc^2}{\hbar\omega_{1,2}}, \quad E_f - E_i + n_1\cdot\hbar\omega_1 + n_2\cdot\hbar\omega_2 = 0 \quad (27)$$

In interference kinematics the electrons emit and absorb photons of both waves in a correlated manner. As a result, the partial probability of stimulated processes in the interference region may be five orders of magnitude greater than the corresponding probability of processes in any other geometry.

$$d\sigma_{n_\pm} = J_{n_\pm}^2(\alpha_\pm)\cdot d\sigma_0, \quad \alpha_\pm \sim \eta_1\eta_2\frac{mc^2}{\hbar(\omega_1 \pm \omega_2)}, \quad E_f - E_i + n_\pm\cdot\hbar(\omega_1 \pm \omega_2) = 0 \quad (28)$$

$$\alpha_\pm \gtrsim 1,\ \gamma_1 \sim \gamma_2 \gtrsim 10^3 \quad \left(F_{1,2} \gtrsim 10^8 - 10^9\,\frac{\text{В}}{\text{см}}\right) \quad \Rightarrow \quad \frac{d\sigma_{n_\pm}}{d\sigma_{n_1 n_2}} \sim 10^5 \quad (29)$$

The Parametric Interference Effect in electron scattering on a nucleus in the Field of Two Pulsed Laser Waves

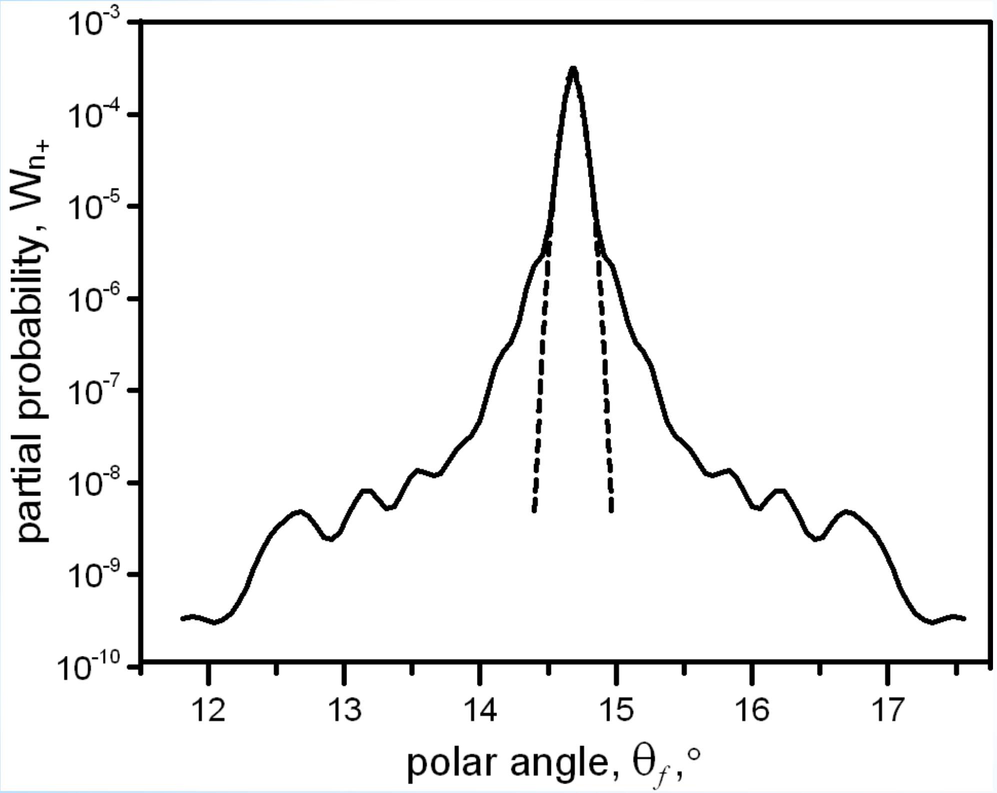


Fig. 12 The partial probability for the absorption process $n_+ = -5$ in electron scattering with the kinetic energy $E_i = 2.55$ keV and angles $\theta_i = 162°$, $\varphi_i = \varphi_f$ on a nucleus in the field of two pulsed laser waves ($I_{01} = 7.1 \cdot 10^{16}\ \mathrm{W/cm^2}$, $I_{02} = 1.7 \cdot 10^{17}\ \mathrm{W/cm^2}$) as a function of the polar angle of the final electron. Dashed line corresponds to the interference region

- **Electron scattering on a nucleus in a pulsed field of the two laser waves was studied. A strong correlation between the outgoing angle and final electron energy is observed in the interference kinematic region.**
- **It is shown that the partial probability of stimulated processes in the interference region may be five orders of magnitude greater than corresponding probability of processes in any other geometry.**

QED processes in strong magnetic field

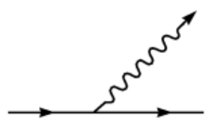
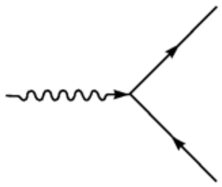
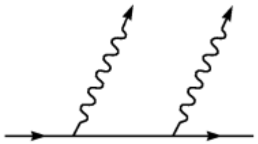
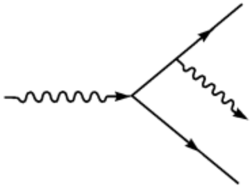
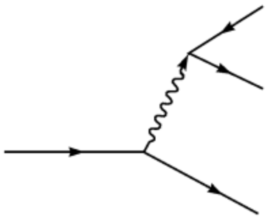
Process	Emission	Photoproduction	Double emission	Photoproduction with emission	Pair production by electron
Diagram					
Initial conditions	$l = 40,\ l' = 0$	$\omega = 2m,$ $l_- = l_+ = 0$	Lowest levels	Lowest levels	$l = 40,\ E = 2m,$ $l_f = 0$
Probability, s^{-1}	$W^{\text{total}}_{e\to\gamma e} \sim 10^{17}$ $W^{\omega>2m}_{e\to\gamma e} \sim 10^{14}$ $W^{1\to 0}_{e\to\gamma e} \sim 10^{16}$	$W_{\gamma\to ee^+} \sim 10^9$	$W^{\text{res}}_{e\to e\gamma\gamma} \sim W^{1\to 0}_{e\to\gamma e}$	$W^{\text{nonres}}_{\gamma\to\gamma ee^+} \sim 10^6$ $W^{\text{res}}_{\gamma\to\gamma ee^+} \sim W_{\gamma\to ee^+}$	$W \sim 10^{13}$

Fig.13

* P. I. Fomin and R. I. Kholodov, Zh. Exp. Theor. Phys. **117**, 319 (2000).
* P. I. Fomin and R. I. Kholodov, Zh. Exp. Theor. Phys. **123**, v.2, 356 (2003)
* O. P. Novak and R. I. Kholodov, Phys. Rev. D **80**, 025025 (2009).
* O. P. Novak, R. I. Kholodov, P. I. Fomin, Zh. Exp. Theor. Phys. **137**, v.6, 1120 (2010)
* O. P. Novak and R. I. Kholodov, Phys. Rev. D **86**, 105013 (2012).

It has been earlier theoretically predicted a series of new physical effects in processes of a quantum electrodynamics in the strong laser and magnetic fields [1-45]

It is shown that in the PHELIX laser field:

- **Resonant cross sections** of QED processes with leptons and photons may be **several orders of magnitude** greater than the corresponding cross sections in the absence of external field and nonresonant cross sections essentially depend on parameters of a pulsed field.
- Effective force of interaction **the same charged particles** in the strong pulsed laser field can become **an attractive force** that essentially changes interaction of particles.
- **The gain coefficient for ultrarelativistic electron energies** depends on the energy as a cubic power of energy and **can be significantly large**.
- **The partial probability** of stimulated processes QED in the Field of Two Pulsed Laser Waves in the interference region **may be five orders** of magnitude greater than the corresponding probability of processes in any other geometry.

New effects are assumed in heavy ion collisions:

- Resonant production of e+e- pairs on Landau levels in aria between colliding nuclei
- Resonant shift of polarization of photons passing thru region of colliding nuclei

THE LIST OF MAIN PUBLICATIONS

Books

1. S.P. Roshchupkin and A.I. Voroshilo, ***Resonant and Coherent Effects of Quantum Electrodynamics in the Light Field*** (Naukova Dumka, Kiev, 2008), in Russian.
2. S.P. Roshchupkin and A.A. Lebed', ***Effects of Quantum Electrodynamics in the Strong Pulsed Laser Fields*** (Naukova Dumka, Kiev, 2013), in Russian.
3. Sergei P. Roshchupkin, Alexandr A. Lebed', Elena A. Padusenko and Alexey I. Voroshilo. Resonant effects of quantum electrodynamics in the pulsed light field. **Chapter in the Book "Quantum Optics and Laser Experiments"**, INTECH - Open Access Publisher, University Campus STeP Ri, Croatia, **2012, PP.107-156.**

Reviews

4. S. P. Roshchupkin. "Resonant effects in collisions of relativistic electrons in the field of a light wave". **Laser Physics, 1996, Vol. 6, № 5, pp. 837-858.**
5. S. P. Roshchupkin, A. A. Lebed', E. A. Padusenko, and A. I. Voroshilo. "Quantum Electrodynamics Resonances in a Pulsed Laser Field", **Laser Physics, 2012, Vol. 22, No. 6, pp. 1113–1144.**
6. S. P. Roshchupkin, A. A. Lebed', and E. A. Padusenko. "Nonresonant Quantum Electrodynamics Processes in a Pulsed Laser Field", **Laser Physics, 2012, Vol. 22, No. 10, pp. 1513–1546.**
7. S. P. Roshchupkin and S. S. Starodub. "Interaction of Classical Nonrelativistic Identically Charged Particles in a Strong Pulsed Light Field", **Laser Physics, 2012, Vol. 22, No. 7, pp. 1202–1219.**

ARTICLES since 2006 year on these processes

8. O I Denisenko, S P Roshchupkin and A I Voroshilo. "Interference suppression in the two-photon annihilation of an electron–positron pair in the light wave field". Journal of Physics B: Atomic, Molecular and Optical Physics, 2006, V.39, PP. 965–973.
9. S.P. Roshchupkin and V.A. Tsybul’nik. "The light amplification effect in the Coulomb scattering of nonrelativistic electrons in a two-mode laser field". Laser Physics Letters, 2006, V.3, No. 7, PP. 362–368.
10. A.I. Voroshiloa, S.P. Roshchupkin, and O.I. Denisenko. “Resonance of exchange amplitude of Compton effect in the circularly polarized laser field”. The European Physical Journal D, 2007, V.41, PP. 433–440.
11. O.I. Voroshilo, S.P. Roshchupkin. “Resonant two-photon emission of an electron in the field of an electromagnetic wave”. Problems of atomic science and technology. 2007, N3 (1), PP. 221-224.
12. Starodub S.S., Roshchupkin S.P. Interaction of the nonrelativistic electrons in the pulsed field of two laser waves. The European Physical Journal D, 2007, V.44, PP. 401–405.
13. V.N. Nedoreshta, A.I. Voroshilo, and S.P. Roshchupkin “Nonresonant scattering of an electron by a muon in the field of plane electromagnetic wave”. Laser Physics Letters, 2007, V.4, No. 12, PP. 872–879.
14. O I Denisenko, S P Roshchupkin and A I Voroshilo. "Interference suppression in the two-photon annihilation of an electron–positron pair in the light wave field". Journal of Physics B: Atomic, Molecular and Optical Physics, 2006, V.39, PP. 965–973.

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The department
«Quantum electrodynamics of strong fields»
of Institute of Applied Physics,
National Academy of Sciences of Ukraine
is ready to participate in project FAIR, studing various processes of the quantum electrodynamics in the strong laser and magnetic fields.

THANK YOU