Załącznik 3 do wniosku o wszczęcie postępowania habilitacyjnego

SCIENTIFIC PORTFOLIO

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1. CURRICULUM VITAE

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EDUCATION AND SCIENTIFIC DEGREES

May 1994	high-school graduation from The Ks. Józef Poniatowski High School in Warsaw; class of mathematics and physics majors
June 1999	MSc degree with distinction in theoretical physics obtained at the Faculty of Physics UW, after completing the master program (1994-1999); MSc thesis entitled *"Zero-range potential as an example of renormalization in nonrelativistic quantum mechanics"* supervised by Dr hab. Jerzy Kamiński; Joanna and Jerzy Glazers' Award for the Best Masters Thesis completed at the Faculty of Physics UW, in 1998/1999 academic year
May 2004	PhD degree in physics obtained at the Faculty of Physics UW, after completing the PhD program (1999-2004); PhD thesis entitled *"Control of resonance states with external electromagnetic fields"* supervised by Prof. Dr hab. Jerzy Kamiński; distinction for the PhD thesis

SCIENTIFIC CAREER

1999-2004	PhD student at the Faculty of Physics, University of Warsaw
October 2004 – till now	assistant professor ("adjunct") at the Faculty of Physics, University of Warsaw
October 2005 – January 2007	postdoctoral fellow at the Department of Physics and Astronomy, the University of Nebraska-Lincoln, USA

HONORS AND AWARDS

1999	Masters degree with distinction obtained at the Faculty of Physics UW
1999	Joanna and Jerzy Glazers' Award for the Best Masters Thesis completed at the Faculty of Physics UW, in the academic year 1998/1999
2001	Dean of the Faculty of Physics Award (given annually to the best lecturer or tutor) for teaching Quantum Mechanics I to the undergraduate students in the academic year 2000/2001, University of Warsaw
2004	Distinction for PhD thesis, the Faculty of Physics UW
2005	Theodore P. Jorgensen Postdoctoral Fellowship at the Department of Physics and Astronomy, University of Nebraska-Lincoln, USA (October 2005 - January 2007)
2008	Chancelor of the University of Warsaw Award in recognition of scientific achievements

PROFESSIONAL ACTIVITIES

2001-2002	advisor for sophomore students, Faculty of Physics UW
2002-2004	member of the Scientific Council of the Institute of Theoretical Physics, Faculty of Physics UW
since 2006	member of the American Physical Society (APS) member of the Division of Atomic, Molecular, and Optical Physics (DAMOP)
2008-2012	member of the Scientific Council of the Institute of Theoretical Physics, Faculty of Physics UW
2010-2011	secretary of the Scientific Council of the Institute of Theoretical Physics, Faculty of Physics UW
2009-2012	Member of the Internship Committee which couples undergraduate physics majors with industry leaders and scientific institutions, Faculty of Physics UW
since 2010	webpage administrator for the project *"Physics - education for economics"*, Faculty of Physics UW
2011	chairman of the session during the *XX International Laser Physics Workshop*, Sarajevo, Bosnia and Herzegovina
since 2012	co-leader of the workpackage *"Networking through exchange of know-how and experience"* for the project *"PhoQuS@UW: Fostering Excellence in Photonics and Quantum Science"*, Faculty of Physics UW
since 2013	member of the Recruitment Committee for the project *"PhoQuS@UW: Fostering Excellence in Photonics and Quantum Science"*, Faculty of Physics UW
2013	member of the Local Organizing Committee of the international conference *Quantum Optics VIII*, Jachranka, Poland

SCIENTIFIC ACHIEVEMENTS

Data as of April 25th, 2013, quoted from the Web of Science (WoS).

1. Authorship and co-authorship of scientific papers:
   total number of publications (in accordance with Appendix 5): **24**
   – including publications in scientific journals from Journal Citation Reports (JCR) database: **24**

2. Total impact factor (IF) of 24 publications based on Journal Citation Reports (JCR) database, according to the year of their publication (for 2012, the impact factor from 2011 was used):
   IF **– 61.94**

3. Number of citations according to the Web of Science (WoS):
   without self-citations **– 135**

4. Hirsch index according to the Web of Science (WoS): **9**

5. Leadership or participation in Polish or international projects:

Among the projects listed below, only (a) was completed before obtaining my PhD degree. All other **projects (b-h) have been carried out after I received my PhD**.

(a) **investigator** in the project *"Control of quantum processes by external electromagnetic field"* sponsored by the Committee for Scientific Research for years 2000-2003; grant KBN 2 P03B 039 19.

(b) **investigator** in the project *"Control of quantum processes by electromagnetic field"* sponsored by the Committee for Scientific Research for years 2005-2008; grant no KBN 1 P03B 006 28.

(c) **investigator** in the project *"Recoil effects in pair creation and control of resonant transmission in a strong laser field"* sponsored by the Ministry of Science and Higher Education for years 2009-2011; grant no N N202 033337.

(d) participation in the ongoing project *"Physics - education for economics"* founded by the Operational Programme Human Capital, Faculty of Physics UW; **webpage administrator**.

(e) participation in the ongoing project of International PhD Studies at the Faculty of Physics UW sponsored by the Foundation for Polish Science. Within the project, I am a **co-supervisor** of the subject *"Engineering and Control of Quantum Processes by Attosecond Laser Pulses"*.

(f) **leader** of the ongoing project *"Laser-induced pair creation processes in quantum electrodynamics"* sponsored by the National Science Center; project conducted at the Faculty of Physics UW; grant no 2011/01/B/ST2/00381.

(g) participation in the ongoing project *"PhoQus@UW: Fostering Excellence in Photonics and Quantum Science"* sponsored by the EU 7th Framework Programme; a **co-leader of the workpackage** *"Networking through exchange of know-how and experience"* and a **member of the Recruitment Committee**; project conducted at the Faculty of Physics UW.

(h) **investigator** in the ongoing project *"Quantum processes in ultrashort laser pulses"* sponsored by the National Science Center; project conducted at the Faculty of Physics UW; grant no 2012/05/B/ST2/02547.

6. International collaboration:

a) University of Durham, Great Britain, Prof. Robert M. Potvliege group
b) University of Düseldorf, Germany (until recently, at Max Planck Institute in Heidelberg), Prof. Carsten Müller group
c) University of Colorado and JILA, Boulder, USA, Prof. Andreas Becker group
d) University of Nebraska-Lincoln, USA, Prof. Anthony F. Starace group

7. Scientific experience gained abroad:

a) USA, University of Nebraska-Lincoln:

– a couple of one-month scientific visits over the years 2003, 2009 - 2012

– Theodore P. Jorgensen Postdoctoral Fellowship (October 2005 - January 2007)

– six-month scientific visit in 2008

b) France, University of Rennes 1, one-month visit in 2009

c) Germany, Max Planck Institute in Heidelberg, one-month visit in 2011

8. Participation in international conferences:

a) **Participation in 25 international conferences and workshops** (for details, see, Appendix 6).

b) **Chairing the oral session** during *XX International Laser Physics Workshop*, Bosnia and Hercegovina, July 2011.

c) **26 conference presentations**, including 18 talks and 8 posters. Among them, **16 talks and 6 posters** I presented **after I received my PhD**. See, a complete list of my conference presentations in Appendix 6. Below, I list only oral presentation that I have given.

Oral presentations at conferences and workshops:

2003 *"Control of resonance states in crossed magnetic and laser fields"*
XII International Laser Physics Workshop, Hamburg, Germany

2003 "*Stabilization of resonance states in crossed magnetic and laser fields"*
Wildcorn Conference, Kansas State University, Manhattan, USA

2004 "*Stabilization of resonance states in crossed magnetic and laser fields in a parabolic quantum well"* XIII International Laser Physics Workshop, Trieste, Italy

2005 „*Autoionizing states in crossed magnetic and laser fields"*
XIV International Laser Physics Workshop, Kyoto, Japan

2005 "*Electron-positron pair creation by powerful laser-ion interaction"*
XIV International Laser Physics Workshop, Kyoto, Japan

2006 "*Electron-positron pair production by the impact of a high-power laser pulse on relativistic ions"*
37th Annual DAMOP Meeting, Knoxville, USA

2006 "*Resonant-like enhancement of the high-energy plateau in ATD"*
37th Annual DAMOP Meeting, Knoxville, USA

2006 "*Channel-closing-related enhancement of the high-energy plateau in above-threshold detachment"*
The 2006 Conference on Super Intense Laser Atom Physics, Salamanca, Spain

2006 "*Threshold-related effects in the high-energy plateau in above-threshold detachment"*
XV International Laser Physics Workshop, Lausanne, Switzerland

2006 *"Resonant-like plateau enhancements"*
KITP Attosecond Science Workshop, Santa Barbara, USA

2007 *"Angular correlations in pair creation"*
XVI International Laser Physics Workshop, Léon, Mexico

2009 "*Electron-positron pair creation - Relevance of recoil effects"*
Workshop on Super Intense Laser-Atom Physics, Zion National Park, USA

2010 *"Electron-positron pair creation and Oleinik resonances"*
XIX International Laser Physics Workshop, Foz do Iguaçu, Brazil

2011 *"Laser-induced electron-positron pair creation: from tunneling- to multiphoton regime"*
XX International Laser Physics Workshop, Sarajevo, Bosnia and Herzegovina

2012 *"Nonlinear Compton scattering in short laser pulses"*
43rd Annual DAMOP Meeting, Anaheim, USA

2012 *"Compton process in intense laser pulses – can we see the mass effects?"*
XXI International Laser Physics Workshop, Calgary, Canada

2012 *"Electron-positron pair creation in a bichromatic laser field"*
during *Symposium on Strong-Field Quantum Electrodynamics*, XXI International Laser Physics Workshop, Calgary, Canada

2012 *"Nonlinear Compton scattering in ultrashort laser pulses"*
XXXII European Conference on Laser Interaction with Matter, Warsaw, Poland

2. SCIENTIFIC CAREER

My research career has been divided into two stages: before and after I completed my PhD. Note that the research area that I worked on during my PhD was still in the focus of my scientific activities after I received my PhD degree. In general, I can distinguish four research areas that have been my focus for my entire scientific career:

I. Quantum processes in strong magnetic and electric (in general, time-dependent) fields

– area related to my PhD thesis, continued after completing my PhD

II. Multiphoton processes in strong laser fields

– area I worked on during my postdoctoral fellowship, continued after completing my postdoc

III. Fundamental processes of quantum electrodynamics in strong laser fields

– area I became attracted to after finishing my PhD, main focus of my current research interests

IV. Control of quantum processes by attosecond pulses

– area I became interested in more than a year ago, related to a PhD topic conducted within the program International PhD Studies at the Faculty of Physics UW

A. BEFORE COMPLETING PhD

In 1994, I started studying at the Faculty of Physics, University of Warsaw. After completing the first three years, I chose to specialize in theoretical physics under the supervision of Dr hab. Jerzy Kamiński from the Division of Field Theory and Statistical Physics, the Institute of Theoretical Physics. At that time, my research focus was on the description of a contact interaction (also called a zero-range interaction) and on its renormalization. The results I collected during this time, I put towards my Master thesis *"Zero-range potential: an example of renormalization in nonrelativistic quantum mechanics"* (in Polish). I was awarded the Joanna and Jerzy Glazers' Award for the Best Masters Thesis completed at the Faculty of Physics UW, in the academic year 1998/1999. I graduated with distinction in June 1999.

During my PhD studies (1999-2004) at the Faculty of Physics UW, I focused on applications of the zero-range potential, which is widely used to describe weakly bound systems in many branches of physics, including atomic and solid state physics. More specifically, I studied the quantum dynamics of an electron subject to the crossed, strong magnetic and electric fields, coupled with the interaction of a neutral atom; the latter was described by a zero-range potential. My work was supervised by Prof. Dr hab. Jerzy Kamiński from the Division of Quantum Optics and Atomic Physics.

As it followed from my studies devoted to two-dimensional systems, in the absence of an electric field, the contact interaction between an atom and electron partially removes the degeneracy of Landau levels, which characterize an electron's quantum dynamics in a static magnetic field; there appears an additional discrete energy spectrum between the Landau levels. Futhermore, when a static electric field is turned on, the new localized levels change into resonance states, whose lifetime decreases monotonically with increasing electric field strength. Here, the most important result was to discover that in the presence of the electric field new resonance states are also generated. In addition, it turns out that those electric-field-induced states undergo stabilization. Namely, for some particular combinations of electric and magnetic field strengths as well as for a particular choice of the coupling constant characterizing the zero-range potential, the lifetimes of those new resonance states show an unexpected dependence on the electric field; instead of decaying monotonically with increasing field strength, those states become stable. This effect together with a systematic analysis of electron resonance states was presented in [A1,A2]. In accordance with the hydrodynamic formulation of quantum mechanics, I was able to relate the observed stabilization to the vortex-like motion of the probability density fluid describing the electron quantum dynamics. I showed that this motion is controlled by the electric field, resulting in the stabilization of electric-field-induced states. This is the main topic of Ref. [A3]. Next, I generalized the aforementioned analysis by replacing the static electric field with a laser field. I considered the case when the laser field is circularly polarized. It turned out that if a field frequency equals the cyclotron frequency of the electron motion in a magnetic field, one can use the theoretical methods that were developed in [A1-A3]. This physical situation was the focus of Ref. [A4].

During my PhD, I was an investigator in the research grant *“Control of quantum processes by external electromagnetic field”* (grant no KBN 2 P03B 039 19) sponsored by the Committee for Scientific Research. In Fall 2003, I visited the Atomic, Molecular, and Optical group of Prof. Anthony Starace from the Department of Physics and Astronomy at the University of Nebraska-Lincoln, USA. This visit resulted in my follow-up postdoctoral fellowship with Profs. A. Starace and I. Fabrikant. Towards completing my PhD, I published four articles [A1-A4]. I also presented the results of my studies at international conferences and workshops in the form of oral (two talks) and poster (two posters) presentations. The material collected during that time was summarized in my PhD thesis entitled *”Control of resonance states with external electromagnetic fields”* (in Polish), which I defended in May 2004. I was awarded distinction for my PhD thesis by the UW Physics Faculty Board.

A1. **K. Krajewska**, J. Z. Kamiński, *“Stabilization of impurity states in crossed magnetic and electric fields”*, J. Math. Phys. **43**, 3937 (2002)

A2. **K. Krajewska**, J. Z. Kamiński, *“Generation and control of resonance states in crossed magnetic and electric fields”*, Phys. Lett. A **301**, 369 (2002)

A3. **K. Krajewska**, J. Z. Kamiński, *“Vortices and stabilization of resonance states in crossed magnetic and electric fields”*, Phys. Rev. B **68**, 064418 (2003)

A4. **K. Krajewska**, J. Z. Kamiński, *“Control of resonance states in crossed magnetic and laser fields”*, Laser Phys. **14**, 194 (2004)

B. AFTER COMPLETING PhD

After receiving my PhD degree, I was hired in the Institute of Theoretical Physics, Faculty of Physics UW (the Chair of Quantum Optics and Atomic Physics) as an assistant professor ("adjunct"). My duties relate to both conducting research and teaching students at the Faculty of Physics UW. As I mentioned in the Introduction, my research interests have centered around four different topics, which I will describe in turn.

I. Quantum processes in strong magnetic and electric (in general, time-dependent) fields

When already working towards my PhD degree, I started a collaboration with Prof. Robert M. Potvliege from the Durham University, Great Britain. We joined our efforts to generalize the theoretical two-dimensional model I worked on, an electron interacting with a parent atom in the presence of crossed magnetic and electric fields, to three dimensions. In order to make our model as realistic as possible, in particular resembling a typical situation met in solid state physics, we have incorporated into our model a quantum well along the magnetic field vector. Similar to the two-dimensional case [A1-A4], we have used the Green's function method in order to analyze properties of electronic resonance states. A special emphasis was placed on control of those properties by external fields. The first results proving the existence of resonance states undergoing stabilization, similar to the two-dimensional case, were presented at the conference LPHYS'04. They were also published in Ref. [B1]. In addition, we discovered that long-lived electric-field-induced resonances may occur for systems that do not have any field-free bound states: While the potential does not support any bound state or resonances in the absence of the fields, and no bound state or resonances exist in the presence of the two fields if there is no potential, the combination of the three generates long-lived resonances [B2]. Our work was supported by the Committee for Scientific Research, within the project entitled *"Control of quantum processes by electromagnetic field"* (grant no KBN 1 P03B 006 28).

Another situation that I have studied in the context of quantum control by means of a strong electromagnetic field concerned an electron interacting with a neutral atom placed in an external magnetic field. Due to the coupling of discrete Landau levels with the continuum of states, we observed the appearance of autoionizing states. Next, by switching on the perpendicular electric field, we showed that the autoionizing states exhibit a typical stabilizing dependence of their decaying rates on the electric field strength. To my knowledge, a similar effect has never been observed before for autoionizing states. The related results have been published in [B3] and presented during the conferences LPHYS'05 (talk) and DAMOP 2006 (poster).

In all of the aforementioned works [B1-B3], a zero-range interaction model has been used. It is one of very few exactly solvable models in quantum mechanics, and thus it is widely used in various branches of physics. As it is known, the theory based on zero-range potentials requires renormalization. There exist various formulations in the literature treating the contact interaction. In [B4], we presented the alternative description of a zero-range interaction in terms of separable potentials. The advantage of our method is that it allows for a systematic analysis of physical problems in an arbitrary number of dimensions, which has been demonstrated for ionization by a static electric field.

B1. **K. Krajewska**, J. Z. Kamiński, R. M. Potvliege, *"Stabilization of resonances in crossed magnetic and laser fields in a parabolic quantum well"*, Laser Phys. **15**, 238 (2005)

B2. **K. Krajewska**, J. Z. Kamiński, R. M. Potvliege, *"Long-lived resonances supported by a contact interaction in crossed magnetic and electric fields"*, Ann. Phys. (NY) **323**, 2639 (2008)

B3. **K. Krajewska**, J. Z. Kamiński, *"Autoionizing states in crossed magnetic and laser fields"*, Laser Phys. **15**, 1700 (2005)

B4. **K. Krajewska**, J. Z. Kamiński, K. Wódkiewicz, *"Zero-range interaction in arbitrary dimensions and in the presence of external forces"*, Opt. Commun. **283**, 843 (2010)

II. Multiphoton processes in strong laser fields

High harmonic generation (HHG) is a fundamental process which enables the synthesis of coherent, ultra-short pulses of electromagnetic radiation. There is a technological problem which has been struggled with for years, namely, how to enhance the intensity of the irradiated electromagnetic field. In order to control the process of HHG it is necessary to fully understand the mechanisms responsible for it – in particular, to understand multiphoton ionization and electron recombination. In my work, together with Profs. Anthony Starace and Ilya Fabrikant from the University of Nebraska-Lincoln, USA, we study the former, i.e., multiphoton ionization of atomic species. The purpose of our research is to comprehend the origin of the resonant-like enhancements of plateau electrons that was observed experimentally in the above-threshold ionization (ATI) of nobel gases, as it leads directly to the enhancement of the HHG signal. This effect, which is very important in the context of further technological progress, was investigated in Refs. [C1-C4]. The first results concerned model potentials which do not have a Coulomb tail, therefore they are appropriate for the description of the above-threshold detachment (ATD) process from negative ions.

In October 2005, I started my one and a half year appointment at the University of Nebraska-Lincoln, USA, as a *Postdoctoral Theodore P. Jorgensen Fellow*. My research focused on treatments for an ultra-strong laser field interaction with negative ions, leading to their detachment; in particular, I studied the above-threshold detachment of hydrogen (H^-) and fluorine (F^-) negative ions, which can be described within the single-active-electron approximation by a short-range potential. We analyzed the dependence of detachment rates of both ions on the laser field intensity. We discovered pronounced enhancements of the ATD rates (up to an order of magnitude) as the laser-field intensity passes across ponderomotive-potential-induced channel closings. Because the ponderomotive potential raises the continuum threshold, the minimum number of photons necessary to detach an electron from a negative ion, n, increases with increasing laser intensity, or, in other words, the n-photon channel for detachment can become closed as the laser intensity increases. Near the intensity for which this happens, a group of ATD peaks within the rescattering plateau is raised significantly. Therefore, by controlling parameters of a driving laser field it is possible to dramatically increase the efficiency of the process. In this context, the importance of the initial-state symmetry of the active electron has also been shown. Depending on the s (H^-) or p (F^-) symmetry, very pronounced enhancements of the ATD plateau spectra have been found for intensities in the vicinity of even- or odd-photon detachment channel closings, respectively. Our results were in agreement with the Wigner threshold law describing near-threshold behavior of partial (i.e., concerning a fixed number of laser photons) detachment rates. Those results have been published in [C1]. A more detailed analysis of the dependence of partial detachment rates on the laser field intensity as well as the results concerning the total detachment rates for both ions (H^- and F^-) have been presented in Ref. [C2].

In the context of threshold effects, we also analyzed the detached electron angular distributions (ADs). Initially, we focused on few photon angular distributions and their variation with laser intensity near detachment thresholds [C1,C2]. Dramatic changes in the shapes of those ADs in the vicinity of the channel closings confirmed a strong sensitivity to the initial-state symmetry of the active electron. A systematic analysis of threshold-related effects of angular distributions, primarily for electrons from the ATD plateau region, was conducted in [C3]. By investigating angular distributions of photoelectrons close to multiphoton thresholds, we showed that the enhancement occurs in a narrow angular interval that is far from the linear polarization axis at electron energies near the onset of the plateau and moves toward the polarization axis with increasing electron energy. Although enhancements in detached electron energy distributions have not been observed for energies near the cutoff of the ATD plateau, we showed that the corresponding electron angular distributions change shape dramatically as a function of intensity near the closing of ponderomotively-shifted detachment thresholds. Therefore, the threshold-related effects extend over a wider range of energies on the ATD plateau than heretofore expected.

In light of those results, the question arises: Can similar conclusions be drawn in the case of above-threshold ionization (ATI) of neutral atoms? In this case, one must account for the role of the attractive Coulomb potential, including specifically the Rydberg series converging to each multiphoton ionization threshold (note that this is in contrast to weakly bound negative ions where an electron-atom interaction is short-ranged). Generalization of previous studies [C1-C3] to account for a Coulomb potential in the final electronic state has been presented in Ref. [C4].

In Ref. [C4], the behavior of strong-field ionization rates of neutral atoms in the vicinity of multiphoton ionization thresholds has been studied, with an emphasis on the role played by the intense laser field. It was demonstrated that this behavior is determined by the coupling of the laser field with the Rydberg states which have high, moderate, and low orbital angular momenta. In particular, the coupling to those Rydberg levels which have high orbital angular momenta led to the flat dependence of ionization rates on the laser intensity. This nonoscillatory behavior above the threshold (going in the direction of increasing laser intensity) is consistent with the idea of an effectively lowered ionization continuum, which has been anticipated in various theoretical papers although never given a detailed analytical explanation. Another threshold-related effect is the occurrence of multiphoton resonances with Rydberg levels possessing moderate orbital angular momenta, which lead to pronounced enhancements of ionization rates. These structures exhibit a clear dependence on the parity of the active electron which has been illustrated for hydrogen (*s* electron) and neon (*p* electron) atoms.

Based on the aforementioned results, I gave talks during the international conferences DAMOP 2006, SILAP 2006, LPHYS'06, and Attosecond Science Workshop, and I presented posters at ICPEAC 2007, LPHYS'07, and ICOMP XI. Some of these presentations along with publications [C1-C3] were sponsored by the grant of the Committee for Scientific Research entitled *"Control of quantum processes by electromagnetic field"* (grant no KBN 1 P03B 006 28).

C1. **K. Krajewska**, I. I. Fabrikant, A. F. Starace, *"Threshold effects in strong field detachment of H^- and F^-: Plateau enhancements and angular distribution variations"*, Phys. Rev. A **74**, 053407 (2006)

C2. **K. Krajewska**, I. I. Fabrikant, A. F. Starace, *"Threshold-related effects in the high-energy plateau in above-threshold detachment"*, Laser Phys. **17**, 368 (2007)

C3. **K. Krajewska**, I. I. Fabrikant, A. F. Starace, *"Threshold effects on plateau electron angular distributions in above-threshold detachment"*, Phys. Rev. A **78**, 023407 (2008)

C4. **K. Krajewska**, I. I. Fabrikant, A. F. Starace, *"Threshold effects in strong-field ionization: Energy shift and Rydberg behaviors"*, Phys. Rev. A **86**, 053410 (2012)

III. Fundamental processes of quantum electrodynamics in strong laser fields

Recent progress in laser technology has led to the development of laser field sources reaching unprecedented intensities; currently, the capability exists to produce laser fields with the electric field component stronger than the Coulomb field that bounds electrons in atoms and molecules. At the same time, it has been possible to shorten the time duration of laser pulses and so the femtosecond, or even attosecond, lasers became standard tools in laboratories worldwide. In light of continued technological progress, investigation of laser-matter interactions in a regime of strong-field quantum electrodynamics (QED) start to play a major role.

Electron-positron pair creation is one of the most fundamental QED processes. Initially, my investigations were devoted to multiphoton electron-positron pair creation in collisions of an atomic nucleus with an ultra-strong laser field. The laser field was treated as a monochromatic plane wave while the colliding nucleus was treated as an infinitely heavy particle (i.e., the nuclear recoil was neglected). The corresponding results were published in a series of papers [D1-D4], and later on also summarized in a review article [D5]. I gave talks at the conferences LPHYS'05, DAMOP 2006, and LPHYS'07 presenting these results. Our research was funded by the Committee for Scientific Research within the project entitled *"Control of quantum processes by electromagnetic field"* (grant no KBN 1 P03B 006 28).

The first papers on laser-induced pair creation [D1,D2] concerned the probability rates of the process for a fixed configuration of produced particles, along with their spin correlations. Next, we investigated angular correlations in electron-positron pair creation [D3]. Moreover, in Ref. [D3] we presented the dependence of total probability rates of pair creation on laser intensity. We noted that the total rates show stabilization features with increasing field intensity. Calculations of angular distributions of created particles performed in [D4] showed that the pairs are mainly created in the plane spanned by the polarization vector of the laser field and by its propagation direction. Angular correlations of the emitted particles showed that the electrons and positrons are anticorrelated (i.e., they are emitted in the opposite direction), and that this tendency has little dependency on the driving field intensity. These preliminary studies have shown that the electron-positron pair creation by a strong-laser-beam–heavy-particle impact process, even though still quite inefficient, is by far more efficient than pair creation from a vacuum by a static electric field [D1]. This has pushed our interest towards laser-induced pair creation scenarios.

In all of these works [D1-D5], the colliding laser beam was described as a monochromatic plane wave. In recent years, I try to go beyond this approximation. In particular, I study nonlinear Compton scattering in short laser pulses [D6,D7]. Note that Compton scattering of a laser beam with relativistic electrons has become an efficient source of highly polarized, nearly monoenergetic and tunable X-ray and γ-ray photons. These Compton photon beams have various industrial, medical, and scientific applications. Therefore it is of great importance to theoretically predict spectral and spatial distributions of Compton photon beams, and to control their properties using the incident beam parameters. So far, we have studied the sensitivity of energy and angular spectra of Compton radiation to the incident pulse duration [D6]. We compared the resulting spectra to those which are obtained when the driving field is described as a modulated plane wave. We found very good agreement between the results for long pulse durations which broke down, however, for ultra-short laser pulses. The dependence of angular distributions of emitted radiation on a pulse duration was also investigated. Pronounced asymmetries of angular distributions were found for very short pulses, which gradually disappeared with increasing the driving pulse duration. Regarding these results, I gave talks at the conferences DAMOP 2012, LPHYS'12, and ECLIM 2012. In the follow-up article [D7], nonlinear Compton scattering by a linearly polarized laser pulse of finite duration was analyzed, with a focus on spin effects. Our work in this area is supported by the National Science Center under the grant *"Quantum processes in ultrashort laser pulses"* (grant no 2012/05/B/ST2/02547).

D1. P. Sieczka, **K. Krajewska**, P. Panek, J. Z. Kamiński, F. Ehlotzky, *"Electron-positron pair creation by powerful laser-ion impact"*, Phys. Rev. A **73**, 053409 (2006)

D2. **K. Krajewska**, J. Z. Kamiński, F. Ehlotzky, *"Electron-positron pair creation by powerful laser-ion interaction"*, Laser Phys. **16**, 272 (2006)

D3. J. Z. Kamiński, **K. Krajewska**, F. Ehlotzky, *"Monte-Carlo analysis of electron-positron pair creation by powerful laser-ion impact"*, Phys. Rev. A **74**, 033402 (2006)

D4. **K. Krajewska**, J. Z. Kamiński, *"Angular correlations in pair creation"*, Laser Phys. **18**, 185 (2008)

D5. F. Ehlotzky, **K. Krajewska**, J. Z. Kamiński, *"Fundamental processes of quantum electrodynamics in laser fields of relativistic power"*, Rep. Prog. Phys. **72**, 046401 (2009)

D6. **K. Krajewska**, J. Z. Kamiński, *"Compton process in intense short laser pulses"*, Phys. Rev. A **85**, 062102 (2012)

D7. **K. Krajewska**, J. Z. Kamiński, *"Spin effects in nonlinear Compton scattering in ultrashort linearly-polarized laser pulses"*, Laser Part. Beams (in press) (2013)

IV. Control of quantum processes by attosecond pulses

Current technology enables the generation of ultra-short and ultra-intense laser pulses that permit investigations of laser-matter interactions in the attosecond domain. The capability exists to produce single attosecond pulses or attosecond pulse trains. Such pulses allow the study of multi-electron dynamics in atoms, molecules, or nanostructures. A major role for theory in this field, also my area of focus, is to clarify new ways to study and to control quantum processes which occur on an attosecond scale.

Since June 2011, I have been a co-supervisor of Felipe Cajiao-Veléz, a PhD student at the Faculty of Physics UW. Mr. Cajiao-Veléz has been recruited by the EU program "International PhD studies In Nano and Bio Science at the Faculty of Physics University of Warsaw" (now, "International PhD studies at the Faculty of Physics University of Warsaw") sponsored by the Foundation for Polish Science within the European Regional Development Fund. His research concerns *"Engineering and Control of Quantum Processes by Attosecond Laser Pulses"* and is primarily centered around two problems: quantum control of transport in nanostructures along with quantum control of ionization and high harmonic generation by attosecond pulses. The former topic is performed under the supervision of Prof. Dr hab. Jerzy Kamiński. Under my supervision, Mr. Cajiao-Veléz has been developing methods related to generalized eikonal approximation, which will be used in the context of ionization and high harmonic generation. Even though the work is still in progress we expect to publish the first results in the near future. Some results concerning ionization were already presented as a poster during the conference LPHYS'12. Note that our work is supported by the National Science Center within the project *"Quantum processes in ultrashort laser pulses"* (grant no 2012/05/B/ST2/02547). Let me also add that this project is carried out in collaboration with the group of Prof. Andreas Becker from the University of Colorado and JILA, USA. For this reason, Mr. Cajiao-Veléz spent six months at JILA, where he has been working on HHG.

3. A MONOGRAPHIC SERIES OF PUBLICATIONS

A. On which grounds the habilitation procedure has been started?

A basis of the habilitation procedure is a monographic series of six publications entitled ***"Electron-positron pair creation in strong laser fields"***, being a scientific achievement according to the Act of 14th March 2003 on the Academic Degrees and the Academic Title as well as on the Degrees and the Title within the Scope of Art, article 16th. All publications contained in the series have been published in journals from the Journal Citation Reports database.

B. List of publications contained in the series:

The series consists of six publications. Their written text can be found in Appendix 7. Here, I list them in chronological order:

E1. **K. Krajewska**, J. Z. Kamiński, *”Recoil effects in multiphoton electron-positron pair creation”* Phys. Rev. A **82**, 013420 (2010)

E2. **K. Krajewska,** *“Electron-positron pair creation and Oleinik resonances”* Laser Phys. **21**, 1275 (2011)

E3. **K. Krajewska**, J. Z. Kamiński, “*Correlations in laser-induced electron-positron pair creation”* Phys. Rev. A **84**, 033416 (2011)

E4. **K. Krajewska**, J. Z. Kamiński, *“Phase effects in laser-induced electron-positron pair creation”* Phys. Rev. A **85**, 043404 (2012)

E5. **K. Krajewska**, J. Z. Kamiński, *“Symmetries in the nonlinear Bethe-Heitler process”* Phys. Rev. A **86**, 021402(R) (2012)

E6. **K. Krajewska**, J. Z. Kamiński, *“Breit-Wheeler process in intense short laser pulses”* Phys. Rev. A **86**, 052104 (2012)

C. Overview of the contribution to the development of the field:

Due to recent advances in laser technology, ultra-high intense laser pulses of short durations are routinely produced in contemporary laboratories. The technological progress resulted in the development of petawatt lasers that deliver laser radiation in the near-visible spectrum with intensities as high as 10^{22} W/cm^2 [1,2]. On the other hand, the synthesis of pulses which contain only a few optical cycles and last in the femtosecond (or, even attosecond) time-domain is currently feasible. It is worth noting that the European Union, with its large-scale projects like ELI (Extreme Light Infrastructure) [3], HiPER (High Power laser Energy Research facility) [4], and FLASH (Free-electron LASer in Hamburg) [5], is on the cutting edge of laser physics. The aim of these projects is to produce such laser fields which will revolutionize the area of laser-matter interaction. It is believed that these laser fields will make it possible to verify the fundamental processes of quantum electrodynamics (QED); in particular, the formation of electron-positron (e^-e^+) pairs by means of laser radiation.

Theoretical studies of laser-induced electron-positron pair creation processes is the topic of the presented series of publications. Its purpose is to explore quantum vacuum, which is one of the most important issues of fundamental physics today. Of a strictly practical importance, is to analyze suitable conditions for increasing the efficiency of e^-e^+ pair creation processes. To this end, the energy and the angular distributions of produced particles will be analyzed. The series centers around two problems: (a) *recoil effects* in electron-positron pair creation via collisions of a strong laser beam with a beam of relativistic nuclei (for instance, protons) [E1-E3], and (b) *control* of the e^-e^+ pair creation processes by a driving laser field [E4-E6]. Our analysis is particularly important in view of upcoming experiments which are fundamental for verifying the predictions of quantum electrodynamics (see, for instance, the previously mentioned ELI, HiPER, and FLASH projects [3-5]). In further perspective, it can also stimulate the development of a very efficient source of highly-polarized positrons, which have broad applications in solid state and material sciences.

(a) Recoil effects in laser-induced electron-positron pair creation processes

Nonlinear Bethe-Heitler process in which electron-positron pairs are created in collisions of a super-intense laser beam with a beam of relativistic targets is one of the most commonly studied mechanisms of pair creation [6-21] in the literature. In this context, it is worth mentioning that for a head-on collision of the two, in the rest frame of the projectile, the laser field intensity is enhanced by $4\gamma^2$, where $\gamma \gg 1$ is the relativistic Lorentz factor. This suggests that for currently available laser sources and ultra-relativistic targets, the Bethe-Heitler scenario of pair creation can be realized experimentally. From the theoretical point of view, it is worth noting that the Compton wavelength of electrons is much bigger than typical linear sizes of atomic nuclei. For this reason, one can treat the colliding nuclei as point-like particles. As was argued in Refs. [22,23], the same approach cannot be used when the same process leading to production of muon-antimuon pairs is considered.

In the vast majority of theoretical studies devoted to this process, the approximation treating the projectile as an infinitely-heavy particle was used [6-15,17-21]. In this case, the projectile recoil during the emission of an e^-e^+ pair is neglected. We also used this approximation (known as the potential approximation) in our previous works [9-12]. During that time we raised the question whether the potential approximation – although widely used – is physically justified for contemporary available laser fields, for which the ponderomotive energy of electrons driven by such a radiation can be significantly larger than the electron rest mass. This problem has been addressed independently by ourselves [E1-E3] and by the group from the Max Planck Institute in Heidelberg, Germany [16]. Note that a very broad overview of literature regarding this topic can be found in our review article [23] and in a recent review article by the Heidelberg group [24].

In Ref. [16], recoil effects in nonlinear Bethe-Heitler process were investigated for the case when a driving laser field is a circularly polarized monochromatic plane wave. The authors considered the situation when the field intensity is relatively low while its frequency is relatively large. Under such conditions, a relativistically invariant parameter μ that distinguishes between different regimes of laser-induced pair creation [26], satisfies the condition $\mu \ll 1$. In other words, the results presented in Ref. [16] were related to a perturbative regime of pair creation [26]. For this case, no pronounced recoil effects were observed.

Our work in this area was sponsored by the Ministry of Science and Higher Education within the research project *“Recoil effects in pair creation and control of resonant transmission in a strong laser field”* (grant no N N202 033337), which was granted to us for years 2009-2011. Also, I presented the results collected in publications [E1-E3] at international conferences as talks (SILAP 2009, LPHYS'10, and LPHYS'11) and as a poster (Gordon Research Conference).

E1. **K. Krajewska**, J. Z. Kamiński, *”Recoil effects in multiphoton electron-positron pair creation”* Phys. Rev. A **82**, 013420 (2010)

We investigated the e^-e^+ pair creation process via laser-beam–target-particle collisions, with an account for the finite mass of the colliding particles. Our purpose was to investigate the role of recoil effects on properties of the Bethe-Heitler process. Despite the results published in [16], we had serious doubts about the validity of the potential approximation with respect to the target particles for then record laser field intensities [1,2].

In Ref. [E1], we introduced a *S*-matrix formulation of nonlinear Bethe-Heitler pair production process for the case when a driving laser field can be treated as a monochromatic plane wave. The theory was based on a two-vortex Feynman diagram which accounts for the momentum transfer from the colliding target during its collision with the laser beam. We concentrated on the nonperturbative regime of laser-induced pair creation [26]. Even though we presented the results for neon nuclei, comparable results were also obtained for lead (and independently for proton) projectiles. Both the differential and total probability rates of pair creation were calculated. The results related to the reference frame in which the projectile is at rest long before the collision.

In one of our papers, where the nuclear recoil was disregarded [10], we demonstrated that even for ultra-strong electromagnetic radiation the efficiency of e^-e^+ pair production is still rather low. In light of this result, we performed a systematic analysis of the process taking into account the nuclear recoil. Pronounced enhancements of differential probability rates of multiphoton pair production were recognized for a nonzero momentum transfer from the colliding nucleus. Those enhancements were observed for laser beam parameters such that $\mu \gg 1$. Moreover, the differential rates showed a very dramatic dependence on the polarization of the laser field impinging on the nucleus; only for linearly polarized light were the multiphoton rates for e^-e^+ pair production considerably large. For this reason, in Ref. [E1] we focused on the case of a linearly polarized driving field.

Also in Ref. [E1], we investigated the dependence of angular distributions of product particles on a spatial configuration of the final nucleus. Our numerical results demonstrated that, for the linearly polarized laser field of an infinite extent, the pair creation is far more efficient if the nucleus is detected in the direction of the laser-field propagation (in the chosen reference frame). The angular distributions of created particles showed that while the high-energy pairs are predominantly produced in the plane spanned by the polarization vector and the laser-field propagation direction, the low-energy pairs are spread around the latter of the two directions.

Since differential probability rates of pair creation turned out to be rapidly oscillating functions of the nuclear recoil, estimating the corresponding total probability rate was possible only by exploiting the Monte Carlo method. In Ref. [E1], we presented the Monte Carlo estimates of the total probability rates of pair creation for different values of the parameter μ in the nonperturbative regime. We observed a tremendous enhancement (up to few orders of magnitude) of those rates when, in the considered intensity regime ($\mu \gg 1$), a more accurate approach with an exact account for the nuclear recoil is applied. This is particularly important in view of future experiments.

Other aspects of laser-induced electron-positron pair creation processes were further analyzed in the paper [E2].

E2. **K. Krajewska**, *“Electron-positron pair creation and Oleinik resonances”*
Laser Phys. **21**, 1275 (2011)

The paper centers around the e^-e^+ pair creation induced by a linearly polarized laser beam, which is modeled as a monochromatic plane wave, in the nonperturbative regime. In the paper, I analyzed the effect of dressing of the colliding particle by the laser field. To this end, I compared numerical results of differential probability rates for two cases: when the nucleus does not exchange photons with the laser field, and when it does exchange them. I concluded that for neon or heavier nuclei, it is justified to disregard the laser field dressing in the considered regime, i.e., when $\mu \gg 1$. This follows from the fact that for a nucleus with atomic number Z, the energy correction that originates from the dressing by the laser field, $(Z\mu m_e c^2)^2/2$, is negligibly small in comparison with the nucleus rest-mass energy squared, $(Mc^2)^2$, (here, m_e is the rest mass of the electron while M is the rest mass of the nucleus). It followed from my analysis that even for lighter targets such as protons, one can also neglect the laser-field dressing, if the condition holds: $(Z\mu m_e c^2)^2/2 \ll (Mc^2)^2$. In the remainder of the paper, I used this fact when analyzing resonances in the laser-induced pair creation. Note that the appearance of resonances in a laser field is one of the most fundamental effects of strong-field QED [27,28].

Analysis of resonances in nonlinear Bethe-Heitler process of pair creation was another important aspect of Ref. [E2]. Numerical illustrations were shown for the case when a relativistic proton collides with a linearly polarized laser field such that μ=1, which still relates to the nonperturbative regime of strong-field pair creation [26]. Numerical calculations showed the existence of very narrow resonances in differential probability rates of pair production. These resonances were observed when the momentum transfer from the colliding proton was a multiple of $2m_ec$. The numerical results were in agreement with the analysis of poles in the photon propagator, that was performed in Ref. [E2]. Therefore these resonances were recognized to be Oleinik resonances [29,30] which, in general, originate from the poles of the photon propagator. To my knowledge, these are the only published numerical results related to resonant pair creation via Bethe-Heitler scenario taking into account the projectile recoil.

In Ref. [E2], the very first results on Bethe-Heitler pair creation processes in the nonperturbative regime such that μ~1 were published. This has been further pursued in the following work [E3].

E3. **K. Krajewska**, J. Z. Kamiński, *"Correlations in laser-induced electron-positron pair creation"* Phys. Rev. A **84**, 033416 (2011)

The work was devoted to the nonlinear Bethe-Heitler process of pair creation, in which electron-positron pairs are created in a collision of a linearly polarized laser beam, such that μ~1, with a relativistic proton. The paper was based on the *S*-matrix formalism which we introduced in [E1,E2]. A new aspect of the theoretical treatment was to define the coarse-grained probability distributions of pair creation, which in turn allowed us to study the correlations characterizing the process.

In Ref. [E3], the coarse-grained differential probability rates of pair creation were compared for two cases: when the recoil of the colliding proton is taken into account and when it is disregarded. In the latter case, the potential approximation regarding the proton was used. It was shown that the momentum transfer from the projectile leads to the emission of more energetic pairs. Also, some signatures which are typical for other above-threshold processes, such as ionization, were observed. For this reason, the considered regime of laser-induced pair creation (μ~1) is typically called the above-threshold regime. The coarse-grained distributions showed that the e^-e^+ pair production occurs for a non-zero momentum transfer from the colliding proton, and the process is most effective when the transfer varies between m_ec and $2m_ec$. The same stays true in the perturbative regime, which was illustrated for μ=0.01. While for μ=0.01 the lowest-order multiphoton process dominates, for a much stronger field (μ=1) the higher-order multiphoton processes become dominant. As a consequence, a more efficient pair production is observed for stronger fields. In addition, the exact treatment of the proton leads to a rather marginal enhancement of the partial rates of pair creation in the perturbative case. On the other hand, with increasing the laser field intensity a more pronounced enhancement is observed. The same concerns the total probability rates. Those were calculated in Ref. [E3] in the range of laser field intensities spanning across the perturbative and the above-threshold regimes of pair creation. Once again, it was shown that the stronger the laser field, the more pronounced recoil effects are.

Except for an analysis of recoil effects, Refs. [E1-E3] showed that the driving field plays a crucial role in electron-positron pair creation processes; in particular, the importance of the field strength [E1-E3] and its polarization [E1] were demonstrated. Following this direction, my main interest became to analyze the effect of the laser field on the laser-stimulated e^-e^+ pair creation. This is also the main focus of proceeding works [E4-E6].

(b) Control of electron-positron pair creation processes by a laser field

In theoretical investigations on laser-induced electron-positron pair creation processes, it is traditionally assumed that the laser field can be described as a monochromatic plane wave. In Refs. [E4-E6] we went beyond this approximation, investigating a bichromatic plane wave, a modulated plane wave, and a finite laser pulse cases. The necessity exists to provide as realistic description of laser-field-involved processes as possible. This has been stimulated by continued technological progress and the experimental availability of intense, ultra-short laser pulses with precisely controlled properties. Various quantum processes, which are either induced or modified by such laser fields, are currently studied in laboratories worldwide. Special efforts are put towards quantum control of these processes which is usually done by exploiting various phases of the laser field. In this context, relative phases of the multicolor field or the carrier-envelope phase in the case of a laser pulse are used (see, for instance, in Refs. [31,32]). It was demonstrated that with the help of such phases, one can control photoionization of atoms or molecules, high harmonic generation, or photoemission from solids. However, there was very little effort made regarding phase effects in strong-field QED processes.

At that time, the only publications discussing the dependence of pair creation on the phase of a driving laser field related to the case when electron-positron pairs are created in collisions of a laser beam and a nonlaser photon [33-36]; the process known as the nonlinear Breit-Wheeler process. More specifically, the above-mentioned papers treated the case of a bichromatic plane wave field which permitted the studies of relative phase effects. In Refs. [33-36], the situation was considered when both field components are circularly polarized. Excluding theoretical treatment, only in Ref. [36] were the numerical results presented. Those results were obtained for the case when one of the field components is dominant. The calculated differential probability rates of pair creation showed a dramatic dependence on relative phase. On the other hand, it was argued in [35] that the total probability rates do not depend on relative phase.

At this point, let me make a comment. The Dirac theory of electron led Sauter and Schwinger to their prediction of electron-positron pair production from a vacuum in the presence of a static electric field [37,38]. The electric field, which is not accessible in the laboratory, $E_{cr} = 1.3\text{x}10^{16}$ V/cm (known as the critical Sauter-Schwinger field), is required to reveal this nonlinear process; a similar conclusion was drawn subsequently for an alternating electric field [39,40]. With the availability of very powerful laser sources such as near-visible lasers working presently at intensities of 10^{22} W/cm^2 [1,2], or even more powerful lasers built within the ELI, HiPER, and FLASH projects [3-5], the laser-induced pair creation from a vacuum is becoming feasible in the laboratory. In fact, there has been one experiment performed in the mid 1990s at the Stanford Linear Accelerator Center (SLAC), where laser-induced electron-positron pair creation was observed [41,42]. This famous E-144 experiment is the only experiment so far that confirms the predictions of nonlinear quantum electrodynamics. In this experiment, the laser field was involved only indirectly, as it was backscattered by a relativistic electron beam to produce γ-rays, which finally collided with the incoming laser beam to produce electrons and positrons. As one can see, the second step was realized via the Breit-Wheeler scenario. At this point, let us note that this two-step process was highly suppressed as the generation of γ-photons was not very efficient. Therefore it is believed that a more efficient scheme of producing electron-positron pairs lies in the direct collisions of highly relativistic particles with an intense laser pulse, i.e., the nonlinear Bethe-Heitler process.

The purpose of this series of publications is to better understand the role of the laser field in laser-stimulated pair creation processes. This has been done through theory and modeling, giving a strong background for further applications. Our investigations in this area are supported by the National Science Center within the research project *"Laser-induced pair creation processes in quantum electrodynamics"* (grant no 2011/01/B/ST2/00381), which has been granted for years 2011-2014. The results, which will be discussed next, thus far have been presented as a poster (DAMOP'12) and as an invited talk during *Symposium on Strong-Field Quantum Electrodynamics* (LPHYS'12).

E4. **K. Krajewska**, J. Z. Kamiński, *"Phase effects in laser-induced electron-positron pair creation"* Phys. Rev. A **85**, 043404 (2012)

Based on the *S*-matrix formalism, I further developed the theory of the nonlinear Bethe-Heitler process of electron-positron pair creation by a bichromatic plane wave field. I considered the most general case when each component of the field has an arbitrary polarization and strength, as well as when both components are shifted in phase. In Ref. [E4], the finite mass of the colliding target was accounted for, similar to the previous works dealing with pair creation by a monochromatic laser field [E1-E3].

Preliminary calculations showed that, when it comes to recoil effects, the features of the process under considerations fully agree with the features discussed in [E1-E3]. Keeping this in mind, in Ref. [E4] we presented the results for a collision of a relativistic proton with a bichromatic laser field, such that both field components are linearly polarized and both are equally strong (reaching the nonperturbative regime of pair creation, with $\mu\sim1$). In the case when the projectile acquires momentum along the direction of the field propagation, we showed angular maps of partial differential probability rates of emitted electrons. This concerns the rest frame of reference for the initial proton. A very strong dependence of those maps on the phase shift between both field components was observed. In contrast, the total rates of pair creation did not exhibit such a dependence. Therefore one can conclude that the overall control of laser-induced pair creation processes is not possible by means of relative phases.

Another possibility of phase control exists, which is using the carrier-envelope phase (CEP). The CEP can be defined for a single laser pulse or for a modulated plane wave. As we showed in [E4], for a particular choice of the modulated plane wave [namely, when in addition to the carrier wave, $\sin(k\cdot x+\chi)$, there is also the envelope $\sin^4(k\cdot x)$], it is possible to use the bichromatic plane wave field approximation. For this reason, the treatment developed in Ref. [E4] allowed us to study the CEP effects in the Bethe-Heitler process of pair creation. (For completeness, let us remind that the CEP is a phase shift of the carrier wave with respect to the envelope, χ.) We realized in Ref. [E4] that an additional condition has to be imposed when comparing the pair creation signal while induced by different laser fields, for instance, by fields with different CEPs. In article [E4], we considered two variations of this condition; either we kept the ponderomotive energy of the free particle's oscillations in a two-color field or the mean intensity carried by a two-color field fixed, irrespectively of the CEP. Next, for each of these cases, we investigated how the total probability rates of pair creation depend on the carrier-envelope phase. For the considered modulation of the laser wave, the most pronounced CEP effects were observed when we do the scaling with respect to the ponderomotive energy. The calculations were performed for different values of μ (i.e., different peak intensities of the field), starting from the perturbative regime of pair creation ($\mu\ll1$) up to the nonperturbative regime ($\mu\sim1$). Even though the respective results for different values of μ did not differ qualitatively we did observe an enormous quantitative difference; namely, a pronounced enhancement of the total rates of pair creation (by a few orders of magnitude) was observed when increasing the parameter μ.

To my knowledge, the article [E4] is the only one in the literature where phase effects in the nonlinear pair creation via Bethe-Heitler process, with an account for nuclear recoil, were investigated. In another paper from the series [E5], further consequences of the laser field on properties of e^-e^+ pair creation were also analyzed.

E5. **K. Krajewska**, J. Z. Kamiński, *"Symmetries in the nonlinear Bethe-Heitler process"* Phys. Rev. A **86**, 021402(R) (2012)

The work focused on electron-positron pair creation in collisions of a bichromatic laser field and relativistic protons, based on theory and numerical methods developed in Ref. [E4]. This time, angular distributions of product particles were compared for two different forms of the driving laser field, each of them characterized by a different symmetry with respect to the field propagation. For both cases, the threshold energy for pair creation determined by the ponderomotive energy of electrons quiver motion in a laser field (for more details, see [E4]) was kept the same. The results presented in [E5] relate to the nonperturbative regime of laser-induced pair creation.

Our main observation in Ref. [E5] was that the symmetry of angular distributions of emitted particles is governed by the behavior of the vector potential characterizing the laser field, rather than by the respective electric-field component. This was demonstrated for both partial angular distributions and coarse-grained angular distributions of created electrons. In this sense, the tunneling mechanism of pair creation which relies on the electric-field dependence of pair creation probability rates appears not to be responsible for the process under investigation, at least for the chosen laser-field parameters. This was particularly intriguing since the results concerned a quasi-static regime (namely, in the considered case we performed calculations even for $\mu=10$) for which the electric-field component should play the crucial role.

In Ref. [E5], we proposed that by studying correlations between angular distributions of created particles and the actual form of the driving laser field (more precisely, the form of the vector potential *vs.* the form of the electric-field component) one can verify the correctness of the tunneling mechanism with regard to laser-stimulated pair creation processes. In this sense, Ref. [E5] comprises a proposal for future experiments. Even though it is not specifically discussed, the paper demonstrates the possibility of controlling the pair creation by means of the laser field shape. This was illustrated using two extreme cases when the pair production occurs either symmetrically or asymmetrically with respect to the propagation direction of the laser wave, always in accordance with the symmetry of the vector potential.

The last paper of the series [E6] is also devoted to the role of a driving field in e^-e^+ pair creation processes. This time, however, the sensitivity of laser-stimulated pair production to the time-duration of a driving pulse is investigated.

E6. **K. Krajewska**, J. Z. Kamiński, *“Breit-Wheeler process in intense short laser pulses”*
Phys. Rev. A **86**, 052104 (2012)

As mentioned previously, the electron-positron pair creation can occur via collisions of a laser beam with a nonlaser photon. Such a scenario was realized experimentally at SLAC [41,42]. In the first theoretical papers devoted to this topic, the laser beam was described either as a monochromatic [43-48] or a bichromatic [33-36] plane wave field, or as a weakly nonmonochromatic field within the slowly-varying envelope approximation [49]. Only recently was it possible to generalize these investigations such that a more refined theoretical treatment of the finite laser pulses became possible [50-52,E6]. In these works, the idea of Neville and Rohrlich was used [53], which applies when the transverse motion of an electron (positron) in a laser field can be disregarded (see, also Ref. [54]). In this case, one can describe the laser pulse as finite in the propagation direction of the laser field and as an infinite plane wave in the transverse direction. Using this approach, in Refs. [51,52] the cross sections for e^-e^+ pair creation were calculated with an account for various approximations, which are justified in the perturbative regime only (for $\mu \ll 1$). In addition, in Ref. [50] the results concerning the nonperturbative regime ($\mu \sim 1$) were presented, with a focus on the mass shift effects. At this point, it is worth noting that the same approach has been used recently in theoretical studies on nonlinear Compton scattering (see, Refs. [55-64]), which is related to nonlinear Breit-Wheeler process via a crossing symmetry of the corresponding Feynman diagrams.

In Ref. [E6], theoretical formulation of the electron-positron pair production in a collision of a short laser pulse with a nonlaser photon was introduced. At the same time, a similar formalism for the case when the laser pulse is replaced by a modulated plane wave field was specified. The latter is understood as an infinite train of identical pulses which are not delayed in time. In both situations, we used the standard methods of strong-field QED arising from the *S*-matrix approach. In the case of a modulated plane wave, the respective probability distributions were defined per a pulse from the train. This made it reasonable to compare the results for both cases.

In Ref. [E6], I presented the results for the nonperturbative, linearly polarized driving pulse such that μ~1, with a sine-squared envelope. An infinite sequence of such pulses was comprising a modulated plane wave field. In this paper, we compared probability distributions of particles emitted in a collision of a nonlaser photon with a single laser pulse *vs.* a train of such pulses. In this context, the dependence on the time-duration of an individual pulse was analyzed. To make our comparison reliable, similar to Ref. [E4], we imposed an additional condition for the laser field; this time, we kept the energy contained in a pulse fixed, irrespectively of its duration. While for long driving pulses a very good agreement between the results for a single pulse and a pulse from a train was observed, this agreement was lost for short pulse durations. The reason being that for short pulses (containing very few field oscillations), the necessity exists to account for their actual temporal structure. This was confirmed when the carrier-envelope phase effects were studied. We showed that for a two-cycle driving pulse, by changing the CEP, the angular distributions of positrons (electrons) change dramatically; from being symmetric with respect to the propagation direction of a nonlaser photon, to being asymmetric. Therefore one can conclude that the sensitivity of the energy-angular spectra of created particles to a variation of the CEP can be used as a means of phase control.

Another effect that we observed was that the signal of produced pairs exhibits very pronounced enhancements with decreasing the pulse duration; this was related to the fact that we kept the energy of the field contained in a pulse fixed, when changing the pulse duration. This indicates that the pulse duration can also be used as a control parameter for the electron-positron pair creation processes. The duration of a driving laser pulse determines other properties as well. In particular, for long pulses we observed a characteristic multiphoton maxima in angular distributions of emitted positrons (electrons). However, these maxima vanish when the pair creation by short pulses is considered.

As far as I know, Ref. [E6] is the only one in the literature that presents a systematic analysis of properties of laser-induced e^-e^+ pair creation via the Breit-Wheeler mechanism, depending on the driving pulse duration and its carrier-envelope phase.

Summary:

The quantum vacuum is one of the most fundamental issues of contemporary physics. One can probe it using ultra-intense laser fields from the regime approaching the Sauter-Schwinger limit, which corresponds to the laser-field intensity of the order of 10^{29} W/cm^2. The mechanisms of e^-e^+ pair creation presented in the series [E1-E6] allows the pair creation process to happen much below the required Sauter-Schwinger limit (see, my discussion on page 14 and Refs. [41,42]). For this reason, they are particularly attractive in view of future experiments.

The series of articles [E1-E6] is particularly important in view of upcoming experiments which are fundamental for verifying the predictions of nonperturbative quantum electrodynamics. It contains a number of original results and theoretical predictions regarding the properties of laser-induced e^-e^+ pair production. At the beginning, we aimed to answer the question: Whether the potential approximation, which had been widely used in this context, was justified for available laser fields? In the first papers of the series [E1-E3], we performed a systematic analysis regarding the effect of the finite mass of colliding target particles on properties of the process. This was done in different domains of laser-matter interaction [26]. At the same time, a significant role of the driving laser field was observed; in particular, the role of the laser field intensity [E1-E3] and its polarization [E1] was realized. Since the papers [E1-E3] treated the driving laser field as a monochromatic plane wave, further studies of significance of a driving laser field on the e^-e^+ pair creation processes required to go beyond the monochromatic plane wave approximation. In the following papers, we investigated the role of such parameters of the laser field as a relative phase [E4], a carrier-envelope phase [E4,E6], a shape [E5], and a pulse duration [E6] on laser-induced pair production processes. These papers deal either with a bichromatic plane wave field [E4,E5], a modulated plane wave [E6], or a finite laser pulse [E6]. All publications of the series [E1-E6] center around control of electron-positron pair creation processes by means of laser radiation.

At this point, I would like to mention that my further goal is to study nonlinear Bethe-Heitler process of pair creation by a short laser pulse, with an exact account for recoil effects. This requires the calculation of a two-vortex Feynman diagram dressed by a finite pulse. Such studies require the combination of various computational methods developed in the series of papers [E1-E6]. To solve this problem is a serious theoretical and numerical challenge.

Bibliography:

[1] G. A. Mourou, T. Tajima, S. V. Bulanov, Rev. Mod. Phys. **78**, 309 (2006).
[2] V. Yanovsky, *et al.*, Opt. Express **16**, 2109 (2008).
[3] http://www.eli-laser.eu
[4] http://www.hiper-laser.org/
[5] http://flash.desy.de/
[6] C. Müller, A. B. Voitkiv, N. Grün, Phys. Rev. A **67**, 063407 (2003).
[7] C. Müller, A. B. Voitkiv, N. Grün, Phys. Rev. Lett. **91**, 223601 (2003).
[8] C. Müller, A. B. Voitkiv, N. Grün, Phys. Rev. A **70**, 023412 (2004).
[9] K. Krajewska, J. Z. Kamiński, F. Ehlotzky, Laser Phys. **16**, 272 (2006).
[10] P. Sieczka, K. Krajewska, J. Z. Kamiński, P. Panek, F. Ehlotzky, Phys. Rev. A **73**, 053409 (2006).
[11] J. Z. Kamiński, K. Krajewska, F. Ehlotzky, Phys. Rev. A **74**, 033402 (2006).
[12] K. Krajewska, J. Z. Kamiński, Laser Phys. **18**, 185 (2008).
[13] C. Deneke, C. Müller, Phys. Rev. A **78**, 033431 (2008).
[14] C. Müller, Phys. Lett. B **672**, 56 (2009).
[15] E. Lotstedt, U. D. Jentschura, C. H. Keitel, New J. Phys. **11**, 013054 (2009).
[16] S. J. Müller, C. Müller, Phys. Rev D **80**, 053014 (2009).
[17] A. Di Piazza, E. Lotstedt, A. I. Milstein, C. H. Keitel, Phys. Rev. A **81**, 062122 (2010).
[18] H. Hu, C. Müller, C. H. Keitel, Phys. Rev. Lett. **105**, 080401 (2010).
[19] A. Di Piazza, A. I. Milstein, C. Müller, Phys. Rev. A **82**, 062110 (2010).
[20] T.-O. Müller, C. Müller, Phys. Lett. B **696**, 201 (2011).
[21] T.-O. Müller, C. Müller, Phys. Rev. A **86**, 022109 (2012).
[22] C. Müller, C. Deneke, and C. H. Keitel, Phys. Rev. Lett. **101**, 060402 (2008).
[23] C. Müller, C. Deneke, M. Ruf, G. R. Mocken, K. Z. Hatsagortsyan, C. H. Keitel, Laser Phys. **19**, 791 (2009).
[24] F. Ehlotzky, K. Krajewska, J. Z. Kamiński, Rep. Prog. Phys. **72**, 046401 (2009).
[25] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, C. H. Keitel, Rev. Mod. Phys. **84**, 1177 (2012).
[26] In order to distinguish different regimes in laser-induced pair creation processes, a dimensionless and relativistically invariant parameter μ is usually introduced. It measures the energy that is absorbed by the electron from the laser field over a typical distance, which is the Compton length, in units of the laser-photon energy. In the case when $\mu \ll 1$, the laser field can be treated perturbatively, since the respective total rates follow a perturbative power law $W \sim \mu^{2N}$, where N is the minimum number of photons that has to be absorbed from the laser field in order to create pairs. For values $\mu \sim 1$ or larger, such a power law is not satisfied any longer, which means that we deal with a nonperturbative regime.
[27] S. P. Roshchupkin, Laser Phys. **6**, 837 (1996).
[28] S. P. Roshchupkin, A. A. Lebed', E. A. Padusenko, A. I. Voroshilo, Laser Phys. **22**, 1113 (2012).
[29] V. P. Oleinik, Zh. Eksp. Teor. Fiz. **52**, 1049 (1967) [Sov. Phys. JETP **25**, 697 (1967)].

[30] V. P. Oleinik, I. V. Belousov, *The Problems of Quantum Electrodynamics of the Vacuum, Dispersive Media and Strong Fields* (Kishinev, Shtiintsa, 1983).
[31] F. Ehlotzky, Phys. Rep. **345**, 175 (2001).
[32] M. Shapiro, P. Brumer, Rep. Prog. Phys. **66**, 859 (2003).
[33] V. I. Ritus, Tr. Fiz. Inst. Akad. SSSR **111**, 5 (1979).
[34] A. Yu, H. Takahashi, Phys. Rev. E **57**, 2276 (1998).
[35] N. B. Narozhny, M. S. Fofanov, Phys. Rev. E **60**, 3443 (1999).
[36] N. B. Narozhny, M. S. Fofanov, Zh. Eksp. Teor. Fiz. **117**, 476 (2000) [JETP **90**, 415 (2000)].
[37] F. Sauter, Z. Phys. **69**, 742 (1931).
[38] J. Schwinger, Phys. Rev. **82**, 664 (1951).
[39] E. Brezin, C. Itzykson, Phys. Rev. D **2**, 1191 (1970).
[40] V. S. Popov, Zh. Eksp. Teor. Fiz. **61**, 1334 (1971) [Sov. Phys. JETP **34**, 709 (1972)].
[41] D. L. Burke, *et al.*, Phys. Rev. Lett. **79**, 1626 (1997).
[42] C. Bamber, *et al.*, Phys. Rev. D **60**, 092004 (1999).
[43] H. R. Reiss, J. Math. Phys. **3**, 59 (1962).
[44] A. I. Nikishov, V. I. Ritus, Zh. Eksp. Teor. Fiz. **46**, 776 (1964) [Sov. Phys. JETP **19**, 529 (1964)].
[45] N. B. Narozhny, A. I. Nikishov, V. I. Ritus, **47**, 930 (1964) [Sov. Phys. JETP **20**, 622 (1965)].
[46] D. Yu. Ivanov, G. L. Kotkin, V. G. Serbo, Eur. Phys. J. C **40**, 27 (2005).
[47] D. Yu. Ivanov, G. L. Kotkin, V. G. Serbo, Acta Phys. Pol. B **37**, 1073 (2006).
[48] O. I. Denisenko, Laser Phys. **18**, 920 (2008).
[49] N. B. Narozhny, M. S. Fofanov, Laser Phys. **7**, 141 (1997).
[50] T. Heinzl, A. Ilderton, and M. Marklund, Phys. Lett. B **692**, 250 (2010).
[51] A. I. Titov, H. Takabe, B. Kämpfer, A. Hosaka, Phys. Rev. Lett. **108**, 240406 (2012).
[52] T. Nousch, D. Seipt, B. Kämpfer, A. I. Titov, Phys. Lett. B **715**, 246 (2012).
[53] R. A. Neville, F. Rohrlich, Phys. Rev. D **3**, 1692 (1971).
[54] S. V. Bulanov, *et al.*, Nucl. Instrum. Methods Phys. Res. A **660**, 31 (2011).
[55] M. Boca, V. Florescu, Phys. Rev. A **80**, 053403 (2009).
[56] T. Heinzl, D. Seipt, B. Kämpfer, Phys. Rev. A **81**, 022125 (2010).
[57] F. Mackenroth, A. Di Piazza, and C. H. Keitel, Phys. Rev. Lett. **105**, 063903 (2010).
[58] D. Seipt, B. Kämpfer, Phys. Rev. A **83**, 022101 (2011).
[59] F. Mackenroth, A. Di Piazza, Phys. Rev. A **83**, 032106 (2011).
[60] M. Boca, V. Florescu, Eur. Phys. J. D **61**, 449 (2011).
[61] K. Krajewska, J. Z. Kamiński, Phys. Rev. A **85**, 062102 (2012).
[62] M. Boca, V. Dinu, V. Florescu, Phys. Rev. A **86**, 013414 (2012).
[63] M. Boca, V. Dinu, V. Florescu, Nucl. Instrum. Meth. Phys. Res. Sect. B **279**, 12 (2012).
[64] K. Krajewska, J. Z. Kamiński, Laser Part. Beams (in press) (2013).

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