Załącznik nr 1b do „Wniosku o przeprowadzenie postępowania habilitacyjnego”
Attachment no. 1b to the Application for the start of habilitation proceedings
(file: autoreferat_KGrzelak_EN.pdf)

Warsaw, 24 July 2018

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Summary of academic accomplishments

Contents

1 Personal data

Name and Surname: Katarzyna Grzelak

2 Education

- 2000 – PhD in Physics with distinction (Cum Laude),
  Institute of Experimental Physics, University of Warsaw.
  Thesis title: *Two-photon Production of Charged Meson Pairs at LEP*,
  supervisor – dr hab. Krzysztof Doroba.

- 1993 – MSc in Physics
  Institute of Experimental Physics, University of Warsaw.
  Thesis title: *A Feasibility Study of ϕ Meson Detection in the NA49 Experiment*,
  supervisor – dr Helena Białkowska.

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3 Employment

- Since November 2017 – Senior Lecturer (*starszy wykładowca*) at the Faculty of Physics, University of Warsaw.
- 2001–2017 – Associate Professor (*adiunkt*) at the Faculty of Physics, University of Warsaw.
- January 2003 – January 2005 – in receipt of Marie Curie Individual Fellowship from the 5th EU framework, employed as Post-doctoral Research Assistant at University of Oxford. On leave of absence from the University of Warsaw.
- October 1998 – February 2001 – technician at the Faculty of Physics, University of Warsaw.
- 1993–1998 – PhD studies, Faculty of Physics, University of Warsaw.

4 Academic career

My interest in particle physics started during work on Master-of-Science thesis and extends well beyond one specific topic. I worked on the MSc thesis in the Warsaw heavy ion group. The thesis was devoted to the feasibility study of ϕ meson detection in the NA49 experiment at CERN. Work on MSc thesis started with one-month long research stay at CERN. In Warsaw, I started from installation of the Fritiof program for generation of interactions of relativistic lead nuclei with lead target and GEANT detector simulation package. Then, I prepared the sample of lead-lead interactions for beam energy 160 A GeV and studied possibility to observe in the NA49 experiment the ϕ meson decaying in two charged kaons. I developed the selection method of K^+K^- originating from ϕ meson and the method of finding the basic parameters of this particle. I also discussed the dependence of results on λ parameter describing suppression of strange quark production. The correctness of conclusions that the ϕ particle can be observed at certain level in the K^+K^- decay channel was confirmed a few years later, when the NA49 experiment applied similar procedure for the selection of ϕ mesons in the collected data and published results concerning production of these particles [1, 2].

After finishing MSc thesis I started PhD studies at the University of Warsaw and I became the member of the DELPHI collaboration, one of the four experiments at the LEP e^+e^- accelerator at CERN. DELPHI group in Warsaw was responsible for the construction of the electromagnetic calorimeter HPC (Heavy Projection Chamber).

I worked on the interactions of highly energetic photons originating from the electron and positron beams. The subject of the thesis was: "Two-photon production of charged meson pairs at LEP" and among the main results were the cross sections measurements of the two-photon production of charged pion and kaon pairs at e^+e^- centre-of-mass energies $\sqrt{s}$=91 GeV and $\sqrt{s}$=183 GeV. I studied quasi-elastic interactions of two-photons with electron and positron deflected by such a small angle that they remained undetected. Simplicity of the final state led to one of the challenges of the analysis, because the trigger system in the DELPHI experiment was not optimized for untagged gamma-gamma physics. As a consequence, I am the author of the first successful approach in the DELPHI experiment to estimate the trigger efficiency in the difficult, kinematical region (low p_T and low multiplicity events).

In the PhD thesis, the emphasis had been put on the study of the hardly known region of high invariant masses of the two-photon system in which the theoretical models based on the perturbative QCD could have been tested. The cross sections for the production of charged kaon pairs and charged pion pairs were measured as a function of the photon-photon invariant mass and cosine of the polar angle θ^* in the $\gamma\gamma$ centre-of-mass system and compared to the theoretical predictions. The obtained results were the first results from LEP concerning the exclusive two-photon production of charged kaon and pion pairs in the region of high invariant masses of the two-photon system.

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For the purpose of this analysis, I generated in Warsaw all needed files with simulation of two-photon interactions, using event generators: Vermaseren 1.01, BDKRC (RADCOR), DIAG36 and GALUGA 2.0 and chain of standard programs of the DELPHI experiment to simulate the response of the detector and reconstruction of the interactions inside the detector. In the years 1993–1998 I was responsible for the installation and maintenance in Warsaw of the DELPHI simulation and reconstruction package (DELSIM/DELANA) as well as DELPHI analysis package (SKELANA) on different UNIX platforms (IRIX,HP-UX).

I worked on the PhD thesis mostly at Warsaw, but also during several at most month-long stays at CERN in Switzerland and at the Pierre and Marie Curie University, Paris VI in France. I participated in tests of the ageing of the electromagnetic calorimeter (HPC) at CERN test facility and several times took part in the DELPHI data taking. I presented results of my work at the two conferences from the series International Conference on The Structure and Interactions of the Photon: PHOTON'99 in Freiburg, Germany and PHOTON 2001 in Ascona, Switzerland. In the second case I presented my results together with results from the ALEPH experiment. My PhD work was twice supported by Polish State Committee for Scientific Research. I received a grant for young scientists and my supervisor received a grant dedicated for my PhD work.

After defense of my PhD, I took interest in the neutrino physics and I applied for Marie Curie Individual Fellowship to work on neutrino experiment MINOS (Main Injector Neutrino Oscillation Search) [3] at the University of Oxford. My application was successful and for two years, from January 2003 to January 2005, I was employed as a Research Assistant at the University of Oxford. I became a member of the MINOS collaboration that was created to study oscillations of neutrinos produced at Fermilab laboratory near Chicago in the United States. The neutrinos were detected in two detectors: near detector located 1 km from the neutrino source and far detector, situated 735 km from the source in the Soudan mine in Minnesota.

I started to work in the MINOS experiment when the far detector were already collecting interactions of atmospheric neutrinos and the near detector and NuMI beamline were in the process of construction. Thanks to that, I had an opportunity to gain the experience and participate in the work of the experiment from the very beginning. I took part in the construction of the near detector: I tested planes built from the scintillator strips after they had been mounted on the steel planes in the experiment hall. In the MINOS detectors scintillator strips have orthogonal orientation in the alternate planes. Therefore, the main pieces of information directly available from the MINOS detectors are the two two-dimensional projections of a neutrino interaction. In the final stage of the standard algorithm they are used to reconstruct three-dimensional picture of an interaction. In this approach some information is definitely lost. Thus, I decided to develop the new, three-dimensional approach to the reconstruction of neutrino interactions in the MINOS detectors. Algorithm starts from the formation of three-dimensional objects, named cells, that are formed from the intersections of strips from neighbouring planes.

As the Oxford group was interested in the study of NC interactions (mediated by Z boson) I also worked on the developing of the selection of NC events. For this purpose, I adapted and developed the multivariate event selection using range searching method [4].

In September 2004, I gave an invited talk summarizing the status of long-baseline neutrino experiments in the United States at the plenary session of the Neutrino Oscillation Workshop NOW 2004 in Otranto in Italy.

In the year 2005, I returned to the University of Warsaw and was able to continue to work on the MINOS experiment thanks to the Marie Curie Reintegration Grant (from the 6th European Union framework) I received. Thanks to the ERC grant, the powerful computer system to work on MINOS that included a mass storage system (disk array, server and UPS) and a computer desktop was purchased and configured in Warsaw. The complete MINOS-specific software was installed and automatic procedure for copying the MINOS data and simulation files to Warsaw was created. Also, an educational page about neutrino physics was created [5].

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Further continuation of work on MINOS was possible thanks to the next two grants received from the Polish Ministry of Science and Higher Education and from the Polish National Science Centre. Thanks to my efforts, the application of University of Warsaw to join the MINOS experiment was accepted. Therefore, since the year 2008, Faculty of Physics of the University of Warsaw has been a member of the MINOS collaboration (and later also the MINOS+ collaboration). MINOS+ is the successor of the MINOS experiment, uses the same detectors as MINOS, but studies the neutrino interactions from the beam of higher energy (with mean energy about 6.5 GeV in comparison with 3 GeV in MINOS), wider spectrum and higher intensity.

The institution I represent always fulfilled all obligations to the experiment, related to the membership of the collaboration, including participation in the data taking, work on developing and testing reconstruction packages. I participated many times in the data taking. At first the standard shift procedures were being developed and shifts required traveling to Fermilab. In the MINOS+ era I created in Warsaw remote control room and while being on shift, controlled both MINOS detectors from Warsaw.

I supervised two MSc theses and one BA thesis as well as several (close to twenty) shorter students projects. All supervised by me MSc and BA theses obtained best grade. The thesis of Maciej Pfützner was acknowledged as outstanding by the Faculty of Physics and by the MINOS collaboration when it was presented by the author during one of the collaboration meetings at Fermilab.

In the MINOS and MINOS+ experiments I was in the beginning interested in the search of tau neutrinos at the far detector - expected product of standard oscillations involving three neutrino flavours. I tested possibility of detection of tau leptons from ν_τ interactions in different τ decay channels, using numerous variables describing single tracks or event shape. Detailed analysis showed that in the whole MINOS and MINOS+ statistics, after applied necessary preselection cuts, there is too few ν_τ events expected, while low granularity of the detectors does not allow to reduce big part of background from ν_μ interactions and interactions mediated by Z boson.

The next step in my work has been the search for the new type of neutrinos named sterile, including the unique method to search for the appearance of ν_τ in the near detector. At short distances from the neutrino source at Fermilab, no effects of standard, three-flavour oscillations are expected, including ν_τ production. Observation of ν_τ in the near detector would be the signature of the non-standard oscillations with sterile neutrinos.

The MINOS and MINOS+ experiments are among the leading experiments in searching for sterile neutrinos. The recent limits set in the $(\sin^2\theta_{24}, \Delta m^2_{41})$ [6] parameter space are the most stringent limits [7,8] set to date for wide range of values of $\Delta m^2_{41} > 10^{-4}$ eV^2, where Δm^2_{41} is the squared mass difference between first and fourth massive neutrino state, and θ_{24} is the parameter responsible for the muon–sterile mixing. MINOS and MINOS+ are also among the few experiments that set limits on θ_{34} responsible for the tau–sterile mixing [6].

Currently, there is considerable interest in neutrino physics in the possible existence of light eV-scale neutrino that could explain several anomalies observed in the accelerator experiments LSND and MiniBooNE [21–23], reactor experiments [24] and gallium experiments [25, 26] built to study solar neutrinos. Results of the accelerator experiments that observe anomalous production of electron neutrinos (antineutrinos) in the beam of muon neutrinos (antineutrinos) are presented in the $(\sin^2 2\theta_{\mu e}, \Delta m^2_{41})$ [6] parameter space, where $\sin^2 2\theta_{\mu e}$ is the effective angle defined as the product of squares of two elements ($|U_{e4}|^2$ i $|U_{\mu 4}|^2$) of neutrino mixing matrix [6]:

$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2|U_{e4}|^2. \tag{1}$$

The first matrix element is responsible for the muon–sterile mixing and the second for the electron–sterile mixing.

The reactor experiments as Daya Bay and Bugey-3 study the disappearance of $\overline{\nu}_e$ and therefore set constraints on the matrix element $|U_{e4}|^2$. Likewise, $|U_{\mu 4}|^2$ can be constrained in the ν_μ or $\overline{\nu}_\mu$ disappearance experiments like MINOS. Therefore, the combined analysis of MINOS, Bugey-3 and DayaBay data [20] strongly constrained the regions of parameters allowed for the eV-scale sterile

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neutrinos. The very strong tension between observed experimental anomalies and results from ν_μ disappearance experiments is confirmed by the results of global analyses of neutrino data, including the most recent from March 2018 [27], where results from MINOS and MINOS+ were analyzed together with results from IceCube, MiniBooNE and CDHS.

Observed anomalies, as well as most of the other sterile neutrino related results, concern electron–sterile or muon–sterile mixing. The weakest limits are set on the tau–sterile mixing due to the experimental challenges related to the detection of tau neutrinos. In the MINOS+ experiment I became interested in the study of the tau–sterile mixing by searching for the anomalous production of tau neutrinos in the near detector.

The monograph described below is devoted to the neutrino oscillations in models with three or four neutrinos and presents what can be obtained from the study of the appearance of tau neutrinos, the hardest to detect neutrino type. The particularly important part is devoted to the description of analysis methods to study tau neutrinos I developed, and results obtained in the MINOS and MINOS+ experiment. My analysis, included in the monograph, was performed using MINOS software installed in Warsaw and local copies of MINOS and MINOS+ data and simulation files.

While participating in the various conferences and workshops, I several times presented the MINOS results on behalf of the MINOS experiment. Recently, at the beginning of June 2018, I presented results of my analysis in a poster, in the biggest neutrino conference, Neutrino 2018 in Heidelberg in Germany [28].

More detailed description of international collaboration, participation in conferences, teaching, obtained grants and awards can be found in the attachment no. 2 to the application.

5 Presentation of the academic achievement

As academic achievement fulfilling the requirements of Art.16(2) of the Act of 14 March 2003 on Academic Degrees and Title and Degrees and Title in the Arts (Dz. U. 2016 poz. 882 with further amendmends in Dz.U. from 2016 poz. 1311) I present monograph titled:

Standard and Non-standard Neutrino Oscillations Involving Tau Neutrinos

published by Wydawnictwa Uniwersytetu Warszawskiego (Warsaw University Press), Warsaw 2018, ISBN 978-83-235-3424-2. I am the sole author of this monograph.

The monograph content is related to several problems of great interest in the particle physics, and more specifically in neutrino physics. It is devoted to the neutrino oscillations and possibility to observe or exclude new type of particle – sterile neutrino, with special emphasis placed on possible mixing between tau neutrinos and sterile neutrinos. This monograph is the unique summary of the studies of neutrino oscillations involving tau neutrinos, which is the one of the least known areas in neutrino oscillation physics. The detection of ν_τ is experimentally challenging due to the short lifetime of tau particle produced in the interactions of ν_τ and high energy threshold for the production of τ lepton. Therefore, not many experiments attempted to search for tau neutrinos and not many will be able to do that in the future. The experimental methods developed for searching for interactions of tau neutrinos and experimental results concerning appearance of tau neutrinos are comprehensively reviewed. Particularly important part is devoted to the description of analysis methods developed by the author and results obtained in the MINOS and MINOS+ experiment.

Neutrinos belong to the family of elementary particles. They do not have electric charge and they are are a few orders of magnitude lighter than electrons. Similarly to the situation with other elementary particles, gravitational interactions can be neglected. Therefore, neutrinos effectively interact only via the weak interactions. There are three known neutrino flavours: electron neutrino ν_e,

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muon neutrino ν_μ and tau neutrino ν_τ.

Neutrinos can change their identity while propagating in space. This phenomenon is called neutrino oscillations. The first model of $\nu_e \longleftrightarrow \nu_\mu$ oscillations was formulated by B. Pontecorvo [9] in 1968 and later developed by V. Gribov and B. Pontecorvo [10] in 1969. The work included in the publication from 1969 was motivated by the results from the first experiment that was searching for neutrinos from the Sun. In the experiment located in the Homestake mine in South Dakota, R. Davis observed [11,12] only about 30% of the ν_e flux predicted by the Solar Standard Model [13]. Pontecorvo and Gribov postulated that the number of detected ν_e is smaller than expected because electron neutrinos can change the flavour (oscillate) into muon neutrinos on their way to the Earth. Existence of neutrino oscillations have important consequences: neutrinos can oscillate only if they have non-zero masses. The oscillation hypothesis was confirmed in 1998 by the Super-Kamiokande experiment [14] that studied atmospheric neutrinos and in the years 2001 [15] and 2002 [16] by the SNO experiment that presented evidence that the total flux of neutrinos from the Sun is in agreement with the predictions of the Solar Standard Model. The physicists: Takaaki Kajita leading the oscillation analysis in the Super-Kamiokande collaboration and Arthur B. McDonald from the SNO collaboration were awarded the Nobel Prize in Physics in 2015 for their leading role in "the discovery of neutrino oscillations, which shows that neutrinos have mass". Raymond Davis Jr was awarded the Nobel Prize in 2002 for the detection of solar neutrinos.

Since the discovery, a number of experiments have studied interactions of neutrinos from natural and artificial sources and their oscillations. Disappearance of muon and electron neutrinos in accordance with the three-flavour neutrino oscillation theory has been observed in various experiments. The reduced flux of $\nu_\mu/\overline{\nu}_\mu$ was measured in experiments studying atmospheric neutrinos and accelerator neutrinos. Disappearance of $\overline{\nu}_e$ was observed with neutrinos from reactors and disappearance of ν_e with neutrinos from the Sun. Furthermore, the T2K (Tokai to Kamioka) experiment observed first appearance of electron neutrinos [17] (in the beam of muon neutrinos) and the OPERA (Oscillation Project with Emulsion-tRacking Apparatus) experiment in its final analysis from April 2018 presented 10 events that are consistent with the hypothesis of three-flavour $\nu_\mu \to \nu_\tau$ oscillations [18].

Production of tau neutrinos in the neutrino oscillations is one of the least known areas of neutrino physics because searching for this process is extremely difficult. The only way to discover interaction of ν_τ is by detecting a tau lepton produced in CC (mediated by W boson) interaction of ν_τ in a detector. Tau lepton, however, is an unstable particle with the very short mean lifetime: $t = (290.3 \pm 0.5) \times 10^{-15}$ s. Therefore, in most detectors it is only possible to observe products of decay of the tau lepton – not the τ itself. Additionally, there are several different channels of τ decay. As decay channels are very different from each other, it is not feasible to formulate a single selection procedure for all channels.

Lepton τ is a heavy particle, with mass above 1.7 GeV. This leads to the high threshold energy about 3.5 GeV needed to produce τ particle in the simplest interaction of ν_τ. Consequently, high enough neutrino energies are required to observe this process. Such neutrinos can be found in the spectrum of neutrinos produced in the atmosphere of the Earth and can be produced in accelerators. Most of current accelerator neutrino experiments however, have beam energy too low to study τ appearance. The exception are the OPERA and MINOS+ experiments with mean beam energy about 17 GeV and 6.5 GeV. The OPERA experiment was designed to search for appearance of tau neutrinos in the beam of accelerator muon neutrinos, produced as a result of standard oscillations. Excellent spacial resolution allowed for the direct observation of τ decay point. The only detector of OPERA was located at the Gran Sasso Laboratory, 730 km from the neutrino source at CERN. The most recent and at the same time the final results from OPERA [18] concern 10 produced ν_τ candidates, with expected background 2.0 ± 0.4 and expected signal 6.8 ± 0.75. In the case of standard oscillations of atmospheric neutrinos, in the year 2017 the Super-Kamiokande experiment presented results excluding the no-tau appearance hypothesis at the 4.6σ level [19].

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The three-flavour model of neutrino mixing provides a very good description of most of the world's neutrino data with exception of the described in the previous section anomalies, that can be explained by the existence of eV-scale sterile neutrinos. These non-standard neutrinos do not take part in the weak interactions as described by the Standard Model (SM) of fundamental particles and their interactions. Therefore, experiments cannot search for interactions of sterile neutrinos; what they can do, is to search for the modifications of the oscillation model resulting from the sterile neutrinos mixing with known, active neutrinos.

Neutrinos can oscillate only if they have non-zero masses, but in the Standard Model of strong and electroweak interactions they are strictly massless. Therefore, after the discovery of neutrino oscillations the theory has to be extended to describe neutrino mass generation. There are numerous extensions of the Standard Model and many of them predict existence of right-handed neutrino fields. Therefore, the hypothesis of sterile neutrino is theoretically well motivated.

Theoretically, there is neither bound on the number of sterile neutrinos nor on their mass scales. Therefore, most of the experimental results is compared to the simplest model with one sterile neutrino. Lack of bounds on the mass of sterile neutrino leads to the conclusion that eV-scale neutrino is not the only possible sterile neutrino.

Various experiments search or plan to search for sterile neutrinos in various channels [8, 29–53]. As a result, parameters of the models with one sterile neutrino, constraining electron–sterile and muon–sterile mixing are already severely constrained. The weakest limits are set on the parameters θ_{34} and $\theta_{\mu\tau}$ [6] related to the mixing of ν_τ with sterile states.
Effective angle $\sin^2 2\theta_{\mu\tau}$ was defined [6] as the product of squares of two elements ($|U_{\mu 4}|^2$ i $|U_{\tau 4}|^2$) of neutrino mixing matrix:

$$\sin^2 2\theta_{\mu\tau} \equiv 4|U_{\mu 4}|^2 |U_{\tau 4}|^2, \tag{2}$$

and angles θ_{34} and $\theta_{\mu\tau}$ are related via the formula:

$$\sin^2 2\theta_{\mu\tau} = \cos^4\theta_{14} \sin^2 2\theta_{24} \sin^2\theta_{34}. \tag{3}$$

Constraints on these parameters can be obtained from the study of data related to the neutral-current, mediated by Z boson, NC interactions or in the experiments searching for the anomalous ν_τ appearance. In the MINOS+ experiment, the spectacular signature of sterile neutrinos would be the ν_τ appearance in the near detector (Figs. 2.6–2.11 in [6]), where neither significant number of prompt ν_τ nor three-flavour oscillation effects are expected (Figs. 2.4, 2.5 in [6]).

The MINOS+ experiment is in the good position to search for the appearance of ν_τ due to the presence of sterile neutrinos and to constrain $\theta_{\mu\tau}$. The neutrino beam has high enough energy to produce τ leptons. High-statistics of data collected in the near detector partially compensate low granularity of the detector that is the cause of low-purity of the selection.

Presence of eV-scale neutrino with large value of θ_{34} can have important implications on physics potential of the future long-baseline experiments [56]. If the mixing angle θ_{34} were large, close to its current upper limit, DUNE (Deep Underground Neutrino Experiment) [54, 55] could probe CP-violation induced by δ_{34} phase. Moreover, with large θ_{34} the sensitivity of DUNE to determine mass ordering (hierarchy) could decrease from 5σ to 4σ.

The monograph contains the comprehensive review of results concerning standard and non-standard oscillations where tau neutrinos are involved. The experimental methods developed for searching for interactions of tau neutrinos, with special emphasis placed on the reconstruction and analysis methods developed by the author for the MINOS and MINOS+ experiments are presented. That includes the new, three-dimensional method of reconstruction of neutrino interactions in the MINOS and MINOS+ near and far detectors and application of the Hough [57] transform method to reconstruct very short tracks; selection of ν_τ interactions in the MINOS detectors, including the application of kNN [58] multivariate method to this problem and the procedure to find the sensitivity of an experiment and set the limits in the plane ($\sin^2 2\theta_{\mu\tau}$, Δm^2_{41}).

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In the monograph the unique studies, performed by the author, of ν_τ appearance at short baselines (in near detectors) in the current and future experiments that study neutrinos produced in accelerators are presented. Also shown are the results of analyses of MINOS and MINOS+ experiments, where stringent constraints non only on the parameters related to the LSND anomaly, but also on the θ_{34} parameter have been set. The monograph ends with the discussion of perspectives for the study of standard and anomalous appearance of tau neutrinos.

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