Kraków; 28.02.2020

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Referee report on doctoral thesis
of Muhsin Mohammed
"Study of angular correlations in the ortho-positronium annihilation with the J-PET detector for the search of CPT symmetry violation"

The doctoral dissertation of Mr. Muhsin Mohammed has been completed at the Institute of Physics of Jagiellonian University Cracow. It concerns the research in fundamental physics, in particular the possibility of measurement of the observable sensitive to CPT symmetry violation in the annihilation of the electron-positron bound state (positronium). For this aim the precise measurement of the angular correlations of photons momenta emitted in the annihilation is needed together with determination of the initial direction of spin vector of positronium. A non-zero mean value of the scalar product of the spin vector and a vector perpendicular to the annihilation plane would suggest the possibility of CPT violation.

The experimental examinations of the invariance of fundamental symmetries in physics are conducted for years. CP symmetry violation has been confirmed in hadronic sectors, namely in decays of K and B mesons. The research described in this work applies to the purely leptonic system, where no CP symmetry violation has been observed so far. The studies using ortho-positronium decay are particularly rare in this regard. Due to my knowledge the limits of CP and CPT invariance in positronium annihilation have been tested only in two experiments before.

In order to measure the angular correlation of photons from annihilation of ortho-positronium, a prototype of the Jagiellonian Positron Emission Tomography (J-PET) detector was used. This facility is built as a tool for medical imaging by registering of gamma quanta from positron-electron annihilation. J-PET can be utilized as well for fundamental research. For the studies described in this thesis the special techniques of efficient production of ortho-positonium have been developed. Also the methods permitting the identification and separation of the three-photon signal originating from ortho-positronium annihilation from dominant background of competitive processes were invented.

The construction and optimization of the J-PET detector are carried out by a group of scientists and engineers from the Institute of Physics of Jagiellonian University. Mr. Muhsin Mohammed is a member of this team. From the extensive list of literature references attached to the doctoral dissertation, one can learn that Mr. Mohammed is a co-author of 14 papers describing the J-PET construction, its applications, development of relevant experimental methods as well as the development of the procedures of signal identification and data analysis. From the above, as well as from a clear and convincing presentation in the thesis of the details of preparation phase of experiment, conducting the measurements, and analysis and interpretation of its results, it can concluded that the material for the PhD thesis Mr. Muhsin Mohammed collected to a large extent independently.

The dissertation consists of an introduction, the nine chapters, the acknowledgement and bibliography. It contains large number of figures, mostly well illustrating the described material.

In the first, short chapter the introduction to the problems of discrete symmetries in the context of their measurements with the use of ortho-positronium annihilation is given.

The second chapter describes the properties of positronium and differences between its two spin states, i.e. the para- and ortho-positronium. The Author describes the process of annihilation of ortho-positonium with the emission of three gamma quanta, which is crucial from the point of view of performed research. He also gives a comprehensive description of competitive processes, which contribute to the experimental background. These processes occur as a result of the interaction of ortho-positonium atoms with the medium, leading to the conversion of ortho-positonium into para-positronium and its annihilation with the emission of only two photons. In this chapter, a PhD Candidate demonstrates knowledge not only in nuclear physics, but also in chemistry and in atomic physics.

In the third chapter, the Author focuses on estimation of the spin polarization of ortho-positronium. Ortho-positronium is created as a result of a capture of a slowed down positron from the beta+ decay of sodium ^{22}Na isotope by the electron. The linear polarization of positron is transferred to the positronium atom. Depending on the spin state of the electron, the formation of para- or ortho-positronium takes place with the probabilities of 1/3 and 2/3, respectively. Mr. Mohammed calculates that when using the ^{22}Na isotope as a source of positrons and taking into account the described factors causing positron depolarization and the finite accuracy in determining the direction of their propagation, the total linear polarization of the spin vector of the created ortho-positronium, in the described measurements was about 40%. Also in this chapter, the PhD Candidate shows that although ortho-positronium is a triplet state with three possible spin projections onto the quantization axis, in each case the angular distribution of the annihilation plane determined by the vectors of momenta of emitted photons will be isotropic.

The fourth chapter presents the construction and operation of the J-PET facility. The Author describes the advantages of using the plastic scintillators for the tomography compared to the conventional PET scanners, where the inorganic crystalline scintillators are utilized. These include: (i) a good time properties of organic scintillators, which, together with the appropriate signal readout electronics and the data analysis methods, can increase the imaging accuracy, (ii) the ability to build a larger volume scanner by increasing its axial size, (iii) reduction of the total cost of the detector. The Candidate mentions also the possibilities of coupling of the J-PET scanner with other medical devices, what can increase the accuracy and a promptness of medical diagnostics. The methods of measuring the position of annihilation point in the J-PET detector are explained as well. In following the brief descriptions of used front-end electronics, the power supply system, the data acquisition system and the monitoring system of external conditions around the facility are given. Very generally, and in my opinion, too briefly, the description of the software tools for data analysis and for the image reconstruction is treated. However, the reader is referred here to the original publications of J-PET group relevant for these issues.

A technical description of the construction and production of vacuum annihilation chambers for positronium used during the tests and measurements with J-PET detector is given in chapter number five. Two cylindrical chambers have been used. They were installed coaxially in the center of the J-PET scanner. The so-called small annihilation chamber was made out of aluminum and was used only to the initial tests. The large annihilation chamber have been significantly optimized in comparison to the first one. It was used during long measurement providing data for this thesis. In order to increase the probability of positron capture and creation of ortho-positronium, the plastic walls of large chamber are covered with specially selected porous material (R60G form of silica - SiO_2). The wall materials were chosen also in respect to assure the lowest possible depolarization of initial spin of positron. During the described studies two ^{22}Na radioactive sources with activities of 1 and 10 MBq have been used. Methods of production of the positron sources and precise positioning them in the center of annihilation chambers are also described. When measuring possible asymmetry in the distribution of the ortho-positronium annihilation plane it is extremely important to maintain the high symmetry in the detection setup containing the source, the annihilation chamber and the detector. In this chapter, the Author has proved his vast technical knowledge.

The calibration procedures of J-PET detector, which are crucial for the precision of the results obtained in the reviewed work, are outlined in sixth chapter. The speed of light propagation in J-PET scintillating modules and the time dependencies in measurement of scintillation signal were calibrated. They are important for determination of the actual position of photon detection and for reconstruction of the annihilation vertex. For this purpose a specially constructed lead disk with a collimation channel was used. It contained installed in the center a ^{22}Na source. The disc have been installed at the linear drive movable along the z-axis of the J-PET detector enabling the irradiation of J-PET scintillators with a photon beam perpendicular to their surface and at the exactly known axial position. For time calibration, a reference detector (scintillator) with a ^{22}Na source fixed at its surface was used. In this case the gamma quanta irradiated the J-PET scintillation modules in their geometric centers. The methods of time synchronization between individual modules and between the J-PET detection planes were presented. The most extensively described is the method of time calibration with the use of emission of two photons from annihilation of para-positronium, which are emitted in opposite directions. These two gammas are recorded in coincidence with the photon originating from the deexcitation of the intermediate state of the ^{22}Ne isotope of the used radioactive source. In order to distinguish between the low-energy photons from annihilation and the 1.275 MeV energy deexcitation photon, the signal amplitude criterion was applied by means of the Time-over-Threshold method. From the attached figures one can learn that this calibration method is to great extent automatized and permits iterative minimization of time offsets for individual scintillation modules.
Unfortunately, apart from the collective distributions showing the values of time offsets for individual scintillation modules, the Author of the thesis does not provide any numerical values for the obtained calibrations. Perhaps the results of the automatic calibration are directly implemented into the software procedures, which calculate the image of the source of annihilation. However, providing some example of numbers would allow the reader to develop his own opinion about the obtained accuracy of time measurements and their impact on the overall systematic error of measurements.

The longest chapter - the seventh - describes the selection and analysis of data collected during 57 days of measurements done with the use of a large annihilation chamber installed centrally inside the J-PET scanner and the two ^{22}Na sources with activities of 1 and 10 MBq. The software environment called the "Data Analysis Framework for J-PET" is used as a tool to perform the detector calibration, event selection and full chain of analysis. Individual procedures are ordered hierarchically, starting from unpacking of the data, through the calibrations as described earlier, the signal identification and analysis, the event identification up to the event categorization. The Author describes in more detail the selection of signals with an acceptable energy range with the use of the criterion of their Time-over-Threshold. He analyzes as well the acceptable angular ranges between the propagation directions of detected photons in order to distinguish the events with emission of three photons among majority of those with emission of only two photons. The selected two-photon events are utilized for the accurate reconstruction of the spatial distribution of both positron sources used during the data collection. In this way Mr. Mohammad had realized that the stronger source of 10 MBq activity was displaced by 6 mm in the axial direction in respect to the geometrical center of the detector. It was also a slightly tilted in respect to the vertical plane. It has been confirmed as well that the 1 MBq source was installed in the right position, in the center of the detector. Events containing the three registered gamma quanta with adequate energy, and thus being the candidates for ortho-positronium annihilation, were identified by reconstruction of their vertices. They should be located on the surface of the cylinder describing the annihilation chamber. The propagation directions of all three photons should define a common plane of annihilation. If it is a cases the use of a trilateration method allowing to determine a common vertex for all three registered photons is possible. Determination of the annihilation point, and therefore the angles between the directions of propagation of individual photons permits the analytical calculation of their energies. Events which do not meet the kinematic requirements are rejected. Knowing the position of annihilation allows as well the determination of the spin direction of ortho-positronium. The rejection of background events originating from two-photon annihilation where one of these photon due to scattering created signals in two scintillation modules is done by checking the angular dependencies and the acceptable spatial and timing distances between individual detection points. The same is done to suppress the accidental coincidences of three photons. As a result of this multi-stage data selection procedure, the Author obtained the vertex distributions of the events classified as a candidates for the three-photon otho-positrinium annihilation. As a true events he considered only those, having vertices located at the distance of 12 ± 8 cm from the center of the J-PET detector.

From the events selected in chapter eight, the Author creates distribution of cosine of the angle between the vector perpendicular to the defined annihilation plane and the reconstructed spin direction of the ortho-positronium. This observable is a measure of the CPT-sensitive operator. The author shows the separate distributions obtained with both positron sources used in the measurement and the common distribution. In all cases, the distributions are well symmetrical around zero with an average value of zero at a level of at least 10^{-4} and with an uncertainty also at a level of 10^{-4}. The author proceeds to the discussion of errors and as a one component of systematic uncertainty he considers a contribution from reactions caused by cosmic rays recorded during measurements with J-PET and misidentified as originating from annihilation of ortho-positronium. Due to the low statistics obtained during the additional three-day lasting measurement using only cosmic radiation, he estimates this contribution very conservatively, assuming a maximum asymmetry of 1 in a distribution of events caused in this way. The Author estimates also the contributions to the systematic error resulting from the inaccuracy of source position relative to the geometric center of the J-PET detector. He also assumes and demonstrates that when using a detector with full cylindrical symmetry and when measuring a very broad distribution of possible geometrical configurations of photons from ortho-positronium annihilation, any geometrical asymmetries hidden in the detection system itself will cancel out, giving insignificant contribution to the systematic error. However, it seems to me that at this point the discussion about a finite accuracy of all performed calibrations and their possible impact on the systematic error is missing. Nevertheless, the total error of measured observable is dominated by statistical uncertainty. Thus, even another contribution to the systematic error would not change significantly the obtained precision of measurement.

Despite of possible slight underestimation of the systematic error, the already obtained result using the J-PET scanner for the CPT violation studies, even if still preliminary, seems to be more accurate than the results of previous experiments with positronium annihilation carried out in Japan and in the USA.

A certain drawback of the doctoral dissertation itself are the editorial deficiencies - linguistic and typing errors, unnecessary repetitions, lack of connection of some figures with the text of the thesis.

Summarizing: the doctoral dissertation of Mr. Muhsin Mohammed should be treated as a feasibility study of precise measurements of observables sensitive to CP and CPT invariance with the use of a J-PET detector. The PhD Candidate clearly demonstrated the potential of both the detection apparatus and the applied experimental method. After further improvements supplemented with a series of still missing simulations, the facility will be ready to provide the scientific results, of the precision sufficient to push the limit of combined CPT symmetry conservation in leptonic systems. The Author described a broad spectrum of issues related to construction of the detection setup and its performance, conducting of the long-lasting measurements, analysis and interpretation data. He demonstrated extensive scientific knowledge, efficiency in analyzing complex experimental results and technical capabilities.

Despite of some minor shortcomings noticed and described above I affirm that doctoral dissertation of Mr. Muhsin Mohammed satisfies the formal requirements for doctoral theses. The general, high scientific merit of his dissertation allows me to apply for his admission for the public defense.