Akademia Górniczo-Hutnicza
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# Referee report on doctoral thesis: „Test of T, P and CP Symmetry in the decay of ortho-Positronium using the J-PET detector" by Juhi Raj

Submitted Thesis under the title „ Test of T, P and CP Symmetry in the decay of ortho-Positronium using the J-PET detector" describes the analysis of the possible discrete symmetries violation in the charged leptonic sector. Thanks to the novel J-PET (Jagiellonian-Positron Emission Tomograph) device, it was possible to extend the previous experimental techniques and significantly increase the sensitivity of the measurement. The J-PET setup can reconstruct, with high precision, not only the primary annihilation photons but also the scattered ones. With the knowledge of the momentum direction of the secondary photons, it is possible to study new discrete symmetry odd-operators taking into account correlations that have never been studied before. The signal reconstruction algorithms prepared especially for the J-PET detector made it possible to perform simultaneous studies of the T, P and CP symmetry violation via observing potential non-zero expectation values for operators defined using kinematical properties of primary and secondary photons from the ortho-Positronium decays.

The Thesis consists of six chapters (including a short introduction at the begging of the text and a summary at the end). Unfortunately, the Author did not provide the customary statement of the contribution to the described analysis. Thus, I concluded that all discussed results are the original work done by the Author. This assumption is partially supported by the impressive list of publications presented in the Thesis' Bibliography chapter (including papers published in "Nature Communications" and "Science Advances" journals).

A concise yet coherent theoretical introduction regarding the discrete symmetries of the Universe is given in Chapter 2. The Author introduces basic properties of the parity operators, representing the space, charge and time inversions, and related physics vocabulary specific to these operations. The CPT conservation theorem is also briefly presented as the foundation of our best theory of fundamental particles and their interactions, i.e., the Standard Model. As a part of the motivation for the conducted analysis, the fact of CP-violation in the quark sector is invoked using the example of the neutral kaon system. The central part of this chapter is related to the experimental searches of the CP-violation using positronium, which is an atomic-like bound electron-positron system. Since electrons are fermions with spin, the positronium can exist as a, $^1S_0$, or a triplet, $^3S_1$, state. Depending on the spin state, the properties of the positronium are completely different, including lifetime and the final state daughters. The positronium decays are a purely electromagnetic process making it an exceptionally clean "laboratory" for studying subtle CP-violation effects. So far, both searches for CP- and CPT-violation effects have been conducted using odd operators exploiting angular correlations between primary annihilation photons and ortho-Positronium spin. In this context, the J-PET device can be used to perform unique searches, never done before, exploiting new types of discrete symmetry odd operators, $\vec{\varepsilon}_l \cdot \vec{k}_j$, using a polarisation direction of one of the annihilation photons, $\vec{\varepsilon}_l$ , and the momentum direction of another primary photon, $\vec{k}_j$. This is possible thanks to the unique properties of the J-PET detector that is able to reconstruct the momentum directions of the secondary photons, $\vec{k}_j'$, thus, making it in turn possible to determine the linear polarisation vectors of the primary photons coming from the decays of ortho-Positronium, $\vec{\varepsilon}_j = \vec{k}_j \times \vec{k}_j'$.

Chapter 3 introduces the exceptional J-PET device very briefly. I would like to get a complete description, but I understand that there may still be some confidentiality issues regarding the design details. Autor describes the signal formation and its measurement via sampling the Time-over-Threshold (ToT) distribution. The main observables reconstructed are the photon hit position and time. In the second part of this chapter details of the experimental setup are discussed. In particular the construction of the $\beta^+$ source's holder that asserts production of ortho-Positronium systems decaying into $3\gamma$ final state.

Chapters 4 and 5 contain the description of the data analysis. The former chapter is devoted to signal selection algorithms and background discrimination, while the latter focuses on the estimation of systematic uncertainties. The main signature of the final signal events, $o\text{-}Ps \rightarrow 3\gamma + \gamma'$, is defined by observing at least four photons within a predefined time window of $200\,ns$. The hit multiplicity spectrum is a very effective variable for initial event preselection, providing a compression factor for the raw data of about 1000 by requiring at least four hits observed in the final state (three are related to the primary annihilation photons, and the last one to the scattered one). Next, a quality cut is applied to remove the regions of the scintillating strip close to its ends. The raw ToT distribution, plotted for all hits registered within the readout time window, shows a large admixture of cosmic events and shows two distinct peaks. In order to remove them and discriminate the hits coming from the de-excitation photons generated in the scintillating material, a cut on the ToT maximal value is applied. In my opinion, the value of the cut seems a bit random. I understand that the result shows significant background reduction and signal retention, but I would appreciate more thorough analysis with a figure of merit (like signal-to-noise ratio or similar) tuning. Also, the selection of the primary photons is presented too briefly. For instance, there is no justification for selecting the cuts on two key variables emission time spread, $t_{ETS}$, (that maybe driven by the properties of the DAQ system) and on the distance of the annihilation plane, DOP. Also, the Author claims that the DOP cut removes 81% of the background events that seems not be supported by the plot 4.7. Very effective variables used in distinguishing the final event topology are the sum and difference of the ordered opening angles. Finally, the secondary scattered photon must be selected and assigned to the appropriate primary one. This is done in a clever procedure that optimises the difference of the time variable, $\Delta_{lj}$.

In order to tune Monte-Carlo samples, optimisation of three parameters hit time and hit position smearing, and the energy threshold have been performed using the comparison of data and floating simulated samples via calculating $\chi^2$ sampling statistics. Next, the tuned simulated distributions of the sum of two smallest azimuthal angles variable, $(\theta_l + \theta_j)$, were used to estimate the normalisation coefficients. These numbers are necessary to compare the reconstructed and simulated distributions of $cos(\alpha_{lj})$, where the $\alpha_{lj}$ is angle between the linear polarisation vector of photon $l$ and the direction of the scattered photon assigned to the primary annihilation photon $j$. Plots 4.14 show excellent agreement.

As the final step, the background subtraction and efficiency corrections are applied to the selected data sample. The analysis efficiency is estimated using Monte-Carlo modelling, and the acceptance is determined using the geometry description of the J-PET device. The calculations of the expectation value of the discrete symmetry odd operator yielded a result consistent with 0 within the experimental uncertainties.

Systematic uncertainty estimation is discussed in detail in chapter 5. The list of effects is very thorough and the analysis of the significance of respective effects shows clearly, that at present the overall uncertainty is strongly dominated by the statistical uncertainties. This makes excellent prospects for further improvements via collecting more data.

In summary, I believe that the presented Thesis makes a truly unique contribution to the fundamental searches for New Physics phenomena performed within J-PET group. Probing the charged leptonic currents makes a great complementary study to the ones performed currently in the heavy quark sector by large high energy physics experiments at CERN and KEK. The presented Thesis, despite some textual and editorial mistakes (I would really not substitute "selection" with "segregation" and would want that the b-quark is referred to as beauty quark), was clearly written and well structured, and I enjoyed reading it. The presented analysis was performed following due diligence and state-of-the-art statistical tools and methods. The discussion of the systematic uncertainties is a true tribute to the J-PET device, and I'm really glad that a dedicated upgrade, especially planned for studying the discrete symmetries, is on the way

In conclusion, the dissertation presented by Juhi Raj contains valuable and original results and satisfies all the formal and customary requirements for a doctoral thesis, and I hereby agree and strongly support her public defence.

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