Dr hab. Seweryn Kowalski
Instytut Fizyki
Uniwersytet Śląski

Katowice, 2020-03-03

Referee report on Ph.D. thesis entitled:

Study of angular correlations in the ortho-positronium annihilation with the J-PET detector for the search of CPT symmetry violation

The study of CPT violation is important and addresses a very fundamental question. Today, we know from nuclear and high-energy physics that P, C, and T are individually all violated, as is also the combination CP. Only the combined operation CPT remains an exact symmetry in the current "standard model". CPT symmetry has a number of straightforward consequences in particle physics and spectroscopy. Violation of the fundamental CPT symmetry may result in essentially unknown properties of nature.

MSc Muhsin Mohammed in this thesis, is testing the conservation of the CPT symmetry in the decays of positronium as the lightest purely leptonic bound system. For that purpose, the Jagiellonian Positron Emission Tomograph (J-PET) was used, and as the CPT-sensitive observable: angular correlation operator OCPT in the ortho-positronium decay into three photons. The measurements were performed by using two 22Na radioactive sources with different activities and two different kinds of annihilation chambers. Based on the above measurements, the result is consistent with zero and no violation has been found at the precision level of 9.2×10^{-4}

The submitted thesis consists of nine chapters that are preceded by a short introduction, describing the content of the paper and is finished with an overview that summarizes the results.

The first chapter is the introductory part of the thesis. It shortly presents the importance of the main topic and introduces the reader to a concept of the Charge conjugation, Parity, Time reversal, CP, and CPT symmetries. The second chapter (Chapter 2) describes the positron and positronium. Moreover, one can find here explanations of the ^{22}Na isotope decay. The essential part of this chapter is devoted to the description of the positronium (properties, decay, interaction with the medium and spin properties).

Chapter 3 covers the topics connected with positronium polarization. Here author introduces the main analysis tool which is the trilateration reconstruction method. This method was used to identify the decays channel of the positronium and is main observable which help to distinguish between 3γ and 2γ process. This method was used for the J-PET device which is described in the next chapter (Chapter 4).

Chapter 4 gives, in detail, technical information about J-PET device. One can also find the information about software which was used for data analysis. I found comparison of the organic and inorganic scintillators very interesting, this chapter clearly show the main

advantages of the J-PET apparatus. In main opinion The fifth chapter continues the technical description of the performed experiment. Detailed information about necessary preparation for production of the positronium and production setup is included.

From the Chapter 6, the main part of the experimental analysis is beginning. This chapter describes the calibration of the J-PET detector. Which is one of the most important steps in data analysis, without careful calibration, possible outcome from acquired data can be unnoticed.

Next chapter (Chapter 7) is mostly devoted to the data selection and data reconstruction. For proper physics analysis, the most interesting event candidates, should be chosen and the final physical variables should be obtained.

The last Chapter 8 covers final data analysis which is determination of the CPT violation based on the angular correlation. The author introduces the sensitive operator for the CPT violation and does the comparison of this operator with the different experimental setup. Finally the combined result is used as the main result of this work. One can also find here the discussion of the systematic uncertainties. Author recognizes the main source of this uncertainties. Moreover, this chapter clearly presents that the J-Pet device can be not only used in the medical application for diagnostic process but also it is a very good device to address fundamental physics problems.

I have to stress that very good idea was induce in the last chapter of this thesis “The perspectives”, which presents the future possible development of the J-PET device and how those changes can improve future similar measurements,

I have the following comments / questions to the way conducted by PhD student analysis, or interpretation of results:

- The trilateration reconstruction method is described in the Chapter 3 based on the J-PET device. Where the description of the device is in the Chapter 4. In my opinion the method (which is specific for the J-PET) should be described after device decryption, not before.
- On the page 69, author claims that “the angles between two annihilation hits measured with respect to the center of the detector are in the range: $174^{o} < \text{angle} < 186^{o}$“, Why this range was chosen – due to the geometrical acceptance of one scintillating bar?
- The Figure 6.13 has wrong caption – the reference should be to the Fig. 6.11. Similar wrong reference is in the figure 6.14
- What is in pages 76 and 77? Where I can find the description of the plots in these pages
- Which means abbreviation HLD (page 81)?
- The chapter 7 described (simply speaking) the cuts used on the data the select 3γ events candidates originating form positronium which are used for final analysis. What was the influence of these cuts step on the whole data set (statistics). I found

Dr hab. Seweryn Kowalski
Instytut Fizyki
Uniwersytet Śląski

Katowice, 2020-03-03

only the information that from the raw data to the final the events was reduced to about 0,2% of the original volume of the raw data. The question is which part of the analysis reduced data the most. What is events amount after each step of data selection?

- Page 107 – cite "allows collecting the required 3-hit events with a good statistics" – what means "good statistics " in case of this analysis?
- I assumed that the values obtained from the measurements and presented in page 109 were taken from the figure 8.2. and 8.3. The value for the 10 MBq source agree with statistic in figure 8.3 but the values for 1MBq source are different.
- The values in Table 8.1 should be -6.8×10^{-4}.
- The author shows that the cosmic ray contribution is the main source of systematic uncertainty but my question is about measurement time of the cosmic ray contribution. Why is so short in the comparisons to other measurements? When I look at the distribution in figure 8.5 the calculations of the mean and errors for such low statistics are very questionable.
- In the Figure 8.7 on can see clean trend of mean values whit the shift along z-axis – can the author explain it?

The doctoral dissertation MSc Muhsin Mohammed is written in English, in a simple and understandable, and reading it gave me great pleasure. I have no comments about the language of the thesis, but at the same time I do not feel fully competent to evaluate the thesis in this regard.

In summary, I believe that presented thesis makes a fine and valuable contribution to test the CPT symmetry by searching for the possible non-zero expectation values of the operator which used the correlation between the spin direction of the initial o-Ps atom and the decay plane in o-Ps→3ɣ. The obtained results are more than factor of 3 better than the previous experimental results and no violation of CPT symmetry has been found. Moreover, this result clear proved that the J-Pet is a very good device to address fundamental physics problems. The author constantly proves throughout the text his good knowledge of the experimental nuclear physics. In my opinion it is very important that the Author included in the thesis the discussion of the future possible enhancements of J-Pet device which can improve the obtained result.

In conclusion, the dissertation presented by Muhsin Mohammed contains valuable and original results and satisfies all the formal requirements for doctoral thesis and I hereby agree for the public defense.