Research project objectives/Research hypothesis:

The epistemological objective of the proposed investigations is the empirical confirmation of the violation of discrete symmetries in the purely leptonic systems.

We owe our existence to the asymmetry between matter and anti-matter which must have appeared at the early stage of the evolution of the Universe. Otherwise, if the Nature was utterly symmetric the matter would not exist. Surprisingly, however, the processes driven by the gravitational, electromagnetic and strong interactions seem to be symmetric with respect to basic discrete symmetries such as reflection in space (P), reversal in time (T) and charge conjugation (C). So far violations of these symmetries were observed only in processes governed by the weak interaction. Yet, the excess of matter over anti-matter which we observe in the Universe is by about **nine orders of magnitude** larger with respect to the theoretical estimations based on the presently known sources of the discrete symmetries violations.

This huge discrepancy remains one of the greatest puzzles in physics and cosmology.

Hypothesis of leptogenesis explains existence of the matter in the Universe by the appearance of lepton-antilepton asymmetry in the early stage of its evolution. However, the present theory of leptogensis requires existence of very heavy neutrinos and other hypothetical particles which were not confirmed thus far.

In this project we propose to search for discrete symmetries violation in decays of positronium atoms. Positronium is build out of electron and anti-electron, and thus it is a purely leptonic object. It is an atom and at the same time an anti-atom, and this makes it suitable for studies of the discrete symmetries in Nature.

The Proposed project is complementary to studies of symmetries in the quark sector carried out e.g. at CERN, and at the same time, the proposed project is competitive to the studies in the lepton sector carried out in such laboratories as J-PARC in Japan or Fermilab in the USA. The above mentioned world leading institutions so far observed some hints for symmetry violations on the level of one standard deviation in the neutrino oscillations.

Research project methodology:

The core of the project is the **J**agiellonian **P**ositron **E**mission **T**omography scanner (J-PET) whose construction was accomplished in 2015. Its novelty may be quantified by inventions described in 16 recent international patent applications. The J-PET scanner will be used for measurements of gamma quanta originating from the decays of positronium atoms. We intend to determine expectation values for various operators constructed from the momentum and polarization vectors of these gamma quanta as well as from the spin of the positronium. Observation of the non-zero expectation value of any of these operators would imply a non-invariance of these symmetries for which the given operator is odd-symmetric. The experiments will be carried out at the Jagiellonian University by the J-PET collaboration formed and led by the proponent of this project.

The main advantages of the J-PET scanner which may significantly improve precision with respect to the best previous experiments are as follows: (i) unique possibility of determining of photons polarization which opens possibility of pioneering tests of discrete symmetries not available before, (ii) more than ten times better time resolution (of a great advantage for the background reduction), (iii) about ten times better angular resolution leading to improved experimental analyzing power, (iv) more than two orders of magnitude larger statistics achievable during the realization of this project.

Expected impact of the research project on the development of science, civilization and society:

Results of searches for new mechanisms of discrete symmetries violation with high precision can be crucial in solving the puzzle of the excess of matter over anti-matter, and can have impact on our understanding of the cosmology of the Universe we live in. As a by-product of proposed investigation we will develop methods which can turn out useful for the morphometric imaging of the living organisms, which is a new kind of imaging invented by the proponent of this project. It is based on the fact that probability of creation and lifetime of ortho-positronium in tissue depends strongly on the size of the free volumes between molecules and thus it is connected to the morphology of the cells and may be used as an indicator of the stage of development of metabolic disorders. It is worth mentioning that nowadays positronium atoms are formed copiously inside human body e.g. during the routine positron emission tomography imaging or during the hadron-therapy. However such phenomena were never considered and studied before!

This project may become an example of how the technology developed for medical diagnostics can be used for research pushing the frontiers of science, and how the results of this research may give a scientific basis and pave a way to the future in-vivo morphometric imaging.