Studies of the discrete symmetries in Nature

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We exist, so there must also be some sort of asymmetry between matter and antimatter. Otherwise, the whole matter and antimatter would long ago have turned into photons, i.e. light, as a result of mutual annihilation of particles and antiparticles. The explanation of this asymmetry, essentially identical with the explanation of the existence of matter in general, is one of the most interesting cognitive challenges of modern physics and cosmology. Currently we observe more than a thousand million times more light than matter in the universe. The remnant that survived the great annihilation is made of the quarks and leptons. Sakharov gave the necessary conditions that must be met for some matter to survive an early stage of evolution of the universe. These include breaking the charge symmetry (C), which is a violation of the invariance of the physical processes due to the exchange between particles and antiparticles, and breaking the charge-spatial symmetry (CP), which involves converting particles into anti-particles, connected with a mirror reflection in space (P). So far, violation of charge symmetry C and charge-spatial symmetry CP was only observed in the processes induced by the weak force. In contrast, despite many experimental trials in a number of leading laboratories all over the world, we have never observed any asymmetry between the behavior of matter and anti-matter in the processes induced by gravitational, electromagnetic and strong forces, which are interactions that determine the existence of stars, atoms and atomic nuclei. In addition, violating the CP symmetry has been confirmed empirically only in two (K meson and B meson) of the hundreds of known particles made of a quark and an anti-quark, although a violation of this symmetry is yet to be observed in the processes involving leptons.

Positronium is the lightest purely leptonic object decaying into photons. As an atom bound by a central potential, it is a parity eigenstate, and as an atom built out of an electron and an anti-electron, it is an eigenstate of the charge conjugation operator. Therefore, the positronium is a unique laboratory to study discrete symmetries whose precision is limited, in principle, by the effects due to the weak interactions expected at the level of 10^{-14} and photonphoton interactions expected at the level of 10^{-9}.

The newly constructed Jagiellonian Positron Emission Tomograph (J-PET) enables us to perform tests of discrete symmetries in the leptonic sector via the determination of the expectation values of the discrete-symmetries-odd operators, which may be constructed from the spin of the orthopositronium atom and the momenta and polarization vectors of photons originating from its annihilation. We will present the potential of the J-PET detector to test the C, CP, T and CPT symmetries in the decays of positronium atoms and report on the first data-taking campaigns. With respect to the previous experiments performed with crystal based detectors, J-PET built of plastic scintillators, provides superior time resolution, higher granularity, lower pile-ups, and opportunity of determining photons polarization. These features allow us to expect a significant improvement in tests of discrete symmetries in decays of the positronium atom (a purely leptonic system).