Charge conjugation symmetry test in the decay of para-positronium atoms using the J-PET detector

J. Chhokar, S. Sharma on behalf of the J-PET collaboration

Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, Lojasiewicza 11, 30-348 Krakow, Poland

Email: jyotichhokar48@gmail.com, sushil.sharma@uj.edu.pl

Introduction

- **Jagiellonian P**ositron **E**mission **T**omograph **(J-PET)** is being optimized to test the discrete symmetries (charge conjugation (**C**), reflection in space (**P**), reversal in time (T)).
- The charge conjugation symmetry transforms particle into antiparticle and has been observed only in the weak interactions [1]. Positronium (Ps) atom is purely a leptonic system and is a bound state of electron and its anti-particle (positron). Thus Ps can be a potential object to test the discrete symmetries [2-3] violation in the electromagnetic interactions as well as multi-photon entanglement [4-5].
- Positronium atom can be formed in two state based on the spin alignment of its constituting particles, Singlet state ($^1S_0$ – para-Positronium (p-Ps) and Triplet state ($^3S_1$ – ortho-Positronium (o-Ps). Due to the C conservation, p-Ps decays into even number of photons ($^1S_0 \rightarrow 2^*\gamma$, where γ – 1,2,3,..) and o-Ps decays into odd number of photons ($^3S_1 \rightarrow 3^*\gamma$, where γ = 1,2,..). Conservation of energy and momentum forbids single photon annihilation.
- We propose to study the C-forbidden decays of p-Ps ($^1S_0 \rightarrow 3\gamma$) by means of the J-PET detector.

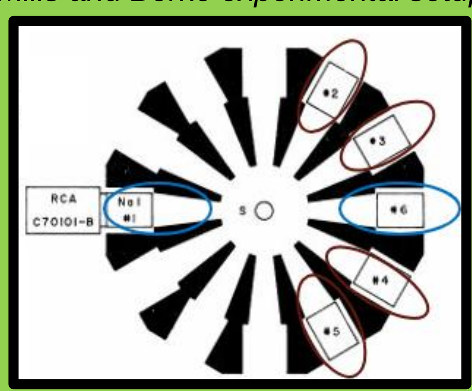
J-PET detector

- J-PET is constructed of 192 polymer scintillators, where each scintillator is attached with photomultipliers at each end.
- ***192 scintillators*** are arranged co-axially in three layers (48, 48, 96) at 3 different radii 42.5 cm, 46.75 cm, 57.5 cm respectively.
- Positronium atom can be formed in the center of J-PET detector using the beta-emitter source placed inside a chamber. The source is sandwiched between an aerogel material.
- Plastic scintillators offers high time and angular resolution.
- Time Over Threshold is adopted as a measure of energy deposition. The signals are measured by using the trigger-less data acquisition [7-9].
- For the Charge conjugate symmetry test, we will use ^{22}Na source.

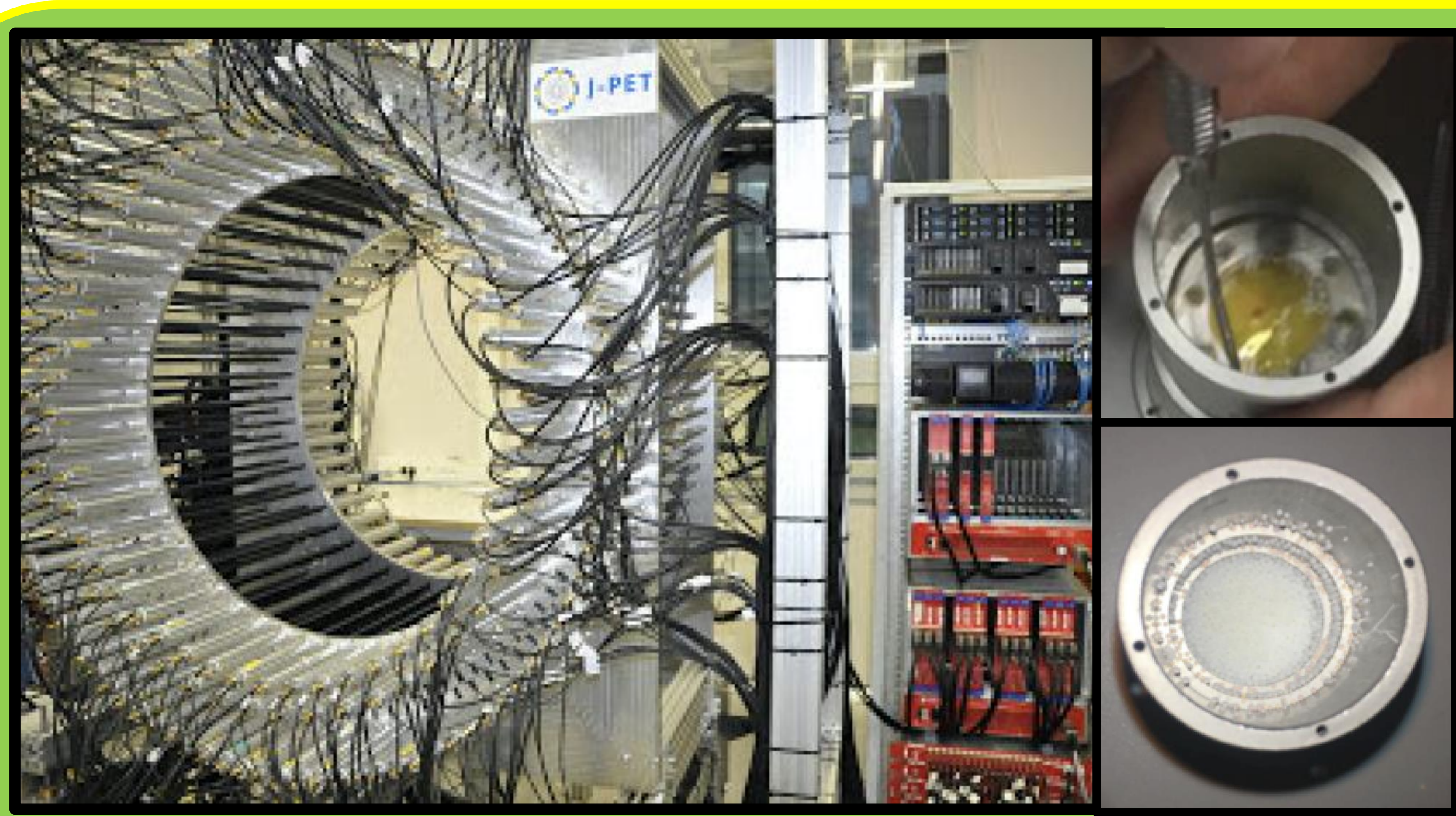
Note on C-symmetry violation tests

- Mills and Berko, perfomed the experiment to search for C-forbidden decays in the decays of p-Ps ($^1S_0 \rightarrow 3\gamma$) [6].

Mills and Berko experimental setup

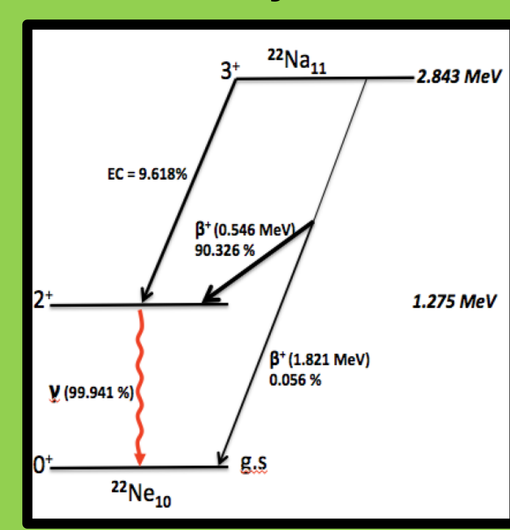


- Experiment was designed to separate the C-forbidden 3γ decay of $^1S_0$ from the allowed 3γ decay of the $^3S_1$ state by studying the "**Angular distribution of the 3 photons**".
- According to **Bose Statistics,** the rate of $^1S_0$ decaying into 3 Photons must vanish a the symmetric configuration (120°, 120°, 120°).
- The limit for the branching ratio for the decay of p-Ps from 3 / 2 was measured ≈ 2.8 x 10^{-6} with the 68 % confidence level.



J-PET detector and annihilation chamber

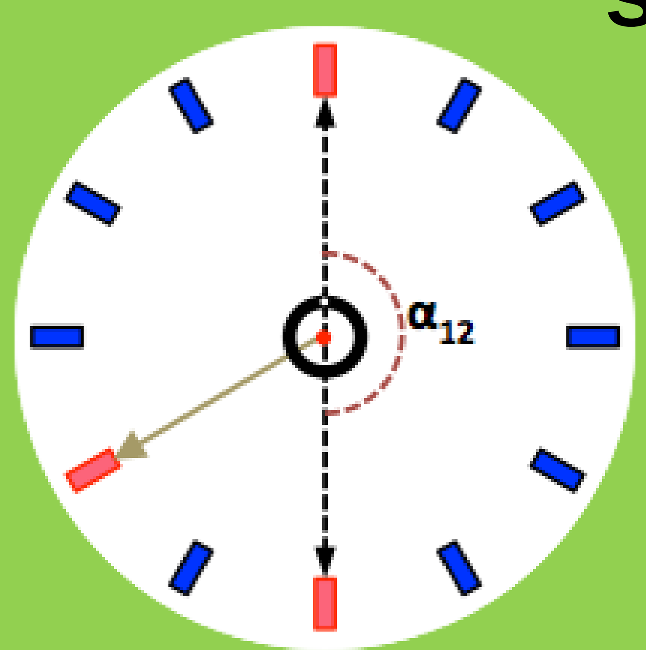
^{22}Na Decay scheme



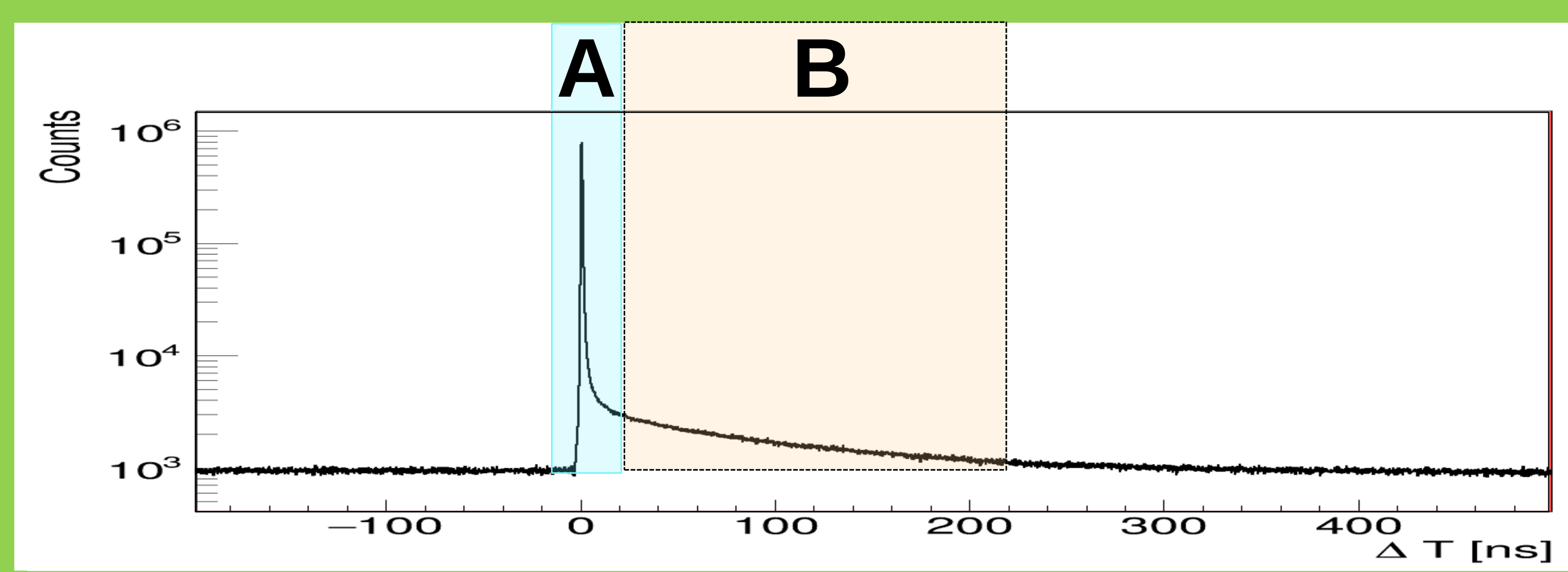
^{22}Na ⟶ ^{22}Ne* + e^+ + ν_e

^{22}Ne* ⟶ ^{22}Ne + $\gamma_{1274keV}$

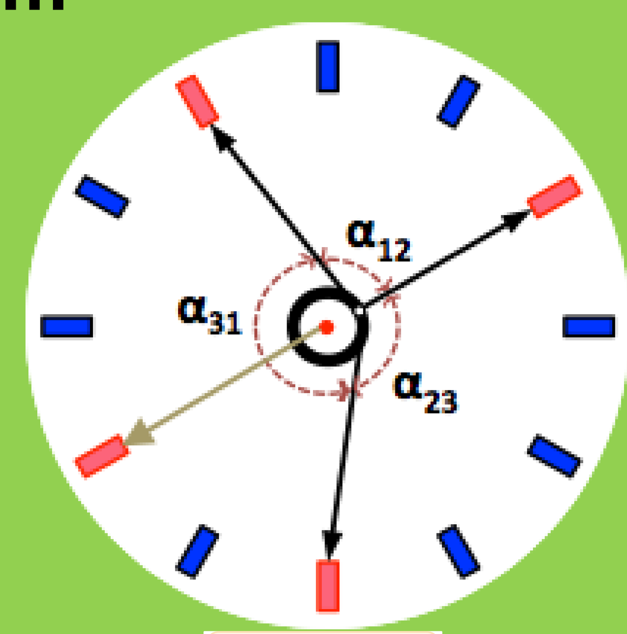
Selection of events based on the life-time of Positronium atom



Ps→2 γ

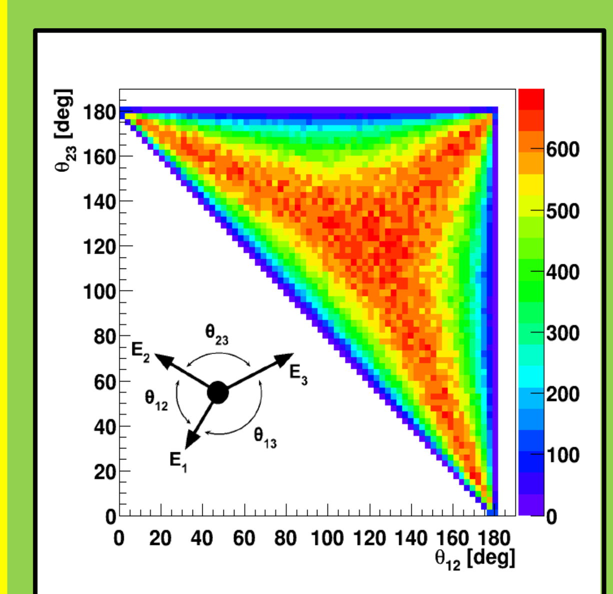


Positronium lifetime spectra [10-11]



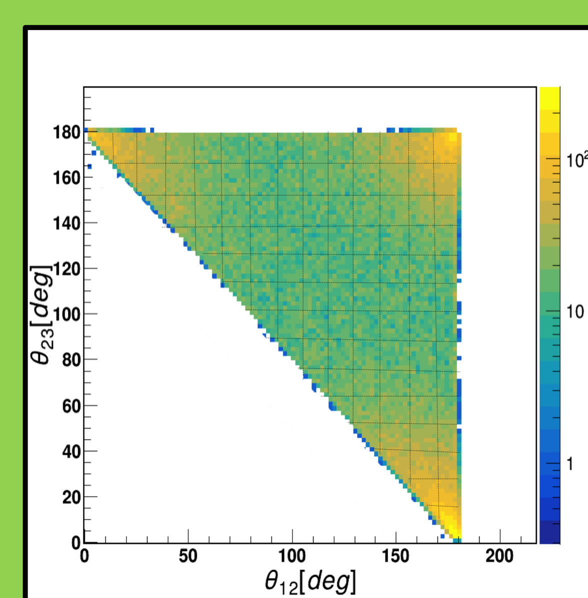
Ps→ 3 γ

Angular correlation of annihilation photons originating from the decay of Ps atom based on the positron life-time spectroscopy



Monte Carlo based generation of o-Ps decays and angular correlations b/w the photons [12]

- ✓ The life time of the positron can be estimated based on the measured time difference (**Δt**) between detection of deexcitation gamma and the annihilation photons.
- ✓ Region **A** presents the time difference where one expect the photons from the decay of p-Ps decay, whereas **B** represents the expected decay from o-Ps with larger **Δt** values.
- ✓ Events with three interactions of annihilation photons with different plastic scintillators will be studied. Angular correlation θ_{12} [deg] and θ_{23} [deg] will be measured for both selected regions separately. Left figure shows the angular correlation between the three photons originating from the o-Ps decay generated by Monte Carlo. Figure on the right side shows such a distribution but simulated based on the Geant4 simulation package by using the J-PET detector geometry. However, in case of 3**γ** from the decay of p-Ps, for the symmetrical configuration one should not expect any contribution at the center.
- ✓ It is planned to compare the angular distributions for the two selected regions (A,B) divided based on the lifetime of positronium atom. The voxelized based ( ) counts will be compared in order to quantify the difference between two measured distributions.



Geant4 based simulation to observe the o-Ps decays and angular correlation b/w the photons using the J-PET detector

Summary:

- ☑ High angular and time resolution along with larger geometrical acceptance of J-PET detector provides the opportunity to study the annihilation photons originating from the decay of positronium atoms.
- ☑ The plan to study the C-forbidden decay (p-Ps → 3γ) by analyzing the angular correlation between the 3-photons investigated over two time scales based on the lifetime of positronium decay is explained.
- ☑ It is expected that due to the characteristics properties of the J-PET detector, one can expect to measure the branching ratio of p-Ps decay (**3γ / 2γ**) with better precision so far.

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