EPJ Web of Conferences **282**, 01003 (2023) https://doi.org/10.1051/epjconf/202328201003
SSP 2022

Search for CP-Violation in ortho-Positronium Decay

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Abstract. We report here on the design and development of a new apparatus aiming at a 10-fold improved search for CP-violation in ortho-Positronium decay to be performed at the Facility for Rare Isotope Beams.

1 Positronium

Positronium (Ps) is a Hydrogen-like system comprised of a bound positron and electron. It is a purely leptonic bound state making it insensitive to hadronic physics or strong interactions. It is an eigenstate of the charge conjugation operator (C), and the Parity operator (P), where the C and P eigenvalues depend on the spin configuration and principal quantum numbers. Positronium constitutes a clean system to search for CP-violation, and any observed CP-violation would be due to Beyond Standard Model physics. Positronium has two spin configurations, para-positronium (p-Ps) the spin-zero singlet state, and ortho-positronum (o-Ps) the spin-one triplet state. By charge selection rules p-Ps can only decay to an even number of photons (primarily 2), and o-Ps can only decay to an odd number (primarily 3). This leads to a much larger lifetime for o-Ps (142 ns) compared to p-Ps (125 ps).

1.1 Positronium Decay

We order the γ's in the 3-γ decay of o-Ps by their energies as indicated in figure 1a). The energy distribution and angular distribution of photons from unpolarized ortho-positronium decay is given in figure 1c) and 1d) respectively. Due to rotational invariance the angular distribution of the decay photons must be proportional to products of the γ momenta and the initial o-Ps spin. We will search for a correlation of the form,

$$\left(\hat{\mathbf{s}} \cdot \hat{\mathbf{k}}_i\right) \hat{\mathbf{s}} \cdot \left(\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2\right) \tag{1}$$

where $\mathbf{s}$ is the spin of the o-Ps, $\mathbf{k}_i$ is the momentum vector for one of the photons. Such a correlation can only be induced by CP-violating physics [1]. Two previous experiments have placed limits on the size of such a correlation of 0.01 in [2], and 0.001 in [3]. We are designing an apparatus to reach a precision of 10^{-4}. We will measure events where we detect both the highest and second highest energy photons. With a highly symmetric detector array we can flip the sign of the correlation and record differences in counts that will be directly sensitive to CP-violating physics.

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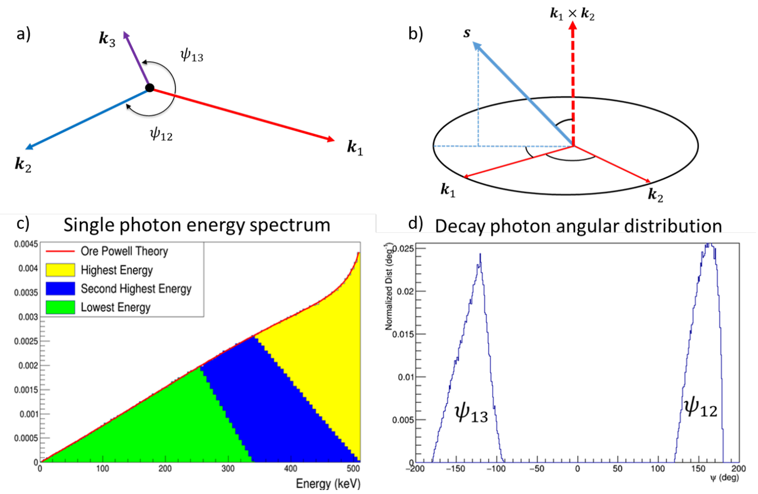

Figure 1. a) Ordering of decay photons by their energies. b) Relevant vectors in o-Ps decay. c) Energy distribution for photons from unpolarized o-Ps. d) Angular distribution of photons within the decay plane for unpolarized o-Ps.

1.2 Positronium Alignment

This correlation requires the use of tensor-polarized positronium and is proportional to the alignment of the o-Ps given as,

$$P_2 = \frac{N_+ - 2N_0 + N_-}{N_+ + N_0 + N_-} \tag{2}$$

where N_i are the population of o-Ps states. We can achieve a nonzero tensor polarization with the same method used in [2]. We utilize a magnetic field to mix the singlet state with the $m = 0$ triplet state. This mixed "pseudo-triplet" state has a shorter lifetime than that of the $N_\pm$ and so P_2 changes over time. The setup includes a cryocooled superconducting magnet which produces a maximum field of 2 T. For a modest field value of 0.4 T the pseudo-triplet lifetime is reduced to 25 ns. Integrating the events within two time windows will give two populations with opposite values of alignment.

2 Positronium Formation

We have constructed a test stand to demonstrate and optimize Ps formation. We use a ^{22}Na source surrounded by finely grained powder. The β^+ slows down while traveling through the powder, and can pick up an electron and form positronium. With our test stand we detect the 1275 keV γ-ray from the ^{22}Na decay, and one of the photons from the Ps annihilation. We use a PIXIE-16 module and NSCLDAQ to read out two LaBr$_3$ detectors in coincidence. A sample time spectrum is shown in figure 2.

Future work includes baking the powder and pumping under vacuum to increase the lifetime of o-Ps by removing moisture. We plan to achieve a larger formation fraction by testing different powders (MgO, SiO$_2$, etc.) as well as different grain sizes for the powders.

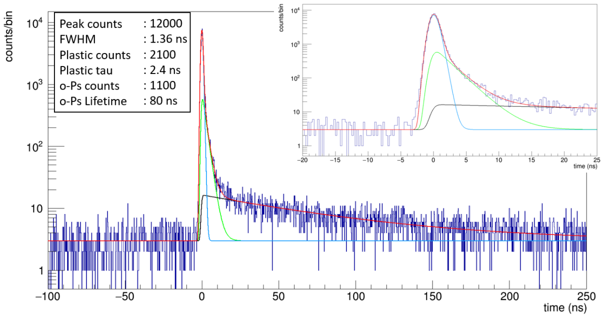

Figure 2. Demonstration of Positronium formation. Early studies clearly show a sharp prompt peak, a component of Ps forming in the plastic surrounding the source, and a long lifetime component of Ps in the MgO powder. The data was taken with 20 nm grain size MgO powder at 0.3 g/cm^3 density and a comercial ^{22}Na source with an activity of 0.16 MBq.

3 Photon Detectors

The annihilation radiation will be detected using crystal scintillators. Lutetium Yttrium Orthosilicate (LYSO) is a crystal scintillator with high scintillation light yield, and moderately fast decay time (45 ns). We have extensively studied LYSO crystals coupled to Silicon Photomultipliers (SiPM). With the prototype detectors we have achieved an energy resolution of 13% at 511 keV using a prototype crystal in the tapered geometry, shown in figure 3. With a pair of crystals we have achieved 1.87 ns timing resolution for coincidences. This will be vital for reducing the rate of random coincidences. We will impose a triple coincidence trigger online, requiring hits in two LYSO crystals and a start coming from a plastic scintillator that the β^+ crosses on its way to the Ps formation region. Due to the compactness of our detectors and the SiPM's we will be able to fit a large number of detectors inside the warm bore of the magnet with a diameter of 22 cm.

Figure 3. A prototype LYSO crystal readout by a Silicon photomultiplier. The tapered design was selected to cover a larger solid angle, and increase photopeak efficiency compared to a parallelepiped. The crystal is 3 cm along the long axis. This picture does not feature any crystal wrapping.

4 Full Apparatus Design

The full apparatus will consist of 3 rings of γ detectors, with 16 detectors in each ring as depicted in figure 4. Due to the angular distribution of k_1 and k_2 shown in figure 1d), for an event where k_1 hits the detector marked with green in figure 4a), k_2 from those decays are detected mostly by our detectors in the opposite ring marked in red and blue. For the process just described the upper red and blue detectors have opposite signs of the angular correlations from their symmetrically located partners (the lower red and blue marked detectors). CP violation would manifest itself as a difference in the number of counts for the upper vs. lower combinations. Similar pairings around the axis of symmetry, as well as other combinations between the outer rings and the center ring, greatly increase the number of detector combinations and solid angle coverage giving us an improved statistical reach compared to previous experiments.

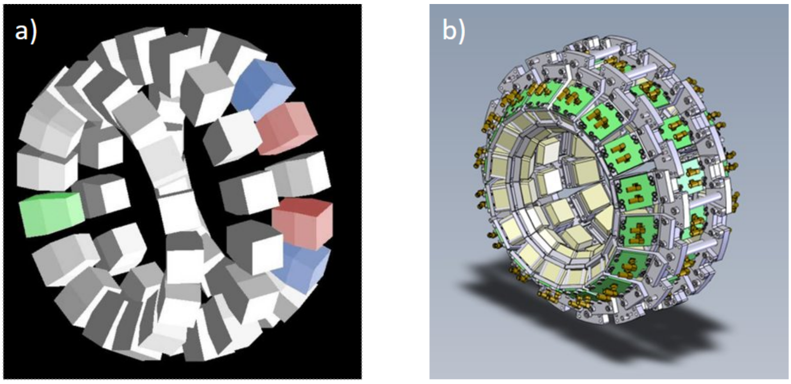

Figure 4. a) Full detector array geometry, placement has been optimized for sensitivity to our observable. b) Support structure to hold all γ- detectors and readout electronics within the warm bore of our magnet.

4.1 Simulations

The geometry has been optimized in concurrent simulations using both Geant4 and EGSnrc. This required writing a custom 3-γ event generator. Effects studied include, 2-γ dilution, random coincidences mimicking signal events, effects of energy resolution and energy cuts, and spreading of the source beyond a point. Our simulations showed no benefit from inclusion of shielding between rings of detectors. With our finalized detector designs, and optimized geometry we have finished design of the full detector array including the support structure as shown in figure 4b).

5 Summary

We have designed an apparatus to search for CP-violation in o-Ps decay. Our compact and highly symmetric design is able to fit within the warm bore of our magnet. We have studied and prototyped our photon detectors, demonstrated formation of Ps, and simulated possible sensitivity limiting effects. Future work includes optimization of Ps formation, construction of the apparatus, and continued study of systematic effects. This design will allow for us to reach a 10 x higher sensitivity than previous searches.

This material is based upon work supported by the National Science Foundation under Grants No. PHY-1920065, PHY-2013557, PHY-1565546, PHY-2111185, and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, operated by Michigan State University, under Award Number DE-SC0000661.

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