

# Caliope: a search for $CPT$ -violation in o-ps

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**Abstract.** CALIOPE, or  $CP(T)$  Aberrant Leptons in ortho-Positronium Experiment, is a tabletop search for fundamental symmetry violations, including  $CP$ - and  $CPT$ -violation, in ortho-positronium (o-Ps). We use a tagged  $^{22}\text{Na}$  source adjacent to a cylinder of aerogel to generate o-Ps at the center of a cylindrical array of 24 NaI(Tl) bars. We search for  $CPT$ -violating angular correlations in the gamma rays emitted in the decay of o-Ps. With an angular acceptance of 75% of  $4\pi$ , and the ability to acquire statistics over a longer period of time, CALIOPE will improve upon the limit set by previous experiments. The experimental setup can also be used in a search for  $CP$ -violation in o-Ps with the addition of an electromagnet. We describe the design of the experiment, results from a characterization of the systematics for the  $CPT$ - and  $CP$ -violating measurements, and a demonstration of the DAQ.

## 1. Introduction

Positronium (Ps) is an unstable bound state of an electron and positron, which exists in both triplet and singlet states. Due to charge conjugation parity, the triplet state (ortho-positronium, or o-Ps) decays primarily to three gamma rays and the single state (para-positronium, or p-Ps) decays primarily to two gamma rays. Bound by a central potential, Ps is an eigenstate of parity. Free from QCD effects, it is a system fully described by quantum electrodynamics with small weak corrections. These properties make it a clean system for fundamental symmetry violation searches.  $CPT$ -violating searches in decay processes are potential sources for new physics beyond the Standard Model. Matter/antimatter tests have constituted the majority of  $CPT$ -violation searches in the past. As such, decay processes present an interesting potential source of  $CPT$ -violation.  $CPT$ -conservation is a foundation of theoretical physics, so its discovery in the lepton would upend our current understanding of physics. These proceedings will focus on the  $CPT$ -violation search, but some discussion of progress towards a  $CP$ -violation search will also be included.  $CP$ -violation searches in the lepton sector are a burgeoning field since more  $CP$ -violation is necessary to explain the preponderance of matter over antimatter in the observable universe [1].

We search for  $CPT$ -violation by measuring the following  $CPT$ -odd observable [2]:

$$\left(\vec{S} \cdot \vec{k}_1 \times \vec{k}_2\right) \quad (1)$$

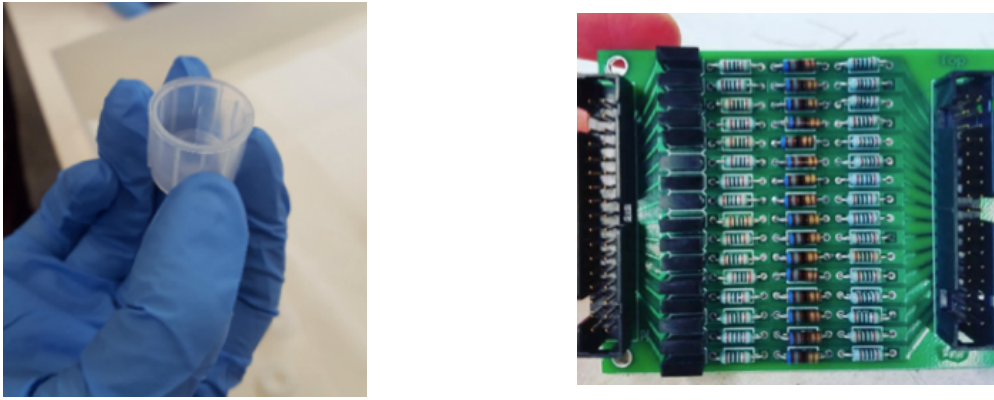
where  $\vec{S}$  is the spin of the positronium,  $\vec{k}_1$  is the highest energy gamma ray emitted in the



decay of o-Ps and  $\vec{k}_2$  is the second highest energy gamma ray emitted in the decay of o-Ps. We know from the position of the source relative to the aerogel and the array that some fraction of the spin is aligned along the z-axis. In our reconstruction of this observable, we assume a net spin polarization along the z-axis. We calculate the up/down asymmetry, or the number of times our observable is positive ( $N_+$ ) or negative ( $N_-$ ) via

$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad (2)$$

To compare with previous experiments, we then compute the *CPT*-violating term  $C = A/\langle P \rangle$ , where  $\langle P \rangle = 0.41$  is the average polarization for  $^{22}\text{Na}$ . We aim to make an improvement a previous, similar experiment, which found no *CPT*-violation and measured  $C = 0.0026 \pm 0.0031$  [3].



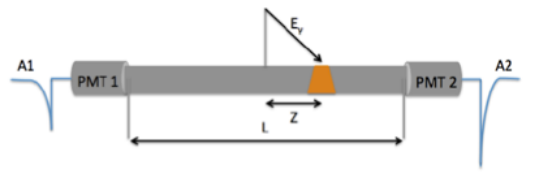
**Figure 1.** Left: Aerogel before being placed into the source holder. Right: Custom-built attenuator board for the DAQ.

## 2. Methodology

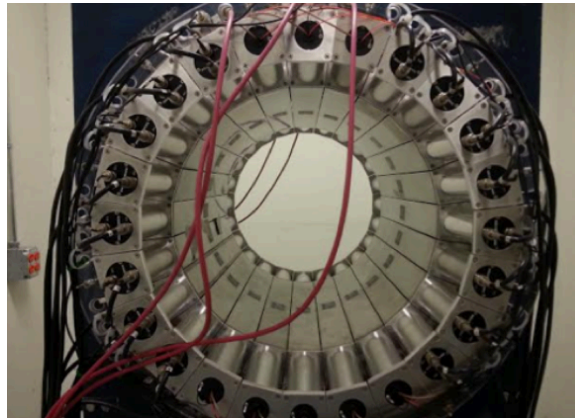
CALIOPE uses the APEX array [4], which consists of 24 NaI(Tl) bars arranged cylindrically. Each NaI(Tl) bar is bookended by PMTs. The positronium is generated at the center of the array using a  $^{22}\text{Na}$  source flush against a solid cylinder of aerogel. The aerogel and source are contained within a holder that sits inside of a carbon fiber tube mounted inside the array. Silica aerogel is highly porous and serves as an effective positronium generator. We flow nitrogen through the carbon fiber tube to purge the aerogel, which helps eliminate pick-off annihilation, where the positron in the positronium annihilates with an electron in the ambient material. Positrons emitted in the decay of  $^{22}\text{Na}$  thermalize in the aerogel and eventually interact with an electron from the surroundings to form positronium. Some fraction of the positrons form positronium in the triplet state (o-Ps), which decays to three gamma rays. These three gamma rays are our signal. The hits are registered in the NaI(Tl) bars. Position and energy reconstruction is achieved using the charge amplitudes from the PMTs at either end of a bar. The light from an ionizing interaction in the bar falls off exponentially as it reaches the end of the bar:

$$A_{\pm} = \frac{E_{\gamma} P}{E_0} \exp(-\mu(L/2 \pm x)) \quad (3)$$

where  $\mu$  is the attenuation coefficient,  $L$  is the length of the bar,  $P$  is the quantum efficiency of the PMT,  $E_{\gamma}$  is the energy deposited by the gamma ray, and  $E_0$  is the energy deposited per light photon created in the scintillator. The energy is then proportional to the square root of the product of the charge amplitudes at either end of the bar, and the position is proportional to the natural log of the ratio of the two charge amplitudes [5].



**Figure 2.** Position reconstruction uses the relative amplitudes of the pulses at either end of a NaI(Tl) bar as shown above.



**Figure 3.** Front view of the APEX array at TUNL.

### 3. DAQ

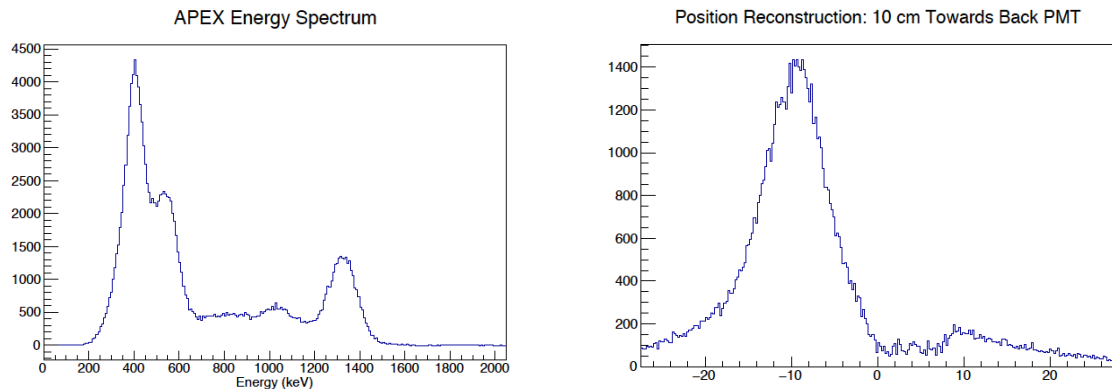
CALIOPE uses a VME-based DAQ consisting of CAEN QDCs and TDCs to measure the charge deposition and timing. Signals from the PMTs are split into high and low gain channels and amplified. Signals for the low gain channels are attenuated before reaching the QDC.

We have successfully calibrated all bars in the array and have been able to demonstrate energy and position reconstruction. The PMTs were calibrated using a  $10\mu\text{Ci}$  source located between two lead cylinders which serve as a collimator. The lead collimator is housed inside of a delrin tube attached to a 1.07 m rod that sits inside of an aluminum pipe. The rod is etched every 0.5 cm, enabling us to position the source with the same level of precision. The lead cylinders constrain the gamma rays such that they only emerge from the gap, which is typically only about 1 mm in width. Using this collimated source, we were able to demonstrate position and energy reconstruction capabilities along the length of the bar. See fig 4 below.

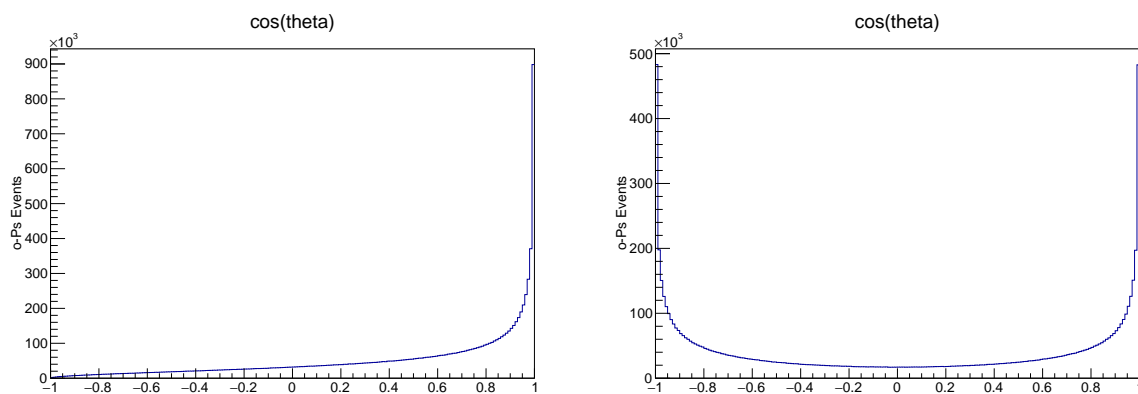
### 4. Simulation

We have developed a Geant4 [6] Monte Carlo simulation to characterize systematic effects of our experiment. Because Geant4 does not include the ability to model positronium physics, we wrote custom code to generate the o-Ps decay kinematics. The APEX array was modeled in its entirety, and the carbon fiber structure which holds the positronium generator was included. An example of our simulation results both with and without *CPT*-violation is shown. The code has the ability to study different systematic effects such as variations in the bar thickness and translations and rotations of the source holder.

One example of a systematic that did not yield any fake asymmetry is a translation of the source holder. A translation of the source holder would have the effect of shifting the decay vertex of the o-Ps. At first glance, this seems to yield a potential systematic. As shown in to



**Figure 4.** Left: Energy spectrum from a collimated  $10\mu\text{Ci}$   $^{22}\text{Na}$  and  $1\mu\text{Ci}$   $^{133}\text{Ba}$  source sitting on an individual APEX bar. Right: Position reconstruction for a  $10\mu\text{Ci}$   $^{22}\text{Na}$  collimated source positioned 10 cm towards the front of the array.



**Figure 5.** Left: Exaggerated example of CPT-violation using the positronium generator code. Right: Example of no CPT-violation, using the same code.  $\theta$  is the angle between the spin axis ( $z$ -axis) and the normal to the decay plane.

the left of fig 6, an assumption that the source holder is centered (red ( $\vec{k}_1$ ) and blue ( $\vec{k}_2$ ) gamma rays) yields a negative triple correlation term, when in reality the true triple correlation term is positive (green  $\vec{k}_1$  and violet  $\vec{k}_2$ ). There is, however, no preferred orientation for  $\vec{k}_1$  as opposed to  $\vec{k}_2$ , so for every positive triple correlation term flipped to negative, there will be a negative triple correlation term flipped to positive. In other words,  $\vec{k}_1$  could equally well be blue instead of red and violet instead of green. Thus, from geometrical considerations alone, a translation should not cause a systematic effect.

Shown below is a Geant4 rendering of the APEX array, with the carbon fiber tube and, therefore, source holder, with an exaggerated rotation about the  $x$ -axis of the array. This was shown to not contribute any source of systematic error.



**Figure 6.** Left: Rotated source holder inside APEX array using Geant4. Right: Example of an event which flips sign when the source holder is translated.

## 5. Conclusion

CALIOPE will search for  $CPT$ -violating angular correlations between gamma rays emitted in  $o$ -Ps decay. We have demonstrated the capabilities of the DAQ and developed the simulation. Data-taking will commence this fall.

### 5.1. Acknowledgments

The authors wish to thank the TUNL staff, especially Matthew Busch and Brogan Thomas for the design of the support structure needed to mount the source inside the array, and Mohammad Ahmed, for his help with the DAQ.

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