Search for CP-Violation in ortho-Positronium Decay

T.E. Haugen[1], E.A. George[2], O. Naviliat-Cuncic[1,3], P.A. Voytas[2]

1. Department of Physics and Astronomy and Facility for Rare Isotope Beams, Michigan State University,
2. Department of Physics, Wittenberg University
3. Laboratoire de Physique Corpusculaire de Caen, IN2P3/CNRS and Universite de Caen Normandie

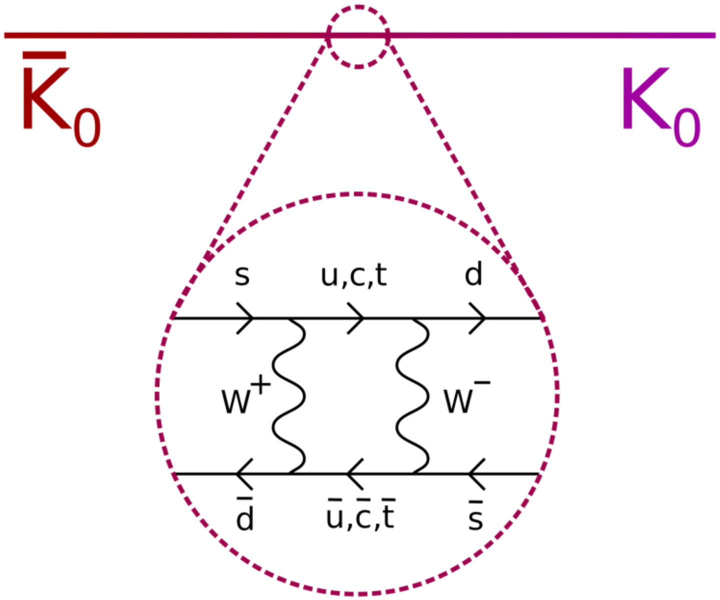
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC000061, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Overview

- CP Violation
- Positronium physics
- Previous measurements and sensitivity goal
- Positronium production and detection
- Hardware design and prototyping
- Full experimental design and simulations
- Next steps

CP Violation

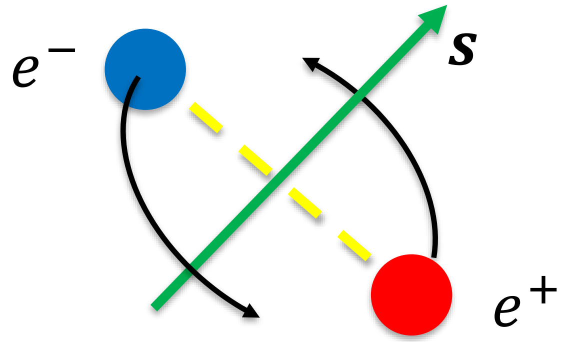
- Combined Charge (C) and Parity (P) reversal.
- Standard model admits CP violation through:
  - Phases in CKM and PMNS mixing matrices.
    - Discovered in Kaons at Na31 experiment in 1964
    - Observed in neutrinos at T2K in 2020
- Generation of observed matter-antimatter asymmetry requires CP-violation.
  - Observed amount requires beyond standard model physics.



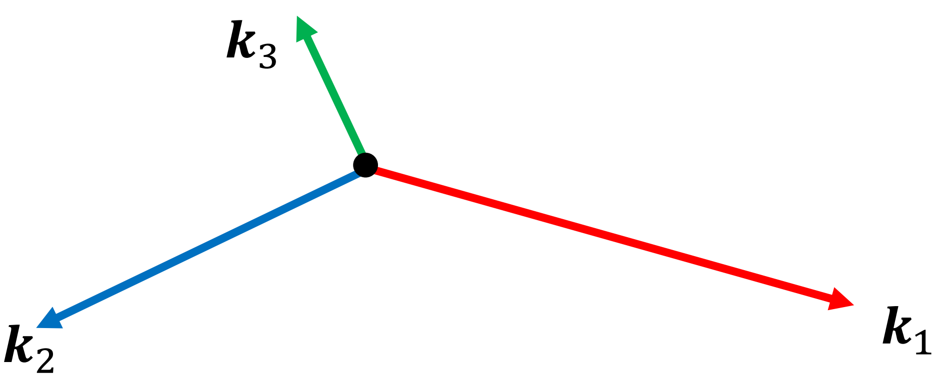
File:Kaon-box-diagram-with-bar.svg. (2016, February 27). *Wikimedia Commons, the free media repository*.

Positronium physics

- Purely leptonic system.
- Charge and Parity eigenstate.
- Forms two states:
  - Spin zero singlet, “para-Positronium”
    - » Two photon decay
    - » Lifetime 125 ps
  - Spin one triplet, “ortho-Positronium”
    - » Three photon decay
    - » Lifetime 142 ns



$$|S=0,m=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\uparrow\downarrow\rangle)$$



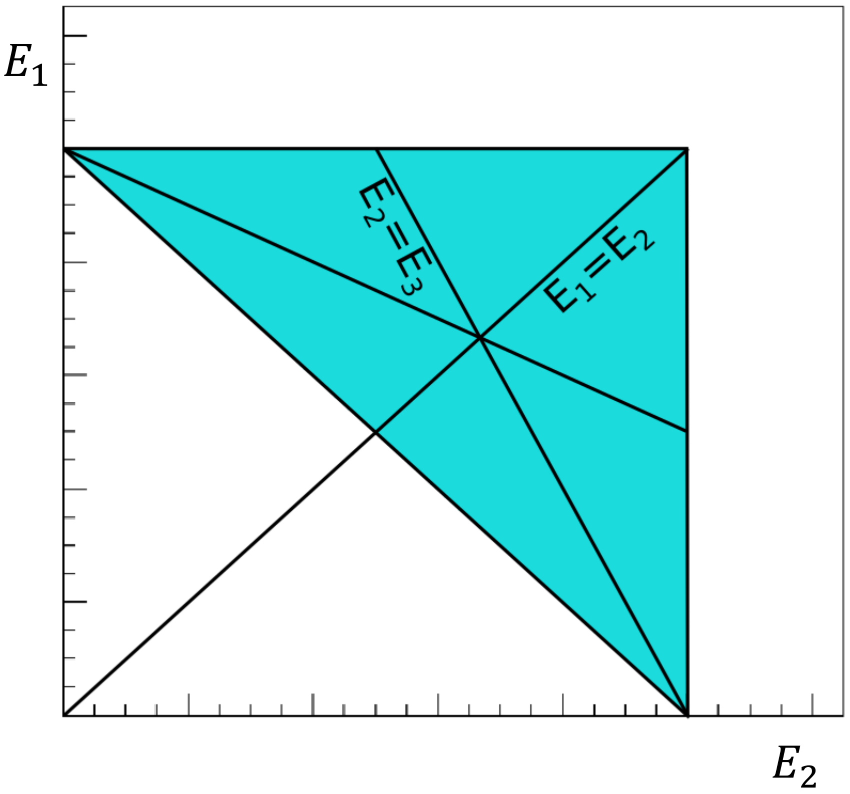
$$|S=1,m=1\rangle = |\uparrow\uparrow\rangle$$

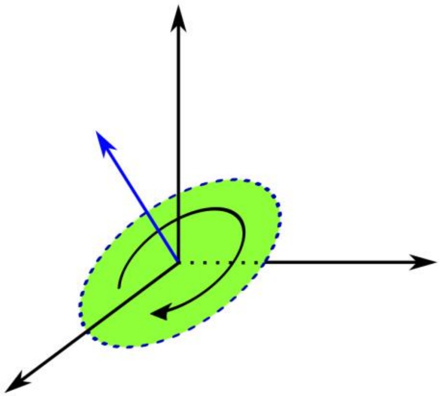
$$|S=1,m=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle)$$

$$|S=1,m=-1\rangle = |\downarrow\downarrow\rangle$$

Kinematics of three photon decay

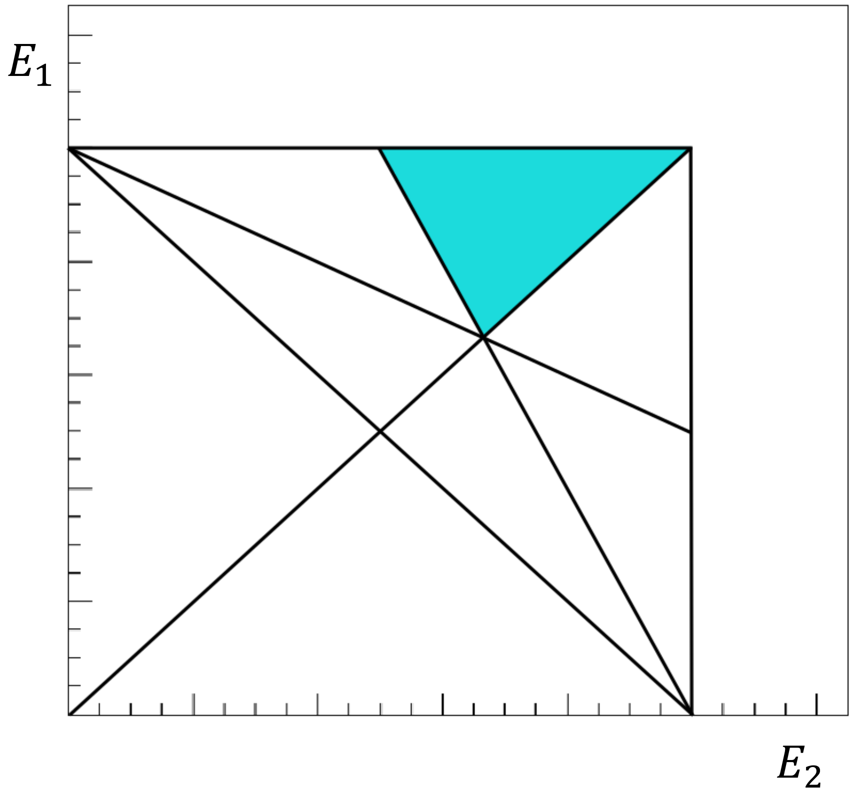
- Three body phase space characterized by:
  - Normal of decay plane,
  - Rotation within decay plane,
  - Energies of two particles.
- Phase space is flat in E_1 and E_2
- Our particles are:
  - Massless, no lower bound.
  - **Identical, region is 6-fold redundant.**

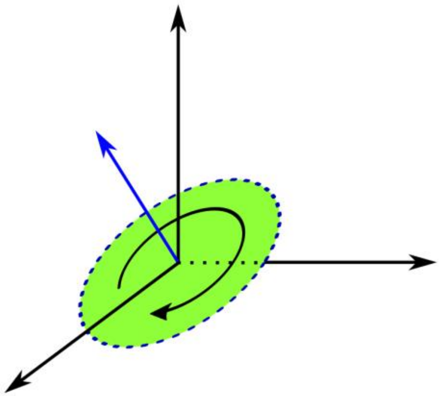




Kinematics of three photon decay

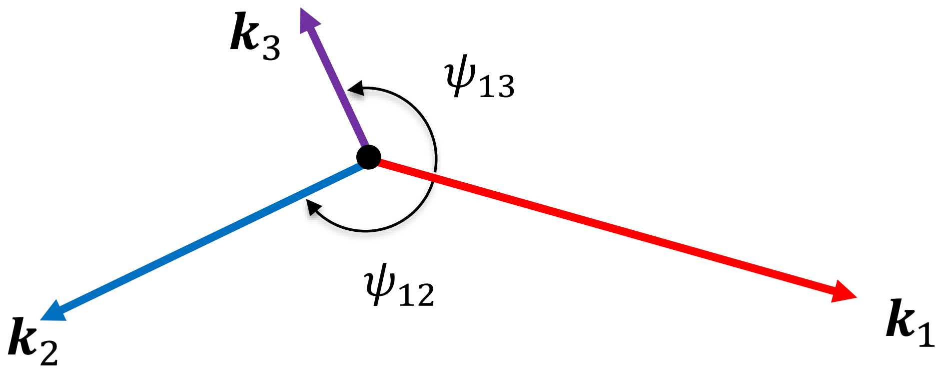
- Three body phase space characterized by:
  - Normal of decay plane,
  - Rotation within decay plane,
  - Energies of two particles.
- Phase space is flat in E_1 and E_2
- Our particles are:
  - Massless, no lower bound.
  - **Identical, region is 6-fold redundant.**

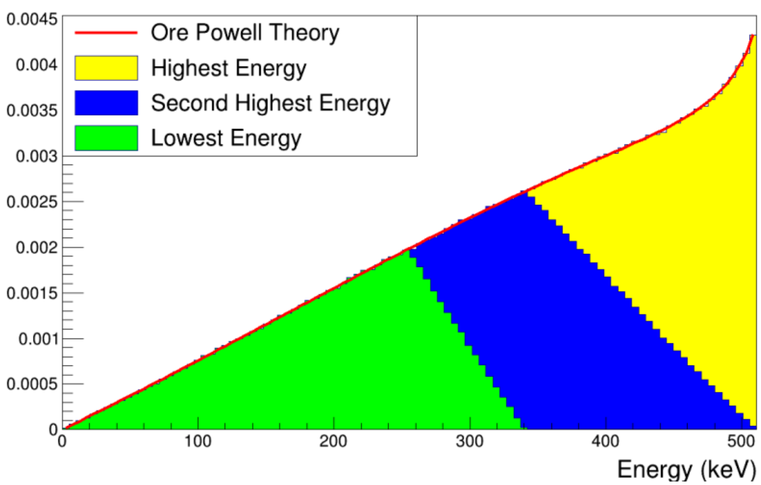


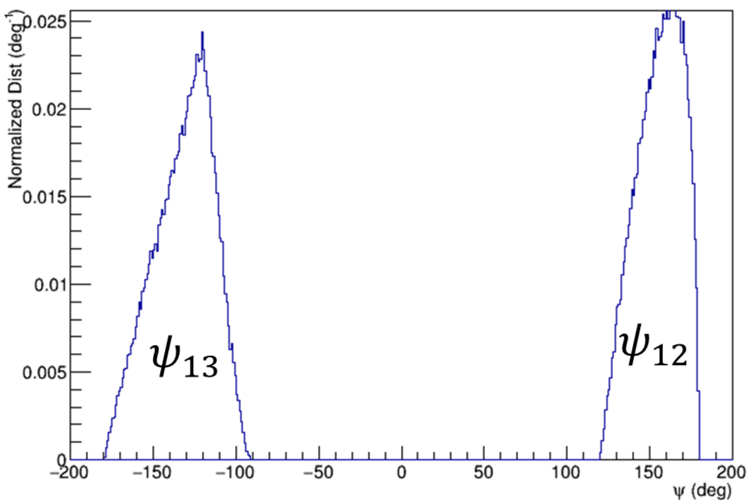


Kinematics of three photon decay (cont.)

- Ore Powell calculated energy distribution for unpolarized o-Ps.
- Simulated angles in the plane, where the energies go as $\boldsymbol{k}_1 > \boldsymbol{k}_2 > \boldsymbol{k}_3$.
- Angular distribution within decay plane shown.

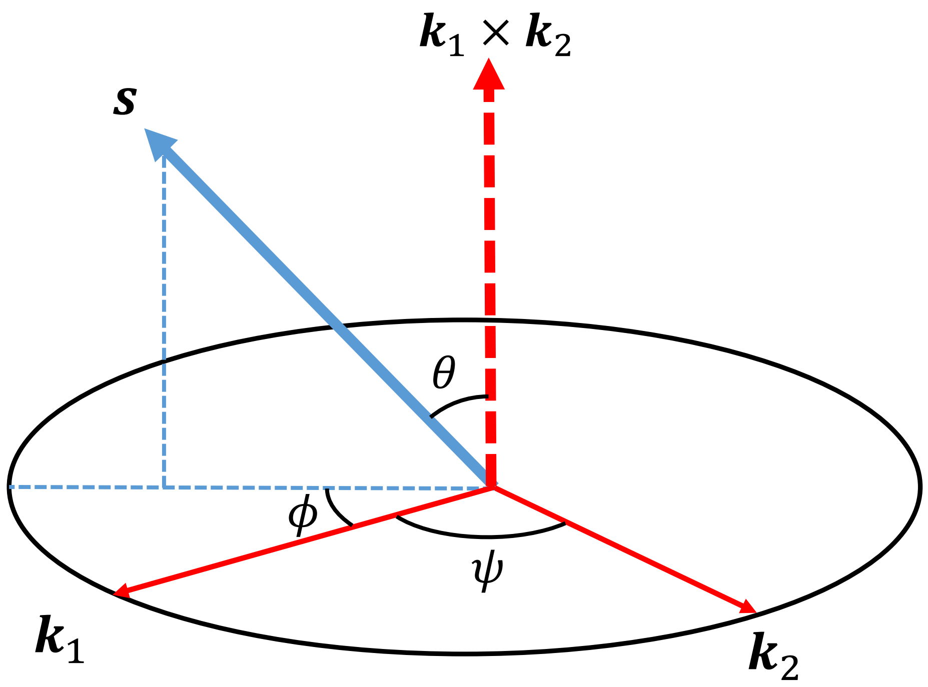






Constructing Observables

- Vectors of interest:
  - Spin of positronium,
  - Photon 1 momentum,
  - Photon 2 momentum,
  - Normal of decay plane.



- CPT odd observable,

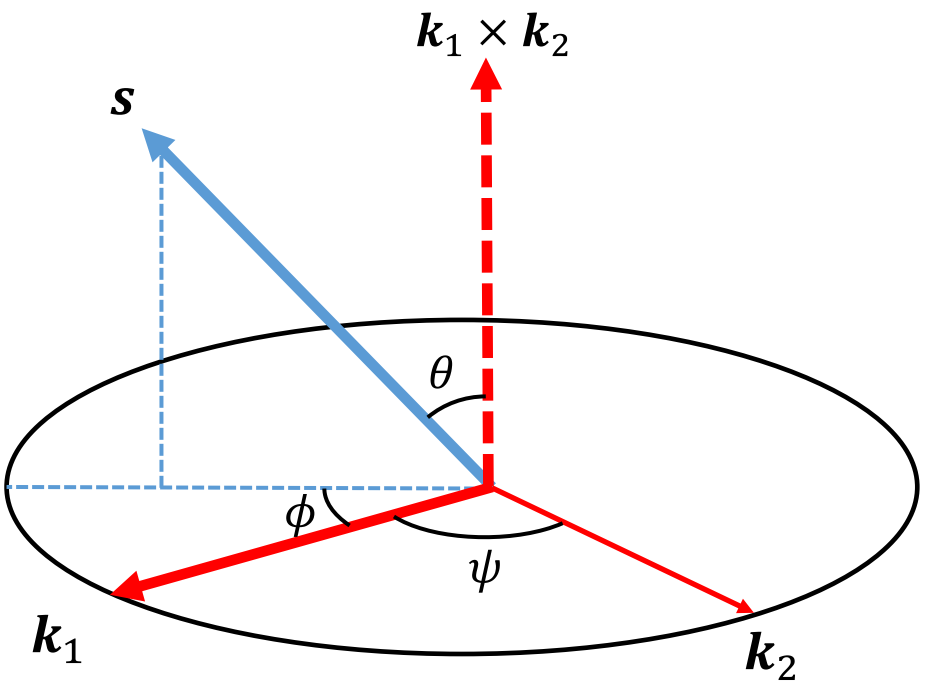
$$C_{CPT}\boldsymbol{s} \cdot (\boldsymbol{k}_1 \times \boldsymbol{k}_2)$$

  - Excluded at 2% precision in 1988 [1]
  - Exluded at 0.3% precision in 2003 [2]

[1] B. K. Arbic, S. Hatamian, M. Skalsey, J. Van House, and W. Zheng Phys. Rev. A 37, 3189 (1988)
[2] P. A. Vetter and S. J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)
[3] W. Bernreuther, U. Low, J. P. Ma, and O. Nachtmann, Z. Phys. C **41**, 143 (1988).

Constructing Observables

- Vectors of interest:
  - Spin of positronium,
  - Photon 1 momentum,
  - Photon 2 momentum,
  - Normal of decay plane.



- CPT odd observable,

$$C_{CPT}\,\boldsymbol{s}\cdot(\boldsymbol{k}_1\times\boldsymbol{k}_2)$$

  - Excluded at 2% precision in 1988 [1]
  - Exluded at 0.3% precision in 2003 [2]

- CP odd observable,

$$C_{CP}(\boldsymbol{s}\cdot\boldsymbol{k}_1)[\boldsymbol{s}\cdot(\boldsymbol{k}_1\times\boldsymbol{k}_2)]$$

  - **Any CP violation** in positronium will result in a non-zero correlation [3]

[1] B. K. Arbic, S. Hatamian, M. Skalsey, J. Van House, and W. Zheng Phys. Rev. A 37, 3189 (1988)
[2] P. A. Vetter and S. J. Freedman, Phys. Rev. Lett. 91, 263401 (2003)
[3] W. Bernreuther, U. Low, J. P. Ma, and O. Nachtmann, Z. Phys. C **41**, 143 (1988).

Constructing Observables

- CP violating observable,

$$C_{CP}(\boldsymbol{s}\cdot\boldsymbol{k}_1)[\boldsymbol{s}\cdot(\boldsymbol{k}_1\times\boldsymbol{k}_2)]$$
$$= \mathrm{C_{CP}}\frac{P_2}{2}\sin 2\theta \sin\psi \cos\phi$$

  - Require *tensor polarized* positronium.

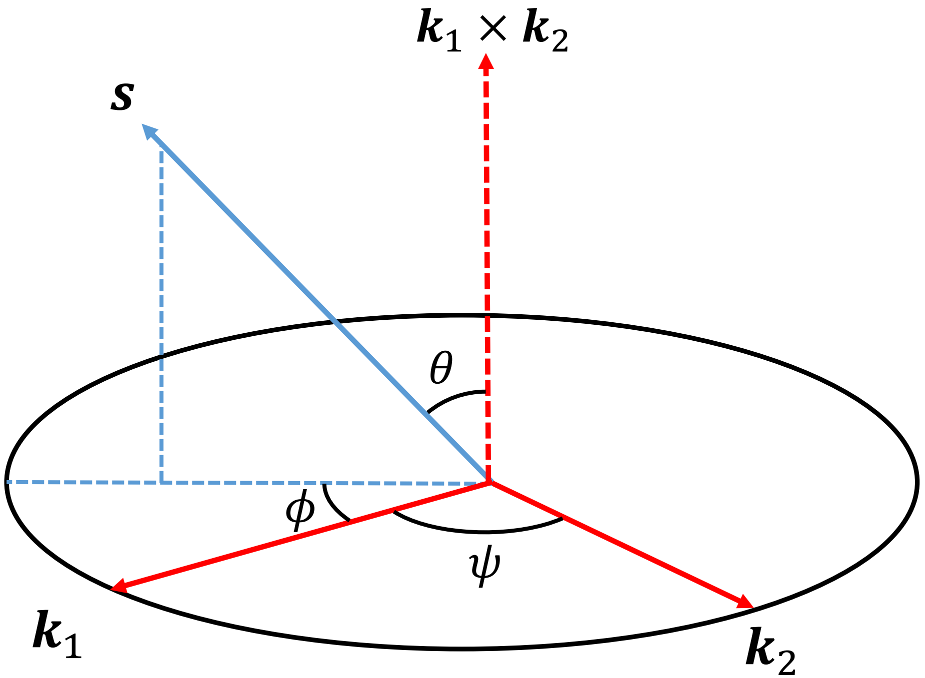
$$P_2 = \frac{N_+ - 2N_0 + N_-}{N_+ + N_0 + N_-}$$

- Define combination of angles as geometric analyzing power

$$G_e = \frac{1}{2}\sin 2\theta \sin\psi \cos\phi$$

- Sign of correlation changes under:
  - Flip of P_2,
  - Flip of normal of decay plane.

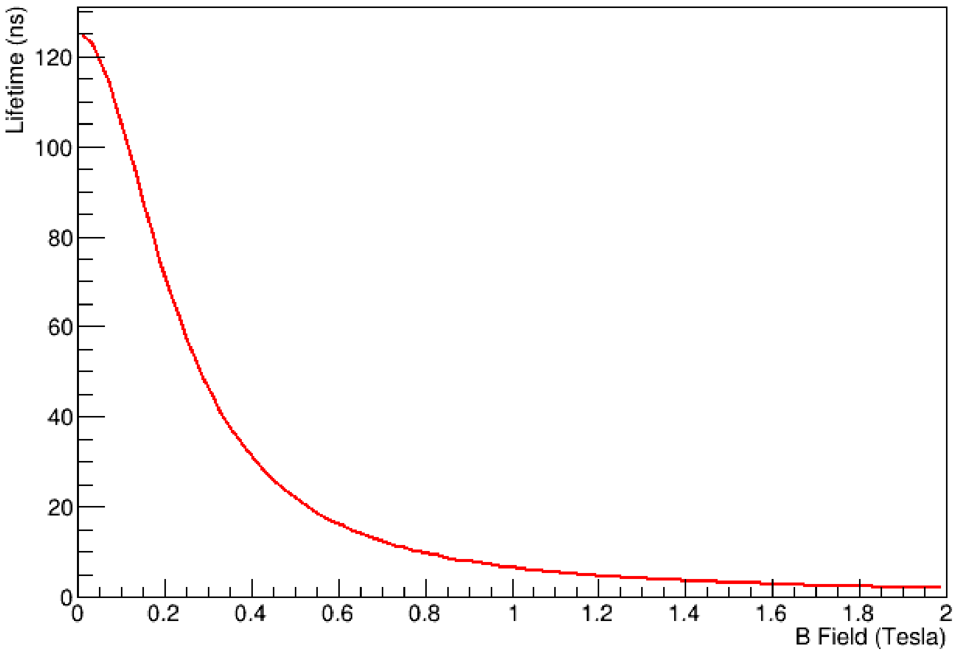
- Sign **does not change** under interchange of $\boldsymbol{k}_1 \leftrightarrow \boldsymbol{k}_2$



Tensor Polarization from Time Spectroscopy

- $\mathrm{m} = 0$ states mix in magnetic field.
- Small mixing leads to large quenching from difference in lifetime.
- New states:
  - pseudoSinglet,
  - pseudoTriplet.
- Tensor polarization now evolves in time.

$$P_2 = \frac{N_+ - 2N_{T'} + N_-}{N_+ + N_{T'} + N_-}$$

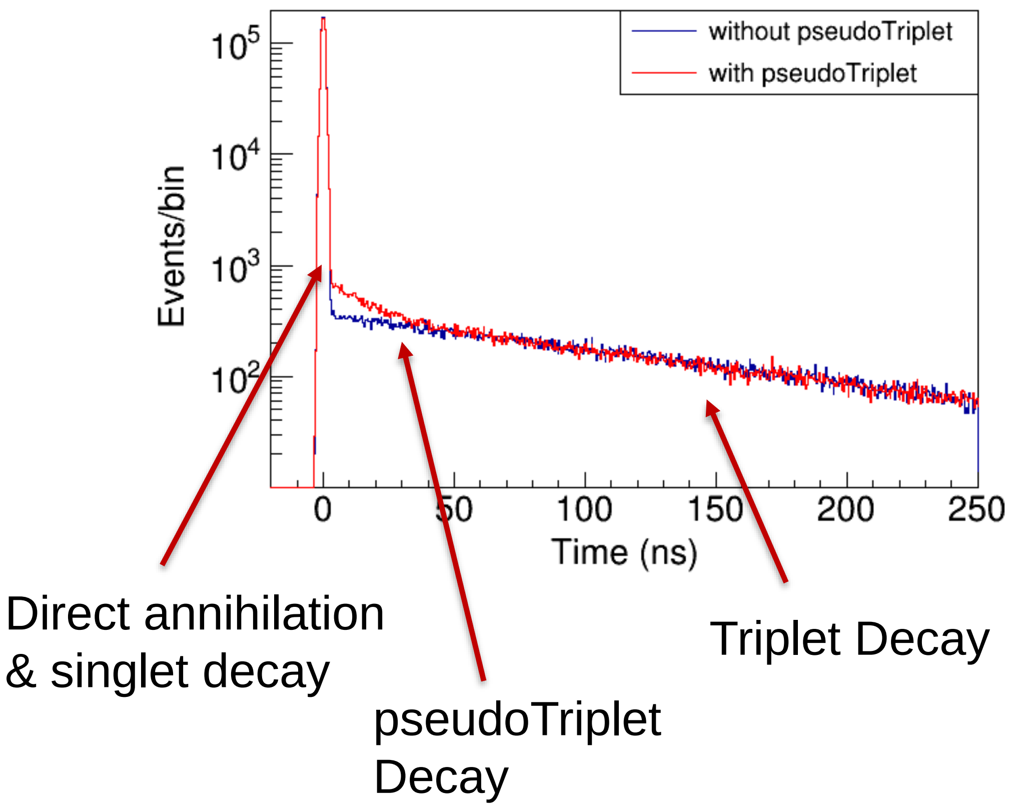


$$|\psi_{S'}\rangle = \cos\theta\,|\psi_S\rangle - \sin\theta\,|\psi_T\rangle$$
$$|\psi_{T'}\rangle = \sin\theta\,|\psi_S\rangle + \cos\theta\,|\psi_T\rangle$$

Positronium Decay Spectrum

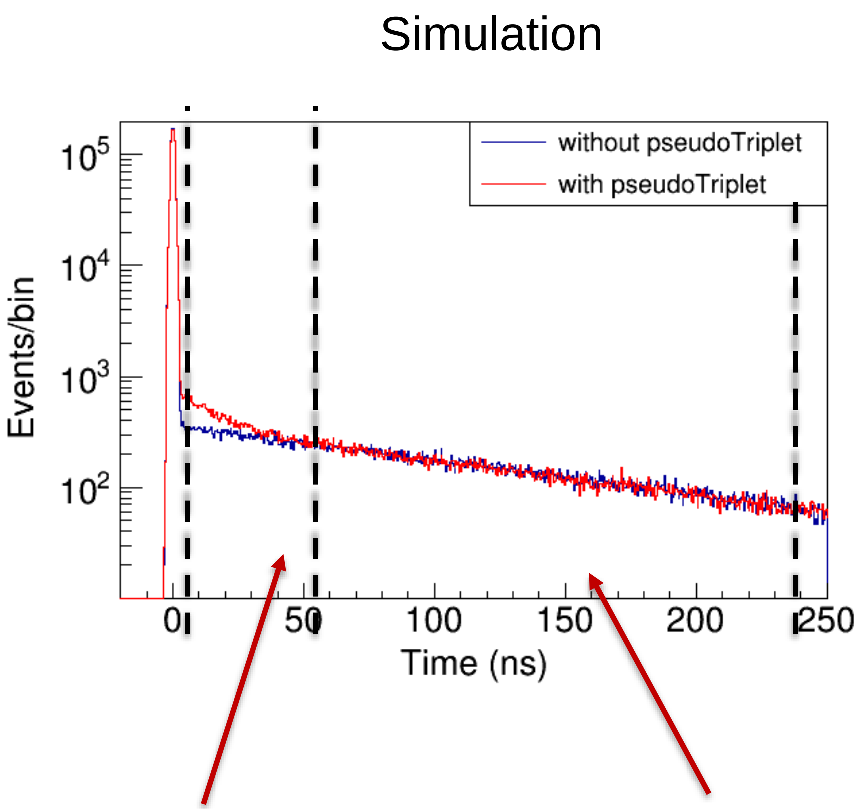
- Construct time spectra of positronium decay.
- Sharp peak from annihilation
- Two lifetime components:
  - Triplet decay
  - pseudoTriplet decay

Simulation



Positronium Decay Spectrum

- Construct time spectra of positronium decay.
- Sharp peak from annihilation
- Two lifetime components:
  - Triplet decay
  - pseudoTriplet decay
- Integrate in 2 time windows flips the sign of the tensor polarization.



$$\langle P_2 \rangle_1 = -0.5 \qquad \langle P_2 \rangle_2 = 0.5$$

UoM measurement

- Form Positronium in magnetic field.
- Measure coincident γ,
  - Dedicated $\mathbf{k}_1$ detector.
  - Flip decay plane by using different $\mathbf{k}_2$ detectors
  - Measure difference in counts between configurations.
- Measured at University of Michigan (1991) [4],

$$C_{cp} = -0.0056 \pm 0.0154$$

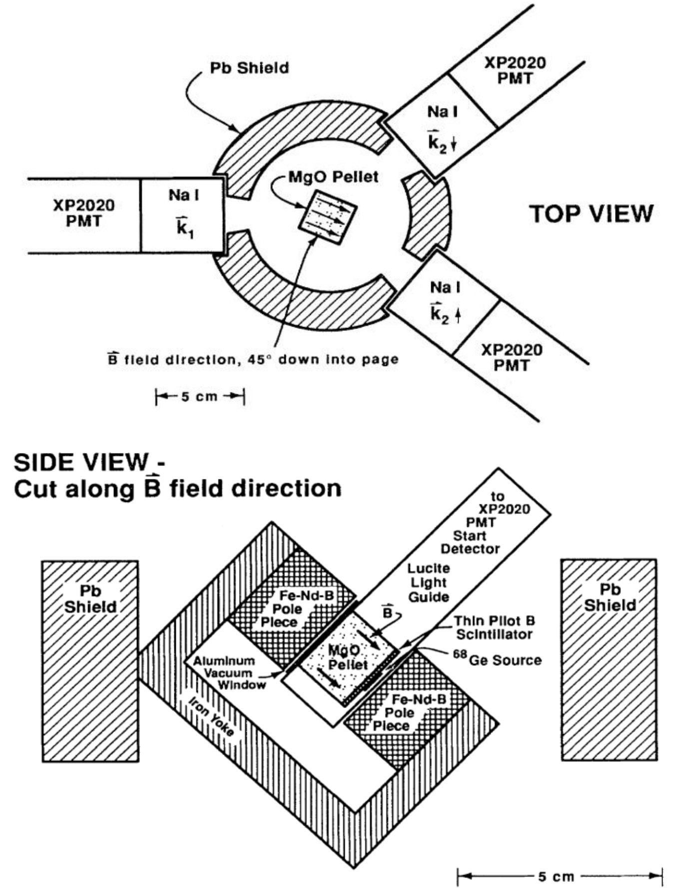


FIG. 1. Experimental apparatus. Spin-aligned Ps is formed in MgO powder from ^{68}Ge e^+ in the presence of a magnetic field. Annihilation γ rays are detected using three NaI scintillators.

[4] M. Skalsey and J. V. House, Phys. Rev. Lett. **67**, 1993 (1991).

UTokyo measurement

- Have detectors in plane
- Move detector setup in circle
- Search for sin(ϕ) correlation
- Measured at University of Tokyo (2010) [5]

$$C_{cp} = 0.0013 \pm 0.0021\ (\text{stat})\ \pm 0.0006\ (\text{syst})$$

- Ran for 6 months and were statistically limited!
- Main systematic uncertainty was step size of stepper motor.

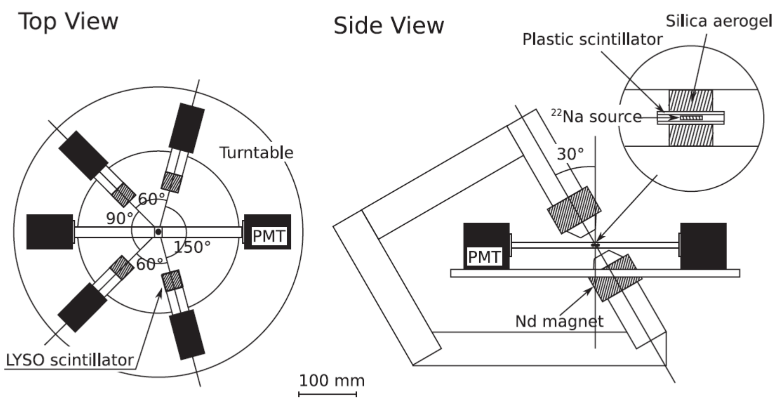
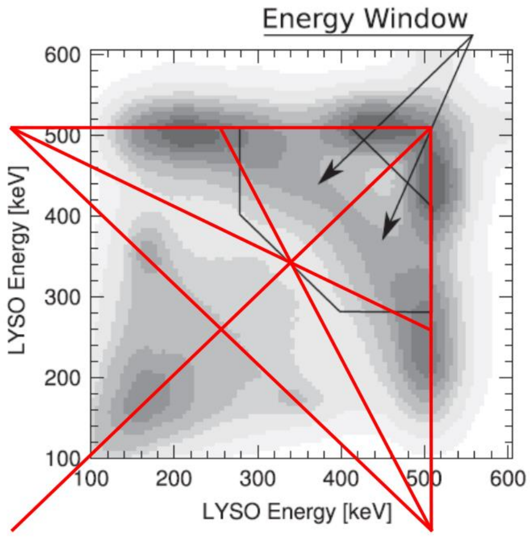


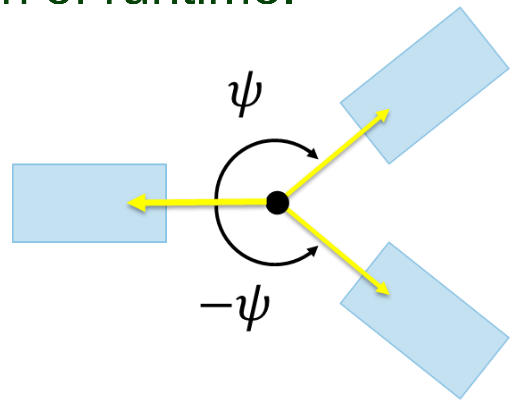
FIG. 1. Schematic diagrams of the experimental setup. The magnified view around the ^{22}Na source is shown in the circle. Left and right show the top and side view, respectively.

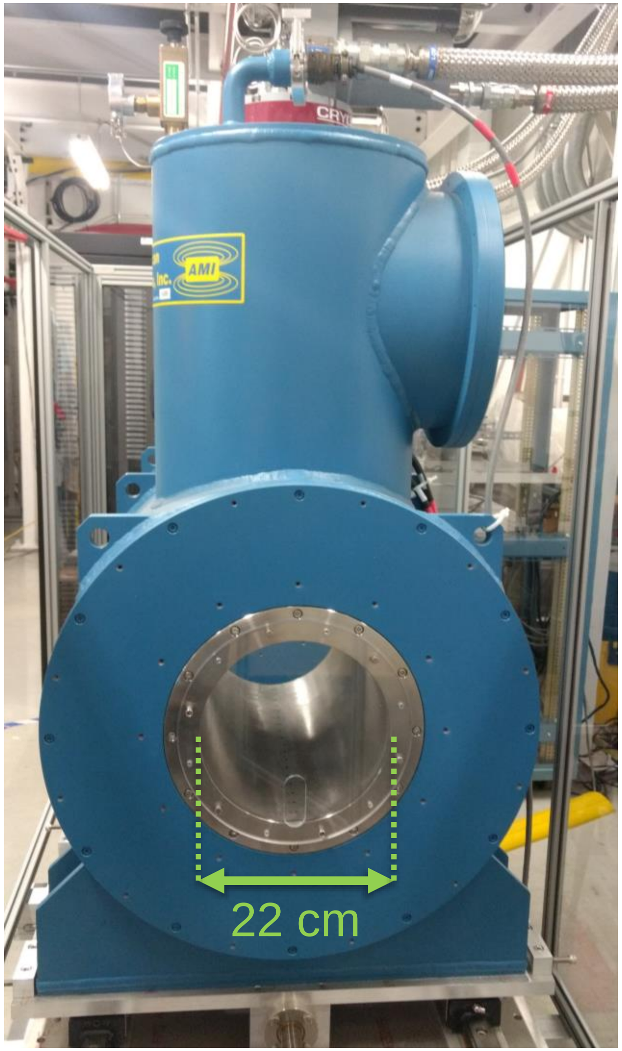


[5] T. Yamazaki, T. Namba, S. Asai, T. Kobayashi, Phys. Rev. Lett. **104**, 083401 (2010).

Design outline

- Follow design of UoM.
- Detector system placed within electromagnet.
  - FRIB Positron Polarimeter magnet will be used.
  - Can run up to 2 Tesla
- Positronium source at center of array.
- Sets of 3-detectors to allow flipping of $\mathbf{k}_2$.
- Maximize number of sets to increase statistics
- Goal of **ten-fold improvement on limit** in one month of runtime.





Super-ratio

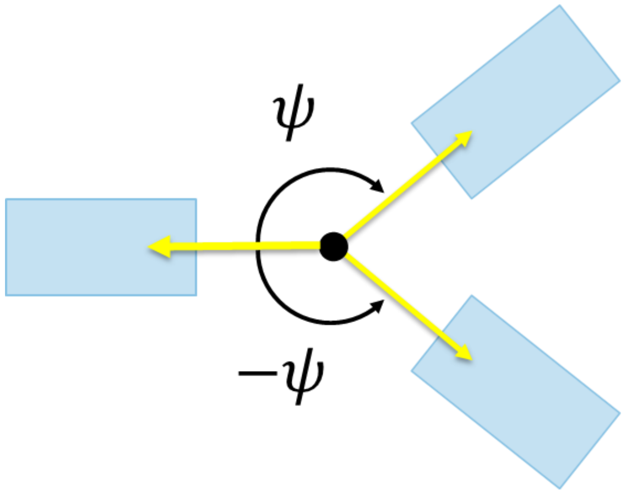
- We can flip sign of correlation twice.
- This allows us to utilize a super-ratio.

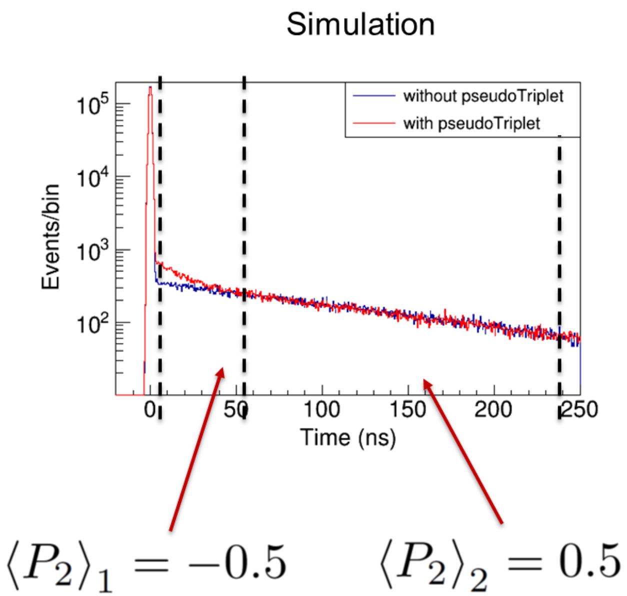
$$r = \frac{N_{+\psi}^{+P_2} N_{-\psi}^{-P_2}}{N_{-\psi}^{+P_2} N_{+\psi}^{-P_2}}$$

- This leads to cancellation of additive backgrounds and multiplicative efficiencies.
- Extract observable as,

$$A_{measured} = \frac{1-\sqrt{r}}{1+\sqrt{r}}$$

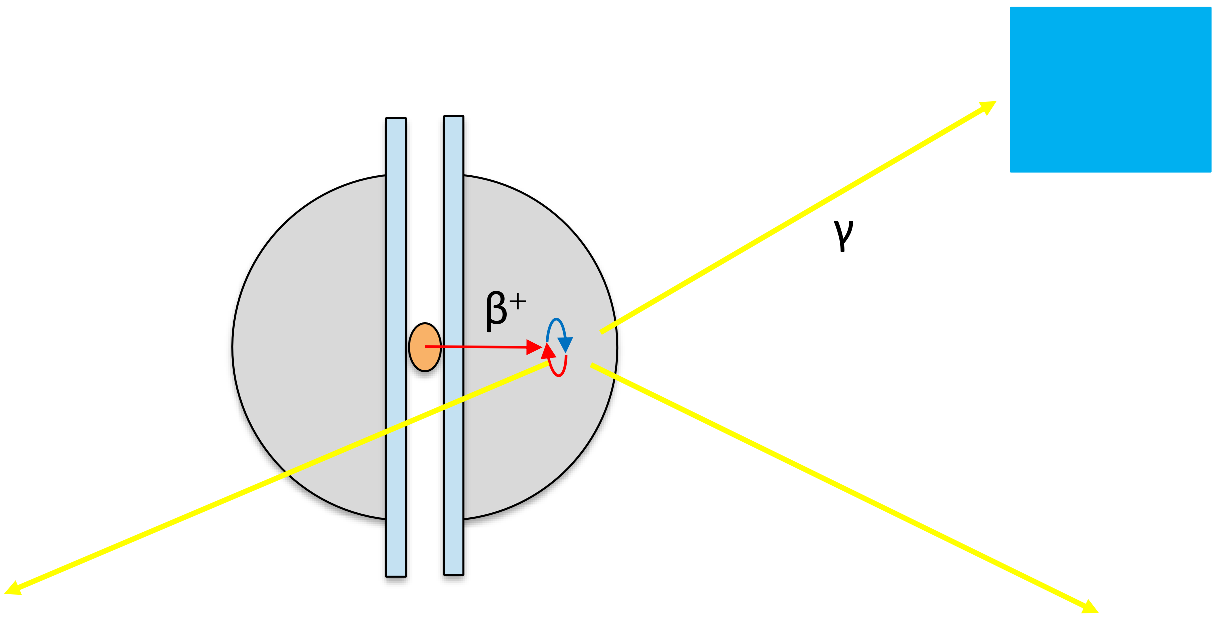
$$C_{CP} = \frac{A_{measured}}{G_e P_2}$$





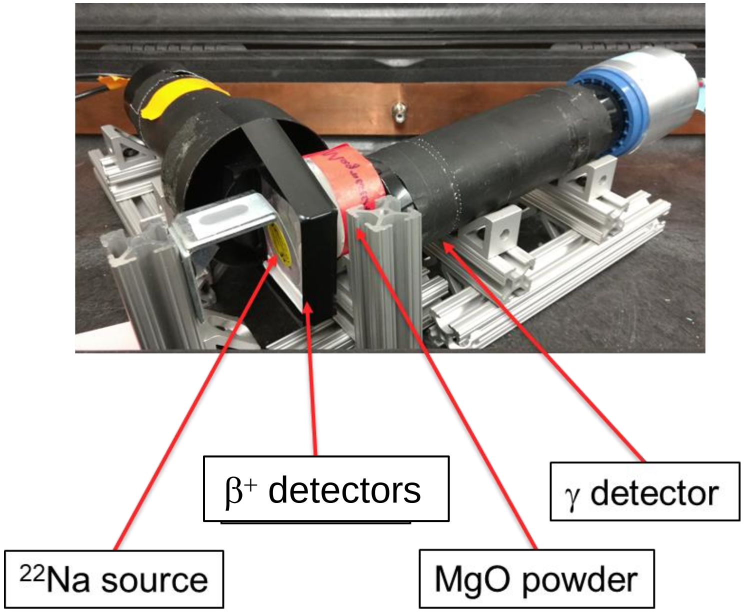
Positronium Formation

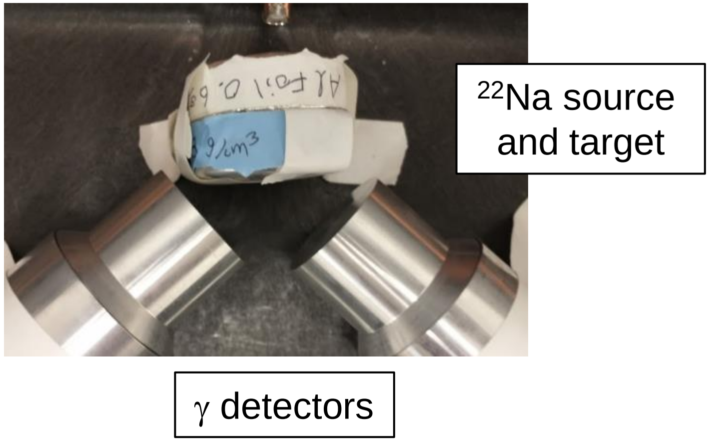
- Take a β^+ emitter
- Surround with low density powder, positron can pick off an electron.
- Detect the β^+, and a photon.
- Record the time difference.
- Decaying exponential shows a bound state.



Positron annihilation lifetime spectroscopy

- Detect emission of beta
  - 1.2 MeV de-excitation photon,
  - or direct detection of beta
- Direct detection of beta will be used in experiment.
- Test stand has been built to quantify positronium formation.
  - Uses two $LaBr_3$ gamma detectors.
  - Can extract:
    - » Lifetime of o-Ps,
    - » Formation fraction of material.

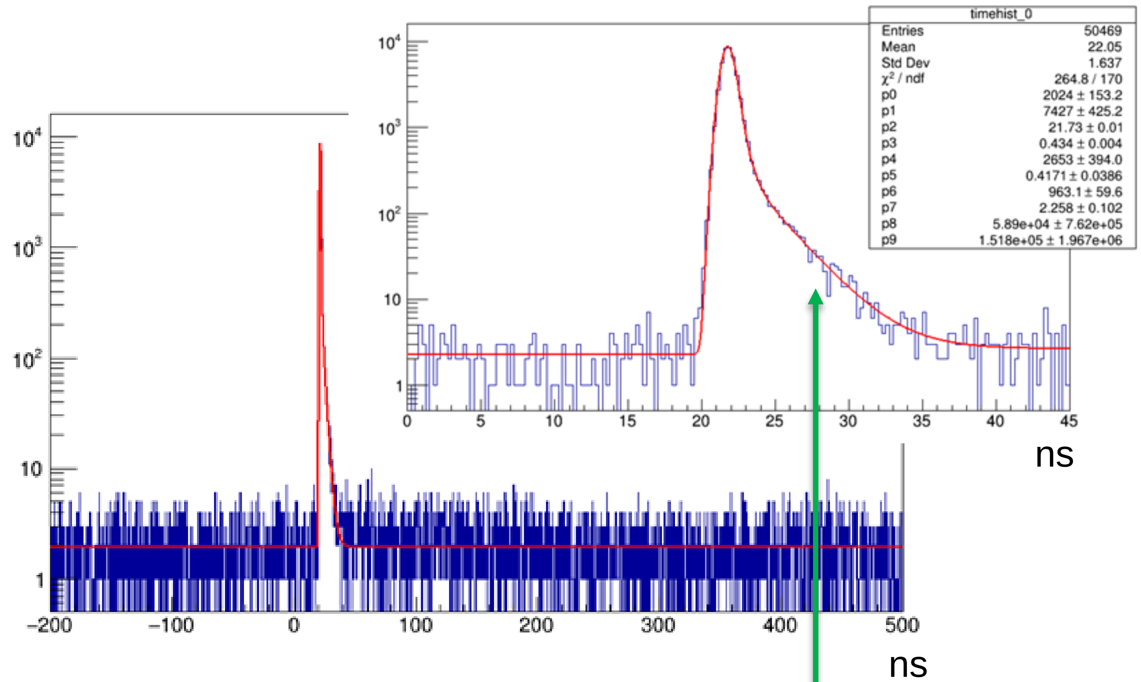




Data acquisition system

- Test stand used for prototyping ultimate DAQ system.
- System using NSCLDAQ and PIXIE-16 modules,
  - 16 channels per board.
  - 250 MSPS boards (will upgrade to 500 MSPS)
  - Digital CFD processing of signal.
  - Impose coincidence triggering.
- Achieved 0.45 ns time resolution with $LaBr_3$ detectors with online CFD algorithm.

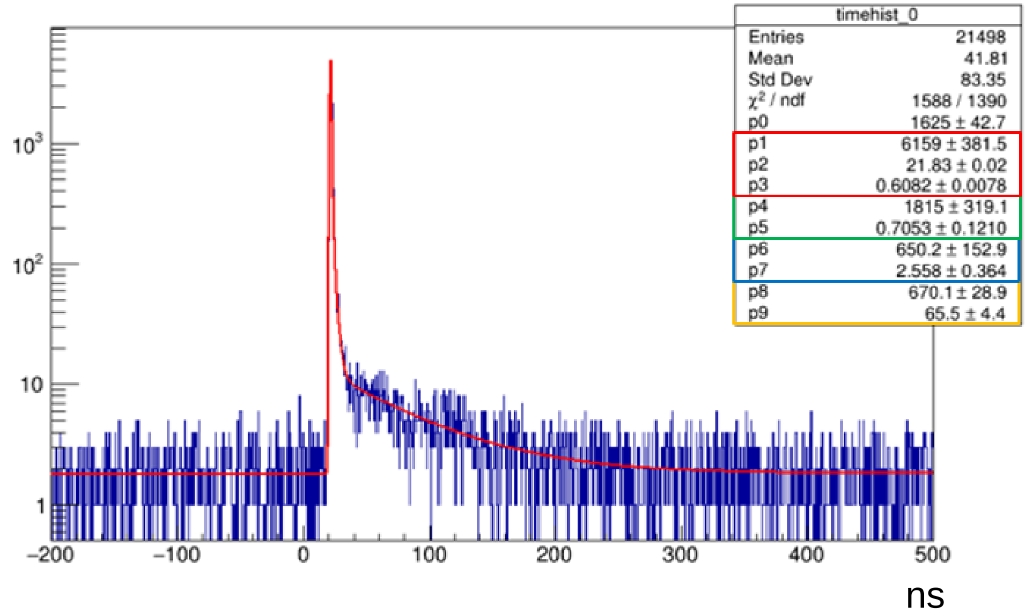
Aluminum Target



Positronium lifetime in plastic surrounding source

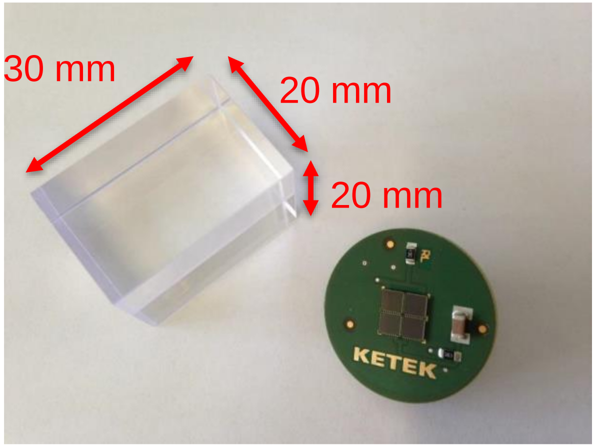
Positronium Formation

- Measured lifetime 70 ns
- Remaining work includes:
  - Testing powder materials
    - » SiO_2,
    - » MgO,
    - » XAD-4
  - Testing grain size of powders.
  - Testing preparation techniques
    - » Dessicating powder.
    - » Pumping powder under vacuum
    - » Flushing with Nitrogen.

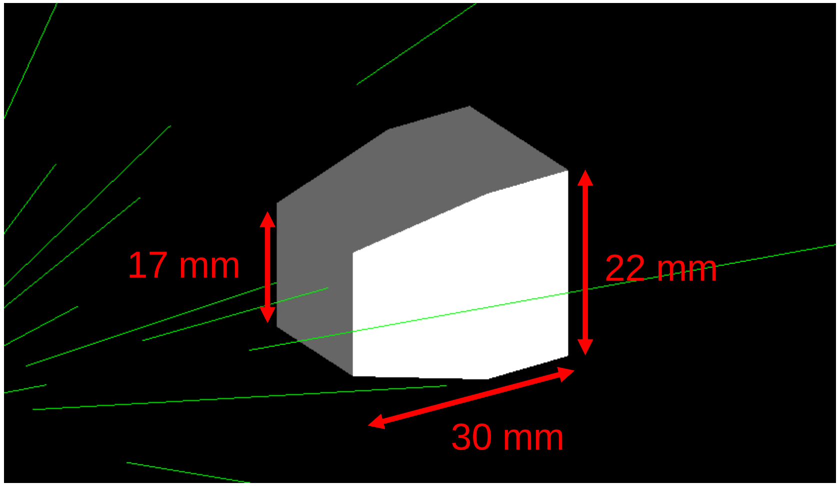


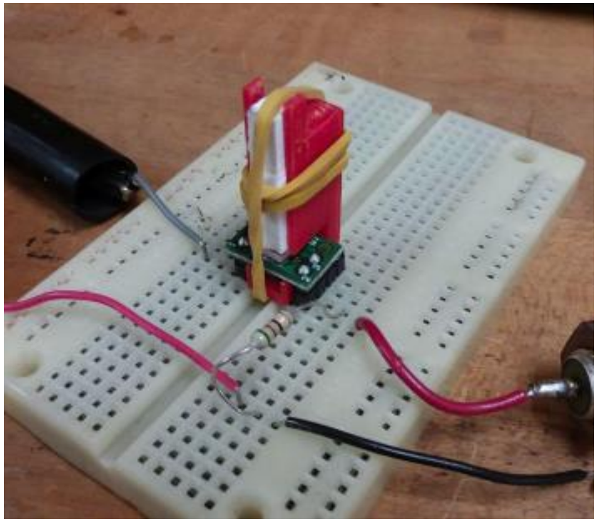
Photon Detector

- Use LYSO crystals as photon detectors.
  - Large effective Z.
  - 45 ns decay time.
- Crystal scintillators read out by Silicon Photomultipliers (SiPM).
  - Impervious to magnetic fields.
  - Much smaller than a PMT



LPC-Caen

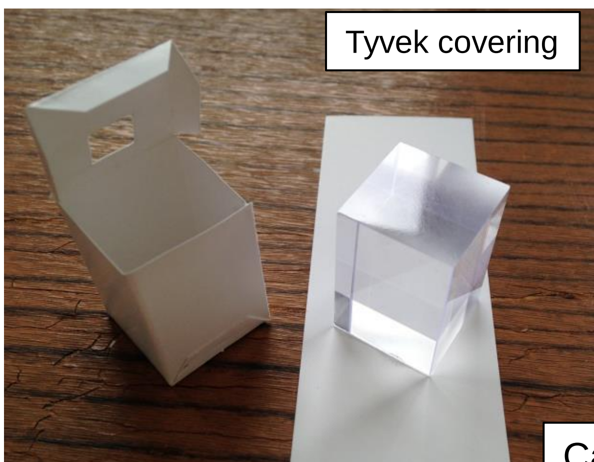




Wittenberg

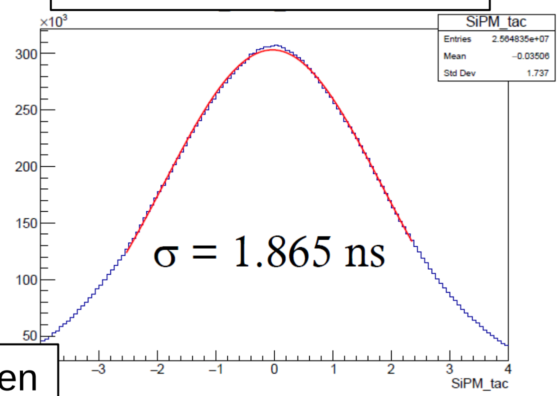
Detector R&D

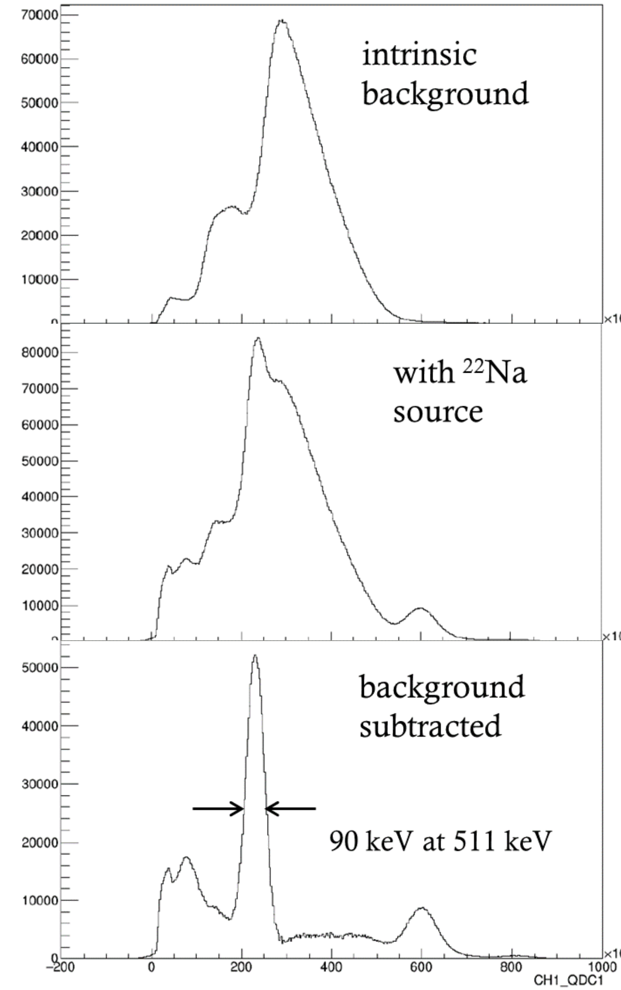
- Effects studied (FRIB, Caen, Wittenberg):
  - Wrapping material and method
  - Coupling method of crystal to SiPM
  - Timing jitter for LYSO + SiPM
  - Timing resolution of pair of LYSO
  - Internal radioactivity of LYSO crystal
  - Accidentals from LYSO background
  - Linearity of LYSO gain
  - Simulation of Energy resolution and light collection of crystals



Caen

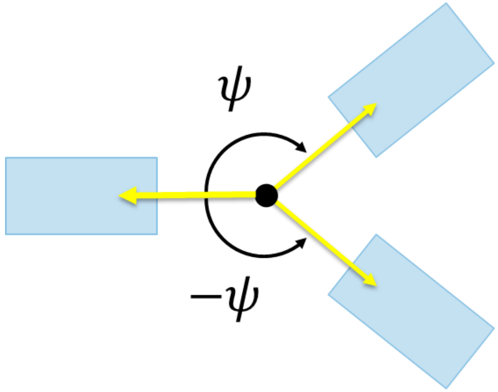
Time Difference between two LYSO detectors.

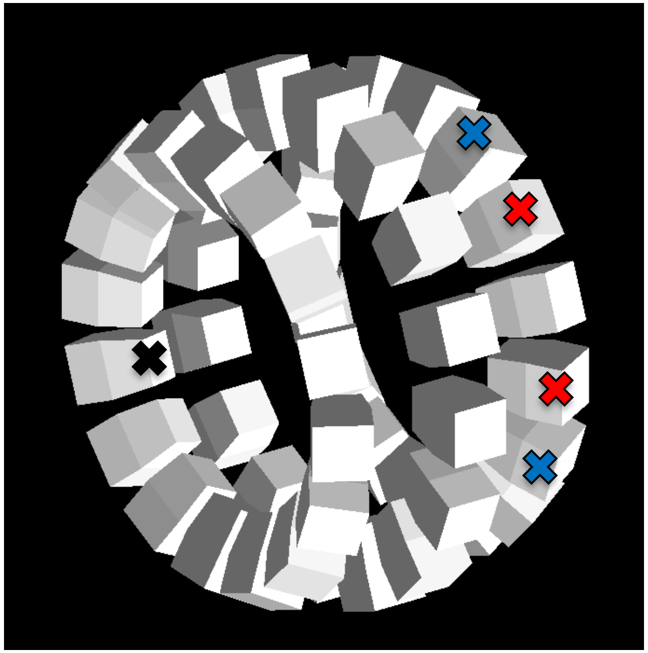




Photon detector apparatus

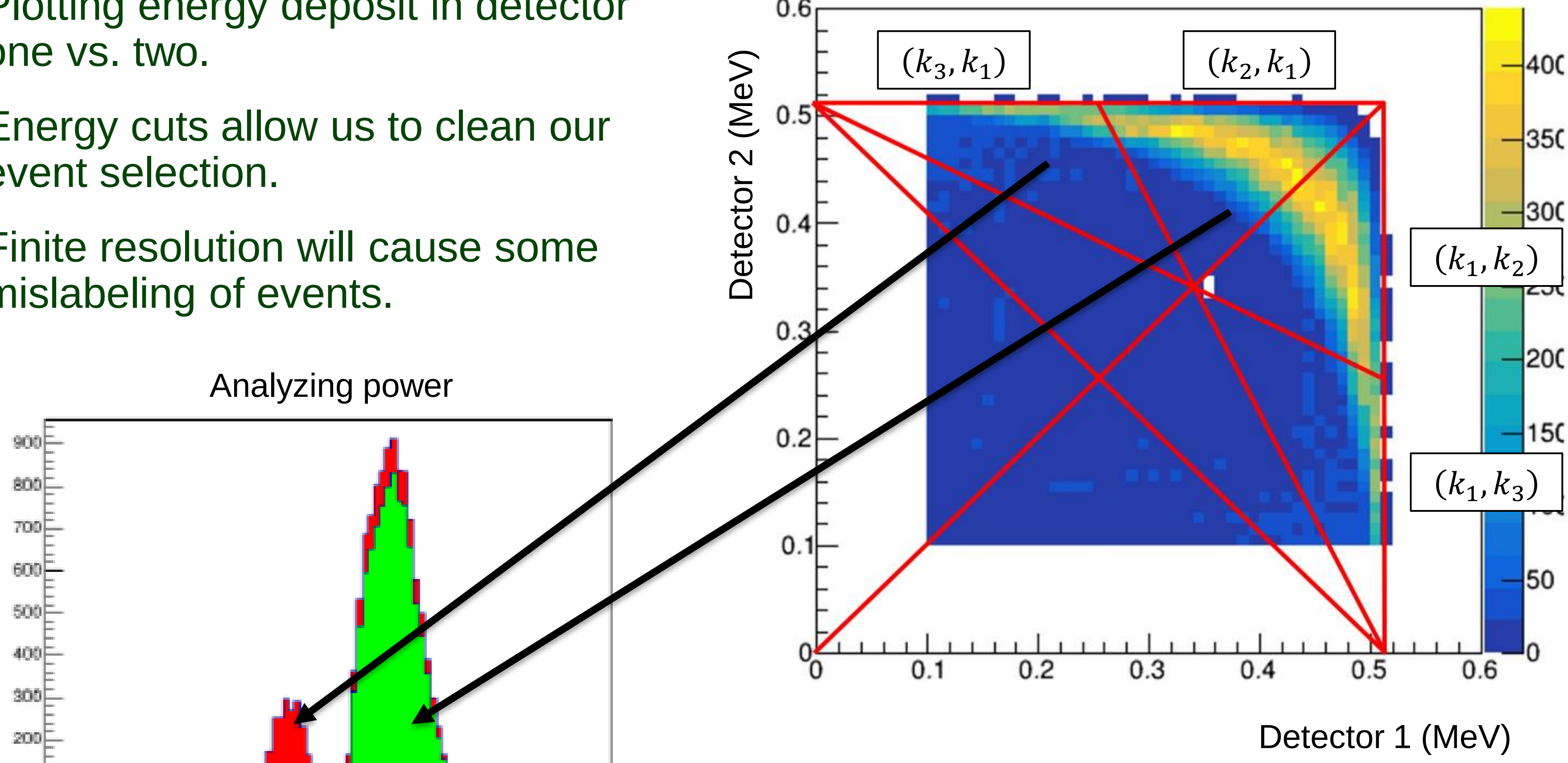
- Full geometry with 48 detectors.
- Count pairs based on reference detector (black)
  - Black-Blue: 135º
  - Black-Red: 157.5º
- Only symmetric is shown, also configurations for hits in middle ring.
- Massive increase in angular acceptance and percentage of decays seen.
- Middle ring doubles configurations and allows study of systematics.





Event distribution

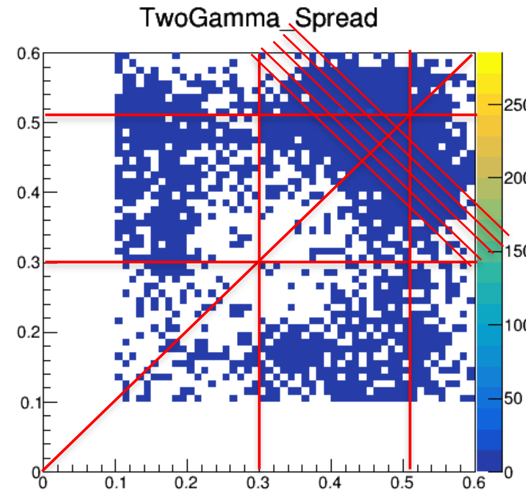
- Geant4 simulation of event distribution from pure 3γ decays.
- Plotting energy deposit in detector one vs. two.
- Energy cuts allow us to clean our event selection.
- Finite resolution will cause some mislabeling of events.

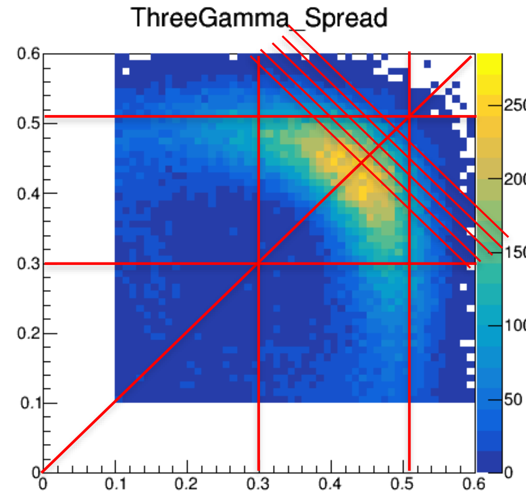


Event contamination

- Two photon events appear as peak at top corner of distribution.
- Finite resolution smears some contamination into our energy window.
- Add cuts on energy sums.
- 511's dilute our analyzing power.

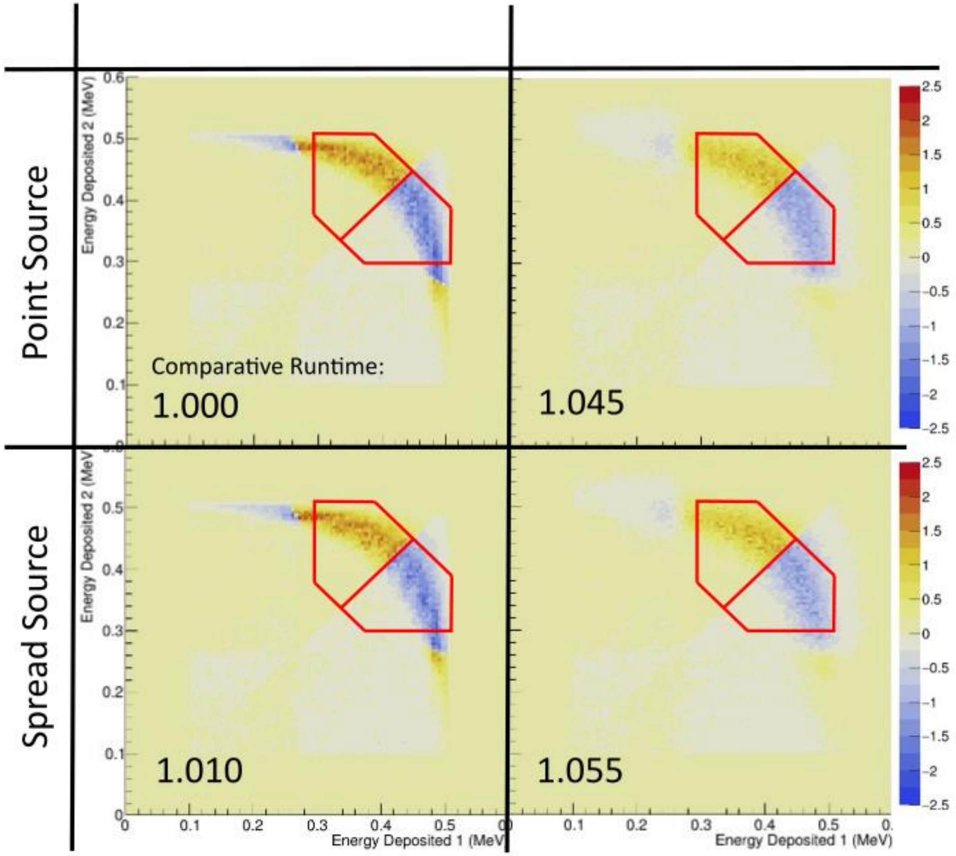
- Shift energy cuts and measure how analyzing power varies.
- Optimal value and 2-gamma dilution are resolution dependent.





Monte Carlo Results

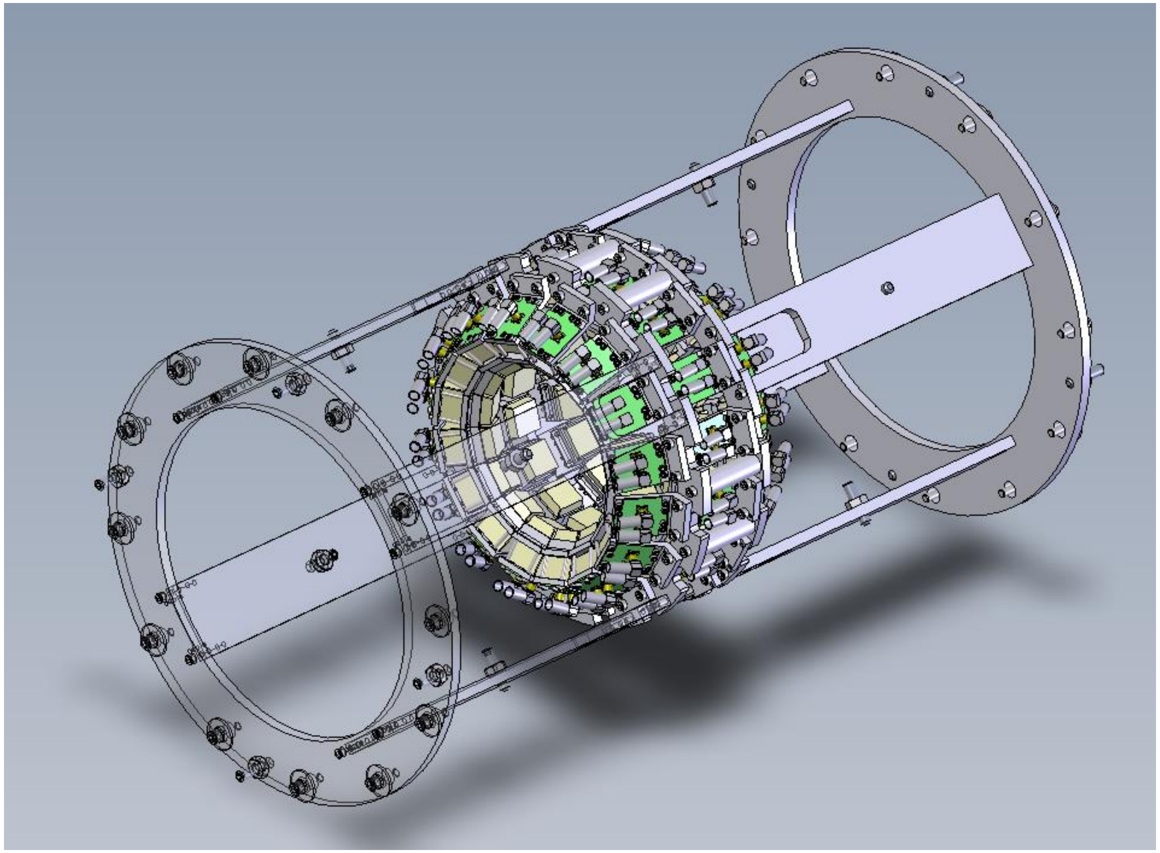
- Sensitivity calculated from Monte Carlo simulations.
- Concurrent simulations in both Geant4 and EGSnrc.
- Effects and backgrounds studied so far (FRIB, Wittenberg):
  - Finite source distribution size.
  - Effect of B-field on source distribution.
  - Contribution from 2g events
  - Accidentals from 2g events and 1.27 MeV de-excitation photon from ^{22}Na decay
  - Scattering of photons from Ps formation region
  - (Dis)advantage of adding shielding between rings
  - Angular misalignment of single ring
  - Longitudinal offset of the source



Engineering the Full Apparatus

- Design of full support structure is underway at FRIB.
- Shown is support of photon detector rings.
  - Includes attachments to outer flanges of magnet.
- Photon detector ring is 22 cm diameter (about the size of a soccer ball).
- Designed to maintain as much symmetry as possible.
  - Allow for systematic tests.

C. Snow, FRIB



Time Estimate

- For statistical sensitivity ~10^{-4}
  - Source rate 1.85 MBq (50 uCi).
  - Ps formation (0.4), ¾ go into O-PS.
  - Alignment ~0.54, 77% of O-Ps decays in time windows
  - Geometric analyzing power (Number of Counts):
    - » 157.5º Symmetric : 0.125 (0.0120)
    - » 135º Symmetric : 0.254 (0.0040)
    - » Asymmetric events not included in estimate.
- Should reach sensitivity with ~34 days of continuous running.

Summary

- We are building an apparatus to reach a high sensitivity goal for CP-violation in ortho-Positronium.
- We have a strong control on systematics by manipulating both angular correlation, and tensor polarization of the system.
- We have demonstrated Positronium formation, tested prototype detectors, simulated the photon detection system, and are now simulating systematics.
- We plan to finish construction and begin taking data in 2023!

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grants No. PHY-1920065, PHY-1565546, and PHY-2013557.

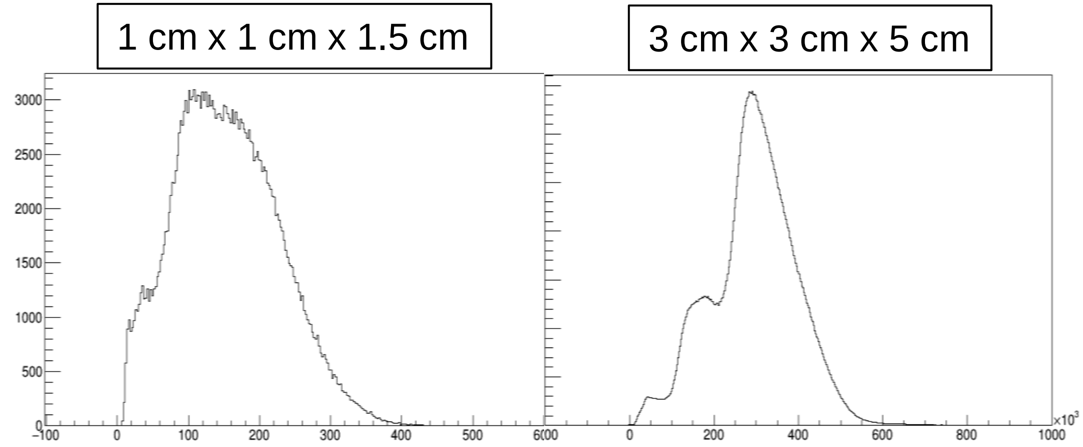
Undergraduate Contributors:

- Evan Zobel[1]
- Ziyan Yuwen[1]
- Katherine Robinson[2]
- Joshua Darang[2]
- Amy Brennan[2]
- Jacob Durmis[2]
- Theo Allard[3]

1. Department of Physics and Astronomy and Facility for Rare Isotope Beams, Michigan State University
2. Department of Physics, Wittenberg University
3. Laboratoire de Physique Corpusculaire de Caen, IN2P3/CNRS and Universite de Caen Normandie

LYSO Background

- Internal radiation from β decay of ^{176}Lu
- For large and small crystal we see 39.4 cps/g and 37.7 cps/g.
  - Saint-Gobain quotes 39 cps/g.



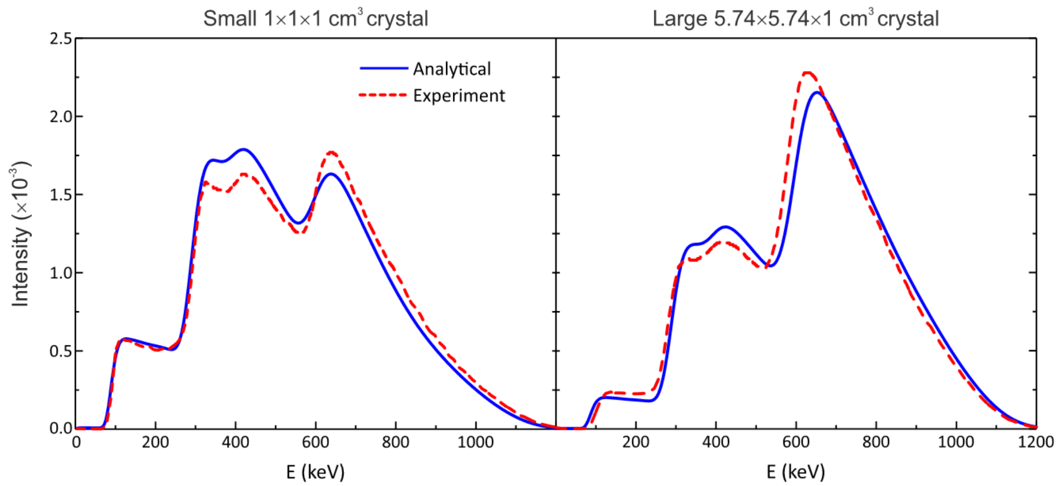


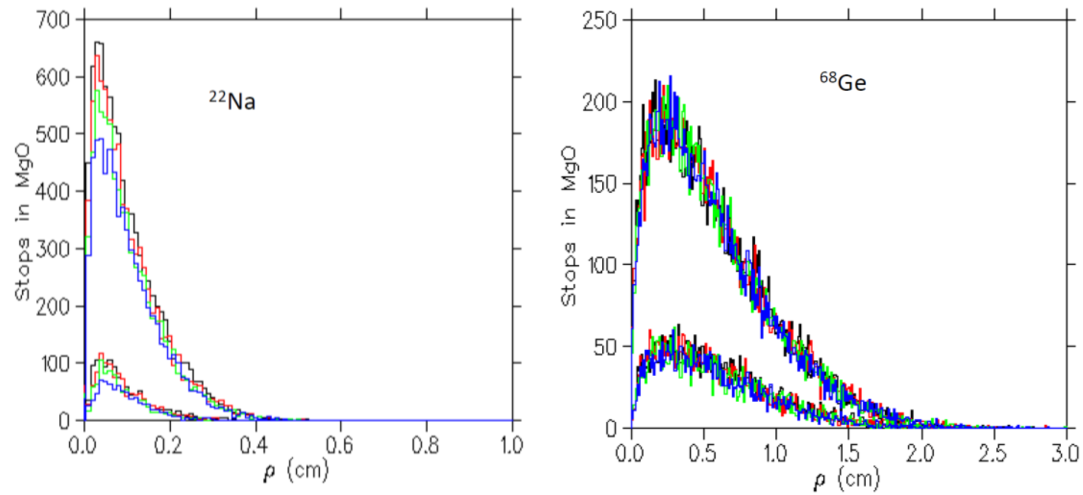
Figure 3. Analytical (solid line), convolved with a varying Gaussian kernel, and experimental (dashed line) LYSO normalized energy spectra.

Alva-Sanchez H. et al. (2018). Understanding the intrinsic radioactivity energy spectrum from ^{176}Lu in LYSO/LSO scintillation crystals. *Scientific Reports 8*

Spreading of Source

- Simulated stopping position of positrons in MgO powder.
  - Simulated in EGSnrc
- Varying thickness of start detector:
  - 0.150 mm (Bk)
  - 0.17 mm (R)
  - 0.19 mm (G)
  - 0.21 mm (Bl)
- Sampled decay spectrum from ^{22}Na and ^{68}Ge.
  - Note different scales of X-axis.

Transverse distribution of stopping position at B = 0.5 T



P.A. Voytas, Wittenberg University