An Accelerator-Based Source of High-Intensity Quantum-Entangled Annihilation Gamma Photons

Low Energy Electron and Positron Physics at Jefferson Lab (LEEPP)

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Outline

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Positron Sources

- Radioactive Sources:
  - Positrons are emitted in decay of several radioactive isotopes
  - Most common positron source is β^+ decay of ^{22}Na ($p \rightarrow n + e^+ + v_e$)
  - Radioactive sources are limited to about 1 GBq (27 mCi) or 10^9 annihilations per second

- Accelerator-based Source:
  - Provides all controls available for accelerator beams, e.g., energy, intensity, polarization, and timing among many other properties of accelerator sources
  - Produces more than 10^{12} annihilations per second

Jefferson Lab Positron Beam

Positron beam properties:

1. Unpolarized positrons $> 6\times10^{12}$ per second

2. Polarized positrons of $> 3\times10^{11}$ per second

Beam Repetition	1-1500 MHz
Duty Factor	100% CW
Unpolarized Intensity	> 1 μA
Polarized Intensity	> 50 nA
Beam Energy	1-10 MeV
Beam Polarization	> 60%
$\sigma_{\Delta p/p}$ (%)	< 1
σ_z (ps)	< 4
ε_{nx}, ε_{ny} (m-rad)	$< 10^{-3}$
Polarization Reversal	5 kHz

Positron Annihilation and Gammas Entanglement

1. Direct Annihilation (BR=~60%, prompt): $e^{+}\,e^{-} \rightarrow 2\gamma$ (maximally entangled gammas)
2. Via formation of positronium (branching ratios are material-dependent):
    - I. Para-positronium (S=0, BR=~10%, $\tau = 0.125$ ns): *p*-Ps → 2γ (maximally entangled gammas)
    - II. Ortho-positronium (S=1, BR=~30%):
        - i. *o*-Ps $+ e^{-} \rightarrow 2\gamma$ (pick-off annihilation, BR =material dependent, $\tau =$ few ns) (nonmaximal entangled gammas, reduced entanglement)
        - ii. *o*-Ps → 3γ (BR=material dependent, $\tau = 142$ ns) (entangled gammas)

- ➢ Degree of entanglement depends on annihilation mechanism – more robust to measure than lifetime (especially, for radioactive sources)
- ➢ Use beam time-structure to measure annihilation lifetime (τ)

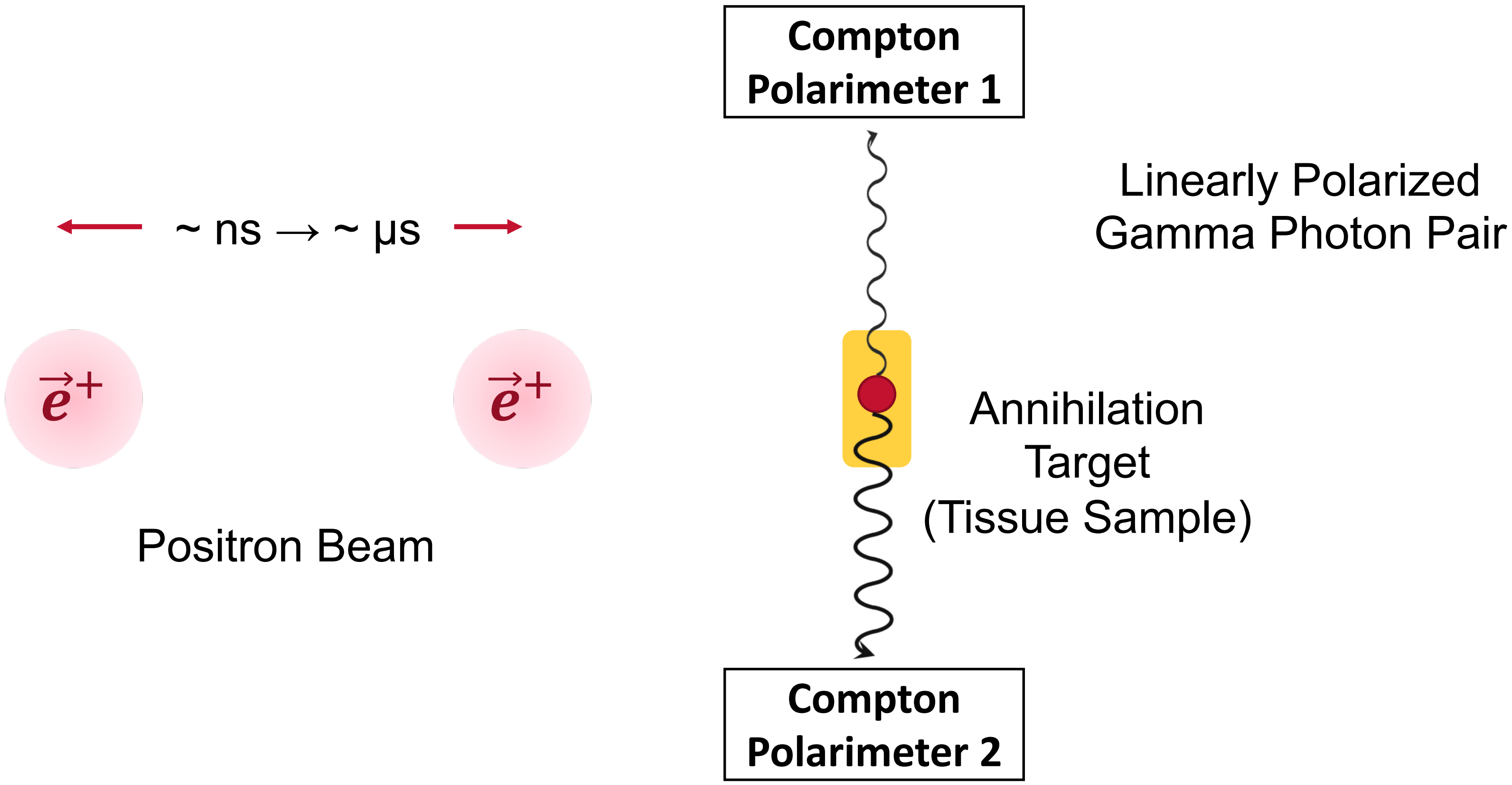
Quantum-Entangled Gamma Source

Quantum-entangled gamma source consists of:

1. Positron beam
2. Annihilation target made of thin metal foil or a tissue sample under study
3. Quantum-entangled gamma photons

4. Two or more Compton Polarimeters, each consist of:
   I. Analyzer: can be a metal block, an object to be imaged, or an active gamma detector where 511 keV gammas scatter from
   II. Gamma detectors to detect scattered gammas with high timing and energy resolutions
   III. Coincidence electronics and data acquisition system

Source Schematics



~ ns → ~ μs

$\vec{e}^{+}$

$\vec{e}^{+}$

Positron Beam

Compton Polarimeter 1

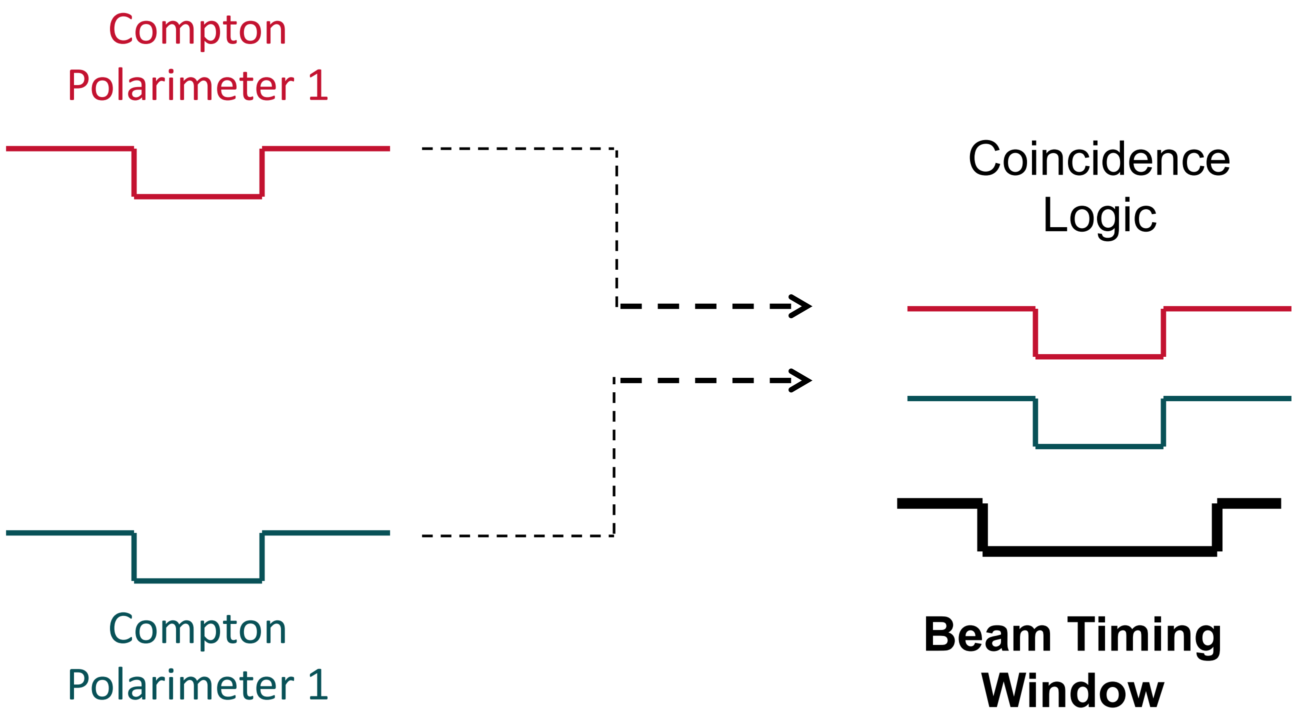
Linearly Polarized Gamma Photon Pair

Annihilation Target (Tissue Sample)

Compton Polarimeter 2

Beam Time-Structure

- Entangled gamma pairs can be identified with triple coincidence



- Use beam time-structure to measure annihilation lifetime (τ)

Compton Polarimetry of Longitudinally Polarized Gammas

- Differential cross section:

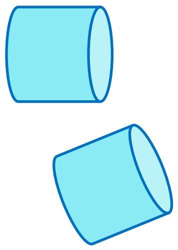
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E'}{E} + \frac{E}{E'} - 2\,sin^2\theta\;cos^2\varphi\right)$$

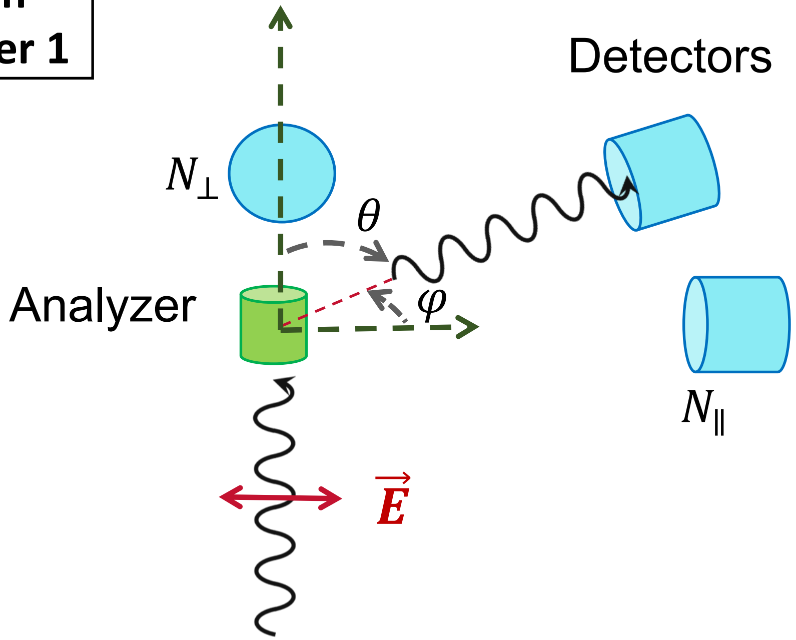
$$\frac{E'}{E} = m_e/(m_e + E(1 - cos\theta))$$

- Analyzing power:

$$A_p = \frac{\frac{d\sigma}{d\Omega}(\theta, \varphi = 90°) - \frac{d\sigma}{d\Omega}(\theta, \varphi = 0°)}{\frac{d\sigma}{d\Omega}(\theta, \varphi = 90°) + \frac{d\sigma}{d\Omega}(\theta, \varphi = 0°)} = sin^2\theta/\left(\frac{E'}{E} + \frac{E}{E'} - sin^2\theta\right)$$

Compton Polarimeter 1





$$A_p = \frac{N_\perp - N_\parallel}{N_\perp - N_\parallel}$$

Double Compton Polarimetry

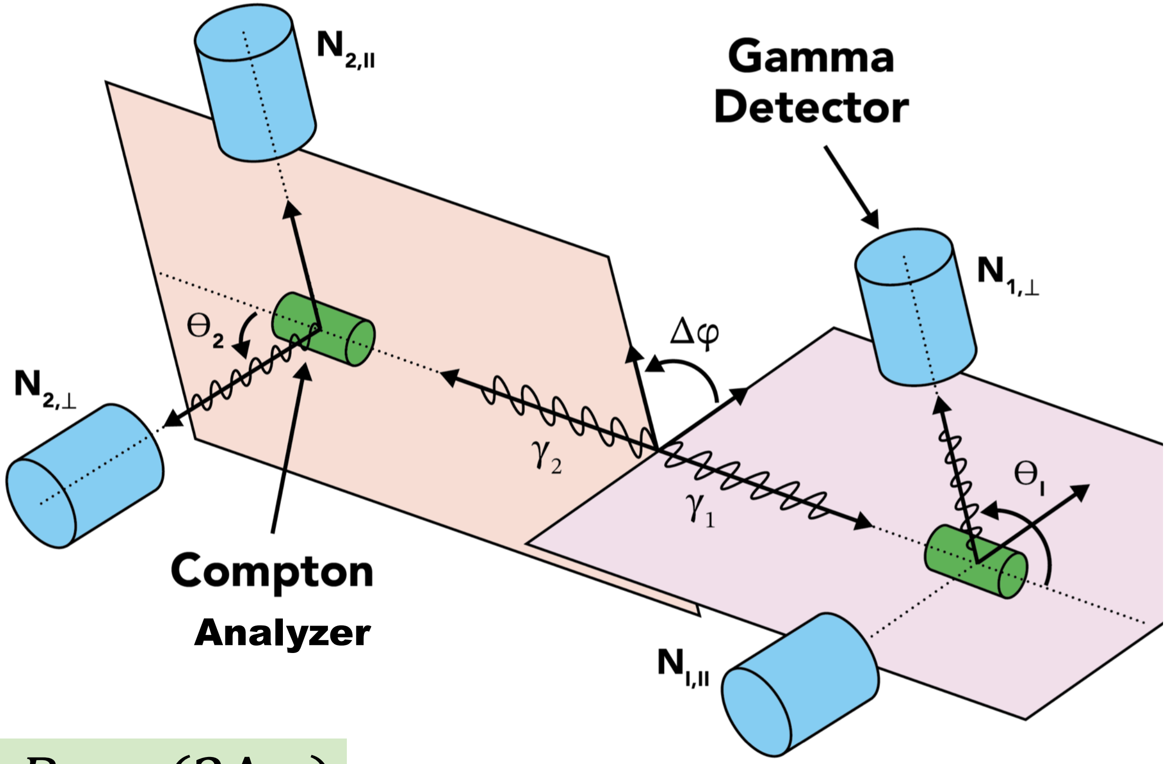
- Differential cross section of double Compton scattering:

$$\frac{d^2\sigma_{double}}{d\Omega_1 d\Omega_2} \neq \left(\frac{d\sigma_1}{d\Omega_1}\right)\left(\frac{d\sigma_2}{d\Omega_2}\right)$$

$$\frac{d^2\sigma(\theta_1,\theta_2,\Delta\varphi)}{d\Omega_1 d\Omega_2} = \frac{r_e^4}{16}[A(\theta_1,\theta_2) - B(\theta_1,\theta_2)\cos(2\Delta\varphi)]$$

$$A = \frac{[(1-cos\theta_1)^3+2]\cdot[(1-cos\theta_2)^3+2]}{(2-cos\theta_1)^3\cdot(2-cos\theta_2)^3}$$

$$B = \frac{sin^2\theta_1 \cdot sin^2\theta_2}{(2-cos\theta_1)^2\cdot(2-cos\theta_2)^2}$$



$$N(\varphi) = A - B\cos(2\Delta\varphi)$$

Quantum Entanglement

- Positron-electron annihilation produces two gammas quantum-entangled by their Horizontal and Vertical Linear Polarization:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2\right)$$

- Entanglement of gammas from annihilation, though predicted by theory, has been difficult to experimentally observe since polarization of photons in MeV energy range cannot be studied using optical methods, only Compton polarimetry
    - Compton polarimetry has an intrinsic low analyzing power (for $E = 511$ keV, maximum $A_p = 0.69$) and Bell's inequality (derived for $A_p = 1$ or 0) cannot be directly applied

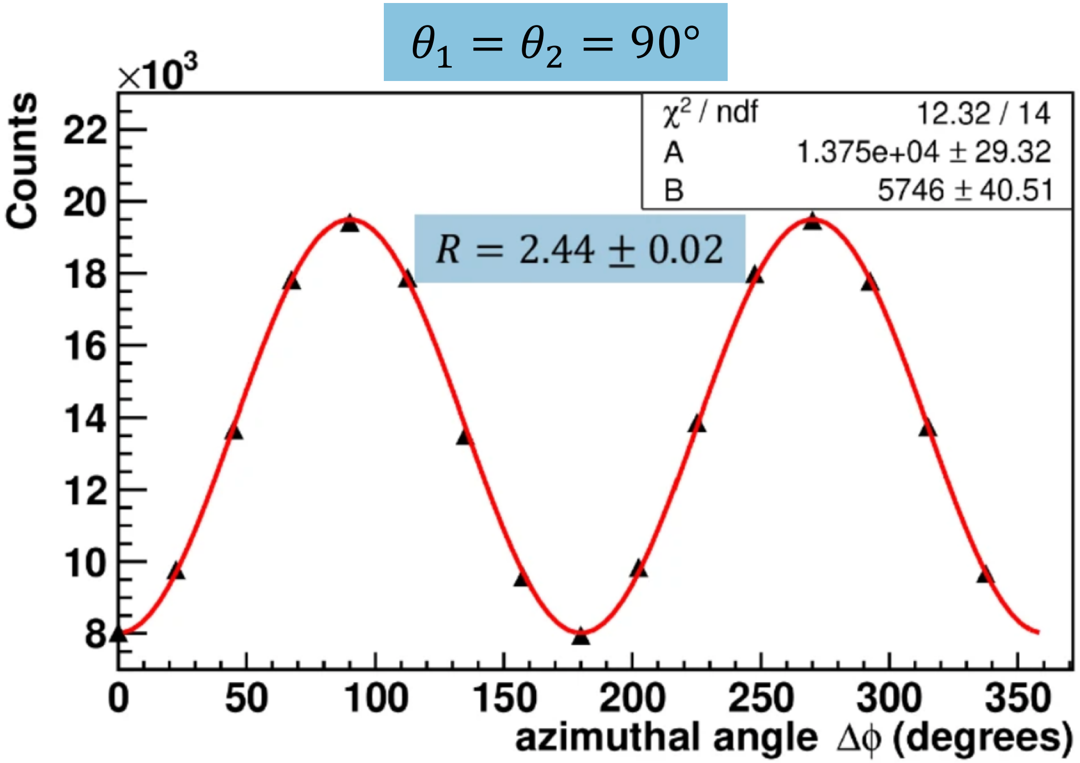
- Instead, calculate double Compton scattering cross section for different two-gamma initial states and define Entanglement Witness:

$$R = \frac{A(\theta_1, \theta_2) + B(\theta_1, \theta_2)}{A(\theta_1, \theta_2) - B(\theta_1, \theta_2)}$$

Entanglement Witness

Two-gamma Initial State	Entanglement Witness (R)
Uncorrelated ($B = 0$)	$R = 1$
Separable (not entangled, classical) $\|H\rangle_1\|V\rangle_2$ or $\|V\rangle_1\|H\rangle_2$	$R = 1.63$
EPR (hidden variables)*	$R \leq 2$
Entangled $\|\Psi\rangle = \frac{1}{\sqrt{2}}\left(\|H\rangle_1\|V\rangle_2 + \|V\rangle_1\|H\rangle_2\right)$	$R_{max} = 2.85$

* For hidden variable theory of Einstein-Podolsky-Rosen (EPR):
$R = f(A_{p,1}, A_{p,2}, hidden\ variables) \leq 2$



Ivashkin, A., Abdurashitov, D., Baranov, A. *et al.* Testing entanglement of annihilation photons. *Sci Rep* **13**, 7559 (2023). https://doi.org/10.1038/s41598-023-34767-8

Quantum-Entangled Gamma Source – Advantages

1. 511 keV gammas are penetrating radiation that can go through material which are not transparent for low energy photons

2. Entanglement can be used to identify positronium systems

3. Entangled gammas are generated using a positron beam from an accelerator:
    I. Positrons arrive at annihilation target with a well-defined time-structure
    II. Ability to control degree of polarization of positrons
        - Note: positrons from radioactive decays are polarized due to parity violation
    III. Ability to set positron initial energy

➢ Control of entangled gamma source can be achieved by controlling either the electron or the positron beam

Applications

Entangled gamma photons have many relevant applications that include:

1. Improving image quality of Positron Emission Tomography (PET) systems
2. Material Ghost Imaging with Entanglement: one gamma interacts with an object and subsequently with a bulk detector, while its entangled pair contributes to generating the image with a second position-sensitive detector
3. Studying Quantum Entanglement: study the basic science of entanglement and local hidden-variable theories

Application I – Medical Application

- Positronium formation depends on material allowing for novel way to study biological samples. Use both measured lifetime and entanglement to identify positronium systems, for example:

    - Ortho-positronium annihilates via interaction with an electron from surrounding atoms → serve as an indicator of intramolecular environment surrounding annihilation site. Utilize entangled gamma photons to improve the image quality of PET systems:
        - Annihilation mechanism is related to cell molecular composition
        - Degree of entanglement depends on annihilation mechanism

- For example: https://www.science.org/doi/10.1126/sciadv.ads3046, where a PET system was used to demonstrate usefulness of entanglement measurements (R) from a radioactive source with 122 days of data collection. No lifetime measurements were performed. Not easy to do both lifetime and entanglement measurements at same setup using radioactive source.

Ortho-positronium Application

- Use positron beam time structure to study positronium system: positron beam with time structure of 5 MHz (200 ns bunch separation) allows for coincidence techniques to isolate such state

- Very high intensity source enables precise second-scale measurements of environmental evolution during physical and chemical processes

    - With a beam-based source, measuring both lifetime and entanglement are straightforward and provides simple setup to study biological sample via positronium formation

Application II – Spintronics Application

- Positronium formation depends on positron spin allowing for novel way to study spintronics. When positron and electron spins are parallel, only *o*-Ps are formed and when spins are antiparallel, both *o*-Ps and *p*-Ps are formed. Use both measured lifetime and entanglement to identify positronium systems.

- ➢ Observing change in fraction of *o*-Ps or *p*-Ps upon spin reversal of polarized positrons, information about spin surface electron density of states can be measured.

- ➢ Spin-polarized positronium spectroscopy can be used to study nature of spin of top surface electronic states and can be instrumental in field of spintronics: https://doi.org/10.1103/PhysRevLett.126.186401

- ➢ With a beam-based source:
  1. Spin reversal of positron beam up to 5 kHz is easily achieved by reversal of electron beam spin
  2. Measuring positronium lifetime can be achieved using beam time structure
  3. Measuring entanglement in double Compton polarimeters provides additional information to identify positronium formation

Summary and Outlook

- A New Accelerator-Driven Source of Quantum-Entangled Gamma Photons:
  1. Orders-of-magnitude intensity increase
  2. Unique beam control capabilities

- Applications:
  1. Improving image quality of PET systems
  2. Quantum imaging
  3. Studying quantum entanglement

- Future Plans:
  1. Source optimization
  2. Compton Polarimeter design
  3. Applications development

Thank you