Progress of positron detection technology in IHEP and applications

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Positron Annihilation

Positron discovery

Zhao Zhongyao (1902—1998)

Beijing electron positron collider (1984)

Circular Electron Positron Collider (~2022?)

IHEP

CEPC

BEPC

Positron imaging
To measure the properties of positron / electron at annihilation site – *e⁺ Spectroscopy*

Applications: Material Science

To measure the locations of positrons at a time – *e⁺ Imaging*

Applications: Medical Science
The Positron Group in IHEP

- Measurement techniques for positron annihilation
- Slow positron beam
- Application research in material science
- Technology support on Gamma-ray detection for nuclear imaging
Techniques for Positron imaging in iHEP

Positron Emission Tomography (PET)

- Dedicated PET systems
- PET related technologies
Imaging

Seeing is believing! A picture’s worth a thousand words —and a thousand data points too. Nothing conveys information to the human eye like a picture!

the first X-ray taken in the late 1890s by Wilhelm Roentgen of his wife Bertha’s hand
CT, MRI images reflecting the structural information body of (density distribution)

- nuclear imaging technology used in clinical diagnosis achieve a true sense of the word "functional" imaging
- obtain a wide range of applications. Disease early diagnosis and treatment

The image at left shows amyloid plaques in the brain of a patient with Alzheimer’s disease. It was produced using positron emission tomography (PET)
PET

Figure 1.1. Positron emission and annihilation.

Figure 1.2. Coincidence detection in a PET camera.

Projections and Sinogram
PET and PET-related imaging projects

- Development of Multi-modality animal PET/SPECT/CT system
- Development of dedicated breast-PET scanner (PEM)
- Research on spatial and timing properties of new scintillators
- Research on PET Based on Time-of-Flight Technology (TOF-PET)
- Research of Scintillation Detector with High Spatial resolution and DOI ability (DOI-Detector)
- Research on PET detector working in magnetic fields
PET and related technologies @IHEP

Derenzo Phantom Imaging
- Sealed phantom with FDG
- 0.5 mCi activity

Rat, 200g, 2.1 mCi of $^{18}$F
scanned for 20 min per bed in four bed positions

Bone imaging of a rat
An animal PET scanner and a PET/CT scanner were developed by IHEP for metabolic and anatomic imaging of rodents and small primates in the 2010.

- **Diameter of detector**: 166 mm
- **Diameter of Entrance**: ~160 mm
- **Transverse FOV**: 110 mm
- **Axial FOV**: 64mm or 96mm
- **Spatial Resolution**: < 2mm
- **Sensitivity**: Better than 2.28%
- **X-ray Source Max Output**: 90KV, 8W
- **Focal Spot Size**: 5um(min)
- **Diameter of CT Active Area**: 60mm
- **CT Resolution**: ~80um
Molecular Imaging Systems@IHEP

Animal PET及PET/CT
Animal Opti-PET
Animal SPECT/CT
Primate Animal PET

Whole-body PET
Breast PET
Breast SPECT
Breast CT
Breast-PET is in clinical

Breast-PET imaging

PET/CT imaging

Category-Ⅲ medical instrument, issued by CFDA to enter the market sales and clinical application (2015)
Detectors and electronics for Nuclear Imaging

Detector ring for animal PET
Detector ring for Breast PET
Detector for Whole-bode PET
Detector for TOP-PET
Detector ring for animal PET
Detector for SPECT, parallel pin-hole
Detector for SPECT, pin-hole
Detector for SPECT
PET detector ring for MRI-PET
DAQ electronics for Nuclear Imaging
SiPM based detector for PET

- Comparable with PMT PET detector
  - Energy resolution: single crystal 12%, matrix 18%-20%
  - Spatial resolution: FDG hot phantom 1.7mm
  - Coincidence timing resolution: 2.6ns (or better)

- Other advantage
  - Magnetic immunity
  - Compact, 1mm vs 40mm
  - Low bias, 30V vs 700V
  - Gain uniformity, 80% vs 40%
  - High mechanization, low cost

SiPM+crystals  PMT+crystals
Magnetic compatibility

Flood histogram, energy spectrum and count rate remain **stable in 1.5T magnetic field**

<table>
<thead>
<tr>
<th></th>
<th>0 T</th>
<th>0.3 T</th>
<th>0.6 T</th>
<th>0.9 T</th>
<th>1.2 T</th>
<th>1.5 T</th>
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</thead>
<tbody>
<tr>
<td>Peak value</td>
<td>70</td>
<td>69</td>
<td>69</td>
<td>69</td>
<td>70</td>
<td>69</td>
</tr>
<tr>
<td>Count rate</td>
<td>892</td>
<td>889</td>
<td>888</td>
<td>892</td>
<td>893</td>
<td>892</td>
</tr>
</tbody>
</table>

- Inner diameter 151mm, external diameter 216mm
- System timing resolution 2.6ns, spatial resolution 1.5mm

3.5×3.5×25mm³ LYSO, 14×14 matrix

SiPM: SensL ArraySM-8
Part II

Positron annihilation techniques developments

- Application on materials
- Methodologies
- Slow positron beam
Slow Positron Beam in IHEP

Phase I (2001~2013)

Phase II (2004~now)

Phase III (2007~now)

Phase IV (2014~now)

2013 earmarks fund from CAS
Positron Annihilation in IHEP

Ne moderator beam

Doppler Broadening, CDB, Ps-TOF...

Linac-based beam

Doppler Broadening, Lifetime measurement, CDB, AMOC, Ps-TOF

22Na- beam plugged

Conventional positron annihilation spectroscopy

Positron lifetime spectrometer
High-resolution positron lifetime spectrometer
Age-momentum correlation
Coincidence Doppler Broadening

Basic measurement
High performance
Multi-parameter measurement
**New e^+ beam = Ne e^+ beam**

- Frozen Ne Moderator
- Temperature: ~ 6.8 K
- Moderating Efficiency: ~1%
- Decay: <4%/day
- 22-Na source, 50 mCi
Beam characteristics

DC positron beam

- Spot: 4.35x5.12 mm
- Void area: ~1.3 mm

Energy: ~ 30 ±3.0 eV
Intensity: 2.0×10^6 e+/s

Pulsed beam

- 1.2 mm (X); 1.2 mm (Y)
- Diameter: ~1.2 mm

Ne Potential: 12 V
Energy: ~ 12 ±0.5 eV
Intensity: 1.06×10^6 e+/s
Frequency: 1~500 Hz
Width: 20~500 ns
(1) Beam development @ (DB, CDB)

DC beam splitting

Ne\(^+\) Beam

Pulsed positron

HPGe

- Beam development
- DC beam splitting
Sub beam line @ chamber

Overall design scheme
DC beam characteristic

① For a big spot
Intensity: $2 \times 10^6$ e$^+$/s
Diameter: 5.5mm

② For a small beam spot
Intensity: $7.5 \times 10^5$ e$^+$/s
Diameter: 3mm
Chamber design

Mini size + Multi-sample import + Simple operation

Pre-vacuum 80*80*80mm³

Sample Chamber Φ100*100mm³

Negative high voltage

Stretching magnet: adsorb sample holder

Sample holder collimation

Fluorine aprons slot

Four sides holder

Rotatable stretching rod

Holder support

e⁺
DBES/CDB measuring system
DBES/CDB results

DBS: S parameter of Si sample

CDB: ratio spectrum of Fe/Cu alloy
atomic inner-shell ionization

low-energy positron (<10keV)

\[\sigma(E) = \frac{4\pi A(1 - K(E))}{N_A t N_{e^+} \varepsilon(E_{ph})} N(E)\]

- \(N(E)\): Net count of characteristic x-ray
- \(N_{e^+}\): The number of incident positrons
- \(\varepsilon(E_{ph})\): Detector (SDD) efficiency
Measure of ionization cross sections

Mechanism and methods

- Improved detection efficiency
- DC beam stability
- Thin film sample
Measure of ionization cross sections

Comparison of results between experiment and simulation

Reliable data is provided for theoretical research

Supported by NSFC NO.11275071
(3) Pulsed beam @Ps-TOF system

**PALs and Ps-TOF**

**Application:**
- Ps: porous silicon & polymers
- Ps⁻: Ps⁻ beam and application
Ps-TOF system

Electronic diagram

With the 4 detectors measurement system, $d>0$ is set, and the energy threshold is selected for eliminating undesired signal.
1. The higher the positron energy, the smaller the Ps-TOF peak
2. The higher the positron energy, the lower the energy of the Ps

Energy of o-Ps flight out doesn't change in a fixed positron energy

\[ T = \frac{d}{v} = \frac{d}{\sqrt{\frac{2E_{o-Ps}}{M}}} = \frac{d}{\sqrt{\frac{E_{o-Ps}}{m_{e^+}}}} \]
(4) Pulsed beam @PALS

Pulsed e\(^+\)  

Sample

3mm slit

\(\gamma\) - detector

Shield

\(d = 0\)  \rightarrow  \text{PALS}

\[
N(t) = \frac{k}{\sum \frac{I_i}{\tau_i}} \exp\left(-\frac{t}{\tau_i}\right)
\]
PALS for a long lifetime measurement

- Distinguish between long life and short life
- The resolution is limited by the width of the pulse (~2ns)
- The counting rate is limited by the pulse repetition rate
1. Frequency = \( \frac{1}{(\text{Fill time} + \text{Store time} + \text{Dump time})} \leq 500\text{Hz} \)

   Fill time \( \geq 1\text{ms} \), Store time \( \geq 0.75\text{ms} \), Dump time \( \geq 0.25\text{ms} \)

2. Fill time → pulsed beam intensity

The pulsed beam intensity should be set ensure that no more than one output signal for a pulse
Part 3  positron burst

Measurement of positron annihilation lifetime for positron burst by multi-detector array
Slow positron beam technology

**Moderation**

- W (110) single crystal foil (negative workfunction)
- Fraction

- annihilation ≈ 13%
- thermalization
- diffusion
- fast e+

- monoenergetic positrons ≈ 0.05% (E=3 eV)
- fast positrons ≈ 87% (in several 100 keV)

**Efficiency ~10^{-4}**

**Beam Intensity**: ~10^5 e+ /s
Intense Beam
(<10^6 e^+/s)

Long-lived isotope

Isotopes based on accelerator

Pair production @LINAC

Pair production by Hard X-ray@SR

(n,γ) @reactor

Positron trap

Pulsed laser

Pulse beam
(10^5~10^{10} e^+/pules)

80s
90s
00s
10s

Decade

Techniques developments for positron beam

Positron beam developments@era

Positron beams in world (4 in China)

Petawatt-level femtosecond laser (10^{15} J)
The “brightness” of the slow positron beam 

PERHAPS be the direction of the future development of positron beam

Space focus

microbeam

+ 

Time focus

burst

Positron beam “BRIGHTNESS”

\[ \sim 10^{19} \text{ e}^+/\text{s mm}^2 \]

1A = 1.6 \times 10^{19} \text{ e}^-/\text{s}
So far, there is no WAY to measure the time distribution for a large number of positron annihilation in one pulse or positron burst.

Measurement of positron annihilation lifetime for positron burst by multi-detector array
Main ideas

- Time spread $\Rightarrow$ space distribution

Random distribution of the annihilation gamma photons in $4\pi$ space
Principle of multi-detector method

The schematic diagram of the multi-detector method for measuring a burst of $M$ positrons annihilation lifetime with $N$ detector cells.
Detector array configuration

- **Circle structure**
  - Detector array configuration

- **Flat structure**
  - Detector array configuration

- **"L" structure**
  - Detector array configuration

- **n^2 cells**
  - Detector array configuration

- **Cells**
  - Detector array configuration
Main factors

- The number/time spread of positrons in one burst
- The number/time resolution of each detector cells
- The efficiency of detector cell for 0.511 MeV $\gamma$
- The timing accuracy of electronics
- The spatial configuration of detector cells

Detection efficiency of a detection array (Probability Theory)

$$K = [1 - (1 - \eta)^n]^N$$

Time resolution

$$\tau^2 = \tau_T^2 + \tau_P^2 + \tau_R^2 + \tau_S^2$$

$N$, the number of cell in a detector array
$n$, the number of photons that reach the detector cells surface
$\eta$, detection efficiency for the annihilated gamma of a cell

$\tau_T$ is the time width of a positron burst,
$\tau_P$ is the propagation time difference of the gamma photon,
$\tau_R$ is the time resolution of the detector cell (the resolution ability of the cells to timing signals),
$\tau_S$ is the time resolution of the detection array (time shaking as different cells detecting the same signal).
System composition
Detector design

- Geiger-Mode APD array (Silicon photomultiplier, SiPM)
- Compact, low bias, high gain, immune to magnetic field, fast timing

In our primal experimental setup, four detector cells equipped with plastic scintillator of $10 \times 10 \times 50$ mm optically coupled to a SiPM with effective photosensitive area of $3 \times 3$ mm
Positron beam (trap)

Positron burst annihilation lifetime is measured using four SiPM detectors. The positron pulse in each case contains at most one hundred thousand positrons with a time width of ~2 ns FWHM and were implanted into an annealed pure Fe sample at ~1.0 keV.
(a) The solid angle factor $\Omega$ calculated and (b) the experimental values of $\eta$ as a function of the distances $D$.

$\Omega$ is the ratio of geometrical solid angle of a detector cell
$\eta$ is the detection efficiency for the annihilated gamma of a cell.
The detector cell efficiency $p$ as a function of the average number of incident photons, wherein the dotted line is the calculated value by equation. The solid lines are the measured results.

\[ p = 1 - (1 - \eta)^n \]
(a) The experimental values and (b) the calculated values of the detection array efficiency $P$ as a function of the average number of incident photons $n$.

“None” means that all the detectors have no signals output, while “one signal” represents that only one detector has a signal output, and other color lines in the same manner.
Parameters measurement

\[ K = [1 - (1 - \eta)^n]^N \]

The probability \( K \) of all the cells having signals output as a function of three basic variables \( n \), \( \eta \) and \( N \).

(a) The variation of the probability \( K \) with different \( N \) and \( n \) when all the detector cells \( \eta \) equal to 10.3%.

(b) The \( K \) changing curve with different \( \eta \) and \( n \) fixing one hundred detector cells.
PALS result for positron burst in Iron sample

Positron burst annihilation lifetime spectroscopy of annealed Fe measured by four SiPM detectors array.

\[ \tau^2 = \tau_T^2 + \tau_P^2 + \tau_R^2 + \tau_S^2 \]
Lifetime system for positron burst in future
Application investigations autonomously

- Fe-Cu alloys (fund Project)
- Irradiation effect of structural materials (Project)
- Polymer materials (Project and cooperative research)
- Nanomaterial (cooperative research)
- Permeable membranes (cooperative research)
Research platform to users

**Ne⁺ Beam + Intense Slow Positron Beam + PALS + CDB + AMOC + TDS**

Open operation 2016-2017 (hours)

- Ne⁺ Beam
- ISPB
- PALS
- CDB
- TDS
- AMOC

- Own Time
- Sharing Time

Member of the Large Instrument Area of Material and Nanoscience in Beijing
Statistics for the open operation of slow positron beam

Intense Slow Positron Beam

+ Ne$^+$ Beam

- 22 institutes
- 38 batches
- 206 samples

Sample Category 2016-2017

- Metal/Alloy: 32%
- Composite Membrane: 26%
- Compound: 24%
- Irradiated Materials: 8%
- Others: 10%
Statistics for the open operation of Conventional spectroscopy

**PALS / DBES**

+ **CDB / AMOC**

- **23 institutes**
- **49 batches**
- **285 samples**

Sample Category 2016-2017:

- **Metal/Alloy**: 17%
- **Polymeric Membrane**: 18%
- **Composite Materials**: 17%
- **Compound**: 30%
- **Others**: 18%
Deuterium occupation of vacancy-type defects in argon-damaged tungsten exposed to high flux and low energy deuterium plasma

The effect of the irradiation dose, the irradiation depth and the Cu content on the Cu coverage fraction of the defects has been investigated by PAS
Effect of helium on electron density surroundings in positron annihilation site
Application research
Application research

![Graph showing positron energy vs S parameter for different samples. The graph compares S parameter values at various positron energy levels (0 to 20 keV) for different compositions: Pebax/PES, Pebax/PES-F127(5), Pebax/PES-F127(10), Pebax/PES-F127(15), Pebax/PES-F127(20), and Pebax/PES-F127(30). The graph highlights the S parameter values at the interface.]

![Diagram illustrating CO₂ philicity and adhesion changes with the addition of F127 to Pebax/PES. The diagram shows a before and after comparison, with the before state indicating a less favorable adhesion and the after state showing improved adhesion due to the addition of F127.]
Application research

Free volume parameters of pure Matrimid® membrane and Matrimid®/NHS composite membranes.

<table>
<thead>
<tr>
<th>Membrane</th>
<th>$l_3$ (%)</th>
<th>$\tau_3$ (ns)</th>
<th>$l_4$ (%)</th>
<th>$\tau_4$ (ns)</th>
<th>$r_3$ (nm)</th>
<th>$r_4$ (nm)</th>
<th>$F_1$</th>
<th>$F_4$</th>
<th>$F_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrimid®</td>
<td>8.30</td>
<td>0.678</td>
<td>3.78</td>
<td>2.852</td>
<td>0.099</td>
<td>0.353</td>
<td>0.035</td>
<td>0.696</td>
<td>0.731</td>
</tr>
<tr>
<td>Matrimid®/NHS-5</td>
<td>9.90</td>
<td>0.648</td>
<td>4.45</td>
<td>2.726</td>
<td>0.091</td>
<td>0.344</td>
<td>0.031</td>
<td>0.759</td>
<td>0.790</td>
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<tr>
<td>Matrimid®/NHS-10</td>
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<td>0.662</td>
<td>4.86</td>
<td>2.691</td>
<td>0.095</td>
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<td>0.036</td>
<td>0.807</td>
<td>0.843</td>
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<tr>
<td>Matrimid®/NHS-15</td>
<td>17.00</td>
<td>0.548</td>
<td>5.48</td>
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<td>0.054</td>
<td>0.331</td>
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<td>Matrimid®/NHS-20</td>
<td>6.53</td>
<td>0.818</td>
<td>5.54</td>
<td>2.686</td>
<td>0.132</td>
<td>0.341</td>
<td>0.063</td>
<td>0.920</td>
<td>0.983</td>
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</table>
Application research
New and typical user results

In May 2017, the international TOP journal Advanced Materials published online (IF: 17.9) new progress on the new hydrogen nanomaterial 1T-MoSe2 by Prof. Bo Song from Harbin industrial university.

Figure 1. Schematic illustration of the phase- and disorder-controlled synthesis of MoSe2 NSs through a hydrothermal technique by tuning the amount of NaBH4 reductant relative to that of Na3MoO4·2H2O (x) and the hydrothermal reaction temperature (T).

Table 1. Summary of the phase content, electrocatalytic performance parameters, and positron lifetime parameters for various MoSe2 samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Phase Content</th>
<th>( \eta ) (vs RHE) for ( j = -10 \text{ mA cm}^{-2} ) [mV]</th>
<th>Tafel slope ( C_{\text{st}} ) [mV dec^{-1}]</th>
<th>( R_{\text{ct}} ) [\Omega]</th>
<th>Positron lifetime parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2H</td>
<td>1T</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoSe2-1-180</td>
<td>100</td>
<td>0</td>
<td>355</td>
<td>146</td>
<td>0.4</td>
</tr>
<tr>
<td>MoSe2-4-140</td>
<td>91</td>
<td>9</td>
<td>211</td>
<td>72</td>
<td>1.25</td>
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<tr>
<td>MoSe2-4-160</td>
<td>57</td>
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<tr>
<td>MoSe2-4-180</td>
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<tr>
<td>MoSe2-4-200</td>
<td>52</td>
<td>48</td>
<td>163</td>
<td>55</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Figure 4. a) Positron lifetime spectra of the MoSe2-1-180 and the series of MoSe2-4-T samples. b) \( I_1 \) and \( I_2 \) as a function of the reaction temperature for the MoSe2-4-T samples with ratio of NaBH4 to Na3MoO4·2H2O is 4:1.
A paper entitled "A highly permeable graphene oxide membrane with fast and selective transport nanochannels for efficient carbon capture from Zhongyi Jiang’s group of Tianjin University was recently published in Energy & Environmental Science (IF 25.427), a top journal of the Royal Society of Chemistry."
Summary

1) Some New types of detectors especially using SiPM for nuclear imaging is studied & used in dedicated PET system with good performance (PET&MRI)

2) Some measuring systems are working based on the Ne\(^{+}\)-positron beam.

3) A new method of PALS for positron burst (pulse) was proposed & primally studied, a detector & electronical system for positron burst were designed with 2048*2048 cells.

4) Some application examples were concluded
Thanks for your attention!
Beam intensity & count rate

1. Frequency = \(1 / (\text{Fill time} + \text{Store time} + \text{Dump time}) \leq 500\text{Hz}\)

   Fill time \(\geq 1\text{ms}\), Store time \(\geq 0.75\text{ms}\), Dump time \(\geq 0.25\text{ms}\)

2. Fill time → pulsed beam intensity

The pulsed beam intensity should be set to ensure that no more than one output signal for a pulse

![Graph showing relationship between Fill time + Store time and Counting rate/Frequency](image.png)