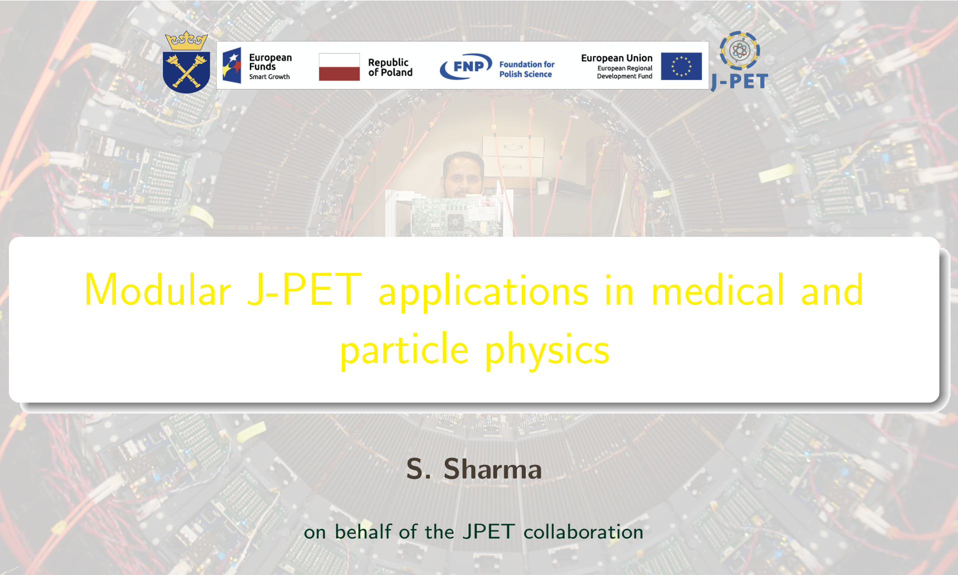


European Funds Smart Growth | Republic of Poland | FNP Foundation for Polish Science | European Union European Regional Development Fund | J-PET

Modular J-PET applications in medical and particle physics

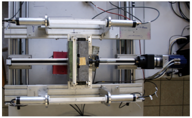
S. Sharma

on behalf of the JPET collaboration

1. **J**agiellonian **P**ositron **E**mission **T**omograph
2. Studies with Positronium decays
3. Modular **J-PET** : *Portable tomograph* (AFOV 50 cm)
4. Summary

Jagiellonian Positron Emission Tomograph

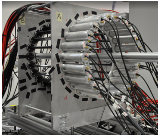
2012



Characterize scintillator properties

Energy resolution, hit time, ..

2014

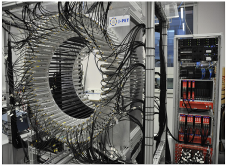


24 strips

Data acquisition for multi-modules

192 strips

2016



Current version

Tests on discrete symmetries

24 modules, each with 13 scintillators

2018

Modular PET – ready for first data campaign

- **2012** : First prototype with 2 plastic strips read by vacuum photomultipliers.
- **2014** : Data acquisition was successfully tested with multiple module system.
- **2016** : Prototype optimized to study the decays of positronium atoms
- **2018-2021** : Modular protoype - major changes in terms of SiPMs readout.

Key features

- 192 **detection modules** arranged in 3 Layers.
- Each module is made made of **plastic scintillators** (50 x 1.9 x .7 cm^3) and **2 photomultipliers** on each end.
- Trigger less and reconfiguration DAQ
- **T**ime **O**ver **T**hreshold (**TOT**) *Measure of energy deposition**
- Multiple photon detection in a **single event**
- Ang. reso.($\approx$ 1^0) Good time reso. ($\approx$200 ps)

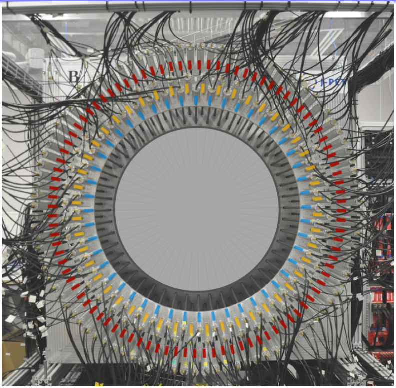
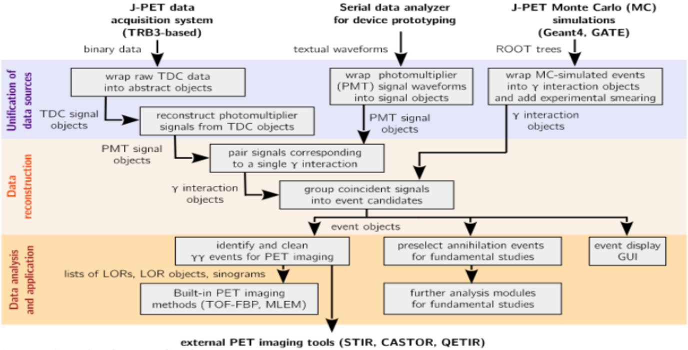


Figure: 3 Layers prototype

$$\text{Eres.}(\sigma_E/E) = 0.044/\sqrt{(E(MeV))}$$

* S. Sharma..,P.Moskal et al., EJNMMI Physics 7, 39 (2020)

Data Acquisition and Analysis : J-PET framework*



* W. Krzemien et al., SoftwareX 11 (2020) 100487

- J-PET Analysis Framework can be categorized in three sequential steps : DAQ (FPGA based), reconstruction of signal events and data analysis
- Mainly written in **C++11** using heavily the **ROOT** and **BOOST** libraries
- Dedicated MC simulations based on **Geant4** toolkit and **GATE** package

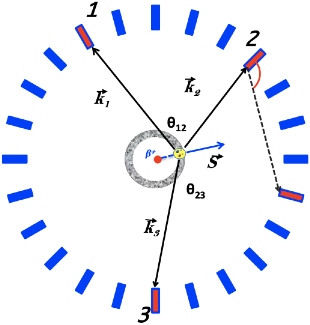
Positronium Decays : Applications in **Fundamental** and **Medical** physics

- First time detected in Gas by Martin Deutsch
  Nobel prize in 1956 for discovering Ps
- Hydrogen like atom without nuclei : purely leptonic object
  particle : e^- and anti-particle : e^+
- Eigenstate of C,P,CP operators
- Undergoes self-annihilation into gamma quanta.
  Number of annihilated photons followd the charge parity conservation.
- Formed in two gnd. states:

para-Positronium(p-Ps - .125 ns)		ortho-Positronium(o-Ps - 142 ns)
(S =0, m_Z = 0).		(S =1, m_Z = -1, 0, 1)
Even no of photons 2,4,..	**Charge Conj.**	Odd no of photons 3,5,..

- J-PET qualifies to perform the tests on discrete symmetries
- **Positronium imaging** in human body (novel concept with J-PET)

Tests on discrete symmetries in the decays of o-Ps atoms



- Odd symmetry operators can be constructed using *momentum vectors of anni. photons*($\vec{k}_i$) and *Spin of Ps*

Positronium production chambers

Target chambers

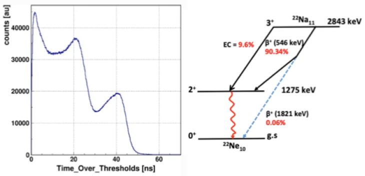
Table: Operators

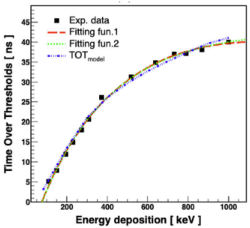
Odd symmetric	C	P	T	CP	CPT
$\vec{S}\,.\,\vec{k}_1$	+	−	+	−	−
$\vec{S}\,.\,(\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S}\,.\,\vec{k}_1)(\vec{S}\,.\,(\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+

Control Spectra for data analysis

Time Over Thresholds

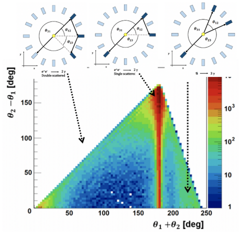
measure of energy depositions



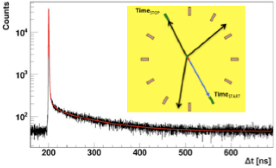


Azimuth angles

Angular correlation b/w anni. photons



Life time of Ps atoms

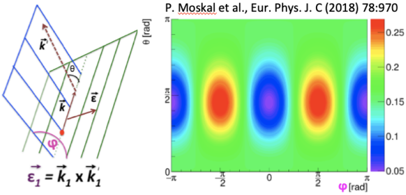


EJNMMI Physics 7, 39 (2020);
K. Dulski et al. NIM A(in press)

Acta Phys. Pol. B 48:10(2017)
Hyperfine Inter. 2018(239:40)

Tests on discrete symmetries using the photons' polarization

- J-PET allows to register primary and scattered photon
- Photon (low energetic) most likely scattered in plane $\perp_{er}$ to electric vector(dir^n of the linear polarization).
- Photon's polarization direction -



With access to *photon polarization direction*, more operators are proposed*:

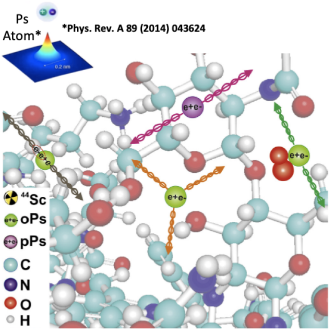
Table: Operators

Odd symmetric	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+
New Operators unique with J-PET $= \vec{\epsilon}$					
$\vec{k}_1 \cdot \vec{\epsilon}_2$	+	−	−	−	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	−	+	−
$\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	+	−	+	−	−

*Acta Phys. Pol. B 47, 509(2016)

Positronium imaging in medical physics

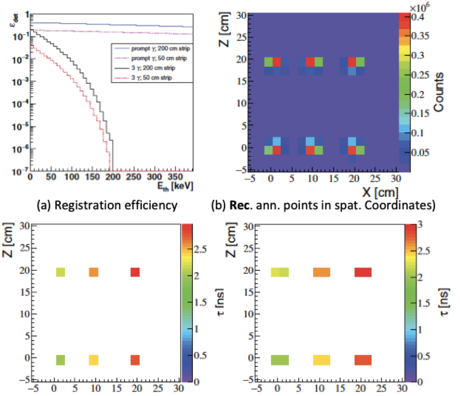
- During PET imaging in **30-40%** cases, e^+e^- annihilation occurs in the tissues via forming the Ps atoms.
- Out of total annihilation, 0.5 % contribution comes from the $e^+e^- \rightarrow 3\gamma$(via formation of meta-stable o-Ps atoms).
- Recent studies(PALS based) has shown that Avg. lifetime of o-Ps atoms (142 ns in vacuum) can be different depending on the **healthiness of tissues** (e.g. for normal tissues, avg. lifetime is generally more than the cancerous tissues) and thus can reveal very **important information about the stage/metabolic disorders** of human tissue.
- Considering relatively low probability of such events, it seems **feasible only** in the context of total-body PET imaging(higher sensitivity and with good time resolution).
- Requires **radiopharmaceuticals** emitting a **prompt photon** (eg ^{44}Sc)



P. Moskal and E.L. Stepien,PET Clinics 15:4 (2020)439-452

Feasibility study of Ps imaging with J-PET*

- MC simulations were performed for the **imaging** of **o-Ps mean lifetime** using ideal geometry of J-PET tomograph constructed of plastic scintillators(7x19x500mm^3).
- Registration efficiency (AFOV 50cm, 200 cm) as a function of energy dep. threshold was simulated (a) for 511 keV and prompt photon(1.16 MeV for ^{44}Sc)
- **Annihilation points** (b) were reconstructed based on the **trilateration** method**
- Six point like sources with lifetime varying in between 2 - 3 ns (voxel size 2x2x2 cm^3) were simulated (c) as described in work*.



(a) Registration efficiency (b) **Rec**. ann. points in spat. Coordinates)

(c) **Gen**. o-Ps life distributions (d) **Rec**. o-Ps life distributions

P. Moskal et al., Phys. Med. Biol. 64 (2019) 055017
*D. Kaminska et al., Euro. Phy. J. C 76 (2016) 445
**A. Gajos et al., Nucl.Instrum. Meth. A 819 (2016) 54–9

Modular J-PET : *Portable tomograph (AFOV 50cm)*

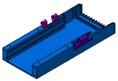


Figure: Digital J-PET

- Composed of **24 individual modules**

- Each module is made of **13** plastic scintillators (50 x 24 x 6 cm^3)
- Each side of scintillator is read out by **matrix of SiPMs**
- Modular construction allows to configure as **one layer** (24) or **multiple layers** (e.g., 8, 16 and thus requirement specific)
- Modules can be operated individually enabling to utilize as multi-role detector
- Easy to transport (full barrel around 60 kg)

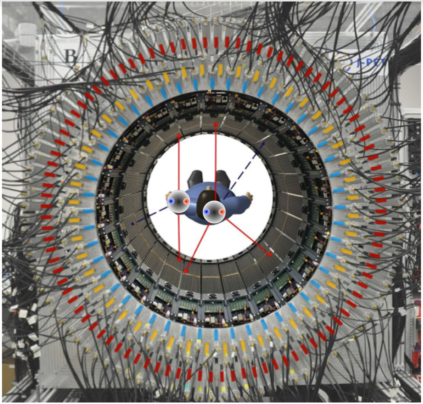


Figure: Modular+3layers

- J-PET is a **cost-effective alternative** to the crystal based PET tomograph.
- **Modular construction** of detection units allows the flexible use in medical and particle physics.
- Modular prototype with AFOV 50 cm is already commisioned and started to collect the data as a standalone layer.
- 24 modules can be reconfigured in multiple layers and can be transported to use in other experimental facilities which demands the the detection of $\mathbf{e}^{+}\mathbf{e}^{-}$ anni. in full phase space.
- It is foreseen that using the modular J-PET with 3 layers prototype will enhance the efficiency by an order of magnitude.

More details : http://koza.if.uj.edu.pl/