POSITRONIUM: AN EXOTIC ATOM AT THE BORDER OF MATTER AND ANTIMATTER

Aleksander Khreptak

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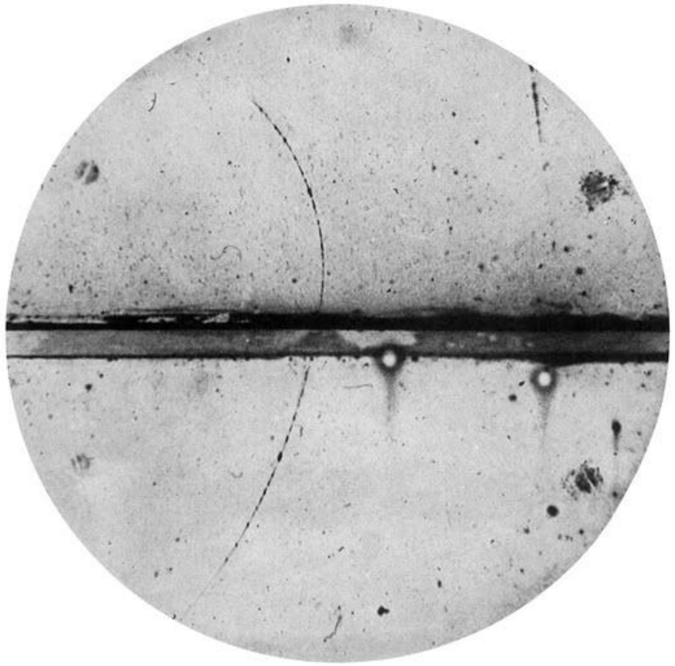
Workshop on Fundamental Physics with Exotic Atoms

EXOTIC MATTER

- In addition to ordinary atoms composed of electrons bound to baryonic nuclei, physics explores various forms of **exotic matter**.
- **Mesic atoms** represent bound systems where an electron is replaced by a negatively charged meson (e.g., π^-, K^-):
  - *Pionic atoms* (π^- bound to nuclei)
  - *Kaonic atoms* (K^- bound to nuclei)
- **Hypernuclei** consist of nuclei in which one or more nucleons are replaced by hyperons (such as Λ or Σ), allowing the study of strange quark dynamics in nuclear matter.
- **Mesic nuclei** (hypothetical): proposed systems where mesons act as binding agents within nuclear configurations.
- **Positronium** is a unique exotic system formed by a bound state of an **electron (e^-)** and its antiparticle, the **positron (e^+)**:
  - ➢ It is a purely leptonic, hydrogen-like atom with no hadronic constituents.
  - ➢ Comprises both **matter and antimatter**, annihilating after a short lifetime.
  - ➢ Enables precise tests of quantum electrodynamics (QED) and discrete symmetry violations (C, CP, T, CPT).

START OF POSITRON PHYSICS

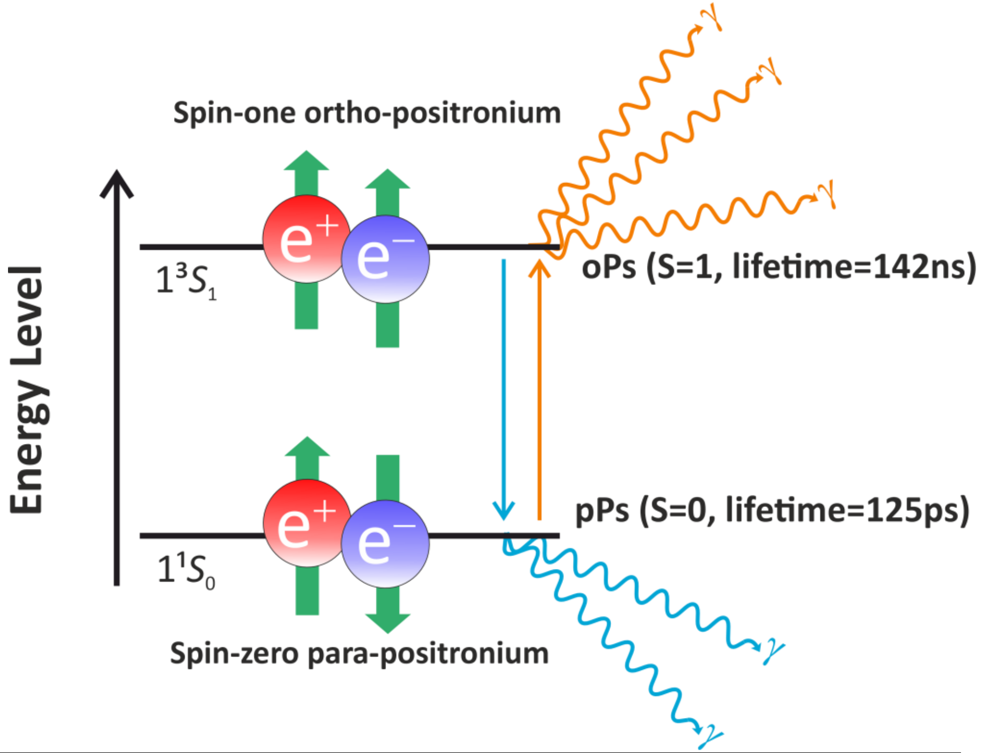


- In 1932, **Carl D. Anderson** observed a positively charged particle behaving like an electron in a cloud chamber exposed to cosmic rays.
- The particle left a curved track in a magnetic field, identical in shape to an electron but bending in the **opposite direction**.
- This was the **first experimental detection of the positron** (e^+) — the **antiparticle of the electron**, predicted theoretically by **Paul Dirac** in 1928.
- The discovery marked the birth of **antimatter physics**, opening the door to new areas of research, including:
  - Positron-electron annihilation
  - formation of positronium (Ps)
  - development of PET imaging in medicine

INTRODUCTION TO POSITRONIUM

- **Positronium (Ps)** has no nucleus — its structure resembles hydrogen, but with **reduced mass $\mu = m_e/2$**, leading to **half the energy levels** of hydrogen.

- Ps exists in two spin states:
  - **Para-positronium (p-Ps)**:
    - Singlet state (anti-parallel spins, total spin S = 0)
    - Lifetime ~125 ps in vacuum
    - Decays into **2 gamma photons**
  - **Ortho-positronium (o-Ps)**:
    - Triplet state (parallel spins, total spin S = 1)
    - Lifetime ~142 ns in vacuum
    - Decays into **3 gamma photons**



PHYSICAL PROPERTIES OF POSITRONIUM

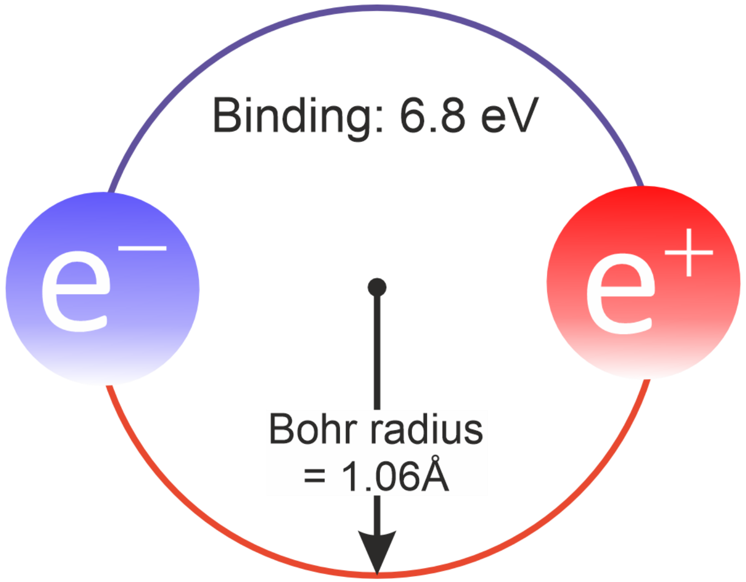
Hydrogen-like system formed by matter and antimatter

Equal mass → midpoint center-of-mass

Both particles orbit symmetrically around a shared point.

Larger than hydrogen

Bohr radius ≈ 1.06 Å (≈2× larger than H atom)



Weaker binding

Binding energy = 6.8 eV (half that of hydrogen)

Hydrogen-like 1s orbital

Same probability distribution as in H, but more spread.

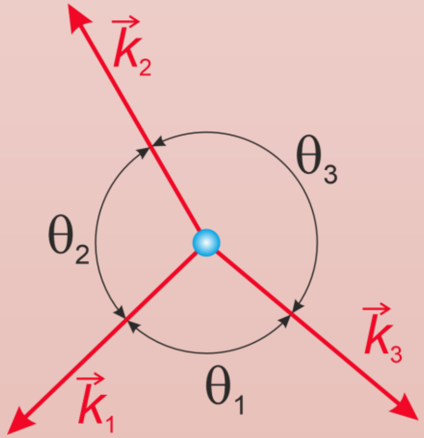
FUNDAMENTAL PHYSICS WITH POSITRONIUM

Ps, a bound state of an electron and a positron, is a purely leptonic system free from strong interactions - this makes it an ideal platform for precision tests of:

- **Quantum Electrodynamics (QED):**
  Measurements of oPs and pPs lifetimes and energy levels test higher-order QED corrections in bound states.
- **Symmetries in Physics:**
  Ps decay channels allow sensitive tests of discrete C, P, T symmetries and CP invariance
- **Search for New Physics:**
  Deviations in decay rates, invisible decays, or anomalies in annihilation spectra could indicate *dark photons, axion-like particles, fifth forces*
- **Gravity on Antimatter:**
  In extended experiments, Ps atoms may allow tests of gravitational interactions with antimatter.

Testing discrete symmetries:

Symmetry-odd observables $(\vec{S} \cdot \vec{k}_i)$ and $(\vec{S} \cdot [\vec{k}_i \times \vec{k}_j])$ serve as precision probes.

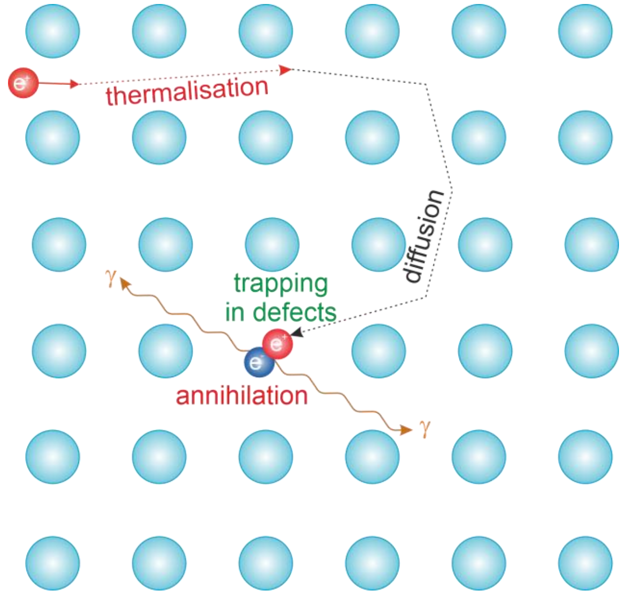


oPs decays into 3γ with angular correlations sensitive to **C**, **P**, and **CP** violations.

J-PET enables **polarization-based tests** via **Compton scattering**, achieving sensitivity at the level of **10^{-4} for CP-odd observables**.

P. Moskal *et al.* Discrete symmetries tested at 10^{-4} precision using linear polarization... *Nature Com.* 15 (2024) 78

MATERIALS APPLICATIONS

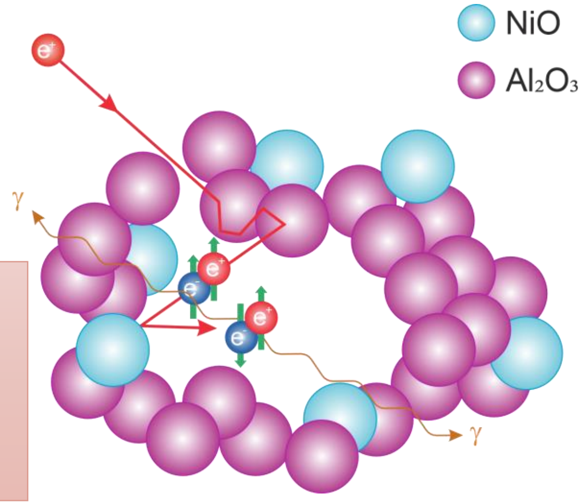


The Tao-Eldrup model links oPs lifetime (τ) to pore radius (R):

$$\tau(R) = \tau_{vac} \cdot \left[1 - \frac{R}{R+\Delta R} + \frac{1}{2\pi}\sin\left(\frac{2\pi R}{R+\Delta R}\right)\right]$$

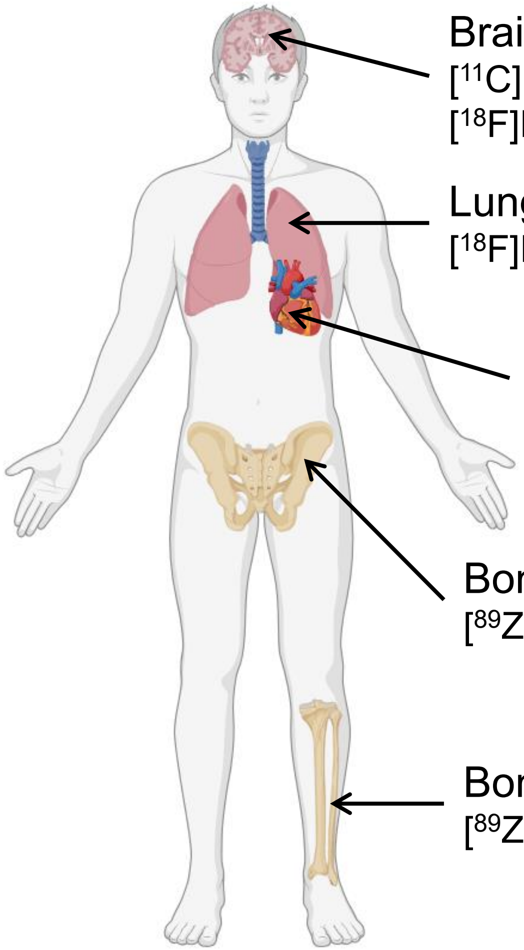
- A positron slows down (thermalisation)
- The positron travels through the lattice (diffusion), exploring local free volume
- The positron captures an electron → forms **oPs**
- If oPs is trapped in a nanopore, it avoids external electrons
- This extends its lifetime due to reduced pick-off annihilation

- A positron diffuses and forms **oPs**
- oPs interacts with **Ni^{2+} ions** in NiO — paramagnetic centres with unpaired electrons
- This induces **oPs → pPs spin conversion**
- Followed by rapid annihilation into two 511 keV γ
- **Al_2O_3** (diamagnetic) does not affect oPs
- **Result:** shortened oPs lifetime due spin conversion.



Application:
Detection of paramagnetic centers in porous materials.

PET APPLICATIONS



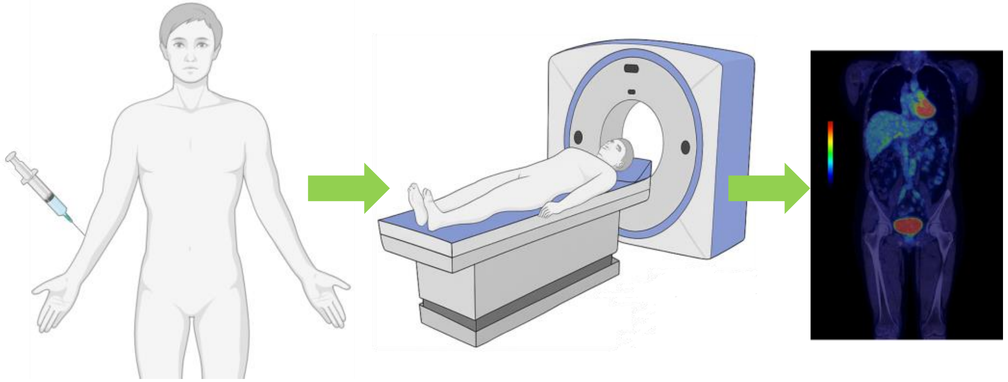
Brain
[^{11}C]PiB – β-amyloid (Alzheimer's)
[^{18}F]DOPA – dopamine (Parkinson's)

Lungs
[^{18}F]FDG – glucose metabolism

Heart
[^{13}N]Ammonia, [^{15}O]Water
– myocardial perfusion & viability

Bone marrow / Immune system
[^{89}Zr]-labelled antibodies

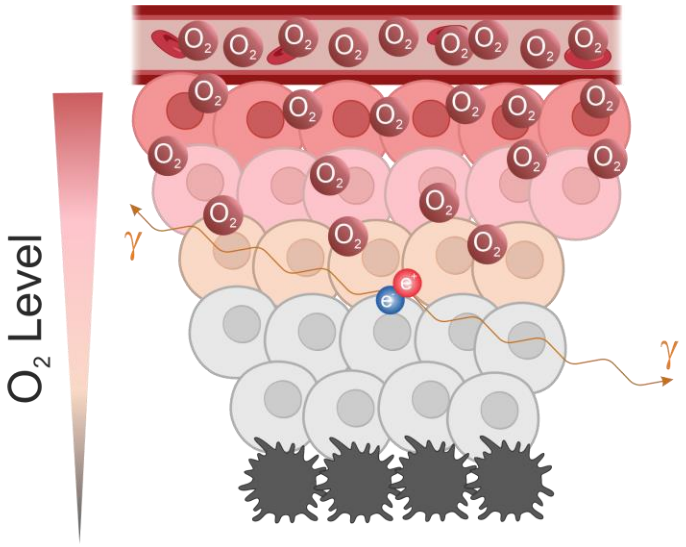
Bone metastases
[^{89}Zr]-trastuzumab, [^{18}F]NaF



- **Tracer Injection**
  - A radiotracer is injected intravenously
  - It distributes via the bloodstream and accumulates in metabolically active tissues or specific targets
- **Data Acquisition**
  - The patient lies inside the PET scanner
  - After β^+ decay, the positron annihilates with an electron → emits **two 511 keV γ photons** in opposite directions
  - Coincident detection allows spatial localization of the annihilation point
- **Image Reconstruction**
  - Detected events are used to reconstruct a 3D image of tracer uptake
  - The final PET image displays the **distribution of metabolic or molecular activity**

POSITRONIUM IN MEDICINE

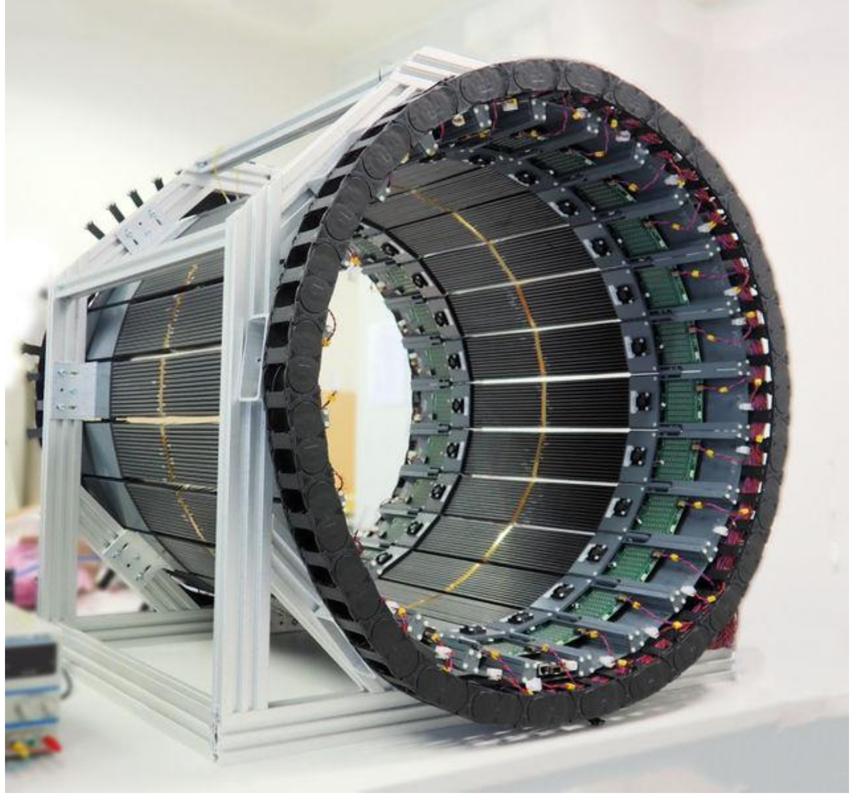
- **Tissue characterization by o-Ps lifetime**
  - ➢Sensitive to molecular environment (density, oxygenation, free volume)
  - ➢Used in studies of skin, brain, lung, liver, and breast tissue
- **Detection of hypoxia**
  - ➢o-Ps lifetime shortened by dissolved O_2 → potential for **tumour hypoxia mapping**
- **Monitoring free radicals**
  - ➢Ps lifetime affected by reactive oxygen species (ROS)
- **Ortho-para conversion as diagnostic tool**
  - ➢Interaction with paramagnetic species (e.g., iron in haemoglobin, copper in Wilson's disease)
- **Ps-based contrast in radiotheranostics**
  - ➢Combining positronium with radionuclides for therapy + diagnostic feedback
- **Early cancer diagnosis**
  - ➢Ps lifetime as a biomarker for malignancy (less invasive than biopsy)
- **Neurodegenerative disease monitoring**
  - ➢Tissue changes in Alzheimer's or Parkinson's affect Ps properties



Why Positronium?
- Acts as a built-in nanoscale sensor inside the body
- Provides complementary insight to conventional PET (structure + function)
- Sensitive to microenvironment, not just tracer uptake

P. Moskal, E. Stępień. Positronium as a biomarker of hypoxia. *Bio-Algorithms Med-Syst.* 17 (2021) 311

J-PET: NOVEL PET SCANNER

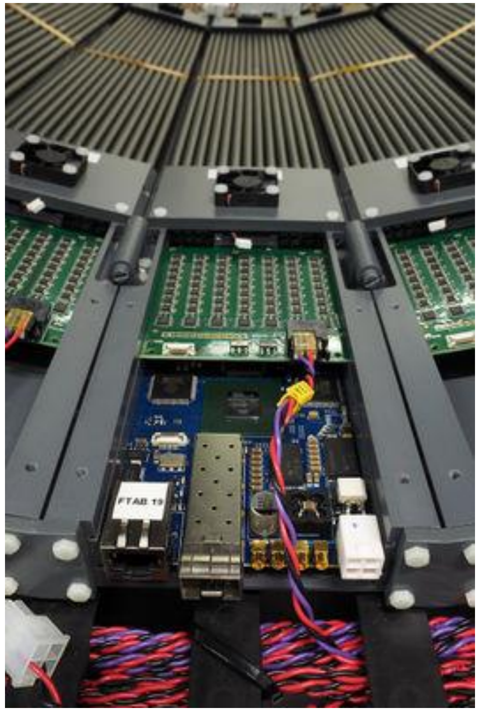


Technology Core

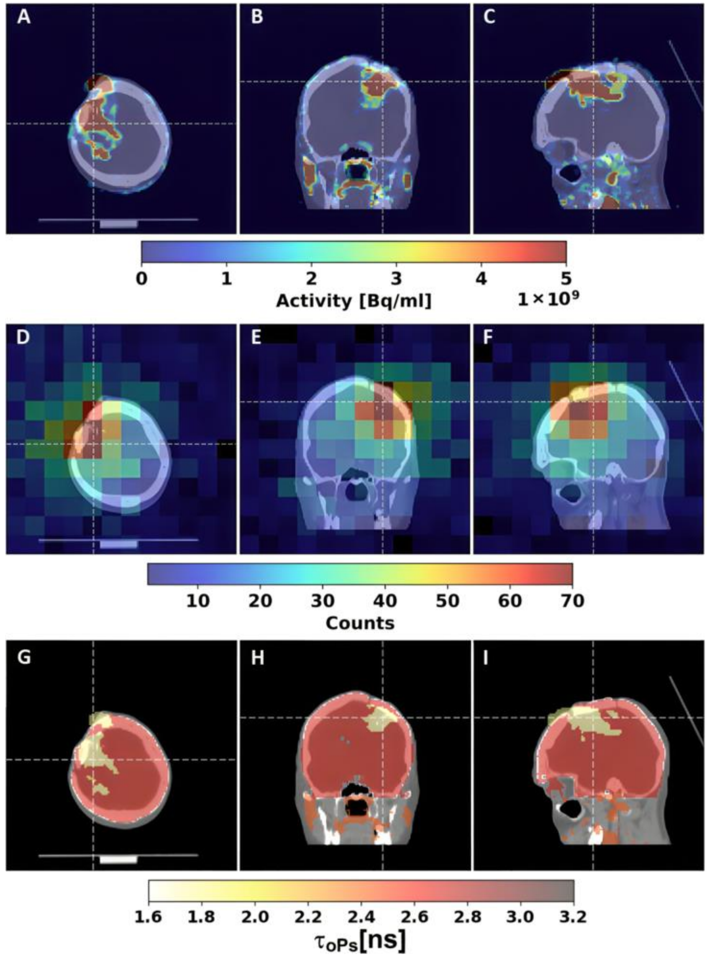
- Plastic scintillator strips in **axial geometry**
- Readout by **8 SiPMs** (4 on each end)
- Ultra-fast: **~20 ps time resolution**
- **Triggerless DAQ**: records all events (2γ / 3γ / prompt γ)

Functional Highlight

- Precise **3D γ-interaction localization**
- Multi-photon detection: 2γ, 3γ, **prompt γ**
- Supports **multi-tracer imaging** (e.g., ^{44}Sc)
- Software-level event classification → by **isotope**



POSITRONIUM IMAGING WITH J-PET



J-PET is the first PET system capable of **positronium imaging** — mapping the mean lifetime of ortho-positronium (oPs) inside tissue.
This method provides information on both the **decay location** and **lifetime** of Ps, which is sensitive to the **nanostructure** and **porosity** of the medium.

How It Works:

- oPs is formed after β^+ decay and annihilates via **3γ emission**.
- J-PET detects coincident annihilation photons and **prompt γ** from isotopes like ^{68}Ga.
- Lifetime is determined per voxel → **τ_{oPs} map**
- Enables **"virtual biopsy"** via differences in τ_{oPs} between tissues.

Key Achievements:

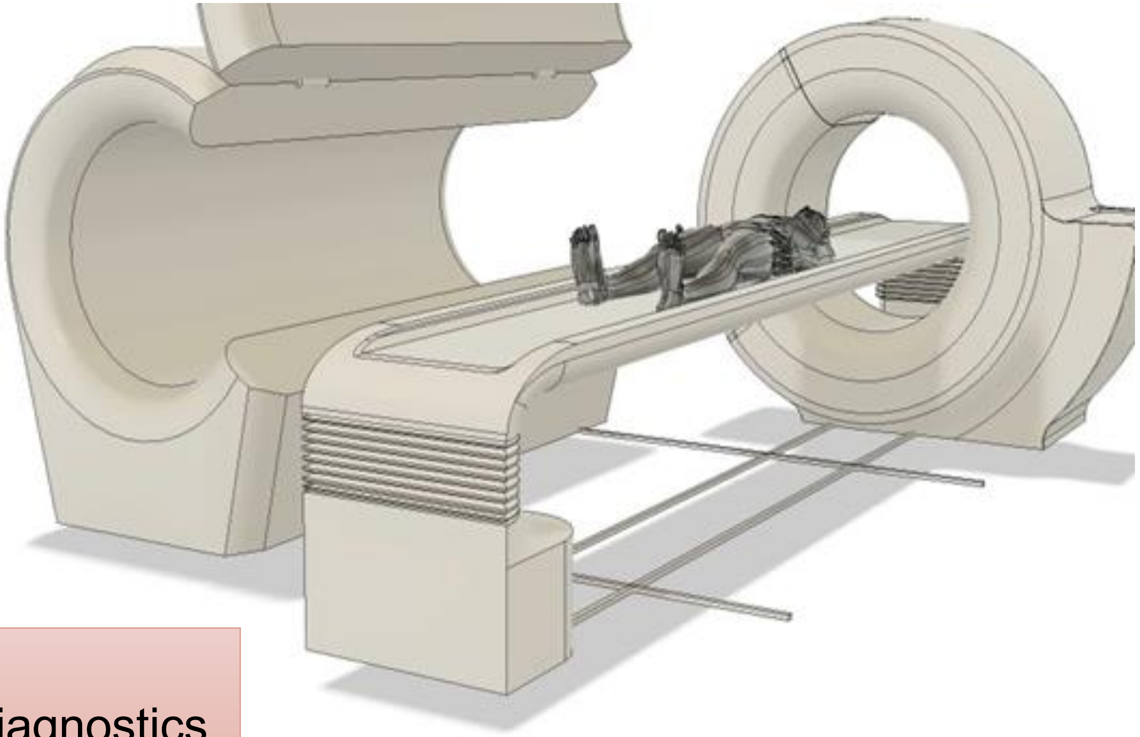
- First-ever **ex vivo** Ps image: human **cardiac myxoma** vs **adipose tissue**
  - τ_{oPs}: 1.92 ns (myxoma), 2.72 ns (fat)
- First **in vivo imaging**: patient with **glioblastoma**
  - τ_{oPs}: shorter in tumour than in healthy brain

P. Moskal *et al.* Developing a novel positronium biomarker for cardiac myxoma imaging. *EJNMMI Phys*. 10 (2023) 22
P. Moskal *et al.* Positronium image of the human brain in vivo. *Sci. Adv*. 10 (2024) eadp2840

FUTURE PERSPECTIVES

Total-body J-PET: New generation of PET scanner

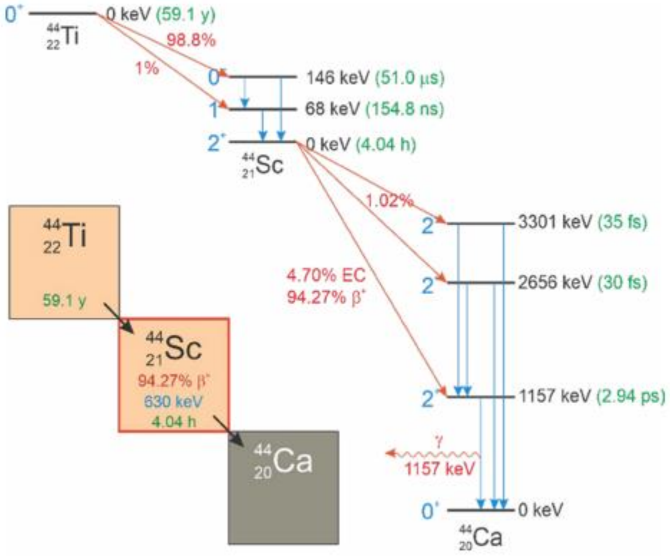
- **Full-body coverage** enables simultaneous imaging of all organs
- **High sensitivity** allows ultra-low dose diagnostics
- **Excellent timing resolution (TOF)** improves image quality
- **Based on plastic scintillators**: low cost, scalable design
- **Sensitive to positronium (o-Ps) →** enables **lifetime imaging**



Applications:
Oncology · Neurology · Cardiology · Functional diagnostics

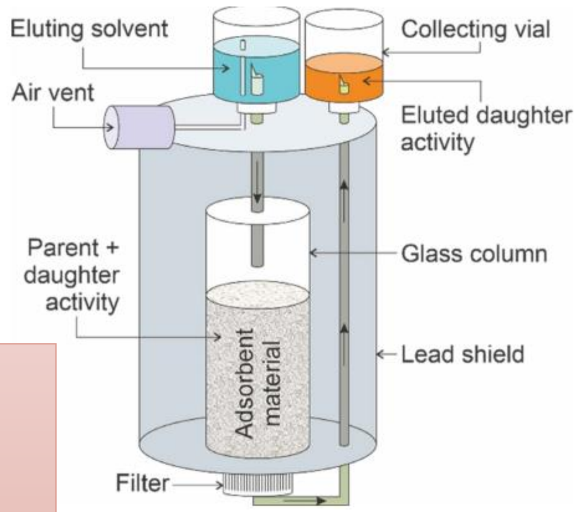
P. Moskal *et al.* Simulating NEMA characteristics of the modular total-body J-PET scanner... *Phys. Med. Biol.* 66 (2021) 175015
J. Baran *et al.* Realistic total-body J-PET geometry optimization: Monte Carlo study. *Med. Phys.* 52 (2025) 2961

EXPANDING PET HORIZONS WITH ^{44}SC



^{44}Sc: Ideal PET isotope with prompt gamma emission

- Decays via β^+ with 94.27% probability
- Emits a **prompt gamma (1157 keV)** nearly simultaneously with positron emission
- Half-life: **4.04 h** – suitable for diagnostics and transport
- Produced via long-lived **^{44}Ti/^{44}Sc generator** → enables **on-site production**



Why prompt gamma?

- ➢ Enables **precise time and spatial tagging** of positron emission
- ➢ Acts as a **reference photon** for determining o-Ps lifetime
- ➢ Allows **3-photon imaging** and **positronium lifetime reconstruction**
- ➢ Improves **event selection and background suppression** in total-body PET

P. Moskal *et al.* A vision to increase the availability of PET diagnostics... *Bio-Algorithms Med-Syst.* 20 (2024) 55
M. Dass *et al.* First positronium imaging using ^{44}Sc with the J-PET scanner… *arXiv:2506.07230*

SUMMARY & CONCLUSIONS

- **Positronium (Ps)** is a unique quantum system that bridges matter and antimatter.
- Its **purely leptonic** nature makes it ideal for testing **QED** and **discrete symmetries (C, P, CP, T)**.
- The **J-PET scanner** enables **positronium lifetime imaging** in biological tissues – a new modality beyond standard PET.
- Ps imaging has already shown promise in detecting **tumours**.
- **Prompt gamma** from ^{44}Sc enhances **event timing** and **positronium lifetime reconstruction**, boosting imaging precision.
- Integration with **total-body J-PET** and **^{44}Sc** offers a pathway to **high-sensitivity**, **whole-body** functional and structural diagnostics.

Positronium is more than a quantum curiosity – it's a versatile probe for fundamental symmetries, material structure, and precision medical imaging.
One probe – many frontiers.

THANK YOU!