Prospects of positron physics with an ultra-intense positron source

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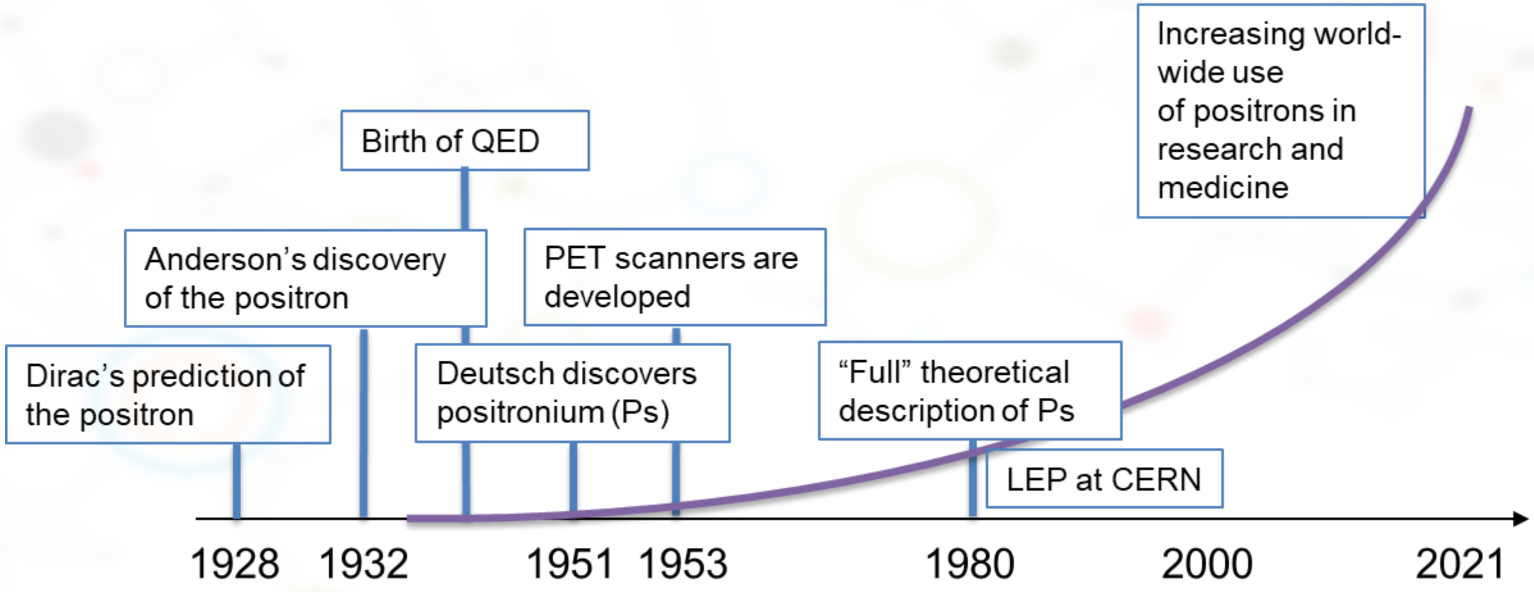
A century worth of positrons (almost)



Few examples for institutions using positrons for research with low energy antiparticles:

- CERN (Antimatter Factory)
- Many universities (UCL, TU Delft, UTokyo, UC Riverside & San Diego, Grenoble …)
- FRM II (NEPOMUC)
- KEK (IMSS)

Low energy positron/positronium physics at one glance
Precision QED studies (annihilation lifetime, Ps spectroscopy)
Fundamental symmetry tests (CPT, WEP, invisible decays)
Material studies (defect studies)

Low energy positrons in experiments

Isotope sources (β^+- decay)

Nuclear reactor-based sources (pair production)
Accelerator-based sources (pair production)

e^+ with MeV energy →

Moderator

$\varepsilon \approx 10^{-3}$

→ e^+ with eV energy →

Continuous slow e^+ beam

e^+ beam →

Trapping, cooling, remoderation, bunching

$\varepsilon \approx 10^{-1}$

→ **Applications of slow positrons**

- Defect studies
- Surface and dislocation probing
- Electronic structures

→ Conversion into positronium (Ps)

$\varepsilon \approx 10^{-1}$

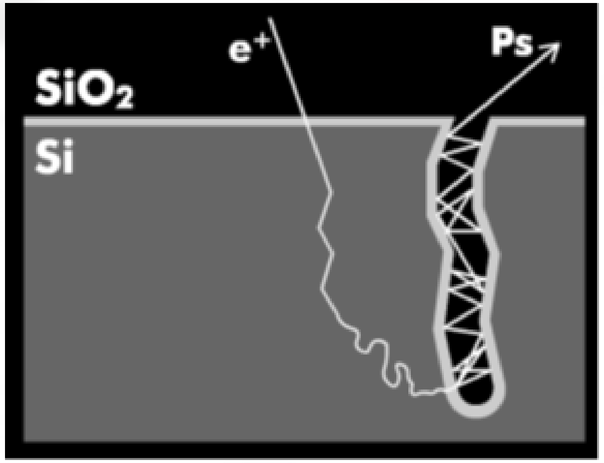
→ **Experiments with slow Ps**

- Precision tests of QED
- Fundamental symm. (CPT, WEP)
- BEC with Ps
- Porosimetry

Next generation of cold Ps sources

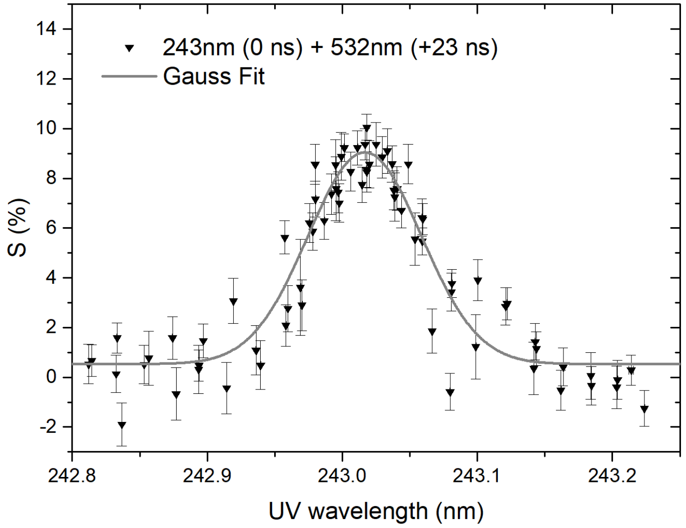
Nanoengineered positron Ps conversion target

PRL **104** (2010) 243401

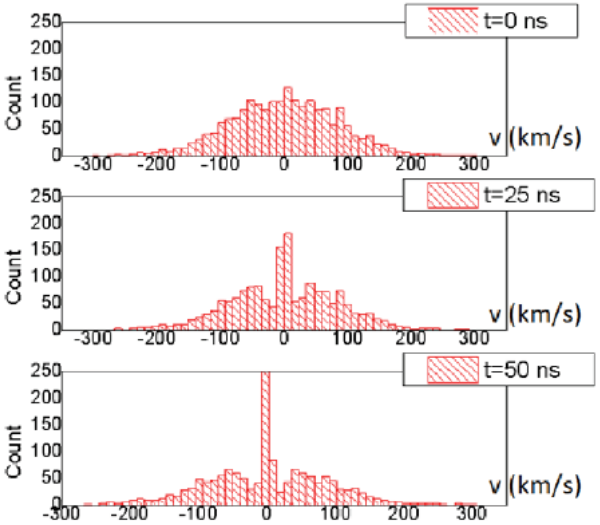


Laser Doppler-selection of the sample coldest atoms

PRA **102** (2020) 013101



Laser cooling of the coldest fraction

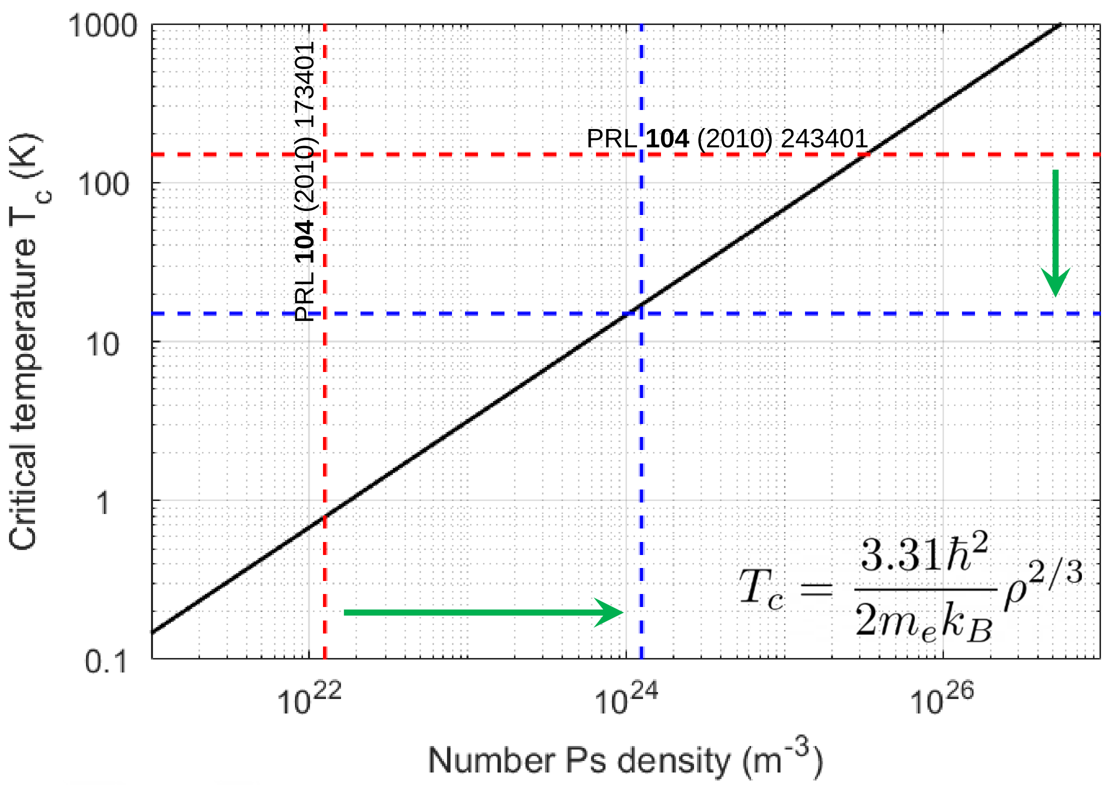


Ongoing research

Gained a lot of experience recently within the AEgIS collaboration on these three pillars

- Limited availability of positrons – currently only one experimental trial every few minutes.
- Experiments would greatly benefit from a reliable LINAC providing e^+ in high amounts.
- Usually, small collaborations do not have the resources to operate a LINAC source.

Area of impact #1 – Efforts towards the first Bose-Einstein condensation of Ps



Nanochanneled silicon converters are able to produce Ps at temperatures of 150 K and below in a cryogenic enviroment.

Laser cooling 100 K Ps atoms for 150 ns (50 cooling cycles) would reduce the temperature by ≈100 K, currently being investigated by AEgIS (ATTRACT)

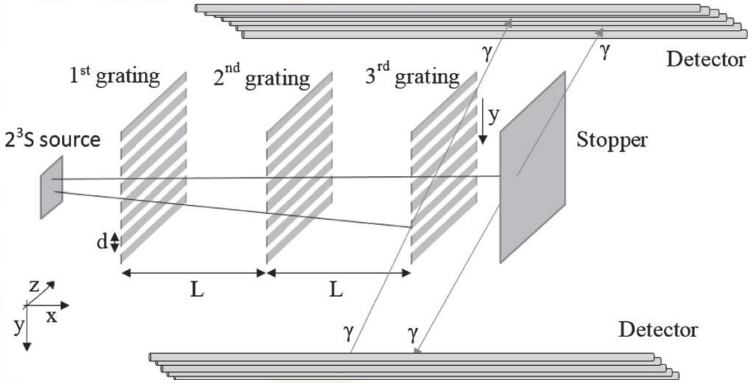
An increase of at least two orders of magnitude in Ps density is necessary. The current limit is the rate of accumulation of e^+ as a cold, dense plasma in a 4.5T magnetic field (10^8 e^+ in 15 minutes).

When a Ps-BEC annihilates, a coherent burst of gamma rays is emitted.
A proposed way to build a 511 keV gamma ray laser.

Area of impact #2 – Tests of fundamental symmetries and beyond the SM searches

Tests of the Weak Equivalence Principle with leptonic systems

Image from EPJ D **74** (2020) 79



Requires cold long-lived Ps sources in very high amounts

Searches for rare Ps annihilation channels

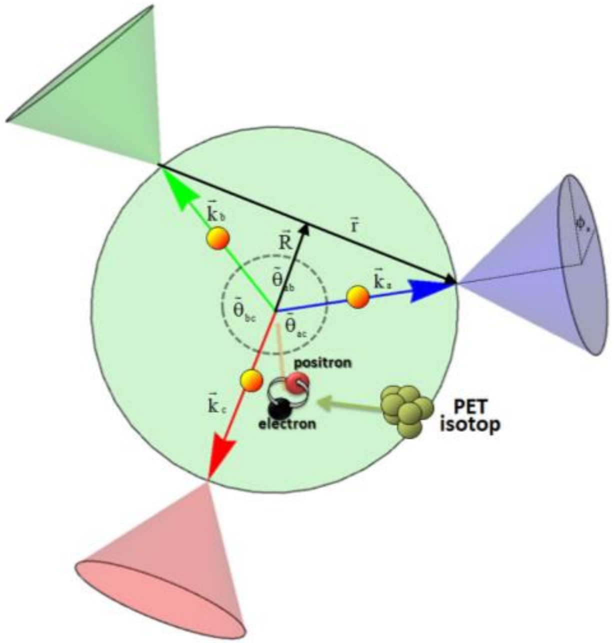
Table from Phys. Part. Nucl. **37** (2006) 321-346

Decay mode	90% upper limit, ppm
$\gamma + X$	5–1
	1.1
	340
$\gamma + X \longrightarrow \gamma + 2\gamma$	28
	300
$\gamma\gamma$	233
	350
$\gamma\gamma\gamma$	2.6
	3.7
$\gamma + X_1 + X_2$	44
Invisible	2.8
	540

Rare-event searches limited by statistics

Detection of multipartite entanglement in Ps annihilation γ rays

Image from Sci. Rep. **9** (2019) 8166



Requires simultaneous detection of three Compton scattering events

Area of impact #3 – Next generation of precision QED measurements employing colder Ps sources

Nuclear effects	Hydrogen-like electronic atom	Positronium
• Magnetic moment (HFS)	$(Z\alpha)^2 m/M$ or $\alpha(Z\alpha)m/m_p$	α^2
• Charge distribution	$(Z\alpha mcR_N/\hbar)^2$	—

Ps is an ideal system to test bound state QED as of the absence of nuclear effects

Status of QED tests with Ps: theoretical calculations are orders of magnitude more accurate than experiments!

Decay times

From Phys. Part. Nucl. **37** (2006) 321-346

$$\Gamma_o^{th} = 7.039979(11)\ \mu s^{-1},$$

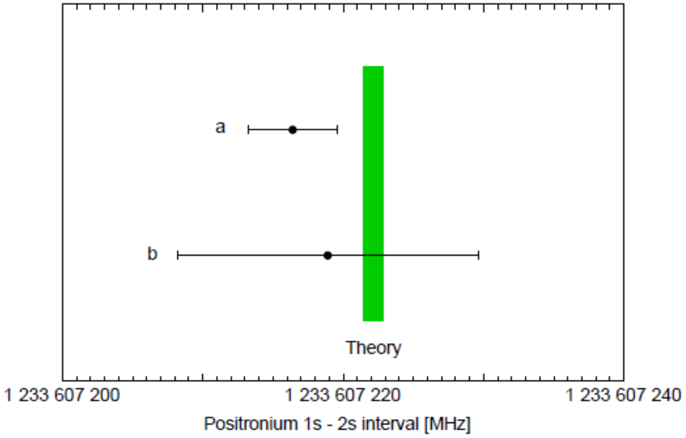
$$\Gamma_p^{th} = 7989.6178(2)\ \mu s^{-1},$$

$$\Gamma_o^{exp} = 7.0404(10)^{stat.}(8)^{syst.}\ \mu s^{-1}$$

$$\Gamma_p^{exp} = 7990.9(1.7)\ \mu s^{-1}$$

1^3S-2^3S transition frequency

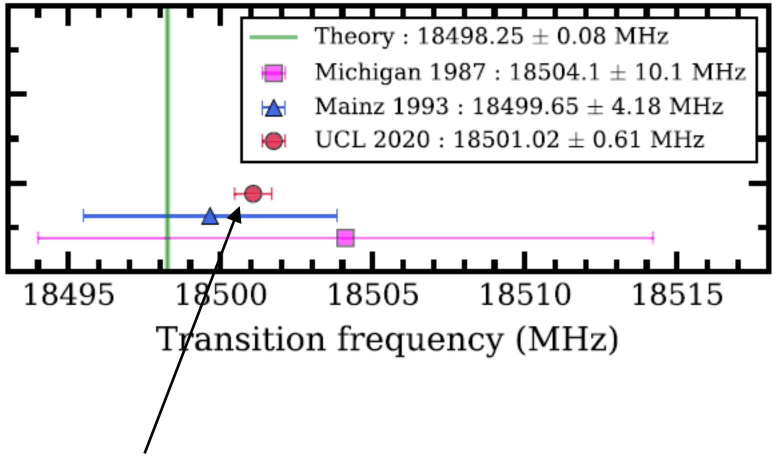
Image from Phys. Rep. **422** (2020) 1-63



Limited by second order Doppler effect, requires colder Ps sources

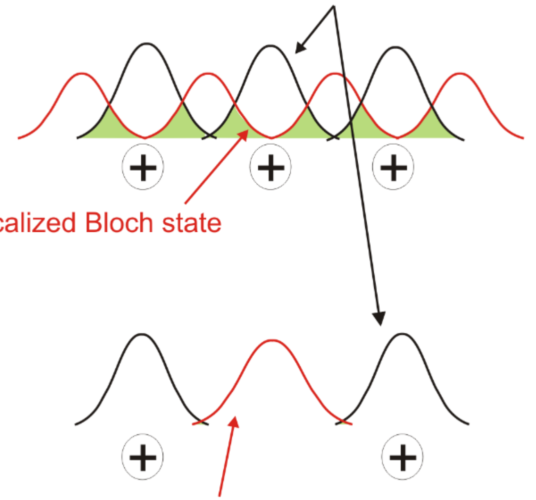
2^3S-2^3P transition frequency

Image from PRL **125** (2020) 073002



In tension with theory

Area of impact #4 – Positrons as non-destructive nanoprobes



Possible use case: Ultra-high density monolithic 3D ICs

→ Depth-resolved defect analysis with positrons

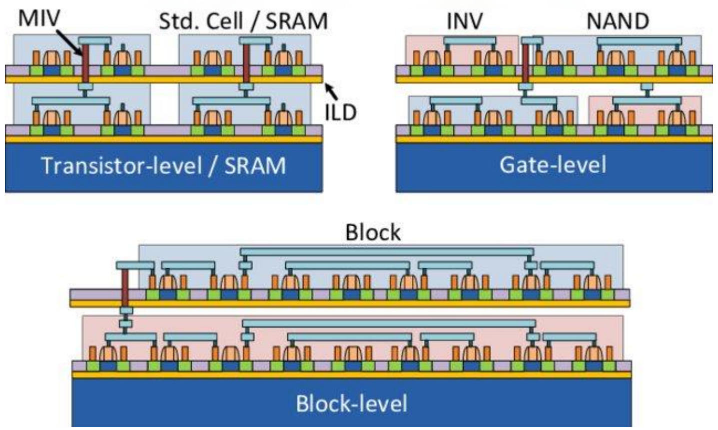


Image from Panth S. et al. (2014), DOI: 10.1109/S3S.2014.7028195

Take away messages

Ultra-intense positron source = Better statistical sensitivity (results/time) + Higher freedom of selecting cold samples (less systematics) + Unlocking exciting new possibilities (e.g. Ps-BEC)

Thank you