FUTURE CIRCULAR COLLIDER

Non collider science opportunities at FCC-ee

Freitag 23.08.2024, 10:00 → 12:20 Europe/Zurich

30/7-010 (CERN)

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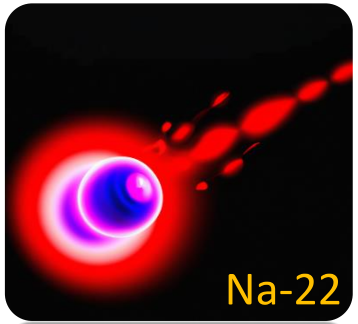
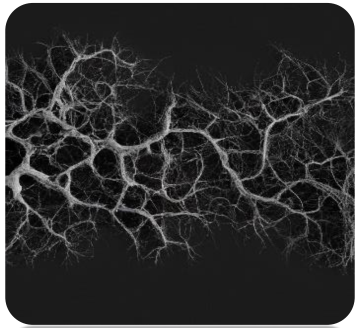
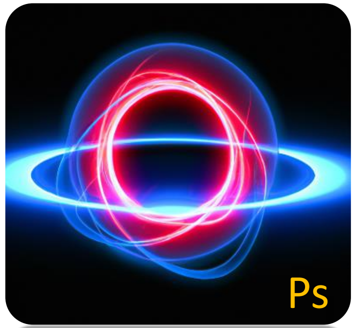
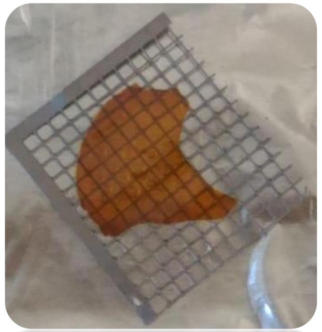


Simple positron source

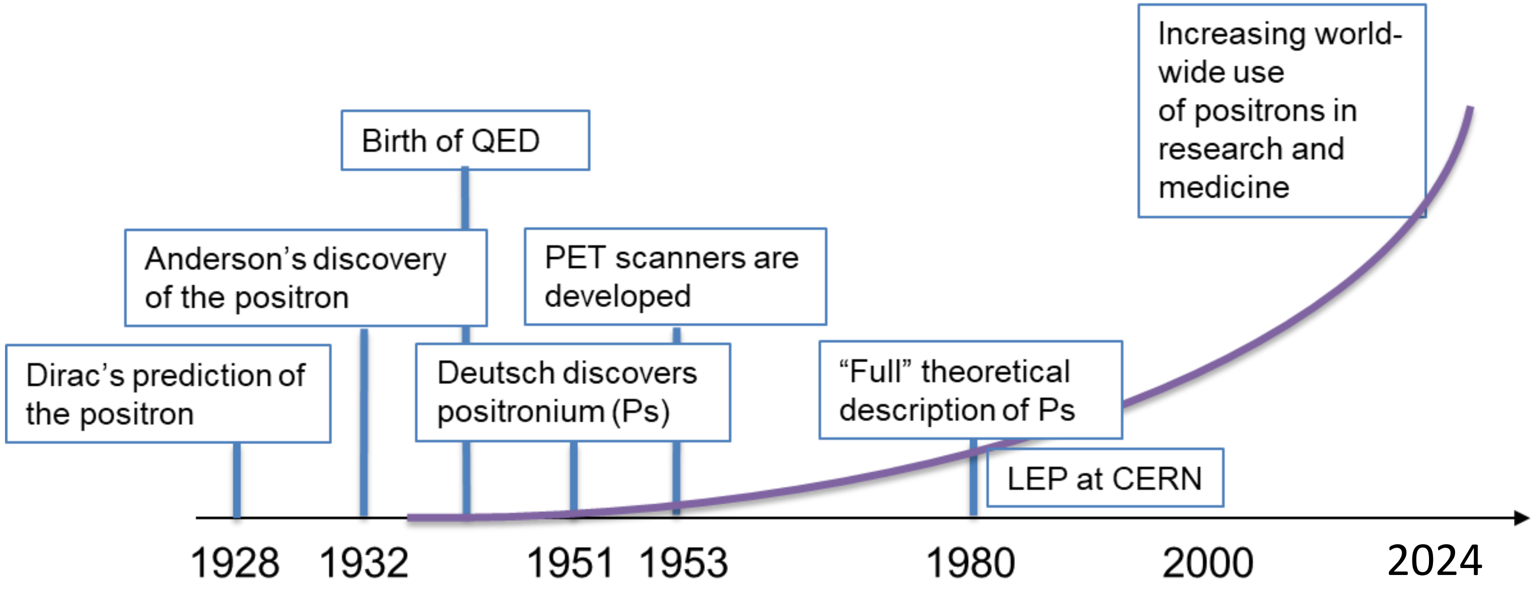

Nanoporous Si



Positronium: e- & e+


Ps converter

A century worth of positrons ...



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, Canberra, ETH)
- FRM II (NEPOMUC)
- KEK (IMSS)

<u>Low energy positron/positronium physics at one glance:</u>

- Precision QED studies (Ps spectroscopy)
- Fundamental symmetry tests (annihilation channels)
- Material studies (defect studies)

Low energy positrons in experiments

Isotope sources (β^+- decay)

Pair production with:

- Nuclear reactor-based sources
- Accelerator-based sources

e^+ with MEV energy →

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

→ e^+ with eV energy →

Continuous slow e^+ beam

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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**

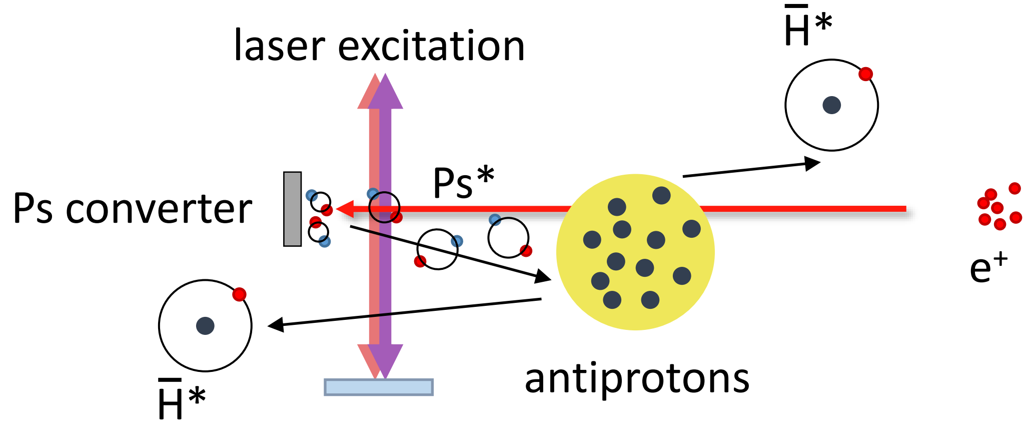
$\varepsilon \approx 10^{-1} \ldots 10^{-?}$

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

Example: Production of anti-hydrogen

Charge exchange reaction:

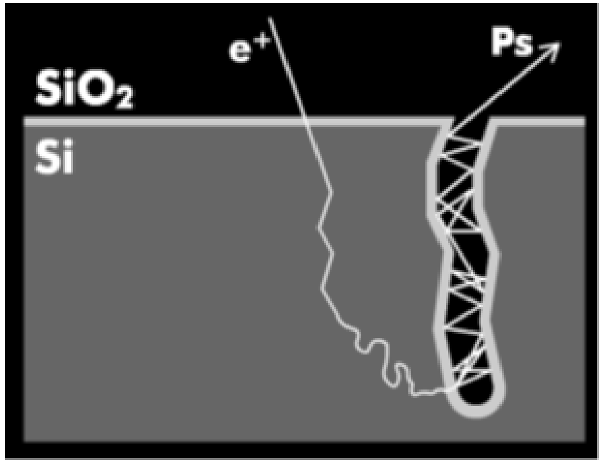
$$Ps^* + \overline{p} \rightarrow e^- + \overline{H}^*$$



*Phys. Rev. A **94**, 022714 (2016)*
https://doi.org/10.1103/PhysRevA.94.022714

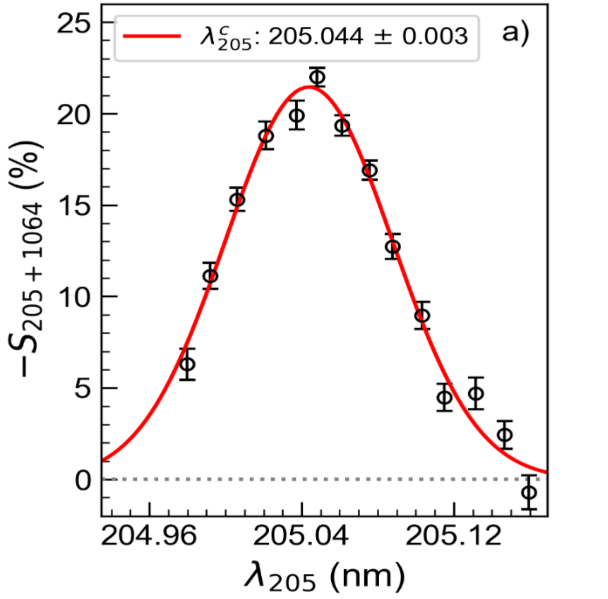
Next generation of cold Ps sources

Nanoengineered positron to Ps conversion target



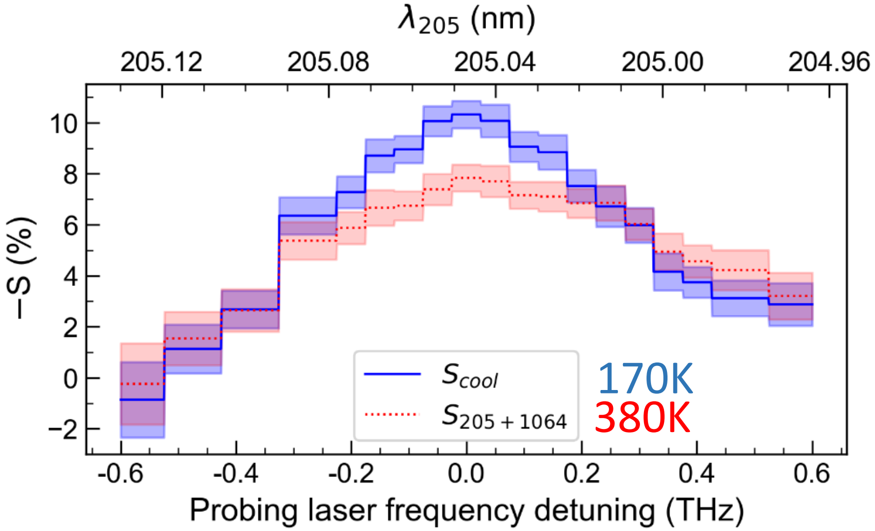
PRL **104** (2010) 243401, J. Phys. B **54** (2021) 085004

Laser Doppler-selection of the sample coldest atoms



PRA **99**, 033405 (2019), PRA **102**, 013101 (2020)

Laser cooling of the coldest fraction



PRL **132** (2024) 083402

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.

Hbar formation at AEgIS

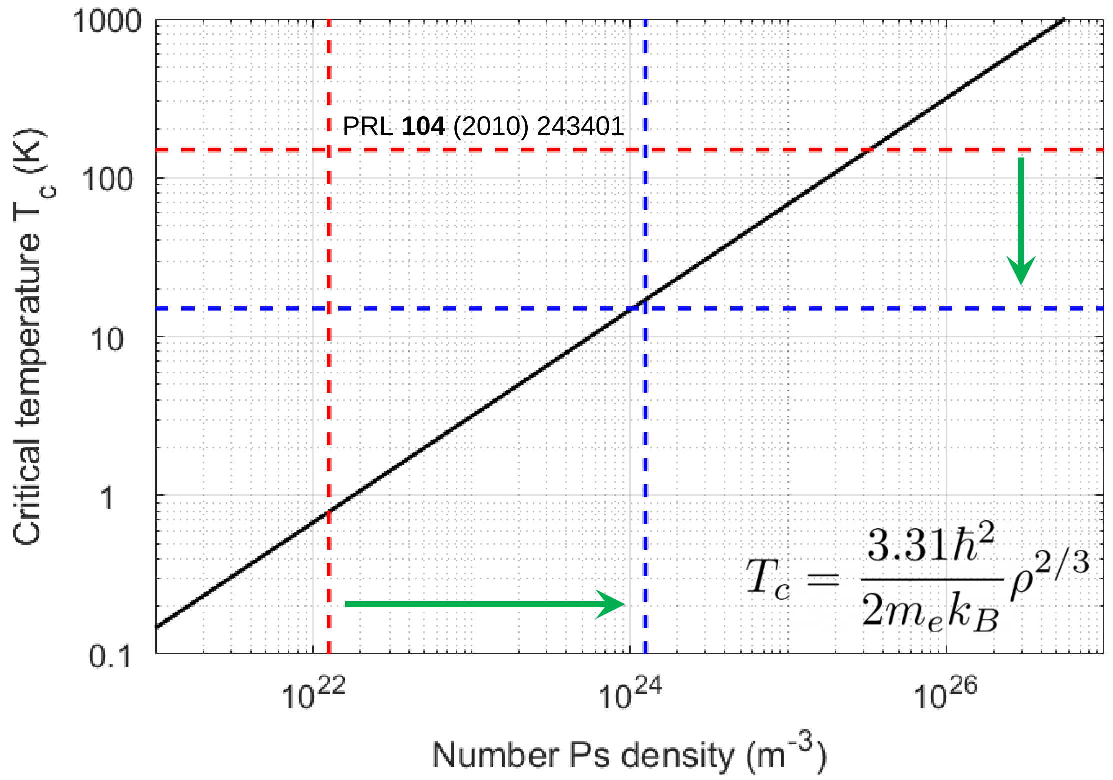
	2018	2023	Improvement factor	2024/25	
Degrader efficiency	(2-3)% of 30E6	≈70% of 5E6 (*)	5	≈88% of 5E6	6
Cross section (n^4)	n = 17	n = 21	2	n=30	10
Positronium target	7.5%	2.5%	0.33	15%	2
Laser Bandwidth coverage	15%	30%	2	30%	2
Pbar plasma – Ps interaction	Perpendicular	Collinear	1.5	Collinear	1.5
Positron Source (**)	1E6 e^+/min	1E6 e^+/min	1	8E6 e^+/min	8
TOTAL IMPROVEMENT			**≈ 10**	**≈ 3000**	
Hbar production	$0.05\bar{H}/min$		$< 1\ \bar{H}/_{min}$	$O(100)\ \bar{H}/_{min}$	

(*) In 2022, a successful trapping of **3.7E6 antiprotons** was demonstrated: https://cds.cern.ch/record/2846698?ln=en

(**) Available from the beginning of 2024 (bottleneck: sole supplier of 22Na sources in South Africa)

Area of impact #1

Efforts towards the first Bose-Einstein condensation of Ps



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

Laser cooling cryogenic positronium atoms for 100ns (15 cooling cycles) could reduce the temperature to **<10K**.

An increase of at least orders of magnitude in Ps density is necessary. The current limit is the rate of accumulation of e^+ from Na-22 sources.

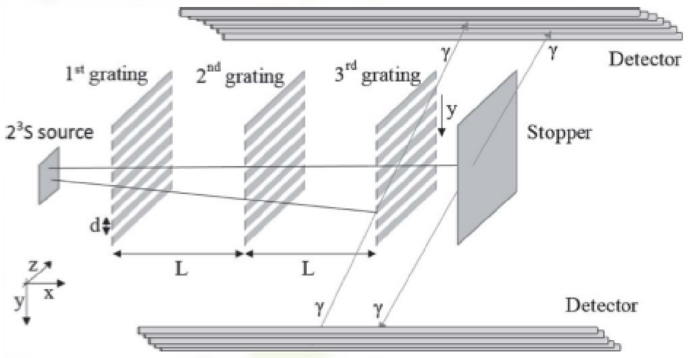
When a Ps-BEC annihilates, a coherent burst of gamma rays is emitted.
A proposed way to build a 511 keV gamma ray laser!

Area of impact #2

Tests of fundamental symmetries and BSM 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

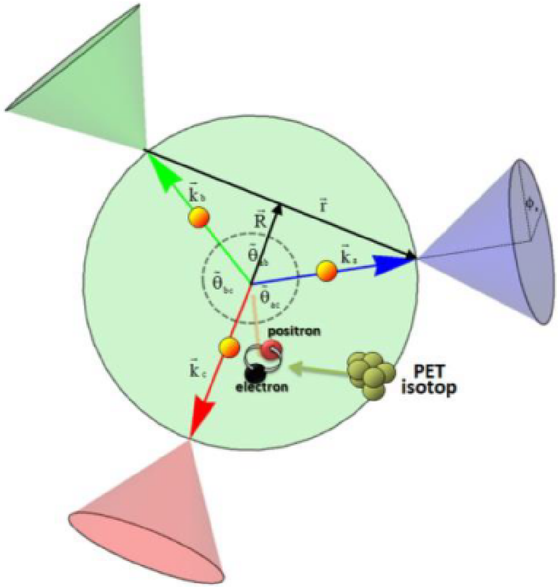
Table from Phys. Part. Nucl. **37** (2006) 321-346

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

New precision QED measurements feasible, with 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	$(Z\alpha mc R_N/\hbar)^2$	—

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

Decay times

$$\Gamma_o^{th} = 7.039979(11)\ \mu s^{-1},$$
$$\Gamma_p^{th} = 7989.6178(2)\ \mu s^{-1},$$

$$\Gamma_o^{exp} = 7.0404(10)^{stat.}(8)^{syst.}\ \mu s^{-1}$$
$$\Gamma_p^{exp} = 7990.9(1.7)\ \mu s^{-1}$$

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

Searches for BSM physics in:

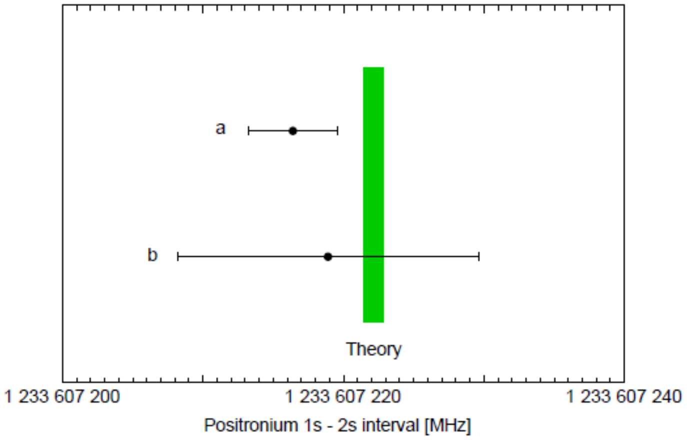
- energy intervals
- decay rates
- decay modes

?

- ➢ Fifth fundamental force
- ➢ Axion-like particles
- ➢ Symmetry violations

1^3S-2^3S transition frequency

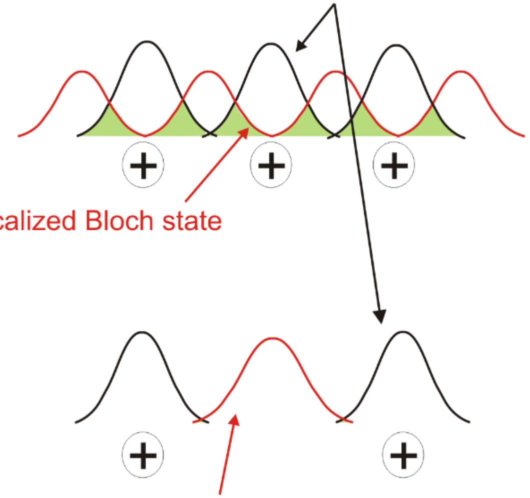
Phys. Rep. **422** (2020) 1-63



Limited by second order Doppler effect, requires colder Ps sources

Area of impact #4

Positrons are non-destructive nanoprobes in material siences



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

→ Depth-resolved defect analysis with positrons

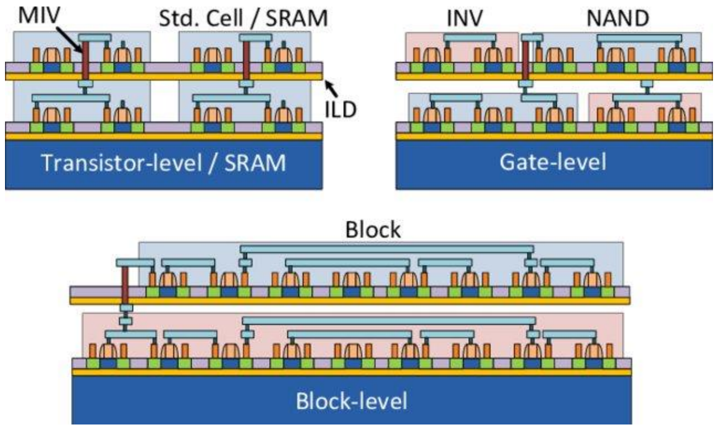


Image from S. Panth et al. *(2014)* , doi: 10.1109/S3S.2014.7028195

Take home message

Positrons

A new intense low-energy e+ beam at CERN

Material Science: non-destructive nanoprobes
=> possibly beam time for global partners in industry and academia?

Next generation Ps sources with high intensity, low energy and higher density

Better measurement efficiency (results/time)

Higher data quality (less systematics)

Unlocking exciting new possibilities (e.g. Ps-BEC, precision QED, BSM)

More antihydrogen for AEgIS <3

THANK YOU