Positronium for fundamental studies

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Outline

• How to obtain cooled Ps in vacuum

• Many positron bunched beams for many Ps in vacuum
  • Ps excitation – long lived Ps
  • Ps for Antihydrogen formation
    • Metastable Ps
    • metastable Ps beam -planned experiments

• Many positron polarized bunched beams planned experiments
**Positronium**

Hydrogen-like bound state of an electron and a positron

**In Vacuum**

- Orto-Ps mean lifetime $\tau$ 142 ns, annihilation in 3 $\gamma$
- Para-Ps mean lifetime $\tau$ 120 ps, annihilation in 2 $\gamma$

In magnetic field the $M=0$ state of pPs and oPs mix together (Zeeman effect). State $M=\pm 1$; -1 are not affected.
Interaction of positrons with matter and Ps formation

1. Slowing down ($0 < t < 10^{-12} \text{ s}$)
   From energy $E$ to thermal energy: ionization, phonon scattering

2. Diffusion motion ($0 < t < 10^{-10} \text{ s}$)

3. Emission if negative work function

$e^+\text{ beam} \quad 0.5 \div 25 \text{ keV}$

$\langle z \rangle = \frac{40}{\rho} E^{1.6} \text{ [nm]}$

Energy

Crystal zero

$\Phi_+ = -\Delta - \mu_+$

$V_{\text{eff}} = \phi(r) + V_{\text{vac}}[\rho(r)]$

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Ps formation in metals and semiconductors

Ps is formed at the surfaces because in the bulk positron is screened by electrons can be a competitive process with e+ emission

Ps from backscattered e+

Ps from epithermal e+

Ps from thermal e+

Ps emission in metals and semiconductors is a thermal activate process

1) e+ trapped in a surface state pick an electron

«Fast» Ps
Energy eV or fraction of eV
Positronium formation in porous materials
collisional cooling mechanism

Formation Mechanisms:

If Ps is formed in the bulk and thermalize, to be emitted in open volumes requires a negative work function

$$\phi_{Ps} = \phi_+ + \phi_- - E_{gap} + E_b - 6.8 \text{ eV} < 0$$

Ps can be formed at the surface when a positron pick up an electron
Ps from nanochannelled silicon converters
avoiding quantum confinement

Classical regime

\[ \lambda_{PS} = \frac{h}{\sqrt{4m_0E_{PS}}} \ll a \]

Quantum regime

\[ \lambda_{PS} \sim a \]

Brusa-Dupasquier -Varenna School 2009
tunable nanochannels in silicon
TOF

ENERGY SPECTRA

300 K
~20% of emitted Ps thermal
~5% of implanted e+

250 K
~15% emitted Ps thermal
~4% of implanted e+

150 K
~10% emitted Ps thermal
~3% of implanted e+

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Nanochannelled silicon simulation and Montecarlo Ps cooling

Figure 1.24: Illustration of the mechanism that leads to the positronium spectrum to show two thermal distribution. Please refer to section 1.10 for a detailed description.
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  • Many positron polarized bunched beams planned experiments
Na22 source
Ne moderator

2 stages
Surko trap

Source
Trap
Accumulator

20 ns
100 V
10^7-10^8 e+

re bunching

3-7 kV
10^7 e+

Field terminator

In magnetic field 700-1000 G

Electrostatic and then Free field

at the e+ -Ps converter

kV pulse, rise 3 ns
Duration 30 ns

Spot at MCP

Bunching (PbF_2+PMT)

System characteristics

Spot at MCP

Na22 source
Ne moderator

2 stages
Surko trap

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Mariazzi et al. NIMB 362,86 (2015)
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Detecting Ps flying in vacuum

SSPALS (Single Shot Positron Annihilation Lifetime Spectroscopy) Techniques, firstly introduced by Cassidy & Mills

10^6 Ps atoms in vacuum for shot
Detector: PbWO₄ scintillator + Hamamatsu R11265-100 PMT
Time decay about 15 ns
Long lived Ps

Route n=2


Route n=3

Para Ps

singlet

Orto Ps

triplet
**n=3 Ps excitation (1^3S - 3^3P)**

-3P excitation line centered at 205.05±0.02 nm

-excitation-ionization efficiency ~15%

Energy : 54 μJ UV; 1.1 mJ IR

\[ S(\%) = \frac{\text{Area laser OFF - Area laser ON}}{\text{Area laser OFF}} \]

Ps excitation $n3$ - Rydberg

$S(\%) = \frac{\text{Area laser OFF} - \text{Area laser ON}}{\text{Area laser OFF}}$
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Motivation

Disappearance of antimatter

Violation of CPT or WEP?

Tests of universality free fall (UFF)

Luigi Catani 1816 - Firenze Palazzo Pitti

“cascai in opinione che se si levasse totalmente la resistenza del mezzo, tutte le materie discenderebbero con eguali velocità”.

Galileo Galilei (1564-1642)
AEgIS (Antihydrogen experiment: gravity, interferometry, spectroscopy) at CERN

**H** production by charge exchange

- Large cross section $\sigma \approx \pi a_0 n^4$ for Ps cold
- Ps needed in Rydberg state for increasing the lifetime and cross section
- Quantum states of antihydrogen related to Ps quantum number
- Antiprotons $T$ determines antihydrogen $T$ (cold antiprotons!)

\[
p + (Ps)^* \rightarrow H^* + e^-\]
Ps * towards the pbar trap

S(%) = (Area laser OFF - Area laser ON) / Area laser OFF

UV laser pulse

e^+ beam

Ps target

MCP electrode

1 cm

e^+/Ps converter

excited 2^3S Ps

Y position [mm]

-55 pm -45 pm -35 pm -25 pm -15 pm -5 pm 5 pm 15 pm 25 pm 35 pm 45 pm

λ_0

204.80 204.85 204.90 204.95 205.00 205.05 205.10 205.15 205.20 205.25

0

5

10

15

20

S(%)
free fall measurement

Moirè deflectometer

- 2 gratings $L \sim 50 \text{ cm}$
- $\Phi=100 \text{ mm}$, slit $12 \mu\text{m}$, pitch $40 \mu\text{m}$
- $\Delta y \leq 10 \mu\text{m}$

Pulsed $\vec{H}$ beam, Stark acceleration $v \approx 400 \text{ m/s}$

\[ \Delta y = \frac{1}{2} g T^2 \left(\frac{L}{v}\right)^2 \]

M.K. Oberthaler et al. PRA 54, 3165 (1996)

Aghion et al. (AEgIS) Nature Comm. 5, 4538 (2014)
Test with a Mini-moiré

Antiproton $E=100\pm 150$ keV
slit arrays in 100-μm thick silicon by ion etching
slit width of 12 μm
periodicity of $d=40 \, \mu m$
Reference measurement with light (Talbot – Lau)

Emulsion Compatible with a force $530 \pm 50$ (stat.) $\pm 350$ (syst.) aN
Corresponding to an $E=33$ V/cm direction of the grating period
or a $B=7.4 G$ perpendicular to the grating period and antiproton direction

With lower $\nu (\overline{H}), L \sim 1 m$, sensitivity 11 order mag better

$\Delta y=9.8\pm 0.9 \mu m$ (stat.)
$\pm 6.4 \, \mu m$ (syst.)

Aghion et al. (AEgIS) Nature Comm. 5, 4538 (2014)
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AEgIS makes positronium for antimatter gravity experiments

The AEgIS collaboration at CERN has found a new way of making long-lived positronium atoms for antimatter gravity experiments
2\textsuperscript{3}S Ps, metastable state 1140 ns, in FREE FIELD

In free field $\Rightarrow$ lifetime 1140 ns

-205 nm

Selecting velocities of $2^3S$ Ps by retarding the laser

Selection of different Ps population cooled from nanochannelled silicon convertres, i.e. population with different velocities
From $1 \times 10^5$ m/s to $7 \times 10^4$ m/s

<table>
<thead>
<tr>
<th>Laser delay</th>
<th>$1^3S \rightarrow 3^3P$ efficiency</th>
<th>$3^3P \rightarrow 2^3S$ efficiency</th>
<th>$2^3S$ average velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 ns</td>
<td>$(13.8 \pm 2.2)%$</td>
<td>$(9.7 \pm 2.7)%$</td>
<td>$(1.0 \pm 0.1) \times 10^5$ ms$^{-1}$</td>
</tr>
<tr>
<td>35 ns</td>
<td>$(8.8 \pm 2.6)%$</td>
<td>$(8.7 \pm 5.0)%$</td>
<td>$(0.8 \pm 0.1) \times 10^5$ ms$^{-1}$</td>
</tr>
<tr>
<td>50 ns</td>
<td>$(6.8 \pm 2.9)%$</td>
<td>$(10.1 \pm 6.2)%$</td>
<td>$(0.7 \pm 0.1) \times 10^5$ ms$^{-1}$</td>
</tr>
</tbody>
</table>
$2^3S$ Ps, metastable state 1140 ns, stimulated production

This give a $2^3S$ Ps yield of about 3 time more than spontaneous decay (with a tuned system we expect about 4.5 % of produced Ps in metastable state)
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Ps metastable beam-apparatus

Metastable Ps drift tube

Ps chamber formation

LaBr3

PbWO4

e+

Ps metastable beam

apparatus

stopper
Rydberg

best exponential fit ($\tau = 191 \pm 11$ ns)

Ps

Rydberg

Ps

Metastable

2\textsuperscript{S} positronium

Ps
Determining the hitting position of the metastable Ps on the stopper, and if possible its annihilation in flight.

With a detector derived by J-PET.
Towards measurement of g acting on Ps

Planned measurement with moire’ deflectometer or Mach Zehnder interferometer
Measurement of dipole forces 100g - 1000g (10%)
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First stage of polarized e+ beam-source at Trento University

First Planned experiments
Study of entaglement of 3 photons of decaying Ps

Collaboration and tasks:

Trento Uni: Polarized Ps in vacuum and selection of oP states by laser or by solid state converters

Vienna Uni: Beatrix C. Hiesmayr Theory

Jagiellonian Uni: Pawel Moskal Detector System to measure momentum and spin of gammas
Conclusions

Manipulation of Long lived Positronium is shown to be possible, opening the route for interesting fundamental studies.

Further improvements of quality of the metastable beam and of its intensity are possible developing techniques like Ps laser cooling and different schemes to bring Ps in the $2^3S$ state.
Aknowledgements

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AEgIS
Collaboration at CERN
in particular laser-positron people
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Benji Rienacker
Antoine Camper

New projects
Pawel Moskal
Sushil Sharma
Beatrix Hiesmayr

Padova INFN
Giancarlo Nebbia
Thank you for your attention!
Interaction of positrons with matter and moderation process

**SLOWING DOWN to attain equilibrium**

$0 < t < 10^{-12} \text{ s}$

Energy loss: core excitation, plasmons, hole-electron, phonons

\[
\frac{\partial f(r, p, t)}{\partial t} + \mathbf{v}(p) \cdot \nabla_r f(r, p, t) + \mathbf{F} \cdot \nabla_p f(r, p, t) = \left[ \frac{\partial f(r, p, t)}{\partial t} \right]_s - (\lambda_b + \kappa) f(r, p, t) + f_i(r, p, t)
\]

**DIFFUSION** Free annihilation and trapping

\[
\frac{\partial f(r, t)}{\partial t} = D_+ \nabla^2 f(r, t) - [\lambda_b + \kappa(r)] f(r, t)
- \nabla \cdot [v_d(r) f(r, t)] + f_i(r, t),
\]

Steady state

\[
D_+ \nabla^2 f(r) - [\lambda_b + \kappa(r)] f(r) - \nabla \cdot [v_d(r) f(r)] + f_i(r) = 0
\]
Positron moderation

Angular distribution

Energy Distribution

transmission

22Na emission spectrum

\[ \theta_{1/2} = \left( \frac{E_{\text{peak}}}{\phi^+} \right)^{1/2} = \left( \frac{kT}{\phi^+} \right)^{1/2} \]

W(110) + O2 @ RT

\[ \text{Maxwell-distribution} \]

\[ kT^* = 0.032 \text{ eV} \]
Solid gas moderator

Energy spectrum of positron emitted by a thick Layer of Ne covering a Na22 source

**TABLE I. Properties of rare gas solid moderators.**

<table>
<thead>
<tr>
<th></th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>0.70(2)</td>
<td>0.13(2)</td>
<td>0.14(2)</td>
<td>0.13(2)</td>
</tr>
<tr>
<td>$\Delta E$(eV)</td>
<td>0.58(2)</td>
<td>1.7(2)</td>
<td>1.8(2)</td>
<td>3.2(4)</td>
</tr>
</tbody>
</table>

Ps excitation - laser system

OPG (Optical Parametric Generator) \( \omega = \omega_1 + \omega_2 \)  

Signal and Idler  

OPA (Optical Parametric Amplifier) after the OPG to match in SUM  

SUM in a BBO (Barium Borate) crystal  

Wavelength tuned by changing the OPG temperature

Cialdi et al. NIMB 269, 1527 (2011), Castelli et al. PRB 78, 052512 (2008)
Detector: Emulsions

Antiprotons 100 keV
Annihilation vertex and tracks. Positions are found with 1-2 μm resolution

Tacks main pions, vertex proton and Heavy nuclear fragments.

Storey et al. Hyp. Inter. 228, 151 (2014), S. Aghion et al. JINST 2013