Ps formation
and
Ps cooling
(I)

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Many experiments with many positrons require high yield of cooled Ps
(see previous and following lectures of this school)

BEC,
Anti-hydrogen formation by Ps*-pbar charge exchange,
Ps spectroscopy, Ps excitation in Rydberg states

For these experiment high intensity bunched beams are necessary but Ps must be formed and cooled, confined or in vacuum, and you need a a 5x5x0.5 mm$^3$ of some material

Ps can be cooled and in some cases it can reach the thermal equilibrium with the host (thermalize)
The target material have to fulfill many requirements:

a) To be stable both at RT as at cryogenic T ie:

b) The material must not be damaged by e+ flux or photon flux
   the Ps yield and cooling can be worsened

c) Charging effect must be avoided

d) Reasonable goal: it must convert about 10 % of e+ in cooled Ps

also for laser cooling a Ps pre-cooling
would be necessary and a Ps converter necessary
If Ps is formed, it could be cooled by lasers, but its final $T$ will depend from its starting $T$.

A two level atom in steady state can spend at most half of its time in the excited state because in $P$ state $\tau=100\mu s$ oPs live 280 ns.

In 280 ns about 44 excitation de-excitation are only possible (6.4 ns for process).

$$ \frac{d\nu}{dt} = -\Gamma \nu_{rec} = -\frac{\nu_{rec}}{3.2 \text{ ns}} \rightarrow \Delta t \Gamma = 44 $$

$$ \nu_{rec} = \frac{\hbar k}{m_{Ps}} = 1.5 \times 10^3 \text{ m/s} $$

$$ \frac{1}{2} k_B T_m = \frac{1}{2} \frac{\hbar^2 k^2}{m} \rightarrow T_m = 0.3 \text{ K} $$

If oPs has RT thermal velocity, it can reach at least $\sim 10 \text{ K}$.
From what we know about Ps formation processes in metals and dielectrics we can point out:

a) In metals, one Ps emission is thermal, it means that high yield are obtained by increasing the temperature, to have Ps emission at low temperature modification of the surface is needed to change the positron activation energy.

b) In silica up to 80% Ps is formed and it can be also emitted in vacuum but with energy around 1-3 eV, cooling mechanism by collision must be used.

Information on Ps collision can be gained by studying Ps thermalization in gases.
• I lecture

  • Ps thermalization and cooling by collisions
  • Thermalization in gases
  • Thermalization in silica oxide powders
  • Ps emission at low temperature from modified metal surfaces

• II lecture

  • Porous materials: cooling at room temperature
    • Porous materials: cryogenic cooling
  • oPs pick-off at cryogenic temperature
  • oPs emission from nano-channels in silicon
Studies in gas are interesting to obtain information on the thermalization process:

Collisions:

- elastic?
- anelastic?

Influence the energy loss and the Thermalization times

Ps formation in gases

\[ e^+ \rightarrow \text{GAS} \rightarrow \text{Ps} \]

Charge exchange process

\[ e^+ + Y \rightarrow Y^+ + Ps + e^- \]

Positronium is formed with energy

\[ E_{Ps} = E_{e^+} + (E_i - 6.8) \]

The energy of interest in Ps thermalization are from few eV (3-6) to meV

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Ps beams are limited at Ps energies of 10 eV because:

a) Ps yield decreases at threshold energy
b) The angular divergence increases

In future, thanks many positrons, measurements with Ps beam from neutralization of Ps− could be possible

See for ex. Gartner poster

Cross sections and oPs thermalization are studied in gases at high pressure injecting fast positrons from radioactive source

two different systems:

in gases at high pressure: time resolved Doppler broadening DB

in gases confined in silica aerogel (1 atm): ACAR measurements
Open channels in the thermalization process of Ps:

Channels that can contribute to Ps slowing down

- **Elastic scattering**
  \[ Ps + Y \rightarrow Ps + Y \]

- **Inelastic vibrational and rotational excitation** (only for molecules)
  \[ Ps + Y \rightarrow Ps + Y^* \]

Channels that remove Ps

- **Pick-off quenching**
  \[ oPs + Y \rightarrow 2\gamma + Y^+ + e^- \]

- **Exchange or conversion quenching**
  \[ oPs + Y(\uparrow) \rightarrow pPs + Y(\downarrow) \]

- **Chemical quenching**
  \[ oPs + Y \rightarrow oPsY + \text{energy} \]
Hypothesis:

1) scattering is spherically symmetric in the center of mass system
2) Molecular motion completely random

The model looks for an expression giving the energy loss for collision.

The Ps slowing down was modeled with the Sauder’s classical elastic scattering model (’68).

If deviation are found, they can be ascribed at inelastic channels.

The model looks for an expression giving the energy loss for collision.

Hypothesis: 1) scattering is spherically symmetric in the centre of mass system
2) Molecular motion completely random

With this hypothesis is possible to average on all possible scattering angles and the energy loss \( \Delta E = K - K_i \) becomes:

\[
\Delta E = -\frac{2m_{Ps}M}{(m_{Ps} + M)^2} \left( \frac{m_{Ps}v_{Ps}}{2} - \frac{M\langle V \rangle^2}{2} \right)
\]

\[
\frac{\Delta E}{E} \approx -\frac{m_p}{M}
\]
From the kinetic theory the mean collision rate is \( \lambda_c = n \sigma \nu_{Ps} \)

Where \( n \) is the number of atoms for cm\(^3\) and \( \sigma \) the elastic cross section

\[
\frac{dE}{dt} = \Delta E \lambda_c
\]

Treated as a continuum process

\[
\frac{dE(t)}{dt} \equiv -\frac{2m_{Ps}M}{(m_{Ps} + M)^2} n\sigma \sqrt{2m_{Ps}E(t)} \left( E(t) - \frac{3}{2} k_b T \right)
\]

Integrating with \( M + m_{Ps} \approx M \) \( \sigma = \cos t \)

\[
\frac{E(t)}{E_{th}} = \coth^2 (\beta + \alpha t)
\]

\[
\alpha \approx n\sigma \sqrt{3k_b T m_{Ps}} \frac{1}{M}
\]

\[
\beta = \coth^{-1} \left( \frac{E_0}{E_{th}} \right)
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Principle of the measurements

The principle of the measurements are based on oPs in m=0 state that annihilate into 2 gammas when mixed with pPs in a magnetic field (Zeeman effect).

\[ \Gamma_{1,0} = \frac{1}{1 + y^2} \left( \Gamma_3 \gamma + y^2 \Gamma_2 \gamma \right) \]

\[ y = \frac{x}{1 + \sqrt{1 + x^2}} \quad x \equiv \frac{B}{36(kG)} \]

At the used field of about 3 kG
64% of oPs is mixed and its lifetime is reduced at 52 ns
pPs lifetime is practically un-changed at this field

Effect: narrowing of DB annihilation spectra and characteristic feature in ACAR spectra

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Delayed Time window 30-50 ns
To avoid prompt events.

\[0 < t < 30\] prompt events:
e+, pPs, annihilations

\[t > 30\] oPs mixed
The oPs average kinetics energy is computed from the FWHM of the narrow peak assuming a Maxwell Boltzman distribution of isotropic velocity for thermalized Ps

$$E_{Ps} = (1.028 \text{ FWHM})^2$$

From Gidley PRA 67(2003)
\[
\frac{E(t)}{E_{th}} = \coth^2(\beta + \alpha t)
\]

\[\arc\coth \sqrt{\frac{E}{E_0}} = \beta + \alpha t\]

\[
\beta = \coth^{-1} \sqrt{\frac{E_0}{E_{th}}}
\]

\[
\Gamma = \frac{\alpha}{n} \equiv \sigma \frac{m_{Ps}}{M} \langle v_{Ps} \rangle_{th}
\]

Ps within 10% \(E_{th}\) \(2\tau=2/\Gamma\)

- N\(_2\) \(\sim 180\) ns
- He \(\sim 120\) ns
- H\(_2\) \(\sim 50\) ns
- Isobutane C\(_4\)H\(_{10}\) \(\sim 32\) ns
- Neopentane C\(_5\)H\(_{12}\) \(\sim 26\) ns

Normalized density thermalization rate

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Measure in silica aerogel 0.1 g/cm³
Mean grains diameter of aerogel 5 nm mean distance between the grain 70 nm

In the measurements the scattering with the walls of the grains
must be take into account

The Sauder’s model is modified

to \( \lambda_c = n \sigma v_{Ps} \) a collision frequency with the grain is added \( \lambda_s = \frac{v_{Ps}}{L} \)

\[
\frac{E(t)}{E_{th}} = \coth^2(\beta + \alpha t) \quad \beta = \coth^{-1}\sqrt{\frac{E_0}{E_{th}}}
\]

\( \alpha \cong n \sigma \sqrt{3k_bT \ m_{Ps}} \ \frac{1}{M} \quad \alpha^* = \left( \frac{n \sigma_m}{M} + s \right) \sqrt{3k_bT \ m_{Ps}} \quad s = \frac{2}{LM_s} \)
\[ E_{av}^{\exp}(\tau) = \frac{3 \int_{-\infty}^{\infty} \frac{p_z^2}{2m_{ps}} N(p_z) dp_z}{\int_{-\infty}^{\infty} N(p_z) dp_z} \]

Nagashima PRB '95, JPB '98
Saito JPB 2003
With $E(t)$ from an improved formula of the type

$$\frac{dE(t)}{dt} \equiv -\sqrt{2m_p s} E(t) \left( E(t) - \frac{3}{2} k_B T \right) \left[ f(\sigma) + f(s) \right]$$
Both the experiments seems to indicate that the thermalization of Ps is only determined by elastic scattering. Also in the complex molecules.

But Ps is neutral and its interaction is a van der Walls interaction effective at short distance

\[
V(R) = -\frac{A}{R^6} + \frac{B}{R^8}
\]

<table>
<thead>
<tr>
<th>interaction</th>
<th>positronium</th>
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</tr>
<tr>
<td>Polarization</td>
<td>Zero</td>
</tr>
<tr>
<td>Exchange</td>
<td>Yes</td>
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</table>
Study of Ps thermalization in gases seems to show that inelastic scattering collisions, if present, are not much effective in cooling Ps
Time resolved DB and ACAR for thermalization in powders and aerogel

Method:

Materials:

Cab-O-Sil or fumed silica

\[ SiCl_4 + 2H_2 + O_2 \rightarrow SiO_2 + 4HCl \]  
(-OH group on the walls)

Aerogel, very light material

\[ nSi(OH)_4 \rightarrow [SiO_2]_n + 2nH_2O \]

From Takada et al. RPC 2000

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Average Ps energy as a function of the time t in powders. Closed circles results on Cab-O-Sil (ρ=1 g/cm³) with time resolved ACAR. Open Circles results on silica aerogel (ρ=0.1 g/cm³).

The line is a fit with the Sauder’s elastic model.
The perpendicular velocity is measured $v_\perp$.

$$E_\perp = \frac{1}{2} m_{Ps} v_\perp^2 = m_e \frac{z^2}{t^2}$$
SiO₂ powders

Fumed silica
0.18 g/cm³
Grain 3.5 nm

F(t) is multiplied for:
exp (t/142 ns) – oPs decay
1/t – time spent by oPs in front to the detector
t³ – for the change of variables

\[
E_\perp = \frac{1}{2} m_{Ps} v_\perp^2 = m_e \frac{z^2}{t^2}
\]

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non thermal Ps emission was found

4.2 K  2% thermal at 19 keV positron implantation
30 % below 10 meV (76 K)

77 K   at 10 keV  54 % below  64 meV (490 K)

Mills-1989
\[ E_a = E_b + \phi_- - 6.8 \text{ eV} \]

To obtain thermal desorption at low temperature the surface must be modified to lower the activation energy $E_a$.

After Lynn ’80, monolayer of O was found to promote Ps desorption.
Practical problems with such a source of cool Ps

the Ps formation and yield is strongly dependent on the Al + O system preparation and the right O₂ exposure conditions at low temperature
the oxygen phase at the Al surface can change as a function of the sample temperature and the adsorbed oxygen.

the oxygen coverage is destroyed by heating the sample after the oxygenation process and probably the oxygen overlayer is also sensible to photons flux that can dissociate the chemical surface bonding between physisorbed oxygen and Al
Ps formation measured by lifetime and peak to valley ratio
Total Ps yield at 325 K up to 65 % was obtained by covering the Ni surface
and the yield increased by increasing the sample temperature up to 525 K.

The linear extrapolation of $E_a$ as a function of the coverage predict spontaneous
emission of Ps ($E_a=0$) at 0.9 monolayer of Na on Ni (100)

$E_a = E_b + \phi - 6.8 \text{ eV}$

Gidley 88
Ps collision at energies below few eV in gases seems to be mostly elastic and very sensitive to the mass of the single atoms more than to the structure of the molecules.

Ps cool down in silica powders and silica aerogel quite efficiently. The cooling rate depends from the size of the open volumes between the grains. Effective mass always larger than the mass of the SiO2 and -HO atoms on the surface.
Psf was found to cool at 77 K in Si powder kept at 4 K.

Metals are requiring more study. Works date ’88-’91.
Possible modification of the surface for activating Ps desorption at low temperature must be search for.
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