Pulsed production of antihydrogen

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The Weak Equivalence Principle
(Universality of free fall, General relativity)

\[ V = -\frac{Gm_1 m_2}{r} \left( 1 \pm a \ e^{-\frac{r}{\nu}} + b \ e^{-\frac{r}{\delta}} \right) \quad (a, b \geq 0) \]
Antimatter moiré deflectometer

Velocity 350 m/s (T = 5K)
Length 0.5m
\( \tau \sim 10^{-3} \) s
\( d = 10^{-4} \) m
\( \varphi = \frac{2\pi}{d} \Delta y = \frac{2\pi}{d} a \tau^2 \)

Resolution
\( R_{acc} = \frac{d\varphi}{da} = 2\pi \frac{\tau^2}{d} \sim \frac{2\pi}{100} \)

Minimal detectable acceleration
\( a_{min} = \frac{1}{R_{acc} C \sqrt{N}} \)
\( a_{min} = 1 \text{ m/s}^2 \) for \( N = 10^4 \) and \( C = 0.16 \)

Aghion S. et al (AEgIS collaboration), Nat Comm 5:4538 (2014)
Antihydrogen production

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

Kellerbauer A. et al (AEgIS collaboration), *NIM B* 266 (2008) 351-356
Krasnicky D., Caravita R., Canali C., Testera G., *PRA* 94 (2016) 022714
The AEgIS setup

Chamber for Ps experiments

Positron accumulator

1T trap

5T trap

Target for Ps production and $\bar{H}$ formation

Positron trap

Positron transfer line

Antiproton line

Positron source
Positronium (Ps) production

Positronium (Ps) 142 ns lifetime

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

<1650nm

205nm

Log\(_{10}\) (Hbar formation cross-section [m\(^2\)])

Ps* ion (10°)

Ps* ion (90°)

Suboptimal Rydberg state

Hbar ionization region

\( B \approx 0 \)

Ps* principal quantum number n

Ps* velocity towards antiprotons at rest [m/s] \times 10^6
SSPALS positronium Doppler velocimetry

Methodology
Excite the $1^3S - 3^3P$ transition (UV)
Photoionize $3^3P$ atoms (IR)
o-Ps signal reduction at later times

Results
First spectroscopy of Ps n = 3
Doppler temperature ~1200K
16 % max. excitation efficiency
- 20 % Doppler coverage
- 80 % geometrical efficiency

Aghion S. et al (AEgIS collaboration), Physical Review A 94 (2016) 012507
Photoelectron imaging

Lines of B field

MCP, Phosphor screen and camera

$e^-$

$e^-$

$e^-$

$e^-$

$e^-$

$e^-$

Production trap electrodes

Secondary electrons picture of the trap

Nanochannel Ps converter

1 mm
Photopositrons: a background free signal

\[ \lambda^D = \lambda_a \left( 1 + \frac{v_\parallel}{c} \right) \approx \lambda_a \left( 1 + \frac{x}{c \times \Delta t} \right) \]

In green: photopositrons from positronium prepared in n=3
Motional Stark effect self-ionization

\[ \vec{F}_{\text{mot}} = \vec{v} \times \vec{B} \]

Antonello M. et al (AEGIS collaboration), *Phys Rev A* 102, 013101 (2020)
Pulsed production of antihydrogen

**Key finding:** 0.05 $\bar{H}^*$ produced every 2 mins (with $1.0 \cdot 10^6$ antiprotons) $\bar{H}^*$ produced in a time window of 250ns

Amsler C. et al (AEgIS collaboration), *Com Phys* 4:19 (2021)
Recent developments

• Connection to ELENA (new degrader scheme)
• On axis Ps production (higher Rydberg states)
• Fiber bundle multispectral imaging system
Positronium laser cooling

- Short annihilation lifetime (142 ns) pulsed cooling with long intense UV pulse → alexandrite laser
- Broad initial distribution ($10^5$ m/s)
- Short decay time of n=2 (3ns)
- Huge recoil (15 km/s)
- Quenching in E and B field

Zimmer C. et al, *Phys Rev A* 104, 023106 (2021)
Formation of cold antiprotonic atoms

1. Precise laser spectroscopy of Rydberg antiprotonic atoms
2. Trapping of cold and trapped highly charged radioisotopes produced after annihilation of antiprotons on the surface.
Conclusions and perspectives

• Antimatter deflectometer
• Pulsed production of antihydrogen
• Ps velocimetry
• Enhanced production of antihydrogen
• Directional beam of antihydrogen
• Ps laser cooling
• Antiprotonic atoms
Thank you for your attention!
Figure 1 | Moiré deflectometer for antiprotons. (a) A divergent antiproton beam impinges on two subsequent gratings that restrict the transmitted particles to well-defined trajectories. This leads to a shadow fringe pattern as indicated in b, which is shifted in the presence of a force (blue trajectories). Finally, the antiprotons are detected with a spatially resolving emulsion detector. To infer the force, the shifted position of the moiré pattern has to be compared with the expected pattern without force. (c) This is achieved using light and near-field interference, the shift of which is negligible. A grating in direct contact with the emulsion is used to reference the antimatter and the light measurements.
