Plasmas and Trap-Based Beams as Drivers for New Science with Antimatter

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* Supported by the U. S. NSF, DoE and the UCSD Foundation
Well, a better title for this audience is: **Gaseous Electronics with Antimatter**

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The Mirror World of **Antimatter**

**positron** ↔ **electron**

**antiproton** ↔ **proton**

New Particles:

**Positron**

\[ e^- + e^+ \rightarrow \text{gamma rays} \]

\[ 2\gamma^* \quad (S = 0) \text{ or } 3\gamma \quad (S = 1) \]

(2\gamma decay: \( \varepsilon_\gamma = m_e c^2 = 511 \text{ keV} \))

**Antiproton**

\[ p + \bar{p} \rightarrow \text{shower of pions (e.g., } \pi^+, \pi^-) \]

New Atoms:

**Antihydrogen** (\( \bar{p}e^+ \)) : \( E_B = 13.6 \text{ eV (stable)} \)

**Positronium atom** (\( e^+e^- \)) : \( E_B = 6.8 \text{ eV} \)

\[ \tau_{s=0} = 0.12 \text{ ns; } \tau_{s=1} = 140 \text{ ns} \]
Tailoring and Delivery of Trapped Antimatter

Antiparticles are scarce in our world of matter

Confine antiparticles as a single-component plasma
in an electromagnetic trap

Accumulate, tailor the plasma, then tailor
the delivery for specific applications
Outline

Tools for antimatter studies
  Trapped antimatter
    Efficient trapping
  Cooling
  Radial compression (for density control)

Beams and delivery
  Narrow energy spreads
  Time bunching
  Merging plasmas
  High quality Ps beams

New science
  Positron binding to matter
  Precision measurements on Ps and $\overline{\text{H}}$
  Ps BEC and $e^+ - e^-$ (“pair”) plasma
Sources of $e^+$ and $\bar{p}$

**Positrons** (energies $\sim$ keV - MeV)
- Radioisotopes ($^{18}$F, $^{58}$Co, $^{22}$Na)
  (portable, or reactor-based)
- Electron accelerators (e.g., LINACs)
  ($\varepsilon \geq 2m_ec^2 = 1$ MeV)

**Antiprotons** (energies $\sim$ GeV)
- Particle accelerators (CERN, Fermilab)
  (fast protons: $\varepsilon_p \geq 6$ m$_p$c$^2 \sim 5.6$ GeV)

Use materials (degraders or moderators) to slow antiparticles to eV energies
History of Trapped Antimatter – the March Goes On

Antiprotons, Penning trap, Gabrielse, 1986

Positron plasma, Penning-Malmberg trap, 1989

Merge antiprotons & positrons for antihydrogen
ATHENA, ATRAP, 2002

Trap antihydrogen, ALPHA, 2010

High-quality positronium atom beams
Antihydrogen

Antimatter
Exploiting
the Plasma
Connection

Positronium physics
Ps$_2$, Ps beams

Pulsar crab nebula

antihydrogen

e$^+$ - e$^-$ (pair) plasmas

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Positron-matter
binding

Ps-atom BEC

Pulsar crab nebula

$\gamma$-ray line

Munich high-flux
positron source

e$^+$

C$_2$H$_3$N

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Ps-atom BEC

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Positron-Auger

Positron-Auger

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A Near-Perfect “Antimatter Bottle”
the Penning-Malmberg Trap

plasma rotates:
\[ f_E = \frac{cne}{B} \]

single-component plasma

Canonical angular momentum
\[ L_z \approx -\frac{m\alpha c}{2} \sum_j r_j^2 \]

No torques \( \Rightarrow \) \( \sum_j r_j^2 \) constant. No expansion!

(Malmberg & deGrassie ‘75; O’Neil ‘80)
Buffer-Gas Positron Trap
(down-home gaseous positronics!)

- Trap using electronic excitation of $N_2$
- Positrons cool to 300K on $CF_4$ in $\sim 0.1s$

30% trapping efficiency using $Ne$ moderator

Surko PRL ‘88; Murphy, PR ‘92
Shuttle to UHV for Long Term Storage

Plasma cools by cyclotron radiation
\[ \Gamma = 0.26 B^2 (T) \, s^{-1} \]
\[ \tau_c \approx 0.2 \, s \]

Confinement times of days possible

annihilation negligible

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Surko, Greaves, Charlton
Hyperfine Int. 1997

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Antiparticle Cooling
Critical for Most Applications

Collisional cooling on molecules 50 K

Cyclotron radiation for positrons and electrons 10 K

Laser cooling (sympathetic on Be\(^{+}\), for positrons) 5 K

Evaporation (positrons or antiprotons) 10 K

Latest result:
Cyclotron cooling in a resonant cavity increases cooling rate by x 100!*  \( T = 10 \text{ K} \) (B = 0.15 tesla)

*Hunter & Fajans
**Increase Density by Radial Compression with Rotating Electric Fields**

"The Rotating Wall Technique"

\[ V = V_{RW} \cos[(2\pi f_{RW}) t + \phi] \]

(Huang, Anderegg, Hollmann, Greaves, Danielson, 1997 - 2007)

*Apply a torque* using a rotating electric field \( f_{RW} > f_E \) => radial compression.
Positron Plasma Parameters

Magnetic field \(10^{-2} \text{ – } 5 \text{ tesla}\)
Number \(10^4 \text{ – } 10^9\)
Density \(10^5 \text{ – } 10^{10} \text{ cm}^{-3}\)
Space charge \(10^{-3} \text{ – } 10^3 \text{ eV}\)
Temperature \(10^{-3} \text{ – } 1 \text{ eV}\)
Plasma length \(1 \text{ – } 30 \text{ cm}\)
Plasma radius \(0.5 \text{ – } 10 \text{ mm}\)
Debye length \(10^{-2} \text{ – } 1 \text{ cm}\)
Confinement time \(10^2 \text{ – } 10^6 \text{ s}\)

Diagnostics:
- modes to measure N, n, T, & aspect ratio
- evaporate to measure temperature
- 2D CCD images
Delivery

Trap-based Positron and Ps Beams
Cold Positron Beam

Cryogenic Buffer-Gas Trap at 50 K

Trap, cool and release:

CO cooling gas

Tunable from ~ 20 meV to tens of volts

Natisin, et al., APL (2016)
Trap-based Beams – Bunch in Time

“harmonic bunching” using a parabolic potential

positrons

Cassidy, RSI 2006
Trap-based Beams – Bunch in Time

“harmonic bunching” using a parabolic potential

15 ns pulse -> 1 ns pulse

Cassidy, RSI 2006
Manipulating Ps Atoms and Novel Ps Beams
exploiting pulsed lasers

Trap efficiently

Cool

Compress radially

Bunch in time

=> then laser excitation
High-Rydberg-state Positronium

Tailored positron pulses, cooled, compressed in space and time

$S = 1$ positronium atoms

Large principle quantum number $n$

$\Rightarrow$ weak positron-electron overlap, so long lifetime
Short $e^+$ Pulses Enable Laser Manipulation
High-Rydberg Ps Beams

Positron pulses, cooled, compressed in space and time. Match to lasers

Stark states
Create Ps in an electric field $\Rightarrow$ E-field manipulation

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Rydberg Ps Atom Stark Focusing Mirror

Focus low-field seekers \( L \sim 6.0 \text{ m} \)

\[ \varepsilon_{Ps} \sim 0.25 \text{ eV} \]

High electric field repels the low-field seekers

Jones, PRL (2017)
Higher-energy Ps Beams

Positron pulses, cooled, compressed in space and time - match to laser

Accelerate and laser-strip $Ps^-$

Na-coated W film

$e^+ \rightarrow Ps^-$

$Ps^- + h\nu \rightarrow Ps$

Beam energy $0.3 - 3$ keV

Divergence $0.3^\circ$

One goal: Ps diffraction from material surfaces

Michishio, Nakagima, et al., RSI (2019)
New Science with Antimatter

Sketches by A. P. Mills, Jr.
Using cold positron beam, measured binding energies for > 85 molecules
Positron Binding to Molecules

predicted: $\varepsilon_b = 135$ meV
measured: $\varepsilon_b = 180$ meV

Tachikawa, PCCP 2011

Want to understand $e^+ - e^-$ correlation & virtual positronium effects
Precision Measurement of the Fine Structure Positronium $2^3S_1 \rightarrow 2^3P_0$ Transition

Positron pulses, cooled, compressed in space and time

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Gurung, PRL (2020)
Positronium $2^3S_1 \rightarrow 2^3P_0$ Transition

A discrepancy! theory? experiment? new physics?

Gurung, PRL (2020)
Stable, Neutral Antimatter

Antihydrogen

Test CPT Theorem and Gravity

Compare H and $\bar{H}$ 1S – 2S interval
Antihydrogen Production

Nested Penning traps

- Trap positrons
- Launch antiprotons into mixing region
- Mix – make lots of antihydrogen!

Formed by three-body collisions: $\bar{p} + e^+ + e^+ = \bar{H} + e^+$

$\bar{p}$, $e^+$ plasmas trapped, cooled, RW-compressed

ATHENA/ALPHA (2002-2007)

ATRAP similar
New Protocol for $\bar{\Upsilon}$ Production *(gaseous leptons)*

- Use **Rotating Wall** to set $n$
- Use **evaporative cooling** to set the plasma potential
- $\rightarrow$ sets $N$, $n$ and $r_p$

Use for $e^-$ and $e^+$ plasma reproducibility

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Number of trappable $\bar{\Upsilon}$ increased tenfold!

Ahmadi, PRL (2018)
2-Photon Spectroscopy 1S – 2S Transition in \( \bar{\text{H}} \) measured using SDREVC

Relative precision \( 2 \times 10^{-12}! \)

Refined spectroscopy, & gravity tests in progress by several groups

Near term goal \( \sim 3 \times 10^{-15} \)

Many-Electron Many-Positron System

Sketches by A. P. Mills, Jr.
Many Body Physics with Antimatter

electron-positron phase diagram

\[ n_{\text{Mott}} \sim 3 \times 10^{22} \text{ cm}^{-3} \]

\[ T \sim 7 \times 10^4 \text{ K} \]

\( \text{Ps B}(\text{g}) \) gas

\( \text{Ps BEC} \)

\( \text{Ps}_2 \) gas

\( \text{e}^+ - \text{e}^- \) liquid

normal /supercond…

\( \text{e}^+ - \text{e}^- \) plasma

\( \text{BEC} \equiv \text{Bose-Einstein condensate} \)

Yabu, NIMB ‘04
Spectroscopy of $\text{Ps}_2$

Optical spectrum of the $\text{Ps}_2$ molecule ($e^+e^-e^+e^-$)

First many-electron many-positron state

Cassidy, PRL 2012
Route to a Ps BEC

10^8 e^+ from accumulator
5 keV -> Ni remoderator
5 keV -> porous silica

5 x 10^5 hat brim
1 x 10^5 top of the hat

n ~ 10^{19} cm^{-3}
T_c = 70 K

many challenges
e.g., sample heating

Mills, Proc. ICPA (AIP 2019)
Classical Electron-Positron ("Pair") Plasmas

Novel nonlinear phenomena for $T_+ = T_-$ and $n_+ = n_-$

- Remarkably good confinement
- Heavily damped acoustic mode
- Faraday rotation absent
- Very strong nonlinear growth and damping processes*


Relativistic $e^- - e^+$ plasmas

- Astrophysical relevance

Electron beam – positron plasma experiment
Greaves, PRL (1995); Gilbert, PP (2001)
e\textsuperscript{−} - e\textsuperscript{+} ("Pair") Plasma – the APEX Collaboration
Levitated Superconducting Magnetic Dipole

Advantages

300 s confinement
Can confine e\textsuperscript{+} & e\textsuperscript{−}

Positron test experiments with permanent magnet
Stenson, PRL 2018
Horn-Stanja, PRL 2018

Reviews:
Stoneking, JPP (in press)
Pedersen, NJP (2012)
A Positron Trap on the NEPOMUC Beam in Munich

\[ \sim 5 \times 10^8 \text{ e}^+ / \text{s} \]

Immediate goal: giant pulses for e\(^+\) - e\(^-\) plasmas
(the APEX collaboration)

Will need a “multicell trap” for large N\(^*\)

* Hurst, Phys. Plasmas (2019)

Goals for other NEPOMUC experiments:

- Positron-Auger spectroscopy using bunched e\(^+\)
- Single-shot PALS (buncher for \(\leq 300 \text{ ps}\) timing)
- RW and centerline-extraction for positron microscope

* Hurst, Phys. Plasmas (2019)
Antimatter in the Laboratory

Gaseous Positronics is the Driver

Much Progress and Many Opportunities

- Materials and atomic physics
- Tests of fundamental physics
- Antimatter plasmas & BEC Ps
Future of Antimatter Plasma Technology

Tools
- Improved plasma compression
- Colder antimatter plasmas

Antihydrogen
- Improved $\bar{p}$ -positron mixing

Antihydrogen beams

Positron and Ps Physics
- Larger numbers of positrons
- Higher quality Ps beams

Portable antimatter traps
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Review Articles:

**Plasma and Trap-Based Techniques for Science with Positrons**

**Experimental Progress in Positronium Laser Physics**

**Plasma and Trap-Based Techniques for Science with Antimatter**

[positrons.ucsd.edu](http://positrons.ucsd.edu)