White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	6/15/15

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Title:	**Plasma Physics Drivers for Physics with Antimatter**
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Plasma Physics Drivers for Physics with Antimatter

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INTRODUCTION AND CONTEXT. In the past two decades, there has been tremendous progress in the ability to trap, manipulate and deliver collections of antiparticles for a range of scientific and technological purposes [1]. Examples include the formation, trapping and study of antihydrogen (i.e., the most elementary form of stable neutral antimatter) [2-5], the formation of dense gases of positronium atoms (e^+e^-, symbol Ps), the creation and study of the positronium molecule, Ps_2, and the formation of high Rydberg Ps for a new generation of beam experiments [6-9]. Near-term goals of this research include fundamental tests of the CPT theorem and the weak equivalence principle (antihydrogen and positronium); and the creation of a classical electron-positron ("pair") plasma [9-11] and its quantum analog, a Bose-Einstein condensed gas of Ps atoms (a Ps BEC) [9].

Technological applications of antimatter plasmas include the development of a variety of positron-based techniques to study materials (e.g., positron-induced Auger spectroscopy to study surfaces and positron annihilation lifetime and Doppler broadening spectroscopy to characterize defects and study porous materials) [12-14]. Research in this area includes the development of a new generation of trap-based positron beams, with finely focused beams for microscopy, short-pulse beams to measure positron annihilation lifetimes, and beams with narrow energy spreads for improved energy resolution [1].

RESEARCH FRONTIER AND CHALLENGES. An exciting forefront of modern plasma physics is the exploitation of plasma techniques to create specially prepared states of antimatter. The fundamental plasma-physics challenge is to understand the physical limits of such states (frequently driven or otherwise non-equilibrium) and to develop optimized techniques to achieve these limits. Such specially prepared states play central roles in other physics fields: examples include nano-fabricated materials in condensed matter and cold-atom BECs in atomic physics. In the case of antimatter plasmas, the approach is to sometimes exploit plasma self-organization, while at other times, it is to overcome or mitigate such tendencies. Key goals for physics with antimatter include new and/or improved techniques for:

- Plasma compression to high antiparticle densities
- Antiparticle cooling
- Advanced manipulation techniques
- Long-term antiparticle storage
- High-capacity (and eventually portable) antiparticle traps

APPROACH AND REQUIREMENTS. Progress in all these areas has been, and will continue to be, driven by new advances in plasma physics. Antiparticles are best accumulated, tailored and delivered in the form of single-component plasmas. Progress in antimatter trapping provides improved particle sources, and novel manipulation techniques permit the tailoring of plasmas for specific applications and for delivery as specially prepared antiparticle beams. **This field is a vital and fast moving area of modern science, and it owes its successes to advances in plasma physics research.**

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We suggest that this is a key area for future plasma physics support. The requirements for an aggressive program in this area center on adequate support for P. I. and few-P. I. driven research programs. **Specific goals, and the physics they will enable are:**

- Merged antiprotons and positrons at or near 1 K (for efficient production of trappable antihydrogen)
- 10^{12} trapped positrons (pair plasma studies) **–** 10^{15} (relativistic pair plasmas)
- 100 ps positron pulses at areal densities $\geq 10^{12}$ cm^{-3} (Ps BEC)
- 100 ns positron pulses (single-shot positron lifetime studies of materials)
- A positron microscope using a trap-based beam (materials studies)
- 1 meV energy spread positron beam (spectroscopy, positron-atomic physics)

This program builds upon a list of demonstrated successes and indicated areas of future promise. In all areas, new research could make an enormous impact.

Plasma compression and long-term confinement. Radial compression using rotating electric fields ("the RW technique") is now widely used. However, the limiting positron density in tesla-strength fields is ~ 10^{-3} of the Brillouin limit. A Ps BEC would be possible today if the density could be improved by a factor of 30. More generally, a high-quality RW is *the key* to long-term confinement of large numbers of particles.

Antiparticle Cooling. Efficient plasma cooling is an absolute necessity. All current techniques (cyclotron, buffer gas, evaporation, laser/sympathetic) have limitations, making this a key area for future research. This will be particularly important for sub-kelvin temperatures, large particle numbers, and/or high particle densities.

Advanced Manipulation Techniques. Autoresonance is now widely exploited. Short bursts are created with bunchers, narrow energy spreads with tailored pulsed-beam extraction, and finely focused beams with controlled extraction. Improved techniques will expand research capabilities and permit a wealth of new science.

High-Capacity (and in long-term portable) Traps. This will be a key ingredient in laboratory studies of pair plasmas and for the creation of robust Ps BECs. The near-term goal of a trap for 10^{12} positrons, while challenging, appears doable. A portable trap for 10^{12} would be exceedingly useful for materials applications. An increase to 10^{15} positrons could enable the study of relativistic pair plasmas.

IMPACTS, INCLUDING SOCIETAL BENEFITS. ***Plasma physics:*** Driven and otherwise nonequilibrium phenomena frequently dominate plasma phenomena. Progress in understanding (and exploiting) the limiting principles for such phenomena can be expected to have widespread applications. ***Other scientific areas:*** There is significant payoff in atomic physics, including enabling tests of gravity and the CPT theorem and work to create a Ps BEC. In materials science, a wide range of positron-based, materials characterization tools could be greatly improved. ***Societal benefits:*** The antihydrogen and other gravity tests are of considerable fascination to the lay public, thus encouraging broad interest and literacy in science. Positron emission tomography (PET) is used for Alzheimer's and cancer detection and drug design. Recent studies help elucidate the fate of positrons in such biological environments. Positrons can also be used to selectively fragment large molecules, including those of interest in biology and medicine [15]. Finally, a portable trap would enable much greater use of positrons in engineering and industrial settings (e.g., for materials characterization).

References

General

For a recent comprehensive review of techniques and physics goals with extensive references to primary work, see:

[1] J. R. Danielson, *et al.*, Plasma and Trap-Based Techniques for Science with Positrons, Rev. Mod. Phys. 87, 247 (2015).

Antihydrogen

[2] M. Amoretti, *et al.*, Production and Detection of Cold Antihydrogen Atoms, Nature 419, 456 (2002).

[3] G. Gabrielse, *et al.*, Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States, Phys. Rev. Lett. 89, 213401 (2002).

[4] G. B. Andresen, *et al.*, Confinement of Antihydrogen for 1,000 Seconds, Nature Physics 7, 558 (2011).

[5] C. Amole, *et al.*, The ALPHA Antihydrogen Trapping Apparatus, Nucl. Instrum. Methods in Phys. Res. Sec. A 735, 319 (2014).

Positronium

[6] D. B. Cassidy, V. E. Meligne, and A. P. Mills, Production of a Fully Spin-Polarized Ensemble of Positronium Atoms, Phys. Rev. Lett. 104, 173401 (2010).

[7] D. B. Cassidy and A. P. Mills, The Production of Molecular Positronium, Nature 449, 195 (2007).

[8] D. B. Cassidy, T. H. Hisakado, H. W. K. Tom, and A. P. Mills, Efficient Production of Rydberg Positronium, Phys. Rev. Lett. 108, 043401 (2012).

[9] A. P. Mills, Positronium Molecule Formation, Bose-Einstein Condensation and Stimulated Annihilation, Nucl. Instrum. Methods B 192, 107 (2002).

Pair Plasmas

[10] T. S. Pedersen, *et al.*, Plans for the Creation and Studies of Electron–Positron Plasmas in a Stellarator, New J. Phys. 14, 035010 (2012).

[11] R. G. Greaves and C. M. Surko, Practical Limits on Positron Accumulation and the Creation of Electron-Positron Plasmas, in Non-Neutral Plasma Physics IV, edited by F. Anderegg, L. Schweikhard and C. Driscoll (American Institute of Physics, Melville, NY, 2002), pp. 10-23.

Materials Studies

[12] P. G. Coleman, Positron Beams and Their Applications, (World Scientific, Singapore, 2000).

[13] D. W. Gidley, D. Z. Chi, W. D. Wang, and R. S. Vallery, Positron Annihilation as a Method to Characterize Porous Materials, Ann. Rev. Mat. Sci. 36, 49 (2006).

[14] J. Mayer, C. Hugenschmidt, and K. Schreckenbach, Direct Observation of the Surface Segregation of Cu in Pd by Time-Resolved Positron-Annihilation-Induced Auger Electron Spectroscopy, Phys. Rev. Lett. 105, 207401 (2010).

[15] L. D. Hulett, J. Xu, S. A. McLuckey, T. A. Lewis, and D. M. Schrader, The Ionization of Organic Molecules by Slow Positrons, Can. J. Phys. 74, 411 (1996).