Emerging science and technology of antimatter plasmas and trap-based beams[a)]

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Progress in the ability to accumulate and cool positrons and antiprotons is enabling new scientific and technological opportunities. The driver for this work is plasma physics research—developing new ways to create and manipulate antimatter plasmas. An overview is presented of recent results and near-term goals and challenges. In atomic physics, new experiments on the resonant capture of positrons by molecules provide the first direct evidence that positrons bind to ''ordinary'' matter (i.e., atoms and molecules). The formation of low-energy antihydrogen was observed recently by injecting low-energy antiprotons into a cold positron plasma. This opens up a range of new scientific opportunities, including precision tests of fundamental symmetries such as invariance under charge conjugation, parity, and time reversal, and study of the chemistry of matter and antimatter. The first laboratory study of electron-positron plasmas has been conducted by passing an electron beam through a positron plasma. The next major step in these studies will be the simultaneous confinement of electron and positron plasmas. Although very challenging, such experiments would permit studies of the nonlinear behavior predicted for this unique and interesting plasma system. The use of trap-based positron beams to study transport in fusion plasmas and to characterize materials is reviewed. More challenging experiments are described, such as the creation of a Bose-condensed gas of positronium atoms. Finally, the future of positron trapping and beam formation is discussed, including the development of a novel multicell trap to increase by orders of magnitude the number of positrons trapped, portable antimatter traps, and cold antimatter beams (e.g., with energy spreads $\leqslant 1$ meV) for precision studies of positron-matter interactions. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1651487]

I. INTRODUCTION

From all observations, the universe is composed almost exclusively of matter—this, in spite of the fact that the underlying equations that describe our physical world appear to be symmetric, treating antimatter and matter on an equal footing. This prevalence of matter over antimatter raises a profound and fundamental question as to the origin of the antimatter/matter asymmetry. To begin to address this question, one would like to conduct precise comparisons of the properties of matter and antimatter. This, in turn, entails carefully preparing states of neutral antimatter (e.g., trapped, cold antihydrogen). On a different level, a central question involves understanding the behavior of antimatter in our world of matter. This behavior will play a crucial role in determining the ways in which antimatter can be used for a range of scientific and technological applications ranging from precise tests of matter/antimatter symmetry to questions in plasma and atomic physics, and the use of positrons, for example, to characterize materials. In this sense, the study of antimatter encompasses broad areas in science and technology.

This article focuses on the creation and use of specially prepared antimatter plasmas and beams as enabling tools for research on antimatter and matter–antimatter interactions. The reader is referred to the wide range of available review material on other aspects of antimatter research, such as positron atomic physics,[1,2] positron studies of materials and material surfaces,[3,4] and physics with antiprotons.[5]

Single-component plasmas are the only method currently available to accumulate, cool, and manipulate large numbers of antiparticles. These collections of antimatter can be stored for very long times in a high-quality vacuum using suitably arranged electric and magnetic fields—a nearly ideal electromagnetic bottle. Not only can these plasmas be made arbitrarily free from annihilation, but also techniques are available to further cool and compress them, so that they can be specially tailored for specific applications. The central message of the present article is that antimatter plasmas now play an important role in science and technology and this can be expected to continue for the foreseeable future.

This review concentrates on positron plasmas, because positrons are more easily produced than plasmas of other,

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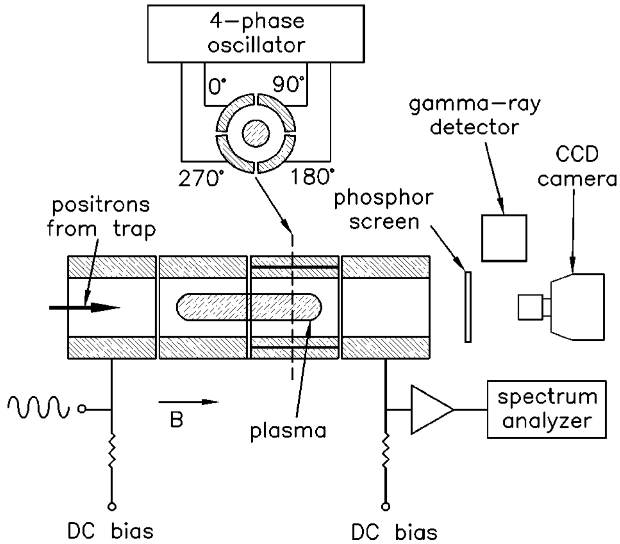

FIG. 1. Typical geometry for studying positron plasmas, showing a segmented electrode for applying a rotating electric field for radial plasma compression, a phosphor screen for measuring radial density profiles, and the electronics to excite and detect plasma modes for diagnostic purposes.

heavier antiparticles such as antiprotons. In particular, the threshold for the production of an antiparticle/particle pair is ~1 MeV for positrons as compared with 6 GeV (i.e., in the laboratory frame) for antiprotons.[5] As a consequence, positrons are readily available from radioisotope sources and electron accelerators, while antiprotons are generated in only a few high-energy particle accelerators. Thus, techniques for antiparticle accumulation, confinement, cooling, and study of plasma behavior have been much more fully explored for positrons. Analogous processes with antiproton plasmas and beams are briefly discussed. The focus of this article is the great amount of progress that has been made since a previous review on this subject in 1997.[6]

The most successful device to confine single-component plasmas is the Penning–Malmberg trap, in which a strong magnetic field inhibits loss of particles across the field while an electrostatic potential well confines the particles in the direction of the field.[7–9] It is the extremely long confinement times that can be achieved in these traps[10,11] that make feasible the accumulation of substantial amounts of antimatter in the laboratory. Recent developments in positron technology include methods to effect rapid plasma cooling using specially chosen buffer gases;[12] application of rotating electric fields for plasma compression,[12,13] and the further development of nondestructive diagnostics using plasma waves.[14] Figure 1 shows a typical Penning–Malmberg trap for confining, manipulating, and studying positron plasmas. Other variations of the Penning trap that have been employed to trap antiparticles and antimatter plasmas include hyperboloidal,[15] orthogonalized cylindrical[16] and multi-ring electrode structures.[17]

Antimatter plasmas in Penning–Malmberg traps have been used to create beams in new regimes of parameter space, including state-of-the-art cold positron[18] and antiproton beams,[19] and improvements in methods to create short pulses. The future of antimatter technology holds promise for other, qualitatively new capabilities. Methods are being developed to create plasmas containing in excess of 10^{10} positrons, cooled to 10 K in a volume $\leq 1\ \mathrm{cm}^3$.[20] Multicell traps have been proposed to extend trapping capabilities by several orders of magnitude in particle number.[21] If successful, these techniques would represent an important step toward the development of portable antimatter traps.

In the area of basic physics research, one dramatic new advance is the creation in the laboratory of the first low-energy antihydrogen atoms. While small numbers of high-energy antihydrogen atoms had been made previously, two recent experiments showed that antihydrogen atoms can be produced in large numbers from positron plasmas and clouds of antiprotons cooled to temperatures ~10 K.[22–24] The advent of improved antiproton traps and low-energy antiproton beams is also enabling new kinds of antiproton experiments.[19,25,26]

Electron-positron plasmas have unique plasma properties[27,28] and are of importance, for example, in astrophysical contexts. They have been studied for the first time in the laboratory using an electron-beam positron-plasma geometry.[29,30] New experiments are now being proposed to create and study simultaneously confined electron-positron plasmas.[31]

One of the unique capabilities of antimatter traps is the ability to accumulate positrons for long periods and release them in an intense pulse. This capability has been proposed as the basis of a new tokamak diagnostic that measures the transport of positrons (which function in this context as electron-mass test particles).[32,33] Methods to produce intense bursts of positrons are also being developed to create the first positronium molecules (Ps_2), as well as a Bose–Einstein condensate (BEC) of Ps atoms.[34] Although this is an exceedingly challenging experiment, it has also been discussed as a method to create stimulated gamma-ray annihilation radiation (i.e., from the condensate).[34]

One area that has blossomed in recent years is the study of the interaction of low-energy positrons with matter. The cold positron beam described above[18] has now been used to study a range of positron interactions with atoms and molecules, including measurements in a low-energy regime previously inaccessible to experiment.[35,36] This cold beam was also used to make the first energy-resolved studies of positron annihilation in molecules at energies below the threshold for Ps formation.[37] These experiments resolved a four-decade-old mystery regarding anomalously large annihilation rates observed in hydrocarbon molecules and provided the first direct evidence that positrons bind to ordinary neutral matter.[38,39] Positron annihilation on large molecules has also been used to selectively create ions for mass spectrometry.[40,41] This technique has the potential to provide structural information about biological molecules. These positron atomic-physics experiments can be regarded as establishing important elements of a quantitative chemistry of matter and antimatter.

Positrons have been used extensively to study materials.[4] One important example is the characterization of low dielectric constant insulators that are key components in high-speed electronics and chip manufacture.[42] An important focus of recent work in the materials area is the development of pulsed, trap-based positron beams that offer improved methods to make a variety of measurements. In a recent advance, commercial prototypes of these positron beam systems are now being developed.[43]

There is an increasing effort to develop improved traps for antimatter plasmas. Applications include specially designed traps for long-term storage of antimatter, and colder, higher density plasmas for cold, bright beams. As mentioned above, one long-term goal is the development of portable antimatter traps. In the case of antiprotons, this would permit antimatter research at locations distant from the few large high-energy facilities in the world that can produce antiprotons efficiently. In the case of positrons, portable traps would enable experiments in settings where use of radioisotope sources is impractical and/or inconvenient (e.g., to characterize materials at a chip manufacturing facility).

In this article we present an overview of the current state of antimatter plasma creation, manipulation and characterization. We describe the development of new kinds of antimatter beams that can be expected to enable a range of new applications in science and technology. We discuss the future of positron trapping and cold beam generation. Finally, we describe new physics results obtained with these tools, including the first laboratory synthesis of low-energy antihydrogen, plans to study electron-positron plasmas, and new kinds of studies of a range of positron-matter interactions.

II. CREATION OF ANTIMATTER PLASMAS AND BEAMS

In this section, we present a summary of techniques to accumulate antiparticle plasmas, methods to characterize them, and their use to form cold antiparticle beams.

A. Positron sources

Fluxes of positrons can be obtained from a number of radioisotopes and from pair-production sources such as electron accelerators.[44] Radioisotope sources are commonly used for small-scale laboratory positron beam lines. Currently, the radioisotope of choice is ^{22}Na (half life, 2.6 years), which is available commercially in sealed capsules with high-transparency windows in activities up to $\sim$100 mCi. There is an ongoing effort to develop high-flux positron sources. One approach is to use short-lived positron-emitting isotopes that can be produced by accelerators.[45–48]

Pair-production sources create positrons by impinging fast electrons on high-Z targets (so-called "converters").[49] This process produces high-energy gamma rays that, in turn, interact with the target nuclei to produce pairs. Alternatively, high-energy gamma rays for positron production can be obtained from the radioactive decay of short-lived reactor-produced isotopes created by neutron capture on targets such as ^{113}Cd.[50]

Regardless of whether the positrons are obtained using isotopes or pair production, they have relatively high energies (e.g., 100's of keV) and must be decelerated to lower energies before they can be captured. This can be accomplished using a "moderator," typically a block or foil of single crystal or polycrystalline tungsten, copper, or nickel; or a layer of rare gas solid at cryogenic temperatures.[4] Positrons lose energy in the moderating material. They are reemitted with energies $\sim$0.5 eV from metals and $\sim$2 eV from rare gas solids. Reemission efficiencies are $\sim 10^{-4}$–10^{-3} for metals[51] and 10^{-2} for rare gas solids.[52]

Using a relatively convenient 100 mCi ^{22}Na source and a solid neon moderator, typical positron fluxes are $\sim 10^7$ s^{-1}.[53] There are several higher-flux positron facilities in the world, such as the one at the U. Delft, the Netherlands.[149] One notable development on the world positron scene is the recent commissioning of the FRM-II reactor in Munich, which is projected to produce moderated positron fluxes in the range 10^9–10^{10} s^{-1}.[54] Also coming on line is a 40 MeV electron linac at the Rossendorf Research Center, Germany. It will have a multipurpose positron facility with an anticipated slow positron flux of 10^9 s^{-1}.

B. Sources of low-energy antiprotons

Antiprotons are produced at only a couple of high-energy accelerator facilities such as Fermilab and the European Center for Nuclear Research (CERN). The unique world facility for low-energy antiprotons is the Antiproton Decelerator (AD) at CERN.[55] This device, commissioned in 1999, takes antiprotons with momenta of 3.5 GeV/c and slows them to 105 MeV/c ($\sim$5 MeV) using a combination of stochastic and electron cooling stages. Typical AD operation provides bursts of 3×10^7 antiprotons every 100 s. Three international collaborations, ATHENA, ATRAP, and ASACUSA, currently have experiments sited at the AD. The ATHENA and ATRAP collaborations use material degraders to further reduce the antiproton energy to $\leqslant$10 keV to permit accumulation in a Penning trap. The latest development in slow-antiproton technology is the installation by the ASACUSA team of a rf quadrupole decelerator at the AD.[19,56] This device is capable of increasing the number of trapped antiprotons by a factor of 100, from 10^4 to 10^6 per AD cycle.

The availability of such a source of low-energy antiprotons is a critical facet of antimatter research. Currently, the operation of the AD is scheduled to stop for a year in 2005 and resume operation in 2006. A new low-energy antiproton facility, to be sited at GSI in Germany, is in the planning stages. If constructed, it would begin operation early in the next decade.

C. Antimatter trapping

1. Positrons

While a number of schemes have been proposed and used to trap antimatter, the device of choice is the Penning–Malmberg trap, because of its excellent confinement properties. It then remains to find an efficient method to fill the trap with antiparticles. A variety of trapping techniques have been developed for positrons. If a pulsed positron source such as a linac or cyclotron is used, the positrons can be captured by timed switching of the potential on the confining electrodes. This technique has been employed extensively for capturing positron pulses from linacs for beam conditioning.[57] It can also be used to transfer positrons from one trap to

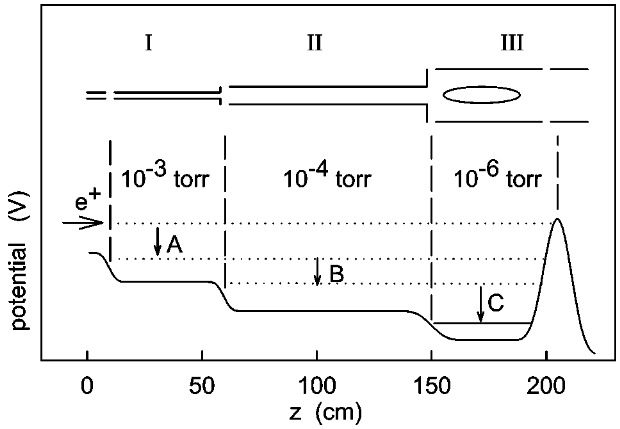

FIG. 2. Buffer gas trapping scheme, showing the electrode geometry of the modified Penning–Malmberg trap (above), and the axial potential profile (below). There is an applied magnetic field in the z direction.

another.[58,59] The requirements for high capture efficiency are that the spatial extent of the incoming pulse be shorter than twice the trap length and that the slew rate on the capture gate be sufficiently rapid. In most circumstances, these conditions are relatively easy to meet.

If positrons are to be captured from a steady-state source such as a radioisotope, this can be done by extracting energy from the positron motion in the direction parallel to the magnetic field. A variety of techniques have been developed for this purpose including collisions with neutral gas atoms,[60] trapped ions,[61] and trapped electrons in a nested potential well.[26] Other methods used to trap positrons include using dissipation in an external resistor,[62] field ionization of weakly bound positronium atoms,[63] and the exchange of parallel and perpendicular momentum exploiting stochastic orbits.[64] Each of these techniques has its advantages and disadvantages.

The positron trapping method most widely used is the buffer-gas technique. It has the highest trapping efficiency and modest magnetic field requirements. Figure 2 illustrates the operating principle of the buffer gas accumulator.[60,65] Positrons are injected into a specially modified Penning–Malmberg trap having a stepped potential profile and three stages, each with a different pressure of buffer gas. Using a continuous gas feed and differential pumping, a high pressure ($\sim 10^{-3}$ Torr) is maintained in the small-diameter region at the left (''stage I''). Positrons are initially trapped by making inelastic scattering collisions (marked A in the figure). The trapped positrons make multiple passes inside the trap and lose energy by subsequent inelastic collisions (B and C) causing them to accumulate in stage III, where they cool to the electrode temperature (i.e., typically room temperature).

The accumulator can be operated using a variety of gases including molecular nitrogen, hydrogen, carbon dioxide and carbon monoxide.[43] The highest trapping efficiency is obtained with molecular nitrogen tuned to a resonance in the positron-impact electronic excitation of the N_2 at 8.8 eV (see Sec. III C 1 for details).[36] The positron lifetime in stage III is typically >60 s. The addition of a small amount of

TABLE I. Typical plasma parameters achieved in a range of positron trapping experiments.

Parameter	Typical value
Magnetic field	10^{-2}–5 T
Number	10^6–10^9
Density	10^5–4×10^9 cm^{-3}
Temperature	10^{-3}–1 eV
Plasma length	0.1–200 mm
Plasma radius	0.05–10 mm
Debye length	10^{-2}–2 mm
Confinement time	1–10^6 s

carbon tetrafluoride or sulfur hexafluoride in stage III (e.g., 10^{-7} Torr) assists in rapid cooling to room temperature.[13] Using a solid neon moderator, trapping efficiencies are typically in the range of 10%–20%, although efficiencies of up to 30% have been observed under optimized conditions. Using a 100 mCi ^{22}Na source and solid neon moderator, 3×10^8 positrons can be accumulated in a few minutes.[66] Once accumulated in a buffer-gas trap, positron plasmas can be transferred efficiently to another trap and stacked (e.g., for long-term storage).[58,59] A two-stage trap of this design with shorter positron lifetime (~ 1 s) is currently being developed by Charlton and co-workers for pulsed positronium beam studies.[67] The characterization and manipulation of positron plasmas is described in Sec. II D below. Table I summarizes the parameters that have been achieved using a range of positron trapping and manipulation techniques.

2. Antiprotons

The AD at CERN provides 100 ns pulses of antiprotons at 105 Mev/c every 100 s. The principal method to trap these antiprotons was developed by Gabrielse and collaborators.[68,69] It first uses a material ''degrader'' to decrease the energy of the incident antiproton beam and produce a low-energy tail in the particle distribution with energies ≤ 10 keV. Approximately 0.1% of these particles can then be trapped in a Penning–Malmberg trap by gate switching. The trap has cryogenically cooled electrodes ($T \leq 10$ K) and is placed in a magnetic field of several tesla. It is preloaded with an electron plasma that cools to the electrode temperature by cyclotron radiation. The potential on an entrance-gate electrode is lowered to allow the antiprotons to enter the trap. The potential of the entrance-gate electrode is then raised quickly before the antiprotons can escape. The antiprotons cool to the electron temperature by Coulomb collisions with the electrons. The electrons can then be ejected from the trap by the application of a series of rapid, negative-voltage pulses, leaving a cold gas of pure antiprotons. Pulses of antiprotons can be stacked to produce collections of 4×10^5 particles.[70] Typically these antiproton clouds are either not sufficiently dense to be in the plasma regime or are borderline plasmas.

D. Manipulating and characterizing antimatter plasmas

In this section we focus on positron plasmas because more work has been done with them than has been done with antiprotons in the plasma regime. Methods to characterize trapped charged particles in the nonplasma (single-particle) regime are discussed elsewhere.[71] A number of tools to characterize and manipulate positron plasmas have been developed. They have proven useful in creating antimatter plasmas tailored for specific applications. Techniques include methods for cooling and radial plasma compression, as well as measuring nondestructively the plasma parameters such as density, shape (i.e., aspect ratio), and temperature. In many cases, these techniques exploit the intrinsic behavior of the non-neutral plasma such as the properties of the plasma modes.

1. Positron cooling

Methods to decelerate positrons to electron-volt energies are discussed above. Typically a moderator material is used, either a metal, such as copper or tungsten, or a solid rare gas such as neon. In order to avoid unwanted annihilation, materials are chosen so that the positrons do not bind to the material or become trapped in voids or at defects.

Gas cooling. At electron-volt energies and below, positron cooling can be accomplished by collisions with a suitable gas of atoms or molecules. The cooling gas is selected to have a large cross section for positron energy loss, but a small cross section for positronium atom formation (i.e., the bound state of a positron and an electron), which is typically the dominant positron loss process. So-called "direct" annihilation of a positron with a bound electron typically has a much smaller cross section.[72] Whenever possible, one tries to work below the threshold for positronium atom formation. As a consequence, direct annihilation is an important factor in determining the lifetime of cold positrons (e.g., seconds to minutes in a gas with pressure $\sim 10^{-6}$ Torr).

As discussed in Sec. III E 1 below, only recently have state-resolved inelastic cross sections been measured, and so a quantitative understanding of the collisional positron cooling processes involving atoms and molecules is not available. Typically, at energies in the electron-volt range, electronic transitions can be used effectively to lose energy. At energies in the 0.05 to several eV range, vibrational transitions in molecules are used, and below 0.05 eV, rotational transitions in molecules and momentum-transfer collisions in atoms are used to cool the positrons. The most efficient gas for buffer-gas trapping has proven to be molecular nitrogen, which has a large, resonant cross section for the lowest lying $A^{1'}\Pi$ state at an energy of 8.8 eV.[36] In N_2, this occurs at an energy where the cross section for loss by positronium atom formation is small.

At lower energies, where vibrational excitation is important, cross sections have been measured for only a few molecules.[35,73] However, positron-cooling rates have been measured for several molecules;[12,43,74] SF_6 and CF_4 are particularly effective in this energy range. The current version of buffer-gas positron traps typically uses a mixture of N_2 and CF_4 in the final trapping stage for rapid cooling. CF_4 has also been used effectively for the cooling required in rotating wall compression of positron plasmas (i.e., to counteract the heating caused by the work done on the plasma by the applied torque).

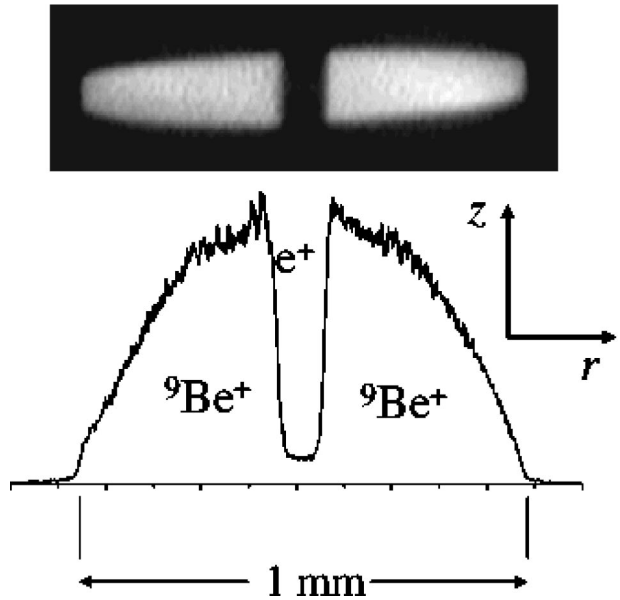

FIG. 3. Above: side view of a laser-cooled Be ion plasma (illuminated shape obtained by laser-induced fluorescence) surrounding a sympathetically cooled positron plasma (dark core). The magnetic field is in the z direction. Centrifugal separation causes the positrons to accumulate in the center of the cloud. Below: radial profile of the Be^+ ion density (see Ref. 61).

Cyclotron cooling. A convenient method to cool electron-mass particles, such as positrons, is cyclotron radiation in a strong magnetic field. In this case, the positrons come to equilibrium at the temperature of the surrounding electrode structure. The cyclotron-cooling rate for electron-mass particles is approximately

$$\Gamma_c = B^2/4, \tag{1}$$

where B is in tesla and Γ_c is in s^{-1}.[75] The characteristic radiation cooling time, $1/\Gamma_c$ of positrons in a 5 T field is 0.16 s. Assuming an emissivity, $\varepsilon = 1$, of the electrodes at the cyclotron frequency, the surrounding electrode structure is at temperature T_e, and there is no external heating, the time dependence of the temperature, T, of a positron plasma at initial temperature T_0 will be

$$T(t) = T_e + (T_0 - T_e)\exp(-\Gamma_c t). \tag{2}$$

Sympathetic cooling of positrons. The techniques described above are limited to producing a temperature equal to the temperature of the environment (e.g., 4 K for cyclotron cooling in a trap cooled to liquid helium temperature). A technique has been developed[61] to reach temperatures significantly below the ambient by sympathetic cooling of the positrons with laser-cooled ions, simultaneously confined in the same trap with the positrons. Typical results are shown in Fig. 3. This technique recently demonstrated a high-density positron plasma (4×10^9 cm^{-3}) at <5 K in a room temperature trap. The technique has the potential to produce positrons with parallel energies less than 100 mK.

2. Rotating wall compression

An important technique for manipulating non-neutral plasmas is radial plasma compression using a rotating elec-

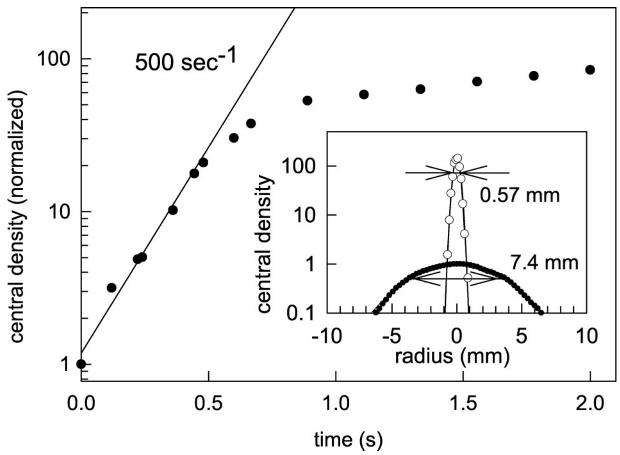

FIG. 4. Radial compression of a positron plasma using a rotating electric field. The inset shows the radial density profiles at $t=0$ (uncompressed) and at $t=4$ (compressed), normalized to the central density at $t=0$.

tric field torque (the so-called ''rotating-wall'' technique). It was first used for the compression of ion plasmas[76–79] and later extended to electron[80,81] and positron[12,13] plasmas. The basic geometry is illustrated in Fig. 1. The rotating electric field is produced by the application of suitably phased sine-wave voltages to one or more azimuthally segmented electrodes. The cooling required to counteract the heating caused by the torque-related work on the plasma can be provided by cyclotron cooling (in the case of a strong confining magnetic field), buffer-gas cooling (in the case of a weak magnetic field), or by laser cooling for certain ion plasmas. Use of the rotating wall technique has provided dramatic new capabilities for single-component plasma research in terms of counteracting outward plasma transport and permitting essentially infinite confinement times.

The process of rotating wall compression involves coupling to the plasma to inject angular momentum, which is related to the second moment of the radial particle distribution.[82] This can be done by coupling to azimuthally propagating Trivelpiece–Gould (TG) modes[80,81] or by coupling directly to the plasma particles.[12,13] Efficient coupling has been found to exhibit different dependences on plasma parameters in different regimes—sharp, resonant behavior corresponding precisely to the frequencies of the TG modes, for low-amplitude drive, and good coupling over a broad range of frequencies at larger drive amplitudes.[20] An example of the degree of positron plasma compression that can be obtained is shown in Fig. 4.[83] The central plasma density exhibits an initial exponential increase at a compression rate $\sim 500\ s^{-1}$, followed by a nonlinear saturation. Shown in the inset are the radial profiles before the application of the rotating electric field and after 4 s. During this time, the central density increases by two orders of magnitude, while the diameter is reduced by a factor of ~ 13.

Rotating-wall compression has been used to produce high-density positron plasmas,[12,13] including those for antihydrogen production[22,59] and for brightness-enhanced positron beams (the latter discussed in Sec. II E 3). As described in Sec. IV F 5, this technique is also an important facet of plans to produce giant pulses of positrons to create Bose–Einstein condensation (BEC) of positronium atoms and stimulated emission of annihilation radiation.

3. Characterizing antimatter plasmas

A variety of destructive and nondestructive techniques has been developed to measure the properties of non-neutral plasmas in traps, parameters such as plasma temperature, density, shape, and the total number of particles. Destructive diagnostics involve releasing the particles from the trap and detecting them either directly or indirectly. Absolute measurements of the total number of particles can be made by dumping the particles onto a collector plate and measuring the total charge.[10] In the case of antiparticles, the annihilation products can be detected and the total number extracted using a calibrated detector. Radial profiles were first measured by collecting the particles in Faraday cups located behind small holes in an end plate.[10] A second technique, which provides excellent spatial resolution, uses a phosphor screen biased at a high voltage (~ 10 kV). The resulting fluorescent light is measured using a charge coupled device camera.[84] Plasma density can be inferred from the radial profiles and total number of particles calculated using a Poisson–Boltzmann equilibrium code.[85] Plasma temperature can be measured by releasing particles slowly from the trap and measuring the tail of the particle energy distribution.[86]

Destructive diagnostics have been employed extensively in the development of new techniques to manipulate and trap antiparticles. However, for experiments where the particles are collected for long times, such as antihydrogen production or the creation of giant pulses, destructive diagnostics are unsuitable. Several nondestructive techniques have been developed, based on the properties of the plasma modes. For long cylindrical plasmas, the frequency of the diocotron mode yields the charge per unit length of the plasma, and hence provides information about the total number of particles.[87,88] For spheroidal plasmas in harmonic potential wells, the frequencies of the axial TG modes[89] yield the aspect ratio of the plasma[90–92] and can be used to measure plasma temperature in cases where the aspect ratio is constant. The total number of particles can be determined by the Q factor of the response,[14] or by independently calibrating the amplitude response.[91] Recent work shows that passive monitoring of thermally excited modes can also be used to determine the plasma temperature.[93] The driven-wave techniques are now used routinely to monitor positron plasmas used for antihydrogen production.[94] They are also being applied to characterize electron plasmas that are used to trap and cool antiprotons.[26]

E. Beam formation techniques using traps

Trapped plasmas have proven extremely useful as beam sources of exotic particles such as positrons because this technique allows the particles to be more efficiently utilized. Unique capabilities for trap-based beams include the ability to produce ultracold beams, short-pulsed beams, and brightness-enhanced beams. They also have the potential to produce giant pulses of antiparticles for a range of applications.

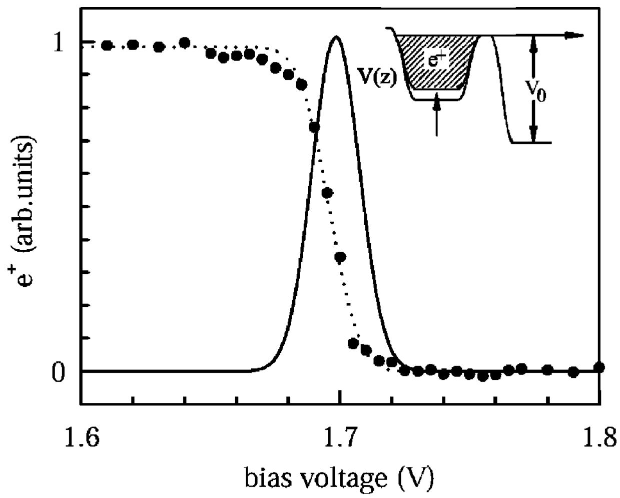

FIG. 5. Parallel energy distribution function (-) of a cold beam released from a trapped 300 K positron plasma, obtained from retarding potential analyzer data (•). Inset: axial potential structure for creating and releasing a positron beam from a trap with an energy of eV_0.

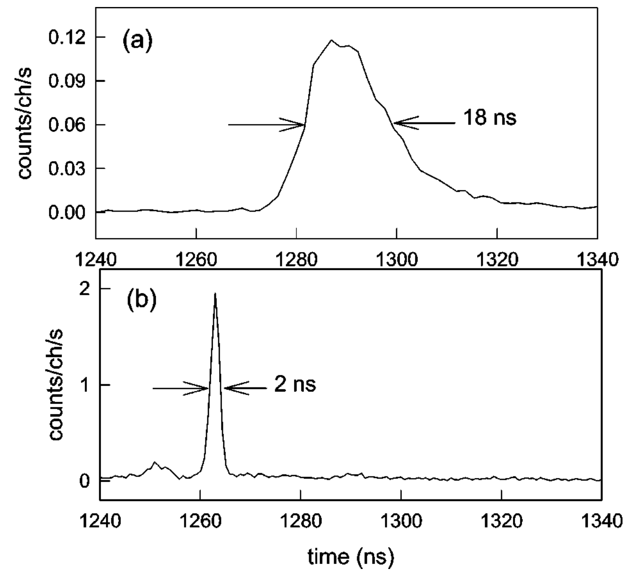

FIG. 6. (a) Typical shape of a positron pulse released from a positron trap without additional bunching. (b) Same pulse using the timed potential technique.

1. Cold beams

As described above, antiparticles in traps cool rapidly to the ambient electrode temperature (i.e., typically room temperature or below). If care is taken in extracting the particles during beam formation, the narrow energy spread can be maintained. This provides a method of efficiently producing cold particle beams that is not possible using other techniques. As an example, shown in Fig. 5 is a positron beam with an energy spread of 18 meV, produced from a trapped, room temperature positron plasma.[18] This beam is much colder than positron beams produced using conventional positron moderators, which typically have energy spreads $\geqslant 0.5$ eV. As described in Sec. III E 1, beams created in this way have been used to investigate a variety of positron-molecule interactions that were previously inaccessible due to lack of a high-energy-resolution, low-energy positron source. This technique is now being used to create cold antiproton beams.[19]

2. Beam bunching

Trap-based beams can easily be bunched in time. Typical pulse widths are of the order of the thermal transit time for the particles to travel the length of the trap (e.g., $\sim 0.1-0.5\ \mu$s for positrons at room temperature). It is also possible to operate such beams in a quasi-steady-state mode by releasing the particles slowly from the trap.[18] For many applications, much shorter pulse widths are desired than can be obtained by simply dumping the trap. For example, as described in Sec. III E 4, a powerful technique for probing materials is the measurement of the lifetimes of injected positrons. This lifetime-spectroscopy technique enables the accurate characterization of defects. However, it requires pulse widths shorter than the positron lifetime in the material (e.g., typically several hundred picoseconds in metals and semiconductors and a few nanoseconds for polymers).

A variety of techniques has been developed for producing pulsed positron beams from continuous positron sources, including rf bunching,[95] harmonic potential bunching,[96,97] and timed potential bunching.[97] Of these, the latter two can be applied to trapped positron plasmas and have significant advantages over conventional techniques. In particular, trap-based pulsed beams have much lower energy spreads than conventional pulsed beams, and they can be operated at much lower repetition rates with proportionally more positrons per pulse. This allows both the long and short lifetime components to be measured and improves signal-to-noise ratios. Figure 6 shows the time structure of positron pulses released from a trap with and without bunching.[83] The data in Fig. 6(b) were obtained using the timed potential technique and show a pulse width ~ 2 ns. With improved shaping of the acceleration wave form, it is expected that pulse widths of <400 ps can be obtained, which will be suitable for positron-lifetime measurements in solids.

3. Brightness-enhanced beams

For many applications, small-diameter beams are desirable, such as 1-μm-diam beams for positron microscopy.[98] In the case of positrons, electrostatic and magnetic focusing techniques, such as those used for conventional electron microscopy, are limited by the low brightness of conventional positron sources. Thus, beams smaller than a few hundred microns in diameter are difficult to achieve without the use of specially designed brightness-enhancement techniques,[97] which, in turn, result in a significant reduction of the positron flux.

Positron traps offer the possibility of producing small-diameter beams in an efficient manner by combining the radial compression technique, described above, with extraction from the center of the plasma. This latter technique is enabled by the fact that, in the regime where plasma space charge is appreciable and only a portion of the plasma is dumped, the first particles exiting the trap come from the plasma center (i.e., the region of largest space charge poten-

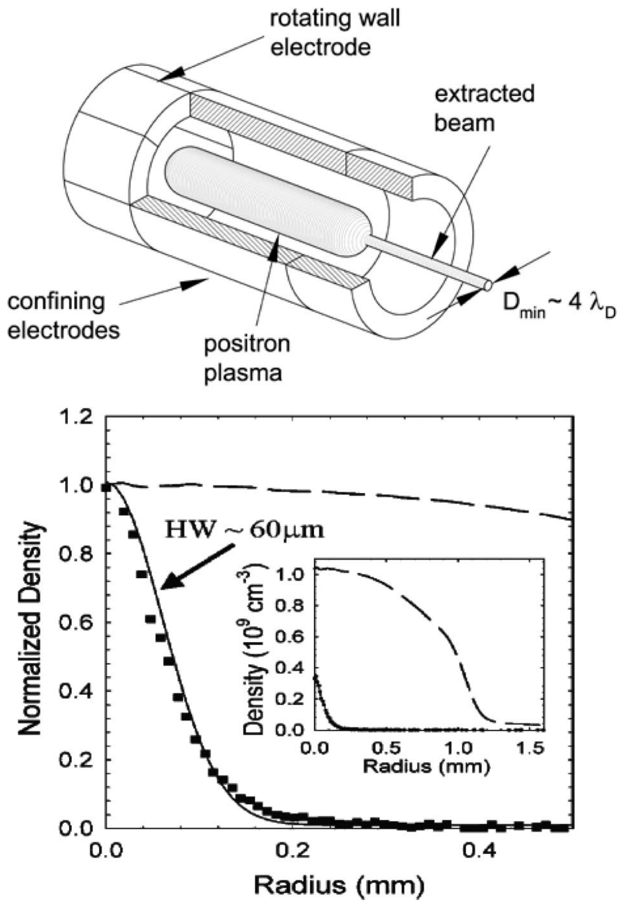

FIG. 7. Above: cutaway view of a positron trap illustrating techniques for brightness enhancement using a trap-based beam. Below: use of these techniques to extract a beam 60 μm in radius from an electron plasma 1 mm in radius.

tial). In principle, it is possible to create a beam with a diameter approximately four times the Debye length, λ_D.[20,86] This technique is illustrated in Fig. 7. A beam of diameter 120 μm is extracted from an electron plasma, 2 mm in diameter, having a central density of 1×10^9 cm^{-3} ($B=5$ T).[20] This technique is currently being developed to produce positron microbeams.

4. Pulse-stretching for linac positron sources

Linacs have the potential to furnish powerful sources of positrons for a variety of applications. Unfortunately, the time structure of linac pulses is unfavorable for many applications such as surface analysis. In particular, the pulse length is too long for lifetime measurements, and the pulse repetition rate is low, which results in the saturation of detectors. The energy spread of the positrons from linacs is also relatively large, leading to poor phase-space matching to rf bunchers. One method to circumvent these limitations is to capture the positrons in a Penning–Malmberg trap and release them slowly during the time between linac pulses, thus creating an essentially steady-state beam (''pulse stretching'').[57,99] The beam can then be bunched as desired. It can also be focused using conventional techniques to produce microbeams for surface scanning applications. This technique has been implemented on a number of linacs around the world.

5. Giant pulses

One of the unique capabilities of positron traps is the ability to accumulate large numbers of positrons and release them as a single giant pulse. As will be discussed in Sec. III F below, it is planned that this technique will play a major role in experiments to create Bose-condensed gases of positronium atoms.[34] As discussed in Sec. III D, giant pulses of positrons can also be converted to intense pulses of fast positronium atoms, which, when injected into a tokamak plasma, can provide a unique diagnostic of plasma transport. In this application, positrons can be accumulated and stored when the plasma device is not running, thereby making most efficient use of the positron source.

F. Future prospects for antimatter trapping and beam formation

1. Accumulating and storing large numbers of antiparticles

For a number of reasons, it is desirable to accumulate and store large numbers of antiparticles. There are three impediments to doing this: large space charge potentials; asymmetry-driven, outward, radial transport; and the heating associated with this transport (i.e., heating that increases rapidly with increasing plasma density). Counteracting the outward radial transport with rotating-wall electric fields does not mitigate the heating, but instead produces comparable amounts of it, since the rotating fields introduce heating through the work done by the applied torque.[21]

Taking the next steps in antimatter-plasma accumulation, storage, and beam development will require a quantitative understanding of the (nonequilibrium) radially compressed, torque-balanced steady-state plasmas that can be obtained using strong rotating-wall compression and available cooling in order to optimize plasma parameters. Of interest, for example, is developing techniques to specifically tailor plasmas for high densities and large particle numbers. However, also of interest is optimizing plasmas for the extraction of cold, bright beams, which imposes different constraints on the plasma parameters.

Experiments on electron plasmas indicate that the outward, asymmetry-driven transport rate scales as $\Gamma_0 \propto n^2 L_p^2/TB^2$,[100] where L_p is the plasma length. This is an empirical relationship and is presently the best available for design purposes. We note that recent experiments to study asymmetry-driven transport due to weak magnetic mirrors and small asymmetric electrode potentials is beginning to address the underlying nature of this transport.[101] The rate of plasma heating, Γ_h, associated with the outward transport scales as $\Gamma_h \sim (e\phi_{sc}/T)\Gamma_o$, where ϕ_{sc} is the space charge potential. This heating must be balanced by the available cooling (e.g., *via* cyclotron radiation). These considerations put important constraints on the antimatter plasma parameters that can be achieved.[21] For example, high plasma densities favor hot plasmas (e.g., $T\sim$ electron volts), while cold

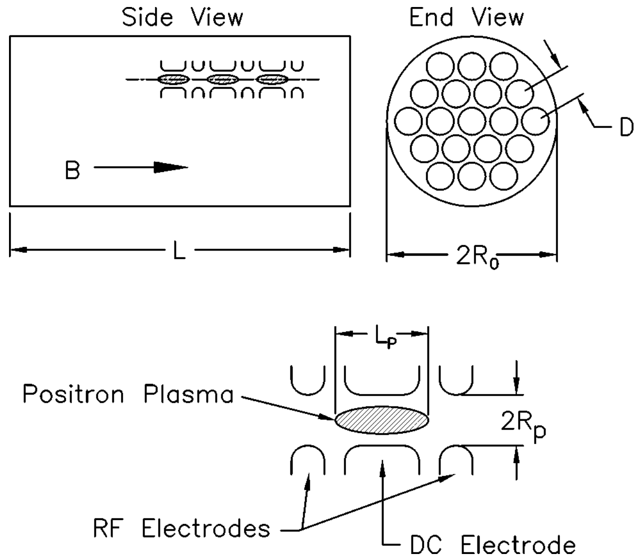

FIG. 8. Schematic diagram of a multicell trap for 10^{12} positrons showing arrangement of the cells parallel and perpendicular to the magnetic field, B.

trap-based beams require low temperatures, and this in turn imposes important limits on the plasma density.[20]

Recently, we proposed a novel design for a multicell Penning trap, shown in Fig. 8, for long-term storage of large numbers of positrons.[21] It is designed specifically to mitigate the constraints imposed by outward transport and large values of space charge potential. The space charge potential is mitigated by dividing the charge cloud into m rod-shaped plasmas, each of length L_p, oriented along the magnetic field and shielded from each other by close-fitting copper electrodes. In this way, for a given maximum electrical potential, V, applied to the electrodes, the number of positrons stored can be increased by a factor of m. In addition, the design breaks up each long rod of plasma into p separate plasmas in the direction along the magnetic field (i.e., separated by electrodes at potential V). The plasma length in the expression for Γ_0 is reduced by a factor $1/p$, and the associated outward, asymmetry-driven radial transport is decreased by a factor of $1/p^2$. The rotating electric field technique can then be used to counteract the remaining, but much-reduced, outward transport.

With applied potentials $\leqslant 2$ kV and magnetic fields of 5 T, it should be possible to construct a multicell trap to store 10^{12} positrons in a trap with ~ 100 cells each containing in excess of 10^{10} positrons. The design of such a trap is discussed in more detail in Ref. 21.

2. Portable positron traps

If a sufficient number of positrons can be accumulated in a compact portable positron trap, such a device could be used as a high-quality positron-plasma and/or positron-beam source in place of a radioactive source. This would have the advantage of providing positron beams for a variety of applications at greatly reduced cost, since a significant fraction of the capital cost of positron beamlines is in the cost of the radioactive source and moderator. For example, if 10^{11} positrons could be accumulated in a compact device, as described above, a beam of 10^5 positrons/s (typical of a laboratory positron beam system) could be supplied for a period of 12 days. The trap would then be shipped to a high flux positron facility for refilling.

3. Ultracold positron beams

As discussed in Sec. III E 1 below, the cold trap-based positron beam described in Sec. II E 1 has enabled a wealth of new atomic physics experiments, such as the first state-resolved inelastic positron-impact cross sections for atomic and molecular processes. This cold positron beam advanced the state of the art for positron atomic physics by a factor of more than 20 in energy resolution. We have now constructed a cryogenic, high-field trap[20] to produce a positron plasma at a temperature of 10 K. Using this plasma and the off-the-centerline extraction technique for increased beam brightness, we expect to be able to create a bright beam with 1 meV parallel energy resolution. This would improve by another factor ~ 20 the available resolution for the study of a range of physical processes. It would, for example, permit the first studies of rotational excitation of molecules by positron impact.

4. Spin-polarized positron plasmas and beams

For a number of applications, such as creating BEC positronium, it is desirable to have positron plasmas with a high degree of spin polarization. Positrons from radioisotope sources are, in fact, partially polarized due to parity nonconservation.[102] It is likely that this spin polarization is preserved in a buffer-gas trap, although this has not yet been measured.

In a cryogenic high-field positron trap, such as that described above, it is possible to confine a positron plasma in a region of appreciable magnetic field gradient.[103] In this case, when the plasma is cooled to low temperatures, the relative populations of the two spin states will vary as a function of position along the direction of the applied field gradient. Thus by raising the potential on an electrode between the two ends of the plasma, it is possible to separate off a spin-polarized plasma that could then be extracted as a spin-polarized beam. Specifically, if ΔH is the change in magnetic field along the plasma length, the fraction, f, of polarization at one end of the plasma will be $f=[1+\exp(-\mu_B \Delta H/k_B T)]^{-1}$.[104] Assuming $\Delta H = 3$ T and T=1 K, $f \cong 88\%$.

An alternative method to polarize the positron spins[71,105] is to excite simultaneous spin-flip and cyclotron transitions at the "anomaly frequency," $f_a=(1/2)(g-2)f_c$, where f_c is the cyclotron frequency and g is the g factor of the positron. Denoting the positron state as $|n, s\rangle$, where n is the cyclotron level and s is the spin state, this provides a mechanism to depopulate the $|0, -1\rangle$ state by way of an anomaly transition to the $|1, +1\rangle$ state, followed by a cyclotron transition to the $|0, +1\rangle$ ground state. The required spin-resonance magnetic fields and considerations regarding possible positron heating due to these fields are discussed in Ref. 105.

III. ANTIMATTER IN LABORATORY SCIENCE AND TECHNOLOGY

A. Synthesis of low-energy antihydrogen

There has been keen interest in making the first neutral antimatter in the laboratory for at least two decades. Among other motivations, this would permit precise comparisons of the properties of hydrogen and antihydrogen to test symmetries, such as the CPT theorem (i.e., invariance under charge conjugation, parity, and time reversal), and to make precise comparisons of the effect of gravity on matter and antimatter. Also of interest is the study of the low-energy interaction of antimatter with matter,[106] the first steps toward the establishment of a quantitative chemistry of neutral matter and antimatter. Small numbers of high-energy antihydrogen atoms were made at CERN and Fermilab in the 1990's.[107,108] However, it is desired to make antihydrogen atoms with sufficiently low energies that they can be trapped (e.g., in a magnetic gradient trap—estimated well depth ≤ 1 K) and studied with precision.

Recently two groups at CERN (the ATHENA and ATRAP collaborations) reported the first successful creation of low-energy antihydrogen atoms.[22–24] We briefly describe the results of these experiments and discuss the challenges remaining in conducting precise experiments to compare hydrogen and antihydrogen. Many of these challenges will benefit by the further development of techniques to prepare specially tailored antimatter plasmas and trap-based beams of antiprotons and positrons.

Both antihydrogen experiments used nested Penning–Malmberg traps to combine cold antiproton and positron plasmas. Two different recombination mechanisms are relevant: spontaneous photon emission in an antiproton-positron collision, and three-body recombination involving an antiproton and two positrons. The formation rates for both processes increase with decreasing positron temperature (i.e., as $T^{-0.63}$ [109] and $T^{-9/2}$,[110] respectively), motivating the desire for cryogenically cooled plasmas (e.g., $T \leq 10$ K).

The antiproton cooling and trapping schemes used by the two groups were similar. ATHENA used a buffer-gas trap to collect $\sim 10^8$ positrons every 3 min. They combined $\sim 10^4$ antiprotons, collected from three AD bunches, with the positrons for 190 s.[22] ATRAP used a novel positron-trapping scheme based on field stripping high Rydberg positronium atoms made on the surface of a cryogenically cooled positron moderator.[63] In the ATRAP experiment, positrons and antiprotons were collected and stored for ~ 500 min and then charge clouds of $\sim 1.5 \times 10^5$ antiprotons and 1.7×10^6 positrons were combined.[23,24] As expected, in both experiments it was necessary to use nonequilibrium configurations to obtain particle overlap, since in nested Penning traps, equilibrium plasmas will separate.[6,111]

The detection schemes for the two experiments were different. ATHENA has developed a detector that is able to spatially resolve both the antiproton[112] and the positron annihilations to ~ 4 mm accuracy, and time resolved to 5 μs accuracy during the 190 s mixing time. They reported the observation of 130 so-called "golden events" where antihydrogen atoms annihilated at an electrode, and the resulting back-to-back gamma rays from the positron annihilation and the charged π mesons from the antiproton annihilation were detected to come from the resolution volume in space and time. Other features of the data, such as two-gamma detection at angles other than 180°, were in good agreement with Monte Carlo simulations of their detector performance. Figure 9(a) shows the reconstructed locations of the annihilations for recombination using a cold positron plasma. For the case shown, corresponding to mixing the antiprotons with cold positrons ($T \sim 15$ K), the figure shows that the annihilation peaks at the inner surface of the electrodes, as expected for these neutral atoms that are not confined by the magnetic field. When the positron plasma is heated, the reconstructed antihydrogen annihilations are much fewer and show no such spatial correlation with the position of the electrodes.

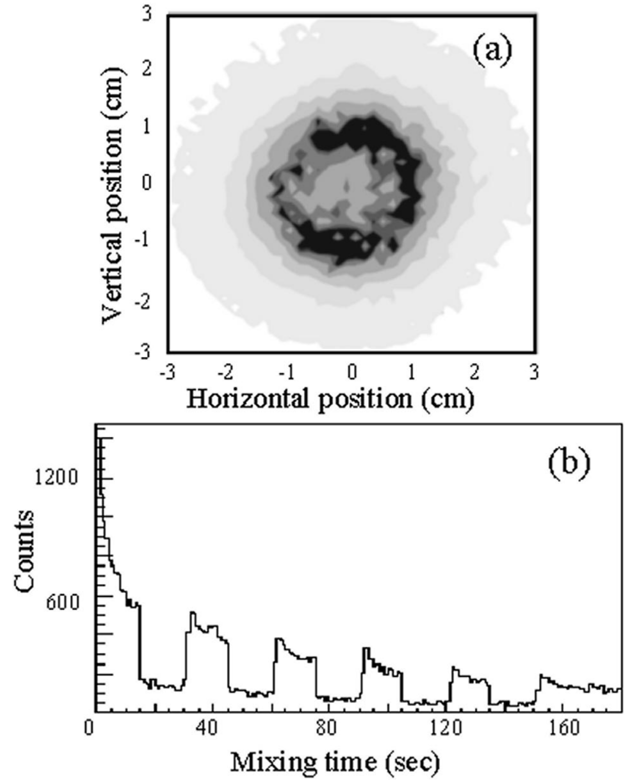

FIG. 9. The creation and detection of low-energy antihydrogen atoms: (a) Spatially resolved annihilation of antihydrogen atoms (dark ring) on the inner surface of the electrodes of the nested Penning–Malmberg trap (see Ref. 148); (b) modulation of the detected antihydrogen annihilation signal by heating and cooling the positron plasma that produced it. See Ref. 22 for details.

As shown in Fig. 9(b), the ATHENA experiment was able to modulate the antihydrogen annihilation signal by heating the positron plasma, in agreement with theoretical predictions for both the spontaneous photon emission and the three-body recombination mechanisms. Measurements of the temperature dependence of the antihydrogen formation rate, Γ, in the ATHENA experiment show that Γ decreases with increasing positron temperature, but a simple power-law scaling was not observed.[113] Remarkably, significant antihydrogen production is observed even for the case of recombination with a 300 K positron plasma.

The ATRAP experiment used a novel technique involving field ionization to detect the antihydrogen produced. They arranged a separate potential well for the collection of antiprotons along the magnetic axis, adjacent to the nested Penning traps used for antihydrogen formation, and they inserted a region of variable electric field between the nested traps and the antiproton collection well. Weakly bound antihydrogen atoms traveling toward the collection well are expected to be field ionized and trapped in the collection well. After collection for a fixed time period, emptying the collection well produced an antiproton annihilation signal which, the ATRAP collaboration convincingly argued, can only come from the field ionization of antihydrogen atoms produced in the nested Penning–Malmberg traps. The ATRAP group presented an analysis of the dependence of the antihydrogen production rate on ionizing electric field. They concluded that the principal quantum numbers of the detected antihydrogen atoms are in the range $50<n<80$. As the ATRAP collaboration points out, casting the result in terms of a principal quantum number is not strictly correct for these atoms in a strong magnetic field. Nevertheless, the analysis does indicate that the atoms are very weakly bound. This is consistent with the predictions for the three-body recombination mechanism.[110]

One important issue is the behavior of the antihydrogen atoms formed from the cold positron plasmas and cold clouds of antiprotons. For weak binding energies ($\leqslant 100$ K), the atoms are strongly affected by the imposed magnetic field with strength $\sim 3-5$ T. These atoms are the strong-magnetic-field analogs of high Rydberg states. The positron wave function is strongly localized, and the positron executes an $\mathbf{E}\times\mathbf{B}$ drift motion about the antiproton. Three-body recombination of these "guiding center atoms" has previously been studied theoretically.[110] A recent analysis[114] shows an encouraging correspondence between the predictions for three-body recombination and the ATRAP results. Open questions regarding these loosely bound guiding center atoms include their dynamics in the electric fields of the positron and antiproton charge clouds, and questions of their re-ionization and/or evolution to more deeply bound states.

These recent, successful low-energy antihydrogen experiments are seminal. The ability to create in the laboratory low-energy antihydrogen atoms for the first time has clearly been established. As described above, one goal of these experiments is to trap the antihydrogen and conduct precision comparisons of antihydrogen and hydrogen using two-photon spectroscopy. However, many challenges remain. The method currently favored to trap the antihydrogen atoms uses a magnetic gradient trap to confine atoms with one sign of magnetic moment (expected maximum well depth $\leqslant 1$ K). This introduces zeroth-order azimuthal magnetic asymmetries, which are extremely deleterious to the confinement of the antiproton and positron plasmas.[115] Azimuthally symmetric trapping schemes have recently been proposed to circumvent this difficulty.[116] In general, the search for solutions to this problem of compatible trapping schemes for the plasmas and the antihydrogen atoms is at an early stage. Nevertheless, it is fair to say that this problem currently presents a serious challenge to further progress. Another problem that arises when the densities of antiprotons and positrons are comparable is the generation of plasma instabilities.[117]

An alternative approach to precise comparison of the properties of antihydrogen and hydrogen is being pursued by the ASACUSA collaboration. They are building a magnetic-cusp trap to confine cold antiprotons and positrons.[118] This type of trap can confine antihydrogen atoms with one orientation of magnetic moment (i.e., low-field seekers). Due to the magnetic geometry, trapped, spin-aligned antihydrogen atoms, once formed, eventually exit the trap and focus on the magnetic axis at a given distance from the cusp that depends on the energy of the atoms. The ASACUSA collaboration proposes to put a microwave cavity at this focal point, tuned to the hyperfine transition, followed by a magnetic lens tuned for the *opposite* sign of magnetic moment. An antihydrogen detector will be placed at the focal point of this lens. The detected signal is expected to be maximized when the microwave cavity is tuned to a hyperfine transition (i.e., that flips the sign of the magnetic moment).

The authors of Ref. 118 estimate that this experiment can provide one part per million or better comparison of the magnetic moments of hydrogen and antihydrogen. This experiment offers the possibility of comparing a different combination of fundamental parameters than measurement of the hydrogen $1S-2S$ transition, and so both experimental tests will be of considerable value.

B. Physics with low-energy antiprotons

The ASACUSA collaboration is using low-energy antiprotons to study a range of scientific issues.[119,120] As described above, they have developed a rf quadrupole decelerator that increases the flux of trappable low-energy antiprotons from the AD by a factor of 100. It is being used to produce a high-quality, low-energy antiproton beam.[19] Experiments to study the structure of radioactive nuclei using antiproton attachment and subsequent annihilation are in the planning stages.[25]

Antiprotons are known to bind to atomic ions, replacing an electron. These species, with in effect, a massive, distinguishable electron, can be thought of as intermediate between an atom and a molecule—a so-called "atomcule." Members of the ASACUSA collaboration have studied the antiproton-He atomcule in detail in a series of elegant spectroscopy experiments.[121–123]

C. Electron-positron plasmas

As pointed out in the seminal paper by Tsytovich and Wharton,[27] electron-positron plasmas possess unique properties because of the equal-mass, opposite sign of charge of the plasma particles. Specific examples of the unique plasma properties include the linear polarization of cyclotron radiation and dramatic differences in the nonlinear plasma processes (e.g., the absence of three-wave coupling, and nonlinear Landau damping larger by the electron/ion mass ratio, M/m). Relativistic electron-positron plasmas have been studied extensively theoretically,[124–128] because of their importance in astrophysical contexts such as pulsar magnetospheres. The first laboratory experiments to study these plasmas were conducted by passing an electron beam through a positron plasma confined in a Penning trap.[29] It is, however, desirable to create an electron-positron plasma in which the two species are not drifting relative to each other.

Various techniques have been proposed for creating such simultaneously confined electron-positron plasmas. These techniques include confinement in magnetic mirrors,[129] stellarators,[31] and combined Penning/Paul traps.[130] Due to the anticipated difficulties in simultaneous confinement of these plasmas, an intense positron source, such as that from a linac or the new FRM-II fission reactor,[131] would be very useful for these experiments.

It would also be of great interest to study the relativistic regime. A magnetic mirror device is expected to provide good confinement for such a hot, electron-mass plasma. However, at the anticipated high temperatures, the Debye length is comparatively large for a given plasma density. Consequently, relativistic electron-positron plasma experiments will require very large numbers of positrons (e.g., $N \geqslant 10^{15}$ per experiment).[130] This is likely to challenge the capabilities of available positron sources for the foreseeable future.[132]

An alternative approach to study relativistic electron-positron plasmas is use of intense lasers. This kind of experiment is outside the scope of the present review. We refer the reader to Refs. 132, 133–136 for further discussion of this promising new direction.

D. Studying plasma transport using positrons

An important topic of current interest in tokamak fusion-plasma research is understanding anomalous electron transport.[137] Since, at present, there are no good techniques available to directly measure electron transport, it would be desirable to have new diagnostics to address this question. One possibility is to inject pulses of positrons into the plasma and detect the time delay between the injection and arrival of the positrons at a plasma divertor by detecting the characteristic 511 keV annihilation gamma rays. This can be accomplished using the giant positron pulses described above. As illustrated in Fig. 10, positrons would first be converted into neutral positronium atoms, which are able to cross the confining magnetic field.[32,33] For positronium beam energies of ~100 eV, most of the positronium atoms will be ionized within a typical plasma, releasing free positrons that function as "tagged electrons."[33] The transport information is contained in the distribution of arrival times of the positrons. In a refined version of this experiment, localized positron deposition could be achieved by using a laser to photoionize the Ps atoms.

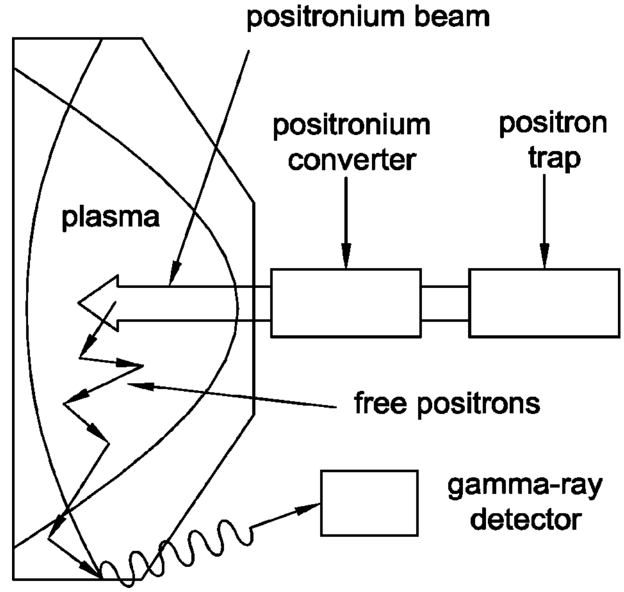

FIG. 10. Schematic view of an experiment to study transport in a tokamak plasma using positrons, which function as electron-mass test particles.

E. Positron-matter interactions

1. Atomic physics

The cold, trap-based positron beam described in Sec. II E 1 has enabled a variety of new positron atomic-physics studies, including both scattering and annihilation experiments. The scattering work exploited a new technique to study scattering in a magnetic field.[138] This technique was developed to be compatible with the trap-based beam that also uses such a field. It permitted measurement of the first state-resolved positron-impact cross sections for electronic and vibrational excitation of target species, as well as a variety of other cross section measurements. For example, in the case of CO_2, the measurements were of sufficient quality and energy resolution to study the ν_2 mode at 80 meV.[35] Data for the electronic excitation of the lowest allowed states of N_2 showed a large, resonant enhancement in the cross section at threshold (8.8 eV). While not yet understood theoretically, this observation explains the empirical discovery that N_2 is the molecule of choice for use in buffer-gas positron traps.[60,65]

The cold beam also enabled the first studies of the annihilation of low-energy positrons in molecules, resolved as a function of positron energy.[37,39] These experiments focused on energies below the threshold for positronium atom formation. This annihilation work represented a qualitatively new kind of experimental investigation and resolved a four-decade-old mystery regarding very large annihilation rates observed in a variety of molecules. Shown in Fig. 11 are data for positron annihilation in pentane as a function of positron energy.

No enhancement in the annihilation rate is observed for energies above those of the molecular vibrations, but large enhancements are observed in the region of energies of the vibrations, indicated by vertical bars in the figure.

The resonances are downshifted from the vibrational energies by an amount that increases with molecular size. These data fit the theoretical picture of vibrational Feshbach resonances (cartoon, Fig. 11). Namely, if the positron has a bound state with the molecule, this state can be populated in a two-body collision if the incoming positron energy, ε, is equal to the vibrational mode energy minus the positron-molecule binding energy (c.f., Fig. 11: $\varepsilon = \Delta E_{\mathrm{vib}} - \Delta E_b$). These data resolve the issue of large annihilation rates in molecules. More importantly, they provide the first direct

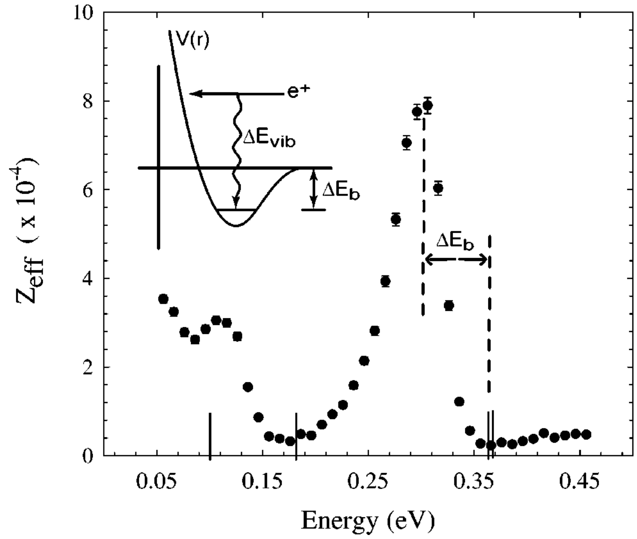

FIG. 11. Evidence that positrons bind to hydrocarbon molecules. Shown is the normalized positron annihilation rate, Z_{eff} for positrons on pentane molecules (C_5H_{12}) as a function of positron energy. If the collision were elastic, Z_{eff} would be $\sim$ the number of electrons in the molecule $(Z=42)$. Instead, it is a factor of 10^3 larger. The cartoon illustrates the attachment process that explains the large values of Z_{eff} that are observed.

experimental evidence that positrons bind to ordinary neutral matter.

2. Positron ionization mass spectrometry

A positron can ionize a neutral molecule by one of four basic processes: (1) direct ionization, which produces both a positron and a free electron in the final state; (2) charge exchange to form positronium; (3) annihilation of an electron following attachment; and (4) annihilation during an otherwise elastic collision. Process (1) is analogous to electron-impact ionization, but the other three processes are unique to positrons. Annihilation following electron attachment was investigated in early experiments in which sample gases were introduced into a Penning trap containing cool positrons.[65,72] The ions created by positron annihilation were confined by the same fields that confined the positrons, and mass spectra were obtained using time-of-flight techniques.[40] This method showed extensive fragmentation, qualitatively similar to that observed in electron-impact ionization. However, subsequent experiments using higher energy positrons, to create ions by positronium formation, showed that the fragmentation could be controlled by adjusting the positron energy.[41] In particular, for positron energies close the threshold for positronium formation (i.e., $E=E_{\mathrm{i}}-6.8\,\mathrm{eV}$, where E_{i} is the ionization energy), the mass spectrum was dominated by the parent ion, and showed increasing fragmentation as the positron energy was decreased or increased from this value. The controllable fragmentation processes have the potential to provide important information about the chemical structure of large organic molecules, including biomolecules.

3. Atomic clusters

The scattering and annihilation techniques described in Sec. III E 1 to study atoms and molecules are directly applicable to the study of atomic clusters and nanoparticles, *in situ*, *in vacuo*. In addition, positron-induced Auger spectroscopy will also be very useful to study these species. This technique is very surface sensitive[139] and capable of studying the outer monolayer of clusters—information difficult to obtain by other methods. Problems of interest include novel "positron cage states" predicted for open structures such as C_{60},[140] understanding the structure of solvated ions, and the physics of molecular clusters such as polycyclic aromatic hydrocarbon molecules.

4. Bulk materials and material surfaces

When a positron is injected into a solid, gamma rays and/or a variety of particles can be ejected. These particles include reemitted, reflected or diffracted positrons, positronium atoms, secondary electrons, Auger electrons and ions. The gamma-ray photons result from either the direct annihilation of the positrons or from the annihilation of positronium atoms formed within the sample. Each of these exiting projectiles can be analyzed to provide useful information about the system, including the composition of the surface of a bulk material, crystal structure and orientation, surface-adsorbed layers, porosity, pore interconnectivity, and the distribution and concentration of vacancy defects. Analyzing the annihilation gamma rays, in particular, provides unique information about defects that cannot be obtained using other techniques. Timed measurements, for example, using ultrashort positron pulses (<500 ps), permit determination of the lifetime of the positrons, which in turn, allows the defect size and concentration to be measured. Depth profiling information can be obtained by implanting the positrons to variable depths using different incident energies.[42] Spatially resolved information can be obtained using scanning microbeams.

These techniques are currently being used to investigate a wide variety of problems of importance in materials science and integrated circuit manufacturing. Topics include study of the properties of low dielectric constant insulators being developed for integrated circuit manufacturing to reduce stray capacitance,[141,142] ion-implantation-induced damage in semiconductors[143] accelerated aging in polymers,[144] hydrogen embrittlement,[145] and fatigue in structural metals.[146] As described in Sec. II E 2, trap-based positron beams are well suited to these kinds of measurements, since they can efficiently produce ultrashort pulses suitable for positron lifetime measurements. Furthermore, as described in Sec. II E 3, brightness enhancement techniques can be used to produce trap-based microbeams with capabilities for spatial resolution not obtainable by other methods. Commercial positron beam systems based on these principles are now under development.

F. The quantum electron-positron system: BEC Ps and stimulated γ-ray emission

As described above, positron traps have the capability to accumulate large numbers of positrons and release them in giant pulses. If such a pulse of spin-aligned positrons is focused onto a subsurface cavity, a significant fraction of the positrons will neutralize to form positronium atoms and enter the cavity. If the temperature is sufficiently low, the atoms will condense into a Bose–Einstein condensate (BEC).[34,147] For a cavity 10^{-13} cm^3 in volume, 10^8 Ps atoms would undergo the transition to a BEC at 1500 K ($n = 10^{21}$ cm^{-3}). This ambitious project would be the first study of the quantum, many-electron/many-positron system. Very little is known about the quantum phase diagram of this unique matter/antimatter system. For example, at higher densities, the Ps gas should undergo a metal-insulator transition. The possibility that a Ps BEC can be used to form a super-radiant beam of gamma rays by stimulated annihilation has also been discussed.[34]

G. Cooling highly charged ions

The interactions of highly charged ions with solid and gaseous targets has been the subject of extensive experimental and theoretical investigations (see, e.g., references cited in Ref. 26.) However, research in this area has been hindered by the relative unavailability of high-quality beams of cold, highly charged ions required for precision studies. This is being remedied using a technique in which trapped, cold positrons are confined simultaneously with the ions.[26] The positrons cool by cyclotron cooling and cool the ions sympathetically.

IV. SUMMARY

The past few years have witnessed tremendous progress in the accumulation, manipulation, and use of antimatter in the laboratory. This progress can, at a minimum, be expected to continue and is likely to accelerate. There are a number of exciting technical challenges facing the field. One is developing a quantitative understanding of the torque-balanced radially compressed steady states of single-component plasmas—antimatter plasmas that can be specially tailored for specific applications. Another challenge is developing methods to simultaneously confine and cool positron and antiproton plasmas in sufficiently close proximity to a trap for neutral antihydrogen atoms so that the atoms can be trapped. Finally there is the quest for practical and efficient methods to create and study neutral electron-positron plasmas. An emerging central theme of low-energy antimatter research is that studying and exploiting antimatter will be driven by our increasing ability to use non-neutral plasma techniques to create and manipulate antimatter plasmas in new regimes of parameter space.

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