# Chapter 7

# Applications

The positron trapping system which we have developed meets the criteria (discussed in Chapter 1) of being small (the positrons originate from a small radioactive source, rather than a large accelerator facility), capable of operating under ultra-high vacuum conditions (no buffer gases are required to slow the positrons), and capable of accumulating positrons continuously over long periods of time. Of primary interest during the development of this trap was the possibility of producing antihydrogen by merging cold, trapped plasmas of antiprotons and positrons; this is discussed in Section 7.1. Another potential application is using positrons to cool highly stripped ions, as discussed in Section 7.2. Several other potential applications are discussed briefly at the end of the chapter.

## 7.1 Antihydrogen

Now that both positrons and antiprotons have been trapped at 4 K, it should be possible to produce and study antihydrogen at these low temperatures [11]. Spin-polarized hydrogen atoms have already been magnetically confined and studied at dilution refrigerator temperatures [16,17,18]. Laser cooling and magneto-optical trapping of atoms such as sodium, rubidium, and cesium has become fairly common in recent years. Laser cooling of (anti)hydrogen is certainly more difficult because of the challenges in producing a sufficiently powerful Lyman-alpha laser, although some laser cooling of hydrogen has already been demonstrated [18]. Spectroscopic comparisons of hydrogen and antihydrogen—for example, measurement of the 1s–2s transition or the fine and hyperfine intervals—would provide extremely precise tests of CPT symmetry. The standard model, while allowing for C-violation, P-violation, and CP-violation, does not allow CPT-violation. CPT symmetry implies that particles and antiparticles must have exactly opposite electric charges and magnetic moments, and identical masses and lifetimes. A spectroscopic comparison of hydrogen and antihydrogen could provide a more precise CPT test than is typically possible with measurements on single particles [65].

It has recently become possible, through the use of laser cooling, to measure the gravitational acceleration on single atoms. Attempts to measure the gravitation force on charged antiparticles would be extremely challenging because very tiny electric forces can easily overwhelm the gravitational force, as was demonstrated with electrons [66]. Electrically neutral antihydrogen atoms would avoid this problem.

### 7.1.1 Trap design for combining antiprotons and positrons

Antiprotons are captured, stored, and studied in an apparatus nearly identical to our positron trapping apparatus. (The antiproton trap is described in Refs. [67,23,24].) The two significant differences are: (1) The bottom of the magnet and the bottom of the antiproton trap can are connected to the Low Energy Antiproton storage Ring at CERN via thin vacuum windows which allow antiprotons to pass through; (2) the antiproton Penning trap electrodes are not of a hyperbolic geometry, but rather of an open-endcap cylindrical geometry which we designed to maximize the harmonicity of the trapping potential (for a cylindrical geometry) to facilitate storage and high-precision measurements [67].

An overview of the proposed scheme for producing antihydrogen is represented

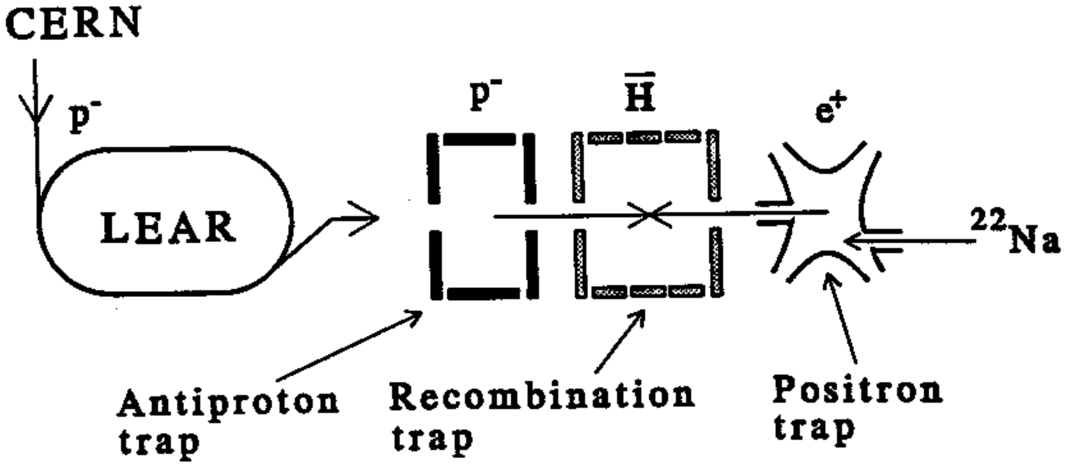

Figure 7.1: Representation of the proposed antihydrogen production scheme. The antiproton trap, positron trap, and recombination trap would all reside in the same cryogenically cooled, vacuum-sealed trap can.

in Fig. 7.1. Antiprotons from LEAR would enter the trap can and accumulate in a storage trap. Positrons would also accumulate (using a trap similar to the one described here) in the same vacuum-sealed trap can. When a sufficient number of both species had been attained, they would be transfered to the "recombination trap" where they could be made to overlap, either by using a nested pair of Penning traps (Fig. 7.2) in which the antiprotons oscillate slowly through a central potential well filled with positrons [68], or by superimposing a radiofrequency signal on the Penning electrodes, which is capable of confining both charged species in the same space by the same mechanism as a Paul trap. Antihydrogen recombination could be signaled by several different mechanisms, including (1) detection of photons, (2) the loss of equal numbers of positrons and antiprotons, and (3) field ionization of the resulting antihydrogen atoms (assuming they are produced in a sufficiently small binding energy state) and detection of the products in a region of the trap

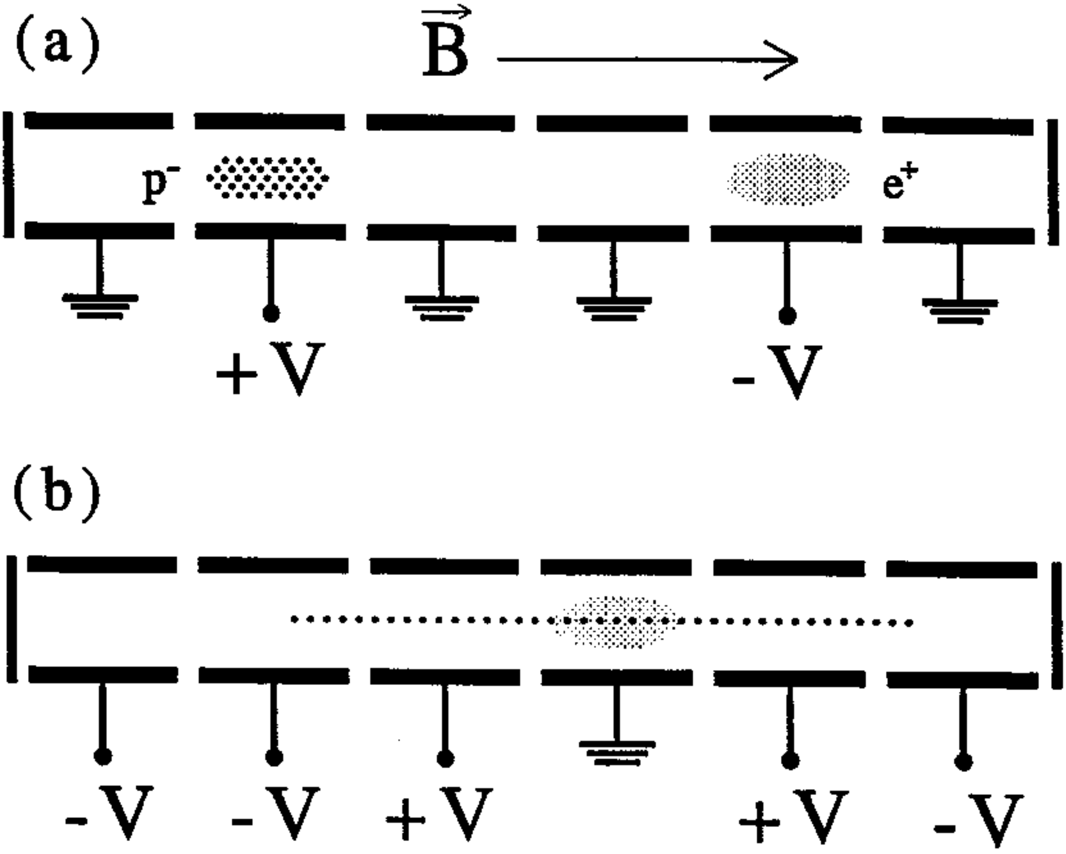

Figure 7.2: Nested Penning traps could be used for antihydrogen production. (a) Antiprotons and positrons are accumulated in separate traps. (b) Antiprotons are made to oscillate through the positron cloud, allowing recombination.

can which is inaccessible to electrically charged particles. We have already built such a trap to test ordinary hydrogen recombination under conditions identical to those expected for antihydrogen, and results are expected in the near future.

### 7.1.2 Recombination rates

When antiprotons are completely contained within a positron plasma, radiative recombination

$$p^- + e^+ \to \overline{H} + \gamma \tag{7.1}$$

proceeds at a rate [11,69]

$$R_{\overline{H}} \simeq 3 \times 10^{-11} \left(\frac{4.2}{T}\right)^{1/2} N_{p^-} n_{e+} \quad s^{-1}, \tag{7.2}$$

where $T$ is the temperature of the positrons. We have assumed that the antiproton velocity is equal to or less than the average positron velocity. For a positron density $n_{e+} = 10^8/\mathrm{cm}^3$ and a number of antiprotons $N_{p^-} = 10^5$, at 4.2 K, this yields a recombination rate $R_{\overline{H}} = 300/\mathrm{sec}$.

The three-body recombination mechanism

$$p^- + e^+ + e^+ \to \overline{H} + e^+ \tag{7.3}$$

may be more efficient by many orders of magnitude [11]. Its rate has been calculated in various ways [70], including under conditions of high magnetic field [71], giving

$$R_{\overline{H}} \simeq 10^{-12} \left(\frac{4.2}{T}\right)^{9/2} N_{p^-} n_{e+}^2 \quad s^{-1}. \tag{7.4}$$

Note the sensitive dependence upon temperature and the squared dependence upon positron density. We can understand these dependences by noting that the relevant length scale for a Coulombic collision is the Thomson radius ($r_T = 2e^2/3k_BT$), the distance at which the Coulomb interaction energy is equal to $\frac{3}{2}k_BT$. Taking $\tau \approx r_T/v$ to be the duration of a collision, $r_T^2$ as the cross-section of an antiproton-positron collision, and $(n_{e+} r_T^2 v\tau)$ the probability of a second positron being in the region during the collision, yields

$$R_{\overline{H}} \sim \frac{(n_{e+} r_T^2 v\tau)^2}{\tau} \sim n_{e+}^2 T^{-9/2}, \tag{7.5}$$

since the positron velocity $v$ scales as $T^{1/2}$.

Assuming $N_{p^-} = 10^5$ and $n_{e^+} = 10^8/\mathrm{cm}^3$ as above, Eq. 7.4 gives a recombination rate of $R_{\overline{H}} = 10^9/\mathrm{sec}$. Of course, $N_{p^-}$ sets a limit on the total *number* of antihydrogen atoms produced. One potential problem with collisional recombination is that the initial positron capture occurs within a few $k_BT$ of the ionization limit, producing highly excited atoms. However, the resulting antihydrogen atoms will be moving slowly and could possibly be held by their large magnetic moment long enough for collisional de-excitation to a state where spontaneous emission de-excitation would dominate.

## 7.2 Cooling trapped ions

It is quite challenging to cool highly stripped, heavy ions from the several-keV energies at which they are typically produced and trapped to sub-eV energies, where they can be studied more carefully. Heavy ions under these conditions do not rapidly radiate away their kinetic energy the way positrons do, nor is their motion easily damped with resistive circuits. Neutral buffer gases which might be used to slow the trapped ions would also undergo charge-exchange processes with the ions. Cold positron plasmas could be a very useful tool in cooling these energetic, highly-stripped ions. The ions would rapidly lose energy via collisions with positrons as they oscillate through the trap; the positrons in turn quickly cool themselves via synchrotron radiation. The process is exactly analogous to electron cooling of trapped antiprotons [13], which has already been demonstrated to work efficiently [12,14]. Unlike buffer gases, the positrons would not cause ion loss via charge transfer processes.

Using a positron buffer plasma to cool heavy ions would have several advantages over other possible buffer plasmas (*e.g.* protons). Unlike positrons, trapped protons do not cool themselves via synchrotron radiation under typical laboratory conditions (several Tesla). Because of their small mass, positrons would be easily purged from the ion trap once the ion cooling was completed. Under many conditions, the ions transfer their energy *more* efficiently to the lighter positrons than they would to a similar cloud of protons. The rate of ion cooling to a buffer plasma which is synchrotron cooled to 4.2 K is given by [13,72]

$$\frac{d}{dt}T_i = -\frac{1}{\tau_{eq}}(T_i - T_b), \tag{7.6}$$

$$\frac{d}{dt}T_b = \frac{N_i}{N_b \tau_{eq}}(T_i - T_b) - \frac{1}{\tau_{synch}}(T_b - 4.2), \tag{7.7}$$

where $T_i$ is the ion temperature, $T_b$ is the buffer plasma temperature, $N_i$ and $N_b$ are the numbers of ions and buffer particles, respectively, and (in cgs units)

$$\tau_{eq} = \frac{3k_B^{3/2} M_i m_b}{8\sqrt{2\pi}\, e^4 (\ln \Lambda) Z^2\, n_b} \left( \frac{T_i}{M_i} + \frac{T_b}{m_b} \right)^{3/2}, \tag{7.8}$$

where $k_B$ is Boltzmann's constant, $M_i$ and $m_b$ are the particle masses, $Z$ is the ion charge, $n_b$ is the buffer particle density, and

$$\Lambda \simeq \frac{3}{2Ze^3} \sqrt{\frac{k_B^3\, T_b^3}{\pi\, n_b}}. \tag{7.9}$$

We can use these equations to numerically simulate ion cooling and obtain equilibration rates. Results for one such calculation. comparing positron and proton buffer plasmas, is shown in Fig. 7.3.

## 7.3 Improved positron lifetime measurement and potential UHV gauge

By loading a large cloud of positrons and monitoring its signal over time, we expect to use this positron trap to establish a new limit on the lifetime of the positron in the same way as was done with antiprotons [15]. In the same way, in limited applications, positron traps could be useful in measuring background gas at pressures below which conventional ion gauges do not operate ($10^{-12}$ torr).

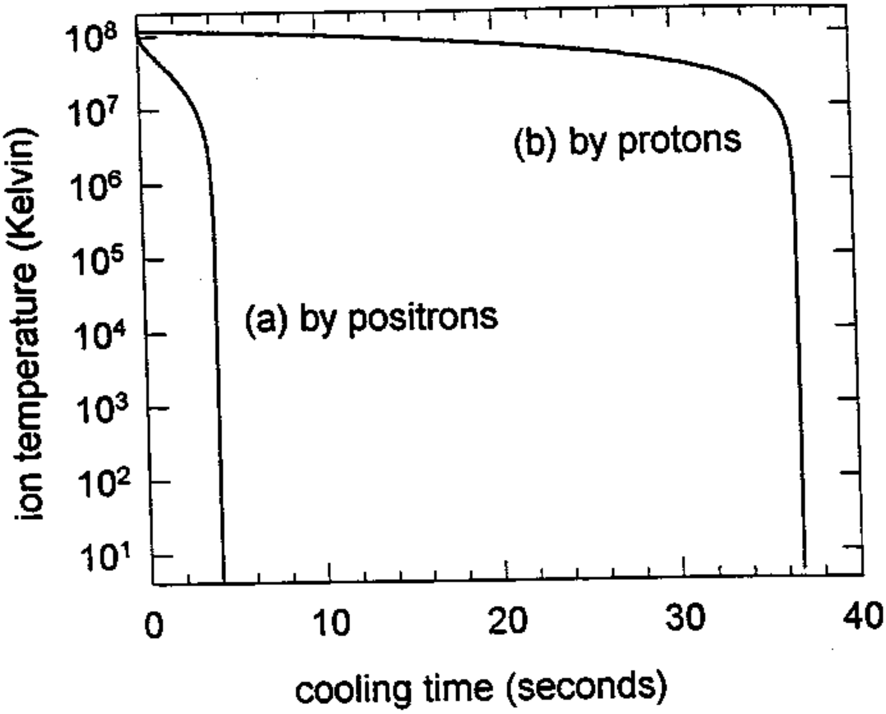

Figure 7.3: Results of a computer simulation cooling $N_i = 10$ fully stripped Uranium-238 ions from 10 keV to 4.2 K using buffer plasmas ($N_b = 10^5$, $n_b = 10^8/cm^3$) of (a) positrons and (b) protons.

Figure 7.4 shows the expected lifetime of a trapped positron as a function of background gas pressure for selected molecules [59,60]. A positron annihilation vacuum gauge would operate by initially loading a cloud of positrons and determining their lifetime by periodically monitoring the number of remaining positrons. To make this device feasible, the positrons would need to be heated by resonant drives to energies which allow positronium formation ($\sim$ 10 eV) in order to increase their annihilation cross-section.

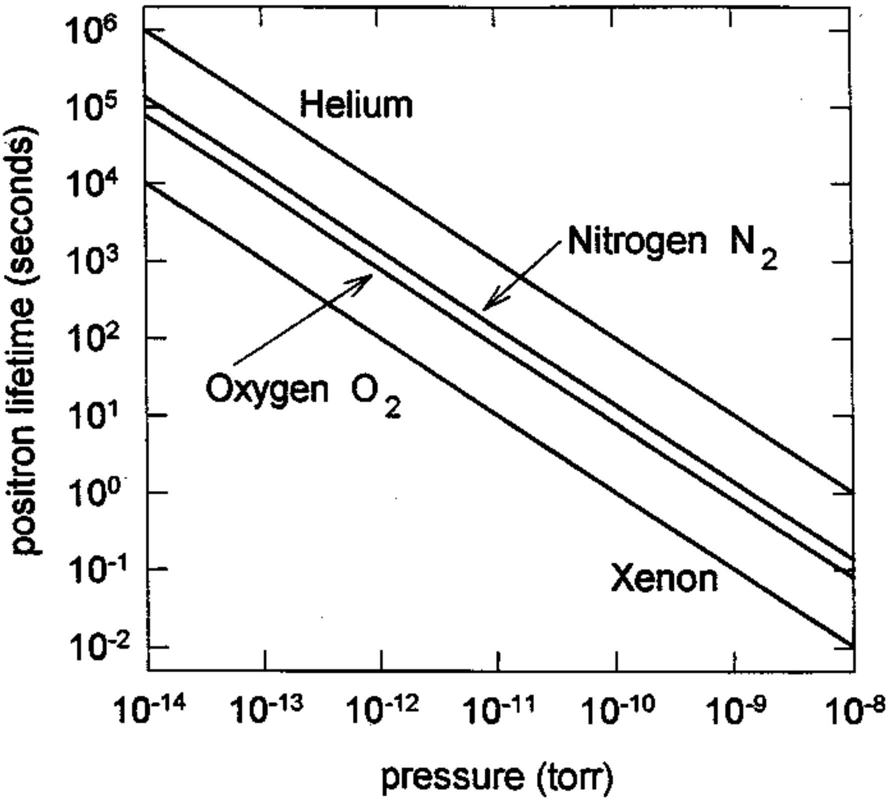

Figure 7.4: Calculated positron lifetime *vs.* background gas pressure for various atoms and molecules. The positrons are assumed to be at 10 eV energy and annihilate via positronium formation.