Chapter 1

Introduction

1.1 Motivation

Positrons were first captured in a Penning trap more than ten years ago at the University of Washington in an apparatus designed for precision measurements on positrons [1,2,3]. The loading rate into their trap was only a few positrons per hour (compared with 10^7 positrons per second which were supplied by their 0.5 milli-Curie radioactive source), since the range of energies with which the positrons entered their trap (hundreds of keV) was much greater than the range of energies which could be captured (a few meV).

During the last decade, great progress has been made in producing slow, nearly monoenergetic positron beams through the use of positron moderators [4,5,6,7]. A carefully prepared moderator can produce positron beams which have energy spreads of less than 100 meV, at an efficiency of nearly one slow positron per thousand fast incident positrons. This experiment utilizes such a moderator to increase by orders of magnitude the rate at which positrons are accumulated in vacuum [8,9].

Antiprotons were recently captured in a Penning trap [10], raising the possibility of using trapped positrons to make antihydrogen at low temperatures [11]. Antiprotons from the Low Energy Antiproton storage Ring (LEAR) at CERN were slowed from their storage energy of 5 MeV via collisions with matter in a degrader foil [10,12], and the Penning trap electrodes were biased shortly after the arrival of the antiproton pulse. Those which emerged from the degrader foil in the energy range 0 to 3 keV were trapped. The antiprotons were further cooled to liquid helium temperatures by collisions with trapped electrons [13] and by coupling their motion to a damping circuit. By stacking several pulses of approximately 10^8 antiprotons from LEAR, as many as 2×10^5 antiprotons have been held at one time in a trap with a volume of about 1 cm^3 and a temperature of 4 K [14]. A cryogenically cooled Penning trap allows antimatter to be stored for long periods of time. The antiproton lifetime in this trap has been demonstrated to be at least several months, setting an upper limit of 5×10^{-17} Torr for the background pressure in the trap [15].

Antihydrogen could be formed at a high instantaneous rate by merging cold, trapped clouds of positrons and antiprotons in the same volume [11]. Since the antihydrogen would already be localized in space and quite cold, this raises the possibility of trapping the antihydrogen in a superimposed magnetic dipole trap, as has been done with hydrogen [16,17,18]. Spectroscopic comparisons of hydrogen and antihydrogen could provide extremely sensitive measurements of CPT invariance. Therefore, with the success of the antiproton trap, it became desirable to build a trap which could accumulate a sufficient number of positrons in a high vacuum at a sufficiently high rate to make antihydrogen production feasible. The design of that trap, and its performance, are the primary focus of this thesis.

Other uses for trapped positrons include the cooling of highly stripped ions in the same way that electrons are used to cool trapped antiprotons [13]. In addition, a limit on the positron lifetime can be measured by monitoring a large cloud of trapped positrons. In the same way, monitoring the loss of positrons from a Penning trap could provide a means of measuring the background gas density at pressures below which ion gauges do not operate ($\sim 10^{-12}$ Torr).

The most precise measurements of the properties of positrons [3] and electrons were made in Penning traps under ultra-high vacuum conditions at 4 K. Plans are currently in progress to improve these measurements on electrons by utilizing a dilution refrigerator. The positron trap described here could easily be adapted to operate at dilution refrigerator temperatures, which would allow more precise measurements of the positron's magnetic moment and charge-to-mass ratio as additional tests of CPT invariance. Moreover, its relatively high trapping efficiency would allow it to operate with a much smaller radioactive source—assuming the experimenter only wants to study one or two positrons at a time—which would reduce the frequency of positrons "spontaneously" loading into the trap, which was occasionally a problem in earlier experiments [3]. Such a trap could also be used to measure the properties of positron moderators at temperatures below 4 K, which has not yet been explored experimentally. Antihydrogen formation and other potential uses of trapped positrons are discussed in more detail in Chapter 7.

1.2 Design constraints

It should be possible to trap and accumulate positrons in the same way as antiprotons, by using an accelerator facility to produce and deliver pulses of positrons to a Penning trap. However, this would not be convenient for initial attempts to make antihydrogen insofar as both the antiproton source and the positron source must be located at the same facility. Currently, the only source for antiprotons at energies below 100 MeV is LEAR at CERN. Fortunately, several readily available radioactive nuclei produce positrons during the course of their decay. These sources are generally quite small physically (less than 1 cm^3) and therefore can be easily transported to the antiproton trap.

Radionuclei (for example, sodium-22) produce positrons continuously over a wide range of energies. Moderators (Chapter 3) can be used to slow the positrons to energies below 1 eV; however, additional energy must be extracted from the positrons while they travel through the trap volume in order for them to remain in the trap.

One way to accomplish this is by periodically ramping the electrode voltages, accumulating positrons during each ramp cycle. Since positrons have high velocities even at these low energies (6×10^7 cm/sec at 1 eV), very rapid voltage ramping is required. Such a trap has been built by Conti *et. al.* at the University of Michigan [19]. A typical duty cycle for the Michigan apparatus is 100 to 1000 Hz, accumulating ~ 200 positrons per pulse from a 30 mCi ^{22}Na source. However, this technique is more suited to ***bunching*** than to long-term accumulation. (The Michigan trap is rapidly dumped at the end of each cycle.) For long-term accumulation of positrons, the duty cycle would need to be drastically reduced to allow time for the positrons to cool at the end of each upward ramping of the electrode voltages.

One way to extract energy from slow positrons *continuously* is by using a neutral buffer gas, as has been demonstrated by Surko *et. al.* at AT&T Bell Labs and U.C. San Diego [20]. Inelastic collisions with buffer gas atoms inside the trap cause a significant fraction of the positrons to remain trapped. However, the buffer gas (nitrogen) also limits the positron lifetime through annihilation. Background hydrocarbon molecules are also a concern with this design, since their positron annihilation cross-section can be orders of magnitude larger than for nitrogen [21]. The longest positron lifetimes achieved in this trap were of order ten minutes. This lifetime is unacceptably short, especially considering that antiprotons (which are much harder to obtain than positrons) will eventually share the same vacuum environment. It is unclear that it is possible to adapt this technique to the cryogenic, ultra-high vacuums required for antihydrogen study.

Therefore, we chose to use a resistive damping technique [1,8,22] to extract energy from the positrons. The positrons' motion through the trap induces currents in an LRC circuit which is connected to the trap electrodes; energy is dissipated in the resistor. This technique works even under cryogenic, ultra-high vacuum conditions. It also works continuously; there is no duty cycle to slow the overall accumulation rate. The trapping efficiency is high enough so that—in a few hours or a few days—a sufficient number of positrons can be accumulated to make antihydrogen production feasible [11], with a radioactive source small enough to ensure the safety of the experimenters. Finally, this technique meets the criteria of being easily portable and adaptable to the existing antiproton trap.

1.3 Overview of remaining chapters

The remaining chapters follow the positrons as they are emitted from the radioactive source, moderated, loaded into the trap, detected, and finally accumulated. Chapter 2 shows the overall design of the Penning trap and support apparatus, and calculates the fraction of positrons which reach the moderator from the radioactive source. Chapter 3 shows the effect of the moderator on the positron energy distribution. Chapter 4 starts with a quick review of the dynamics of a charged particle in a Penning trap, and proceeds to describe the mechanism by which positrons are trapped. An overall trapping efficiency is also calculated. The technique by which positrons are detected and counted is described in Chapter 5, and Chapter 6 shows examples of positron accumulation and storage. Finally, Chapter 7 explores potential applications.