# Chapter 1

# Introduction

Antiprotons were first observed in 1955 at the Berkeley Bevatron in what can be considered the first mass comparison between antiprotons and protons (accuracy ≈ 5%)[18]. Antiprotons are extremely rare in cosmic rays and for most practical purposes are only available for experimentation as products of high energy collisions at large particle accelerators. The relative scarcity and high energy nature of antiprotons make it difficult to achieve high precision measurements of their fundamental properties. Unprecedented accuracies would be possible if only a small number of antiprotons could be studied in the low energy environment of an ion trap [24,61,36].

In this thesis, a measurement of the antiproton inertial mass 1000 times more accurate than previously obtained is described. This substantial improvement is the result of slowing, trapping, and cooling antiprotons into the low energy environment of a Penning trap [37,45] and the application of high precision mass spectroscopy techniques [48].

Measurements of the antiproton inertial mass are made by comparing their confinement eigenfrequencies in a new open endcap cylindrical Penning trap to those of protons. The antiproton to proton mass ratio is measured to be

$$m_{\bar{p}}/m_p = 0.999\,999\,977(42). \tag{1.1}$$

The fractional uncertainty is determined to be $4.2\times10^{-8}$ after a thorough investigation of possible systematic effects. This measurement becomes the most sensitive test of CPT invariance on a baryon system.

## 1.1 Motivation

During the later half of this century, tests of symmetry principles in physics have resulted in most unexpected and fundamentally important surprises. In 1956, the weak interactions were shown to be parity violating [67,118]. In 1964, observations showed that the results of interactions involving the K meson and its antiparticle were different under a combined transformation of parity and a change in sign of electric charge [19]. This phenomena, known as charge-parity (CP) violation, remains one of the most stimulating problems of particle physics.

A fundamental symmetry in our description of nature is CPT symmetry. CPT symmetry implies that the physical interactions in our world are identical to those in a world where you simultaneously change the sign of baryon number, strangeness, lepton number, muon number, and electric charge (Charge conjugation C), change sign of the spatial coordinates (Parity P), and change the direction of time (Time reversal T). Invariance under such a transformation is required by general principles of relativistic field theory [80,112]. Some of the consequences of CPT invariance which can be experimentally tested are the equality of the masses, mean lifetime, and magnetic moment (with opposite sign) of a particle with its antiparticle.

The most precise tests of CPT invariance to date are summarized in Fig. 1.1. Only two tests have an accuracy significantly higher than the the work reported in this thesis comparing the antiproton and proton masses. The electron and positron magnetic moments have been compared to an accuracy of $4\times10^{-12}$ [102]. Of particles that participate in the strong interactions, the only high precision test of CPT invariance results from the $K_L$ and $K_S$ mass oscillation, providing an extremely sensitive test of the mass difference of the eigenstates, $K_0$ and $\overline{K}_0$. This measurement implies a fractional mass difference of $\Delta m_{K^0}/m_{K^0} < 10^{-18}$. Previous measurements of the $p - \overline{p}$ mass difference of $5 \times 10^{-5}$ provide the best limit on CPT invariance in a baryon system. Reaching a proposed goal of measuring the antiproton-proton mass difference to an accuracy of $10^{-9}$ will improve this limit by more than four orders of magnitude [92,36].

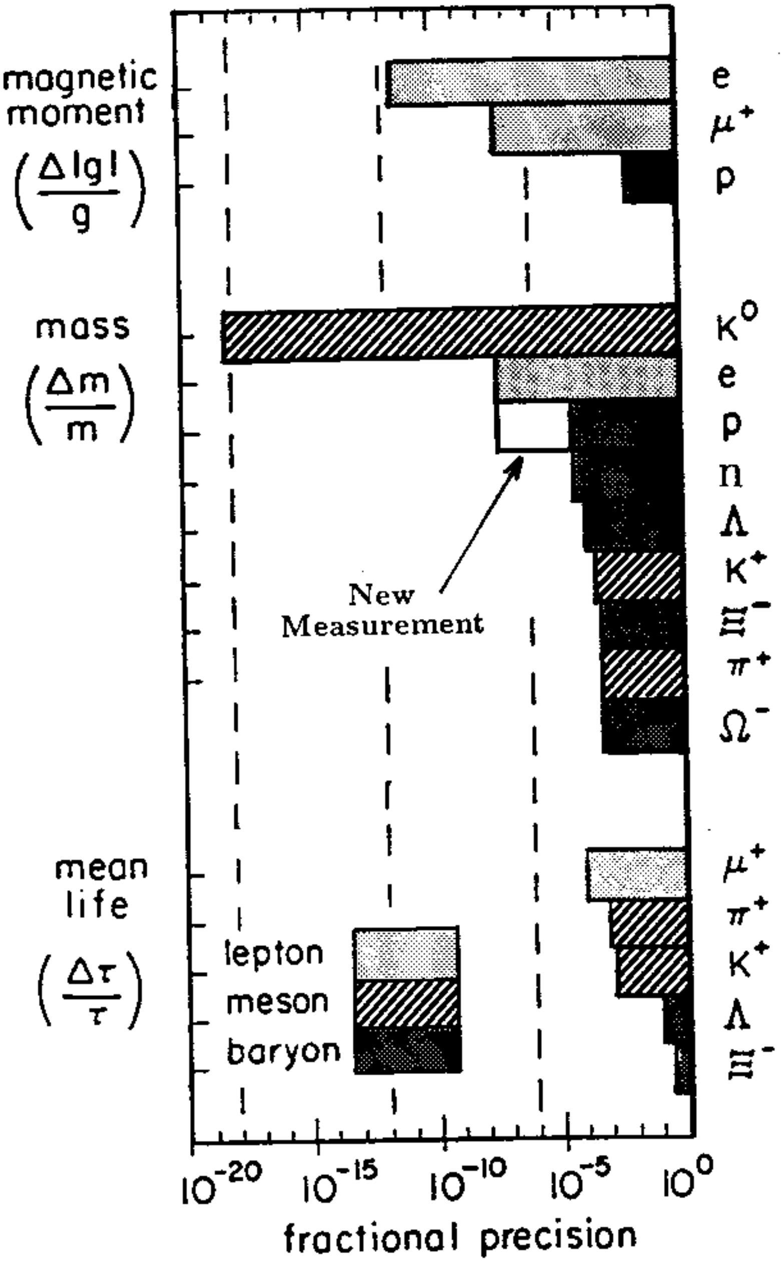

Figure 1.1: Tests of CPT Invariance using baryons, mesons, and leptons. (Data from **Review of Particle Properties**; Physics Letters **B204**, April 1988)

There have been four previous determinations of the antiproton inertial mass [3,56,81,82] as shown in Fig. 1.2 and compared with the measured proton mass which is known to much higher precision. All of the previous mass determinations used exotic atoms formed when an incident high energy antiproton is slowed in a target and captured by a nucleus. Measurements of the exotic atom are made on antiprotons which occupy orbits within the lowest electron orbit, yet are still still outside of the range of nuclear strong interactions. To first approximation, the exotic atom can then be treated as an hydrogenic atom. De-excitation X-rays are measured and the transition identified. The transition energy is nearly proportional to the reduced mass and the antiproton mass can be deduced by comparing the measured values with theoretical values. Corrections to the measured energy eigenvalues taken into account include vacuum polarization, higher order radiative terms, electron screening, finite nuclear size, and nuclear polarization. The most precise measurement from these techniques puts a limit on a possible difference between the antiproton and proton masses of $5\times10^{-5}$ [81].

It has been proposed to put a limit on the antiproton-proton mass difference by comparing the antiproton and proton radii while circulating in a large accelerator ring [94]. This method may be feasible in a ring such as the Super Proton Synchrotron (SPS) at the European Center for Particle Physics (CERN), though it has not been demonstrated that improvements over the accuracy achievable using exotic atom methods are obtainable with present machine parameters.

## 1.2 Mass Spectroscopy in a Penning Trap

The use of static electric and magnetic fields to increase the containment times of electrons was first documented by F.M. Penning in 1936 [77]. In 1949, a device called the omegatron was developed by H. Sommer, H.A. Thomas and J.A. Hipple at the National Bureau of Standards which was subsequently used to measure the charge to mass ratio of the proton by a cyclotron resonance technique [87]. In the 1960's and early 1970's, H. Dehmelt and associates at the University of Washington highly refined the use of static electric and magnetic fields into what

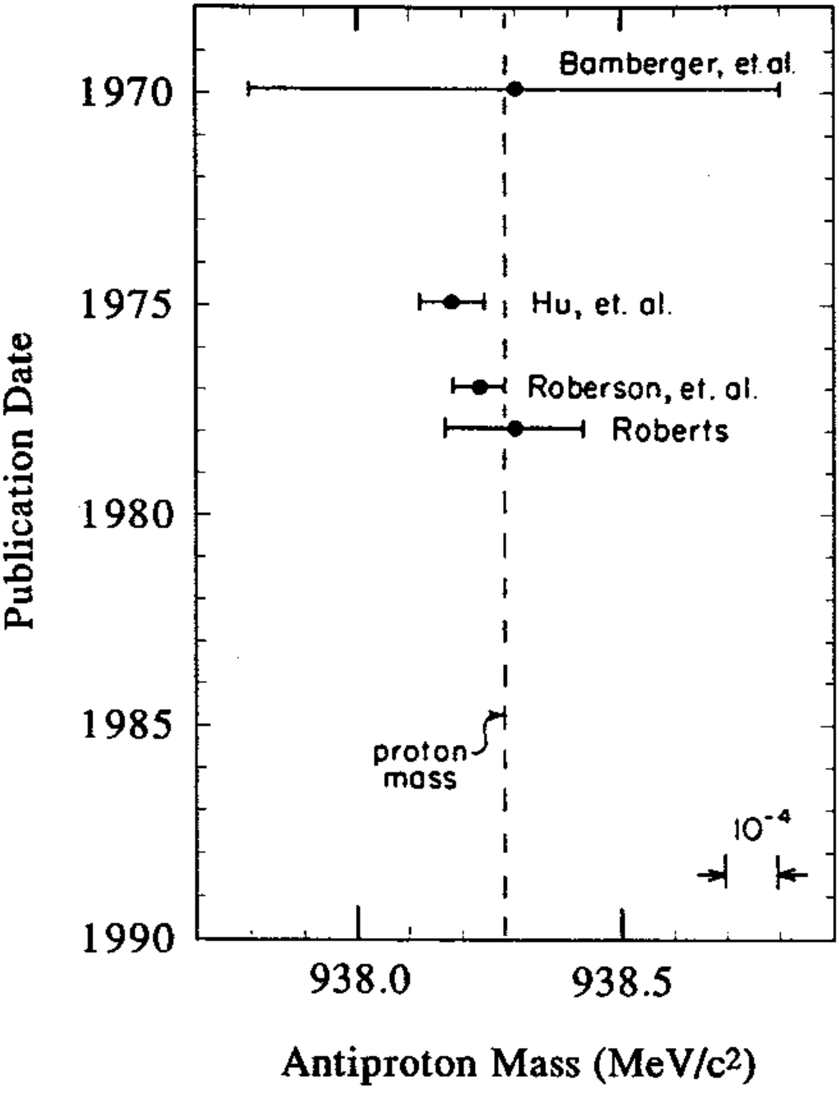

Figure 1.2: Previous measurements of the antiproton inertial mass compared to the proton mass. The uncertainty of the new measurement reported in this thesis is approximately 30 times narrower than the dashed line.

has become known as the Penning trap.

The Penning trap consists of a uniform static magnetic field superimposed on an electrostatic quadrupole potential. Such a device can hold charged particle(s) nearly at rest in free space essentially indefinitely. In 1973, Wineland, Ekstrom, and Dehmelt succeeded in isolating a single electron in such a trap [113] which led to a greatly improved measurement of the electron g-factor [25]. Since then, the use of such traps has greatly expanded and the Penning trap has become an important tool in the field of precision measurements. One such use is as a technique for high precision mass spectroscopy.

The trap technique has a number of advantages over other techniques for performing mass spectroscopy measurements. If the trap environment is cryogenically cooled, an extremely good vacuum can be obtained. This makes possible very long confinement times and the achievement of good signal-to-noise with even a single particle. Another advantage is that very different masses can be compared unlike, for example the Smith-Wabstra RF spectrometer, which is limited to comparing mass doublets. (Such a spectrometer has also been proposed as a method to determine the antiproton inertial mass to higher precision [92]). A final advantage is that detection schemes can be employed with Penning traps that yield very narrow lineshapes (presently $\Delta\nu/\nu \approx 4 \times 10^{-10}$ for RF detection schemes). Narrow lines and long containment times provide the possibility of a thorough quantification of perturbations and systematic effects.

One of the first high precision mass comparisons using a Penning trap was the direct determination of the fundamental mass ratio $m_p/m_e$. A group at Mainz University determined $m_p/m_e$ with a detection scheme that relied on a destructive time-of-flight technique [50,53]. Another group, from the University of Washington performed the measurement also using a Penning Trap, but instead used non-destructive RF detection techniques [98,99,100]. Both techniques have their merits and have been highly refined in recent years. In addition to the proton and electron, the positron has also been studied in a Penning trap [86,102]. The positron magnetic moment and inertial mass has been compared to that of the electrons with high precision resulting in the most precise test of CPT invariance using leptons (Fig. 1.1).

Recent high precison measurements with Penning traps demonstrate the promise of this technique in the field of mass spectroscopy. The Washington group, led by R. VanDyck, have made several different measurments and have claimed a resolution approaching $10^{-10}$ [72]. Their most precise published measurement has a fractional uncertainty of $3.4\times10^{-9}$, limited by the stability of their magnetic field. They have also compared other ions to the $^{12}C^{+4}$ ion, which yields a direct comparison to the defined atomic mass unit (amu) [72] .

Recently, use of a superconducting resonant detection circuit coupled to an RF squid [110] have resulted in a measurement by an MIT group of $m(CO^{+})/m(N_2^{+})$ with a reported fractional uncertainty of $4\times10^{-10}$ [21]. This measurement is also limited by the temporal stability of the magnetic field [47,23].

Finally, the time-of-flight ejection method pioneered at Mainz University is continued today G. Werth [111] and is also used at ISOLDE at CERN to perform mass comparisons of relatively short lived radioactive ions at the $10^{-7}$ level [5].

Over just a few years, spectroscopy in a Penning trap has become the standard for high precision mass determinations of charged particles with long lifetimes.

## 1.3 Antiprotons: Challenges and Solutions

The Penning trap is an ideal environment for studying stable low energy charged particles. Our goal has been to compare the antiproton and proton inertial masses by measuring their cyclotron frequencies in a Penning trap [36]. Because antiprotons are presently only available from a high energy accelerator, the prospect of putting antiprotons into the low energy (typically 4 K) environment has presented us with several major challenges. In this thesis, solutions to these major challenges and the resulting improved measurement of the antiproton inertial mass are described in detail.

We start in Chapter 2 with a brief review of the particle motions and the mass spectroscopy technique in a Penning trap.

In Chapters 3 and 4, we describe how we resolve the challenges imposed by working with antiprotons. In Chapter 3, we discuss the development of a new cylindrical open endcap trap and the cryogenic and support system that allows for interfacing the trap to an accelerator complex while maintaining the trap at 4 K. We also address concerns with large magnetic fluctuations in the accelerator environment and describe a custom built superconducting solenoid capable of producing a strong, highly uniform, and stable magnetic field. This solenoid is unique in that it also is capable of shielding the trap from external magnetic fluctuations by a factor as much as 156.

Chapter 4 presents our techniques for reducing the incoming antiproton energy by more than ten orders of magnitude. We summarize the slowing and capture of antiprotons into the new trap and subsequent cooling to 4.2 K using a novel form of electron cooling. We also measure the antiproton containment lifetime, an important observation that signifies the appropriateness of using non-destructive RF techniques to perform the mass measurement.

In Chapters 5 through 9 we turn our attention to using RF detection in the open access trap. In Chapter 5, we cover the experimental details of detecting the particle motions outlined in Chapter 2. In Chapter 6 and 7, we present experimental results in the new trap using electrons and protons. Chapter 8 and 9 present indirect and direct observations of the antiproton cyclotron motion.

In Chapter 10 we provide a comprehensive discussion of systematic checks and quantify the magnetic and electric perturbations to the trapping field at our present level of accuracy. Chapter 11 describes the mass comparison from a series of frequency measurements using antiprotons, protons, and electrons. In Chapter 12 we conclude this thesis by presenting mass comparisons for $m_{\overline{p}}/m_p$, $m_{\overline{p}}/m_{e^-}$, and $m_p/m_{e^-}$. We compare to previous measurements and discuss possible future research as a result of this work.