Chapter 1

Introduction

1.1 Motivation and history

Low energy antiprotons in storage rings [1,2,3] make a large number of nuclear- and particle-physics experiments and a few atomic physics experiments possible. The availability of cold antiprotons with energies much lower than the beam energies in storage rings opens the way to various interesting experiments and important physics in a new range of the energy spectrum. A comprehensive description of slowing, trapping, and cooling antiprotons below 1 meV is given in this thesis. For the first time, antiprotons have been stored indefinitely in an ion trap, at energies 10 orders of magnitude lower than realized in any storage rings. This makes possible a new antiproton mass measurement [4], a direct antiproton lifetime measurement, and antiproton-atom interaction studies at low energies. In the future, the antiproton source in an ion trap can be compact and movable so that a series of experiments could be carried out in a non-accelerator environment. Trapped antiprotons can be used for possible antihydrogen production [5] and gravitational mass measurements [6]. The technology and experience gained during the trapping experiment are also important for other studies. For example, antiprotons make a very sensitive gauge for vacuum studies based on the antiproton lifetime measurement. An antideuteron mass measurement may be possible in a similar fashion as for antiproton.

In early 1986, we first captured keV protons in an ion trap [7]. In April and May, we used a simple time-of-flight apparatus to measure the energy distribution of protons and antiprotons emerging from a thick degrader. A fraction of protons and antiprotons were slowed below 3 keV [8]. In July 1986, antiprotons were first captured in an ion trap by our TRAP Collaboration during a single 24 h period [9]. During the next two years, while the European Organization for Nuclear Research (CERN) was upgrading their antiproton facility, we prepared a new apparatus for slowing, trapping, and cooling of antiprotons, and for measuring the antiproton mass. Since September 1988, we have made great progress toward our goal [10,11,12] and thus laid the foundation for further achievement.

1.2 Slowing, trapping, and cooling antiprotons

Ultracold antiprotons of the order of meV are not available in any storage rings. Even the Low Energy Antiproton Ring (LEAR) which is the best low energy antiproton facility can only supply beams with an energy down to 5.9 MeV (a 3 MeV beam is now being developed at LEAR). This is 10 orders of magnitude higher in energy (see Fig. 1.1) than we desire (≈ 0.5 meV) for low energy antiproton physics experiments. The major challenge is to produce ultracold antiprotons from the high energy antiproton beams available from LEAR. Slowing antiprotons by atomic collisions and electron cooling is demonstrated in our experiments to be the solution.

Charged particles lose energy when they pass through matter, in collisions with bound electrons in the degrader which cause electron excitation and ionization. Due to the statistical behavior of such collisions, transmitted antiprotons

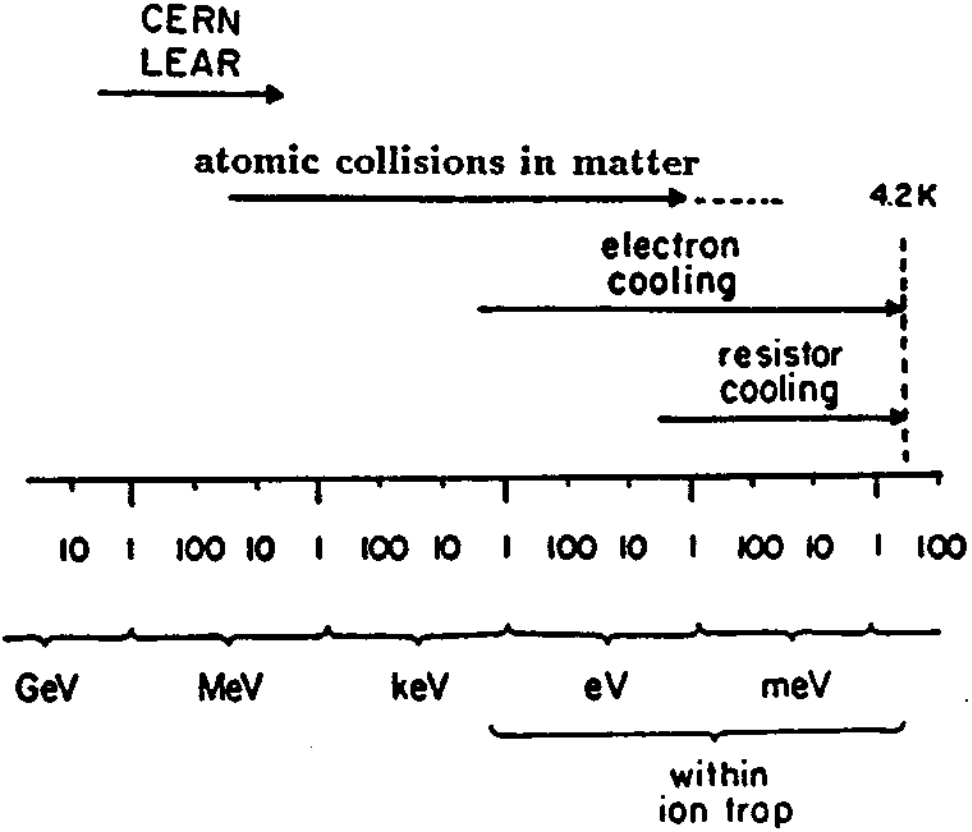

Figure 1.1: The energy span from the LEAR beam energy of about 10 MeV to the energy required for antiproton mass measurements and the methods to slow and cool antiprotons below meV.

have different energies. Only a very small fraction of them are below a few keV even when the degrader thickness is optimized for low energy antiproton yield. Great care must be taken to make the thickness of the degrader as close to the range of the energetic particles as possible. Tests with protons are carried out first due to very precious antiproton beam time. The difference in the range between protons and antiprotons (known as the Barkas effect) must be compensated by adding more material for antiproton experiments.

Our experiment shows that 10^4 to 10^5 antiprotons can be trapped routinely in a 3 keV potential well from one 300 ns pulse of 5.9 MeV antiprotons which contains up to 3×10^8 particles from LEAR [11]. The maximum number of antiprotons trapped from one pulse is 1.3×10^5 antiprotons. It is sufficient to use the degrader technique to slow antiprotons since we only need a modest number of antiprotons to perform some needed experiments. A single antiproton in the trap will eventually be used for the mass measurement. However, more antiprotons are demanded for other experiments.

Antiprotons are initially stored in a long (13 cm) ion trap with energies ranging from 0 eV to 3 keV. If a large number of electrons can be loaded in the center part (approximately 0.5 cm long) of the long trap, antiprotons oscillating through the bound electron cloud will lose kinetic energy the same way as in the material except no annihilations will occur [4]. The electrons rapidly radiate the excess heat from the hot antiprotons via synchrotron radiation. The slowing efficiency for antiprotons is nearly 100%. The slowing process within the ion trap effectively reduces antiproton random energies in 3 dimensions. Therefore it is also a cooling process. This is the first time that electron cooling has been applied in an ion trap.

Fig. 1.1 shows the energy span from the LEAR beam energy of about 10 MeV to below meV. Atomic collisions in matter reduce some particle energies to keV so they can be trapped in an ion trap. Very a few particles have energies less than 100 meV. Further slowing and cooling are accomplished by electron cooling which is very effective and efficient. A thermal equilibrium state can be achieved at 4.2 K. Resistor cooling can damp and maintain the antiproton motions in thermal equilibrium, once most of the antiproton's energy is removed by the electrons.

1.3 Antiproton mass measurement

The antiproton inertial mass $m_{\bar{p}}$ is an important physical quantity. It is of great interest to make increasingly precise measurements of such a basic quantity. High precision measurements of the mass ratio of antiproton to proton also provide experimental verification of the CPT theorem, thus increasing our confidence in this basic symmetry in nature. The CPT theorem states that any quantum field theory described by a local Lorentz-invariant Hermitian Hamiltonian is invariant under the operations of charge conjugation (C), parity inversion (P), and time reversal (T) in any order [13]. The theorem implies that a particle and its antiparticle must have the same magnetic moment (with opposite sign), the same mass, and the same mean life.

When the antiproton was discovered at the University of California at Berkeley in 1955 [14], the new negatively charged particle was identified as the antiproton mainly because it has a mass within 5% of the proton mass. Using an exotic-atom method, the inertial mass of the antiproton was measured to higher precision at the Proton Synchrotron (PS) of CERN [15]. Antiprotons stopped in a thallium target were captured into orbits with high principal quantum numbers. In the antiprotonic atom, the energy eigenvalues are proportional to the reduced mass of the hadron-nucleus system. By measuring the transition energies of X-rays originated from the antiprotonic cascade and making comparisons with the calculated ones, the inertial mass of the antiproton was deduced. Similar experiments were performed at Brookhaven National Laboratory [16,17,18] using various targets. A fractional uncertainty of 5×10^{-5} was achieved in the most accurate measurement and it is consistent with the much better known proton mass (see Fig. 1.2). Due to the complexity of the antiprotonic system, many corrections, such as nuclear finite-size effects, radiative corrections, interactions between the antiproton and higher moments of the nucleus, electron screening, and the anomalous magnetic moment of the antiproton, were needed to obtain the quoted precision.

The lowest energy antiproton beam in a storage ring is on the order of MeV at LEAR of CERN. Further deceleration to meV or below, 10 orders of magnitude lower in energy, can be achieved by inelastic collisions with electrons in degraders and in ion traps. A much more accurate measurement of the antiproton inertial mass becomes feasible with cold antiprotons by well established Penning trap technique once antiprotons are confined in the trap. An ion trap is a device to hold charged particles in the combination of a homogeneous magnetic field and an electrostatic potential. The ion trap technique has been widely used for high precision measurements of fundamental constants and mass comparisons [19,20]. The g factor (representing the magnetic moment of the particle) of the electron has been measured to a fractional uncertainty of 4×10^{-12} [21]. This allows the most precise comparison between theory and experiment for a property of an elementary particle. Its agreement with theory is the most accurate test for Quantum Electrodynamics (QED) theory. Precise measurements of the g factor ratio [21] for electron and positron, with an accuracy of 2×10^{-12}, provide a stringent test of the CPT theorem for leptons. The proton-electron mass ratio previously measured by the ion trap technique [22,23] has an uncertainty of 2×10^{-8}. A mass ratio measurement for single CO^+ and N_2^+ ions with an accuracy of 4×10^{-10} has been reported [20].

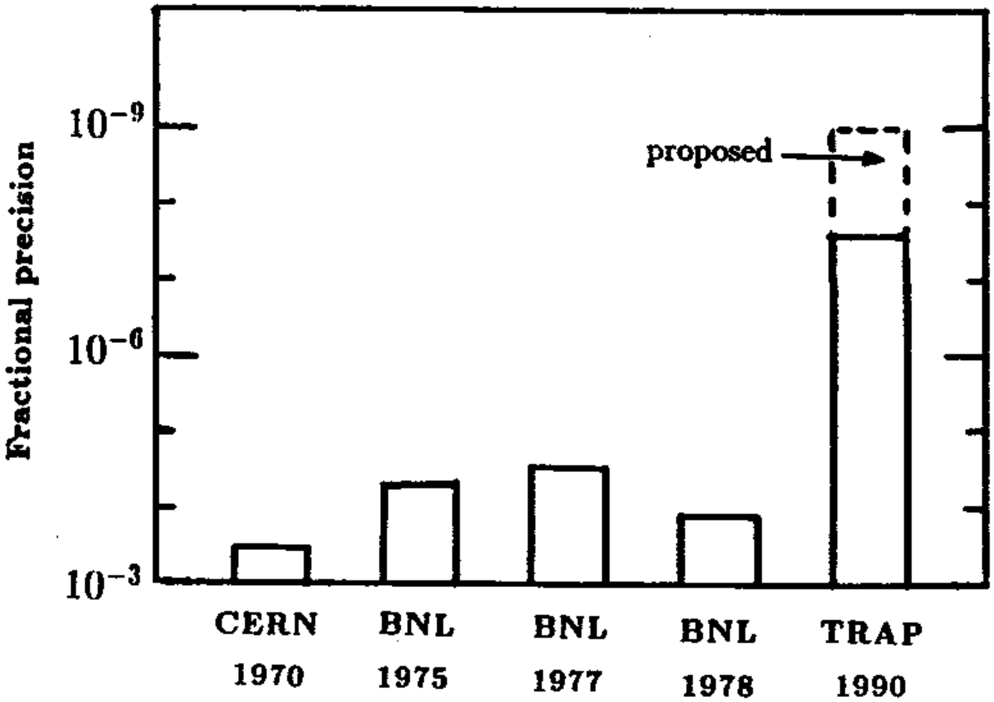

Figure 1.2: The fractional accuracy of antiproton mass measurements by exotic atom methods and by the ion trap technique.

The principle of ion trap mass spectroscopy for ion mass comparison is very simple and elegant. A particle of charge q and mass m in a uniform and stable magnetic field B undergoes a constant circular motion (cyclotron motion) around a magnetic field line with frequency $\omega_c = qB/mc$ with c the speed of light. If a second particle with a different charge and mass is placed in the same magnetic field, the ratio of cyclotron frequencies gives the ratio of charge-to-mass-ratios. If we assume that the proton and antiproton have identical charges, the cyclotron frequency ratio is the inverse mass ratio. Nevertheless, the measurement is actually a comparison of charge-to-mass-ratios.

There are many advantages of using this technique. A conventional FET preamplifier cooled to liquid helium temperature can detect a single particle with a good signal to noise ratio. An excellent resolution of 10^{-10} [19] has been mentioned while 10^{-8} can be routinely obtained. Based on this successful and extremely promising technique, an accuracy of 1 part in 10^9 for the comparison of the antiproton and proton masses was proposed [4,24]. This would be a 50 000-fold improvement in accuracy over previous measurements. Fig. 1.2 shows the fractional accuracy of antiproton mass measurements by exotic atom methods and by the ion trap technique. We have obtained a fractional accuracy of 4×10^{-8} in an ion trap [12,25]. This is already a 1000-fold improvement over previous measurements. The dashed region represents the proposed accuracy. This new measurement of the ratio of antiproton to proton inertial masses by the ion trap resonant method is the most precise test of the CPT theorem with baryons.

1.4 Antiproton lifetime in an ion trap and antiproton-atom (molecule) interaction

Interactions between antiprotons and atoms (or molecules) can be studied by controlled antiproton-atom collisions. The direct antiproton lifetime measurement in an ion trap can probe and indicate an extremely high vacuum beyond the capability of conventional vacuum measurement equipment. An upper limit to the pressure can be established with the knowledge of antiproton-atom cross section.

The measured lower limit of proton lifetime is now above 10^{25} years independent of decay mode [26], though for specific decay modes the lifetime now exceeds 3.1×10^{32} [27]. The CPT theorem thus suggests that the antiproton lifetime is no shorter than 10^{25} years. If baryon number is conserved then there can be no antiproton decay. The speculation that baryon number might not be conserved comes from grand unified theories which unify the strong force with the electroweak force [28,29]. If quarks can become leptons, then a proton (antiproton) might not be absolutely stable. A lower limit of 32 hours was given by a previous direct antiproton lifetime measurement in a storage ring [30], though measurements of specific decay channels yield a lifetime of more than one month [31]. Antiprotons were recently held 11 days at the CERN Antiproton Accumulator, with a particle loss rate corresponding to a storage lifetime of 1.4 months in the rest frame of the energetic antiprotons [32]. We found that the antiproton lifetime in an ion trap was more than 103 days (3.4 months) by trapping a cloud of antiprotons for 59 days (see Chapter 6). This is the best directly measured limit on the antiproton lifetime. The lifetime measurement in an ion trap can also be used for collision studies and vacuum technology development. As discussed in Chapter 6, we use stored antiprotons as a vacuum gauge to measure the residual gas number density and the pressure. The number density is measured to be less than 100 atoms/cm^3. For an ideal gas at 4.2 K, this would correspond to a pressure less than 5×10^{-17} Torr which is the best reported value.

Finally, it has been suggested that measured $\overline{p}/p$ ratios in cosmic rays, together with model calculations of the interaction of cosmic rays and the interstellar medium, may indicate an antiproton lifetime of order the cosmic ray storage time ($\approx 10^7$ years). However, this rather indirect argument has not been studied in any detail, being mentioned in only one sentence [33]. Moreover, the cosmic ray storage time for antiprotons has not been measured to our knowledge.

1.5 Summary

In Chapter 2, the degrader technique used to slow antiprotons will be discussed. Studies include energy distributions of particles passing through a degrader measured by a time-of-flight technique, and the yield of low energy antiprotons at the keV level suited for trapping. It is followed by the observation of the Barkas effect in the range difference between protons and antiprotons. In Chapter 3, we describe the antiproton trapping experiment and discuss the results. In Chapter 4, the high-voltage switching required to capture of keV antiprotons in ion traps are described. Electron cooling as a means of slowing antiprotons until they fall into the harmonic potential well is discussed in Chapter 5. Two important applications of stored antiprotons are presented in the last two chapters. First is the antiproton lifetime measurement in an ion trap and its technical implications in Chapter 6. Second is the antiproton mass measurement at the 4×10^{-8} level in Chapter 7. Other experimental possibilities are discussed in the last chapter.