Chapter 6

Antiproton lifetime and vacuum

6.1 Antiproton lifetime measurement in an ion trap

Our direct antiproton lifetime measurement in an ion trap sets a more stringent antiproton mean life limit than any other direct measurements or any measurements searching for a specific decay mode. It also has important applications in antiproton-gas interaction and as an extreme high vacuum measuring technique. Antiprotons were first trapped in a long trap and then electron-cooled into the harmonic potential well for long time storage after most electrons were ejected as described in Chapter 5. The presence of the antiprotons in the trap was checked daily by non-destructive resonant techniques to see the cyclotron frequency and axial frequency signals so that the magnetic field drift during the 2 months hold time was also monitored. The magnet is persistent when liquid helium in its dewar is sufficient. Batteries were used to hold particles so that the occasional power failures in the experimental area did not result in loss of antiprotons. The battery produced a ring potential of 71.64 V. The battery for compensation electrodes had a potential near 88% V(ring) to keep a harmonic potential well. Actually, the cyclotron frequency was measured when the compensation electrodes were switched to the power supply capable of fine tuning. Then it was switched back to the battery a few minutes later after the measurement was done.

The initial antiproton number is based on the PPAC signal which gives a very conservative upper limit of $N_0 < 1559$ from the load-dump calibration. After a hold time of 58.75 days, a final particle number $N_f = 924$ (of these 42 could be background counts) was measured by ejecting the antiprotons from the trap and detecting annihilation signals in a scintillator detector. Particle loss is caused by annihilations with residual gases in the trap, collision interactions and unexpected heating of the magnetron motion. Thus we have $N_f/N_0 = 882/1559$. This immediately gives the antiproton lifetime in the trap of more than 103 days. The measurement is the best directly measured limit.

An extremely high vacuum limit can be established by the antiproton annihilation vacuum gauge. Based on the existing theories on low energy ion-atom (molecule) interactions and studies of antimatter-matter interactions, we can establish (Sec. 6.3) that the number density of atoms is less than $100/cm^3$ which is independent of the relative velocity. For an ideal gas at 4.2 K this would correspond to a pressure less than 5×10^{-17} Torr.

The long trapping time also demonstrates the stability of the trap for an antiproton cloud. Strictly speaking, the magnetron motion is unstable. However, the estimated time constant of this motion due to the radiation damping is 5×10^{14} years. Imperfections in the trap, the sideband heating drive for the magnetron motion and collisions with residual gas may cause instability and antiproton loss with significantly shorter time constant. This test indicates the possibility of a portable antiproton trap. The long lifetime of the antiprotons in an ion trap demonstrated here shows that particle loss could be insignificant during long shipping and waiting periods of several months.

6.2 Other antiproton lifetime measurements

6.2.1 Proton lifetime measurements

The law of baryon number conservation forbids proton and antiproton decay while CPT theorem requires that the proton and antiproton have the same lifetime. The proton lifetime has been measured to $> 1.6\times10^{25}$ years and this result is independent of decay mode [26]. It was done by analyzing geochemical data on xenon isotopes in a telluride ore and investigating all the possible decay products due to nucleon decay. A much higher limit of $> 3.1\times10^{32}$ years [27] was given for the partial lifetime of the assumed predominant proton decay mode (to positron and neutral pion). This partial lifetime is a factor of 40 longer than the predicted proton decay lower limit by the simplest grand unified theory, minimal SU(5) [28,29].

6.2.2 Direct and indirect antiproton lifetime measurements

The available antiproton lifetime measurements were made by investigating antiprotons in a storage ring, or by measuring the branching ratio for a particular decay mode. In a direct antiproton lifetime measurement, 240 antiprotons were stored in the ICE storage ring at CERN for 85 hours in 1978 [30]. A lower limit of 32 hours (3.7×10^{-3} years) was given. Because this experiment was limited by the beam-gas interactions, a new experiment was set up for looking at an antiproton decaying into an electron and a neutral pion for a partial lifetime measurement at the same storage ring in 1979 [31]. A lower limit was given

$$\tau > BR \times 1700\ h \tag{6.1}$$

at 90% confidence level after antiprotons were stored for 10 days. Here, the branching ratio (BR) can only be given by theories (31 to 46 %) [27]. Usually the limit of 0.08 years (one month) is cited from this experiment. Recently antiprotons were 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].

Based on the cosmic-ray propagation theories, the production of secondary antiprotons through collisions of high-energy cosmic rays with the interstellar medium and a $\overline{p}/p$ ratio is predicted to be of the order 10^{-4} for GeV particles. Consistency between theory and the observed cosmic-ray antiprotons and the $\overline{p}/p$ ratio measurement by using a balloon-borne superconducting-magnet spectrometer inferred that the antiproton lifetime is at least comparable to the cosmic-ray storage time [33] ($\approx 10^7$ years). However, this indirect argument has not been studied carefully in any detail. Moreover, the cosmic ray storage time for antiprotons has not been measured to our knowledge.

6.3 Stored antiprotons as a vacuum gauge

Any residual gas in the trap would cause annihilation of trapped antiprotons. The antiproton decay rate gives not only a lower limit on the antiproton lifetime, but also an upper limit of the neutral atom number density and the pressure. The antiproton cloud is a sensor to probe the density of the gas molecules and atoms in the vacuum chamber.

We expect the pressure in our vacuum container, kept at 4.2 K, to be extremely low. The great advantage of using a cryopump is discussed in Ref. [75]. Properties of cryogenic liquids and vapor pressure data can be found in Ref. [38]. For H_2, the vapor pressure is 10^{-7} Torr at 4.03 K and 10^{-6} Torr at 4.40 K. For helium the vapor pressure is 0.1 Torr even at 1 K. However, we are not limited by these vapor pressures as long as those atoms and molecules do not form more than one monolayer on the metal surface [75].

Since the predominant gases are helium and hydrogen [75] at LHe temperature, we will first discuss the annihilation cross section of hydrogen according to the available literature, then study the antiproton- helium interaction process from a more general principle. The number density of the residual gas is obtained for a given antiproton annihilation rate. The relations between the partial pressure of He and H based on the ideal gas law and antiproton lifetime are derived.

6.3.1 Antiproton-hydrogen interaction

Proton-antihydrogen atom and proton-antihydrogen molecule annihilation cross sections at very low energy in collisions

$$p + \overline{H} \longrightarrow Pn + e^{+}, \tag{6.2}$$

and

$$p + \overline{H}_2 \longrightarrow Pn + e^{+} + (\overline{H} \text{ or } \overline{p} + e^{+}) \tag{6.3}$$

were studied by Morgan and Hughes [76]. Here, Pn is protonium. The cross sections are the same for their charge-conjugate reactions

$$\overline{p} + H \longrightarrow Pn + e^{-}, \tag{6.4}$$

and

$$\overline{p} + H_2 \longrightarrow Pn + e^{-} + (H \text{ or } p + e^{-}) \tag{6.5}$$

The analytic form of the cross section for antiproton-hydrogen atom reaction is given by

$$\sigma(H) = 3.60 \times 10^{5} (c/v_{rel}) \pi r_0^2 \tag{6.6}$$

or

$$\sigma(H) = 1.80 \times 10^5(\sqrt{mc^2/E})\pi r_0^2 \tag{6.7}$$

where v_{rel} is the p-H relative velocity, and $r_0 = 2.82\times10^{-15}$ m is electron classical radius, E = $mv_{rel}^2/4$ is the energy in the center-of-mass system. It is valid when E is between 10^{-5} and 0.1 eV.

In terms of the Bohr radius a_0 instead of the electron classical radius, the same result for the cross section $\sigma(H)$ was rederived by [77] in the form

$$\sigma = 3\pi a_0^2\sqrt{E_0/E} \tag{6.8}$$

where a_0 is the Bohr radius, $E_0 = 27.2$ eV is twice the hydrogen binding energy, and E is the kinetic energy of the antiproton in the center-of-mass system. This is valid for E less than 1 eV. A similar form can also be found in Ref. [78,79]. For E $<<$ 1 eV, the cross section is much larger than the geometrical size of the hydrogen atom (about a_0^2) due to the atomic polarization.

The antiproton annihilation rate is R = $n\sigma v_{rel}$, where n is the number density of the gas. Since the lifetime $\tau = 1/R$, we have

$$n(/cm^3) = 1/(6\pi a_0^2\tau\sqrt{E_0/m}) = 3.72 \times 10^8/\tau(sec), \tag{6.9}$$

or

$$n(/cm^3) = 4.3 \times 10^3/\tau(day). \tag{6.10}$$

The number density of the gas is independent of the collision energy. For $\tau = 103$ days, the hydrogen number density is $42/cm^3$. Using the ideal gas law, the number density at temperature T corresponds to the equilibrium hydrogen partial pressure

$$P_H(Torr) = nkT = 4.45 \times 10^{-16}T(K)/\tau(day). \tag{6.11}$$

The hydrogen pressure is 1.2×10^{-15} Torr at 273 K and is 1.8×10^{-17} Torr for thermal equilibrium at 4.2 K. The distribution of the residual gas is not measured in this experiment. It is likely that the atoms (molecules) are not in Boltzmann distribution.

6.3.2 Antiproton interaction with other gases

Antiproton- helium capture cross section can be understood from general principles. When an antiproton approaches a neutral atom, the electric field of the antiproton $E(\overline{p}) = -e/r^2$ produces an induced electric dipole moment $\alpha E(\overline{p})$ at distance r. Here, α is the electric dipole polarizability of an atom describing the response of the electron cloud to an external electric field. The long-range ion-atom interaction energy is simply given as

$$U(r) = -\alpha E^2(\overline{p})/2 = -e^2\alpha/2r^4 \tag{6.12}$$

The ion-atom capture cross section for this interaction is known as the Langevin cross section:

$$\sigma = 2\pi e\sqrt{\alpha/m_r v_{rel}^2} = 2\pi e\sqrt{\alpha/2E} \tag{6.13}$$

where m_r is the reduced mass of the ion-atom pair, v_{rel} is the relative velocity, and E is the collision energy in center-of-mass system. The number density n = $1/(\tau\sigma v_{rel})$ is proportional to $\sqrt{m_r/\alpha}$ for a given τ. From Ref. [80], we have $\alpha(H) = 0.667 \times 10^{-24} cm^3$, $\alpha(He) = 0.205 \times 10^{-24} cm^3$, and $\alpha(H_2) = 0.802 \times 10^{-24} cm^3$. The reduced mass of the antiproton-atom (or molecule) pairs are m/2 for H, 2m/3 for H_2, and 4m/5 for He, respectively. Therefore n(He) = 2.28n(H), and n(H_2) = 1.05n(H). The He atom number density is $95/cm^3$ for a lifetime of 103 days. If we use the ideal gas law,

$$P_{He}(Torr) = 1.01 \times 10^{-15} T(K)/\tau(day). \tag{6.14}$$

The He pressure is 2.7×10^{-15} Torr for the density of 95 He atoms per cm^3 at 273 K and is 4.1×10^{-17} Torr at 4.2 K.

We have discussed the antiproton-gas interactions without considering the presence of the electric field from the trap electrodes. The collisions in the discussion is only for one antiproton interacting with one atom. Here, we can show that those effects are negligible. The particle kinetic energy is 0.54 meV at 4.2 K. The antiproton velocity at this energy is 3.2×10^2 m/sec. The annihilation cross section for hydrogen is $\pi(26a_0)^2$ and for helium is $\pi(19a_0)^2$. The electric field due to the antiproton point charge at distance $26a_0$ is 7.8×10^8 volt/m. It is much larger than the typical field strength at the center of the trap of 10^3 volt/m. Therefore the effect of the electric field from the trap electrodes is negligible. The effect of an atom interacting with more than one antiproton at the same time is also negligible due to the low antiproton density. The average distance between antiprotons is about 0.02 mm while the interaction distance with an atom is $26a_0 = 10^{-6}$ mm.

Because the Langevin capture cross section is valid for ion-atom interaction, one can also use stripped ions as a vacuum gauge. The capture cross section is proportional to the electric charge number Z and $\sqrt{\alpha/m_r}$. For example, when fully stripped carbon ion interacts with a He atom with $Z = 6$ and the reduced mass $m_r = 3$ atomic mass unit (amu), the interaction rate is approximately 3.1 times more than the antiproton-He reaction where $Z = 1$ and $m_r = 0.8$ amu. Trapping fully stripped carbon ions are much easier than trapping antiprotons which rely on the complex accelerators. Thus it is better than using antiprotons as a vacuum gauge.

6.3.3 Vacuum system and cryopump

The vacuum chamber that houses the ion trap is in the bore at the center of the magnet as shown in Chapter 3. The bore has a vacuum of 10^{-5} Torr when cooled to liquid nitrogen temperature. The pressure is below 10^{-6} Torr when the liquid helium dewar attached to the trap enclosure is cooled to liquid helium temperature. Since gas diffusion through cold material is eliminated, only the joints for different parts are potential leaking locations. There are several types of seals to separate the extreme high vacuum from the bore pressure. They are a glass-metal seal, silver hard solder to seal feedthroughs with the copper, electron beam welding to join Ti foil to Ti rings which is then to copper, and an indium-squeezing seal. All of them worked and ensured the long lifetime of antiprotons in ion trap.

Thompson and Hanrahan [75] used a quadrapole mass analyzer to measure the partial pressures from 300 to 30 K and found that hydrogen and helium pressures are below 10^{-14} Torr at 30 K while other gases are frozen out near 77 K. A completely pre-pumped sealed-off vacuum chamber cooled at 4.2 K provides an extreme high vacuum environment by cryopumping because the outgassing within the vacuum chamber can be eliminated by cooling the gases below the desorption activation energy if the gases form less than one monolayer on the inner surface of the chamber.

We can estimate the pressure at room temperature corresponding to a monolayer coverage when the apparatus is cooled to 4.2 K. The cold surface within the vacuum chamber is about 0.1 m^2. We assume each particle occupies $3\text{Å}\times 3\text{Å}= 9\times 10^{-20} m^2$. That means approximately 10^{18} particles are needed to form a monolayer. At room temperature for a volume of 1 litre in the chamber, 10^{18} particles correspond to a vacuum pressure of 10^{-5} atm (0.01 Torr). The density of 6×10^{23} particles in 22.4 litres is used here. Based on this estimate, we need to obtain 0.01 Torr before sealing at room temperature by rough pumping the chamber to reduce the amount of hydrogen and helium so that there is no more than a monolayer coverage of the surfaces at low temperature. This pressure is very easy to achieve. We should note that there is only a small fraction of helium (5×10^{-6}) and hydrogen (5×10^{-7}) gas in the air at 1 atm. Even without rough pumping, helium or hydrogen from the air would not be able to form a monolayer. In reality, there is much more helium gas in the trap can before rough pumping since liquid helium and helium gas are used in the laboratory. Therefore in practice, the vacuum chamber is carefully pumped and leak checked, then baked to 120^0C with a typical pressure of 10^{-6} Torr or less. After the system cools down to room temperature, the partial pressure reaches about 2×10^{-7} Torr for hydrogen measured by a mass analyzer before sealing. The helium pressure is on the order of 10^{-9} Torr as measured by a mass analyzer. Thus, the residual atoms and molecules are far less than the numbers needed to form a monolayer.

The He mean path length ($1/n\sigma$) at 4.2 K is around 3×10^6 km which is much larger than the size of the apparatus, an indication of ultrahigh vacuum. The vacuum pressure reported here ($< 5 \times 10^{-17}$ Torr at 4.2 K when the ideal gas law is applied) is the best reported value. It is consistent with the previous vacuum pressure measurement ($< 10^{-14}$ Torr at 30 K) using a quadrapole mass analyzer [75].