Positrons for Low Energy Antihydrogen Production

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Based upon the capture of low energy antiprotons in an ion trap, we are investigating the possibility of producing antihydrogen by merging extremely cold trapped plasmas of antiprotons and positrons. In principle, the calculated rate for antihydrogen is very high compared to other techniques. Here we survey the possibility of accumulating a high density of trapped positrons.

I. INTRODUCTION

Antiprotons were recently captured within the small volume ($\approx$ 10 cm^3) of an ion trap by the TRAP Collaboration.[1] They were decelerated from GeV production energies down to 21 MeV within the LEAR facility of CERN, passed through approximately 3 mm of beryllium to slow them below 3 keV,

and caught in an ion trap for as long as 10 minutes. While this is a much shorter time than the 10 month confinement of a single electron in a Penning ion trap,[2] prospects are now excellent for holding antiprotons much longer under improved vacuum conditions.

An interesting possibility raised by the capture of antiprotons in an ion trap is that of producing antihydrogen in this environment. Separately trapped plasmas of electrons and protons are routinely studied at 4.2 K, with lower temperatures possible. Recently we have considered the antihydrogen production that would result from merging such plasmas.[3] In equilibrium at 4.2 K, merging 10^4 antiprotons with positrons at a density of $10^7/cm^3$ would yield an instantaneous antihydrogen production rate exceeding $10^6/sec$. This calculated rate is orders of magnitude higher than either the projected rate for merged beams of antiprotons and positrons in a storage ring[4,5] or for collisions between a positronium beam and trapped antiprotons.[6]

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With antihydrogen in thermal equilibrium below 4.2 K, intriguing experimental possibilities can be considered. It becomes energetically possible to confine the antihydrogen, because of its magnetic moment, in a minimum of a magnetic field as has been done with sodium atoms.[7] Since we began exploring this difficult scenario,[8] spin polarized hydrogen atoms at 0.04 K have also been confined this way.[9] A deeper well may be required than has been used so far to confine atoms (a 1.5 Tesla well is needed to trap antihydrogen at 1 K, for example). The coldest atoms in the thermal distribution can of course be caught in a shallower well. In fact, a trap environment is now considered to be most promising for more precise laser spectroscopy of hydrogen atoms.[10] Comparisons of the fine and hyperfine structure of hydrogen and antihydrogen would provide extremely precise tests of CPT. If the antihydrogen atoms are confined, even a weak, monochromatic Ly α source may be useful for further cooling. With low enough atom temperatures, the gravitational force on antihydrogen can be measured since this force shifts the location of the atoms within the trap.[11] Experimental probes of gravitation are scarce and there is current theoretical interest in possible scalar and vector contributions to gravity which would cancel for matter but not for antimatter.[12]

Only small numbers of positrons have been trapped and sutdied while a single component plasma of trapped electrons has been studied extensively.[13] The problem is that positrons are much more difficult to obtain and are necessarily produced outside of the trapping well. If they have sufficient energy to enter the trap, they have sufficient energy to get out as well, so they must lose energy while within the trap to be captured. A technique developed at the University of Washington is to damp positrons within a harmonic Penning trap by coupling the motions to a resonant tuned circuit which is cold.[14] The time available for damping is increased substantially by introducing the positrons off the center axis of the Penning trap, so that damping can occur over a complete orbit $E \times B$ drift motion. Up to 100 positrons were so trapped[15] directly into an ultra-high vacuum environment in which they could be stored indefinitely (months) and used for high precision experiments. Despite the small number, the density was of order $10^8/cm^3$.

In two experiments at Bell Laboratories,[16,17] positrons were damped within a trapping well via collisions with a background gas introduced into the trap for this purpose. In the first experment,[16] of order 100 positrons were trapped at one time and trapping times were very short, of order 30$msec$. The eventual aim of the second of these experiments[17] is to produce trapped positron densities of $10^6/cm^3$, somewhat less than what is discussed here. In addition, the trap volume used is larger by more than 1,000 than what is discussed here. This requires accumulating 1,000 times as many positrons to get the same density. Also, there is no provision for cooling to lower temperatures or for getting rid of the background gas, as may be required for antihydrogen production, unless heroic differential pumping is employed and/or the positrons are reaccelerated through a window into a trap in high vacuum. This experiment is progressing nicely, but only has preliminary results at this time.

Our approach, which may lead to a significant increase in the density and number of trapped positrons, makes use of a harmonic Penning trap in a high magnetic field field (6 Tesla). We plan to increase the positron loading rate by 10^3 or more over previous positron trapping efforts at UW, by using modern positron moderator techniques[18,19,20]. (Sec. II). Most of this factor comes from the greatly improved damping which is possible with non-relativistic positrons. The use of a moderator and carefully designed shielding will allow a 100-fold increase in source intensity to a 100 mCi ^{22}Na source which is commercially available. Together, these measures should increase the number of positrons available for trapping by 10^5. We will initially use resistor damping of the positrons within a harmonic Penning trap.[21] (Sec. III). The use of a harmonic trap will allow us to use powerful, radiofrequency diagnostics. The initial studies will thus focus upon highest possible densities in relatively small volumes. Already, this should produce a density and number of trapped positrons such that a plasma description is clearly appropriate (Sec. IV). It is not immediately clear that plasma studies with positrons offer any advantages over such studies with electrons. A possible exception is that a plasma of positrons offers some interesting detection properties compared to electrons (Sec. V). The mentioned techniques for capturing positrons and our efforts to increase the number of trapped positrons all allow positrons to be loaded continuously, thus being matched to the continuous positron emission from a radiative source. With a pulsed positron source, positrons could be alternatively loaded into a trap which is pulsed open and closed, as was done to load pulses of antiprotons into a trap[1]. This is certainly possible[22]. A LINAC could be used[23] or positrons from a radioactive source could be bunched and stacked in an ion trap. We are investigating these possibilities. So far, it seems best to start with the simpler, continuous technique. The more complicated options can be pursued if necessary (Sec. VI.).

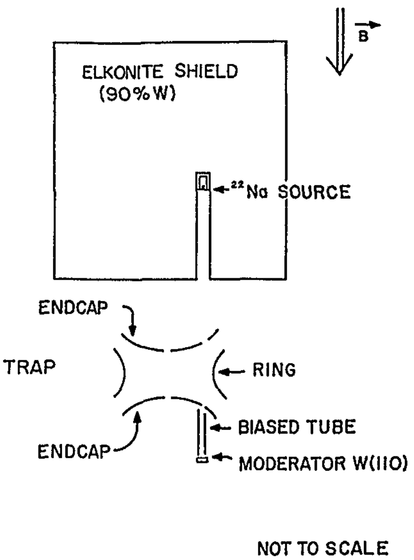
If sufficient positrons can be confined, studies of particle transport within the plasma, etc., similar to those conducted with electrons can be carried out. It may be possible to use the enhanced detection possibilities afforded since positron-electron annihilations can be detected. An ultra-cold source of positrons would also have a variety of other applications.[24] For example, it has been proposed to eject trapped positrons into a plasma as a diagnostic.[25] Also, positrons initially in thermal equilibrium at $4.2K$ within a trap would form a pulsed positron beam of high "brightness" when accelerated out of the trap.

II. Moderated Source

An unmoderated, 1 mCi source of ^{22}Na was used in the UW experiments. The positrons vary in total kinetic energy between 0 and 544 keV and travel along magnetic field lines into the trap. Positrons available for trapping are those whose kinetic energy parallel to the magnetic field is within a 1 meV window. Approximately 6×10^{-5} of the emitted positrons were estimated to be within this window.[26]

We will instead send the positrons into a moderator, for example, a single crystal of tungsten. Many of the positrons will thermalize before annihilating. Of order 10^{-3} will be desorbed from the moderator, ejected by the negative positron work function.[27] The moderator will be in a strong magnetic field which may enhance the efficiency over what has been observed. At 6 Tesla, the ejected positions will essentially be in a beam whose cross sectional area is the size of the illuminated area of the moderator. The moderated positrons are nearly monoenergetic with a very narrow energy width, depending upon the moderator material and its preparation and cleaniness. With a single crystal of tungsten cooled to 20 K, a width less than 65 meV has been observed.[28] Since we will work at 4.2 K, the width may be even narrower. The surface will be carefully cleaned by electron bombardment heating to help reduce surface oxidation that can increase the energy spread of the positrons to a few eV. We thus expect an efficiency comparable to that achieved in the UW experiment in a 1 meV trapping window. The difference is that the moderated

FIGURE 1



positrons will be nonrelativistic. We shall see that this has important consequences for damping and capturing the positrons.

The use of a moderator will also allow us to locate the positron source far enough from the trap to allow adequate shielding and minimze the effects of the decay gammas so that we will be able to use a 100 mCi source of ^{22}Na. This is a 10^2 increase compared to the UW experiment. A possible geometry of the source, traps and moderator is illustrated in Fig. 1.

III. Damping in a Harmonic Trap

We will first accumulate positrons in a harmonic Penning trap. A harmonic Penning trap is composed of electrodes which produce an electric quadrupole potential superimposed upon a uniform magnetic field.[21] The reason for this choice is that both single particle and center of mass motions are easily characterized and well understood in a harmonic Penning trap. In addition, well established radiofrequency techniques can be used as diagnostics, to nondestructively determine the number of particles for example, and for cooling. Once the difficulties of loading large numbers of positrons into a trap are understood and solved, it may then be possible to shift to the long, non-harmonic traps used for previous plasma experiments.[29]

The basic loading scheme was used in an earlier experiment, but made much more efficient by the low energy moderated positrons. Positrons are sent into the trap along a field line of a 6 Tesla magnetic field which makes focussing lenses, etc. unnecessary. The cyclotron radius of a 1 keV positron in a 6 Tesla field is only $15\mu m$. Positrons lose energy by inducing a current in a cold resistor to which they are coupled. The positrons must lose energy quickly or they will retain enough energy to escape along the path upon which they entered the trap. To make this time as long as possible, the positrons are introduced off the center axis of the trap. If a positron avoids leaving the trap after only one oscillation back and forth along a magnetic field line (by careful control of a bump in the trapping potential), further escape is thereby made impossible until the positrons complete an entire magnetron orbit. This orbit is caused by $E \times B$ drift within the trap. The time allowed for damping is thereby made of order 6,000 times longer for our parameters. Positrons will be cooled to the center axis via sideband cooling.

As mentioned, only positrons with kinetic energy along the magnetic field within a 1 meV window can possibly be trapped. In the UW experiment, most of the kinetic energy of such positrons was in the cyclotron motion. The high kinetic energies made a large shift in the "relativistic mass" of the positrons. The axial oscillation frequency, for the oscillation back and force along the magnetic field, depends upon the mass and is thus significantly shifted. The positrons within the 1 meV window thus oscillate with a large range of axial frequencies.

For the positrons to be trapped, the axial oscillation must be coupled to a cold resistor to lose energy. The cold resistor is actually part of a tuned circuit, required to tune out the effect of the unavoidable capacitance between trap electrodes. To get a high resistance, a high Q tuned circuit is required. The result in the UW experiment is that only 3×10^{-3} of the positrons in the 1 meV window have the right axial frequency to be damped via coupling to the resistor in the tuned circuit. With moderated positrons, however, the relativistic mass shift is completely negligible. This is an important advantage insofar as all of the positrons in the 1 meV window can be damped, giving an increase in efficiency of order 3×10^2. With the factor of 10^2 for increased source intensity, this suggests a positron loading rate higher by 3×10^4. We are optimistic that our use of lower temperatures and higher fields will allow us to actually realize a rate of loading positron which is thus larger than for the earlier experiment by 10^5.

Since previously up to 100 positrons were collected, an increase of 10^5 in loading rate suggests that at least 10^7 positrons could be collected in comparable times. Higher numbers may be possible in the future. Densities of $10^8/cm^3$ or more can be expected with reasonable trapping potentials. Long trapping times have been demonstrated so that it may be possible to collect positrons over longer times. In addition, since the point of these experiments is to accumulate large numbers of positrons rather than do precision measurements, further improvements seem likely with higher Q tuned circuits, higher trapping potentials, etc. It may even be possible to coherently bunch and inject the positrons as has been done with ions in a radiofrequency trap.[30]

The challenge of these experiments is to demonstrate that this loading scheme can be scaled up without introducing new problems. It is reassuring to note that the particles are loaded into the trap far off the center axis, where densities are low enough so that plasma effects should not be important during loading. They are then cooled to the center of the trap where a plasma is eventually formed. We are therefore optimistic that we can initially obtain more than 10^7 positrons at densities of order $10^9/cm^3$, with larger numbers available in the future.

IV. The Single Component Plasma of Positrons

Although our primary goal is to produce sufficient positrons for antihydrogen production, it is useful to examine the plasma that will be formed and to see if trapped positrons may also be useful for plasma studies. A single component plasma can be confined within a trap. As with two component plasmas, the Debye length

$$\lambda_D = \sqrt{\frac{kT}{4\pi n e^2}} \tag{1}$$

is a crucial parameter, where n is the number density of particles with charge e at temperature T. The minimal condition for collective plasma behavior is that λ_D be much less than a dimension of the trapped cloud of particles, D,

$$\lambda_D << D. \tag{2}$$

If we define the cloud dimension D such that the cloud occupies a volume D^3, then the total number of trapped particles N is related to the number density n by

$$nD^3 = N \tag{3}$$

The minimal condition for a trapped plasma may thus be written as

$$n\lambda_D^3 << N. \tag{4}$$

The total number of particles must be much greater than the number in a Debye volume, λ_D^3.

Properties of the plasma are often characterized by expansions in $(n\lambda_D^3)^{-1}$. Figure 2 shows $n\lambda_D^3$ plotted versus number densities for various plasma temperatures, T. The upper region in the figure, above the dashed line for $n\lambda_D^3 = 1$, is the classical plasma region, characterized by

$$n\lambda_D^3 >> 1 \tag{5}$$

This is the region where more than one particle is in a Debye volume λ_D^3, and expansions to lowest order in $(n\lambda_D^3)^{-1}$ are useful. A goal of one of the Bell experiments with positrons[17]

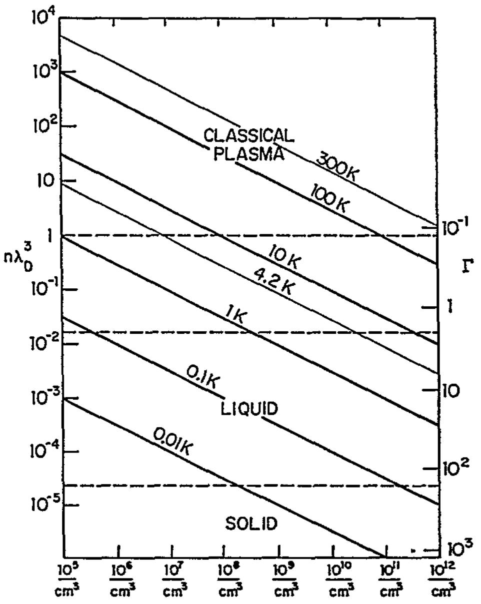


FIGURE 2

is to eventually get $n = 10^6/cm^3$ at $T \approx 300K$. This is is well within the the classical plasma region.

Below $n\lambda_D^3 = 1$ the plasma becomes increasingly correlated. In this region the plasma behavior is often equivalently characterized by the ratio Γ of the average Coulomb energy between particles, $e^2/n^{-1/3}$, to the thermal energy kT. Specifically, Γ is defined as

$$\Gamma = (\frac{4\pi}{3})^{1/3} \frac{e^2/n^{-1/3}}{kT} \tag{6}$$

where the constants are a convention. In terms of $n\lambda_D^3$,

$$\Gamma = [\frac{1}{4\pi\sqrt{3}}]^{2/3} [\frac{1}{n\lambda_D^3}]^{2/3}$$
$$\approx 0.128(n\lambda_D^3)^{-2/3} \tag{7}$$

Increasing Γ represents increasing correlation. The onset of liquid behavior[31] is expected at $\Gamma \sim 2$ while crystalization to form a solid[32] is expected at $\Gamma \sim 155$. In Fig. 2, the equivalent scale for Γ is indicated on the right. The liquid and solid regions are the the indicated regions between the dashed lines.

Experiments with trapped a "cryogenic plasma" of electrons at temperatures as low as 50K and densities as high as $10^{10}/cm^3$ have begun to probe plasma behavior below the classical plasma region in Fig. 2. Experiments with laser-cooled trapped ions have been underway to probe the liquid region.[33] Very recently crystalization was observed with only a few ions[34,35] and with more than 100 ions.[36] A very nice feature of the measurements is that one can learn the positions of shells of ions and even individual ions by imaging the fluorescence from the ions. A numerical simulation produced crystalization very similar to what was observed.[37]

In our initial experiments with trapped positrons, if we achieve densities of order $n = 10^8/cm^3$ with $N = 10^7$ positrons in the trap at T = 4.2 K, we will clearly have a plasma in the sense of Eqs. (2) and (4). The Debye length will be much smaller than the dimension of the positron cloud. Correlations will be important since $\Gamma \sim 0.3$. This may make it possible, for example, to study particle transport for a plasma with $n\lambda_D^3 \approx 1$. To produce a classical plasma for study, the positrons can easily be heated using radiofrequency drives. The range of accessible $n\lambda_0^3$ for positrons in the initial stage of these experiments is shown by the cross hatched region in Fig. 2.

Finally, it may be possible to lower the plasma temperature below 4.2 K. The temperature of 4.2 K is only a choice of convenience, being the boiling point of liquid ^4He at atmospheric pressure. By pumping on the ^4He, or pumping on a dewar with ^3He in it, or by using a dilution refrigerator, it should be possible to probe the liquid and even solid behavior of the highly correlated plasmas. The question here is whether one can develop tools for probing the liquid and solid regime as powerful as the optical techniques available for trapped ion experiments? This remains to be seen.

V. Detection of Positron Annihilations

One unique feature of a plasma of positrons (compared to an electron plasma) is that position annihilation can be detected in detectors placed outside the vacuum system of the trap. Each direct annihilation results in a pair of back-to-back gamma rays. With appropriately designed apparatus, it may be possible to identify the position or vertex of the annihilation and thus learn where and when losses are occurring. Detection of annihilation gammas can produce an extremely clean signal, with exceedingly low background.

To illustrate the detection, we consider positrons annihilating at a point. We assume that two 7.5 cm diameter sodium iodide detectors can be located 13 cm away to either side of the trap, outside a copper vacuum system 0.5 cm thick. The photopeak efficiency for 511 keV annihilation, including geometry and scattering, is 2×10^{-2} for a single detector and 5×10^{-3} for coincident pair annihilation. More pairs or larger detectors could, of course, be used as space permits. To determine the verticle position of the initial annihilation to within a centimeter, it is necessary to mask off part of each detector. With a 0.5 cm slit collimator, the efficiency would be 4×10^{-4} and 10^{-4} for single and coincident detector efficiencies. The spacial resolution would be 0.4 cm full width at one-tenth maximum.

We will not immediately rely on annihilation detection, since initial experiments will be carried out inside an existing superconducting magnet. This means that the detectors must be located 45 cm from the annihilation region, thus reducing the solid angle by a factor of 10. In addition, the magnet windings and dewar effectively present 5 cm of copper and 5 cm of aluminum through which the gamma rays must pass, thus reducing by a factor of 200 the probability that an annihilation gamma will be detected. For the two detectors in the illustration, this reduces the detection efficiency to 2×10^{-5} for detection of one of the gammas and to 7×10^{-7} for detection of coincident gammas.

Radiofrequency detection is thus a much more effective diagnostic for the initial experiments in existing magnets. In the future, however, we are interested in a magnet which is specially designed to get the detectors very close to the trap. Then detection of annihilations could be very useful. Meanwhile, we estimate that the detection of annihilation gammas will be useful initially for steering the positrons from the ^{22}Na source into the moderator and into the trap region. We will assemble the detectors needed for this purpose. The detection system and experience we acquire will make us ready for a new magnet system at a later date, if this proves to be advantageous.

VI. Pulsed Positron Sources

Discussion so far has been upon continuous loading of positrons into a trap. This is because positrons are ejected continuously from radioactive sources. Such continuous loading of positrons is, in fact, a way of bunching the positrons since all of the positrons in the trap can be ejected in a very small pulse.

On the other hand, if a pulsed source of positrons was available, pulses of positrons could be loaded into a trap much differently, the way we loaded pulses of antiprotons into a trap, for example.[1] The positrons could enter the trap electrodes through one electrode which is grounded to allow entry. While the positrons are inside, the potential on this electrode would be quickly changed to prevent their escape. This is manageable for moderated $\approx 1eV$ positron beams.

An appropriate pulsed source exists. An electron LINAC has produced[38] 4×10^6 positrons in a $3\mu sec$ pulse with a repetition rate of 300 Hz and has produced 4×10^5 positrons in a 1 ns pulse with a 1.4 kHz repetition rate. An order of magnitude increase in intensity may be possible.[39] Bell Labs presently has a microtron based beam producing moderated positrons at a rate of 5×10^4 e^+ per pulse,[40] with large intensity increases expected.

The obvious drawback to this approach is that an electron LINAC (or comparable accelerator) is a fairly major facility which does not easily fit in our laboratory. We may attempt some experiments, nonetheless, at an appropriate facility, but initially it seems appropriate to get more experience with higher density positrons plasmas using more modest and manageable sources. Moreover, even though the LEAR facility at CERN (where we trap antiprotons) does have a LINAC, it is not very easy to get positrons and antiprotons from two very substantial and separate facilities to the same point.

Another possibility is to efficiently bunch the positrons from a radioactive source in a first apparatus, then transport the positrons into a trap apparatus where they are loaded. A bunched positron source has been made[24] but the efficiency of loading a positron from the source into a bunch was only 4×10^{-2}. Up to 100 positrons were in each 7 ns bunch, with a repetition rate of 1 KHz. We believe that intense bunched positron sources could be built. For initial experiments, however, it seems desireable to avoid separating the experiment into two regions, for separately bunching and loading the positron, making it necessary to transport the intense bunch of positrons into a high field region between. Our initial experiments will take place within a 6 Tesla field which effectively guides the positrons without need for lenses, etc. normally required.

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