Cold Antimatter Plasmas, and Aspirations for Cold Antihydrogen

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Abstract. Only our ATRAP Collaboration is yet able to accumulate and store 4.2 K antiprotons and positrons. The antiprotons come initially from the new Antiproton Decelerator facility at CERN. Good control of such cold antimatter plasmas is key to aspirations to produce and study antihydrogen atoms that are cold enough to confine by their magnetic moments. In the closest approach to cold antihydrogen realized to date, the cold positrons have been used to cool antiprotons, the first time that positron cooling has ever been observed. The Penning-Ioffe trap, one possibility for simultaneously confining antihydrogen and the cold ingredients from which it is formed, is introduced and discussed.

INTRODUCTION

Cold antiproton plasmas are required to make cold antihydrogen. A recent review [1] recounts the TRAP Collaboration's development and demonstration of slowing, trapping and electron-cooling antiprotons to thermal equilibrium at 4.2 K – an energy that is reduced by more than a factor of 10^{10} compared to the lowest energy antiprotons realize previously (Fig. 1). The slowed and cooled antiprotons reside within a small volume (of order mm^3) of an ion trap in a nearly perfect vacuum, better than 5×10^{-17} Torr. Their average kinetic energy is so low, less than 1 meV, that temperature units are often used. The energy "thermometer" of Fig. 1 represents the energy of antiprotons and protons in various giant storage rings at the top, with the lowest storage ring energies (for LEAR and the AD) near the middle. Towards the bottom, 10^{10} times lower in energy than has been realized in the lowest energy storage rings, is the new low energy frontier at only 4 degrees above absolute zero (4 K). Even lower antiproton temperatures should be possible as illustrated by the 70 mK temperatures some of us recently realized with trapped electrons [2].

In a series of three charge-to-mass ratio measurements, TRAP compared the cyclotron frequencies of an antiproton and a proton. Fig. 2 shows comparisons of the antiproton and proton as they improved in time, starting with the first observation of the antiproton. The final TRAP comparison, to 9 parts in 10^{11}, is the most accurate comparison of any baryon and antibaryon by almost a factor of

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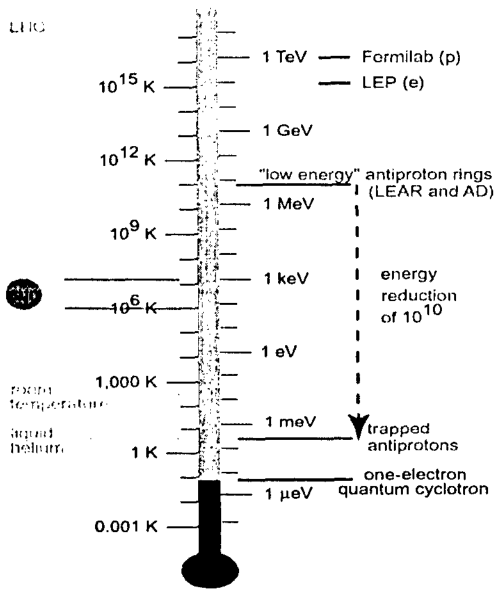

FIGURE 1. Particle energies

a million. An improved baryon CPT test (e.g. involving cold antihydrogen as we will discuss) should arguably improve upon this accuracy.

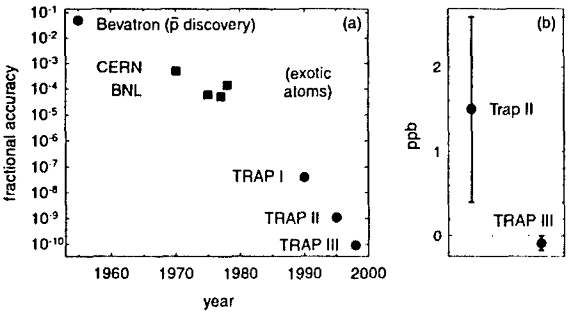

FIGURE 2. (a) Accuracy in comparisons of $\bar{p}$ and p. (b) The measured difference between $|q/m|$ for $\bar{p}$ and p (TRAP III) is improved more than ten-fold.

The TRAP techniques mentioned are being used by all three collaborations using CERN's new Antiproton Decelerator (AD). The AD delivers far fewer antiprotons per pulse of antiprotons sent to experiments than did its predecessor LEAR. However, the AD pulses come more often. Using the stacking techniques developed and demonstrated by TRAP, the experiments are left to accumulate as many antiprotons in a Penning trap as are desired. It is much less expensive to accumulate antiprotons in a small trap than in much larger storage rings.

QUEST FOR COLD ANTIHYDROGEN

Now TRAP has expanded to become ATRAP, and our goal is to produce and study cold antihydrogen atoms. As enunciated shortly after antiprotons were first trapped, the most attractive approach "would be to capture the antihydrogen in a neutral particle trap ... The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time" [3]. As discussed in the next section, we believe that the laser spectroscopy of cold, trapped antihydrogen may yield even more precise tests of CPT invariance with baryons and leptons than have been realized so far.

The pursuit of cold antihydrogen thus began some time ago, long before others of us observed a few antihydrogen atoms traveling at nearly the speed of light [4], revealing great public interest in antimatter atoms. Unlike the extremely energetic antihydrogen, cold antihydrogen that can be confined in a magnetic trap for highly accurate laser spectroscopy offers the possibility of comparisons of antihydrogen and hydrogen at an important level of accuracy (Fig. 4). Interesting gravitational measurements can also be contemplated [5] since the antimatter atom is electrically neutral and hence somewhat insensitive to electric and magnetic forces.

Not only ATRAP is now pursuing cold antihydrogen. The competing ATHENA Collaboration has similar goals, and is using the techniques for accumulating cold antiprotons discussed above. The third collaboration working at the Antiproton Decelerator, ASACUSA, is not pursuing antihydrogen. However, they too have recently started to use the same techniques for trapping and cooling antiprotons.

SEEKING MORE STRINGENT CPT TESTS

Experimental tests have made physicists abandon earlier mistaken but widely held assumptions about fundamental symmetries – first, that reality is invariant under parity transformations (P) and then, that reality is invariant under CP transformations, where C stands for charge conjugation. The current assumption, that reality is invariant under CPT transformations with T indicating a time reversal operation, is based in large part upon the success of quantum field theories. These are invariant under CPT as long as reasonable assumptions (like causality, locality and Lorentz invariance) are made. Of course, this argument is not complete since gravity has not yet been fit into a quantum field theory. Theoretical investigations of possible CPT violations are thus now beginning to appear in the context of string theory [6, 7]. A theoretical model of possible Lorentz invariance violating extensions to the standard model [8] now allows quantitative comparisons of existing CPT tests and possible antihydrogen measurements.

Whether reality is invariant under CPT transformations is in the end an experimental question, and is one important motivation for experiments which compare either antiprotons and protons, or antihydrogen and hydrogen. A reasonable requirement for any new test is that it eventually be more stringent than existing tests with leptons and baryons (Table 1). Here the accuracy of the CPT test must

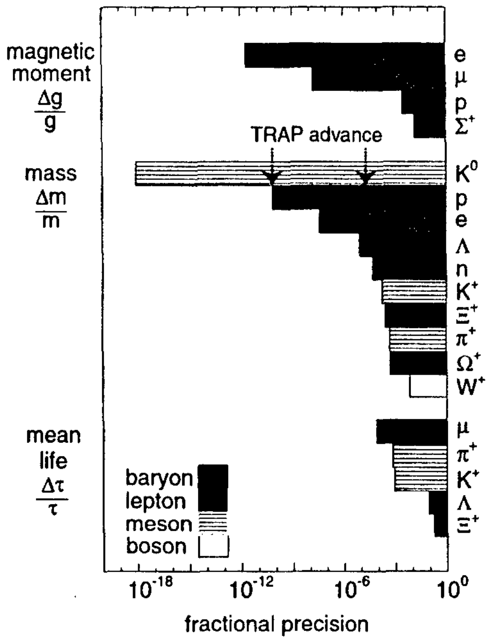

FIGURE 3. Tests of CPT Invariance (taken primarily from the Review of Particle Properties by the Particle Data Group). The particle-antiparticle pair is identified on the right. The shading indicates which species of particles (leptons, mesons or baryons) are involved in the test. The accuracy achieved in the comparison is indicated below. Charge-to-mass ratio comparisons are included in "mass" measurements.

be distinguished from the accuracy with which the relevant physical quantity must be measured since these can be very different. The most accurate baryon CPT test is the 9×10^{-11} (0.09 ppb) comparison of the charge-to-mass ratios of the antiproton and proton that some of us carried out [9] after developing the techniques to obtain 4 K antiprotons. For this measurement, as for the proposed antihydrogen/hydrogen comparison, the CPT test accuracy is the same as the measurement accuracy, requiring extremely accurate measurements.

Current CPT tests with leptons and mesons involve free enhancement factors that make the accuracy of the CPT test substantially greater than the corresponding accuracy needed in a measured quantity. The most accurate lepton CPT test is a 2×10^{-9} comparison of measured magnetic moment anomalies of electron and positron [10], interpreted as a comparison of magnetic moments at 2×10^{-12}. A meson CPT test is even more precise [11]. The delicately balanced nature of the unique kaon system makes it possible to interpret a measurement at an accuracy of only 2×10^{-3} as a comparison of the masses of the K_0 and $\bar{K}_0$ to an impressive 2×10^{-18}. (A recent theoretical speculation [6] suggests that quantum gravity could produce a CPT violation which is smaller by only a factor of 10.) The three most accurate tests of CPT invariance are represented in Table 1, and a summary of the

CPT tests listed by the Particle Data Group is in Fig. 3.

TABLE 1. Comparing the Accurate CPT Tests for the Three Species of Particles

	CPT Test Accuracy	Measurement Accuracy	Enhancement Factor
Mesons ($K_0\bar{K}_0$)	2×10^{-18}	2×10^{-3}	10^{15}
Leptons (e^+e^-)	2×10^{-12}	2×10^{-9}	10^{3}
Baryons ($p\bar{p}$)	9×10^{-11}	9×10^{-11}	1

In principle, the comparisons of antihydrogen and hydrogen could make possible a CPT test at the meson precision. We label this the "antihydrogen dream" in Fig. 4. The 1s-2s transition has an extremely narrow fractional linewidth of only 5×10^{-16}. With a measurement signal-to-noise ratio of 200, line splitting by this factor would allow a comparison at the kaon precision. There are serious obstacles to attaining this extremely high precision, including a 2.4 mK laser cooling limit, a second order Doppler shift, and possible Zeeman shifts depending on the configuration of the magnetic trap. Nonetheless, even a measurement at an accuracy of 10^{-13}, the level at which the difficulties mentioned seem manageable in the first traps [12], would give a substantially improved CPT test involving leptons and baryons.

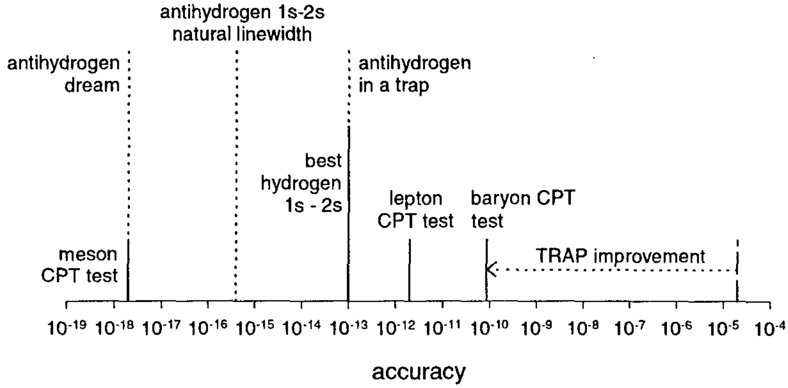

FIGURE 4. Accuracies for the precise 1s - 2s spectroscopy of antihydrogen are compared to the most stringent tests of CPT invariance carried out with mesons, leptons and baryons.

The most precise laser spectroscopy of hydrogen attained so far was obtained with a cold hydrogen beam by one group in our ATRAP collaboration [13]. The narrowest observed width is still much wider than the natural linewidth, but we expect that steady and substantial improvements in accuracy will continue as they have been for many years. If such a line were available for antihydrogen as well as hydrogen, the signal-to-noise ratio would be sufficient to allow the frequencies to be compared to at least 1 part in 10^{13}, a large increase in accuracy over the current tests involving baryons and leptons. The first use of cold trapped hydrogen for 1s-2s spectroscopy [14], in an environment similar in many respects to that we hope to arrange for antihydrogen, already came close to this linewidth.

The ratio of the 1s-2s transition frequencies can be used to determine a ratio of Rydberg constants. It is instructive to express this ratio in terms of other fundamental constants (assuming the very long range Coulomb interaction to have the same form for $\bar{H}$ and H),

$$\frac{R_\infty(\bar{H})}{R_\infty(H)} = \frac{m[e^+]}{m[e^-]} \left(\frac{q[e^+]}{q[e^-]}\right)^2 \left(\frac{q[\bar{p}]}{q[p]}\right)^2 \frac{1+m[e^+]/M[\bar{p}]}{1+m[e^-]/M[p]}.$$

The only ratios on the right that have been measured accurately are the electron-to-proton mass ratio and the ratio of the electron and proton charges. This CPT test comparison thus clearly involves fundamental lepton and baryon constants but in a combination which makes it difficult to simply interpret the comparison as a measurement of the electron-to-positron mass ratio, or any other such simple ratio. The comparison of 1s-2s transition frequencies measured for antihydrogen and hydrogen would be a test of CPT invariance that involves the charges and masses of leptons and baryons at an unprecedented precision. Fig. 4 illustrates the punch line. The accuracy scales for 1s - 2s spectroscopy of antihydrogen (mentioned above) are compared with the accuracies attained in existing CPT tests with leptons, mesons and baryons.

A second motivation for experiments which compare cold antihydrogen and hydrogen is the possibility to search for differences in the force of gravity upon antimatter and matter [15]. Making gravitational measurements with neutral antihydrogen atoms certainly seems much more feasible than using charged antiprotons, for which the much stronger Coulomb force masks the weak gravitational force. Members of the ATRAP Collaboration have considered the possibility of gravitational measurements with trapped antihydrogen [16], and routinely time the free fall of cold atoms released from a trap [17]. We are intrigued by the possibility of experimental comparisons of the force of gravity upon antihydrogen and hydrogen, and will pursue this direction when the techniques are sufficiently advanced to permit attaining an interesting level of precision.

ACCUMULATING COLD ANTIPROTONS

A 5.3 MeV pulse of antiprotons from the Antiproton Decelerator arrive at the ATRAP apparatus approximately once every two minutes. These are slowed in a thin berylium window whose thickness has been chosen to slow as many of the antiprotons as possible to the lowest possible energy. Antiprotons which emerge with energies below 3 keV, in the original direction of antiproton propagation, are trapped by the sudden application of trapping potentials. Fig. 5 shows an example of the measured energy spectrum of 12,000 trapped antiprotons.

Electrons are preloaded into the trap before the antiprotons arrive. They rapidly cool via synchrotron radiation to the ambient temperature of the trap, 4.2 K. Trapped antiprotons oscillate back and forth through these cold electrons, with

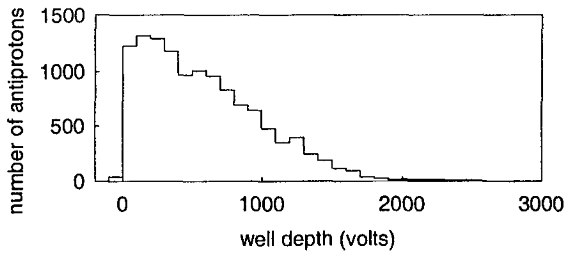

FIGURE 5. Energy of 12,000 of the first antiprotons trapped from a single pulse of AD antiprotons.

collisions cooling them down to 4.2 K. The antiprotons are cooled into the regions of the trap that contain the cooling electrons before another pulse of antiprotons arrives from the Antiproton Decelerator. The trap can be open in time for the next pulse of antiprotons to be trapped and cooled by the same electrons. Fig. 6 shows the measured energy spectrum of 106,000 antiprotons accumulated from successive pulses of antiprotons. Fig. 7 shows how the number cold antiprotons builds as a function of the number of pulses of antiprotons that are "stacked" into the trap.

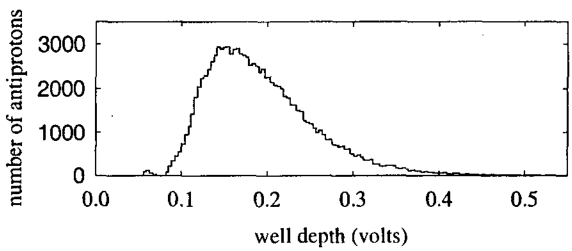

FIGURE 6. Energy of 106,000 of the first antiprotons electron-cooled and stacked at the AD.

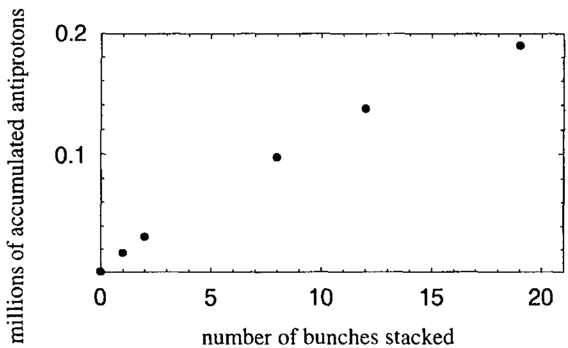

FIGURE 7. Stacking successive pulses of antiprotons.

ACCUMULATING COLD POSITRONS

Positrons accumulate in the upper trap region at the same time that antiprotons accumulate below. The new and efficient method for accumulating large numbers of 4.2 K positrons [18, 19] is the only one yet demonstrated. The positrons accumulate directly in a 6 Tesla field, and in the extremely good cryogenic vacuum.

The positrons originate in a 110 mCi ^{22}Na source that is lowered until it settles against the 4.2 K trap enclosure. They follow magnetic field lines and enter the trap vacuum through a thin Ti window. Some of them slow as they enter the trapping region through a 2 μm thick single crystal of tungsten. Others slow while turning around within a thick tungsten crystal that is rotated to the trap axis when the rotatable electrode is in its closed position.

Slow positrons emerging from the thin crystal pick up electrons while leaving the thin crystal form Rydberg positronium atoms. These atoms travel parallel to the axis of the trap until they are ionized by the electric field of the trap well, and captured. The frequency spacing of the two peaks in the electrical signal induced across an RLC circuit attached to the trap reveals the number of accumulated positrons. Fig. 8b shows approximately 2 million positrons accumulating in an hour [19], a 27-fold increased rate compared to the recent report [18] announcing the method.

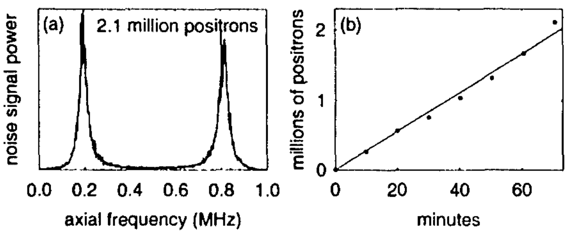

FIGURE 8. (a) Electrical signal from trapped positrons. (b) Positrons accumulate 27 times faster than reported in a recent introduction to the technique.

FIRST DEMONSTRATION OF POSITRON COOLING

The closest approach to cold antihydrogen so far is ATRAP's first demonstration of positron cooling [19]. Fig. 9 shows the trap electrodes that we used to simultaneously capture and confine antiprotons and positrons, and to make them interact. Surrounding scintillating fibers and plastic scintillators detect the annihilation signals from antiprotons released from the trap, and electrical circuits allow nondestructive detection of particles remaining within the trap.

The next step on the path to cold antihydrogen is to bring the cold ingredients together. Since the positrons and antiprotons have an opposite sign of charge, they cannot be confined in the same Penning trap well. Our "nested Penning trap", proposed for this purpose [20], was first tested with electrons and protons [21]. The motional energy of the trapped antiprotons is transferred to the lighter

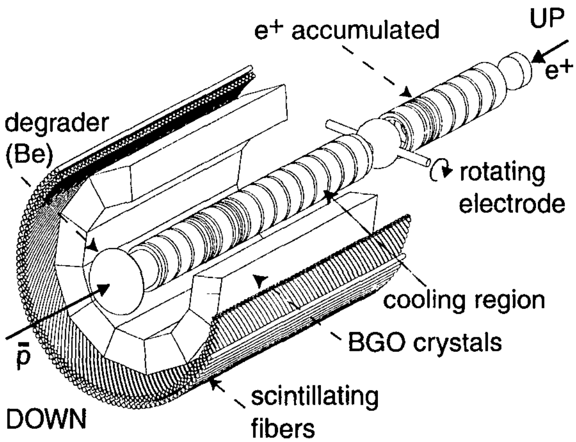

FIGURE 9. Outline of trap electrodes surrounded by annihilation detectors.

trapped particles by Coulomb collisions, and these lighter particles cool rapidly via synchrotron radiation. Fig. 10a-b contrast the energy spectra observed without and with positron cooling.

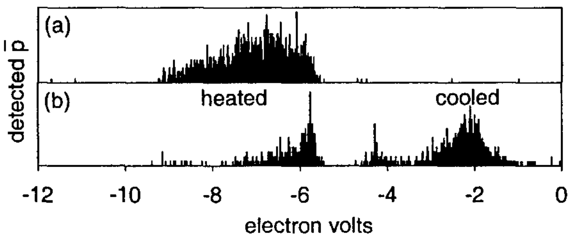

FIGURE 10. (a) Uncooled antiproton energy spectrum. (b) Energy spectra showing cooled antiprotons.

The cooled antiprotons have a low relative velocity with respect to the cold positrons that cooled them. A low relative velocity is one condition under which antihydrogen formation processes (e.g. radiative recombination and three body recombination) are expected to have their highest rates. These rates are nonetheless very small so that observing these processes will take much time and care. In addition, the electric fields of the trap will ionize any high Rydberg state produced by the latter process.

Much remains before cold antihydrogen is produced, stored and studied with precise laser spectroscopy. However, significant progress has been made. The cold ingredients are now readily available, and their interaction at low relative velocity has been clearly demonstrated.

PENNING-IOFFE TRAP

An intriguing question is whether it may be possible to trap cold antihydrogen atoms along with the charged antiprotons ($\bar{p}$) and positrons (e^+) from which they form. Fig. 11a shows a Penning-Ioffe trap configuration that has now been investigated theoretically [22] to see if a charged particle and a neutral atom could be confined at the same time. The Ioffe trap would confine the antihydrogen atoms, and the Penning trap would trap a charged ingredient. The stability of the trapped charge is crucial; the charged ingredients of antihydrogen must remain confined long enough for neutral atoms to form.

The simplest experimental realization (Fig. 11a) could direct the magnetic field of a solenoid (not pictured) along the axis of the stacked rings of an open-access Penning trap [23]. The Ioffe field would come from currents through vertical Ioffe bars and through "pinch coils" above and below. The latter can be away from the central region where charged particles are trapped, so only the leading term of the radial magnetic field from Ioffe bars are considered.

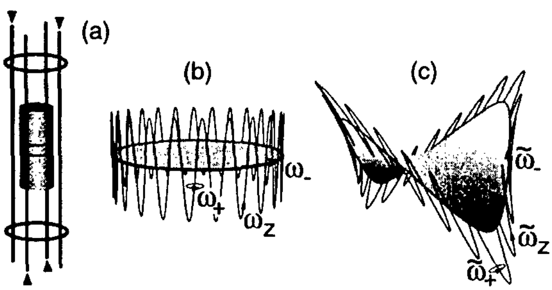

FIGURE 11. (a) Open access Penning trap electrodes, with vertical current bars and pinch coils of a Ioffe trap. Orbits for a charged particle in a Penning trap (b) without and (c) with a radial Ioffe field.

The theoretical analysis [22] of the Penning-Ioffe system, and the analysis of the motion of a charged particle within it, are simple and clean, yet nontrivial. Despite the breakdown of axial symmetry, and the loss of a confinement theorem [24], we find stable orbits (Fig. 11b) centered upon the intersection of an electrostatic potential and a force free sheet (Fig. 12a). The stable orbits are associated with adiabatic invariants, and occur within a central region of the trap (Fig. 12a). Expressions are given for their frequencies, and resonances that must be avoided are characterized. A guiding-center approximation [25], a perturbation expansion using the method of multiple time scales [26], and exact numerical calculations are compared and discussed.

Confining antiprotons and positrons in a nested version [21] of a Penning-Ioffe trap, along with cold antihydrogen atoms that are formed, now seems feasible for low particle densities. At a higher density, yet to be determined, collisions could break the adiabatic invariants, space charge could modify resonance frequencies, and collective plasma modes could be crucial. These effects may be more pronounced in a Malmberg-Ioffe trap [27] where oscillation frequencies are less well

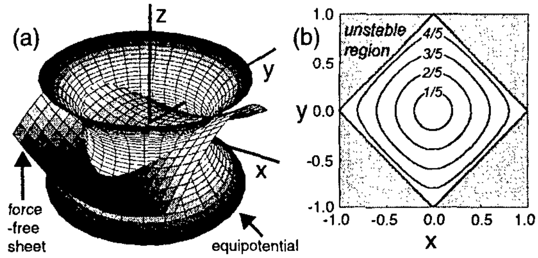

FIGURE 12. (a) The force-free sheet and an equipotential of the electrostatic quadrupole. (b) Projections of stable magnetron orbits upon the xy plane lie within a square.

defined. The relationship of density and stability for charged plasmas in a Penning-Ioffe trap remains to be investigated.

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