

TRAPPED ANTIHYDROGEN FOR SPECTROSCOPY AND GRAVITATION STUDIES: IS IT POSSIBLE?

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Possibilities for trapping and cooling antihydrogen atoms for spectroscopy and gravitational measurements are discussed. A measurement of the gravitational force on antihydrogen seems feasible if antihydrogen can be cooled to of order 1 milli-Kelvin. Difficulties in obtaining this low energy are discussed in the hope of stimulating required experimental and theoretical studies.

This contribution surveys an experimental goal which seems worth pursuing even though a complete experimental strategy is not yet clear and the goal may not even be attainable. I have hinted at this approach for several years since being convinced that we would be able to trap antiprotons. This occasion of an entire conference related to atomic antimatter (none of which has been experimentally observed) has emboldened me to speculate more openly. I also have been greatly encouraged by advances with trapped hydrogen which followed shortly upon the capture of antiprotons in an ion trap.

Antiprotons were slowed below 3 keV and then confined in an ion trap by our TRAP collaboration [1] with the intent of doing a precise comparison of the inertial mass of the proton and antiproton [2]. Experience with the apparatus for the mass measurement should also contribute to the goal of producing antihydrogen insofar as it may be possible to merge low temperature plasmas of positrons and antiprotons from ion traps to make low energy antihydrogen at a very high rate [3]. Besides the rate, however, a principal difference between this and other proposed techniques [4,5] is the very low kinetic energy of the antihydrogen which may be produced, of order 4.2 K in units of temperature.

Two types of experiments with antihydrogen benefit from a low kinetic energy: precise spectroscopy of trapped antihydrogen and a measurement of the gravitational force on antihydrogen. Both possibilities involve antihydrogen confined in a trap for neutral particles [6], which allows very efficient use (and reuse) of the antihydrogen. This is attractive because it is likely that antihydrogen will be in short supply for some time and thus that experiments with antihydrogen will need to be done much differently than experiments with hydrogen if comparable precisions are to be achieved. High precisions are desired to permit precise comparisons between properties of hydrogen and antihydrogen. Available trapping wells for neutral particles are so very shallow (less than 1 K as shall be discussed) that a method of producing low energy antiprotons is essential for this approach.

We only briefly mention spectroscopy here, because this subject is being treated separately in these proceedings [7]. The great advantage of doing spectroscopy in a particle trap, of course, is that hydrogen or antihydrogen with very low kinetic energy will be relatively free of Doppler shifts. The attention of several groups to trapping [8] and slowing [9] hydrogen suggests that vigorous experimentation with trapped hydrogen will be done in the next few years (perhaps at Harvard as well), thereby developing techniques and establishing more clearly the possibilities for antihydrogen.

We focus here upon the possibility of using antihydrogen in a trap to measure its gravitational properties. Direct measurements of the gravitational properties of simple particle systems are in very short supply. A measurement with antiprotons is made more interesting because of intriguing hints of baryon number dependences in gravity [10], with conflicting experimental results to date [11–13]. Since gravity has not yet been successfully incorporated into a quantum field theory, appeals to CPT invariance cannot be made as easily [14]. There have also been specific theoretical speculations as to how gravity could be different for baryons and antibaryons [15].

For gravitational measurements, uncharged antihydrogen is, of course, an attractive alternative to charged antiprotons. The gravitational force is so weak compared to the electromagnetic force that a single elementary charge only 12 cm away from an antiproton near the earth's surface exerts the same force on the antiproton as does the entire earth. A gravitational measurement with antihydrogen thus avoids the extreme sensitivity to stray electric fields which will be an intrinsic and serious difficulty in a proposed gravitational measurement with antiprotons [16].

To illustrate the basic idea of a gravitation measurement with trapped antihydrogen, we note that antihydrogen has a magnetic moment of approximately 1 Bohr magneton μ_B . We consider a field

$$B = B_0 + \beta \left(\frac{z}{z_0} \right)^2 \quad (1)$$

directed along the vertical z axis with z_0 as a measure of the spatial extent of the field gradient. This choice is for convenience; a quadratic field dependence is not required. The magnetic moment will align parallel to the z axis. The vertical force on the antihydrogen is the sum of the force due to the inhomogeneous field, $\pm 2\mu_B\beta z/z_0^2$, and the gravitational force, mg . In the appropriate spin state an atom is thus confined at equilibrium location z_e given by

$$\frac{z_e}{z_0} = - \frac{1}{2} \frac{mqz_0}{\mu_B\beta} \quad (2)$$

which is essentially the ratio of the gravitational energy variation mgz_0 over the trap dimension z_0 , to the well depth of the magnetic gradient trap $\mu_B\beta$. For a well depth comparable to the gravitational energy, the equilibrium position z_e can

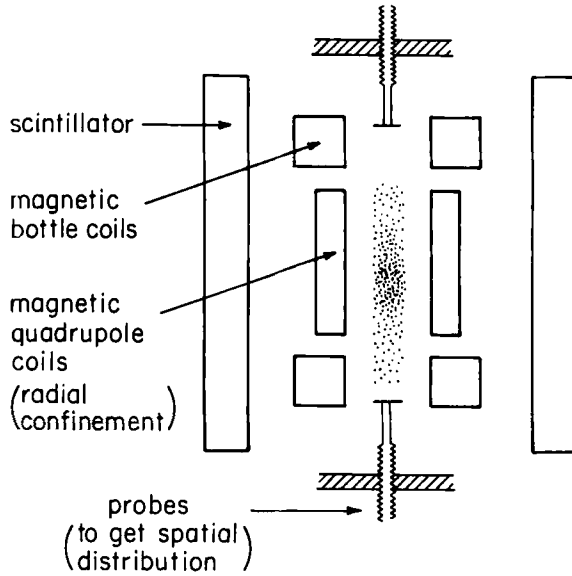


Fig. 1. Schematic apparatus for a gravitational measurement with trapped antihydrogen atoms.

be shifted from $z_e = 0$ by an appreciable fraction of z_0 . For $z_0 = 1$ m, the gravitational energy mgz_0 is equal to only 1.2 mK. This sets the energy scale which must be achieved to do the measurement, as we shall discuss.

A very nice feature of antihydrogen (compared to hydrogen) is that the spacial distribution of trapped antihydrogen can be detected with very high efficiency, so that the measurement could be done with very small numbers of antihydrogen atoms in a suitable trap. An apparatus might take the form shown in fig. 1. The z^2 magnetic field gradient is provided by coils at the ends which are axially symmetric about the vertical z axis. Radial confinement is provided by radial quadrupole field coils. A small number of antihydrogen atoms are contained in the magnetic gradient trap, with the center of the distribution lowered from the center of the field gradient by gravity. We assume that the density of particles is low enough that the atoms are uncoupled from each other during a measurement. Small plates, first lowered from the top after the trap is filled and then raised from the bottom following a second fill, probe the extent of the spatial oscillations and the centroid of the distribution with very high efficiency. The antihydrogen will annihilate upon striking a plate, producing high energy pions which can be detected externally in scintillators with near unit efficiency. The distribution of annihilations detected as a function of the position of the plates reveals the center of the spatial distribution.

In practice, gravity can be mimicked by a linear field gradient

$$\frac{dB}{dz} = 0.18 \frac{G}{\text{cm}} \quad (3)$$

and such a gradient could be used instead of, or in addition to, the plates. The magnetic field can be mapped with sufficient accuracy at this level to ensure that stray magnetic fields do not compromise the measurement.

Since we have been considering such measurements, experimental progress with hydrogen has clearly indicated the feasibility of the measurements outlined (once sufficiently low energy antihydrogen atoms are so confined). First, of order 10^{12} hydrogen atoms were confined in a magnetic gradient trap (580 mK deep) for more than 1000 seconds [8]. After the higher energy atoms evaporated out, the average energy of those remaining was estimated to be 40 mK. We look for a second development with laser-cooled sodium atoms confined in a similar trap [17], with a well depth of approximately 120 mK. Despite the initial indications, the downward displacement of the atom distribution due to gravity, as reflected in the spatial distribution of fluorescence, has not yet been observed [18], but should be shortly.

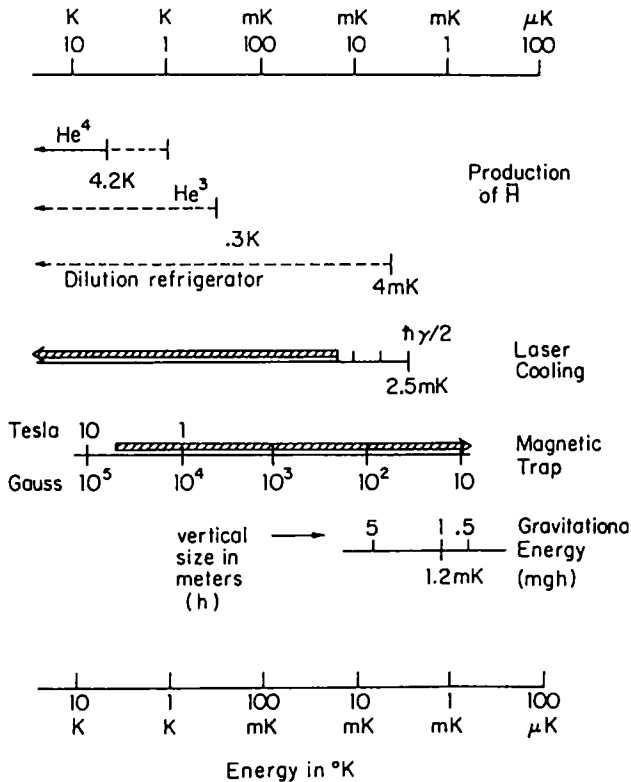


Fig. 2. Energies involved in the production, slowing, and trapping of antihydrogen atoms along with the energy scale appropriate for gravitational experiments. Energies are specified in units of temperature.

With even a small number of antihydrogen atoms in a shallow neutral particle trap, a measurement of the gravitational force on antihydrogen actually seems feasible. However, the kinetic energy of these atoms must be very low. This is a major difficulty. The relevant energies (and difficulties) are summarized in fig. 2. Antihydrogen kinetic energies are indicated by logarithmic temperature scales above and below. Production of low energy antiprotons has been discussed so far [3] at 4.2 K, which is near the left of the figure. The energy scale for a gravitation measurement, mgz_0 , is indicated on a lower axis for various z_0 . For $z_0 = 1$ m this is 1.2 mK which is near the right of the figure.

The way to bridge the energy gap represented in fig. 2 is certainly not clear yet and may not even be possible. The comments which follow should thus be regarded only as incentives for further investigation. Before discussing specific possibilities, we note that a hydrogen or antihydrogen atom could be confined in a magnetic trap for much of the kinetic energy range shown in fig. 2. The well depth energies $\mu_B \beta$ for magnetic gradient traps are indicated in the figure on the axis marked "Magnetic Trap" as a function of the depth of the magnetic well depth β , in Tesla and Gauss. To confine hydrogen atoms with a kinetic energy of 4.2 K requires a magnetic well which is nearly 6 Tesla deep, for example. Superconducting solenoids are routinely used to make much stronger fields, but such a strong gradient is much more difficult to produce. Simply reversing the direction of the current in half of the windings of the 6 Tesla solenoid we use for antiprotons experiments, those windings at $z > 0$, would make a magnetic trap for hydrogen with a maximum well depth of approximately 2 K, for example. However, the solenoid must be made with sufficient mechanical stability to avoid quenching the superconducting system. Also, such a simple configuration gives a vanishing magnetic field at the center which is not desirable for keeping the spin aligned. In the trap configuration shown in fig. 1, the difficulty would be in making a strong enough radial field for a trap of reasonable diameter. Traps with well depth below 1 K certainly seem possible, with the weak trap required to do the actual gravity measurement relatively easy to construct because only weak magnetic fields are involved.

The first possibility for bridging the gap between antihydrogen production energies of 4.2 K and the 1.2 mK required for gravity measurements is to reduce the production energies even further. In fact, 4.2 K is a choice of convenience which comes about when the production apparatus is put in thermal equilibrium with liquid helium at atmospheric pressure. The dotted lines indicate that it may be possible to lower the production temperature by pumping on the liquid He⁴, by using He³ or by using a dilution refrigerator. A lower temperature could even increase the recombination rate [3]. Both theoretical and experimental investigations are needed to establish the lowest possible energies at which antihydrogen can be produced.

A second possibility is laser cooling of the antihydrogen. This possibility immediately comes to mind because laser cooling of Na and other atoms made it

possible to capture these atoms in magnetic and optical traps. I only summarize here since details are being provided by others in this workshop [9,19]. The well known laser cooling limit ($\hbar\gamma/2$) is 2.5 mK for the 2p state of hydrogen and is indicated on the laser cooling axis in fig. 2. This is not far from the desired 1.2 mK. If the laser cooling limit could be reached, it would be simply possible to evaporate the hotter atoms out of the trap, by temporarily reducing the trapping well, without unacceptable particle loss. With achievable sources of coherent $L\gamma$ α radiation, it looks like more realistic cooling limits might be at least several times higher [9]. Such sources would be pulsed, but this is not a problem if antihydrogen is produced at a high rate when trapped plasmas are merged at a definite time [3]. More serious is the need to tune either the laser frequency or the atom frequency (by changing the magnetic field) as the atoms are slowed and cooled. The rate of laser frequency chirp looks to be prohibitively high [9,19], leaving the (also difficult) requirement of directing the atoms and laser along an appropriate field gradient. Such a gradient could be arranged along certain axes of a magnetic trap and a trap would lengthen the time the antihydrogen atoms are available for cooling. Given the relatively large volume of such a trap, however, it would be difficult to achieve a useful cooling rate.

Finally, we intend to look into the possibility of colliding antihydrogen atoms with a background gas of matter atoms which have been laser cooled. Whether annihilations can be avoided must yet be determined.

In conclusion, a gravitational measurement on trapped antihydrogen seems feasible if antihydrogen can be produced at sufficiently low kinetic energies of order 1 mK. Cooling antihydrogen to such low energies promises to be very difficult. An overview of the relevant energy scales was presented to identify the difficulties and hopefully to stimulate fresh ideas, along with experimental and theoretical studies.

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