ANTI-ATOMS ON THE BORDERLINE

Some antihydrogen sits dynamically on the border between plasmas and atoms.

Recent plasma theory is elucidating the novel "guiding center drift atoms" which are dynamically on the border beween plasmas and atoms. To make things more interesting, these unusual atoms are now being created from anti-matter constituents, i.e. anti-electrons (positrons) and antiprotons. These borderline plasma/atomic states are just one aspect of a broad range of plasma research supporting antimatter experiments and technologies which will be described in a plenary review talk by Cliff Surko [AR1.001].

Particles and anti-particles generally behave identically, as "mirror images" of each other; but antimatter annihilates completely when it meets regular matter. Thus, the magnetic trapping techniques developed for pure electron and pure ion plasmas work for positrons also, and Cliff Surko has substantially optimized these traps to accumulate many positrons (about 50 million) in about a minute (Figure 1). His specific motivation is to shoot the positrons at normal gas molecules, to characterize and manipulate the molecular bonds. This has recently demonstrated that positrons actually *bind* to normal matter before annihilating; and analyzing the x-rays produced by the annihilation enables very precise molecular diagnostics.

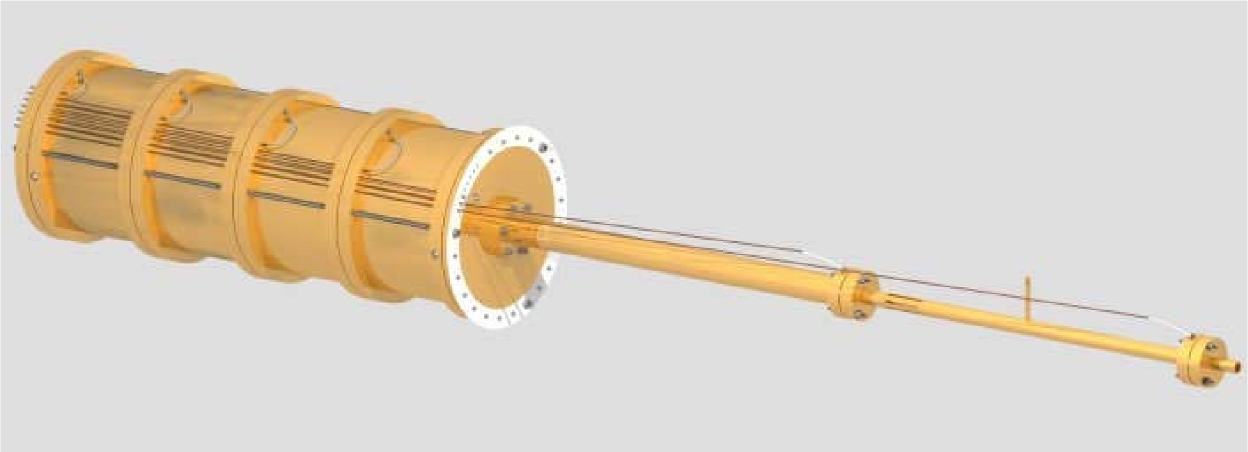

FIG. 1. The Surko positron trap, with 3 progressively smaller stages for positron accumulation.

Similarly, shooting positrons at solid surfaces such as computer chips, can check for microscopic voids or defects under the surface. These voids are undesirable in many parts, but are critical to modern insulators for high-speed electronics; and positrons are the only method that can measure void sizes and void fraction accurately.

Finally, shooting positrons into today's fusion research plasmas may eventually be used to diagnose the turbulent flows which allow the plasma to leak out of its magnetic bottle. Here, the positrons would move across the magnetic field much like normal electrons, but their positions could be accurately diagnosed from their annihilation x-rays.

Another important long-term goal for antimatter experiments is to check for violations of the "CPT theorem," describing reflections of charge, physical space, and time. With this motivation, the ATHENA and ATRAP research collaborations at CERN in Geneva hope to probe the deeply bound atomic states of antihydrogen with a laser, for comparison to normal hydrogen. Figure 2 shows a diagram of the sophisticated ATHENA detectors for "seeing inside" the trap by analyzing the annihilation products and determining the exact position where the antihydrogen annihilated.

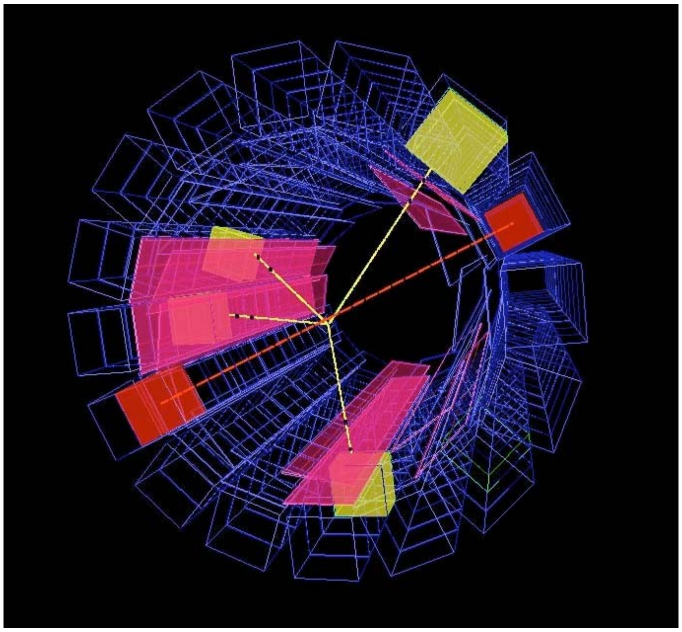

FIG. 2. The ATHENA system for detecting and locating annihilation radiation [use permission pending].

To create the antihydrogen, they separately trap positron and antiproton plasmas in magnetic bottles, then bring the two plasmas together. In the mixed plasma, the oppositely charged particles attract each other and form pairs: the pairs are weakly bound together at first, then become more strongly bound, hopefully eventually resulting in completely bound antihydrogen atoms.

The problem here is that the pairs have no net charge, so the magnetic bottle can not hold them in place. This is essentially the same problem faced in magnetic confinement fusion research: how to keep positive *and* negative charges confined magnetically, even though their combined charge sums to zero. In the antihydrogen experiments, even weakly bound positron/antiproton pairs may escape the magnetic bottle and annihilate on the walls.

These weakly bound pairs are interesting in their own right, however, forming the novel "guiding center drift atoms" shown schematically in Figure 3. The positron (e bar) spirals tightly around a magnetic field line; it also oscillates rapidly back and forth along the field line because of the antiproton (p bar) attraction; and it more slowly "drifts" in a large circular orbit around the antiproton. Here "large" means stunningly large on atomic scales, with orbit sizes about 10,000 times larger than in a deeply-bound atomic state.

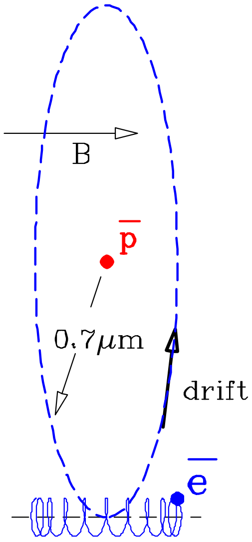

FIG. 3. A guiding center atom, with a positron ($\overline{e}$) spiraling tightly on the magnetic field lines, bouncing back and forth, and slowly drifting in a "large" orbit.

As an analogy, picture a “regular” antihydrogen atom as a marble-sized positron probability wave zipping around a pin-point-sized antiproton, making spherical orbits one thousand times every second. The analogously-sized guiding center drift atom would have a hollow positron *tube* 6 feet in diameter and hundreds of feet long, circling the antiproton at a distance of 500 feet, orbiting once every eight hours.

One striking and perhaps useful consequence of these large sizes is that the orbit shape is readily distorted (i.e. polarized) by electric fields. Tom O'Neil and graduate student Stas Kuzmin have recently analyzed the broad range of drift motions available to these weakly-bound atoms. They find that under some conditions the pairs can be pushed around and effectively “guided” by strong electric fields; this offers a new possibility for trapping the neutral atom. However, too strong an electric field or too much antiproton momentum can result in destruction of the pairing. These new results have recently been submitted for publication, and will be described in an invited talk by O'Neil [QI1.003].

When in the plasma environment, these weakly-bound atoms are “borderline,” in that they may separate and blend back into the plasma, or they may evolve towards deeper bindings. When out of the plasma environment, however, the atoms can not readily relax to deeper bindings, due to constraints of the magnetized particle motions.

One important question, then, is how *rapidly* the positrons and antiprotons can snuggle together into their preferred tightly-bound atomic state; and whether they will do so before escaping the trap as a weakly-bound neutral pair. The plasma dynamics of this collisional relaxation in a strong magnetic field was first analyzed by Mike Glinsky and Tom O'Neil in 1991, as groundwork for the present experiments at CERN. They found that many weakly-bound pairs are rapidly formed, but that it takes a substantial time for more strongly-bound pairs to form.

Fred Driscoll recently analyzed data from the initial ATRAP experiments, and found that the measured energies are consistent with theory and simulation for recombination in a strong magnetic field: essentially all of the pairs detected are apparently in the weakly-bound guiding center drift atom states. The detected pairs are typically bound by 2 or 3 *thousandths* of an electron-Volt, whereas fully recombined antihydrogen atoms would be bound by 13.6 electron-Volts. These new results have been submitted for publication as a Physical Review Letters Comment, and will be described in presentation [C03.001].

One simplifying factor in analyzing the large guiding center drift atoms is that the positron motion can be described by classical physics, rather than by the fuzzy quantum probability waves which necessarily occur on atomic size scales. Moreover, the motion has the distinctive “drift” characteristics of plasma particles in magnetic fields: applied forces cause velocities which are *perpendicular* to, rather than parallel to, the force direction. This drift motion is commonly seen in large-scale plasmas, such as the earth's magnetosphere or the magnetic bottles used in fusion research, but it is rather unusual for atoms.

Thus, exploring the symmetry between matter and anti-matter also motivates exploration of the border between plasmas and atoms. Look for many exciting new results as high-energy physicists, atomic physicists, and plasma physicists work towards antimatter production, characterization, and utilization in a variety of technologies.

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