Slow antiprotons galore

A workshop in Japan in the spring looked at how to make and use beams of ultra-slow antiprotons over a wide range of physics.

Participants enjoy an excellent buffet during the workshop.

In the 50 years since Owen Chamberlain, Emilio Segrè, Clyde Wiegand and Tom Ypsilantis discovered the antiproton in October 1955, an extremely diverse range of research topics has developed that involve antiproton beams with kinetic energies of order kilo-electron-volts or less. This was the subject of the Workshop on Physics with Ultra Slow Antiproton Beams, held 14–16 March 2005 at RIKEN, Japan.

The workshop was motivated by the recent progress in manipulating large numbers of ultra-slow antiprotons that has been made by the antihydrogen and antiprotonic-helium collaborations working at CERN's Antiproton Decelerator (AD). The latest of these developments was in summer 2004. That was when the Monoenergetic Ultra-Slow Antiproton Source for High-Precision Investigations (MUSASHI) group of the ASACUSA collaboration first slowed the 5.3 MeV pulsed AD beam in a radio-frequency quadrupole decelerator (RFQD) to some tens of kilo-electron-volts, then confined and cooled more than 1 million antiprotons in a large multi-ring Penning trap (*CERN Courier* March 2005 p8). The trapping efficiency of about 4% is approximately 100 times higher than any previously achieved. The group also succeeded in extracting antiprotons from the trap as an ultra-slow DC beam of 10–500 eV. The fact that this unique beam can, in principle, be transported for some distance without serious loss makes beam sharing for a variety of experiments a real possibility.

Although the workshop was announced only two months beforehand, it attracted some 70 participants from all the related fields, and covered subjects ranging from fundamental questions about charge-parity–time-reversal (CPT) symmetry and gravitation, to the structure of exotic nuclei, atomic collisions and atomic physics. This report relates just a few of these topics; a full account will soon be published in the *Proceedings* series of the American Institute of Physics.

The early days of antiproton research were reviewed by John Eades of the University of Tokyo. Eades turned back the pages of scientific history in a talk entitled "The Antiproton and How It Was Discovered", quoting the thoughts and opinions of some of the main participants, made both at the time and in retrospect. He underlined the initial doubts and inconsistencies that surrounded Paul Dirac's relativistic-wave equation of 1930, and its final triumph as the positron, antiproton and other antiparticles were discovered.

Klaus Jungmann of the Kernfysisch Versneller Instituut (KVI), Groningen, gave a comprehensive overview of the current status of low-energy antiprotons and other exotic particles, and the experimental opportunities they offer as windows on fundamental forces and symmetries in nature. On the theoretical side, Ralf Lehnert of Vanderbilt University pointed to the large gap that will remain in our understanding of nature at the smallest scales until a consistent quantum theory is developed that underlies both the Standard Model and general relativity. He discussed the so-called Standard Model Extension (SME) as a theoretical framework that may bridge this gap, and which incorporates all Lorentz- and CPT-violating corrections compatible with key principles of physics (*CERN Courier* December 2004 p27). The SME predicts diurnal variations in spectroscopic measurements of matter and antimatter atoms, and could therefore be a guiding principle in designing future antihydrogen experiments.

Antihydrogen atoms and antihydrogen ions

The past three years have seen important progress by both the ATHENA and the Antihydrogen Trap (ATRAP) collaborations in synthesizing and experimenting with antihydrogen atoms at the AD. Some of the main results concern the accumulation of large numbers of positrons and antiprotons in "nested" Penning traps of various geometrical designs, leading to the observation of high formation rates for antihydrogen atoms. An unexpected consequence is that these antihydrogen atoms seem to be created before their constituent antiprotons have been fully cooled, with the result that they are themselves too hot to be easily stored and manipulated with existing techniques. Moreover, they are primarily formed in highly excited Rydberg states, while it is the ground and first-excited states that are of most interest for testing CPT invariance.

These obstacles to preparing usable antihydrogen atoms for physics experiments demand new ideas in trap design, going beyond the configuration of the nested electrostatic potential well used so far. Thus, Jeff Hangst of Aarhus described the present status of the high-field-gradient magnetic multipole trap proposed by the newly formed Antihydrogen Laser Physics Apparatus (ALPHA) collaboration; and Dieter Grzonka of Jülich reported on tests made on long-term electron storage in the ATRAP collaboration's quadrupole magnet, which has a more moderate field gradient. ▷

The storage of neutral atoms of antihydrogen requires the presence of magnetic field gradients to drive the so-called low-field-seeking atomic-spin states towards field minima, and will be essential to carry out high-precision antihydrogen spectroscopy. Since it appears that the atoms are produced in highly excited Rydberg states, they must be stored for long enough to allow them to relax to the ground state. Discussions at the workshop centred on various multipole and quadrupole trap designs that are likely to be useful in preparing such ground-state antihydrogen atoms.

Further new designs involve the so-called "cusp trap", consisting of a potential well formed by two oppositely directed Helmholtz-coil fields, and a high-Q RF trap resonating at two frequencies, which can store positively and negatively charged particles simultaneously.

Ryugo Hayano of the University of Tokyo summarized both the present status of precision spectroscopy of antiprotonic helium and the development of the two-frequency RF trap for antihydrogen synthesis. In the latter, positrons and antiprotons may recombine within a volume of around 1 mm^3, and thus form a source for an antihydrogen atomic beam. Sextupole magnets installed in such a beam could select and analyse specific antihydrogen spin alignments to measure the hyperfine structure of the antihydrogen ground state, much as was done with ordinary hydrogen atoms several decades ago.

Akihiro Mohri of RIKEN, Japan, showed that stable long-term storage of an electron plasma has been achieved at finite temperature in a cusp trap and that this can also trap synthesized antihydrogen atoms in low-field-seeking states. When the temperature of antihydrogen atoms and the magnetic field of the cusp trap are properly set, antihydrogen atoms in the ground state are selectively guided and focused along the magnetic axis, enabling an intensity-enhanced spin-polarized antihydrogen beam to be prepared.

A new path towards gravitational experiments with antihydrogen was proposed by Patrice Perez of CEA/Saclay, who discussed synthesis of antihydrogen ions ($\overline{H}^+$). These could be formed via two-step reactions ($\overline{p} \rightarrow \overline{H} \rightarrow \overline{H}^+$) when a 13 keV antiproton beam passes through a dense cloud of positronium atoms. The resulting $\overline{H}^+$ ions would then be trapped, sympathetically cooled with laser-cooled alkali-earth ions, and finally ionized to the neutral state by a laser-detachment process to create the ultra-cold $\overline{H}$ atoms necessary for detecting the extremely weak gravitational interaction.

Kanetada Nagamine of KEK proposed studying muonic antihydrogen ($\mu^+\overline{p}$), the antimatter equivalent of muonic hydrogen (μ^-p), as an alternative to antihydrogen. The advantage of comparisons between μ^-p and $\mu^+\overline{p}$ is that because of their larger mass, muons probe CPT-violation effects at a distance 200 times closer to the antiproton nucleus than positrons and electrons do.

Further studies

Collision dynamics with antiprotons is also a potentially important subject, in which the antiproton behaves like a heavy electron. Although the Coulomb force is understood, its collision dynamics are not well known when more than three particles are involved. A familiar, puzzling example is the double ionization of helium by fast antiprotons, the cross-section for which is about twice as large as that for protons having the same velocity. Almost 20 years have passed since this observation, but it is not yet fully understood theoretically. This contrasts with the case of bound systems such as antiprotonic helium ($\overline{p}He^{++}$), where the observed transition levels have been theoretically accounted for at the level of one part per billion.

Joachim Ullrich of the Max Planck Institute, Heidelberg, discussed the importance of studying collision dynamics with antiproton energies in the range of 100 keV for which the time required to traverse atoms or molecules is of the order of 100 attoseconds (as). Since this is comparable to the orbital period of outer-shell electrons in atoms or molecules, crucial information on collision dynamics involving electron–electron correlation can be extracted.

Antiprotonic atoms have long been used to probe neutron density distributions in stable nuclei through studies of antiprotonic X-ray spectra, radiochemistry of the residual nuclei, and the charged pions emitted when the antiprotons annihilate. An antiproton captured in an electronic orbit de-excites to successively lower atomic levels until its overlap with the nucleus becomes appreciable. At this point annihilation takes place with a proton or a neutron near the "surface" of the nucleus (atomic number A), the actual charge state being identifiable from the charge balance of emerging pions; a nucleus of atomic number A-1 results.

Michiharu Wada of RIKEN proposed extending the pion-detection method by storing antiprotons and unstable nuclei in a nested trap. The charge-balance method can be applied to various nuclei including those for which the A-1 nuclei have no bound states. Slawomir Wycech of the Soltan Institute, Warsaw, emphasized that all these measurements test neutron density distributions in different regions of nuclei and yield complementary information on the rms and higher moments of density profiles as low as 0.001 of the central neutron density.

Looking to future antiproton facilities Paul Kienle of the Technischen Universität München discussed the possibility of an antiproton–ion collider at GSI's Facility for Antiproton and Ion Research (FAIR), with energies of 30 MeV and 740 AMeV for protons and ions respectively. Cross-sections for antiproton absorption on protons and neutrons would be measured by detecting residual nuclei with A-1, using Schottky and recoil detectors respectively. This would permit rms radii for protons and neutrons to be determined separately in stable and short-lived nuclei by means of antiproton absorption at medium energies. A general discussion around the subject of ultra-slow antiproton physics ended this extremely fruitful workshop.

Résumé

Antiprotons froids à volonté

Au cours des 50 années écoulées depuis la découverte de l'antiproton, une gamme extrêmement diversifiée de sujets de recherche s'est développée autour des faisceaux d'antiprotons de très basse énergie – dans les kilo-électronvolts et en-dessous. C'était le sujet de l'atelier de la physique avec des faisceaux d'antiprotons ultralents qui s'est tenu en mars au RIKEN (Japon). L'atelier, motivé par les récents progrès accomplis dans la manipulation de grands nombres d'antiprotons ultralents, a examiné les techniques de formation et d'utilisation des antiprotons d'énergie ultrabasse.

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