ASACUSA measures microwave transition in antiprotonic helium

The ASACUSA collaboration has reinforced its status as a paragon of precision physics by following up its impressive six parts in $10^8$ measurement of the antiproton's charge and mass with new measurements of its magnetism. John Eades reports.

Recent months have seen the much-awaited synthesis of cold antihydrogen atoms by two groups working at CERN's Antiproton Decelerator (AD; Amoretti et al.; Gabrielse et al.). The aim of these collaborations is to compare spectral features of hydrogen and antihydrogen as a test of the CPT invariance principle, which states that under certain realistic assumptions about the quantum fields that represent them, matter and antimatter will always behave in the same way. However, it is not just in antihydrogen atoms that CPT symmetry can be tested, as the ASACUSA collaboration is demonstrating. If CPT violation occurs anywhere in nature, it must be very small, and experimental searches for it have usually been done with kaon beams. These beams are coherent superpositions of particle and antiparticle waves, and since slightly different masses imply slightly different de Broglie wavelengths, a limit of a few parts in $10^{19}$ can be reached.
In the antiprotonic helium atom (figure 1, inset), a 1S electron and an antiproton are bound to an alpha-particle nucleus by the Coulomb force. As the 1S electron carries no orbital angular momentum, its magnetic dipole moment $\mu_e = g_e S_e \mu_N$ comes only from its spin, $S_e$. The dipole moment due to the antiproton spin $S_p \times h$, is a thousand times smaller, but it carries a large orbital angular momentum $L_p = 35 - 40h$, and this dominates the value of its total magnetic dipole moment $\mu_p = (g_p L_p + g_p S_p) \mu_N$.

In these expressions the various “$g$-factors” measure the coupling of a particle’s magnetism to its orbital or spin electric currents, $g_e = Q_e h / (4\pi m_e c)$ is the Bohr magneton and $g_p = Q_p h / (4\pi m_p c)$ is the antinuclear magneton.

As the two leptonic and hadronic magnetic dipoles $\mu_e$ and $\mu_p$ interact at a distance similar to the electron–proton distance in the hydrogen atom, the magnetic properties of antiprotonic helium are qualitatively similar to those of ground state $H$ and $\bar{H}$ atoms. However, the frequency needed to flip the electron spin is expected to be near 13 GHz in antiprotonic helium rather than the 1.42 GHz value for the hydrogen atom’s ground state; that required for the antiproton spin-flip should be a few hundred MHz. The helium nucleus, having no spin, plays no role.

These arguments are more quantitatively displayed in figure 1 for the state with principal quantum number $n = 37$ and orbital quantum number $L = 35$. The figure shows the electron spin up and down hyperfine doublet (left centre), and at higher resolution, the further splitting of these into superhyperfine doublets with antiproton spin up and down (right centre). In the experiment, antiprotonic helium atoms were created in cold helium gas contained in a microwave cavity (see picture on opposite page). The frequency of microwaves entering the cavity through a waveguide could then be tuned to search for stimulated electron spin-flip transitions. But why are two laser beams required in addition to the microwave beam? Certain atomic states like (37,35) can be metastable against annihilation, while adjacent ones, for example (38,34), reachable from them by laser stimulation, are not (CERN Courier October 2001 p35). A laser pulse at frequency $f$ stimulates transitions between the two, forcing atoms in the two states with electron spin up to annihilate, but not in those in with electron spin down, for which the transition frequency $f$ is slightly different. A resonant microwave pulse will then flip some of these untouched “electron-down” atoms to the “up” state, and a second $f$ laser pulse following the microwave pulse can be used to detect this population transfer. The experiment was done by scanning the microwave frequency near the QED-calculated down–up frequency, and looking for resonant peaks in the ratio of annihilation rates forced by the two laser pulses. The resulting frequency spectrum is shown on the right.

Although we have no quantum interferometer for the CPT conjugate $H-\bar{H}$ pair, we do have powerful laser beams, which we can use to probe its members with extremely high precision. Since no other assumption than CPT invariance need be made in interpreting what happens when one of them is removed from a spectrometer and replaced by the other, the $H-\bar{H}$ pair is in many ways the ideal CPT test-bench. However, it is very difficult to produce antihydrogen atoms moving so slowly that they do not drift out of a laser beam before it can stimulate one of their spectroscopic transitions. Solutions to this problem are now evidently in sight, but many difficulties remain before the extreme sensitivity afforded by laser tech-
FUNDAMENTAL SYMMETRY

ASACUSA’s microwave cavity. The fine mesh windows admit the pulsed antiproton beam on one side and the two laser beams on the other with 90% efficiency. They are, however, opaque to microwave energy introduced into the cavity through the rectangular waveguide.

The present result has an unusual feature. According to the equation for \( \mu_p \) (see box), what is being measured is mainly the ratio \( g_p/g'_p \) of the factors defining the orbital current magnetism relationship for the members of the CPT conjugate pair. However, we have no atoms with orbiting protons in our matter world, and \( g_p \) has always implicitly been taken by definition to be equal to 1. Thus while CPT invariance is respected within the six parts in \( 10^5 \) limit given above, we do not know, in the empirical sense, that either g-factor really has the value unity.

Further reading

John Eades, Tokyo.

Log-ratio BPM
for linacs, transfer lines synchrotrons and cyclotrons

Very large dynamic range
4 pick-ups parallel processing
Single bunch or CW
X/Y outputs: ±1V, 50Ω, 10 MHz

Instrumentation
01630 Saint Genis-Pouilly, France
sales@bergoz.com

CERN Courier January/February 2003