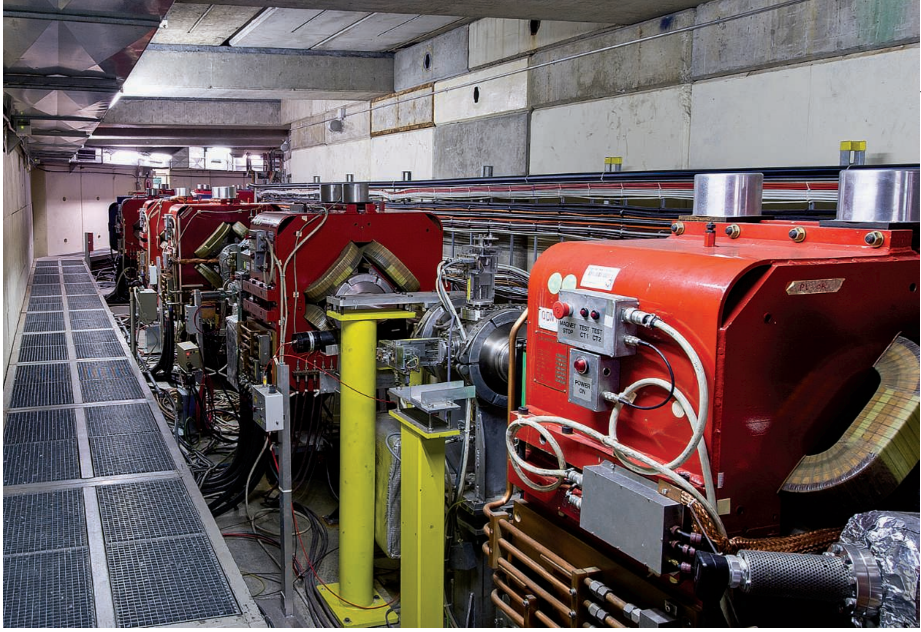


The Antiproton Decelerator at CERN used in the preparation of the antiprotonic helium atoms.

PHYSICS

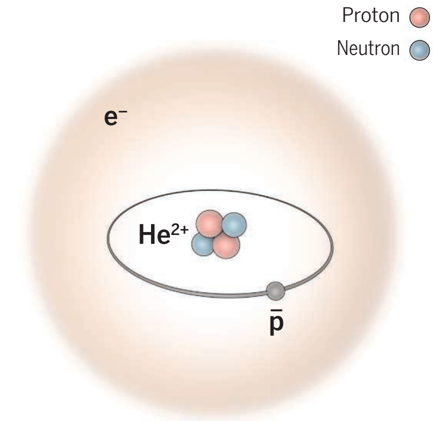
A testing time for antimatter

Precision measurement of antiprotonic helium provides a test of physical laws

By **Wim Ubachs**

Spectroscopy is the most accurate branch of science. Optical transition frequencies in isolated atoms and molecules can nowadays be measured to many-digit accuracies by applying the tools developed in the atomic physics community: ultrastable lasers, locked via frequency-comb lasers to atomic clocks, and the techniques to cool and control the motion of atoms. Precision measurements on small quantum systems can be compared with theoretical descriptions of these systems at the most fundamental level, allowing physics theories to be tested and enabling the search for physics beyond the standard model (*1*). On page 610 of this issue, Hori *et al.* (*2*) apply these tricks of the trade to a small atomic quantum system with a built-in antiparticle to perform precise spectroscopic measurement in antiprotonic helium (see the figure). The technique of buffer-gas cooling is demonstrated for the first time on a composite matter–antimatter particle.

The laws of physics conspire to create the conditions for producing relatively long-lived states in the exotic antiprotonic helium atom ($e\bar{p}$He). In all other cases of antiprotons stopping in matter, the characteristic annihilation process by which a matter particle and an antimatter particle end their lives in a flash of energy takes place on a time scale of less than a nanosecond. The Heisenberg uncertainty principle then prohibits a precision measurement. The capture of antiprotons in a helium atom, under replacement of an electron, is the exception (*3*). The inclusion of the antiproton produces a $\bar{p}He^+$ ionic core in a heavy-Rydberg two-particle state. Energy conservation dictates that $\bar{p}He^+$ emerges in a quantum state n of typically $n = 38$; in the experiment by Hori *et al.*, states with $n = 31$ to $n = 40$ are probed. The overlap of the wave functions of $\bar{p}$ and He^{2+} is minimal if the high-n Rydberg states exhibit a large angular momentum—for example, in a state such as $n = 38$ with $l = 36$ or 37 (where l denotes the quantized angular momentum). These circular states have typical lifetimes of microseconds, long enough to perform a laser experiment. Narrow spectral lines can be measured to determine level energies to high accuracy. The Rydberg constant of the heavy-Rydberg $\bar{p}He^+$ ion pair is so large that the transitions by which the n-quantum number changes by unity lie in the wavelength range of the near-infrared, visible, and ultraviolet, where Hori *et al.* have narrowband and stable lasers at hand.



Structure of the antiprotonic helium system ($e\bar{p}$He). The positive He^{2+} and negative $\bar{p}$ ions can be considered to be bound as a heavy-Rydberg ion (*11*). For $n = 38$, the typical state in which the antiproton is captured, this yields a characteristic distance of 0.16 Å. The electron is then bound in the field of the two-particle ionic core of charge 1, similar to the way it is bound in the hydrogen atom at a typical distance of the Bohr radius $a_0 = 0.5$ Å. The quantum-level structure of antiprotonic helium can be calculated to 10-digit precision (*6, 7*).

The second electron of the helium atom remains in its 1s orbital, and it acts as a spectator during the capture process. It favorably shields the composite newly built electrically neutral $e\bar{p}$He system during collisions with the outside world. This property makes it possible for the antiprotonic helium atom to survive while it undergoes multiple collisions in the surrounding bath of cold helium atoms at a temperature of 1.5 K above absolute zero. This buffer-gas cooling technique, originally developed for the preparation of cold atoms and molecules (*4*), is applied to the exotic atom bearing an antiparticle in its structure. After a number of collisions, without annihilation, the exotic atoms are equilibrated and take up the temperature of the bath. At 1.5 K, the velocity of the particles is very low, and hence the usual spectral line broadening due to the Doppler effect is suppressed, allowing for the measurement of narrow spectral lines.

The precision frequency measurements performed by Hori *et al.* on 13 energy-level transitions in antiprotonic helium, and obtained with nine-digit precision, can be interpreted in three ways. First, it is a test of charge-parity-time (CPT) invariance, arguably the most fundamental theorem on symmetries in physics. All calculations in particle physics would lose validity if CPT symmetry were not valid (*3*). The exchange of particles by their antiparticles (C), reflection in a mirror (P), and letting time run backwards (T) should not cause a change in the measurable properties of a physical system. The measurements verify that CPT is a valid symmetry, at least at the level of accuracy now obtained.

Second, antiprotonic helium is a three-particle Coulomb system, the stability of which was already investigated by Poincaré in the framework of classical mechanics. In the fully quantized version of electromagnetism, quantum electro-dynamics (QED), the stability of the helium atom (*5*) and the H_2^+

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molecular ion (*6*) is well established, and the bound-state level energies can be calculated to 10-digit precision. The same is true for the $e\bar{p}He$ system (*6, 7*) that is found to withstand a test of QED.

Third, the transition frequencies sensitively depend on the mass ratios of the constituent particles. Similarly, as in a spectroscopic determination of the proton-electron mass ratio from HD^+ spectroscopy (*8*), evaluation of the data of Hori *et al.* yields a value for the antiproton–electron mass ratio. We learn that antiprotons weigh the same as protons, up to the 10th digit.

The frontier of particle physics is commonly approached in the realm of high-energy physics, using particle accelerators like the Large Hadron Collider (LHC). The detection of the Higgs boson at the LHC marks the culmination of the standard model of physics, but the quest is on to explore new physics beyond that. Alternative approaches exist in the low-energy domain by performing extreme precision measurements on small atomic and molecular systems for which the quantum-level structure is calculable (*1*). This can be done, for example, through the search for an electric dipole moment of the electron in molecules that might reveal signatures of supersymmetry (*9*). Laser precision measurements of optical transitions in molecules constrain the existence of higher dimensions beyond the 3 + 1 (spatial and time) that we regularly observe, or the occurrence of a fifth force beyond the three forces known in the standard model plus gravity (*1*). Previous measurements on antiprotonic helium have already set limits on the strength of such a hypothetical fifth force at sub-ångström length scale (*10*); the present data constrain these phenomena even further.

This exotic atom involving antimatter seems a fortunate accident of nature. It exhibits long-lived (metastable) quantum states that can be probed with lasers, and it survives the collisional conditions needed to cool its kinetic motion, as Hori *et al.* have demonstrated. It is likely that these properties may be further exploited to reveal new physics in future experiments on this extraordinary atom-like particle. ■

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CONSERVATION

Migratory birds under threat

Habitat degradation and loss, illegal killings, and climate change threaten European migratory bird populations

By **Franz Bairlein**

The populations of migratory bird species that breed in Europe and overwinter in sub-Saharan Africa are declining considerably faster than those of nonmigratory resident species or of migratory species that overwinter in Europe (*1*). Likely factors are habitat changes due to changes in land use, illegal killing and taking along the northern African coasts, and climate-induced changes in timing of migration and breeding. However, not only European trans-Saharan migrants are declining fast. This holds also for North American long-distance migrants wintering in Central and South America. To halt these declines, preservation of remaining habitats and restoration of habitats both at breeding and nonbreeding grounds is essential, as well as stopping illegal killing and taking of birds along their migration routes.

ILLEGAL KILLING AND TAKING

Every year, between 11 million and 36 million birds are killed or taken illegally in the Mediterranean region (*2*). The areas of greatest concern are in the eastern and central Mediterranean, with more than 5 million birds taken in both Egypt and Italy and an estimated 1 million each in Cyprus and Lebanon. Common migratory species such as Eurasian chaffinch, blackcap, and song thrush are most affected, but many less common migratory species are also taken in substantial numbers, including species of global conservation concern such as red kite and Eurasian curlew. On average, the annual illegal killings and takings of threatened or near-threatened migratory bird species amount to 1.0 to 3.5% of their populations (*2*)—percentages that are very likely to have considerable impacts on the fate of these species.

Illegal trapping can cause a collapse in population numbers within a short period of time. For example, the yellow-breasted bunting was abundant in its Eurasian breeding range until illegal takings in China caused an 84% population decline between 1980 and 2013 (*3*). Similarly, the passenger pigeon was once the most abundant migratory bird in North America, numbering around 3 billion to 5 billion birds in the early 19th century. Massive-scale hunting as cheap meat resulted in its extinction at the turn of the 20th century (*4*).

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HABITAT DEGRADATION AND LOSS

Many European migratory birds that overwinter in sub-Saharan Africa do not travel across those areas of the eastern Mediterranean most affected by illegal killings. Rather, they use a flyway across the western Mediterranean where illegal taking is much less intense (see the figure). Other factors must play a role in their decline.

A large number of European migratory species overwinter in the dry savannas of sub-Saharan Africa. Annual survival of many of these species correlates with rainfall in the Sahel zone (*1*). However, despite an increase in rainfall in the Sahel in recent decades, bird populations have continued to decline. Thus, factors other than rainfall must contribute to the population declines. Land-use and land-cover changes are the most important (*5*). Between 1975 and 2000, agriculture increased by 57% in sub-Saharan Africa at the expense of natural vegetation, with nearly 5 million hectares of forest and nonforest vegetation lost per year (*6*). Most affected are the Sahel and Guinea Savanna zones where the majority of the Eurasian migratory species overwinter. An analysis of breeding-bird survey trends of 26 long-distance migratory species in the United Kingdom shows that wintering habitat is the most important determinant of population trends, with specialist species that occupy either open or woodland habitats in Africa showing declines (*7*).

CLIMATE CHANGE

Climate change is another major driver for biodiversity changes, including responses of bird populations (*8*). Many migratory species, including those that overwinter in sub-Saharan Africa, now arrive earlier at their spring breeding grounds (*9*). However, different organisms do not respond to climate change at the same pace, which has led to an ecological mismatch between some consumers and their prey (*10*).

Dutch pied flycatchers, which overwinter in sub-Saharan Africa, do not arrive earlier at breeding grounds, but the populations of their insect food peak earlier as a result of warmer spring temperatures.

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Wim Ubachs (November 3, 2016)

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Editor's Summary