

Unique Atomic Spectroscopy Aims at Answering a Universal Question

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There is far more matter than antimatter in our universe, but scientists don't know enough about the properties of antimatter to understand why. By spectroscopically analyzing atoms created when antiprotons collide with helium, physicists at CERN are measuring the properties of antimatter with unprecedented accuracy.



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We live in a universe constructed from atoms composed of light, negatively charged electrons orbiting positively charged protons and uncharged neutrons (both heavy). We know now that our universe could have been predominantly composed of antimatter — atoms with light, positively charged positrons orbiting a nucleus containing negatively charged antiprotons and antineutrons, which, although uncharged, differ from neutrons in having opposite magnetic properties.

The question of why we live in a universe of matter as opposed to antimatter is being addressed in what may seem to be an unlikely place, using an unlikely technique. Physicists at CERN, the European Laboratory for Nuclear Physics in Geneva, Switzerland, are using innovative spectroscopic techniques to un-

cover the detailed properties of the antiproton.

In 1930 Paul Dirac theoretically predicted the existence of these antimatter particles, which are the exact opposite of common particles. The positron was experimentally verified in 1932, while the antiproton (\bar{p}) was not observed until 1955. Why did it take so long to experimentally identify the antiproton? One reason is that it is essentially nonexistent in our earthly environment, and it can only be produced in particle accelerators more powerful than those required to produce positrons.

The absence of antimatter was not a subject of much concern until physicists began to improve our understanding of the origin of the universe. The early universe, filled with dense energy, almost instantaneously expanded to the point where matter condensed from the initial sea of energy.

So where is the problem?

The problem is that our current understanding predicts that as the universe cooled, both matter and antimatter should have been produced in roughly equivalent quantities. Something has to account for the observed matter predominance in today's universe, and scientists around the world are searching for possibilities. The researchers of the "Atomic Spectroscopy and Collisions Using Slow Antiprotons" (ASACUSA) experiment at CERN are seeking the answer within the details of antiproton properties.

If the antiproton is a perfect analogue to the proton, then its charge will be exactly opposite, and its mass and magnetic moments will be identical. There is, of course, a significant obstacle to measuring these quantities: antiprotons don't hang around very long. When a proton and antiproton meet, they mutu-

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ally annihilate, leaving only a burst of pions. And, as previously noted, our universe has plenty of protons around, so quick annihilation is the rule. Protons and antiprotons are used as probes to investigate the structure of matter and antimatter, which is one reason that particle accelerators such as Fermilab (Argonne, IL) and CERN create high-energy particle beams and observe the products of their collision with various targets.

In 1991 researchers at KEK, the accelerator located in Tsukuba, Japan, noted an anomaly in the time spectrum of annihilations following the collision of antiparticles with cryogenic-temperature helium atoms. The annihilation spectrum showed the expected nearly instantaneous burst — over in nanoseconds — but in addition, a 20- μ s-long tail was observed in the annihilation spectrum. About 3% of the antiprotons incident on the helium target were not immediately annihilating. Instead, the annihilation was somehow delayed. The experimental accuracy was limited by the presence of other particles in the incident beam, so the Japanese team moved their experiment to CERN, where a higher-purity antiproton source was available. With the higher-quality CERN data, the explanation was soon confirmed: the negatively charged antiprotons were replacing one of the electrons in the helium atoms, creating a metastable antiprotonic helium atom molecule, or *atomcule* (see Figure 1).

The creation of this relatively long-lived exotic atom was a fascinating result in its own right, but even more intriguing were the experimental possibilities inherent in the new atom. In the same way that the simplest atom, hydrogen, with its single proton and single electron, served as the principal testbed for investigating the properties of the electron and proton (and indeed, for discovering the fundamental laws of quantum mechanics), antiprotonic helium (\bar{p} helium) could serve as a testbed for investigating the characteristics of the antiproton. Again, similar to the investigations into the hydrogen atom of the last century, spectroscopy would serve as a unique window into the in-

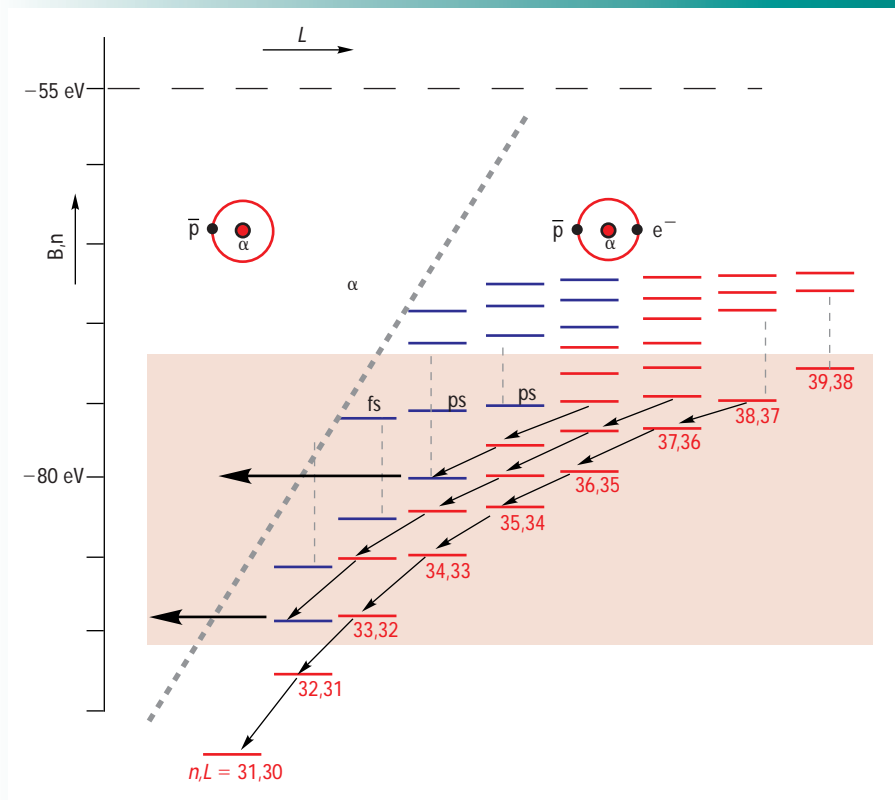


Figure 1. Antiprotonic helium is created when an antiproton replaces an electron in a helium atom. The initial state is far from the ground state, with an antiproton orbit that keeps it far from the nuclear protons. Laser excitation at energies resonant with energy level differences within the \bar{p} helium induce a transition to less stable states, where the antiproton rapidly collides with a nuclear proton, leading to a peak in the annihilation rate.

teractions of the particles within the atom. “The challenge is always to reach ever-higher precision, ever-tighter comparisons between the proton and antiproton, the world and the antiworld,” said John Eades, a physicist on the ASACUSA team. “The universe is a very big place and has been around for a very long time. There is time and space enough for extremely tiny violations of the symmetry laws that we believe to govern its behavior to have produced very large effects, like the observed matter–antimatter imbalance.” To detect differences between protons and antiprotons, a set of theoretical predictions must be developed.

The Theoretical Model

If antiprotons are slowed enough, and helium atoms are dense enough, then all the antiprotons will be captured in the target by helium atoms, each replacing one of the orbital electrons. \bar{p} helium can be thought of as a three-body

system: the alpha particle of the helium nucleus, the antiproton, and the remaining electron. The three-body quantum electrodynamics (QED) calculation, although complex, is a tenable problem, and extremely accurate theoretical predictions can now be made.

The initial \bar{p} helium atom is not a ground state system. Although the remaining electron is typically in the ground state, the antiproton starts out in a state with $n \sim (M^*/m_e)^{1/2} \sim 38$, where n is the principal quantum number (for the ground state $n = 1$), M^* is the reduced mass of the \bar{p} helium system, and m_e is the mass of the electron. The initial orbit is nearly circular, with l , the antiproton angular momentum quantum number, $\sim n - 1$. The metastability is a consequence of the large angular momentum difference between the antiproton and electron orbits, which makes it difficult for the energy to be transferred directly from the antiproton to the electron. In addition,

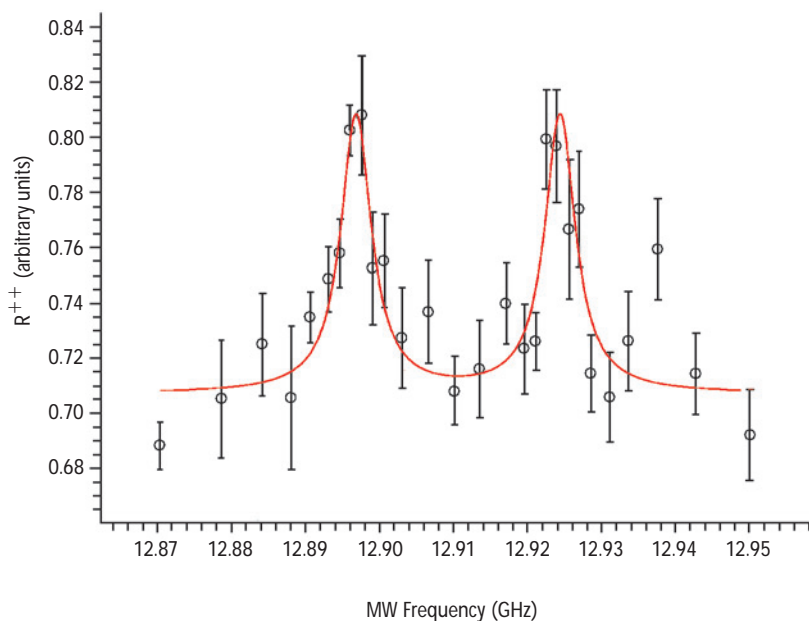


Figure 2. In addition to being split by electron spin magnetic interactions, each energy level of the \bar{p} He is further split by the smaller interactions of the antiproton spin. By tuning a laser to the transition between one super hyperfine structure level and the energy level associated with the next principal quantum number the population of the SHFS levels is indicated by peaks in the annihilation resonance. Frequency scanning a microwave beam repopulates the SHFS levels at the resonance energies, which are again detected by annihilation peaks.

the initial \bar{p} helium state is also well-shielded from collisions, minimizing the interaction with electric fields from other nearby atoms. The consequence is that \bar{p} helium deexcites by radiating optical-frequency photons as the antiproton cascades through a series of constant $n - 1 - 1$ metastable states. At $n = 32$ and lower, collisions with other atoms in the target chamber rapidly bring the antiproton orbit close enough to the nucleus that close-range, strong-force interactions dominate, and the antiproton subsequently annihilates with a nuclear proton.

The annihilation products, the burst of pions, are detected by Cerenkov radiation emitted as the particles travel through transparent sheets of Lucite. Approximately 97% of the incident antiprotons immediately annihilate, while, without intervention, the remainder annihilate along one of several possible $1/e$ distributions of about $3 \mu\text{s}$. The ASACUSA scientists, however, do provide additional intervention, in the form of laser irradiation. The second or

third harmonic of a Coherent Laser Division (Santa Clara, CA) Q-switched Nd:YAG laser pumps a Lambda Physik (Göttingen, Germany) dye laser to produce 4–6 ns pulses at wavelengths from 529–745 nm. To produce pulses from about 264–372 nm, the dye laser output is doubled in a β -barium borate crystal. As the laser wavelength is varied, absorbed photons induce transitions in the \bar{p} helium. If the final state is not metastable, resonances in the annihilation rate are detected (see Figure 2).

Varying the laser pulse wavelength provides information for a detailed spectrum of \bar{p} helium. Already more than 20 resonances have been identified and compared with predictions. The transition energy is a function of the Rydberg constant, which is proportional to $Q_{\bar{p}}M_{\bar{p}}^2$, where $Q_{\bar{p}}$ is the charge of the antiproton and $M_{\bar{p}}$ is the antiproton mass. The agreement between theoretical and experimental transition energies combined with previous measurements of the antiproton charge to mass ratio confirmed that the antipro-

ton mass is identical to the proton mass, within 60 ppb. Eades noted that this accuracy is equivalent to “measuring the height of two mountains the height of Everest, and finding them the same to within about half a millimeter.”

Extending the Investigation

With the first-order transition energies confirmed, the ASACUSA group turned itself toward measuring higher-order effects. Each (n, l) state is modified by spin-orbit interactions. The antiproton total magnetic moment is a function of both angular momentum quantum number and spin quantum number, where the *angular momentum* depends on orbital characteristics, while *spin* refers to the intrinsic magnetic moment of the respective particles. In the initial orbit, the antiproton’s angular momentum is on the order of 38, while its spin is $\frac{1}{2}$, as indeed is that of the electron. However, the electron’s spin moment results in a much stronger magnetic moment, so that the predominant interaction is between the antiproton’s orbital angular momentum and the electron’s spin. This hyperfine structure (HFS) is further complicated by the energy splitting of antiproton spin-orbit interactions, which creates a super hyperfine structure (SHFS). The end result is that each (n, l) state is first split into a doublet with level spacing of 10–15 GHz, then each of those levels is split into a doublet with 100 to 300 MHz level spacing. Again, if the energy level spacing created by the HFS and SHFS can be compared with prediction, values of both the antiproton’s orbital and spin magnetic moments can be determined. The antiproton’s orbital magnetic moment is known as the *antinuclear magneton*.

When \bar{p} helium is created, each of the four quadruplet substates is equally represented within the population. Although transitions between the quadruplet states can be induced by irradiating with microwave radiation of the proper frequency, all this does is redistribute specific atoms in different energy states, ending with the quadruplets still equally populated. To make the energy splitting detectable, the ASACUSA re-

searchers use a laser–microwave–laser triple resonance method.

The first laser pulse, triggered by the arrival of a packet of antiprotons into the helium target chamber, is tuned to excite a transition from a specific SHFS pair of a metastable level to a short-lived level. This pulse does two things. First, it creates an annihilation rate pulse with intensity proportional to the number of atoms excited into the unstable level. Second, it depletes one SHFS pair of the quadruplet states associated with level (n, l) . Then microwave radiation of a specific frequency is directed to the target chamber. If the microwave frequency is resonant with the energy required to flip the electron's spin direction relative to that of the antiproton's orbital angular momentum, then the incident pulse will induce transitions, tending to equalize the populations of the lower and upper quadruplet pairs once again. But this resonance is undetectable because it does not induce a change in the annihilation rate. If, however, a second resonant laser pulse is directed to the target chamber, then any atoms that have transitioned to the lower doublet will again be stimulated into an unstable state, leading to a detectable pulse in the annihilation rate. The measured quantity is then $I(t_2)/I(t_1)$, with $I(t)$ representing the Cerenkov radiation intensity at time t . If the microwave energy is off resonance, then the pulse at t_2 will excite no atomcules, and there will be no measurable annihilation rate increase. Peaks in the t_2/t_1 intensity ratio as the microwave frequency is scanned correspond to HFS energy level differences.

The first result, which the ASACUSA team recently published (*Phys. Rev. Lett.*, 9 Dec. 2002), concerns the strength of the antiproton's orbital magnetic moment. This is the product of the so-called *antinuclear magneton* (proportional to $Q_{\bar{p}}/M_{\bar{p}}$), the angular momentum quantum number, L , and an additional orbital g -factor, g_l , which is defined equal to 1 for the proton. If the antiproton is not the perfect opposite of the proton, then the antiprotonic g -factor will differ from 1. Although

initial analysis makes it appear that great surprises are unlikely, the results of this experiment will firm up our understanding of the antiproton's notoriously poorly known magnetic properties. Because protons do not orbit the nucleus of any known atom, this measurement of the ratio of antiproton magneton to proton magneton is the only direct evidence of their equivalence.

Consistent with Francis Bacon's statement that "if a man will begin with certainties he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties," the ASAC-USA team is constantly striving to achieve higher accuracy. Eades summarized this attitude: "Is the mass of the antiproton the same as the mass of the proton to one part in a million? Yes! Then let's see if at one part in ten million, they are different. Still the same? Yes! Then how about one part in a hundred million?"

More on the Way

The ASACUSA experimental plan includes measuring many more \bar{p} helium spectra, including some measurements of even more exotic atomcule configurations that have already begun. The researchers also hope to improve the experimental accuracy, and extend the precision of the comparison of protonic and antiprotonic quantities. The plan is ambitious. The measurements being made on antiprotonic helium essentially repeat "many of the classic experiments in the history of the hydrogen atom which took a century or more," Eades said. "This we are doing in a few years!

"We're aiming at high-precision measurements of as many of the antiproton's properties — mass, charge, magnetic properties, et cetera — as we can get at. The aim is ever-more-precise comparisons of the antiproton with the proton, because even a minute difference would be tremendously important to our picture of, and interpretation of, the world." ■