atoms to less than 100 atoms per cubic centimeter, a level which may be the best vacuum ever demonstrated. The greatest storage period so far, almost three and a half months, constitutes the longest directly measured lifetime limit for antiprotons.

To contain the antiprotons, the trap has a cylindrically shaped solenoid that creates a 6-T magnetic field. The powerful field forces the antiprotons into tiny circular paths. Making 90 million cyclotron orbits every second, the antiprotons generate a radio-frequency signal. The frequency, related to the particle's charge to mass ratio, can be used to calculate the mass of the antiproton.

Using this relationship, the research group compared the frequency generated by the antiproton to a frequency generated by a proton in the same field. At this new energy frontier,[2] they found the masses to be the same to at least 4 parts in 100 million, an accuracy more than 1000 times better than previous measurements that used an entirely different technique involving exotic atoms. This is the most stringent test yet of whether a baryon system is invariant under CPT transformations, an invariance which is widely assumed but infrequently tested at high precision. The Harvard–Mainz collaboration is now working to improve the precision by an order of magnitude or two.

The need to make precise mass spectroscopic measurements at the accelerator facility led to two innovations that show promise more generally. First, a Penning trap, composed entirely of standard ring electrodes, provided the large opening required for entering antiprotons. While similar configurations using hyperbolic electrodes have been employed before to merely contain particles, it is now possible to study the properties of "pseudo atoms"—the cylindrical trap plus its occupant particles, which may be only a single electron.[3]

The second innovation, a 6-T superconducting solenoid, cancels changes in the ambient magnetic field in which it is located. Conventional shielding materials, such as metal and iron, are worthless in a 6-T magnetic field, or even in the lower fringing field outside the solenoid. The new solenoids reduce fluctuations by a factor of 156, making precise mass spectroscopic measurements in the magnetically noisy accelerator environment possible. The innovation promises more precise mass spectroscopy in less noisy environments.

This past year scientists also made progress with more conventional ions isolated in Penning traps. Although field instabilities limited or greatly complicated mass spectroscopy, higher precision was obtained in more hospitable, magnetic environments. A University of Washington group reported a measurement[4] of the atomic mass of the proton with a precision of 3×10^{-9}. A Massachusetts Institute of Technology experiment,[5] similar except for an interesting sideband coupling technique, reported a record precision of 4×10^{-10} in a comparison of the masses of the ions CO^+ and N_2^+. Despite questions about the magnetic environment,[6] this progress bodes well for future measurements with more interesting species.

Gerald Gabrielse, Harvard University

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The Quantum Zeno Effect

In a thought-provoking article published in 1977, B. Misra and E. C. G. Sudarshan of the University of Texas claimed that an unstable particle would never decay if observed continuously.[1] Recording the track of the particle in a cloud chamber approximates a continuous observation, but does not seem to modify its lifetime. They called this apparent contradiction the quantum Zeno paradox, named after Zeno of Elea, a Greek philosopher known for formulating several paradoxes, one of which seemed to prove that motion is impossible.

According to Misra and Sudarshan's argument, the particle is initially in the undecayed state. In time, however, the wave function characterizing the particle changes to a superposition, which includes a component that corresponds to a decayed particle. Superposition states are fundamentally quantum objects, not describable in terms of classical physics. A measurement projects the system into one state or the other. If the period before the measurement is very short, the system will almost certainly be projected back to the undecayed state, since the wave function has not had much time to change, and if measurements are made frequently enough, the system is prevented from decaying at all.

A system like this one has never been observed. Apparently, measurements can never be made quickly enough to have much effect on a spontaneous decay rate. This is the resolution to Misra and Sudarshan's original paradox. An effect can, however, be observed on stimulated transitions. Suppose a system is prepared in one state, and a perturbation is applied to drive it to another state. If frequent measurements are made, the system can be prevented from changing its state. This form of the quantum Zeno effect is another consequence of Misra and Sudarshan's general arguments.

Following a suggestion by Richard Cook of the United States Air Force Academy,[2] researchers at the National Institute of Standards and Technology devised an experiment using $^{9}Be^{+}$ ions to demonstrate this form of the quantum Zeno effect.[3] The research team suspended about 5000 ions in a vacuum by a combination of electric and magnetic fields called a Penning trap. Using laser radiation, the research team pumped all the ions into a sublevel of the electronic ground state. After applying a 321-MHz radio frequency for 256 ms, the ions made a transition from the first sublevel into a second, slightly higher sublevel.

The researchers shot from 1 to 64 short laser pulses at the ions during the 256 ms that the radio-frequency energy was applied. Ions that made the transition did not emit photons when subjected to the laser pulses. Ions remaining in the first sublevel, however, were excited to a higher, third level, and then immediately decayed, emitting photons. At the end of the 256-ms period, the laser was turned on and kept on, and the intensity of the photon emission was recorded. The intensity was proportional to the number of ions remaining in the first sublevel. The number of ions reaching the second sublevel decreased as the number of laser pulses increased. For 64 pulses, the number of ions reaching the second sublevel was no more than the experimental uncertainty of 2%.

Since the results are completely in accord with standard quantum mechanics, there is no paradox. What the experiment demonstrates is the creation and destruction of superposition states in a well-controlled manner.

Wayne M. Itano,
National Institute of Standards and Technology

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High-Order Harmonic Generation

Harmonic generation in gases, a method of providing short-wavelength coherent radiation, has been the subject of active research for many years. Harmonic generation of laser photons in a nonlinear medium produces photons at frequencies that are integer multiples of the original laser frequency. This process, which requires high laser intensities, is limited, however, by several factors, including ionization of the gas, absorption of the short-wavelength radiation in the medium, and the difficulty of efficiently phase matching the different harmonics simultaneously. Therefore, high-order harmonic generation in gases was believed to be an unlikely path to the production of very-short-wavelength radiation.

Recently, exciting experimental results obtained using short-pulsed, intense lasers show that these problems can be avoided to a significant extent. Very high harmonics of the pump frequency were observed in jets of rare gases with relatively high conversion efficiencies. These experiments demonstrate the possibility of producing short-wavelength, short-pulse, coherent radiation at frequencies normally available only at synchrotron facilities.