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Experiment challenges theory in positronium measurements

Positronium—the bound state of an electron and positron—appears to decay more rapidly than calculations based on quantum electrodynamics predict. Four experiments over the last ten years have measured decay rates for positronium's triplet ground state that were higher than current theoretical estimates, but never by more than a few standard deviations. In a recent experiment with four times greater precision, Chris Westbrook, David Gidley, Ralph Conti and Arthur Rich at the University of Michigan determined a decay rate that is ten standard deviations higher than the theory predicts.¹ They reported a value of 7.0516 ± 0.0013 per second, compared with the theoretical prediction of 7.03830 ± 0.00007 per second. Numerical integration contributes an uncertainty in the fifth decimal place of the prediction.

The QED calculations have so far only included the first-order radiative corrections, and the next-higher-order term might explain the discrepancy. With considerable additional effort, theory and experiment may yet come into line. At this point, theorists are eyeing with some trepidation the formidable task of computing the next radiative correction while experimenters are still checking carefully for hidden systematic errors.

Precision measurements. The University of Michigan team managed to determine with an accuracy of 200 parts per million the fleeting lifetime of a relatively rare entity. They are measuring the 140-nsec lifetime of the triplet ground state 1^3S_1 of positronium, called orthopositronium. The other positronium ground state is the singlet state (1^1S_0), called parapositronium, which lives only about 0.1 nsec.

Rich and his colleagues used a 10-microcurie sample of radioactive sodium-22 to produce positrons. Those with a forward velocity entered a 14-cm-long gas chamber, spiraling in a confined region under the influence of an applied 6.8-kG magnetic field. The positrons from the sodium decay had sufficiently low energy that about 25% of them stopped in the gas and formed positronium. The magnetic field mixes the singlet state with the $m = 0$ triplet

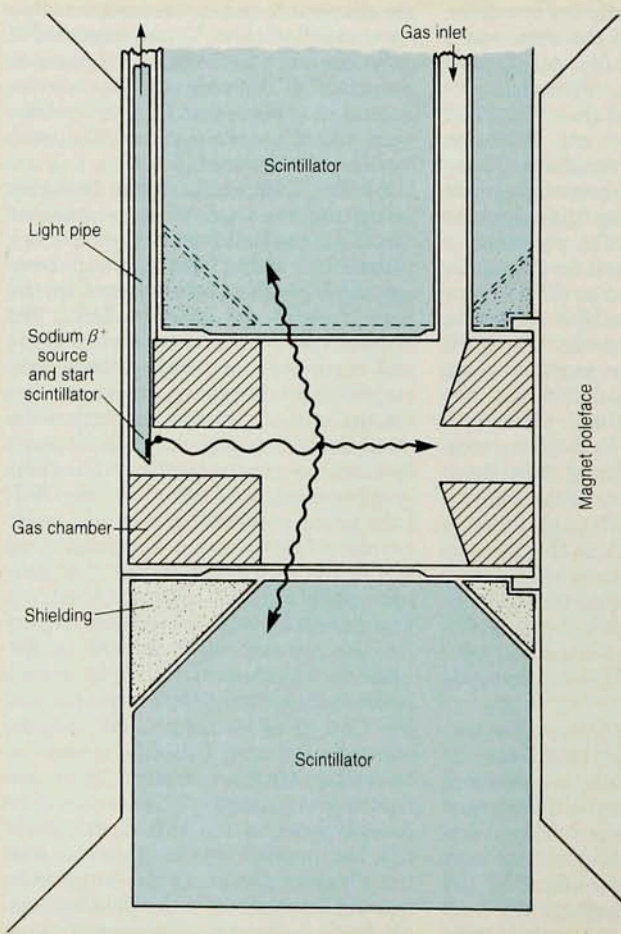
substate, and the longer lived of these perturbed states has a lifetime of 13 nsec.

The lifetime count began when positrons from the sodium source passed through a scintillator, and stopped when annihilation gamma rays were detected by an annular plastic scintillator surrounding the gas chamber. (See the drawing below.) The Michigan team then fit an exponential decay rate to the histogram of the measured time intervals, using only times greater than 150 nsec so as to exclude background from shorter-lived states. They took data with two independent timing systems to eliminate the possibility that a systematic error in either one biased the results.

The greater the gas pressure, the higher is the measured decay rate: More frequent collisions make it more

likely that the positron annihilates with an electron from a molecule. Thus the Michigan team measured the decay rate at several different densities and extrapolated to the value at zero density.

Even for measurements at the same density, however, they had difficulty fitting an exponential to the observed decay distribution. At the lowest pressures used in their experiments (about 100 torr), the decay rate declines as shorter time intervals are excluded from the fit, and approaches an asymptotic value for time intervals greater than 175–200 nsec. When early time data were included, the decay rate appeared artificially high. Rich and his colleagues attribute this effect to thermalization, or slowing of the positronium atoms by collisions in the gas. At early times, the positronium is



Gas chamber to measure positronium lifetime is the central region in this schematic drawing. Positrons from a radioactive source spiral into the chamber and form positronium in the gas. A scintillator detects the sodium decay to start the timer, and plastic scintillators surrounding the chamber sense the annihilation gammas to stop the timer.¹

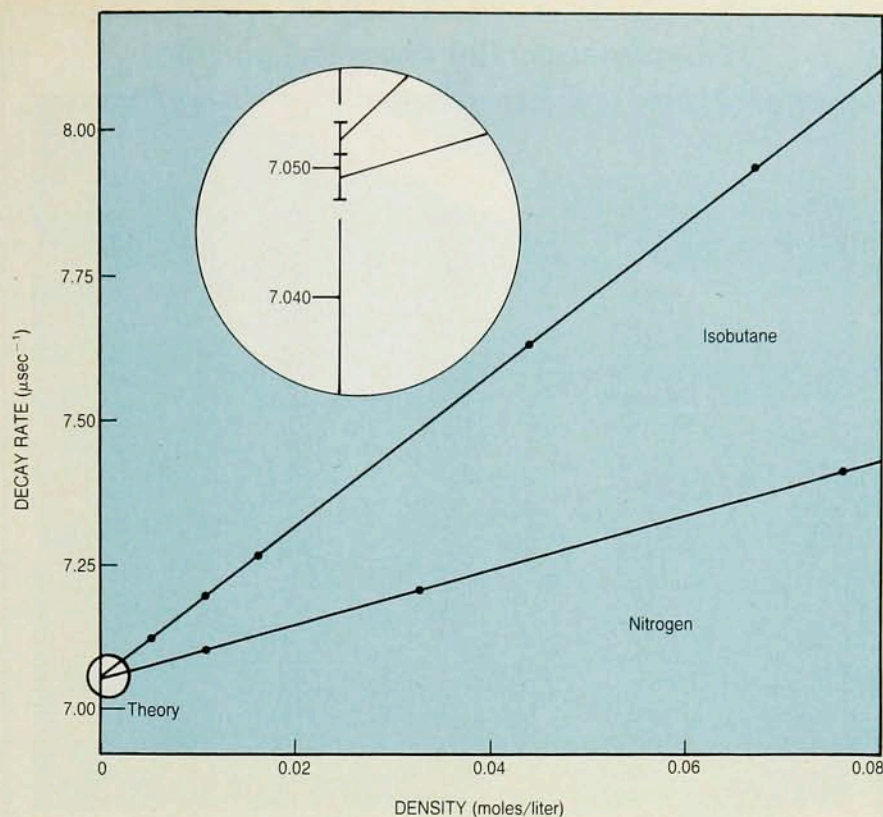
traveling faster and its decay rate is spuriously high. The effect is not apparent at higher pressures, where thermalization may occur on a time scale short compared with the triplet lifetime. Thus the Michigan team uses the asymptotic decay rate for the low-pressure data.

Rich told us that the most likely source of a systematic error in their experiment would be some interaction not yet accounted for between the positronium and the gas. To minimize the effects of any such errors, he and his colleagues ran their experiment with four different gases. Two of the gases were isobutane and neopentane, which are preferred because they quickly annihilate those positrons whose energy is too low to form positronium. However, these substances have relatively large virial coefficients, so the Michigan group also made measurements on nitrogen and neon, both of which are closer to ideal gases. Data from all four gases converged to the same decay rate when extrapolated to zero gas density, increasing one's confidence that no gas-dependent errors were present. (See the graph at right.)

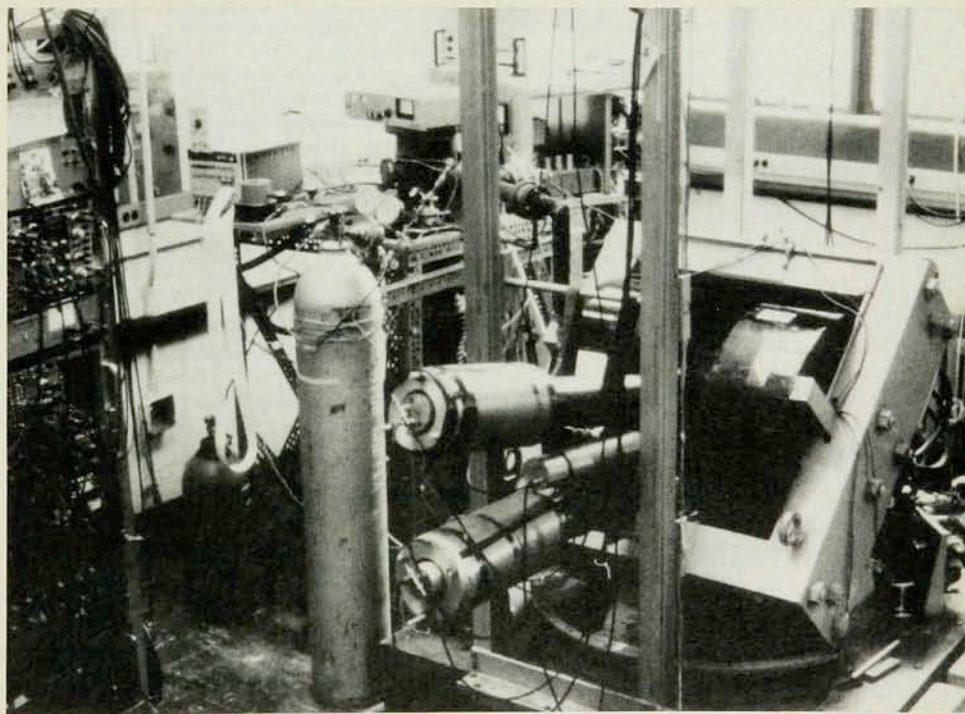
Although the influence of the magnetic field on positronium is better understood than its interactions with the gas, this experiment alone cannot rule out magnetic field effects because it used the same magnetic field throughout. Westbrook, however, has compared the present measurements on isobutane at 200 torr with data from an earlier Michigan experiment² conducted at about 4 kG. He told us that the data agree within 300 parts per million.

Another factor that might distort the measured decay rate would be the presence of excited states of positronium. While most of the $n=2$ levels decay in a few nsec or less, the triplet S state annihilates with a lifetime of 1.1 microseconds. The Michigan team estimates that their sample might include 1% of this state, at most, and they expect that it very quickly dissociates or falls to the ground state. In a separate experiment they determined a 20-nsec lifetime for the 2^3S_1 state in 1 millitorr of gas. Although the gas composition (mostly N_2) in this test was not known precisely, so short a lifetime at such a low pressure precludes the effect of a long 2^3S_1 lifetime on the orthopositronium measurements.

Other experiments. The best check on systematic effects is to measure a consistent result with a totally different method. The four previous determinations of the orthopositronium decay rate featured positronium formation in a gas,³ in a powder² and in a vacuum.⁴ To obtain a level of accuracy



Positronium decay rate in vacuum is extrapolated from measurements in four gases at different densities. Data for neopentane and neon fall nearly on top of lines shown for isobutane and nitrogen, respectively. Magnified inset compares experimental measurements to QED predictions.



Experimental setup with which the University of Michigan group found a discrepancy between a positronium decay rate and its QED predicted value. The gas chamber sits between the poles of the 12" nmr magnet. Positrons come from a radioactive source in the chamber.

LEP preaccelerator linacs inaugurated



The tandem pair of linear accelerators shown here comprise the first stage of the Large Electron Positron collider injection system. These LEP injector linacs were inaugurated at CERN in July. The first linac will accelerate electrons to 200 MeV and focus every second pulse onto a positron-production target. The second linac will accelerate the electrons and positrons to 600 MeV, before they are passed on to a sequence of accumulator and accelerator rings preparatory to final injection into the 27-km-circumference collider astride the French-Swiss border near Geneva. In the main LEP ring, countercirculating electron and positron beams will be accelerated to 60 GeV. The linacs were built at CERN in collaboration with the Orsay Laboratoire de l'Accélérateur Linéaire.

LEP is scheduled to be ready for physics in the spring of 1989. Tunneling is nearing completion, and the first bending magnets were ceremonially installed in June. Also in June, the CERN Council formally adopted the long-range plan that calls for the gradual upgrading of the LEP beam energy to 100 GeV by the installation of superconducting rf cavities. The Council's long-range planning committee, headed by Carlo Rubbia, urges continued "vigorous" examination of the prospects for eventually building a proton-proton collider in the LEP tunnel with 14–16 TeV in the center of mass. (See the news story on page 71.)

comparable to the most recent experiment, Gidley, Rich and their Michigan colleagues Jeffrey Nico and Paul Zitzewitz (all of University of Michigan) have begun a measurement of the orthopositronium decay rate in vacuum. Low-energy positrons form positronium in the magnesium oxide powder coating of an evacuated cavity. When the positronium escapes into the vacuum and decays, annihilation photons are detected by a plastic scintillator surrounding the cavity. The slow positrons are formed when a beam of fast positrons strikes a nickel crystal—a technique used in other positronium experiments (see *PHYSICS TODAY*, July 1982, page 17). Secondary electrons generated at this crystal signal the formation of slow positrons, and this time tag controls a gate that allows the

incoming beam to enter the vacuum chamber. Annihilation gammas must be correlated with this start signal.

Theoretical implications. The expression for the decay rate of orthopositronium into three gammas is given as follows:

$$\lambda_3 = \frac{\alpha^6 mc^2}{\hbar} \frac{2(\pi^2 - 9)}{9\pi} \left[1 + A \cdot \left(\frac{\alpha}{\pi} \right) + \frac{1}{3} \alpha^2 \ln \alpha + B \cdot \left(\frac{\alpha}{\pi} \right)^2 + \dots \right]$$

where α is the fine-structure constant. (The decay rate to five gammas is a million times slower.) The calculated value for A is about -10.2 , and the value for B remains to be determined. B would have to be 340 for the predicted decay rate to match the recent experiment. For most other expansions in QED, the coefficients of all

terms are on the order of one, although larger coefficients cannot be ruled out.

Peter Lepage (Cornell University), who together with William Caswell and John Sapirstein (Notre Dame) calculated⁵ the second term in 1977 told us that the value of A already surprised everyone by being so large. He cannot give any physical reason why the coefficient is so large, but given that it is, he sees no reason to doubt that the coefficient of the next term might be about 300. Gregory Adkins (Franklin and Marshall College), who calculated⁶ a value for the second term consistent with the recent results of Caswell and Lepage,⁷ also expected that the next term would bring the theory in line with the experiment.

If B is as large as 300, however, it might signal that the perturbation expansion is an inappropriate way to treat the radiative corrections. Any such problems in the treatment of leptonic bound states by QED might be exaggerated in treatments of the relativistic quark-antiquark bound states in quantum chromodynamics; the formalism is analogous but the hadronic expansion parameter in the series of radiative correction terms is ten times the fine-structure constant that appears in QED. The decay rates of the quark-antiquark states J/ψ and Υ into three gluons would be the most directly affected. These decay rates are currently used to determine the strong-interaction coupling constant, but that method would be suspect if the perturbation series expansion in QCD is shown to be inappropriate.

The positronium-QCD discrepancy has opened the door for some speculations about exotic particles not yet observed into which the orthopositronium may be decaying. Lepage thinks it unlikely that such particles could exist without affecting properties like the magnetic moment of the electron, which is known to 11 decimal places.

—BARBARA G. LEVI

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