

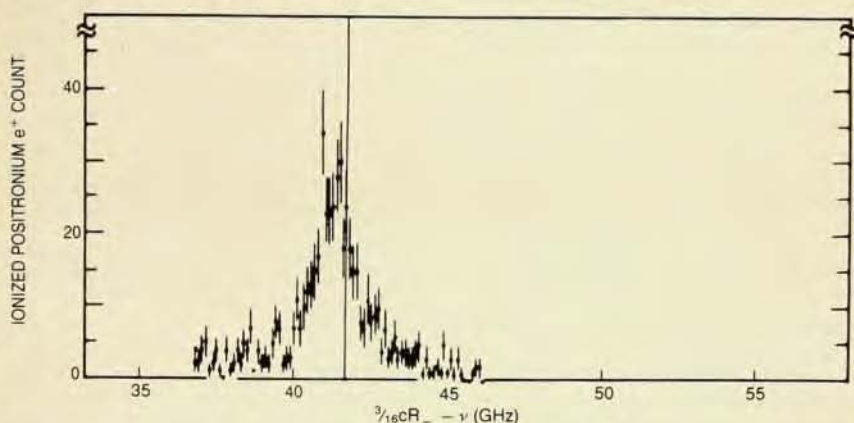
Two-photon laser excitation yields positronium 1S–2S line

Positronium—the bound state of an electron and a positron—entices the experimenter with a unique opportunity for testing the predictions of quantum electrodynamics. Not only does this purely leptonic “atom” avoid the complications of hadronic nuclear structure, but it also involves virtual-annihilation terms absent in the case of hydrogen or muonium. Furthermore, because the usual reduced-mass formalism for hydrogen-like atoms is relativistically inappropriate for this system of two equal masses, one must use the Bethe-Salpeter formalism rather than the Dirac equation as the starting point for calculating QED corrections in positronium.

The experimental problems confronting positronium spectroscopy are however formidable. Positrons produced by β^+ emitters are exceedingly scarce compared with the usual objects of spectroscopic investigation, and they emerge from nuclear decays with far too much energy. The triplet state 1^3S_1 survives for only about 100 nanoseconds before annihilating—and that is the longer lived of the two ground states of positronium. Being much lighter than hydrogen, positronium is severely afflicted by Doppler broadening. The most straightforward method of producing positronium—stopping positrons in a gas—results in unacceptably large pressure broadening.

In spite of the prodigious difficulties inherent in this exotic spectroscopy, we now have the first measurement of an optical excitation in positronium. In a recent *Physical Review Letter*, Steven Chu and Allen Mills at Bell Labs report¹ a Doppler-free measurement to one part in a million of the two-photon excitation from the triplet ground state to the 2^3S_1 state. They find no departure from the QED prediction. Indeed one does not expect to find disagreements with QED as large as a part in 10^6 . Chu and Mills hope soon to refine their techniques to measure this transition to a part in 10^8 —the accuracy to which the analogous transition energy is known for hydrogen.

Positronium formation was first seen by Martin Deutsch at MIT in 1951, by



Positron signal from ionized positronium, plotted against the laser frequency that excites and then ionizes the positronium, provides a high-precision measurement of the 1^3S_1 – 2^3S_1 excitation energy. The transition frequency is twice the peak laser frequency because two photons from opposite directions accomplish the Doppler-free excitation. The frequency is plotted as GHz below $\frac{3}{16}cR_\infty$, the first-order value of half the transition frequency. The vertical line gives the higher-order QED prediction. Absolute calibration is provided by a Fabry-Perot interferometer frequency marker, calibrated to the Balmer β lines of hydrogen and deuterium.

examining the annihilation of positrons stopped in gases. Ignoring fine structure and higher corrections, the spectrum of positronium is the same as the hydrogen spectrum, except that the Rydberg constant is only half its usual value. That is to say, the fact that the reduced mass in positronium is $\frac{1}{2}$ the electron mass reduces all first-order transition energies by a factor of two.

The 1S–2S transition is particularly interesting in both hydrogen and positronium because the natural linewidth for this transition is exceedingly narrow. This sharply defined energy corresponds to the fact that the 2S state is very long lived; a single-photon transition to the ground state is prohibited because there is no change of angular momentum. But the 2S state of hydrogen can decay to the ground state by the emission of two photons, with a lifetime of about $\frac{1}{7}$ of a second.

In 1970, L. S. Vasilenko and his colleagues at the Institute for Thermophysics in Novosibirsk suggested that the inverse process (1S→2S) in hydrogen could be induced by the “simultaneous” absorption of two photons of equal energy from counterpropagating

beams. Such a technique, they pointed out, would cancel (to first order) any Doppler broadening of the linewidth due to the thermal motion of the hydrogen atoms; the blue shift of one photon would (in the nonrelativistic limit) cancel the red shift of the photon absorbed from the opposite direction. An additional experimental advantage of the two-photon technique for hydrogen is that it involves two photons in the near ultraviolet range rather than a single vacuum-ultraviolet (1215 Å) photon. If one could apply this technique to positronium, where all binding energies are halved, one would be using two 4860-Å photons—in the visible.

The Doppler-free two-photon excitation of the 1S–2S line of hydrogen was finally accomplished in 1974 by Theodor Hänsch, Siu Au Lee and Carl Weiman at Stanford. To induce the absorption of two photons in a sufficiently short time interval for this technique to work, one needs an intense source of highly monochromatic light. To this end Hänsch and his colleagues developed a high-power, pulsed, tunable dye laser. The visible light output of the laser was tuned to $\frac{1}{4}$ the transition

frequency, passed through a frequency doubler and reflected off a mirror to produce two beams that illuminated the hydrogen from opposite directions.

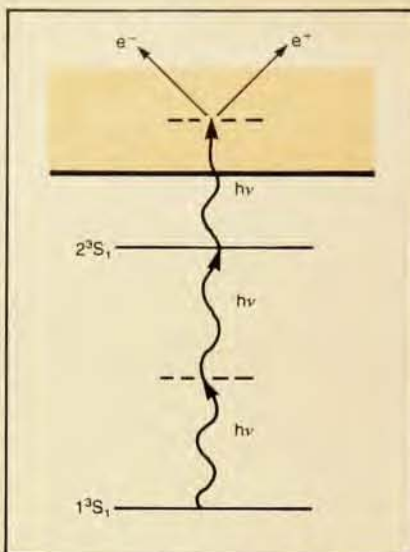
Applying this technique to achieve a Doppler-free measurement of the 1S-2S line of positronium requires the solution of a number of special problems: Starting with MeV positrons from a β^+ source, one wants to obtain a sample of *slow* positronium atoms, with thermal energies on the order of 0.1 eV, because even the second-order Doppler broadening is severe for so light an atom. Furthermore, to avoid pressure broadening of the transition line, the positronium must be in vacuum; one cannot use Deutsch's method of forming positronium in a gas.

Another problem is how to cram enough positronium into the all-too-brief laser-pulse time intervals. Lasers of the type developed by Hänsch have a pulse duration of only about 10 nanoseconds; they must then recover for about 100 milliseconds. Thus one is wasting all but one part in 10^7 of the output of a β^+ source unless one can devise a method for time-bunching the positron beam to match the laser's duty cycle.

In 1974 Stephan Berko, Karl Canter and Mills (all then at Brandeis) succeeded for the first time in producing slow positronium efficiently in a vacuum. They discovered that when a beam of slow positrons (a few eV) is made to strike a solid surface in vacuum the positrons penetrate a short distance into the material, and then a large fraction diffuse back to the surface and emerge as slow positronium. In 1975 the Brandeis group exploited this technique to make the first observation of the $n=2$ excited state of positronium and measure the microwave-excited Lamb shift: 2S $\rightarrow$ 2P (PHYSICS TODAY, May 1975, page 17).

The slow positron beam in the Chu-Mills experiment has its origin in a cobalt-58 β^+ source. The first problem is to reduce the energy of these positrons by three orders of magnitude. MeV positrons would penetrate far too deeply into the positronium-formation target to generate positronium at its surface with reasonable efficiency. Chu and Mills obtain a slow positron beam by directing the fast positrons from the cobalt source at a "position moderator"—a single crystal of ultra-clean copper oxide. The method exploits the negative affinity for positrons exhibited by copper (and a number of other materials). The technique was first attempted by Leon Madansky and Franco Rasetti at Johns Hopkins about 30 years ago, and later developed by William Cherry at RCA, J. W. McGowan and his colleagues at Gulf Atomic Research, and Canter at University College, London.

In the late 1970s, Mills undertook a



The two-photon excitation of the $1^3S_1 \rightarrow 2^3S_1$ positronium transition is Doppler-free to first order because the two 4860-Å photons come from opposite directions. A third photon ionizes the excited state, the resultant positrons providing the experimental signal.

systematic study at Bell Labs of the interaction of positrons with clean metallic surfaces, resulting in the development of a copper moderator that yields an enormous increase in the emission efficiency of slow positrons. The fast-decay positrons penetrate into the copper crystal, thermalize, and then some fraction diffuse back to the surface. The diffusion length is greatly enhanced by the fact that the copper is a single crystal. If the copper surface is sufficiently clean, Mills found that fully half of the thermalized positrons returning to the surface will be spontaneously expelled by its negative work function, the negative affinity of the bulk copper for positrons. The moderator in the Chu-Mills experiment yields about one slow positron for every thousand fast incident positrons. The result, after collimation, focusing and velocity selection is a beam of 1-eV positrons with an intensity of about 10^6 per second.

Although this intensity exceeds by a factor of thirty the best that Berko and his colleagues had been able to achieve at Brandeis in the mid-1970s, it is still far too meager for two-photon positronium spectroscopy, unless one can bunch the positrons to coincide with the laser pulse. To this end, Mills has developed a magnetic bottle to store slow positrons during the recovery time of the laser. The beam is transported into the bottle, which consists of a magnetic mirror at the downstream end and a positively biased grid upstream. A transverse rf field is imposed on the trapped positrons to excite cyclotron motion, thus preventing their passage

through the mirror. After the slow positrons have been collected in this manner for 100 microseconds, a harmonic-oscillator potential is suddenly imposed on the system, impelling the accumulated positrons toward the positronium target in a 10-nanosecond burst. "This bunching gives us a much improved impedance match with the pulsed laser," Mills told us.

The positronium-formation target employed by Chu and Mills is also a copper crystal, heated to 1000 K. They find that about $1/3$ of the positrons diffusing back from the target interior become bound in an image potential well at the copper surface long enough to form positronium, which is then thermally desorbed with a 1000-K thermal distribution (about $1/10$ eV).

Spectroscopy. After the positron beam hits the heated target, one waits 30 nanoseconds for a "cloud" of thermal positronium to drift away from the surface. At this point the laser beam and its mirror reflection are fired in opposite directions through the cloud. The dye laser is tuned by adjusting the nitrogen pressure in the laser oscillator. The experimenters tune the laser output frequency through one half the 1S-2S transition frequency of positronium and the frequencies of the nearby Balmer β lines ($n=2$ to 4) of hydrogen and deuterium. The hydrogen and deuterium, confined in a discharge tube that receives a portion of the laser beam, provide the absolute calibration of the laser frequency. To first order, the Balmer β frequencies of H and D are just one half the positronium 1S-2S frequency.

Because the positronium transition involves the absorption of two photons of equal energy, the transition frequency is of course twice the laser frequency. But there is in fact a *third* photon involved in each positronium excitation. When a positronium atom is excited by two photons to the 2S state, its binding energy is now sufficiently low to permit its ionization (breakup into e^+ and e^-) by a third photon from the laser beam. It is precisely the positrons thus generated that provide the signal for the excitation of the 2S state in this experiment. Chu and Mills use this signal rather than delayed annihilation gammas because charged particles can be detected with much greater efficiency than high-energy photons, thus providing a very good signal-to-noise ratio. The 10-ns time resolution of the charged-particle detector permits one easily to distinguish the ionization positrons from stray positrons generated 30 ns earlier by the arrival of the beam. The use of the ionization signal is another reason why the positronium must be excited in vacuum.

Because the singlet ground state of

positronium lives only about $\frac{1}{8}$ of a nanosecond, one knows that the 1S-2S line recorded by the ionization signal represents the triplet-state transition $1^3S_1 \rightarrow 2^3S_1$. The two-photon transition frequency thus recorded turns out to be (41.4 ± 0.5) GHz below $\frac{3}{16}cR_\infty$, the first-order frequency of the positronium 1S-2S transition. (R_∞ is the ordinary Rydberg constant.) This result agrees within the experimental uncertainty (about one part in 10^6) with the second- and third-order QED corrections calculated by Thomas Fulton and Paul Martin (Johns Hopkins), and Richard Ferrell (Princeton). Fulton, who has recently updated² his earlier third-order calculation for comparison with this experiment, told us that such positronium predictions "make the Bethe-Salpeter formalism jump through hoops." Thus they should provide useful insights, he suggests, for analogous calculations of light-quark bound states in quantum chromodynamics, which also require the Bethe-Salpeter formalism.

"Nobody doubted that at this level of accuracy the result would agree with QED," Mills told us. "The number is interesting primarily because it points the way to ultrahigh-precision optical spectroscopy for positronium." The

success of this rather eclectic experiment has already generated considerable enthusiasm among spectroscopists. The precision of the present result is limited basically by the linewidths of the calibrating H and D Balmer β absorption lines rather than by statistics. Thus, with better laser metrology and a continuous-wave dye laser, Chu and Mills, working with John Hall from the National Bureau of Standards, hope soon to measure the $1^3S_1 \rightarrow 2^3S_1$ transition to a part in 10^6 .

Vernon Hughes (Yale), Hänsch and Richard Howell (Livermore) are planning to use a Livermore 100-MeV electron linac as a pulsed source of slow positrons for positronium spectroscopy. This should provide at least a thousandfold increase of positronium formation over the Bell Labs experiment, Hänsch told us. Chu and Mills are planning eventually to avail themselves of the beam dump from a free-electron laser being built at Bell Labs by Earl Shaw and Kumar Patel to achieve a ten-thousandfold increase in positronium intensity. —BMS

References

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Monte Carlo yields hadron masses

The odds look increasingly favorable that Monte Carlo methods will pay off as a computational tool in the theory of quarks. Over a year ago, theorists began to gain insight into the nature of strong interactions by applying statistical methods to a formulation of quantum chromodynamics on a discrete space-time lattice, but their calculations involved only a pure gluon field and no quarks. The inclusion of fermions, and hence the calculation of physical observables, appeared to require formidable amounts of computer time. In the interim, several theorists have devised approximations and algorithms that allow them to estimate some hadron masses with fairly good agreement and with reasonably small errors. Reaction to this new work has ranged from careful scrutiny of the specific premises to great enthusiasm for the general promises of the technique.

The first estimates of hadronic masses were reported in several papers last winter. Herbert Hamber (Brookhaven) and Giorgio Parisi (National Institute of Nuclear Physics, Rome) based¹ their computations on the group SU(3) and found the masses of the rho meson, the proton and the delta resonance (among others) to be (800 ± 100) MeV, (950 ± 100) MeV and (1300 ± 100) MeV, respectively. (Compare

these to experimental values of 765, 941 and 1236 MeV.) Enzo Marinari (G. Marconi Institute of Physics, Rome), Parisi and Claudio Rebbi (Brookhaven) performed² similar calculations using SU(2); although this group does not include the baryons it is similar to SU(3) and allows greater simplicity in calculations. They estimated the rho mass to be about (800 ± 80) MeV. At the same time Donald Weingarten (Indiana University) submitted³ his results on the icosahedral subgroup $\bar{I}$ of SU(2). Weingarten cites a rho mass of (670 ± 100) MeV and argues that this value would not change if the calculation were performed on SU(3). Since then, Weingarten told us, he has repeated his computations for SU(3) and has obtained masses for the rho, proton and delta of $610 (+100, -120)$, $1200 (+380, -430)$ and $1490 (+250, -310)$ MeV, respectively.

All these treatments adjust free parameters in the theory to fit the known pion mass and the slope of the Regge trajectory. (The Regge trajectory is the line in a plot of mass versus angular momentum along which lie all members of the same hadron family. In the quark theory, the slope of this line is equal to the "string tension," or long-distance potential between quark and antiquark.) The recent calculations also make the critical assumption

that the mixing of a given state with extra quark pairs can be ignored. Equivalently, in the language of the parton model, they include only the "valence" quarks and ignore the effect of the quark-antiquark "sea." The gluon gauge field is treated exactly.

This approach has since proved fruitful for at least one other collaboration to explore⁴ further aspects of quantum chromodynamics. The team consisted of John Kogut, Michael Stone and H. William Wyld (University of Illinois), Junko Shigemitsu (Brown University), Stephen H. Shenker (University of Chicago) and Donald K. Sinclair (Stanford). They have been investigating the range of forces responsible for the breaking of chiral symmetry—the symmetry dealing with the relative directions of velocity and spin—using a formulation of a theory involving a lattice of fermions that has no free parameters.

A European collaboration has taken an entirely different tack. Those involved are Anna Hasenfratz (Central Research Institute, Budapest) and Z. Kunzst (Eötvös University, Budapest) together with Peter Hasenfratz and Christian B. Lang (CERN). They treat all orders of quark interactions but use an expansion similar to a high-temperature expansion in statistical systems. The range of validity of their results is thus limited to lattice grid spacings greater than a certain length. They find the masses of some mesons and of the quarks, using the rho mass as one input.

Sidney Coleman (Harvard) is enthusiastic about the significance of this recent work for elementary-particle theory. He feels that, regardless of the validity of each particular step, the important contribution has been to show that quantum chromodynamics lies within the grasp of numerical computation. Coleman likens this period to the early days of quantum mechanics, when the crucial test of the new theory was not the exact derivation of the orbits in the hydrogen atom but rather the more complex numerical calculation of the ground state in the helium atom.

Details of the methods. The latest calculations build on the earlier progress in applying statistical methods to a lattice gauge theory of quantum chromodynamics (PHYSICS TODAY, October 1981, page 18). Kenneth Wilson (Cornell University) and Alexander Polyakov (Landau Institute in Moscow) first proposed a lattice gauge theory for particle physics. Formulating a gauge field on a discrete space-time lattice avoids the ultraviolet divergences because no wavelength can be shorter than twice the grid spacing. Associated with each pair of points on the lattice is the link variable, an element in a