

levels and quantized steps in Hall conductivity by just the observed amount.

Both in the quantum Hall regime and in the absence of a magnetic field, the longitudinal resistance rises markedly when the gate voltage is turned off so that the Fermi level lies at the intersection between the two bands. The density of states should be extremely small there, effectively zero where the bands meet. That makes it exceedingly sensitive to fluctuations. But, contrary to their expectations, both research teams find that the electrical conductivity of graphene never falls below a certain minimum value, even when there are no mobile electrons in the graphene sheet.

Geim's graphene devices differ from Kim's in only one respect. Both groups peel away graphite layers and follow similar protocols to locate their monolayer flakes, which come in various sizes. To make devices, though, Geim's group etched away the edges of each flake to create Hall-bar geometries with well-defined lengths and widths. In an experiment that measured the resistivity of 15 such samples with widely varying electron mobilities, Geim and colleagues found that the maximum resistivity averaged, to within 10%, a distinct value, $h/4e^2$. A quarter century ago Nevill Mott argued that the mean-free path for electrons in a metal can never be shorter than their Fermi wavelengths. Geim says his experimental result makes sense in that context, at least for 2D Dirac fermions, and demonstrates a fundamental quantized limit to the metallic system's minimum conductivity. But not everyone agrees, and the actual value for such a limit remains unclear. Boston University's Antonio Castro Neto comments, "We'll have to rewrite the theory of metals for this problem."

Making devices

Advocates of carbon nanotubes have long argued that their remarkable electronic properties—ballistic transport observable up to room temperature, for instance—make the material an ideal replacement for silicon electronics. The hurdle in achieving that vision has always been what to do about the 1D nature of the tubes. Making a circuit always involves attaching the nanotubes to other metals, which creates large contact resistances.

The availability of graphene layers provides a way around the problem. Electronically, graphene sheets should be identical to nanotubes. But its 2D structure—effectively an unrolled tube—allows the material to be engineered to suit different device applications. Graphene is a semimetal at the micron scale or larger. But when it is trimmed down to less than 100 nm, electron confinement opens its bandgap, an effect that can be used to tune the crystal's electronics for different purposes. Georgia Tech's Walter de Heer envisions graphene sheets sliced wider or narrower and in different patterns depending on whether it's a wire, ribbon, or some other component needed to make up a circuit. To avoid the contact-resistance problem, for instance, one could pattern the graphene sheet into an array of thin parallel strips or wires.

Interest in the micromanipulation of graphitic crystals has been intense, even before researchers could isolate graphene. Paul McEuen's group at Cornell University recently wired up 5-nm-thick graphitic quantum dots on SiO_2 and measured conductance properties.⁵ And prior to their *Nature* report, Kim's group measured the transport in crystals made using a "nano-pencil," which rubs off thin layers from a force microscope's cantilever whose tip is a graphite crystal.⁶ De Heer and his colleagues take a dif-

ferent approach, growing ultrathin graphite on silicon carbide, which provides an epitaxial orientation.⁷ "We peeled layers [too]," de Heer said, "but that reminded me too much of the nanotube track," which involves the labor-intensive process of harvesting the nanotubes and then manually laying them on some surface. Growing single sheets of graphene remains a problem—the monolayer crystal flakes are most vulnerable to damage while being cooked up in the ovens.

Still, de Heer's group has achieved mobilities up to 10 000 cm^2/Vs in their graphite crystals. In comparison, graphene has shown mobilities as high as 50 000 cm^2/Vs . The 10⁷ cm^2/Vs now achievable in quantum-well heterostructures like gallium aluminum arsenide seems a long way off. But the tough, resilient nature of carbon may allow some chance of getting clean and nearly perfect crystals at some future stage, argues Columbia's Horst Stormer. "In all the research in 2D, higher mobility was always what led you to new horizons."

Mark Wilson

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Densely Packed Positronium Atoms Interact Chemically

Nature's simplest atom does not appear in the periodic table. Positronium (Ps), the short-lived bound system of an electron and its antiparticle, the positron, was independently predicted by Arthur Ruark and John Wheeler after the positron was discovered in 1932. Four years before positronium itself was discovered in 1951, Egil Hylleraas and Aadne Ore had performed a variational calculation¹ and concluded that Ps atoms could combine to form the diatomic

For the first time, experimenters have seen atoms made from an electron and a positron exchange spins and perhaps form diatomic molecules.

molecule Ps_2 . Two Ps atoms can also interact by swapping the spins of their two electrons or positrons.

Interactions of Ps atoms with each other are much more difficult to observe than to envision. To create Ps, researchers shoot positrons at a suitable target. If the Ps atoms are to be close enough to react, a large number of positrons must be accumulated and

then quickly dumped onto a small-diameter spot. That's a challenge, because the positrons are available only at low currents; to be accumulated, they must be drastically cooled and also must be isolated from ordinary matter to prevent their rapid annihilation with electrons. In addition, the Ps formed in the target quickly decays into annihilation photons, so experimenters need

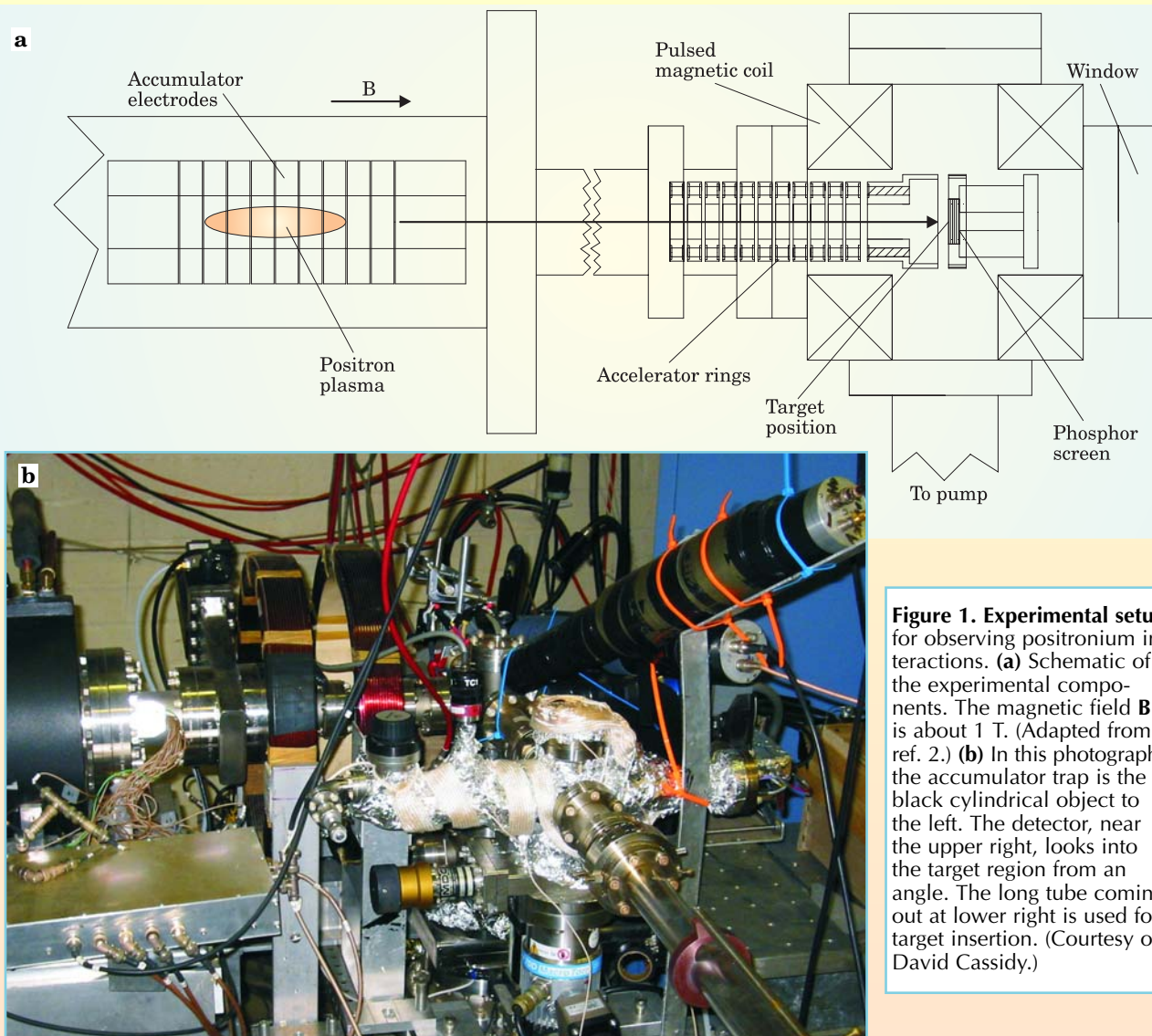


Figure 1. Experimental setup for observing positronium interactions. **(a)** Schematic of the experimental components. The magnetic field B is about 1 T. (Adapted from ref. 2.) **(b)** In this photograph, the accumulator trap is the black cylindrical object to the left. The detector, near the upper right, looks into the target region from an angle. The long tube coming out at lower right is used for target insertion. (Courtesy of David Cassidy.)

nimble detectors to discern any reactions. In late 2005 David Cassidy, working with Allen Mills and colleagues at the University of California, Riverside, successfully overcame those hurdles.²

After collecting positrons in a trap whose basic design was developed by Clifford Surko and colleagues at the University of California, San Diego, Mills's group shot positron pulses into a porous silica film, a material in which a dense gas of Ps atoms could form. They then tracked the photons produced by the annihilation of Ps atoms over a period of 300 ns. By compressing the positron beam—that is, by decreasing its cross section—they could increase the density of the Ps trapped in the silica. Differences in the photon profiles resulting from the compressed and uncompressed positron beams provided the evidence that densely packed Ps atoms reacted

in the porous film.

The Mills group's exploration of Ps reactions is part of a broader research program of which one goal is to study dense, many-Ps systems. Because the positron has the same light mass as the electron, the Ps atom cannot be envisioned as an electron cloud about an essentially stationary nucleus. The egalitarian relation between positive and negative entities may lead to unpredictable surprises.

One novel feature of the many-Ps system is a predictable consequence of the low Ps mass. When crowded together, Ps atoms have much greater wavefunction overlap than do conventional, heavier atoms. As a result, Ps should be able to form a Bose-Einstein condensate at significantly higher temperatures than do the atoms of the periodic table. Mills and company are working to increase the Ps density so as to form such a BEC.

They estimate that if they can achieve a thousandfold increase—a challenge they believe they can meet—then a BEC will form at about 15 K. Ultimately, a BEC of Ps atoms may be a key component of a gamma-ray laser that emits photons with an energy of half an MeV.

A shot in the light

Figure 1 shows the setup of the Riverside group's recent Ps experiment. To the left is the Surko-type trap, which collects positrons generated by sodium-22 decay. By applying an effectively rotating electric field³ as the positron plasma is accumulated in the trap, the experimenters can exert a torque that compresses the plasma in the plane perpendicular to the trap axis. If the rotating field is turned off, the plasma relaxes to an expanded state.

The trap collects some 15 million positrons before a rapidly applied

dumping voltage expels the positrons and narrows them along the trap axis; once released from the trap, the positron pulse has a length of about 20 ns. After the positrons leave the accumulator, they are focused onto a thin, porous silica film where they combine with electrons to form Ps.

To observe the photons resulting from the annihilation decay of the Ps, Mills and company invented a new technique: single-shot positron annihilation lifetime spectroscopy. The photons created in the silica film enter a scintillating crystal, which in turn generates a photomultiplier signal. A fast oscilloscope, triggered by the release of positrons from the trap, records that signal in real time. The single-shot technique's temporal resolution is limited by the positron pulse width and the response time of the photon detector (about 15 ns).

Single-shot spectra for compressed and expanded initial positron pulses appear together in figure 2. After 40 ns or so, the spectrum derived from the compressed beam dips below its counterpart derived from the expanded beam. The late-time depletion in the compressed spectrum's signal is the sign that earlier reactions have removed densely packed Ps atoms from the silica film.

The key to interpreting the figure in greater detail is understanding how Ps decay depends on the atom's spin state and environment. In vacuum the lifetime of Ps states with total spin $\hbar$ (ortho-Ps) is 142 ns, whereas spin-zero, para-Ps decays with a lifetime of 0.125 ns. In a material like porous silica, Ps can interact with its host, and the new reaction channel decreases the Ps lifetime. Specifics depend on the details of the pore structure; typical lifetimes for ortho-Ps range from 2 to 40 ns. The presence of a magnetic field can also affect the lifetime of Ps. In particular, for the 1-tesla field present in the Mills experiment, the lifetime of the $m = 0$, antiparallel spin state of either ortho- or para-Ps is much shorter than the lifetime of the $m = \pm 1$ ortho-Ps states in which the electron and positron spins are aligned. Indeed, any decays of $m = 0$ states are hidden below the broad initial peak in figure 2.

Once the compressed and expanded spectra have diverged, the expanded spectrum is consistent with a single lifetime of 36 ns; it tracks $m = \pm 1$ ortho-Ps reacting with the silica film. Beyond about 100 ns, the compressed and expanded spectra are parallel. Evidently, after several lifetimes the compressed-beam Ps has been

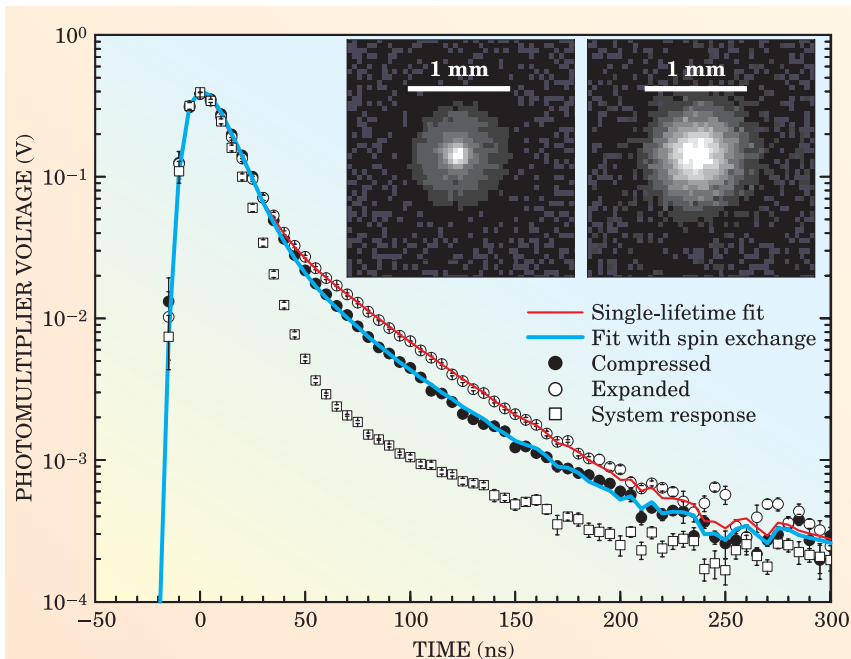


Figure 2. Single-shot spectra. The system response shown is derived from trials in which positrons are shot onto uncleaned silicon, in which very little positronium forms. Beyond about 40 ns, the curve resulting from the expanded positron beam can be fit with a single lifetime corresponding to positronium interactions with the silica film. The smaller response from the compressed beam at late times indicates that Ps has been depleted by formation of molecules or spin-exchange reactions. The inability to fit the compressed-beam curve by a single lifetime is further evidence for Ps reactions; the plot gives a fit that assumes Ps atoms undergo spin-exchange reactions in addition to interactions with the film. The insets show profiles of compressed (left) and expanded (right) positron beams. (Adapted from ref. 2.)

thinned enough that its only reaction is with the film. But the lower position of the compressed spectrum at late times (and the inability to fit earlier times with a single interaction lifetime) indicate that other reactions remove $m = \pm 1$ ortho-Ps from the system. The two most plausible possibilities are formation of the diatomic Ps_2 molecule and spin-exchange formation of $m = 0$ Ps. In both cases, the decay of the product would be hidden under the prompt peak that dominates the first 40 ns of the spectrum, and so the experiment cannot directly distinguish between Ps_2 formation and spin exchange. The Riverside researchers are working to increase the resolution of their single-shot technique so that they can peek under the peak and tease out the reaction channels hidden there.

Indirect evidence suggests that Ps_2 formation could be significant: The total cross section that Mills and colleagues deduce for Ps depletion in the silica film is some four times the theoretical cross section for spin exchange. That factor of four does not seal the argument for Ps_2 formation because the film's pore structure

could shepherd Ps atoms into regions of unexpectedly high density. In that case, the Mills estimate of the total cross section would be too high, and the actual value of the total cross section could be compatible with pure spin exchange being the only mechanism for Ps depletion.

One loose end must be tied up to clinch the interpretation of the data in terms of Ps interactions. When a high-energy positron passes through a silica film, it strips electrons from the film. Those electrons and the positive ions they leave behind are, in principle, available to participate in spin-exchange reactions with Ps atoms created in the silica. In other words, the depletion of Ps formed via the compressed positron beam might not have been caused by interactions of Ps with Ps, but rather by interactions of Ps with surface radicals. Exactly how to calculate the effect of those radicals is not clear, but Mills and the University of Tokyo's Toshido Hyodo have made independent estimates and both conclude that the radicals do not have a significant impact. Neither researcher, however, regards the case as closed.

Antihydrogen coda

The many-Ps systems being studied by Mills and company may, in time, be useful to antihydrogen researchers. Within the past few years, two independent groups located at CERN—the ATHENA and ATRAP collaborations—have succeeded in producing and characterizing slowly moving antihydrogen atoms (see PHYSICS TODAY, November 2002, page 17, and January 2003, page 14). Rolf Landua, a member of the ATHENA group,

notes that colliding a dense gas of Ps with cold antiprotons could be an efficient way to produce cold antihydrogen. And with that antihydrogen, the CERN groups might ultimately test the equivalence principle of general relativity and the *CPT* theorem, which asserts physics is invariant under the combined operations of charge conjugation *C*, spatial inversion *P*, and time reversal *T*. Ironically, in addition to being an aid to antihydrogen researchers working to test

the equivalence principle, Ps is also a competitor: The neutral electron–positron system might itself serve to test equivalence. **Steven K. Blau**

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Optical Trap Resolves the Stepwise Transfer of Genetic Information from DNA to RNA

DNA encodes the amino acid sequences of each protein in our bodies, but carries no instructions for how much of each protein to make. Instead, a cell's protein factories, its ribosomes, are set spinning by RNA, DNA's single-stranded relative. By controlling when and which genes are transcribed from DNA to RNA, a cell regulates its protein production.

Transcription is carried out by an enzyme called RNA polymerase. RNAP wraps around DNA like a collar. As it proceeds along DNA, RNAP pulls the helix apart to expose a short stretch of the bases whose sequence embodies the genetic code. Then, from the surrounding solution, RNAP grabs free-floating bases and adds them in the proper, complementary sequence to the end of a growing chain of RNA.

Now, Steven Block of Stanford University in California and his collaborators have used an innovative optical trap to track the progress of a single RNAP molecule along a single DNA molecule. Their results, which shrink

The assembly of RNA can now be tracked with a precision finer than the distance between its bases.

the resolution of optical traps from nanometers to angstroms, confirm what biochemists expected: RNAP advances along DNA and assembles RNA one base at a time.¹

Optical trap

If you could watch a movie of transcription, you'd see a long floppy molecule, the DNA, waving like a leaf of kelp in seawater as a bulky blob, the RNAP, advances along its length and extrudes a floppy molecule of freshly made RNA.

DNA and RNA undulate on scales of microns, yet their constituent bases are just 3.4 angstroms apart. To observe RNAP move along DNA, the Stanford team had to stretch a DNA molecule between two tethers: one attached to RNAP, the other attached to the DNA upstream of RNAP's ad-

vance. Gently and continually pulling the tethers apart straightens the DNA. As RNAP carries out transcription, the distance between the tethers increases by a tiny and potentially measurable amount.

That, in outline, is how Block and his colleagues did their experiment. To put the scheme into practice, they had to make several innovative improvements to the construction and operation of optical traps.

Devised in the 1970s by Arthur Ashkin, optical traps work by illuminating a micron-sized transparent bead, typically polystyrene, with a tightly focused laser beam. The bead is trapped and suspended because the convergent beam creates a strong electric field gradient. The dielectric molecules that make up the bead act like dipoles in the electric field and are drawn to the region of strongest field intensity: the focus of the laser beam.

The laser not only traps the bead, but also, through lenses, mirrors, and other optical components, provides the means to change and measure the bead's position.

In a typical biological application, one end of the molecule of interest is fixed to a bead while the other is fixed to the surface of a coverslip or other stationary object. The bead, molecule, and surrounding solution occupy a tiny glass vessel. The laser and other optics sit on an optical bench.

To attain angstrom resolution, the Stanford team had to quell two of the biggest sources of noise in optical traps: the small, jittery vibrations of the fixed tether and the "twinkling" or fluctuations of the laser beam as it makes its way through the optical system.

Fixed tethers jitter because the objects they are attached to can move very slightly with respect to the optical trap. To address the problem, Block and his team applied a tech-

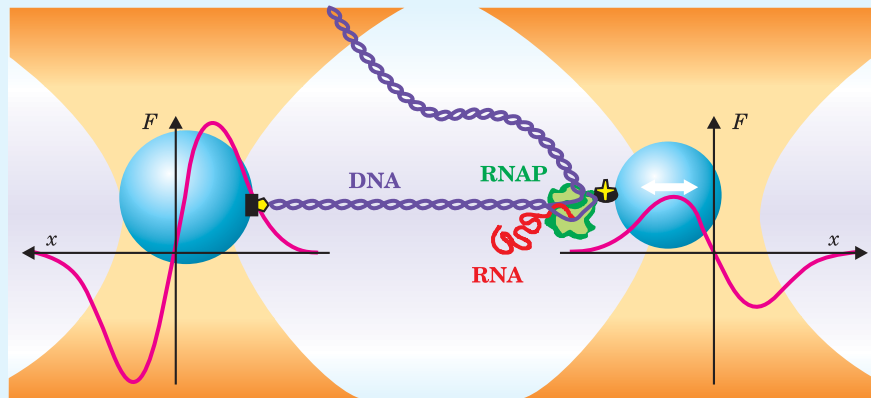


Figure 1. Pulling apart two trapped beads under constant force yields the size of the steps RNA polymerase makes along DNA as it produces RNA. Constant force is maintained because the trapped bead on the right is in a regime where force does not depend on position. (Courtesy of Steven Block.)