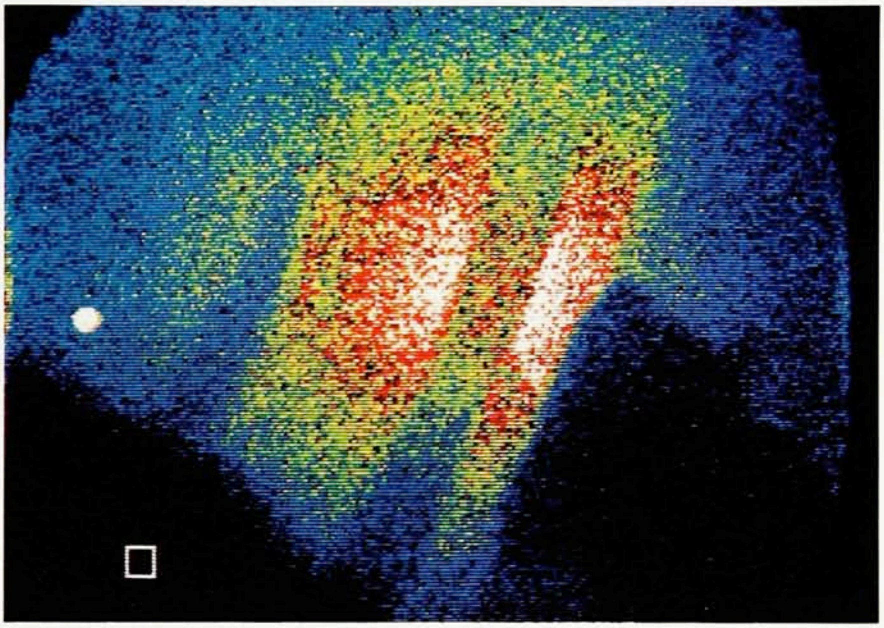
POSITRON MICROSCOPES OFFER A NEW VIEW OF THINGS

A positron microscope may soon open a new window to the realm of the very small. While the view through this device would not be as finely resolved as that through its antimatter cousin, the electron microscope, it could reveal a qualitatively different landscape. Hopes for a positron microscope were boosted recently when independent groups successfully operated two such instruments, one with an especially high resolution. Both the devices are based on the reemission of positrons from a surface. James Van House and Arthur Rich of the University of Michigan, who last year also built a transmission positron microscope,[1] have operated their reemission microscope[2] with a resolution of 2000 nm. George Brandes and Karl Canter of Brandeis University, together with Allen Mills of AT&T Bell Labs, have constructed a reemission positron microscope of slightly different design[3] that has a resolution of 300 nm—the limit for optical microscopes—and a magnification factor of 1150. Both groups feel that further enhancements could give the positron microscope a resolution of 1 nm. At such a resolution, the microscope could facilitate studies of crystal defects and of biological molecules.



Thin nickel film, as imaged with a resolution of about 300 nm by a positron microscope built by a team from Brandeis University and AT&T Bell Labs. A low-energy beam illuminated the sample from the rear; positrons became thermalized in the film and then were reemitted from the surface. In this false-color image, areas are colored white, red, yellow and so forth in descending order of brightness. The low-intensity, largely blue "finger" protruding into the sample is apparently an area where positrons are trapped in the material—perhaps by boundary layers in the film. (Courtesy of George Brandes and Karl Canter, Brandeis, and Allen Mills, AT&T Bell Labs.)

The dark and light areas in the image from a positron reemission microscope reveal regions where positrons are more or less readily emitted from the surface. Thus the image reflects structural features of the sample that differentially affect its interaction with positrons. For example, positrons are strongly attracted to and readily trapped by defects in crystals. Kelvin Lynn of Brookhaven National Laboratory explained to us that although field emission and scanning tunneling microscopes are already capable of probing for defects at the surfaces of crystals, these devices must scan a large number of atoms to spot one defect. The positron microscopes may be able to single out individual sites. Canter suggested to us that one might use a positron reemission microscope to study spatial distributions of monovacancies—sites of single missing atoms—and to follow them as they migrate and recombine. These studies could yield insights into such phenomena as the early stages of radiation damage.

The positron reemission microscope also offers some distinct advantages over the electron transmission microscope for the nondestructive study of some biological specimens, such as RNA molecules or viruses. The positrons traverse the sample with energies of only a few eV, while the electrons must go tearing through at energies hundreds or thousands of times greater. Furthermore, the small energy spread across the positron beam facilitates sharp images. However, the high vacuum required in any particle microscopy technique may limit the ability to study some biological samples.

Reemission microscopes

The new positron microscopes are variants of a positron reemission microscope design first suggested by Lester Hulett, John M. Dale and Subra Pendyala of Oak Ridge National Laboratory.[4] In such a microscope, a beam of positrons with an energy of several keV enters the sample and

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the positrons become thermalized. A large fraction of these positrons may be reemitted from the surface if the sample has a negative affinity for positrons. The positrons are typically kicked out of the surface at about 1 eV, with a fairly small energy spread. They are then accelerated and focused to form an image on a detector that is sensitive to the position of the positron.

In the Oak Ridge conception of a reemission microscope, the sample was to be placed on a substrate with a thickness on the order of 1–10 nm, and the positron beam was to illuminate the back side of the substrate. The positrons would be slowed to thermal energies by inelastic scattering in the substrate and would be reemitted from the front side. The sample would then be imaged by a shadowing effect.

The Brandeis–Bell Labs instrument closely follows the original Oak Ridge concept, with the exception that the sample—a 150-nm-thick nickel film—*is* the substrate. The Brandeis–Bell Labs experimenters feel they have already gleaned some information about this sample. In a false-color image taken at 300 ± 100-nm resolution with their positron microscope (see the figure on page 17), Brandes, Canter and Mills identify what they describe as a "finger" of greatly attenuated emissivity in the middle of a region of relatively high positron counts. The experimenters point out that when a strained specimen is annealed at moderate temperatures, as their sample was, the dislocations tend to become ordered, resulting in low-angle, or tilt, boundaries. They suggest that the positrons in the finger region may have been trapped by boundaries at large tilt angles.

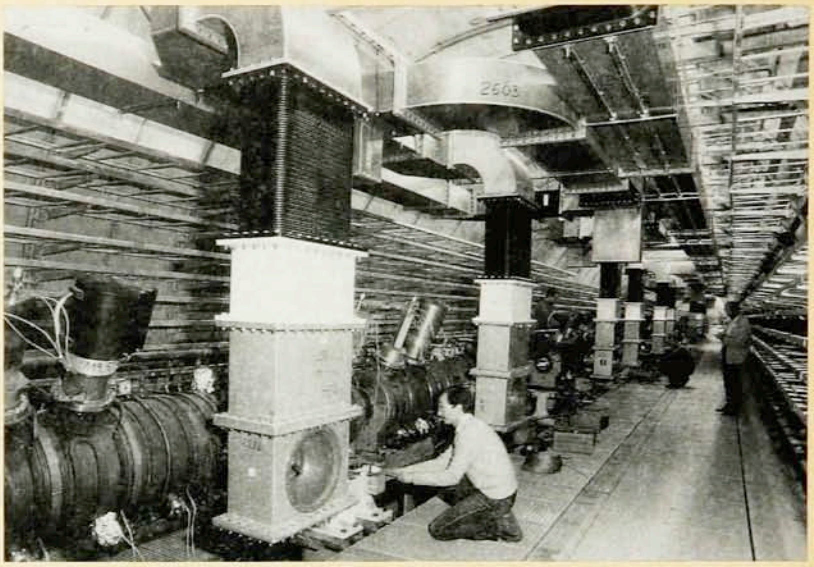
The Michigan reemission microscope features an off-axis positron beam that illuminates the sample at an angle from the front. Positrons entering the sample are reemitted from its front surface and then imaged. With this instrument, Van House and Rich studied tungsten and molybdenum foils whose surfaces had been masked in places prior to bombardment with ions. The image of these samples shows the contrast between the bombarded and masked portions of the target. Thus the two experimenters feel they have conclusively showed the defect sensitivity of the positron microscope. The Michigan team also imaged a biological sample—a human hair.

A year ago, Van House and Rich built a transmission positron microscope, the positron equivalent of the conventional electron microscope. In this design, the positron beam enters the sample from the rear and passes through it rather than thermalizing within it. The experimenters got a resolution of 4000 nm and a magnification factor of 55 with this instrument. In transmission microscopy, positrons can hardly compete with electrons, which already offer high resolution; by contrast, the reemission microscope exploits unique features of the positron.

The reflection-type reemission microscope operated by the Michigan group is not restricted to samples with thicknesses of a few hundred microns, as the transmission type is, because the positrons are incident from the front. In addition it can provide a depth profile of subsurface features. However, its ultimate resolution is slightly limited by geometry: The off-axis beam up front prevents one from moving the imaging lens closer to the sample.

The transmission-type reemission microscope requires careful preparation of the sample to assure that it is thin enough to allow passage of positrons yet thick enough to thermalize them, and that it has good reemission properties. Both the reflection and the transmission-type reemission microscopes may allow study of features of the sample below the surface as well as of overlying molecular structures. Canter hopes that the transmission-type technique will lend itself to a form of holographic imaging, in which one would record the interference between positrons emitted from a substrate and those scattered from atoms within the molecule lying on the surface of the substrate. The multiple scattering would make this technique extremely complex, but it

HERA Stores Its First Beam



HERA, the world's first electron–proton storage-ring collider, successfully stored its first electron beam on 20 August. The 6-km-circumference accelerator is nearing completion at the DESY (Deutsches Elektronen-Synchrotron) laboratory in Hamburg. In this first trial, a circulating beam of some 3 billion 7-GeV electrons was maintained in the ring for two minutes. When physics experiments begin at HERA in 1990, countercirculating beams of 30-GeV electrons and 820-GeV protons will produce e–p collisions with center-of-mass energy of 314 GeV.

The photograph shows one of the HERA tunnel's straight sections in which 500-MHz rf power accelerates and maintains the electron beam. The 60-cm-diameter horizontal tube running along the left wall of the tunnel is the rf accelerating structure through which the electron beam threads. This 360-meter-long straight section requires no bending dipole magnets. The 60-cm-wavelength radiation produced by klystrons above the tunnel is fed into the electron-accelerating structure by the array of vertical waveguides seen here. The 820-GeV proton beam will run about 1 meter above the electron beam, except where the two beams are made to collide. Installation of the superconducting dipole magnets for the proton ring has just begun.

—Bertram Schwarzschild

has the possibility of circumventing the resolution limit imposed by the 1-nm de Broglie wavelength of the positron.

Brightness-enhanced beam

The impressive resolution achieved by Brandes, Canter and Mills results largely from their use of brightness enhancement, which Mills proposed[5] in 1980. Brightness, which may be defined as the intensity of particles per solid angle in a narrow energy range, is a measure not only of the intensity of the beam but of its angular divergence. Many had once felt that increases in beam brightness were prohibited by Liouville's theorem, which states that a swarm of particles occupies a constant phase-space volume in the presence of conservative forces. In less precise words, one cannot focus a beam to a smaller spot size without increasing its angular divergence.

Mills, however, recognized that the "moderation" of a positron beam is not a conservative process and that Liouville's restriction thus should not apply to it. Moderation is a process used to generate a positron beam: The positrons from a radioactive beta-emitting source impinge on a surface that has a negative positron affinity and are reemitted at lower energy but with a smaller energy spread. Mills proposed that one could generate a beam with enhanced brightness by accelerating and focusing the positron beam onto a small crystal. That crystal, the "remoderator," would reemit the low-energy positrons from a small area with low angular divergence. Through successive stages of this type, the beam loses some intensity (typically less than half the incident positrons are reemitted from the remoderator) but gains many factors of ten in brightness. Mills's concept was verified in 1985 by William Frieze, David Gidley (both now at the University of Michigan) and Lynn, who implemented it on an electrostatic positron beam at Brookhaven National Laboratory.[6]

The brightness-enhanced beam used in the Brandeis–Bell Labs positron microscope has two stages of brightness enhancement to reduce the beam area by a factor of several hundred thousand and to increase its brightness by a factor of 500. The final result is a 5-keV beam whose full width at half maximum diameter is 12 microns. Its flux is 5×10^4 positrons per second. Brandes, Canter and Mills plan to improve the resolution further by using a more intense radioactive source of positrons, switching to a more efficient primary moderator and using cooled remoderators. Van House and Rich, who are now collaborating with Frieze and Gidley, plan to build a brightness-enhanced beam to achieve higher resolution and magnification. Van House told us they too plan to use a more intense radioactive source and that they have already reduced their computer processing time.

Even with the brightness enhancement, however, image taking is a slow process. Especially to get the high-magnification images, one must spread the image over a large area, and collection times are long. Typically, it requires 8 to 12 hours to accumulate enough positrons for a good image.

To become a useful quantitative probe, a reemission microscope must move beyond the laboratory to a positron beam with even greater intensity. The experimenters are hoping to be able to use positron beams provided by reactor facilities or linear accelerators. David L. Donohue, Hulett and Pendyala are building a positron microscope that will use the positron beam fed by the linac at Oak Ridge. Its flux is 10^8 positrons per second. To increase the signal-to-noise ratio at the image detector of this microscope, Hulett plans to gate the detector at the pulse rate of the linac. Hulett is working with members of the field emission group at Oak Ridge to benefit from their experience in studying defects in metals.

The greater the flux is, the more capable the microscope will be. Several of the institutions that operate positron beams are interested in upgrading their fluxes, motivated not only by the positron microscope but by other interesting physics as well. Those experiments include positronium spectroscopy, analogs to electron experiments and positron diffraction. Brookhaven already is in the process of upgrading its positron beam to a higher flux. Lynn estimated that within six months to a year Brookhaven will operate with a flux of at least 10^9 sec^{-1}, a factor of 10 improvement over its present beam. Livermore National Laboratory now has a positron beam whose maximum flux is 10^9 sec^{-1}, although Richard Howell of Livermore told us that most experiments cannot handle the high pulse rate at the higher flux levels. He expects that the full flux could be used to operate a positron microscope and said that Livermore has made such proposals. At the 8th International Conference on Positron Annihilation, held in Ghent, Belgium, last summer, Yasuo Ito (University of Tokyo) unveiled plans by a Japanese consortium to build a slow-positron factory with an anticipated flux of 10^{10} sec^{-1}, but he noted that the facility was not funded for the coming year.

—Barbara Goss Levi

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