project, which was initiated in FY 1981, the budget calls for an additional $18.0 million in FY 1983.

The Trilling subpanel had recommended implementation of the Tevatron II program in all three experimental areas and completion of Tevatron I with one major detector facility.

SLAC. DOE plans to support R&D on the Stanford Linear Collider with about $11 million in FY 1983. The subpanel recommended "construction of associated conventional facilities to begin in FY 1984 such that the R&D phase can be completed in FY 1986." SLC would collide 50-GeV electrons with 50-GeV positrons; initially it would have only one interaction region. "Funding of major new detectors and provision of a second beam–beam intersection region could occur once the R&D program has demonstrated adequacy for physics research," the subpanel says.

At the HEPAP meeting in February, the panel drafted a submittal letter to Alvin Trivelpiece, director of energy research at DOE. It said that SLC is an accelerator research project central to the long-term development of a very high-energy e^+e^- collider and at the same time offers the opportunity to do exciting physics in timely fashion. However, the transmittal letter says that SLC is not the major new facility that would begin construction in the mid-1980s and be available for research in the 1990s, as recommended by the Trilling subpanel and endorsed by HEPAP. SLC is an example of the type of relatively large R&D project now necessary in developing new accelerator systems, the letter says.

Other recommendations. The subpanel also recommended "adequate utilization and maintenance of existing accelerator and storage-ring facilities, and support of important non-accelerator particle-physics projects."

Fermilab magnet-assembly facility. A superconducting magnet is moved towards its installation in the iron yoke assembly. When upgrading is done, the accelerator will produce 1000-GeV protons for fixed-target and proton–antiproton experiments.

Another recommendation was "pursuit of other advanced accelerator R&D activities on items such as high-field superconducting magnets, high-gradient accelerating structures, superconducting rf cavities and novel means of acceleration." The final recommendations of the subpanel do not specifically mention CESR II, which would be an electron–positron storage ring with 50 GeV in each beam, using superconducting rf cavities. Trilling, at the San Francisco APS meeting in January, said CESR II was not viewed as an alternative to SLC, which has an ongoing proposal. Cornell anticipates submitting a firm proposal this year for funding CESR II in FY 1985. —GBL

Microscopy by vacuum tunneling

The earliest work on quantum tunneling in solid-state physics, more than fifty years ago, dealt with electron tunneling through a vacuum barrier. But for the next half century we had no clear experimental demonstration of this conceptually simplest of tunneling phenomena. Spectroscopic and technological exploitation of quantum tunneling was developed only with solid tunnel barriers. Metal–vacuum–metal tunneling requires a gap held constant at a few angstroms. At such small distances—just a few atomic widths—it is extraordinarily difficult to control the gap size and insure that surface contamination layers or irregularities do not result in an unwanted contact across the gap.

Theory predicts that the tunnel resistance across the vacuum barrier will increase exponentially with gap size, with a logarithmic slope proportional to the square root of the mean work function of the two tunneling surfaces. Thus the most direct evidence of successful metal–vacuum–metal tunneling would be the observation of such an exponential resistance curve with an exponent appropriate to the work functions.

A recent *Applied Physics Letter*[1] by Gerd Binnig, Heinrich Rohrer, Christof Gerber and Edmund Weibel of the IBM Research Laboratory in Zurich reports just such an observation. This has been accomplished with a novel tunneling instrument that makes it possible to control the distance between tunnel electrodes with a precision of one or two tenths of an angstrom. Furthermore, the ability of their three-legged piezoelectric support system to control precisely the lateral position of the electrodes has enabled the group to exploit vacuum tunneling for scanning surface microscopy with a resolution of 5 to 20 Å in the surface plane.

Earlier attempts[2,3,4] to demonstrate and exploit vacuum tunneling were plagued by insufficient suppression of vibrations in the experimental apparatus. Binnig and his colleagues achieved the necessary protection against external vibrations by placing their tunneling experiment on a heavy stone slab resting on inflated rubber tires. Vibrations internal to the apparatus were suppressed by magnetically levitating the tunneling unit on a superconducting bowl of lead cooled by liquid helium.

The Zurich group stresses that its primary purpose was not simply to observe vacuum tunneling, but "to demonstrate its feasibility . . . with modest means . . . in a configuration that simultaneously allows spatially resolved tunneling spectroscopy and other surface spectroscopic methods." Aside from the superconducting lead bowl, they point out, the apparatus is near room temperature and it requires only moderate vacuum. Vacuum-tunneling spectroscopy has a number of evident advantages for the study of surfaces: It is conceptually simpler; the vacuum is obviously easier to characterize than any solid-state barrier layer. Furthermore, one has the advantage of free access to the surfaces between which the electrons are tunneling.

The Zurich vacuum-tunneling junction described in their *Applied Physics Letter* consists of a tungsten needle point separated from a platinum plate by a few angstroms of moderate vacuum (down to 10^{-6} torr). Both electrodes were held in piezoelectric mounts that could be moved in any direction with extreme sensitivity—only two angstroms per volt. This, together with the suppression of vibration, permitted the gap length and position of the needle in the plane of the platinum surface to be controlled with high precision.

A microtorr vacuum is insufficient to keep the electrode surfaces free of contaminants. But the group employed a self-cleaning procedure that kept the surfaces sufficiently clean so that no change in the work function (which is very sensitive to contamination) was observed over tens of minutes. The application of a 10-kilohertz voltage to the piezoelectric mounts generates ultrasonic vibration that appears to rid the surface of contaminants.

(The Zurich group is now doing vacuum tunneling between gold electrode surfaces in a 5×10^{-10} torr vacuum; in so high a vacuum, Rohrer told us, surface contamination is no longer a problem.)

The tunnel resistance curve at 10^{-6}

torr was measured by applying a constant voltage of 60 millivolts across the gap—a voltage sufficiently small to avoid field emission of electrons from the needle point. One measures the change of tunnel resistance as the separation of the needle point from the platinum plate is increased in subangstrom steps. Prior to ultrasonic cleaning, the group found only a weak, non-exponential dependence of the resistance on gap size. With repeated ultrasonic cleaning the resistance curve approached the expected steep exponential, with the logarithmic slope giving an effective work function of 3.2 eV. Because the platinum surface is locally irregular, Rohrer told us, this should be thought of as a lower limit. For perfectly clean platinum and tungsten surfaces of ideal geometry one expects a mean work function of about 5 eV.

These measurements, Binnig and his colleagues tell us, are the first published results that demonstrate directly the exponential dependence of tunnel current on distance—over four orders of magnitude in resistance. Such exponential behavior had previously been inferred for solid-barrier tunneling by comparing the current across different junctions. But, the Zurich group points out, solid-state barriers do not have constant widths on a microscopic scale. Consequently tunneling will tend to occur dominantly at the weakest (that is the narrowest) point in the vicinity.

Applications. The vacuum-tunneling resistance across a vacuum barrier is an extremely steep function of distance, falling by an order of magnitude for every angstrom of increased separation—about a factor of a thousand for the width of a typical atomic monolayer. This extreme distance sensitivity, together with the demonstrated positioning precision of the piezo-mounted, vibration-suppressed Zurich tunneling apparatus, strongly suggests that vacuum tunneling could be exploited for extraordinarily precise surface-profile microscopy.

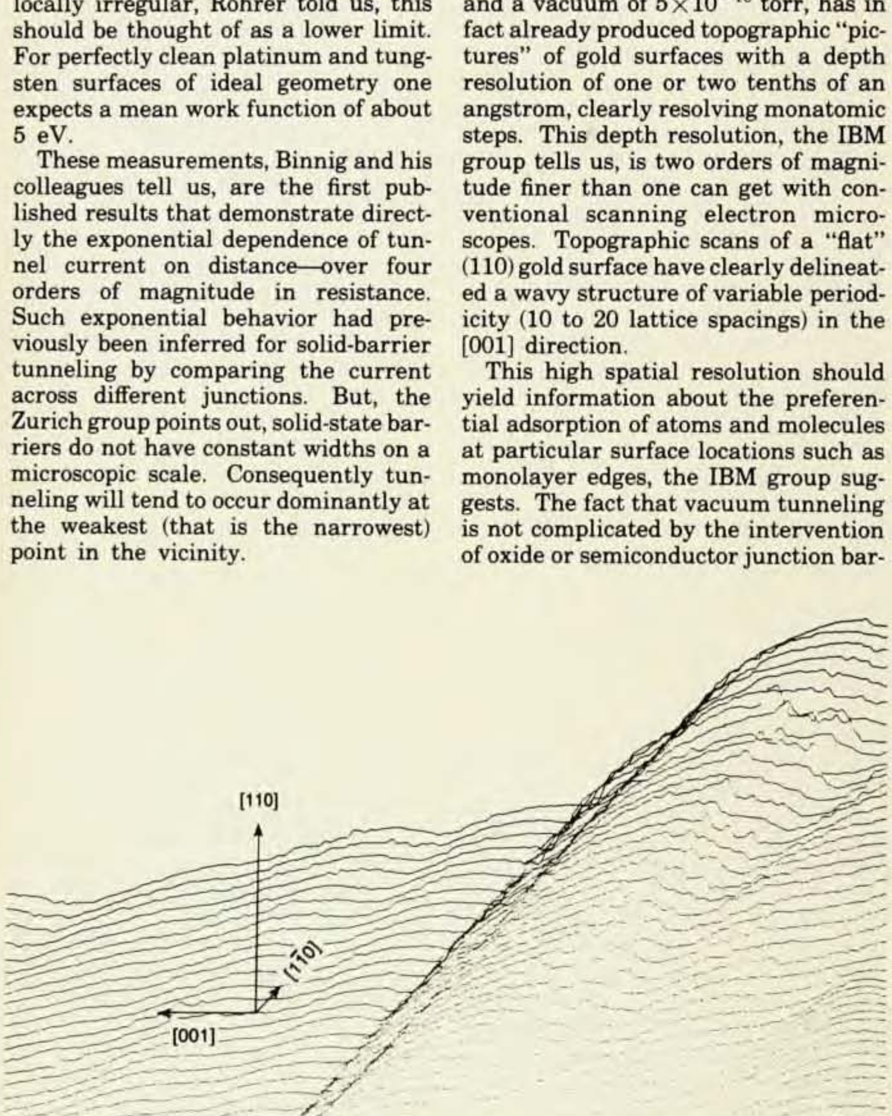
The second-generation Zurich instrument, operating at room temperature and a vacuum of 5×10^{-10} torr, has in fact already produced topographic "pictures" of gold surfaces with a depth resolution of one or two tenths of an angstrom, clearly resolving monatomic steps. This depth resolution, the IBM group tells us, is two orders of magnitude finer than one can get with conventional scanning electron microscopes. Topographic scans of a "flat" (110) gold surface have clearly delineated a wavy structure of variable periodicity (10 to 20 lattice spacings) in the [001] direction.

This high spatial resolution should yield information about the preferential adsorption of atoms and molecules at particular surface locations such as monolayer edges, the IBM group suggests. The fact that vacuum tunneling is not complicated by the intervention of oxide or semiconductor junction barriers renders it particularly interesting for the investigation of surface adsorption bonding by inelastic tunneling spectroscopy—measuring the energy loss of tunneling electrons.

Vacuum tunneling might also be exploited to monitor continuously the growth and properties of the ultra-thin insulating layers that are becoming so important in microelectronic technology. Even a monatomic insulating layer would drastically affect the tunneling current. For such applications as well as for inelastic tunneling spectroscopy it is encouraging to note that field ionization of molecules in the barrier made no noticeable contribution to the Zurich tunnel current, even at modest vacuum.

How do we know that the Zurich results at 10^{-6} Torr do in fact indicate vacuum tunneling, and not simply tunneling through a contamination layer or current across an inadvertent ohmic contact point? A non-tunneling ohmic current would not exhibit a steep exponential dependence on distance. Binnig and his colleagues explain that tunneling through a contamination layer can be ruled out on several grounds. Deformation of a hard contamination layer such as tungsten oxide would have resulted in nonreproducible and hysteritic curves of resistance *vs* gap length. Further evidence, they point out, is the increase of the effective work function with repeated ultrasonic cleaning. Metal–insulator–metal tunneling curves are known to have logarithmic slopes corresponding to a work function of about one electron volt. An effective work function of 3.2 V for such a solid barrier would therefore appear most unlikely. They therefore concluded that they were really seeing a vacuum gap of varying width in this modest vacuum. The more recent ultra-high-vacuum results, where ultrasonic cleaning is no longer required, make the observation of vacuum tunneling quite unambiguous, Rohrer told us.

These first vacuum-tunneling experiments were done near room temperature. In future experiments the Zurich group expects that lower temperature will afford even better mechanical stability. They regard this work as "a first step toward the development of scanning tunneling microscopy ... which should open the door to a new area of surface studies." —BMS



Scanning microscopy with the second-generation Zurich vacuum-tunneling apparatus at 5×10^{-10} torr produced this topographic picture of a "flat" (110) gold surface. Lengths of coordinate axes indicate 30 Å in each crystallographic direction. Resolution is a few tenths of an angstrom in the [110] direction normal to the surface. A wavy structure of variable periodicity (10 to 20 lattice spacings) is clearly visible in the [001] direction along the surface.

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