particular group representation. The amplitude for a particle to follow some path through the lattice in this theory is an integral of a product of these link variables along the particle's path. This integral over link variables is analogous to a sum in a statistical ensemble. Monte Carlo techniques can generate a random sequence of link variables and thus simulate the statistical ensemble.

The addition of fermions to this theory greatly complicates it. The path integral over quark degrees of freedom is not an integral in the usual sense because of their anticommutation relations. One way to circumvent the problem is to perform essentially a formal integral over the fermion degrees of freedom before applying the Monte Carlo technique. The remaining expression involves the determinant of the reciprocal quark propagator—still no cinch to evaluate with statistical means. The great simplification comes from approximating this determinant by the pure number 1. Both the Brookhaven–Rome collaborations and Weingarten give some arguments for the validity of this approximation. This step is essentially the neglect of the mixing with extra quark pairs.

The procedure for calculating the masses is to create a set of quarks and antiquarks with the quantum numbers of some hadron. The computer simulation propagates these quarks and then annihilates them at some time later. In the limit of large time, Hamber explained to us, the expectation value of the propagator goes as the exponent of the mass times the time. (In this limit the mass is that of the lightest hadron carrying those quantum numbers.)

The errors in these calculations are both statistical and systematic. The main source of the former is the inherently random nature of the Monte Carlo technique. One of the causes of the latter is the limitation to a finite size of lattice grid. Most of the lattices in this recent work have had space–time dimensions on the order of five by five by five by ten points. While these lattices are still substantial they are perhaps near the lower limit of lattice size that allows good statistics. Some critics worry that the grid spacing in all these treatments is too coarse relative to the size of the hadrons they are probing. The theorists try to answer this concern by checking whether certain parameters change in a predictable way as the grid size varies.

Hamber and Parisi not only estimated masses and decay constants for some mesons but also investigated the property of chiral symmetry. They discovered that this symmetry is spontaneously broken. Kogut and his collaborators pursued that result in detail and found that chiral symmetry becomes broken at a length scale shorter than that of confinement. They conclude that the symmetry breaking is independent of the forces of confinement but depends strongly on the color representation of the quarks. This result may be significant in understanding the dynamic symmetry breaking necessary to make realistic models of weak interactions.

David Politzer (Caltech) is particularly excited about these latter results, for to him they give a rationale for the neglect of the internal quark loops: They suggest that the quarks may have a "soft" mass large enough to render them nonrelativistic in bound states. Thus, at least for some masses, no extra quark loops could contribute without altering the hadron mass. More generally, we asked Politzer what items were on his wish list for tests of quantum chromodynamics that might now be feasible. His list includes: some static properties of hadrons, the masses of the glueballs and their mixing with quark–anti-quark states and the cross section for lepton–hadron inelastic scattering.

Buoyed by success, Parisi and his collaborators and Weingarten are currently attempting to estimate the hadron masses with the inclusion of the quark loops. Weingarten is extending his work to SU(3). Kogut and his colleagues are hoping to calculate masses at some higher energy scales. And many others are continuing to contribute their energy and insights in this promising direction. —BGL

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High-resolution scanning ion microscopy

Scanning electron microscopes operating in the reflecting mode can resolve surface detail at the level of a few tens of angstroms. A University of Chicago–Hughes Research Laboratories collaboration expects to do about as well with ions by the end of the year. A pair of scanning ion microscopes being built at Hughes (Malibu, California) is designed to achieve a resolving power as fine as 20 Å.

The design of these high-resolution microscopes embodies the experience gained in the past few years by Riccardo Levi Setti at Chicago and Robert Seliger at Hughes with scanning ion microscopes capable of 1000-Å resolution. Although conventional (non-scanning) ion microscopes of comparable resolution had been built in France and Germany in the 1950s, the further development of high-resolution microscopy had largely been deferred in subsequent decades by the spectacular successes of the scanning electron microscope. Japan Electro-Optical Laboratories (Tokyo) expects to market the world's first commercial scanning ion microscope—a 1000-Å device—at the end of this year.

Because the interactions of ions and electrons with target materials are quite different, ion microscopy is potentially capable of complementing electron microscopes with important subsurface information not readily accessible to the latter. The secondary electrons that provide the primary imaging signal in a scanning electron microscope are for the most part sensitive only to surface topography; deeper information is provided only by energetic backscattered electrons, which are much less copiously produced than are the secondary electrons.

The secondary electrons generated by ion beams, on the other hand, come mainly from hard Rutherford scattering off (shielded) nuclei. Therefore, Levi Setti told us, they can serve as a more sensitive probe of the underlying atomic structure of the target. Cascades of such hard-core collisions transport bulk information out to the surface. The Chicago group has found that the direction-sensitive deep channeling of incident ions between crystal planes produces secondary-electron pictures with "astonishing" crystallographic contrast. Levi Setti believes that this channeling-induced contrast will prove to be important for microscopic analysis in metallurgy, microelectronic fabrication and mineralogy.

Ion beams also sputter ions off the surface under examinations. These secondary ions also exhibit channeling contrast, and they can be passed through a mass spectrometer to provide elemental analysis of the sample.

The incident ions also serve to clean contamination layers off the surface under scrutiny, Levi Setti told us. His Chicago group finds that micrographs of metallic surfaces became progressively brighter during the first few minutes of examination under the scanning ion microscope, as the bombarding heavy ions (60-keV gallium) clean off the contaminating oxide layer. This "milling effect" could be exploited, he suggests, to study bulk samples layer

Striking crystallographic contrast, strongly dependent on the angle of beam incidence, is seen in these two scanning ion micrographs of the same sample of recrystallized brass. At left, the scanning beam of gallium ions strikes the polished sample surface at normal incidence; at right, the beam is tilted 10°. Light and dark regions are reversed. The high contrast and its directional dependence are attributed to channeling of the ions between crystal planes, affecting the strength of the secondary electron signal that generates the image. Micrographs by University of Chicago group. Full scale is 64 microns; resolution is 1000 Å.

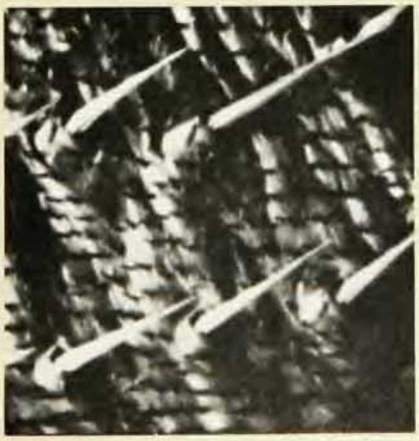
by layer, as successive surfaces are milled away by the ion beam. But the milling effect also presents a problem; the ion microscope can hardly be described as a non-destructive testing device.

In a similar vein, Seliger's group at Hughes is investigating the use of the scanning ion microscope for microelectronic fabrication. With the 1000-Å beam-spot size of their present machine, the group is etching and implanting ultrathin lines on integrated-circuit substrates without the lithographic masks such tasks normally require.

Scanning electron microscopy of an insulating sample requires that the surface be coated with a thin conducting layer; otherwise the accumulating of negative charge tends to defocus the electron beam spot. With metallic ion beams such as Ga^+, the Chicago–Hughes collaborators find that the scanning ion microscope does not require such a conducting layer; the beam appears to implant enough metal to make the sample sufficiently conducting to carry away much of the accumulated positive charge. For the microscopic study of biological samples, the conducting layer required for scanning electron microscopy sometimes obscures interesting detail; in any case, it requires an extra step of sample preparation that scanning ion microscopy can do without.

A scanning microscope (electron or ion) differs from its conventional (non-scanning) cousin primarily with regard to where the focusing is done. A conventional reflecting electron microscope is a straightforward analog of a reflected-light microscope. The sample is flooded with a broad electron beam, and the backscattered electrons from each point on the surface are focused to a point on the imaging surface. A scanning microscope, on the other hand, does all of its focusing on the incident beam, whose spot size as it impinges on a sample surface determines the resolution of the instrument. To image an entire surface, one moves the beam spot across the sample in a raster scanning pattern, recording the particles coming back as a function of spot position.

Because a scanning microscope simply collects the reflected signal without requiring further focusing, it affords much greater analytic flexibility than a conventional microscope. One can sort the particles collected from each point by momentum, mass, charge or angle. With a scanning ion microscope, for example, where the "reflected" particles are mostly secondary electrons and secondary ions, one can pass the secondary ions through a mass spectrometer.



Fruitfly leg, seen with 1000-Å resolution by the University of Chicago's scanning ion microscope. Full scale is 72 microns.

This would provide a chemical microanalysis of the sample, with a resolution given by the width of the incident focused ion-beam spot.

We have been concerned here only with reflecting microscopes. Scanning *transmission* electron microscopes have in fact achieved resolutions of about 3 Å; but they can examine only very thin samples (PHYSICS TODAY, March 1981, page 34). Levi-Setti's 1000-Å instrument began life in 1974 as a scanning transmission ion microscope, but the more recent work at Chicago, Hughes and JEOL has concentrated on reflecting ion microscopes. "Reflecting" is really a misnomer in the case of ion microscopes. The Chicago and Hughes groups have used ion beams with masses ranging from hydrogen to gold. The heavier ions are of course never reflected backwards when their masses exceed those of the specimen atoms. Secondary ions emerging from the surface are sputtered as the end products of collisional cascades. In any case, the best pictures produced by these ion microscopes are made from secondary electrons, which are far more copiously emitted than are the secondary ions.

Bright ion sources. Because a scanning microscope illuminates a given point on the sample for only a very small fraction of the total exposure time, it requires a much brighter (electron or ion) source than does its non-scanning counterpart. The primary impetus for the Chicago–Hughes effort to build a high-resolution scanning microscope has been the successful development during the last decade of extremely bright ion sources, particularly liquid-metal sources. Following the pioneering work of Roy Clampitt and Derek Jeffries in England, Victor Krohn and George Ringo at Argonne, and John Orloff and Lynwood Swanson at the Oregon Graduate Center on liquid-metal ion sources, Seliger's group built a scanning ion microscope in 1978 with a liquid-gallium source capable of generating (after acceleration and focusing) an 80-picoamp beam of 60-keV Ga^+ ions only 1000 Å wide.

Gallium has the convenient property of being a liquid at room temperature. The liquid gallium source is basically a fine tungsten needle point wetted with gallium. (For metals with higher melting temperatures, one heats the needle.) In the presence of a strong extracting electric field the liquid metal forms itself into a conical shape with an ultrafine point. This cone serves as a field-ionization source of Ga^+ ions. Because the extracted ions follow the electric field lines, which are perforce normal to the gallium surface, their trajectories extrapolate back to an apparent "point" source on the order of a hundred angstroms across.

The great advantage of these liquid

metal sources, Levi Setti told us, is that "they produce usable ion beam currents with very little effort." Levi-Setti's group had been using field-ionization sources to do transmission scanning microscopy with beams of hydrogen, helium and argon ions. The principle of such sources is similar to that of the liquid-metal sources, except that the ions are generated in a gas surrounding a needle point rather than on the point itself. The liquid-metal sources generate high ion-beam currents with such ease precisely because they are liquid. The supply of ions is continually renewed as metal flows toward the tip. These sources are in fact called "electrohydrodynamic field-ionization sources." The attainment of comparable currents with the gas field-ionization sources requires a "heroic effort," Levi Setti told us.

Nonetheless, Levi Setti concluded ten years ago that field-ionization gas sources could be made bright enough for high-resolution scanning microscopy. "Only the funds were lacking," he explained. The high-resolution instruments nearing completion at Hughes will use both liquid-metal and gas field-ionization sources. "We expect to get the best resolution (about 20 Å) with the light ions from the gas source," Levi Setti told us. The liquid-gallium source, although brighter, suffers more from chromatic aberration. The heavy ions emerge with an energy spread of 6 or 7 eV, limiting the focused spot size to a minimum of 50 to 100 Å.

In addition to the very-high-resolution Chicago–Hughes work, there is a worldwide effort to exploit liquid-metal ion sources for surface analysis and microfabrication in the 1000- to 5000-angstrom range. Groups at Hitachi, Osaka University and Nippon Telephone and Telegraph have developed Ga^+ scanning ion microscopes. Orloff and Swanson have built gas-phase and liquid-metal scanning ion microscopes for surface analysis and microscopy in the 2000- to 5000-Å range.

Recent results obtained by the Chicago group with its 1000-Å microscope were reported in January at the US–Japan Seminar on Charged Particle Penetration Phenomena in Honolulu. Since the Chicago–Hughes collaboration was formed in 1980, this Chicago microscope, which is very similar to the low-resolution instrument that Seliger and his colleagues had built independently, has been employing a liquid gallium ion source produced at Hughes.

The Chicago group has found that the intensity of the secondary-electron ion signals from brass and iron samples illuminated by 60-keV Ga^+ ions is a very sensitive function of the beam direction relative to the crystallographic orientation of the sample. They attribute this effect to ion channeling (see PHYSICS TODAY, May 1980, page 17). When the incident beam direction falls within a critical channeling angle, the gallium ions can pass relatively unhindered between lattice planes. In this lower-density interplane region the ions lose less energy per unit length than they would if they entered at a random angle. The channeled ions can then penetrate the sample to depths of more than five times the normal ion penetration depth of about 200 Å. The reduced energy loss of such channeled ions suppresses the emission of secondary electrons and ions.

In this way striking contrast is achieved between adjacent regions of different crystallographic orientation. Though he had expected some channeling effect, Levi Setti told us that he was stunned by the quality and magnitude of the contrasts exhibited by the micrographs. "They demonstrate clearly that we can detect dislocations in very pure crystals," he explained. The present microscopes are still limited by resolution, but with the high-resolution microscope he hopes to be able to detect single crystalline dislocations.

Secondary-electron images have exhibited contrasts of more than 3 to 1 across crystal boundaries. As samples are rotated under the scanning beam, contrasting regions can be made to reverse relative brightness. Scanning electron microscopes can also see channeling effects, but the resulting contrasts do not generally exceed 5%. The Chicago group has been able to see laminar arrays of "twinning" dislocations resulting from impact shock in iron meteorites. Scanning ion micrographs of integrated circuits exhibit much better contrast, Levi Setti asserts, than one sees in scanning-electron micrographs. He expects that the scanning ion microscopes will become a standard instrument for the routine examination of crystal imperfections in metallurgy and microelectronic fabrication.

In addition to the channeling-induced contrast between differently oriented crystalline regions of the same material, the scanning ion micrographs exhibit very pronounced contrasts between chemically different areas of a sample. This suggests that one could use the instrument for microscopic elemental mapping even without secondary-ion mass spectrometry. Levi Setti also told us that his secondary-electron micrographs have clearly delineated magnetic domain boundaries in ferromagnetic samples.

While producing high-quality micrographs with 1000-Å resolution of a wide variety of samples—from *Drosophila* eyes to meteorites—the Chicago–Hughes collaborators have been exploiting their low-resolution microscopes to determine the optimum design parameters for their high-resolution scanning ion microscope. Examining the energy spectra of gallium ions as a function of source current, for example, they have discovered that there exists an optimum current that minimizes the effects of chromatic abberation, which is the limiting factor determining the ion microscope's resolution.

The optics required for a high-resolution ion microscope are trickier than what one needs for a scanning electron microscope. The Chicago–Hughes collaboration's calculations lead them to expect that the two-lens electrostatic focusing system of their second-generation microscope will by the end of this year achieve a resolution as good as that of the best scanning electron microscopes. But, Levi Setti cautions, one can't be certain until the instrument is completed. —BMS □

Bevalac accelerates uranium

The Bevalac at the Lawrence Berkeley Lab is now accelerating uranium ions. This photographic emulsion shows the last half millimeter of track for three uranium ions accelerated to 150 MeV/nucleon. The bottom nucleus is seen to split into fragments. With its new injector for the Superhilac and a new Bevatron vacuum system, the Bevalac (as one calls the tandem system of Superhilac and Bevatron) is now capable of accelerating uranium to 900 MeV/nucleon.