Large facilities for condensed-matter science

Experimental floor of the uv ring at the National Synchrotron Light Source at Brookhaven National Laboratory. The floor is crowded with beam lines and users' equipment, almost hiding the synchrotron itself. Figure 1

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Because they provide beams for many experiments simultaneously, intense neutron sources and synchrotron radiation sources are becoming exciting multidisciplinary research centers.

Martin Blume and David E. Moncton

Arise, order,
out of necessity!
Mock, you crystals,
with all appearance of chiselled design,
our hope of a Grand Artificer.

—John Updike
"Ode to Crystallization"

The structural perfection and the optical beauty of natural crystals have always been a source of fascination. The attempt to provide a scientific understanding of crystal structure—to understand the natural laws that underlie the aesthetic appeal— marked the beginning of condensed-matter physics. This intellectual revolution began in 1912, when Walter Friedrich, Paul Knipping and Max von Laue presented an elementary theory of x-ray diffraction by crystals and reported the first experimental results. Remarkably, this monumental work not only heralded the modern era of condensed-matter physics, it demonstrated conclusively the wave nature of x rays—one cornerstone in the modern development of physics. The discovery of electron and neutron diffraction—in 1926 and 1936, respectively—greatly increased the range of phenomena that could be studied in condensed matter. Today the quest for useful new probes continues; muons and positrons, for example, are being investigated. However, it is overwhelmingly clear that electrons, neutrons and photons are still the most important probes in their collective contributions to our field and their potential for future discovery. The profound impact these probes have had on the microscopic understanding of materials becomes clear when one asks questions such as: What would we know about the geometric and electronic structure of solids without photon scattering and spectroscopy? What would we know about magnetism, phase transitions and excitations in solids without neutron scattering?

Great as the scientific and technological consequences of these probes have been for condensed matter, the promise for the future is even greater, particularly for multidisciplinary studies. Already a substantial fraction of the capability of x-ray and neutron facilities is used by biologists, chemists, materials scientists and medical physicists. More and more, these facilities serve not just condensed-matter physics but all condensed-matter sciences, and they thereby foster the multidisciplinary interactions that lead to new scientific concepts and directions.

We are entering an era when technological progress is limited by our ability to discover and fabricate new materials and optimize their properties. Understanding and improving materials from polymers to semiconductor surfaces, from ceramics to cell membranes, relies heavily on detailed microscopic geometric and electronic structural information. Were the current facilities for producing neutrons, x rays and electrons at the limit of technological feasibility, this job would pose perhaps an insurmountable challenge. Fortunately, the technology for all of our principal probes is rapidly developing, and large gains are within our grasp. The imaging capabilities of electron microscopes are rapidly being developed to the atomic level for a substantial fraction of the periodic table. New laser technology is on the threshold of the soft x-ray region. Novel instrumentation for neutron scattering is dramatically improving the effectiveness of existing research reactors and creating new opportunities for users of spallation sources. A new generation of low-emittance synchrotron radiation sources dedicated to condensed-matter sciences is beginning operation. Together with newly improved wiggler magnets, these sources have greatly enhanced the spectral brilliance available with electromagnetic radiation from infrared to hard x rays. We will discuss below the role of such facilities in condensed-matter science from a sociological as well as scientific viewpoint. We review a few exciting scientific accomplishments at the most modern synchrotron-radiation facilities and briefly mention neutron-research activities, which were covered in detail recently in PHYSICS TODAY (special issue on neutron scattering, January). Finally we offer a vision of the opportunities presented by a recently proposed 6-GeV synchrotron-radiation facility; it is planned to have up to 26 undulator magnets that would produce x-ray

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Neutron scattering experiment at the Oak Ridge High Flux Isotope Reactor. Joe W. Cable (left) and Herbert A. Mook are preparing a triple-axis neutron-scattering experiment. The sample container and the cryostat (at the left of the picture) indicate the typically modest scale of the equipment used at neutron sources. Figure 2

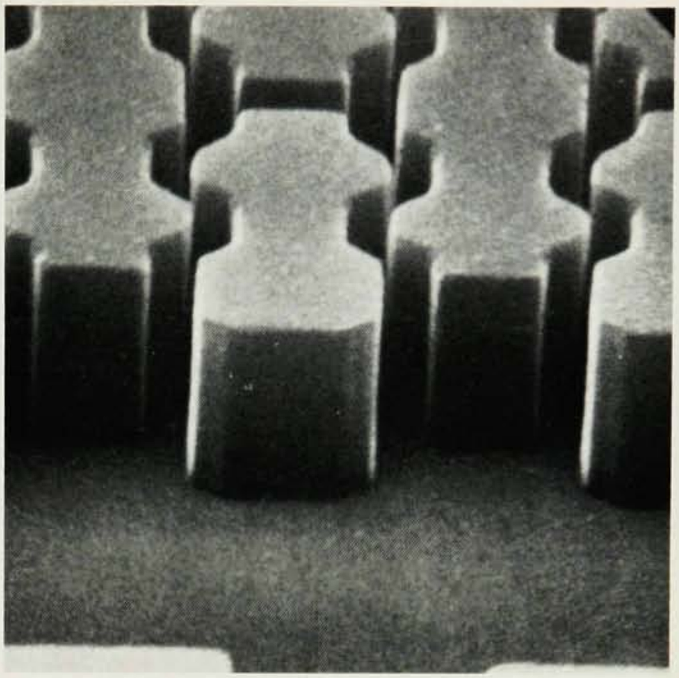
beams with a brilliance approximately twelve orders of magnitude greater than a laboratory x-ray tube.

Large facilities

The role played by large facilities in condensed-matter research differs from the role of large facilities for high-energy physics, fusion research or nuclear physics: Virtually all the research in high-energy and fusion physics, and much of that in nuclear physics, is performed at large facilities—and the cost of an individual high-energy or fusion experiment is often in excess of $10 million. Condensed-matter research, on the other hand, is still very much the domain of "small" science, with research carried out by small groups with equipment of modest expense. Many experimental techniques of importance in condensed-matter research—materials preparation, magnetic resonance, light scattering, and measurements of conductivity and susceptibility—allow the investigators to work in their own laboratories and, usually, at their own pace. The most important questions that affect the future research directions in high-energy physics, nuclear physics and fusion concern the scientific merits of the next large facilities to be built. Condensed-matter science presents a broader range of choices; in setting priorities one must assure the health of *all* modes of research: It would be foolish to build large facilities at the expense of the vitality of traditional research efforts. Indeed, the problems addressed in condensed-matter research require many different techniques for elucidation. A neutron-scattering study of a magnetic structure will complement nmr studies, measurements of electrical conductivity, and other "small-science" experiments often performed by different groups on the same sample.

There is considerable leeway in defining "large" facilities for condensed-matter science. The Division of Condensed Matter Physics of APS, at the March 1983 meeting in Los Angeles, organized an invited poster session on national facilities of importance to condensed-matter physics; the 23 facilities represented ranged from nuclear reactors and synchrotron radiation sources to high-voltage electron microscopes and materials-preparation facilities.[1] In this article we will discuss only the most sizable of these: sources of neutrons and photons on a large scale. Most other large facilities—such as the Materials Research Laboratories funded at many universities by NSF, the National Magnet Laboratory at MIT, and the Center for Microanalysis of Materials at the University of Illinois—are deemed "large" by ordinary funding standards, but their size actually represents a collocation of many facilities usually considered small. Centers for electron microscopy are intermediate in cost between "small" science laboratories and the largest facilities.

Unlike the small number of (expensive) experiments typically carried out at high-energy particle accelerators or fusion physics laboratories, an enormous number of experiments can be carried out simultaneously on the machines at "large" condensed-matter facilities. At the Stanford Synchrotron Radiation Laboratory, for example, nearly 20 experiments with uv and x rays can go on simultaneously; when the same SPEAR storage ring is used for high-energy physics, it can serve only two experiments at once. The High Flux Beam Reactor at Brookhaven National Laboratory provides neutron beams for 15 simultaneous experiments. Even more striking is the scale of the experiments. At condensed-matter facilities the experiments themselves are often even smaller than a typical small-science laboratory experiment. Figure 1, which shows the experimental floor of the uv ring at



Pattern generated by x-ray lithography. The resist layer shown here is 3.4 microns thick, and the channels are less than 1 micron across. Such high resolution is made possible by the collimated radiation and small effective source size available at synchrotron sources—in this case the IBM x-ray lithography beamline at the National Synchrotron Light Source. (Photo courtesy J. Silverman, IBM.) Figure 3

Brookhaven's National Synchrotron Light Source, illustrates this situation. The floor is very crowded with a great many individual experiments. The chambers in which the experiments themselves are carried out are each quite small. Frequently the experimental apparatus is unplugged from the beamline and brought back to the investigator's home institution for modifications, testing and other uses. The experiments are typically no more than a few weeks in length, and relatively small groups carry them out. Because many groups use the same storage ring and beamlines—and, indeed, the same spectrometers and sample chambers in some cases—the cost effectiveness of these facilities is very high. Most laboratory equipment is used less than 60 hours per week, but the large facilities generally run 24 hours a day. In a way, large condensed-matter research facilities are like electric power plants without distribution systems. If all scientists who used electric power in their experiments had to go to the power plant for electricity, the plants would become large facilities in the sense that neutron and photon sources (reactors and storage rings) are.

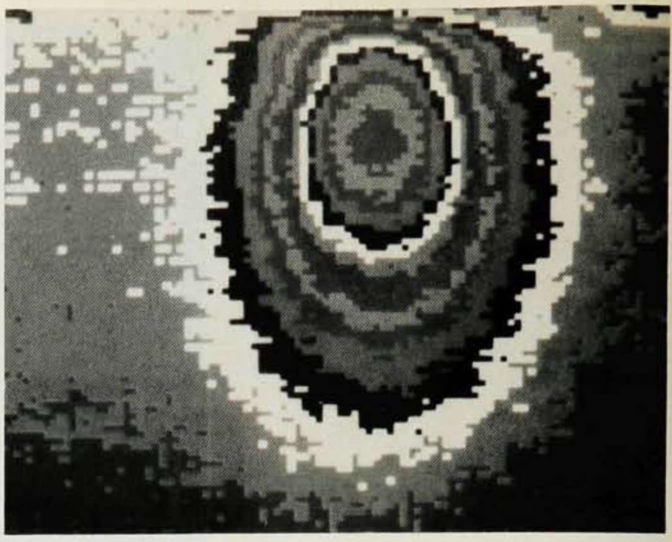
The facilities are on a large scale because, to date, it has not been possible to produce small sources with the necessary properties. Neutron beams with adequate flux are available only from reactors or large accelerators (see figure 2). (Laboratory-scale sources, such as Pu–Be sources, are inadequate for all but demonstration experiments.) Laboratory sources of light, on the other hand, have long been available. In the uv and x-ray portions of the spectrum, however, the sources are weak and unevenly distributed in wavelength. The advent of synchrotron radiation sources provided very highly collimated radiation throughout the spectrum, with intensities far greater than laboratory sources.

Many studies of large facilities for condensed-matter physics have been carried out in the past decade.[2] Most recently, the National Academy of Sciences charged[3] its Major Materials Facilities Committee—whose 22 members were drawn from universities and industrial research laboratories—to undertake the "difficult and painful" task of recommending priorities in two categories: upgrades of existing facilities and the construction of new ones.

For new facilities, the committee concluded that highest priority should be given to the construction of a 6-GeV synchrotron radiation facility—at a cost of about $160 million—designed to make optimum use of wigglers and undulators and thus provide radiation brighter by orders of magnitude than what is currently available. As a second priority the committee recommended construction of an advanced steady-state neutron facility—to cost about $240 million—with five to ten times the neutron flux of existing reactors. This facility would provide new capabilities for high-resolution neutron spectroscopy of condensed matter; with low-energy, or "cold," neutron sources built in, it would also serve for small-angle scattering and for metallurgical and biological studies. Among the recommendations for the upgrade of existing facilities, highest priority was given to the addition of guide halls and new instrumentation ($30 million) at existing research reactors. The full program that was laid out includes a number of additional initiatives, which together should provide the opportunity to address many of the outstanding problems in condensed-matter sciences into the next century.

European and Japanese scientists are already pursuing comparable paths in the development of these large facilities. The European Synchrotron Radiation Facility, a device comparable to the proposed 6-GeV ring, is tentatively to be located in Grenoble, adja-

Small-angle x-ray scattering patterns obtained, in real time, from crazes during the unloading portion of a 2-second fatigue cycle. The contours represent levels of scattering intensity. The change in pattern from maximum load (left) to minimum load (right) indicates that the craze fibrils (which are 6 nm in diameter) buckle during unloading, accelerating the fibril breakdown that converts the crazes into cracks. These patterns were obtained with an image-intensifier–video system at the Cornell High Energy Synchrotron source, each in 33 msec; a conventional x-ray system using film would have required 24 hours for each image. (Photo courtesy Edward J. Kramer, Cornell.) Figure 4



cent to the high-flux reactor at the Institut Laue-Langevin, which is itself the premier neutron-scattering facility in the world. Japan built the Photon Factory at Tsukuba; the same site now also boasts a spallation neutron source. The British spallation neutron source, which, along with the Weapons Neutron Research facility at Los Alamos, will be the most powerful in the world, is nearing completion at the Rutherford–Appleton Laboratory, and there is a German proposal for a spallation source with an *average* neutron flux greater than that of Grenoble. The tables on page 74 list major neutron and synchrotron radiation sources now operating or planned throughout the world.

Neutron research

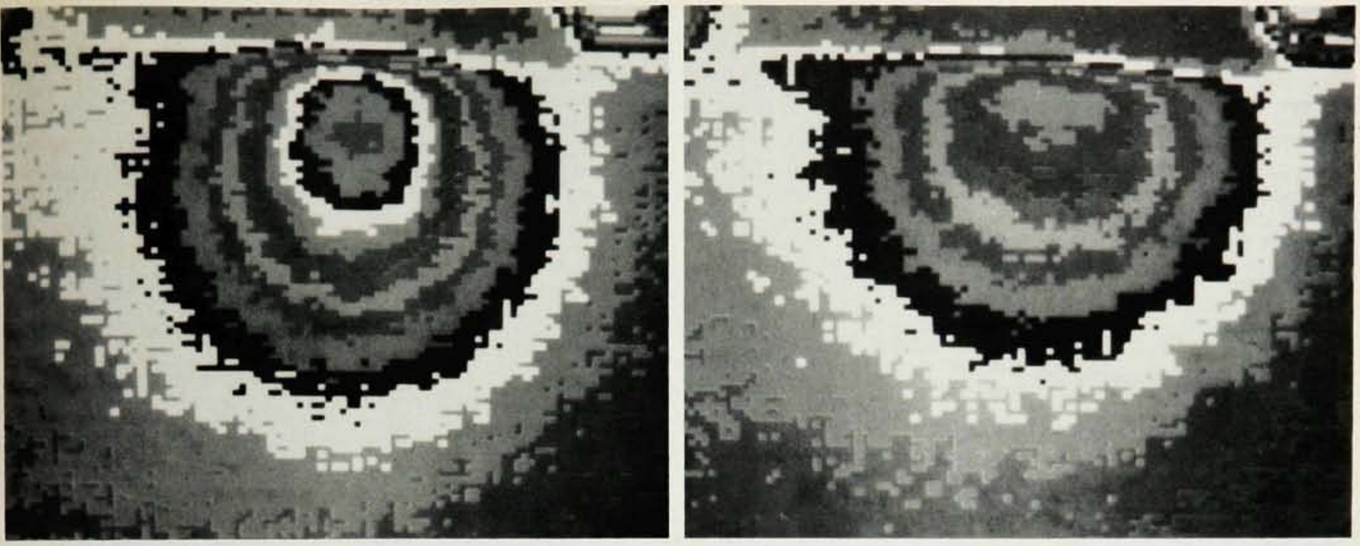
Neutron scattering techniques provide extremely important tools for the exploration of condensed matter, as described in the January issue of PHYSICS TODAY. The promise lies in two directions. First, improved sources of "cold" neutrons—neutrons with wavelengths greater than 4 Å—will open up new vistas in studies of complex structures such as polymers and in high resolution studies of magnetic vibrations and electronic excitations in solids. A new reactor optimized for the production of cold neutrons together with new developments in neutron optics can provide flux and resolution levels many orders of magnitude beyond what is currently available. Second, pulsed neutron sources will open new frontiers in the epithermal region, providing copious neutrons with energies of the order of electron volts and making possible high-resolution studies of excitations of crystalline and amorphous materials.

Few of the neutron sources now in use to study condensed matter have been designed from the beginning with neutron-beam production as the primary purpose. In the US—and, indeed, throughout the world—the reactors initially used for condensed matter had been designed for broader research purposes involving the peaceful use of atomic energy. In the 1960s the High Flux Beam Reactor at Brookhaven and the reactor at the Institut Laue–Langevin were designed with neutron beams in mind. Neutron-scattering experiments at these and other high-flux facilities have provided unique information not obtainable from other techniques. The understanding of magnetic order in superconductors, random fields in antiferromagnets, spin glasses, phase transitions, one- and two-dimensional order, charge-density waves and quantum fluids is based largely on neutron scattering. New sources and new experimental techniques, such as neutron interferometry, small-angle scattering and spin-echo spectrometry, will allow neutron scattering to grow into regimes of more subtle physics in more complex systems.

To get some idea of the gains that could be realized with a next-generation neutron-scattering facility, consider a reactor source based upon conventional moderator and cooling technology. With optimized designs it should be possible to increase the raw thermal-neutron flux in the core by a factor of 5 or 10 before reaching fundamental constraints due to heat transfer. But it is important to emphasize that this is only one of a number of factors by which the overall performance would be enhanced. In the very important area of cold-neutron research, designs for improved cold-neutron moderators and neutron guides based on recent experience in Western Europe offer further gains. Because of their intimate coupling to the reactor core, cold sources must be an integral part of the total reactor design; they cannot be easily put into the existing high-flux reactors.

Conservative estimates based upon currently available technology with nickel guides suggest a potential figure of merit not less than ten times better than the best cold-source guide systems currently operating in the US. In addition, replacing the conventional Ni guides with multilayer-coated beam-transport optics promises a further increase in usable flux by a factor of 2.5–10 for those experiments that can tolerate the increased beam divergence. Thus a cold-neutron scattering instrument at a new reactor may have available a neutron beam some 125 to 1000 times as intense as what is now available.

These gains in intensity could be immediately transformed into increased sensitivity or resolution. The factor of 125–1000 even underestimates the true increase in effectiveness, because it does not take into account the fact that neutron guides transport beams into low-background areas and away from the crowded reactor face; they thus allow more instruments to operate simultaneously and with less



interference from background radiation.

Synchrotron radiation research

The development of synchrotron-based research has been driven by the development of ever-increasing source flux and brilliance. (Flux is the total photon rate per unit bandwidth per unit area at the sample, while brilliance is the photon rate per unit source area per unit solid angle per unit bandwidth.) Generally, experiments that do not require highly collimated beams—such as photoemission spectroscopy and studies of extended x-ray-absorption fine structure—have signal rates proportional to source flux, while experiments that require highly collimated beams and small sample areas—such as surface diffraction studies—have signal rates that scale with source brilliance.

As sources have developed from high-energy facilities used parasitically to rings specially designed for higher brilliance, the scientific results they have produced have become more and more important. For example, uv photoemission spectroscopy has elucidated electronic structure, gas phase spectroscopy has contributed to the study of excited atomic and molecular states, and soft x-ray lithography has become an important technology (see figure 3). The high brilliance and high flux of synchrotron x-ray sources have allowed experimenters to use EXAFS techniques in studying grain boundaries in alloys, active sites in catalysts and the local structure of amorphous materials and biological materials. Small-angle scattering has advanced to permit time-resolved studies of various materials phenomena, such as phase separations in multicomponent glasses and crazing in stressed polymers (figure 4). Further development of the sources has allowed x-ray scattering techniques to be so refined that one can now study directly the structure of microcrystals only 1 micron on a side, and even crystal surfaces. While x rays scatter very weakly from magnetic structures—the scattering is 10^{-6} times that of ordinary Bragg scattering—one can now examine x-ray magnetic scattering with higher resolution than neutron scattering, and medical researchers are beginning to use synchrotron radiation for imaging coronary arteries.

▶ Angle-resolved photoemission has become to the electronic structure of materials what x-ray scattering is to crystal structure and what neutron scattering is to phonon structure. One can use angle-resolved photoemission to determine the three-dimensional (bulk) or the two-dimensional (surface) band structure of most single crystals. The unique capabilities that are available with a polarized, tunable, and intense radiation source allow the experimenter to tune to any part of the two- or three-dimensional band structure and to determine the orbital symmetry of each state. One can then use these experimental symmetries to determine band symmetries of the bulk material, orbital characters of the surface states, and bonding orientations of adsorbed molecules. Electronic-structure measurements have been made on such materials as simple metals and semiconductors, transition metals and rare earths, compound semiconductors and alloys, and intercalated graphite and layered compounds.

Measurements of angle-resolved photoemission from surfaces of single crystals have revealed in detail the character of the two-dimensional electronic states for surfaces bearing adsorbed atoms or molecules or carrying bulk impurities segregated to the surface. Not only can one observe the electronic state of the adsorbate–substrate bond, but one can also measure the adsorbate–adsorbate interaction—either directly or through the coupling to the substrate. An excellent example of this type of work is the detailed examination of the bonding of H to the surface of Pd or Ti crystals, or the bonding of S segregated to the surface of Fe crystals.

▶ Surface x-ray diffraction techniques are quite new, but substantial progress has been made, and the future potential of this technique is clear. Measurements made so far include determinations of the reconstructed surfaces of Ge(100), Si(111) and InSb(111); studies of adsorbate structures such as Pb and O on single-crystal Cu, and Kr and Xe on single-crystal graphite; work on thin liquid-crystal films and thin amorphous layers, and time-dependent studies of recrystallization following laser annealing. It is now well established that available x-ray fluxes from insertion devices (that is, wigglers and undulators) permit studies of single atomic layers of materials with low scattering power. The wide range of systems available for study therefore includes essentially the entire periodic table (except H and possibly He). There have been successful studies of systems with opaque substrates and with transpar-

Principal synchrotron sources

Location	Energy (GeV)	Type
USA		
National Bureau of Standards	0.28	dedicated
Cornell University	5.5	parasitic
University of Wisconsin	0.24	dedicated
	0.8	dedicated
Brookhaven	0.75	dedicated
	2.5	dedicated
Stanford	4.0	parasitic
	15.0	parasitic
LBL	1.3	dedicated*
(Various proposals)	6.0	dedicated*
Japan		
Tokyo	0.3	dedicated
Tsukuba	2.5	dedicated
	0.6	dedicated
Okasaki	0.6	dedicated
England		
Daresbury	2.0	dedicated
France		
Orsay	0.54	dedicated
	0.8	dedicated
	1.8	dedicated
Germany		
Hamburg	5.0	parasitic
Berlin	0.8	dedicated
Italy		
Frascati	1.5	parasitic
USSR		
Moscow	0.45	dedicated
Karkhov	0.1	dedicated
Novosibirsk	0.7	parasitic
	2.5	parasitic
	5.0	parasitic
China	2.8	dedicated*
India	0.8	dedicated*
Taiwan	1.0	dedicated*
USSR	2.5	dedicated*
Europe	5–6	dedicated*

*Proposed

Principal neutron sources

Location	Type
USA	
Brookhaven, HFBR	reactor
Oak Ridge, HFIR	reactor
Argonne, IPNS	spallation
Los Alamos, WNR	spallation
National Bureau of Standards	reactor
Canada	
Chalk River	reactor
France	
Grenoble, ILL	reactor
Grenoble	spallation*
Saclay	reactor
England	
Rutherford-Appleton Lab., SNS	spallation
Denmark	
Risø	reactor
Japan	
Tsukuba	spallation
Tokai	reactor
Germany	
Jülich	spallation*
Munich	reactor
Berlin	reactor

There are many smaller reactors throughout the world where some neutron scattering is carried out. We have listed only the major sources of this type.
*Proposed

ent substrates,and of freely suspended systems with no substrates. The penetration of x rays also has been shown to allow the study of structures below the surfaces and at interfaces.

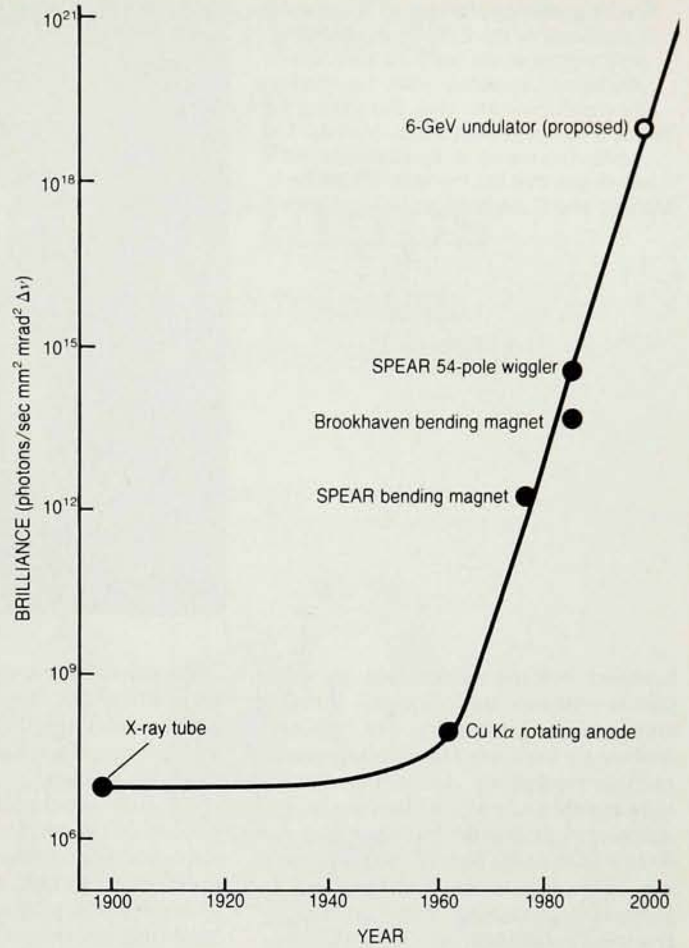
▶ X-ray lithography is still in its development stages, yet it represents a significant commitment in the programs for synchrotron-radiation research, both in the US and abroad. In the US most of the efforts have centered on 1:1 contact lithography, where the ultimate objective is to integrate x-ray lithography into a semiconductor processing line for fabricating VLSI circuits. In addition to working on circuit applications, researchers are also studying structures having a very high aspect ratio. Synchrotron radiation has recently also been used to study the spectral response of sensitized photoresists; the resulting data will be especially useful to determine the imaging quality of soft-x-ray optics for future x-ray projection printers. In Europe, x-ray lithography is also a very active field, and semiconductor processing facilities are being integrated into synchrotron-radiation facilities.

▶ Magnetic x-ray scattering shows the promise of complementing traditional neutron-scattering studies. For example, recent experiments have shown that the sample volume can be up to six orders of magnitude smaller than required for an optimal neutron experiment, and calculations show that it may be possible to study surface magnetism. Furthermore, the high intrinsic collimation of synchrotron radiation makes possible excellent wavevector resolution (that is, with Δq on the order of 10^{-4} Å^{-1}). Such resolution is essential in studies of incommensurate magnetic structures. Finally, the polarization dependences of the cross section permit not only the separation of charge scattering and magnetic scattering, but also the separation of orbital and spin contributions. It is clear that x-ray diffraction experiments using synchrotron radiation will ultimately make significant contributions to the field of magnetism.

A new synchrotron source

The enthusiasm of researchers in condensed matter for the construction of a new synchrotron facility (recommended with the highest priority by the Major Materials Facilities Committee) stems both from the technological opportunity to produce dramatically brighter x-ray beams and from anticipating the results that will certainly flow from research at such a source. Before we discuss these research opportunities, we will mention the key points in the technical rationale for a new facility. The starting point is the understanding of the consequences of the spectral effects produced by undulator magnets. Figure 5 schematically represents the history of x-ray brilliance; figure 6 shows what is now the brightest beam in the world. Undulators clearly represent an enormous gain over current synchrotron sources. Instead of the broad fan of radiation with a continuous spectrum produced by bending magnets and wigglers, the constructive interference that takes place in an undulator produces radiation whose spectrum peaks at a wavelength λ_p (and its harmonics) and which is collimated into a solid angle $d\Omega$ given by $2\lambda_p/L_u$, where L_u is the undulator length. The wavelength λ_p at which constructive interference occurs is given approximately by $\lambda_u/2\gamma^2$, where γ is the electron energy in units of mc^2, and λ_u is the undulator magnet period. (This expression is quite different[4] from that for the critical wavelength of bending magnet radiation.) To produce undulator radiation peaked at 20 keV ($\lambda_p = 1$ Å) with a reasonable undulator period, one thus requires an electron energy of about 6 GeV. This energy level represents the first requirement for a new machine.

There is a second requirement for the machine that stems from the highly collimated nature of undulator radi-



Brilliance of x-ray sources as a function of time, as indicated by some important devices. The most recent sources marked on the graph are a parasitic bending magnet at Stanford, a bending magnet at Brookhaven's low-emittance ring, and the 54-pole wiggler at SPEAR. (The unit bandwidth $\Delta\nu$ is 0.1%.) Figure 5

ation. For a peak wavelength of 1 Å and an undulator 2 m long, we find that the beam is emitted into a solid angle $d\Omega$ of 10^{-10} rad²—a spectacularly small divergence: The beam will pass through a 200-micron pinhole some 20 m from the undulator. To achieve this high collimation, the undulator must be installed on a "low-emittance" storage ring, that is, a ring with a small, highly collimated electron beam. Fortunately, progress in storage-ring design made over the last 10 to 15 years offers the possibility that rings based on current technology can have both crucial properties.

We should make one final point before discussing the scientific opportunities of a new synchrotron. A 6-GeV ring, while optimized to produce hard x rays, would also produce longer-wavelength radiation of high brilliance. In fact, beams of wavelengths shorter than about 100 Å would be more brilliant on a 6-GeV source than on any existing lower-energy storage ring. A high-energy storage ring is therefore expected to serve users representing a broad spectral range.

Scientific opportunities

The scientific opportunities for the 6-GeV ring fall into four well-defined categories. The first category contains all the unanticipated research that emerges once the facility is in use. Inevitably the most exciting and far-reaching discoveries made with newly developed experimental tools are those that were not predicted. To confirm this view, one need look no further than the preconstruction vision of what physics was likely to emerge from the SPEAR storage ring. Not only was the J/ψ particle unpredicted, but no one had imagined how useful SPEAR would be as a synchrotron-radiation facility. The gain in brilliance provided by the proposed 6-GeV undulator beam is so substantial that unanticipated work will be a large—perhaps the largest—component of the work to be done a decade from now.

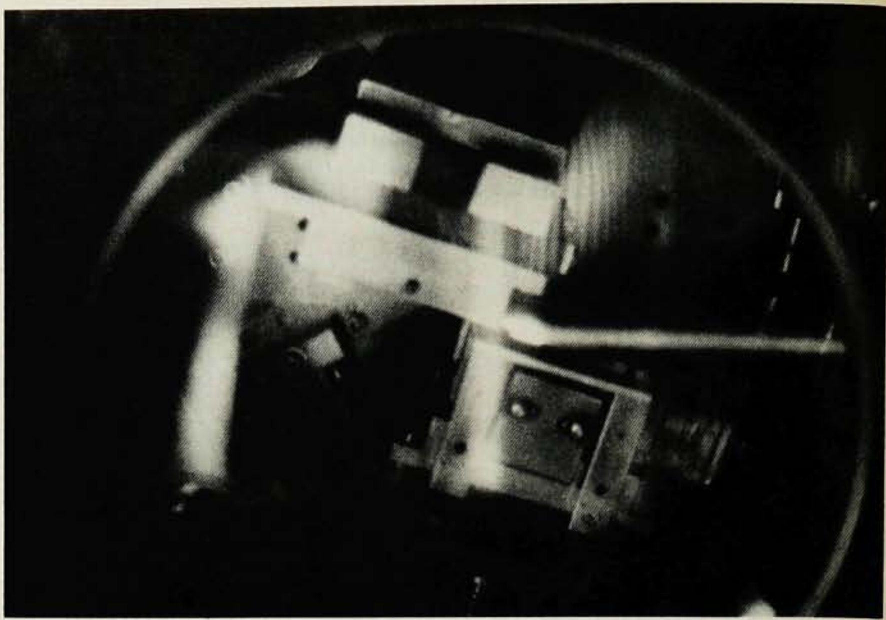
The next category contains the research we anticipate doing but cannot now accomplish for lack of the special properties of undulator radiation. Condensed-matter phenomena generally have both a temporal and a spatial scale. An example would be the energy–momentum relation (dispersion curve) of a phonon mode in a crystal. Currently, x-ray experiments involve an energy-transfer resolution of less than 1 eV and a momentum-transfer resolution generally poorer than 10^{-3} Å^{-1}; their real-space resolution is generally poorer than 100 microns, and their time resolution is generally longer than about a nanosecond. The x-ray undulator, however, will permit us to work *routinely* in regions not currently accessible to experiments.

Two examples demonstrate how techniques based on the 6-GeV undulator will permit improved resolution:

▶ The x-ray microprobe, in which microfocused x rays are used for spectroscopic studies of the elemental constitution of matter. Calculations show that a 6-GeV undulator microprobe would have an advantage of at least 10^3 in detectability over the state-of-the-art electron microprobe; it would be able to resolve spatial variations at the 500-Å level. This level of spatial resolution is a direct consequence of the brilliance of radiation from an undulator. When one realizes that approximately $1 billion is invested nationally in electron microprobes, the scale of the potential impact of a factor of 10^3 in minimum detectability becomes clear.

▶ Inelastic x-ray scattering from solids. Neutron scattering is at present the preferred technique for resolving meV (that is, thermal-energy) excitations in solids. The best x-ray energy-transfer resolution available with techniques based on current sources is about 0.1 to 1.0 eV. It may be possible to use spherically bent crystals in a back-scattering geometry to obtain resolutions of 10^{-2} eV. If so, one can at best hope to demonstrate the potential of the method on existing synchrotron sources. The proposed low-emittance 6-GeV source will, however, be sufficiently powerful that x-ray inelastic scattering can become as routine as neutron techniques. Of course, x-ray scattering has advantages over neutron scattering in some cases. For example, the x ray couples directly to electronic excitations, and it is considerably more sensitive to surface features; high-energy transfer is much more easily accomplished with x rays, and essentially no kinematic restrictions prevent access to the low-momentum–high-energy-

The brightest photon beam in the world is produced by the Exxon–LBL–SSRL 54-pole wiggler at the Stanford Synchrotron Radiation Laboratory. Here it is entering the monochromator tank and striking the first of a pair of perfect silicon crystals. The beam shows up as fluorescence in the helium gas that fills the tank. (Photo by H. Morales and S. Brennan.) Figure 6



transfer regime of interest in amorphous systems and liquids. Another spectacular possibility for inelastic scattering involves the development of nuclear-resonance scattering to provide monochromatic x-ray beams with submicrovolt resolution. In principle a 6-GeV undulator source with appropriate instrumentation would allow for inelastic scattering with an energy-transfer resolution of 10^{-7} eV.

We turn now to the third category of opportunities for the 6-GeV ring: extensions of existing techniques. Scattering experiments of various sorts are the primary beneficiaries of increased brilliance because they generally require high flux, good collimation and small beam size in varying degrees. High flux is necessary for studying materials with low atomic number, for studying samples with few scattering particles (such as atomic microclusters) and for performing time-resolved experiments. Good collimation is necessary in scattering experiments for studying long-range order and structures having large length scales, and for accurately varying the incidence angle (and, therefore, the penetration depth) of the beam. Small beam size is necessary for studying small crystals or materials in restricted volumes (as in high-pressure experiments), for diffraction microscopy and for studies involving glancing-angle diffraction.

We finally arrive at the last category: the science that could result from radiation sources at the new facility other than x-ray undulators. Although x-ray undulators are the primary scientific goal, the 6-GeV ring would have the standard complement of bending magnets which could support a large number of beam lines, perhaps doubling the nation's capacity for application of well-developed synchrotron techniques: EXAFS, surface EXAFS, powder diffraction, low-resolution microprobes, small-angle scattering, crystallography, surface diffraction and time-resolved studies.

A 6-GeV synchrotron would have an impact on experiments involving the electromagnetic spectrum from roughly 100 eV to 10 keV, providing from two to four orders of magnitude more brilliant illumination. Given the history of photons in condensed-matter research, the scientific success of such a facility is assured.

Consequences

Thirty years ago Rudolf Peierls wrote[5] in the preface to his book on theoretical solid-state physics, "The quantum theory of solids has the reputation of being rather less respectable than other branches of theoretical physics." He explained that this was the consequence of the use of extremely simple single-particle approximations to make the connection between microscopic and macroscopic phenomena. This situation has radically changed in the intervening years. The development of the many-body theories of superconductivity and superfluidity and the microscopic understanding of phase transitions has placed the theory of condensed materials in the intellectual forefront of physics, with high-energy and nuclear physicists often using theoretical results from condensed-matter physics. But the payoff has been far greater than Peierls could have imagined. Not only is the intellectual core of condensed-matter physics as deep and exciting as any branch of physics, but the impact of this knowledge—and the methods used to obtain it—in other branches of science and technology is enormous. Condensed-matter science, broadly construed, provides the scientific basis of our high-technology society. Among the key experimental methods that have driven this explosion of knowledge are the studies of the space–time correlations of phenomena in condensed matter, which have used electron, neutron, and electromagnetic probes. The continued development of facilities for these probes will keep condensed-matter science in both the intellectual and technological forefront.

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