A 6-GeV Storage Ring: An Advanced Photon Research Facility

P. EISENBERGER

The high brightness of synchrotron radiation produced by storage rings has enhanced research capability by factors of 10^6 to 10^8, from the ultraviolet to the x-ray region. There has been a steady growth in synchrotron radiation research of interest in physics, chemistry, biology, geology, and the other physical sciences and their associated technologies. A large number of university, government, and industrial research organizations are utilizing this new capability at existing facilities. In the process, new partnerships have been created among these communities that have enabled each to contribute its expertise and to obtain its needed capability. A 6–giga-electron volt storage ring, designed for use with periodic magnetic insertion devices called wigglers and undulators, has been proposed; such a facility could provide further enhancements of 10^4 to 10^6 in capability and could double the synchrotron radiation research capacity in the United States. This enhanced capability and capacity will provide new opportunities for a broad range of scientific and technological interests.

SCIENTISTS IN MANY DISPARATE FIELDS PERCEIVE THE STUDY of complex materials, from biological membranes to metallurgical alloys, as entering an era of rapid progress similar to the revolution in solid-state technology of the 1950's and 1960's. Furthermore, there is a belief that the technological changes in electronics and computers that followed the advances in solid-state physics could be repeated on a much broader scale because of these imminent scientific advances in our understanding of complex materials.

An important component of these growing perceptions is our rapidly improving arsenal of analytical tools. These tools enable us to look inside complex materials and systems to see how they are structurally arranged, to determine their microscopic dynamics, and to relate their microscopic properties to their special features. Significant advances in static and dynamic measurement capabilities are being made on many fronts, including electron microscopy, neutron-scattering techniques, laser-based measurements, and various spectroscopies such as nuclear magnetic resonance. In particular, truly revolutionary advances are occurring in the use of photons (light) from the ultraviolet to the hard x-ray region to study complex materials. Because photons have been a primary tool for studying properties of matter, it is particularly significant that photon-based techniques are rapidly advancing. These changes are being driven primarily by advances in synchrotron radiation (SR) sources, which offer photon sources that provide from 10^6 to 10^8 times more radiation for experiments than previously available to researchers pursuing a broad range of scientific and technological objectives.

However, as discussed below, the proposed 6-GeV storage ring will provide a further enhancement—by a factor of 10^4 to 10^6—in SR research capability and will roughly double the existing SR capacity in the United States. Thus the 6-GeV storage ring will truly be an advanced photon source that serves as the centerpiece of an advanced photon research facility (APRF). The potential of the APRF for scientific and technological advances has been recognized in two recent national studies: it was given top priority for new facilities in an SR planning study conducted by the Department of Energy (*1*), and it also received the highest priority for new facilities in a subsequent National Academy of Sciences study of major facilities for materials research and related disciplines (*2*). This priority was recently endorsed by the Energy Research Advisory Board of the Department of Energy.

Synchrotron Radiation

Synchrotron radiation is produced when charged particles, particularly electrons or positrons, are accelerated by means of a magnetic field perpendicular to the particles' direction of motion. Its detailed properties, described by J. Schwinger in 1949 (*3*), were first observed in 1947 at a General Electric synchrotron. In a synchrotron, the charged particles are accelerated through time-dependent electric and magnetic fields; in a storage ring, the fast-moving (relativistic) particles are "stored" in bunches at constant energy and kept in a quasi-circular orbit by time-independent fields from bending magnets. A klystron system is used to replenish the radiated energy (SR) lost by the charged particles as they pass through the magnet fields. Bending magnets produced the first observed and useful SR and have provided enhancements of three to six orders of magnitude in flux available for a typical experiment over conventional sources of photons, such as gas discharge lamps in the ultraviolet region (50 to 1000 eV) and x-ray tubes in the x-ray region (1 to 100 keV).

Because of relativistic effects, SR is emitted in a narrow cone around the direction in which the particle is moving. The opening angle of the cone (in radians) is given by m_0c^2/E, where m_0 is the rest mass of the particle, c is the speed of light, and E is the energy of the particle. This fundamental ratio is known as $1/\gamma$. For a 6-GeV electron, the opening angle is about 0.005°. This means that SR from a bending magnet is emitted only over that small angle perpendicular to the direction of the bend while covering an angular spread equal to the bending angle of the electron beam in the plane of the bend (Fig. 1). The radiation is more than 90 percent linearly polarized. To first order, both the bunch length of the particles and the resulting pulse length of the radiation are determined by the radiofrequency (rf) system. Pulse lengths as low as 50 psec have been achieved.

The author is currently senior director at the Corporate Research Science Laboratories, Exxon Research and Engineering Company, Clinton Township, Route 22 East, Annandale, NJ 08801.

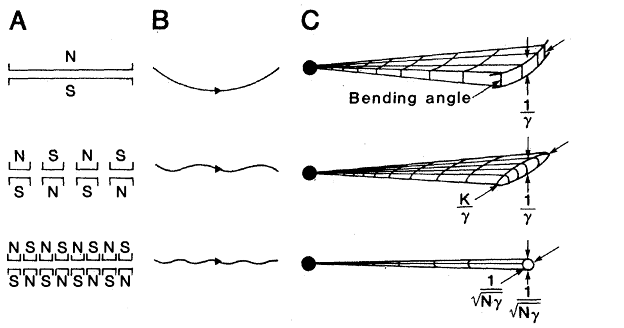

Fig. 1. Typical magnet configurations (side view, A), charged particle orbital variations (top view, B), and resultant SR radiation patterns (side view, C) for bending magnets (top), wigglers (middle), and undulators (bottom).

The SR produced by bending magnets is continuous radiation with significant intensities from the infrared up to roughly four times the critical energy (E^c), which is given by

$$E^c \text{ (keV)} = 0.06651\ BE^2 \tag{1}$$

where B is the magnetic field in kilogauss and E is in gigaelectron volts (Fig. 2). Therefore, a 13-kG bending magnet produces an E^c of 500 eV for the 0.75-GeV storage ring at the Brookhaven National Synchrotron Light Source (NSLS) and of approximately 7.5 keV for the storage ring at the Stanford Synchrotron Radiation Laboratory (SSRL) when it operates at 3.5 GeV and 9.2 kG. While the enhancements that the bending magnets provide are significant (Fig. 3), they are just the tip of the iceberg in terms of the intensity and quality of the SR.

The conceptual advance forming the basis for the proposed 6-GeV advanced photon source and the 1- to 2-GeV Advanced Light Source (ALS) in the United States as well as for new machines in Europe has been the recognition that radiation of much higher quality can be produced from special magnetic devices inserted into straight sections of a storage ring. In a straight section, a magnetic array of length L can wiggle the electron trajectory in a transverse magnetic field that has alternating north and south poles, say, N times with no net change in direction of the beam (Fig. 1). These insertion devices immediately provide an increase in intensity by a factor of N because the radiation from each of the N magnetic sources is superimposed in the beam direction. In addition to enhanced intensity, other characteristics of the photon beam can be controlled by varying the magnetic period λ_u, which is equal to L/N, and the strength of the magnetic field, B. A key parameter determining performance is K, equal to $0.093\ B\lambda_u$, with B in kilogauss and λ_u in centimeters. To a first approximation, K is the ratio of the maximum angular excursion of the electron due to beam bending in the magnetic field to the SR opening angle $1/\gamma$. If K is less than or equal to 1, the device is an undulator; for K much greater than 1 it is a wiggler. Although the same theory describes the behavior of both these devices, their properties can be significantly different.

The radiation produced by wigglers is similar to that of a bending magnet in its vertical opening angle, $1/\gamma$, and its energy distribution (Figs. 1 and 2). However, its horizontal opening angle is K/γ, and its intensity is multiplied by N (Figs. 1 and 2). A wiggler can use higher fields than a bending magnet, including those generated by superconducting magnets. These higher fields will shift the spectrum of the SR to higher energies (Fig. 2). An important feature of an advanced photon source is that the spectrum of each insertion device can be individually tailored to its intended use by adjusting B and λ_u.

To understand the properties of undulators, one must take account of the interference of the radiation emitted by each of the $2N$ magnetic poles. For the purposes of this discussion, the important properties for small angular deviations of the electron ($K < 1$) are as follows: (i) the radiation is now limited to the horizontal angle of $1/\sqrt{N}\gamma$, assuming that the electron beam itself is highly directional so that it does not blur the radiation pattern; and (ii) on the central axis of the device within the solid angle $1/N\gamma^2$, the radiation is not continuous in energy but shows peaks (λ_p) at the values given by

$$\lambda_p^m = \frac{\lambda_u}{2\gamma^2 m}(1 + K^2/2) \tag{2}$$

with a fractional energy width of $1/N$. For a magnetic period λ_u of 1.5 cm and an electron energy of 6 GeV, the fundamental ($m = 1$) is at approximately 0.61 Å or 20 keV; for 1 GeV it would be 36 times lower, or only about 560 eV. Thus while a wiggler achieves a factor of N increase in intensity, an undulator has a factor of N^2 increase in brightness due to the decreased solid angle (Fig. 2). An undulator also offers the potential bonus for some experiments of a quasi-monochromatic beam. With N being as large as 100, the improvements can be significant, and a highly coherent source can be produced. In fact, under certain conditions, the radiation will become stimulated and increase in amplitude as it travels through the periodic magnetic structure. This is called a free-electron laser (*4*). Such behavior has already been observed on the storage ring at Orsay, and a similar device is being tested at Brookhaven on the 0.75-GeV ring. Such devices promise very high power levels of radiation that can be tunable from the infrared to the near ultraviolet.

Undulators and wigglers have been tested, and their behavior agrees with predictions (*5*). The first hard x-ray (10-keV) undulator is under construction on the 15-GeV high-energy research facility at Stanford.

The Proposed APRF

The details of the proposed APRF have not been fixed because various designs are possible. However, with the terminology developed in the previous section, a general description of such a facility can be given. It will be a storage ring roughly 800 m in diameter with bending magnets operating around 10 kG, producing a critical energy of 25 keV (Fig. 4). It will have 32 straight sections for insertion devices with lengths of about 5 m. The energy of the machine was chosen on the basis of several factors. First, current magnet technology gives roughly 1.5 cm as the minimum periodicity λ_u that can generate a large enough magnetic field to produce significant SR intensities from a beam that is transversing the middle of a gap roughly 1 cm in diameter. A gap of that size is required to prevent substantial loss of the beam due to interaction with the walls of the chamber. Second, the scientific opportunities represented by undulators will require radiation up to roughly 20 keV. Substituting into Eq. 2 the values of 1.5 cm for λ_u and 0.61 Å (20 keV) for λ_p and a reasonable value for the magnetic field B ($K \cong 0.5$) gives 6 GeV ($\gamma = 1.7 \times 10^4$) as the required energy of the storage ring. The APRF can also produce undulator radiation at lower energy (Fig. 3) by making λ_u longer (for example, 50 cm provides a 150-eV undulator fundamental for $K = 2.7$ with a broad bandwidth because N would be only 10 in a 5-m straight section). Thus, not only can the APRF provide undulator radiation in the hard x-ray region but advances of several orders of magnitude can be achieved below 1 keV, as indicated by recent results with the high-energy ring in Germany. In this region the proposed 1- to 2-GeV ALS would provide radiation with superior properties.

In order for the beneficial properties of SR produced by an undulator on the advanced photon source to be realized, the size and divergence of the circulating positron (*6*) beam must be very small indeed. The size and angular divergence of a positron beam varies as it travels through the various magnetic lenses that define its path, but the product of size and divergence (emittance) is roughly conserved in a given machine. Typical values needed for the x-ray undulator are 50-μm sizes and 50-μrad divergences.

The National Academy of Sciences study (*2*) estimated that the APRF will cost about $160 million, which includes $125 million for construction and $35 million for instrumentation. The allotment for instrumentation would fully equip ten insertion devices with 20 experimental beamlines. Beamlines, which contain monochromatizing and focusing elements, tailor the radiation from the ring to meet a particular experiment's requirements. The intensity of the radiation provided by the APRF will require special designs for beamline components exposed to the high power densities.

It is envisaged that in full operation both the straight sections and bending magnets will be used for research, and thus more than 200 experiments can be conducted simultaneously with SR from the infrared to the hard x-ray region. However, this large facility will have small-facility equipment and operation economics. The equipment at the end of the beamlines is virtually identical to that used with conventional sources of radiation. With 200 simultaneous experiments and with each beamline capable of supporting at least four independent experimenters, the projected $20-million annual operating cost becomes only $25,000 per experimenter per year. Thus, both in equipment use and operations, an APRF can be cost effective.

Figures 2 and 3 indicate the enhanced capability, in terms of the quality of SR, that the APRF can provide over existing sources in the United States. The next section describes the simultaneous evolution of improved capability and scientific advances that have led to the present status of the APRF and that have helped to shape the vision of what it could provide in the future.

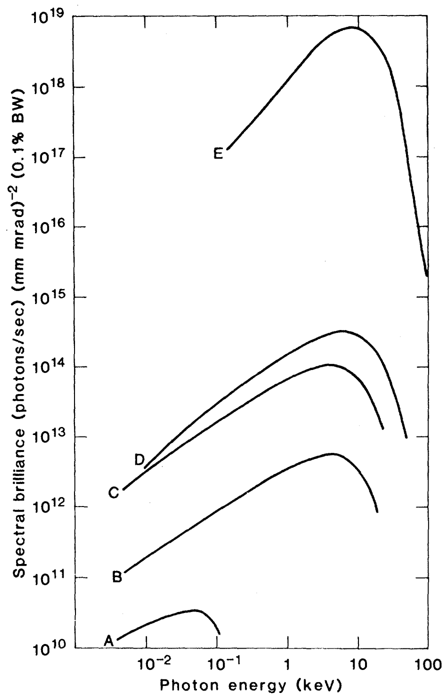

Fig. 2. The SR spectrum of the Tantalus bending magnet (A), the SSRL bending magnet (B) and 54-pole wiggler (D), and the Brookhaven NSLS bending magnet (C). For the APRF undulators (E), the spectrum represents the range and intensities achievable by varying the periodic spacing and magnetic field strengths.

Synchrotron Radiation Research: Past, Present, and the APRF

After the observation of SR in 1947, investigations of its properties were performed on existing synchrotrons such as the 0.3-GeV machine at Cornell University. In the early 1960's the fundamentals of photoabsorption in gases were explored on the 0.18-GeV synchrotron at the National Bureau of Standards (*7*). Since the first use of SR as a structural probe, there have been a large number of studies that have made significant additions to our understanding of atomic and molecular electronic structure and dynamics (*8*). An APRF would provide a significant additional increment in capability that should enable the simultaneous observation of electrons and ions produced in the photoabsorption process, the study of laser-induced excited states, and experiments with molecular beams.

In 1968, the 0.240-GeV Tantalus storage ring was commissioned at Stoughton, Wisconsin. While still designed for high-energy research, it became the first storage ring dedicated to SR research. It was at this facility that the first SR photoemission measurements were made for solids and surfaces (*9*). This marked the beginning of the productive use of SR for the successful study of bulk and surface electronic properties of various materials (*10*). Other related techniques were used or developed in these studies, including angle-resolved photoemission (*10*), photon-stimulated desorption (*11*), and photoelectron diffraction (*12*). In particular, angle-resolved photoemission with a tunable SR source provided unambiguous determinations of the band structure of solids.

The first use of an undulator (*13*) was in angle-resolved studies of the Auger electrons emitted after the excitation of inner-shell electrons from monolayer absorbates such as CO and N_2 on a nickel surface. The undulator experiments demonstrated an improvement of four orders of magnitude over similar experiments carried out on a bending magnet line. Those experiments, together with others, have helped to define some possibilities that the APRF presents, such as the simultaneous detection of the primary photoelectron and the subsequent Auger electrons. Such an approach could utilize the slight differences in binding energy of different sites on a surface, such as that of an atom on the edge of a step on a surface, to study selectively the Auger electrons and thus the electronic properties of a surface. In addition, the advanced photon source makes it possible to study the role of very low level impurities and surface electronic structure changes under real-time reaction conditions.

The first microscopy studies (*14*) were performed in 1972 at the

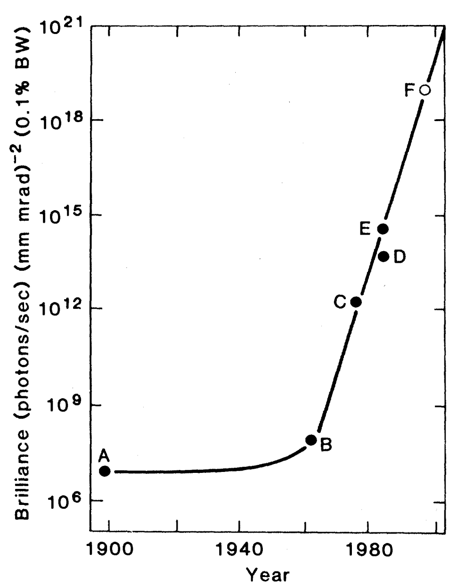

Fig. 3. X-ray source improvements as a function of time as characterized by the source brilliance. Higher source brilliance, together with x-ray optics, makes it possible to perform experiments with higher energy, higher angular and spatial resolution, and greater sensitivity. (A) X-ray tube, (B) CuKα rotating anode, (C) SSRL bending magnet, (D) Brookhaven NSLS bending magnet, (E) SSRL 54-pole wiggler, and (F) 6-GeV undulator (proposed).

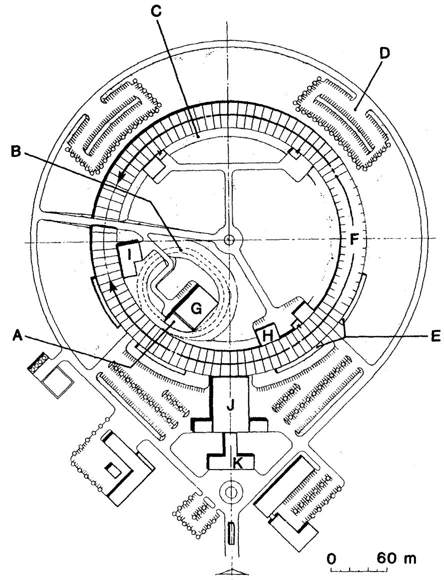

Fig. 4. Schematic for a facility such as the APRF. The injector (A) provides the beam of charged particles at modest energy, which the synchrotron (B) raises to 6 GeV for injection into the storage ring (C). The multiple magnetic sources, insertion devices, and bending magnets and the large size enables more than 200 simultaneous experiments to be performed. (D) Car park, (E) laboratories and offices, (F) experimental area, (G) synchrotron power supplies, rf equipment, vacuum support, and diagnostic interface equipment, (H) storage ring power supplies, (I) storage ring radiofrequency equipment, (J) machine and experimental support, and (K) administration and general facilities.

Cambridge electron accelerator. They clearly demonstrated the potential importance of the bright, tunable SR for x-ray microscopy and imaging in general. Another imaging development in Europe involved the use of SR-based topography to study low-level defects and distortions in solids (*15*). A significant development for the future is the work that began in 1978 on the use of SR in x-ray lithography for microcircuit replication and for taking pictures of biological structures with spatial resolutions slightly better than 100 Å (*16*). These initial studies have led to a major effort by IBM on the Brookhaven 0.75-GeV storage ring, as well as the dedication of a fourth of the new ring at Berlin (BESSY), to explore the potential of SR for electronic microcircuit replication.

Another imaging use of SR is for noninvasive angiography (imaging of blood vessels and heart chambers) (*17*). The SR-based procedure shows enough sensitivity on the basis of the intensity and tunability of the radiation that the catheterization procedure, which requires expensive hospitalization and entails higher risk to the patient, can be replaced by a much simpler intravenous injection of a lower dose of iodine. The successful development of this safer, higher quality, and lower cost medical technique may offer a large potential economic payoff, since approximately 500,000 conventional angiographic procedures that use conventional x-ray sources are performed in the United States each year at a cost of $1.5 billion to $2 billion (*2*).

An x-ray offers many advantages over a charged particle for microprobe investigations. The advantages arise from the ability of x-rays to be tuned in energy and thus to excite more effectively the element or elements of interest. This effectiveness means that for the same number of x-rays and electrons incident on the sample the x-rays can detect 10^4 to 10^5 fewer atoms, or that for a given specimen they can detect the atoms present with 10^3 to 10^4 less energy deposition (damage) than the electrons. Until now, x-ray beams could not be produced with sufficient brightness that their inherent advantages could be realized. Photon beams produced by the advanced photon source will be as bright as the most advanced electron probes. This will enable unprecedented low levels of detection for diffraction, extended x-ray adsorption fine structure (EXAFS), Auger, and photoelectron spectroscopy for both chemical and elemental identification. As is the case with the existing electron microprobes in which the United States has invested $1 billion, this increased capability will have great importance not only in materials science but in physics, chemistry, biology, geology, and medicine.

With the high coherence of SR from the advanced photon source, holographic-type imaging with unprecedented short wavelength radiation and thus high spatial resolution may be possible. An initial demonstration of this application took place at the new, high-brightness 0.75-GeV ring at Brookhaven, where 31-Å radiation was used to take a hologram of 0.5- to 2-μm asbestos fibers (*18*).

A significant era in SR research also began in 1972 with the Stanford Synchrotron Radiation Project on the 4.0-GeV Stanford Positron-Electron Accumulation Ring (SPEAR). Again, this machine was designed for high-energy physics research and was used to discover the Ψ particle, for which a share of the 1980 Nobel Prize in physics was awarded.

In 1974 the use of SR for EXAFS studies was demonstrated. For the purposes of this article, the important EXAFS characteristics are the ability to determine the local atomic structure (bond distance, number, and atomic type of neighbor) around an atomic species that is chosen simply by tuning the radiation through a region in which the species of interest absorbs strongly (*19*). This previously difficult and limited technique, when practiced with a conventional x-ray source, has been transformed by the intensity and tunability of SR into a powerful and versatile analytical tool. On existing sources it can determine structure around atomic species present at the parts per million level and for atoms covering only a fraction of a monolayer on a surface. The latter capability has developed its own acronym, SEXAFS (surface EXAFS) (*20*).

The EXAFS technique has been successfully applied to many diverse problems in a broad range of sciences and technologies. In biology, many life-supporting enzymes (such as hemoglobin) and particularly membrane-bound oxidases and phosphatases that cannot yet be subjected to crystallographic study have been shown by EXAFS to have structural parameters that define their modes of action (*21*). Nitrogen-fixing reaction centers in plants have been studied (*22*), as well as the structure of certain potential anticancer drugs (*23*). Examples in chemistry include fundamental studies of catalysis (*24*) of simple metals, bimetallic clusters, and zeolites. Of considerable importance are the studies of catalyst changes under real reaction conditions (*25*). In materials science studies, EXAFS has been used to investigate various low-level constituents in solids and solutions of interest in electronics, geology, and metallurgy. For example, studies of high-strength, low-alloy steels (*26*) containing 0.05 to 2 percent niobium, vanadium, or titanium have helped to determine the influence of fine carbide or nitride precipitates on the properties of the steel, and time-resolved studies have helped to characterize the precipitation process itself.

Besides extending the EXAFS capability to even greater dilutions (parts per billion in certain cases), time-resolved studies of intermediates in chemical and biochemical systems (*27*) are expected to undergo a major advance with the APRF. Currently the shortest time in which an EXAFS spectrum can be taken is a fraction of a second, but submillisecond studies should be possible with the new facility. As previously mentioned, the APRF is expected to aid in the development of a combination of EXAFS and microscopy for the study of heterogeneous materials of importance in many materials science and technology problems. EXAFS has been a major factor in SR research growth and will in the future continue to make important contributions to SR-based research.

The more powerful sources recently available and the additional enhancements in capability provided by the APRF will also profoundly affect x-ray scattering experiments; together with imaging, these are now likely to become major areas of growth in SR science. The most established x-ray scattering technique is x-ray crystallography, which is responsible for much of our current knowledge of the atomic structure of bulk materials, from simple solids such as silicon to complex macromolecules such as DNA. The first crystallography experiments that used SR were performed in 1971 with the German synchrotron DESY (*28*). The initial uses of SR were associated with using the high intensity to perform time-dependent studies of flight muscle (*29*). The use of SR for time-dependent studies has continued to grow. A recent successful experiment used the storage ring at the Cornell High-Energy Synchrotron Source (CHESS) to investigate the laser annealing of silicon (*30*). That study helped to determine the basic mechanism of the observed laser annealing. The very short pulse length, perhaps as short as 40 psec, coupled with the high brightness will provide improved time resolution with the APRF. The capability will be used to study the time-dependent structural changes associated with temperature, pressure, and chemistry as well as to access the realm of molecular dynamics.

By the mid-1970's, SR crystallography studies had been extended to make use of the tunability of the radiation in solving the phase problem (*31*) that limits many structural determinations and to use its high flux to obtain more data from a sample before x-ray damage sets in (*32*). Since then, the application of SR to crystallographic studies has grown rapidly. With a wiggler insertion device, it has been possible to perform diffraction studies of a single outer atomic layer of a solid surface (*33*) or of any submonolayer adsorbate other than H_2 on a surface (*34*). Also, elegant experiments on multilayer liquid crystal films with thicknesses from two to hundreds of layers have been successfully conducted (*35*). Thus, the two-dimensional world of surface, adsorbate, and interface structures can now be investigated by the same crystallographic technique that has given us our knowledge of the three-dimensional world of bulk materials. The brightness of SR was also instrumental in demonstrating that crystals as small as 1 μm^3 could be used for crystallographic studies (*36*). This capability opens up important classes of materials for study, such as zeolites and biological systems for which it has been impossible to grow single crystals large enough for study by conventional sources.

Recently, an SR experiment with the 54-pole Exxon–Lawrence Berkeley Laboratory–SSRL wiggler (Fig. 3) demonstrated that x-rays can also be used to study magnetic (spin) structures with some advantage over the prevailing standard approach, which uses neutrons (*37*). The x-ray cross section for magnetic structures is lower by a factor of about 10^6 than both normal x-ray electronic structure cross sections and those appropriate for neutron studies. However, the high brightness of SR more than compensates for the weak cross section, so that it can advance the capabilities. With the APRF the advances would include the study of much smaller crystals with the higher resolution necessary for magnetic phase-transition studies. It could also open up the entire field of surface magnetism.

Another use of SR scattering techniques has been in the study of two-dimensional phase transitions in bulk materials surfaces and monolayer films or adsorbates. Disparate systems such as inert gases adsorbed on graphite (*38*), multilayer liquid crystals (*35*), and a monolayer of lead on a copper surface (*34*) have been studied from the perspective of two-dimensional phase transitions.

There are other scattering techniques in which the signals are much smaller and which consequently make greater demands on the properties of the radiation. Two notable examples are small-angle and inelastic x-ray scattering. An indication of what is to come from small-angle scattering studies is provided by the real-time studies of crazing in polymers (*39*) and of chromatin (DNA) organization and condensation (*40*). The APRF will make it possible to extend such studies from length scales of 10 Å to 10,000 Å. The latter is now only accessible by laser techniques, which of course are limited to transparent media. The APRF will also enhance the rate at which dynamic studies can be performed. Inelastic scattering with neutrons has provided us with knowledge of the world of atomic motions, such as vibrational modes in a crystal. Together with difficult but possible monochromator advances, the advanced photon source will provide the capability to perform such experiments with x-rays with 0.001- to 0.01-eV resolution on samples smaller than those that can be used with neutrons.

In fact, the APRF may have its biggest impact in the area of novel scattering and imaging techniques. The brightness and coherences made available by the advanced photon source are ideally suited for scattering or imaging experiments that demand high angular, spatial, and energy resolution. In general, even though SR science and technology have flourished in the past, experts from the many diverse fields affected by SR are of the opinion that the quality of the APRF radiation will make the future SR science and technology even more important.

For the most part, the rapidly evolving SR scientific capabilities have been developed on machines initially designed for high-energy physics research. However, beginning with the SOR 0.4-GeV synchrotron in Tokyo in 1974, new sources designed and dedicated to SR have increased. In the United States the Brookhaven NSLS has had its 0.75-GeV ring in operation since 1982 and has initiated x-ray operation this year on its 2.5-GeV ring. Japan has a full complement of SR machines, as does Europe and, to a lesser extent, the Soviet Union. There are approved plans to provide SR capability in several technologically emerging countries such as China, India, and Taiwan. From the perspective of SR facilities designed around insertion devices, it appears that Europe is clearly in the lead. The 0.8-GeV Super ACO machine in France is currently being constructed, and the European Synchrotron Research Facility (ESRF), the joint European version of the 6-GeV facility, has been approved and is scheduled for construction to begin in 1986. Recently disclosed plans for a 6-GeV facility in Japan have 1992 as the target date for completion.

The ARPF: Planning, Implementation, and Use

As this article has discussed, SR research in general and the APRF in particular offer significant opportunities to an unprecedented breadth of scientific and technological interests. It is partially for this reason that research at existing facilities has involved new creative relationships among disciplines and among the government, university, and industrial research communities.

SR research has brought together the interdisciplinary teams necessary to overcome the technical challenges and to help harness its potential. Physicists and engineers are working together to design the machines, providing the broad range of technological expertise necessary to implement and run them. Condensed matter physicists, to a large extent, have helped pioneer the beamline instrumentation needed to monochromatize, focus, and, in general, control the radiation to optimize its properties for a particular experiment. Then, of course, there is a diverse group of specialists, from physicians to geologists, who have pioneered the application of SR in their respective fields and in many cases have developed specialized instrumentation. These interdisciplinary teams of scientists are a distinctive feature associated with the past growth of SR research, and they will continue to be important in its future. It is literally breathtaking to walk around the two rings at Brookhaven and to see the diverse scientific communities that have come together to capture the opportunities that SR provides.

The institutional relationships have evolved in an equally creative way to capture the benefits inherent in SR. In its infancy it was recognized that, while having a central funding agency (such as the Department of Energy or the National Science Foundation) to construct and operate SR facilities was desirable, it would be virtually impossible and ineffective for the financial, manpower, and specialized talent resources of any single community or laboratory to support adequately the breadth of SR research. In fact, having the funding for constructing and operating SR facilities in the United States coming mainly from the materials science budgets of funding agencies, even though it serves a much broader range of scientific, technological, and funding agency goals, has created a significant burden on those budgets. The breadth of SR research has created at the U.S. facilities a new partnership among government, university, and industrial research communities for its use. One result of such a partnership is the Exxon–Lawrence Berkeley Laboratory–SSRL development of the 54-pole wiggler and associated beamline at Stanford. Brookhaven has pioneered the concept of participating research teams. This approach has allowed 92 universities, 17 industries, and 11 government laboratories to provide their expertise, manpower, and financial support to build beamlines at Brookhaven. In exchange for that contribution, the participating research team can use up to 75 percent of the beamline it provided, with the other 25 percent made available to the research community as a whole. Similar relationships have developed at all the other U.S. facilities, and it is expected that a project of the size of the APRF will utilize a similar approach.

The planning for the APRF is also being conducted in a novel manner. At existing facilities and for the future APRF, the staff of the host institution will be a minority user of the facility. Thus, there is truly a national community of users spanning many disciplines whose interests are directly involved in the fate of the APRF. Also, because the scope and cost of such a facility is large, its procurement cannot be justified on the basis of regional or institutional self-interest. For both these reasons a national advanced photon source steering committee was created. I chair the 40-member committee, which represents broad research, institutional, and scientific interests. The committee was developed at a meeting held in Ames, Iowa, in October 1984 to begin the planning process for the APRF, which, as mentioned previously, had been identified as the top priority for new facilities in several studies. The committee coordinates the machine design efforts, machine R&D program, and development of site selection criteria and helps to develop and advocate the scientific and technological case for such a facility. One workshop on machine design has already been held; workshops on project management, scientific opportunities, and site selection criteria are being planned. At both the Ames meeting and the machine workshop it was concluded that there are no major obstacles to achieving the design specification of low positron beam emittance that is necessary for undulator operation. However, those meetings and other recent work have shown that some complications affecting injection rate and beam positioning are more important in the low-emittance regime than was previously appreciated. Several designs addressing these problems have been prepared, and detailed studies of their properties are under way.

The committee has received widespread support from the SR community, most notably from the various institutions competing for the APRF. They have all accepted the premise that no matter where the facility is to be located it will continue to receive the support of the entire community as its top priority for new initiatives.

Perhaps the most significant cloud on this otherwise very positive situation is the delay in implementation that has plagued the new U.S. facilities at Brookhaven and Wisconsin. Although no fundamental technical reason caused these delays, results could not be delivered because of planning, management, and funding problems. These issues are now being aggressively addressed by the SR community, including users and machine builders. The Ames meeting, the machine workshop, the planned project management workshop, and the broad participation in the steering committee are all indications that these issues will be successfully addressed for the APRF. However, a more general issue which I believe has not yet been totally resolved is how the APRF should be implemented. As discussed, both the planning and use are in a partnership mode that draws upon the vast resources and expertise of the various user communities. The question naturally arises as to whether the implementation should not also be some form of a partnership, with each community contributing its skills and expertise. This important issue will be discussed as part of the planning process. The planning study of the Department of Energy (*1*) did recommend that a large fraction of the funding for beamlines be distributed to the university research community on future facilities.

The scientific and technological challenges and opportunities involved in the APRF are very great indeed. The details of the APRF's implementation, including procedures and timing, are still somewhat uncertain, although current plans are aimed at obtaining funding for construction by February 1988. Construction is expected to take 4 years.

It is an exciting time for the many sciences and technologies that SR research affects. The APRF will considerably enhance this excitement, and it may have the broadest scientific and technological impact ever achieved by a single facility. Together with progress being made in other techniques and the science of complex materials in general, the late 1980's and the 1990's hold the promise of significant technological advances in the health, industrial, and defense fields.

REFERENCES AND NOTES

1. P. Eisenberger and M. L. Knotek, cochairpersons, *Planning Study for Advanced National Synchrotron Radiation Facilities* (Department of Energy, Washington, DC, 1984).
2. D. E. Eastman and F. Seitz, cochairpersons, *Major Facilities for Materials Research and Related Disciplines* (National Research Council, Washington, DC, 1984).
3. J. Schwinger, *Phys. Rev.* **75**, 1912 (1949).
4. J. M. J. Madey, *J. Appl. Phys.* **42**, 1906 (1971).
5. G. Brown *et al.*, *Nucl. Instrum. Methods* **208**, 65 (1983).
6. Because electrons can be removed from the beam by positive ions, future synchrotrons are likely to use positrons.
7. K. Codling and R. P. Madden, *Phys. Rev. Lett.* **10**, 516 (1963).
8. B. Craseman and F. Wuilleumier, *Phys. Today* **37**, 34 (June 1984).
9. D. E. Eastman and W. D. Grobman, *Phys. Rev. Lett.* **28**, 1327 (1972).
10. E. W. Plummer and W. Eberhardt, *Adv. Chem. Phys.* **49**, 533 (1982); F. J. Himpsel, *Adv. Phys.* **32**, 1 (1983).
11. M. L. Knotek *et al.*, *Phys. Rev. Lett.* **43**, 300 (1979).
12. C. Fadley, *Prog. Surf. Sci.* **16**, 275 (1984); S. D. Kevan *et al.*, *Phys. Rev. Lett.* **41**, 1565 (1978).
13. H. Winick *et al.*, *Nucl. Instrum. Methods* **208**, 127 (1983); K. Halbach, J. Chin, E. Hoyer, *IEEE Interact. Nucl. Sci* **NS28**, 3136 (1981).
14. P. Horowitz and J. A. Howell, *Science* **178**, 608 (1972).
15. S. Weissmann *et al.*, Eds., *Applications of X-Ray Topography to Problems in Material Science* (Plenum, New York, 1984).
16. E. Spiller *et al.*, *J. Phys. Colloq.* **39**, 205 (1978).
17. E. B. Hughes *et al.*, *Nucl. Instrum. Methods* **208**, 665 (1983).
18. M. Howells *et al.*, *Proc. Int. Soc. Opt. Eng.* **447**, 193 (1983).
19. P. A. Lee *et al.*, *Rev. Mod. Phys.* **53**, 769 (1981).
20. P. Citrin, *Springer Ser. Surf. Sci.* **2**, 149 (1985); J. Stohr, *Springer Ser. Chem. Phys.* **35**, 231 (1984).
21. P. Eisenberger *et al.*, *Nature (London)* **274**, 5666 (1978); L. Powers, *Biochim. Biophys. Acta* **683**, 1 (1982).
22. S. Cramer, *Advances in Inorganic and Bio-organic Mechanisms*, A. G. Sykes, Ed. (Academic Press, London, 1983), p. 259.
23. B. K. Teo *et al.*, *J. Am. Chem. Soc.* **100**, 3225 (1978).
24. P. Lagarde and H. Dexpert, *Adv. Phys.* **33** (6), 567 (1984).
25. M. Boudart *et al.*, *Science* **228**, 717 (1985).
26. G. P. Huffman *et al.*, *Scr. Metall.* **18**, 719 (1984).

27. B. Chance et al., Nucl. Instr. Methods 222, 180 (1984).
28. G. Rosenbaum et al., Nature (London) 230, 129 (1971).
29. K. C. Holmes et al., Proc. R. Soc. London Ser. B 207, 1 (1980).
30. D. M. Mills et al., Nucl. Instr. Methods 208, 511 (1983).
31. J. C. Phillips and K. O. Hodgson, Acta Crystallog. A 36, 856 (1980).
32. T. J. Greenhough and J. R. Helliwell, Prog. Biophys. Mol. Biol. 41, 67 (1983).
33. P. Eisenberger and W. C. Marra, Phys. Rev. Lett. 46, 1082 (1981).
34. W. C. Marra et al., ibid. 49, 1169 (1982).
35. D. E. Moncton et al., ibid. 51, 1865 (1982).
36. P. Eisenberger et al., Nature (London) 39, 45 (1984).
37. D. Gibbs, D. E. Moncton, K. L. D'Amico, J. Appl. Phys. 57, 3619 (1985).
38. P. W. Stephens et al., Phys. Rev. B 29, 3512 (1984).
39. H. R. Brown et al., Polymer Eng. Sci. 24, 825 (1984).
40. G. L. Perez et al., Nucleic Acids Res. 12, 2987 (1984).

Mathematics Achievement of Chinese, Japanese, and American Children

HAROLD W. STEVENSON, SHIN-YING LEE, JAMES W. STIGLER

American kindergarten children lag behind Japanese children in their understanding of mathematics; by fifth grade they are surpassed by both Japanese and Chinese children. Efforts to isolate bases for these differences involved testing children on other achievement and cognitive tasks, interviewing mothers and teachers, and observing children in their classrooms. Cognitive abilities of children in the three countries are similar, but large differences exist in the children's life in school, the attitudes and beliefs of their mothers, and the involvement of both parents and children in schoolwork.

POOR SCHOLASTIC PERFORMANCE BY AMERICAN CHILDREN has focused attention on education, especially in mathematics and science. Funds for research on how to improve teaching have been allocated and commissions formed, such as a National Research Council committee exploring a research agenda for precollege education in mathematics, science, and technology. Recommendations to be made by this committee and others that have preceded it concentrate on the nation's secondary schools. The wisdom of this emphasis is questionable. Results emerging from a large cross-national study of elementary school children suggest that Americans should not focus solely on improving the performance of high school students. The problems arise earlier. American children appear to lag behind children in other countries in reading and mathematics as early as kindergarten and continue to perform less effectively during the years of elementary school. When differences in achievement arise so early in the child's formal education, more must be involved than inadequate formal educational practices. Improving secondary education is an important goal, but concentrating remedial efforts on secondary schools may come too late in the academic careers of most students to be effective.

Our research deals with the scholastic achievement of American, Chinese, and Japanese children in kindergarten and grades 1 and 5. Children were given achievement tests and a battery of cognitive tasks. The children and their mothers and teachers were interviewed, and observations were made in the children's classrooms. These procedures have yielded an enormous array of information (*1–5*). In this article, we focus on the discussion of achievement in mathematics and factors that may contribute to the poor performance of American children in that area.

Harold W. Stevenson is a professor of psychology and Shin-ying Lee is a graduate student in the Department of Psychology, University of Michigan, Ann Arbor 48109. James W. Stigler is an assistant professor, Committee on Human Development, University of Chicago, Chicago, IL 60637.

Achievement Tests

Comparative studies of children's scholastic achievement are hindered by the lack of culturally fair, interesting, and psychometrically sound tests and research materials. It was necessary to construct material in order to test children in Taiwan, Japan, and the United States for our study. A team of bilingual researchers from each culture constructed tests and other research instruments with the aim of eliminating as much as possible any cultural bias (*1, 2*).

Mathematics tests were based on the content of the textbooks used in the three cities in which we conducted our research. Analyses were made of each mathematical construct and operation and of the time that it was introduced in the textbook. The test for kindergarten children contained items assessing basic concepts and operations included in the curricula from kindergarten through the third grade. The mathematics test constructed for elementary school children contained 70 items derived from concepts and skills appearing in the mathematics curricula through grade 6. Some items required only computation, and others required application of mathematical principles to story problems.

Reading tests were based on analyses of the words, grammatical structures, and story content of the readers used in the three cities. There were separate tests for kindergarten and for elementary school children. The kindergarten test tapped letter and word recognition and contained comprehension items of gradually increasing difficulty. The reading test for grades 1 through 6 consisted of three parts: sight reading of vocabulary, reading of meaningful text, and comprehension of text.

Tests were constructed for administration to one child at a time. The tests were not timed. The testing procedure required that the child continue in the test to the point where over a quarter of the items at a grade level were failed. The mathematics tests and the kindergarten reading test were given 6 months after the beginning