CHESS: The New Synchrotron Radiation Facility at Cornell

Intense x-rays will soon be available to scientists as a by-product of high energy physics research at Cornell.

Boris W. Batterman and Neil W. Ashcroft

Summary. A new synchrotron radiation laboratory, CHESS, will soon be completed at Cornell University. The facility will operate in a mode parasitic to high energy physics experiments on the new 8-billion-electron-volt electron-positron storage ring (CESR) at Cornell. Electron and positron beams have already been stored and the first photons have been extracted. When completed, the laboratory will be available to the scientific community nationally and will provide the most intense tunable source of high energy x-rays in the country.

Synchrotron radiation is now generally accepted (*1*) as an important scientific tool for the study of matter in all its forms. There are many synchrotron sources throughout the world providing radiation over a considerable portion of the electromagnetic spectrum. The new facility under construction at Cornell University will provide a source of radiation primarily in the x-ray regime at unprecedented intensities. Just why this source opens new vistas for research becomes apparent when one compares it to the well-known sources available from conventional solid-target x-ray tubes.

The output of a standard tube is mainly in a line spectrum, the characteristic line. Most of the energy is found at a rather definite frequency, the radiation generally emanating from the tube in all directions. In addition to the characteristic radiation, there is a very weak continuous background of radiation at all wavelengths that is some five orders of magnitude less intense than the line spectra. In the case of the spectrum from the Cornell synchrotron, pulsed x-radiation is emitted with a continuous spread of energies, and this continuous radiation is already two orders of magnitude more intense than the line spectrum of a good x-ray tube (and therefore seven orders of magnitude more intense than the continuous background radiation from a tube). But in addition to the advantage of high intensity, the synchrotron source has the striking property that it is confined to a very narrow angular spread, which allows the experimenter to combine the twin properties of high intensity and intrinsic collimation to enhance dramatically the number of photons incident on even very small specimens. In a very real sense, comparing the "brightness" of a synchrotron source to that of a conventional x-ray tube is analogous to comparing a laser to a conventional light source.

Tunable X-Radiation: Uses

A continuous spectrum makes available to the researchers a tunable source of x-rays of very high intensity. Tunability allows one to investigate the scattering and absorption of x-rays in the vicinity of characteristic absorption edges of particular atoms of a specimen. The singular behavior of the absorption of x-rays in the vicinity of an absorption edge yields important structural information about the near-neighbor environment of the absorbing atoms.

The measured changes of the scattering amplitudes of x-rays at energies close to an absorption edge offer tremendous possibilities in x-ray structural crystallography. With a tunable source, the crystallographer can literally pick a wavelength that is very close to an absorption edge of a particular atomic species in a molecule. Depending on the proximity of the chosen wavelength to the absorption edge, the scattering amplitude of that particular atom can be changed markedly. By then comparing x-ray crystallographic data taken with the wavelengths near the edge to those taken with the radiation far from an absorption edge, the crystallographer can also obtain information on the relative scattering phases of different atoms in the molecule and thereby gain additional information that helps in unraveling crystal structure. Heretofore, to get this information the crystallographer had to actually replace particular types of atoms in the structure in a process called isomorphous substitution and assume that the subsequent arrangement of remaining atoms was unchanged. By using tunable synchrotron radiation one can simulate isomorphous substitution without the necessity of tinkering with the structure of the molecule.

The brightness and intrinsic collimation of a synchrotron x-ray source provide new impetus for the construction of x-ray microscopes. It has already been demonstrated that a resolution of 100 angstroms can be obtained in these devices. The possibility now exists of carrying out in situ x-ray microscopy of protein matter in an aqueous environment with a resolution that may even be better than 100 Å. This has biological applications and will complement structural electron microscopy.

X-ray diffraction by structures with widely spaced components usually involves scattering at extremely low angles. It is an important tool in biological and material sciences. This low-angle x-ray scattering (LAS) requires a very highly collimated x-ray beam. Collimation of a conventional source, which emanates in all directions, results in an extremely large reduction in intensity. Synchrotron radiation will have a tremendous impact in this field, since it is naturally collimated and will therefore allow one to obtain low-angle diffraction patterns in milliseconds—even permitting the experimenter to study certain phenomena in real time. An example of this is the diffraction studies of muscle contraction by Kulipanov and Skrinskii (*2*), in which the diffraction data were obtained in time intervals very small compared to the muscle contraction cycle time of 64 milliseconds.

As we will explain further on, synchrotron radiation from a storage ring

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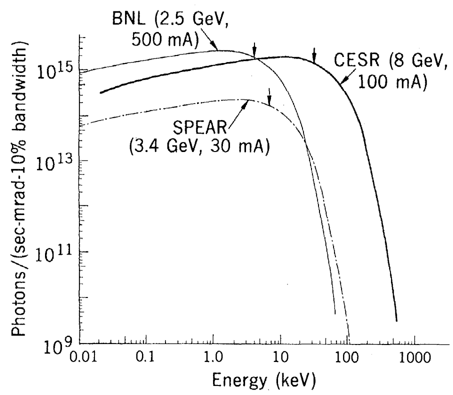

Fig. 1. Spectrum of emitted synchrotron radiation as a function of photon energy. Vertical arrows mark the critical energies. The curves shown are for Cornell (*CESR*), Stanford (*SPEAR*), and Brookhaven (*BNL*).

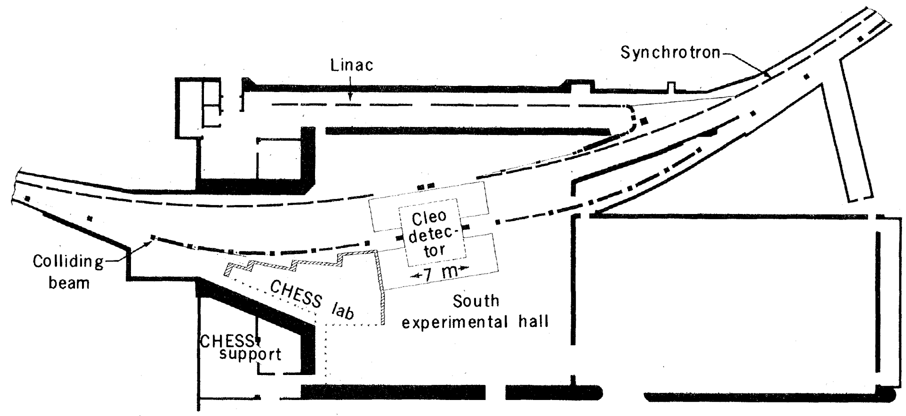

Fig. 2. A portion of the Wilson Synchrotron Laboratory operated by the Laboratory of Nuclear Studies at Cornell. The interaction area of the colliding beam project is at the center of the Cleo detector. Just before this, in the high curvature region of the colliding beam, can be seen the CHESS lines.

has an intrinsic time structure. For example, at the Cornell Electron Storage Ring (CESR), from which the Cornell High Energy Synchrotron Source (CHESS) obtains its radiation, the light bursts come every 2.5 microseconds and have an intrinsic width of 0.13 nanosecond. These extremely short periodic bursts with a relatively long delay between pulses offer remarkable possibilities in the study of time-resolved spectroscopy of excitation, emission, and decay of excited states in organic and inorganic molecules.

It is not in the scope of this article to present in great detail all the ramifications of the availability of the new source synchrotron radiation. However, we wish to indicate briefly the exciting field that is opening up in the potential applications of a very bright, intense, unique x-ray source.

Origin and Nature of Synchrotron Radiation

Synchrotron radiation is emitted when relativistic charged particles move in curved paths in magnetic fields. It is, in fact, the centripetal acceleration of the particle which, according to electromagnetic theory, is essential to produce the radiation. In the CESR storage ring, electrons and positrons are circulated in an evacuated chamber with an average radius of about 100 meters. The particles travel in single bunches close to the velocity of light in a counterrotating sense. The bunches of positrons and electrons, each about 4 centimeters long, intersect twice per revolution. When they collide, new elementary particles are created. It is for the purpose of elucidating the physics of these new particles that CESR was primarily constructed.

The synchrotron radiation is emitted in the course of establishing the intense electron and positron beams and is incidential to the high energy experiment. The radiation is, in fact, the limiting design parameter in high energy electron and positron storage rings. If one is constrained to construct a machine of a given radius, the ultimate electron energy that can be produced is very much limited by the power that has to be supplied to the circulating charge to make up for the loss in synchrotron radiation. As a specific example, CESR at its design energy of 8 billion electron volts (GeV) and 100 milliamperes of electrons and positrons will emit in synchrotron radiation about 1 megawatt of electromagnetic radiation. In general, the total synchrotron radiation production varies as the fourth power of the electron energy. It is easy to see that the limiting factor becomes the power requirement, which is then determined primarily by synchrotron radiation loss. As an example, increasing the stored beam energy at CESR to 12 GeV would require 5 MW of makeup power, as opposed to 1 MW at 8 GeV.

The radiation from the centripetally accelerating electron is emitted in a narrow cone around the instantaneous path of the charged particle. The beam is similar to one swept out by the headlight of a train moving in a circular track. It is emitted in a plane parallel to the orbital plane of the particles. Its angular height perpendicular to the plane is determined by the particle's relativistic energy. For CESR this corresponds to a vertical divergence of only 13 arc seconds and it is this remarkably small divergence that makes the source so intensely bright in the optical sense.

Whereas in the past, synchrotron radiation was often considered a nuisance by the builders of high energy storage rings, it is now regarded as a major experimental tool. There are basically two types of machines that provide synchrotron radiation. Those such as CESR are built and operated primarily for high energy physics experiments, and a small synchrotron radiation laboratory is attached in what is often called the parasitic mode. Sources of the other type have as their sole purpose the provision of synchrotron radiation, and they are called dedicated sources. In the United States, Tantalus I at the University of Wisconsin and SURF II at the National Bureau of Standards are dedicated sources for low energy vacuum-ultraviolet light. The colliding beam facility SPEAR at Stanford University has associated with it a major synchrotron radiation laboratory (SSRL) operating in a parasitic mode. (In the coming year, up to 50 percent of the operating time of SPEAR will become dedicated for SSRL.) At Orsay, France, there is a dedicated low energy ring and a parasitic high energy machine. In Germany, DORIS, part of the DESY synchrotron complex at Hamburg, is a storage ring that has facilities for high energy synchrotron radiation. A testimony to the importance of synchrotron radiation is the growing number of storage rings being built solely for its production. In this country, a new machine, Aladdin, dedicated to the production of low energy photons, is under construction at the University of Wisconsin. At Brookhaven National Laboratory the dedicated National Synchrotron Light Source is under construction. This facility, which is scheduled for completion in 1981 at a cost of approximately $30 million, will have two storage rings, one for high energy photons and another for ultraviolet light. In England, Germany, and Japan dedicated sources are also being built. It is clear that synchrotron radiation is riding a crest of interest throughout the world.

To get an idea of the synchrotron radiation spectrum obtainable from some selected facilities, we show in Fig. 1 the computed spectrum expected at maximum design energies from the Brookhaven source, the SPEAR storage ring at Stanford, and the nearly completed CESR ring at Cornell. A parameter useful in describing the spectrum is the critical photon energy E_c. This is defined as the photon energy at the midpoint of the integrated flux of the spectrum (that is, there is as much total flux above E_c as there is below). For Cornell this critical energy is 35 keV (corresponding to a wavelength of 0.35 Å). The flux at the critical energy is very nearly at the maximum of the photon spectrum. In Fig. 1 the critical energies are indicated by vertical arrows; it is clear that the range above 30 keV is unique to the Cornell facility, CHESS.

Cornell High Energy Synchrotron Source

At Cornell University we are in an unusual position in the field of synchrotron radiation. Nearly 25 years ago one of the first significant experimental studies of synchrotron radiation was made on the Cornell 300-MeV synchrotron. This work was carried out by Tomboulian and Hartman and was reported in a paper (*3*) that remains a cornerstone in the literature of synchrotron radiation. Their study brought together the use of electromagnetic radiation as a tool for the study of atoms and their aggregation, and the activities in high energy physics that produce the radiation as a by-product. We seem to have gone full circle in the last quarter century.

For the past 15 years, the Laboratory of Nuclear Studies at Cornell has operated a high energy electron synchrotron with a maximum electron energy of 12 GeV that has been used for studies of particle physics by physicists from all over the world. For nearly 2 years the laboratory has been in the process of converting the synchrotron to an electron-positron storage ring (CESR) with a maximum design energy of 8 GeV. Since the new storage ring will use the old electron synchrotron as an injector, CESR requires no major building construction. In fact, the two rings share the same half-mile tunnel on the Cornell campus. Figure 2 shows the interaction area of the laboratory part of the CESR storage ring project. The main high energy physics experiments take place in the middle of the rectangle marked "Cleo detector."

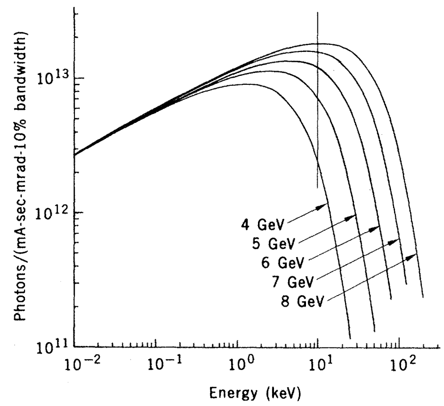

Fig. 3. Spectrum of emitted radiation from CESR (see Fig. 1) as a function of beam energy, for a beam current of 1 mA.

To make room for this very large detector, the storage ring (labeled "Colliding beam" in Fig. 2) had to be physically separated from the synchrotron, with the result that the two rings are separated by a straight section in CESR followed by a rather sharp bend into the interaction region. It is this sharp bend area (which has a bend radius approximately one-third that of normal bending magnets) that makes CESR a very potent source of synchrotron radiation.

In June 1978, a \$1-million grant was provided by the National Science Foundation to create CHESS, a synchrotron radiation laboratory designed to operate in a parasitic mode to the CESR high energy physics operation. The grant, which covers a 3-year period, provides for staffing the laboratory and constructing three beam lines and four experimental stations. The arrangement of the laboratory is shown schematically in Fig. 2. The high E_c and therefore high x-ray energy content of the CHESS spectrum is a direct result of the need to install high-bend magnets in the CESR storage ring. The encouragement and initiative of B. D. McDaniel, director of the Laboratory of Nuclear Studies, was vital in seeking the support to create the laboratory. Thus, only a relatively small additional investment was needed to create a unique source of synchrotron radiation.

There has been much discussion in the synchrotron radiation community of the advantages and disadvantages of dedicated versus parasitic sources. A machine built solely for synchrotron radiation will, of course, have the advantage that control of the machine parameters will be dictated by the scientists who want to use the radiation. In a parasitic operation, the beam parameters (such as energy) are dictated by the high energy physics experiments and are not necessarily compatible with the photon flux requirements for experiments carried out with synchrotron radiation. In these cases certain classes of experiments may have to be postponed until the machine energy changes.

This situation has been a particular problem in the past 2 years at the Stanford Synchrotron Radiation Laboratory, where machine energies in the vicinity of 2 GeV have not produced sufficient photon flux for experimentation in the medium x-ray energy regime (although they provide more than ample ultraviolet radiation). Figure 3 shows how we might expect a similar situation to affect CHESS experimentation. In Fig. 3 the synchrotron radiation spectrum is shown as a function of beam energy for a given beam current. The vertical line represents a photon energy of 10 keV (wavelength, 1.2 Å). Over the anticipated operating energies of CESR, 4 to 8 GeV, the flux at this photon energy changes by a factor of only 7. Thus, regardless of operating energy, experimentation in the vicinity of 1 Å should still be feasible since the intensity is so high that even a factor of 7 can be comfortably absorbed. From this point of view, users of moderately hard x-rays—that is, up to 10 keV—would not suffer from the parasitic use of the synchrotron radiation operation. Note that at low photon energies the flux is essentially independent of machine energy. In this sense, the x-ray users of CHESS will be in the same position as users of the vacuum ultraviolet at SPEAR. Whether one suffers as a parasite depends very much on the energy range of the machine and the photon energy needed for the experiment.

CHESS Laboratory

Figure 4 shows a more detailed representation of the CHESS laboratory presently under construction. The CESR vacuum system was closed on 31 March 1979. The first circulating electron beam was observed the next day, and stored beam lifetimes of approximately 90 minutes were achieved by June 1979. Our first photon beam was observed on 28 April 1979, and a diffracted x-ray beam was detected in a preliminary experiment on 27 May. Three beam lines are now installed up to the shielding wall (shown in Fig. 4 by the zigzagged hatched area), and the remaining shielding wall will be installed very soon. A view of some of the equipment that has been installed is shown in Fig. 5. We plan to have in line A one or possibly two fixed-wavelength stations, as well as two tunable stations covering the range from about 3 to 60 keV (4 to 0.2 Å). Because of the high energy photon flux of CESR, the CHESS experimental stations have unique problems. The monochromators that select the needed wavelengths from the spectrum have to be designed so that the high energy harmonics are not diffracted into the experimental stations. With machines of relatively low E_c, high energy harmonics are not present. In addition, the problem of heating of the monochromatizing crystals by the photon beam will be quite severe.

For a somewhat different view of the intensity of the radiation from a synchrotron source, it is interesting to compare the heat fluxes associated with photon beams from conventional and synchrotron sources. In a typical x-ray tube running at 50 keV and 20 mA, the total input power is 1 kW. Of this 1 kW, only about 0.1 to 1W resides in x-ray photons, which leave the target in all directions. In each of the beam lines shown in Fig. 4 there will be at maximum operating conditions 2.5 kW of photon power. Severe thermal effects on the monochromatizing crystals due to the incident beam itself will have to be faced. Each line will transmit approximately 14 millirads of orbital radiation. This corresponds to a beam at the shielding wall with a horizontal width of 14 cm and a height of about 0.5 mm. The beam is split into smaller segments by different optical elements (usually single crystals of silicon or germanium) in a box called the monochromator cave (see Fig. 4). These split beams are then diffracted out horizontally or vertically to the experimental stations, space permitting. Even with the limited floor area available, judicious design allows for many experimental stations on a particular beam line.

Additional optical elements, such as very low glancing angle focusing mirrors, will be included in the upstream portions of the beam lines to further focus the synchrotron radiation in the case of very small specimens. It is anticipated that experimenters will be able to work in the experimental area with a circulating beam in the storage ring. Each of the experimental stations, shown schematically in Fig. 4, will be an enclosure approximately 4 feet cubed which will contain the experimental apparatus. It will be possible to gain access to the cubicle (even with a stored beam in the machine) by using suitable x-ray shutters and interlock systems. The support space will house the permanent technical staff of CHESS and will provide space for visiting scientists. In addition to the space shown in Fig. 4, there will be staging areas, offices, and laboratory space for outside users in the Physical Sciences Building on the Cornell campus.

It is our intent and that of the National Science Foundation to make CHESS nationally available to users who need an x-ray source with energies from approximately 2 to 3 up to 150 keV. In the high energy end of a spectrum, from 25 keV up, no other sources under construction will offer comparable fluxes. A program committee will review proposals and, if the demand exceeds availability, a reviewing procedure will be implemented to allot time according to the scientific merits of proposals.

We mentioned that a first diffracted beam was observed in May 1979 with

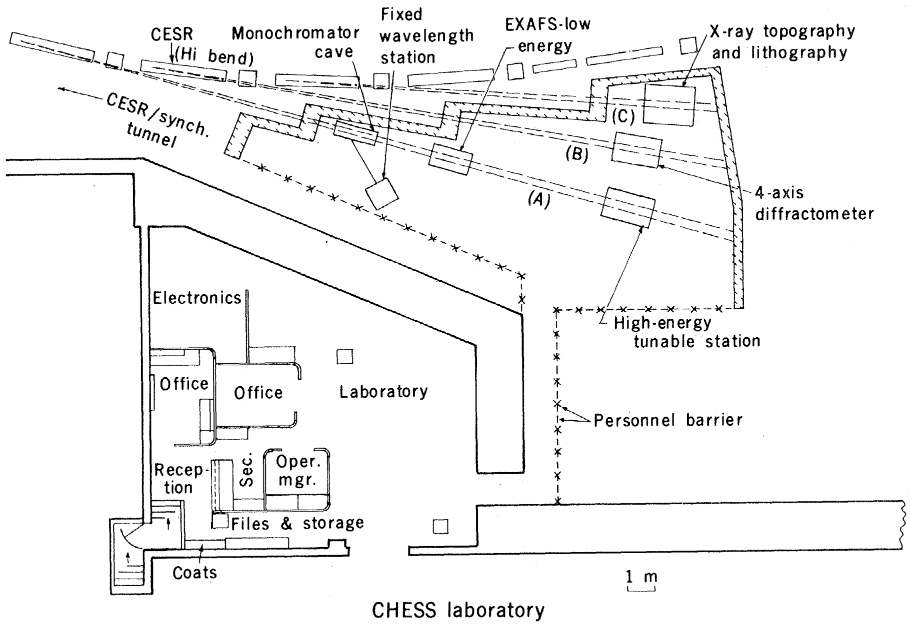

Fig. 4. Planned arrangement of the CHESS laboratory and the support area. The boxes show the approximate locations of the experimental stations.

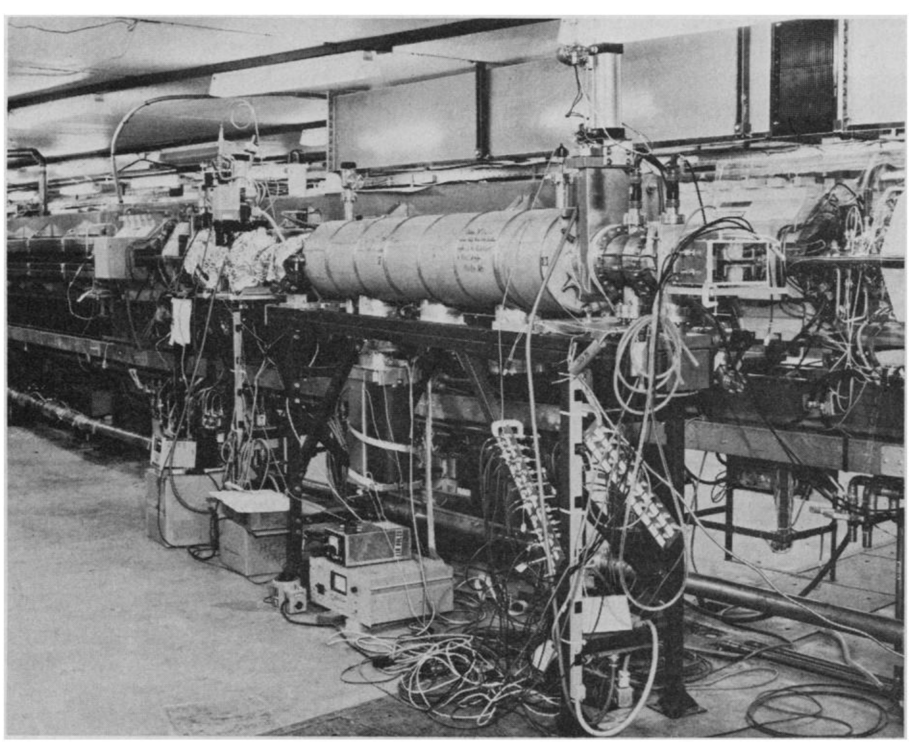

Fig. 5. View of the partially completed A line (see Fig. 4) showing the photon beam pipe emerging tangentially from the storage ring. The large cylindrical object is an acoustic delay line, which is included in the design to ensure the vacuum safety of the storage ring in the event of an accident in the CHESS facility.

rather rudimentary experimental equipment. The date is important to us because it represents some tangible progress for our efforts over the past year and a half. The availability of CHESS for users within Cornell and in the outside community will be closely coupled with the completion of CESR and the first high energy experiments. It is our hope that the first diffraction experiments will be performed sometime in early winter and that users will find experimental laboratories available toward the end of 1979.

Proposed Experiments

The experimental work to be done at CHESS will include crystallography with anomalous dispersion, studies requiring the tuning of x-radiation across critical atomic levels, small angle scattering experiments, materials science, x-ray microscopy and topography, biophysics experiments utilizing the particular time structure of CESR, and many other types of investigations. It is important that we consider experiments that take advantage of the unique high energy portion of the CHESS spectrum, since photons in this range of energies have never been available at the intensities and degree of monochromatization that can now be provided. Accordingly, we can only speculate on what might be done and discovered. But if permitted to speculate, we would certainly include the experiments outlined below.

Since the binding energies at deep levels in elements of high atomic number (Z) lie in the range 50 to 100 keV, the CHESS spectrum will permit the study of many-body effects in heavy elements. Relativistic effects play an increasingly important role in high-Z elements—vacuum polarization effects and self-energy corrections, for example, can perturb bound states by as much as 100 eV. With a tunable source providing energies in the range of many tens of kiloelectron volts, it will be possible to test some of the predictions of quantum electrodynamics for such deep levels.

Solid state x-ray detectors and radioactive gamma sources at high photon energies have made possible measurements of the profile of Compton scattering on high-Z materials. These profiles give a measure of the electron momentum distributions in solids and are a check on the precision of band structure calculations. At high photon energies, scattering theory is much simplified and the interpretation of the Compton profiles in terms of electron momentum is much more straightforward. The high flux available with synchrotron radiation will allow measurements to be made at much higher resolutions so that the band structure effects in the Compton profile can be more easily seen. For example, a 100-millicurie ^{241}Am source produces about 10^5 60-keV photons per square centimeter per second at 30 cm from the source. The CHESS spectrum at maximum operating conditions can provide, in a 1-eV bandwidth at 100 keV, 10^{11} photons per second in an area of 1 by 0.1 cm at the sample. There is no high energy gamma source that can compete with such an extraordinary photon flux in a Compton scattering experiment.

High energy tunable x-rays offer exciting possibilities in x-radiography. It will be possible to carry out x-radiography with high energy photons that are tuned very close to the absorption edge of material injected into portions of the body. By taking x-radiographs above and below an absorption edge, far greater selectivity can be obtained. This is an area of x-ray dichromatography that has barely been explored (*4, 5*).

In the biological sciences, it is the tunable nature of the CHESS source for x-ray macromolecular crystallography that is of greatest interest. Although this may not necessarily involve the high energy end of the spectrum, it is nevertheless an exceedingly important aspect of the work at CHESS. With this in mind, we arranged to have a substantial portion of the flux in one of the beam lines dedicated to a tunable x-ray crystallographic station. In a related area, the prospect of studying biochemically interesting processes in the time range of nanoseconds to milliseconds is of great interest for biophysics.

The prospect of direct observation in real time of conformational changes in biochemically interesting processes is very attractive. It is possible to use the pulsed nature of the CESR source (with a time delay of 2.5 μsec) by initiating a change in structure by an electrical impulse (for example, in a muscle or nerve) and then viewing the subsequent change by various scattering and imaging techniques at controlled times after the initial impulse. Experiments of this type have been discussed but very few have been carried out. This is likely to prove a very important area in the field of macromolecular structures.

What is exciting for us at Cornell, and for our colleagues nationally, is that a new and very intense source of synchrotron radiation will be available within the year. Although modest in scope, we expect CHESS to come on-line several years before the dedicated National Synchrotron Light Source will be available. Many of the problems to be faced in future facilities will have to be faced here at CHESS, and therefore our experience will be useful in the design of new facilities. We also feel the excitement of having a new tool with which to explore areas that have never before been touched and where much of the future research activity will be.

References and Notes

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