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Coherence, Optics and Applications
at X-ray Wavelengths

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COHERENCE, OPTICS AND APPLICATIONS AT X-RAY WAVELENGTHS

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ABSTRACT

The extension of coherent optical techniques to the x-ray region of the electromagnetic spectrum opens many new opportunities for science and technology based on very short wavelengths and on photon energies which span the primary atomic resonances of many elements.

SYNCHROTRON RADIATION

The development of third generation storage rings, based on tightly controlled (small phase space) relativistic electron beams and a multiplicity of long periodic magnet structures, as well as new technologies which permit the construction of x-ray optical elements, such as lenses and mirrors, permits the extension of classical electromagnetic techniques to x-ray wavelengths. The new synchrotron sources, schematically illustrated in Figure 1, provide a very bright source of radiation with interesting coherence properties¹ -- particularly valuable for applications involving spatial localization in conjunction with various spectrally selective techniques. The brightness of the generated radiation is related to the small transverse dimensions of the radiating electron beam and the very narrow cone of radiation -- the latter being due to both the narrowly constrained random angular motions within the electron beam and the narrow "searchlight" nature of radiation from relativistic charges. Since brightness is a conserved quantity (crudely, space-angle product is conserved), such radiation can be refocused to extremely small spot sizes (with proper lenses), essentially by trading small angular extent for small lateral dimensions.

The fact that such radiation has considerable coherence properties is of great interest and also derives in large part from the very small phase space volume, which approaches Heisenberg uncertainty limits for x-ray radiation. In discussing the coherent properties² of radiation it is convenient to consider the wavefront (phase relations) longitudinal and transverse to the propagation direction. The transverse coherence properties -- which largely determine focusing limits -- are set by the degree to which the phase-space of the emitter approaches the wave length of radiation. Following Heisenberg's limit for transverse momentum, one finds that as the area -- solid angle product of the emission, $\Delta A \cdot \Delta \Omega$ -- approaches $(\lambda/2)^2$, the radiation appears to emanate from a point-source: one cannot determine where from within the source the photon was emitted. This in turn implies a spherical wave front (as it contains no information about the spatial structure of the source). In this limit the phase is perfectly correlated in the transverse direction, and the radiation is said to be "spatially coherent". In addition to being useful for phase sensitive encoding and interference techniques, spatially coherent radiation can be focused (imaged) to the smallest possible spot size with an unaberrated lens. Longitudinal coherence, generally characterized by a coherence length $(\lambda^2/\Delta\lambda)$ in the direction of propagation, is simply a product of the wavelength (λ) and the spectral width of the radiation $(\lambda/\Delta\lambda)$. For radiation from electrons accelerated as they traverse

Figure 1. (a) Today's synchrotron radiation facilities are circular or near circular machines generating primarily "white light" (broad band) bending magnet radiation. In some cases a straight section or two exists where periodic magnet structures (undulators or wigglers) have been retrofitted. In general, the electron beam lateral size and angular divergence (phase space product, or "emittance") is not particularly small. Tomorrow's machines, now under construction or in the planning stages in many countries, combine two major features: very small phase space products for the generation of high brightness radiation with varying degrees of spatial and temporal coherence, as well as a multiplicity of long straight sections for periodic magnet structures. (b) Anticipated spectral brightness and coherent power at the two U.S. facilities now under construction, the 1.5 GeV ALS in Berkeley emphasizing soft X-ray radiation, and the 7GeV APS at Argonne National Laboratory, emphasizing applications with more energetic photons.

a periodic magnet structure, the spectral width is equal to the number of magnetic periods N , that is, the number of oscillations.* Thus the longitudinal or temporal coherence length is equal to $N\lambda$ -- on the order of one micron for soft x-rays and several hundred-period magnetic structures. This is actually a very useful coherence length, since in this spectral region sample probing depth is generally limited to a similar scale by absorption. Figure 1 illustrates the brightness and coherent power expected from the new third generation synchrotron facilities under construction in the USA, the Advanced Light Source (ALS) in Berkeley and the Advanced Photon Source (APS) at Argonne National Laboratory.³

X-RAY OPTICS

To realize the potential of these new high brightness radiation sources for probing and exploring physical and biological structures -- on a spatial scale previously unattainable with electromagnetic radiation -- requires appropriate optics for transport, reflection, focusing and spectral dissection. During the past decade, much progress has been made in the development of specific components such as lenses and mirrors, to the point where it is now possible to contemplate experiments which seemed impossible just a short time ago.^{4,5} Diffractive lenses, illustrated in Figure 2, have now demonstrated spatial resolution in the 300-400 Å region^{6,7}, at wavelengths in the 24-45 Å (soft x-ray) range. Multilayer mirrors^{8,9} have demonstrated normal incidence reflectivities in the 40-60% range at somewhat longer wavelengths, and reflectivities of 80-90%

Figure 2. (a) Diffractive zone plate lenses with outer zone widths of 300 Å have achieved resolutions of 360 Å (ref. 7) in synchrotron radiation experiments, and have been used for experiments in the life, materials and microelectronics areas. Combinations of high resolution and high efficiency are just becoming available. (b) Multilayer interference coatings for high reflectivity (40-60%) are now available in many laboratories for normal incidence imaging and focusing experiments at certain relatively long x-ray wavelengths, and at glancing incidence for shorter x-ray wavelengths.

* In fact, some degree of laboratory monochromator is needed, although this may be as simple as a pinhole in some cases.

at shorter wavelengths, albeit at glancing incidence. All these components have been used recently in demonstration experiments which show a clear path towards new scientific and technical capabilities at x-ray wavelengths.

APPLICATIONS TO THE PHYSICAL AND LIFE SCIENCES

The photon energies generated by the new facilities range from tens of electron volts (eV) to more than one hundred kiloelectronvolts (keV), as we saw in Figure 1, thus spanning the primary atomic resonances (K, L and many M shells) of most elements.¹⁰ Further, because the radiation is tunable^{**}, it can be used to explore details of the resonance structure, features due to many particle quantum interactions, near-edge unoccupied states, structure of excited state atoms, perturbations due to chemical bonding, and near-neighbor induced line structure. Because of the high photon flux concentration available with focusing lenses, of order 10^{10} watts per square centimeter at 20 Å or so wavelength, it is also possible to consider multiphoton, pump-probe and other yet to be devised non-linear experiments.

Figure 3 illustrates some areas of interest¹¹ in surface and material science, microelectronics, and quantum confined structures where mesoscopic structures -- having feature sizes between 10 and 1,000 Å -- provide interesting new challenges and opportunities to chemists, condensed matter physicists, and technologists alike, and which are approachable with these new short wavelength electromagnetic techniques. As material structures become ever smaller, the area to volume ratio increases to the point where surface properties dominate bulk properties with regard to transport, strength, etc. Microelectronics, shrinking now to nanometer feature sizes (~ 1000 Å), require tools to study dilute quantities of dopants and impurities on these spatial scales. The challenges of the future for solid state physics clearly lie, at least in part, with an understanding of quantum confined nanostructures. Figure 4 illustrates additional topics, of interest to biologists¹², which involve structures too small to be visualized with visible light microscopy, and never seen in a near-native living state with electron microscopy because of the restrictive preparative procedures required. Following the biologists' emphasis on the relation between structure and function, major new insights can be expected if these sub-cellular organelles and macromolecular structures can be observed with minimal distortion, and to some degree dynamically, so as to understand more accurately the intricacies of processes such as genetic expression and cell function.

SCIENCE AND TECHNOLOGY: INTERTWINED AT A SINGLE FACILITY

As illustrated in Figure 1, the new synchrotron radiation facilities, with several available straight sections for undulators and wigglers, provide opportunities for exploiting these new tools simultaneously in various areas of science and technology. This is fortunate because the development of new science and technology must go hand in hand, exchanging ideas, insights and the means to an end. Historic examples include the telescope and the microscope

^{**} Tuning is accomplished by varying the magnetic gap in the undulator, thus affecting the overall transit time and therefore (for a fixed number of cycles N) the radiated wavelength.

Figure 3. Experiments in the physical sciences which benefit from spatially resolved probing, phase sensitive, or multiphoton techniques include: (a) surface science studies, (b) nanoelectronic structures, (c) quantum electronic excitations, (d) phase sensitive projection and imaging techniques, (e) two photon pump-probe experiments, and (f) element specific photon-assisted tunneling microscopy. Material is borrowed from references 11 and 12.

(a)

(b)

Figure 4. From the molecular basis of life (a) to the intricate processes of cell function (b), life scientists are interested in utilizing knowledge of structure to better understand function. New x-ray imaging techniques offer opportunities to visualize important structural features in the 50-5000Å region, not observable in near native state conditions by presently available techniques. Material is borrowed from J. Gray and S. Rothman, reference 12.

lenses which had major impacts on man's understanding of the universe surrounding him and the cells within him. These in turn provided motivations and challenges toward the development of ever more refined tools. Today the microelectronics industry has provided us with the capability to fabricate diffractive lenses which are providing new views of tiny atomic material and sub-cellular universes never seen before, while the scientific understandings that follow provide paths to ever more challenging technologies - examples being new developments in the areas of nanostructure fabrication, quantum electronics, interface formation, and nanoelectronic devices fabricated with x-ray lithographic techniques.¹³ Figure 5 illustrates the types of science and technology that will be explored side by side at Berkeley's Advanced Light Source.¹⁴ Clearly this is an ideal site for germinating ideas and fostering the growth of new scientific and technical opportunities. Facilities are available to all, both individually and as teams, on a competitive proposal basis.

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Figure 5. The Advanced Light Source (ALS) at Berkeley will provide unique opportunities for the hand-in-hand development of new scientific opportunities based on short wavelength, high-brightness radiation. Scientists in a broad variety of disciplines will work side by side with others involved in advanced technology projects. See reference 13 regarding access to ALS.

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