73/87 JEM (5)
BNL-51988

I. 70603

DR 0242-9

BROOKHAVEN LECTURE SERIES

Using The Light Fantastic

Gwyn Williams

Number 211

January 16, 1985

BROOKHAVEN NATIONAL LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

BNL--51988

DE87 009459

Using The Light Fantastic

Gwyn Williams

Number 211

January 16, 1985

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

BROOKHAVEN NATIONAL LABORATORY

Associated Universities, Inc.

Under Contract No. DE-AC02-76CH00016 with the

United States Department of Energy

MASTER

DISTRIBUTION OF THIS

USING THE LIGHT FANTASTIC

Gwyn P. Williams

It is a tremendous pleasure to be selected to give the first Brookhaven lecture on the light source. Before describing the National Synchrotron light source, I will put it into perspective. Figure 1 is an aerial view of Brookhaven National Laboratory, with an arrow indicating the Light Source Building. It is a circular building, giving us a strong hint that it is an accelerator. Figure 2 is a plan of the building, with its two large circular accelerators and a small circular accelerator. Let me begin with some questions that can be answered straightforwardly. What is an accelerator? Is this accelerator different from the other accelerators we have at BNL? And, how does it work?

An accelerator takes a charged particle, which, in the case of the light source, is an electron which is traveling in a certain direction, and applies a magnetic field perpendicular to its path. The magnetic field deflects the

electron around a corner. Using many magnets we can bend the electron around so that it completes a circle, and continues to go around, again and again. One of the properties of charged particles is that when they are accelerated, they emit light (electromagnetic waves). The changes of direction of the electrons around corners are accelerations. A commonplace analogy would be to take a cord and shake the end of it; a wave travels down it. When we accelerate the electrons, or small particles which we cannot see, light waves are emitted. An equivalent analogy to the radiation from the electron is found in a CB antenna on the trunk of a car, in which electrons in the antenna are accelerated by a radio-frequency voltage and the device radiates or transmits.

Figure 3 shows a history of the brightness of x-ray sources. The horizontal axis starts with the discovery of x rays in 1895 by Roentgen.

Figure 1. An aerial view of Brookhaven National Laboratory. The arrow shows the Light Source Building.

Figure 2. A plan of the Light Source showing the two large and the small circular accelerators.

The brilliance, or brightness, of the x-ray sources is plotted vertically. Each vertical increment represents a tenfold increase in brightness. Some progress took place from 1900 to 1960 in the developments of x-ray tubes; however, a dramatic rise occurs after 1960. Following some improvement from what is called a rotating anode source (a laboratory source), the rise in the curve is caused by the use of accelerators as generators of x rays. Already we have increased brilliance some ten thousand times over any conventional x-ray tube, and we are still only halfway up the projected curve.

It is instructive at this point to compare the light source with a conventional x-ray tube. In a conventional tube, you have an anode and a cathode. Electrons from the cathode are accelerated towards and into the anode, and x rays are emitted in all directions following the

deceleration of the charged particle as it strikes the anode. In a conventional source, x rays are emitted in all directions from a large area, and the electrons that collide with the target must be replenished continually so the actual number of x rays is limited. There are three main differences between this standard type of source and accelerator sources. First, in the case of an accelerator we can store electrons since we essentially recycle rather than lose them each time. We can put a million million electrons into the NSLS VUV ring. Secondly, since these electrons are traveling very close to the speed of light, the x rays are directed in space like a laser beam instead of spraying everywhere. Finally, if all the electrons in the ring are packed close together, they constitute an extremely tiny source, about one one-thousandth of a square centimeter in area. All of these factors, the large number of x rays, the

small angle of emission, and the small size of the source, contribute to the quality that we call brilliance.

The projection in Figure 3 is based on our proposal to extend the curve of increasing brightness using devices called wigglers and undulators. They work in the following way. Instead of bending the electrons around the corner, we use a straight device having a series of magnets of alternating fields, which make the electrons go first one way then the other, wiggling from side to side, and emitting light all the time. With these we can enhance the brilliance 100-10,000 times.

Brookhaven has the brightest light source in the world. There are about 30 other light sources in the world which have approximately one-tenth to one one-hundredth the brightness of the Brookhaven light source. It is therefore, a very exciting source, and I will now illustrate how rapid our progress has been in getting the source into operation.

I would remind you that the light source is really two rings, both of which are used as light sources. The larger ring produces shorter wavelengths or harder x rays. I am concerned here with the smaller ring, where the first results have been obtained. Figures 4 to 8 show the year-by-year development of the small ring. The large magnets which bend the electrons around the corners are clearly visible, as are the beamlines which collect the light radiated by the electrons. The other magnets and devices shown keep the electrons together and replace the energy they lose as they go around the ring.

I explained briefly how the light source generates light. What is interesting about this light? As I told you it is very bright, in fact, ten thousand times brighter than any other x-ray source. Light is otherwise known as electromagnetic waves which comprise the spectrum, shown in Figure 9. The unique feature of the NSLS light source is that it gives this entire spectrum to us. We usually think of light as the visible region, but beyond red is the infrared and the radio waves, which are all electromagnetic waves. In the other direction, there is the ultraviolet and then the x rays. The only difference between x rays and radio waves is that the wavelengths are different: x rays have shorter wavelengths. On the figure the wavelengths are expressed in nanometers or one thousand millionths of a meter. I have also indicated approx-

Figure 3. A history of the development of brightness of x-ray sources.

imately the size of atoms. To give you some idea of scale, a human hair is 50 microns thick, the same as 50,000 nanometers. There are approximately 200,000 atoms in that distance. X-ray light also carries higher energy than light of longer wavelengths. Aside from the wavelength, which matches the size of atoms and thus allows us to look at atoms, the energies are such that we can study the electrons in atoms. This is a large area of interest.

Let me now give you a perspective on what we can do with the light source, or more specifically, what kinds of questions we can ask and hope to answer. We can use it to address problems in quite a new way. For example, rather than observing or measuring that glass is transparent we can ask, why is it transparent? Why are leaves green? Why is stainless steel stainless? Why does iron rust? Cars rust more when salt is put on the roads. Why is copper copper-colored? Why do some materials have good elastic properties? Why doesn't aluminum rust? Why does it have such different properties than steel? Polymers are an area of

Figure 4. The development of the small accelerator, 1980.

Figure 5. The development of the small accelerator, 1981.

Figure 6. The development of the small accelerator, 1982.

Figure 7. The development of the small accelerator, 1983.

Figure 8. The development of the small accelerator, 1984.

keen interest. At the light source we can address some very fundamental questions. We will use light, invisible light, which is very bright and whose wavelengths are of the order of atomic sizes, to study these kinds of fundamental questions.

Basically, we can do two kinds of experiments which are illustrated in Figure 10. One is an absorption experiment: light comes in, some gets absorbed, some comes out. Some-

times light of a different color, or electrons, or sometimes other atoms, or ions, come out. The remainder of my talk is concerned with this. For completeness, we note that we could also do experiments in which light is scattered off the atoms. This is the research area of the larger ring.

Now let's take a perspective view of where research at the light source fits into the work of the rest of the laboratory. Figure 11 shows two isolated atoms in a schematic form, each having a nucleus within which there are nuclear particles. High energy physics is concerned with the smallest particles within the nucleus, while nuclear physics is concerned with the nucleus itself. We are primarily concerned both with the electrons which surround the nucleus and, with the separations and positions of atoms. If we look now at Figure 12 we see what happens in a solid or liquid. These two atoms now are so close together that they share the outermost electrons. All of what we know of the physical properties of materials, such as why you can see through glass, why some things are stronger

Figure 9. The spectrum of light at the NSLS.

Figure 10. Research at the NSLS: Above, a light-absorption experiment at the small ring; Below, a light-scattering experiment at the large ring.

than others, why metals corrode, and why others are magnetic, are controlled by these outermost electrons, and by nothing else. These electrons glue the atoms together to form all known solids or liquids. If we can learn something about these electrons, then we can learn a lot about the fundamental properties and behavior of materials.

Ninety percent of the experiments on the light source have used the experiment shown in Figure 13 to study these electrons. The experiment is called photoelectric emission, which was first discussed theoretically by Einstein for which he received a Nobel prize. Starting with light of known energy, we collect and measure the energies of the electrons which are released. Figure 14 shows an experimental chamber which is used for experiments of this type, on a beamline, tangential to the ring. Since the light spectrum from the ring is very broad, it must be filtered to a single color or energy. A device called a monochromator picks out a single color and delivers it into the experimental, sample chamber. In practice, we extract some electrons of each type and plot a spectrum for each material under study. From these spectra we are beginning to learn the nature of the electron "glue."

I can return to why, for instance, tree leaves are green. If I brought another electron from the outside world into this system, it would go into another orbit outside the existing ones. However, a very important property of electrons is that they can hop between orbits. In

Figure 11. Diagram of two isolated atoms, showing the nucleus, nuclear particles and electrons.

Figure 12. The same two atoms now in a solid or liquid, sharing the outermost electrons.

Figure 13. Photoelectric emission experiments made at the Light Source to study the electrons in atoms.

the case of the green leaves, light is absorbed by an electron which hops between an occupied orbit and a new one, called a $2\pi^*$ orbital that lies outside the others. Tree leaves are green so that they can absorb sunlight and energy.

Figure 15 shows the spectrum obtained in our first experiment. In the sample chamber was less than one atomic layer of iron sitting on top of another metal called palladium. Measurement of the spectrum showed two peaks, which told us that even when there were so very few iron atoms, the iron was magnetic. The Brookhaven light source was bright enough to allow us to do this experiment, that is, to "see" a few atoms of iron, and help understand magnetism on this scale. Other sources were simply not bright enough to do this experiment.

The next experiment concerns measuring the intensity of one of these peaks, that is, how high it is, as we change the photon energy. In other words, what we were doing was putting an electron into a series of ever-increasing outer orbits. The idea behind the experiment was to learn something about the separation of two atoms, in this case by measuring the separation of these empty orbits. There are six spectra on Figure 16; we will look at the one marked (b). In this spectrum, we took an elec-

Figure 14. The experimental chamber for studying photoelectric emissions.

Figure 15. The photoemission spectrum of iron.

Figure 16. First demonstration of photoemission EXAFS. Measurement of atomic distances using emission spectra produced as the energy of an electron is increased. Left column, EXAFS; right column, radial distribution. (Rothberg, Choudhary, Williams, denBoer, Hecht, Lindau).

Figure 17. The bonding of a small molecule on to a metal surface, revealed by the emission spectrum.

tron at a certain level and increased its energy, to one level, another level, and so on. It is an exciting but difficult experiment to do and there is a great deal of background noise. From these data we can derive spectrum (e) in which peak A gives the separation ($2 \text{ \AA}$) of the two atoms. We thus have an accurate rule for measuring atomic distances. This is the first demonstration of this technique.

I will talk now about rusting of cars. Let us look at an atomic picture again, as we frequently do when we are using the light source. In Figure 17 the light circles represent the atoms of a metal: this represents in fact the surface of the metal. There are 100,000 atoms in a thousandth of an inch. The dark circles represent a small molecule, such as carbon monoxide, sitting on the surface. The lines joining the atoms represent chemical bonds. We want to know how the molecule sits on the surface of the metal. As before using light of known energy, some of the electrons forming the bond are extracted, and from their spectra we can deduce how the molecule sits.

Figure 18 shows some of the experiments that were done by researchers from Exxon Corporation prior to those at the light source.

Figure 18. The emission spectra for carbon monoxide, formic acid, and methanol, on copper. The intensity and separation of the peaks provides information on bond length.

Figure 19. The emission spectrum of a molecule of carbon monoxide on gold.

From the spectra for carbon monoxide, formic acid, methanol, on copper we can deduce the surface bonding geometry, which is shown. The arrangement of the molecule on the surface is determined from the intensity changes of the peaks as the sample is rotated in the light beam. The separation of the two main peaks gives information about bond lengths. The next result, an exciting one for us, was obtained with a molecule of carbon monoxide sitting on gold (Figure 19). Scientists from IBM, who made this experiment, found two side bands to their main peak. It turns out that these are caused by the molecule vibrating up and down on the surface, because the bond stretches. So not only can we learn about those electrons and their positions, but we can also learn something about the kinetics of the bonding.

These experiments are the very first of their kind. There is a strong interplay between theorists and experimentalists. If you know atomic distances and if you know what electrons you have, maybe the energies of bonding electrons could be calculated. Indeed, we rely very heavily on calculations to help us to understand these spectra. Somebody may make a calculation, someone makes a measurement, and then another calculation is done, and so on, until experiment and theory converge. The ultimate goal is to be able to understand how everything works on the atomic level.

The last example, shown in Figure 20, concerns a polymer. Light is shone on the polymer,

Figure 20. The electron spectrum and ion emission of a polymer. (Hanson, Anderson, Lucas and Williams).

Figure 20. The electron spectrum and ion emission of a polymer.

slowly increasing the energy of the light. The electron spectrum is the upper line. The lower curve represents ion emission from the same sample. The polymer broke apart when we reached the energy of the first ion peak. Thus we could identify the bond energy responsible for glueing the molecules together to form a polymer.

I have given you a flavor of photoelectron emission experiments that have made up 90% of the experiments at the light source. In these experiments, we looked at materials on an atomic scale and at the electrons that glue them together. At the level of atoms all the disciplines merge — biology, chemistry, and physics, everything becomes the same at that level.

There are other experiments which show exciting possibilities. I shall describe three of them. The first of these is x-ray microscopy, the second is x-ray holography, and the last one is x-ray lithography. Figure 21 provides a schematic view of an x-ray microscope. Recall the electromagnetic spectrum; visible light waves are rather long compared to x rays, so that if we could use the latter, we could "see" things on a smaller scale, maybe on the scale of a few hundred atoms or less. The electron microscope uses electrons, which can also be considered to be waves, to study things on a small

Figure 22. A living human blood platelet, as shown by the x-ray microscope.

scale. But, to use an electron microscope, samples have to be killed, dried, and stained before they can be studied. Thus you can never look at living cells. With an x-ray microscope, we take the light source and pass it through a filter so that we get a single color, and then pass that through a window into the air, where we have a sample and a detector behind it. In principle we can make images of living cells at high resolution. Presently the resolution is a thousand angstroms; we plan to go down to a couple of hundred angstroms.

The picture of a living human blood platelet shown in Figure 22, was taken with an x-ray microscope. The platelet was in water and shows long protrusions, or pseudopods, that are responsible for blood clotting. With an electron microscope, the sample would be dry and these pseudopods would not be seen. Many of the structures that have been seen with the x-ray microscope cannot be seen with the electron microscope.

The second micrograph is of a human skull section (Figure 23). This is the most interesting one to date and it shows the progress we have made. There are three pictures in this figure and they demonstrate another important aspect and advantage of the x-ray microscope. With the x-ray microscope we can "tune" the

Figure 23. Micrographs of sections through the human skull, taken by the x-ray microscope. By manipulating the light energy (top and middle), the bottom picture, representing the difference, shows the distribution of calcium.

energy by changing the filters. The micrograph on the top was taken with light of energy below, and the one in the middle with energy just above the level required to kick out a calcium electron. The third picture, at the bottom, representing the difference between the two, shows the distribution of calcium. It showed calcium occurred throughout the section, with living cells in between. This microscope allows one to zoom in on particular areas at high magnification, because the data are stored digitally. Thus we can look at a living cell and say, "I want to look specifically at the carbon, or the oxygen, or the calcium." This picture has a resolution of $2000 \text{ \AA}$, which is equivalent to 800 atoms. Better resolution will be achieved but it is a difficult process.

Let me move to the subject of holography: we are familiar with the three-dimensional images which are called holograms. Using the light source we can make three-dimensional photographs of matter on the scale of a micron or two. (Remember, this is one-fiftieth of a human hair). This might mean that ultimately we could take pictures of chromosomes in three dimensions, on a near atomic scale. Figure 24 shows an x-ray holography camera with which we can make holograms with light, not of $5000\text{-}\text{\AA}$ wavelength, which is visible light, but of 50 or $30 \text{ \AA}$, or one one-hundredth of visible light. In Figure 25A we see a sample of very small asbestos particles, roughly 1μ across. Figure 25B, shows an x-ray hologram of these, made possible because the light source is so bright and, therefore, coherent enough. Although the figure is a two-dimensional pres-

Figure 24. An x-ray holography camera.

Figure 25a. A sample of small asbestos particles.

Figure 25b. X-ray hologram of the asbestos particles.

Figure 25c. Reconstruction x-ray hologram of the asbestos particles.

Figure 26. Stages of lithography for the manufacture of integrated circuits.

entation, the interference effects of the hologram can be seen. It is possible to reconstruct a three-dimensional image of the original object using 6000-Å wavelength, so that it can be seen by eye. The advantage of this technique is that the image is proportionally magnified because of the differences in the wavelengths. Figure 25C shows such a reconstruction again only in two dimensions.

My last topic concerns the manufacture of advanced integrated circuits, again taking advantage of the brightness of the light source. The idea behind lithography, as it is called, is the following. All of modern electronics comprises silicon chips, on which very small circuits are printed. These circuits have dimensions which are of the order of a few microns, a tenth of a human hair. The way that these are made is similar to making a contact print (Figure 26). A mask is made for you, and the idea is to copy the mask onto a silicon chip. This is accomplished by exposing the "photoresist" on the chip, which acts like a film, to x rays.

Figure 27. X-ray lithography by IBM at the NSLS.

When it is developed the silicon dioxide on top of the silicon chip is etched and the resist is dissolved away leaving the beginning of the circuit. X rays are used because of their short wavelengths. Visible light has a wavelength which is of the order of the size of the features that you are making. Electrons could be used, but the process is much slower as the brightness is poor and the beam has to be scanned. Figure 27 shows examples of the test patterns. They represent a huge stride forward, which was made at Brookhaven. Thus, in the smallest structures, such as the columns that are beautifully lined up the tops consist of only a few hundred atoms. If chips could be made with features at least a tenth of the size of those in the chips that are used today, ten times as many components could be put into a linear dimension and a hundred times as many in a two-dimensional chip.

I have tried to convey a flavor of the kind of work which is just beginning to be possible at the light source, and of the excitement among those of us fortunate to be participating. In my closing remarks I would like to give credit and acknowledge our debt to Ken Green and Renee Chasman whose innovative design made the NSLS the brightest source in the world. I came to Brookhaven just after ground breaking and was not involved with the proposal. The light source would not be here without the early efforts of Marty Blume, Dick Watson and Morris Perlman who established the light source and to whom we all owe a great deal of gratitude.

I would personally like to thank BNL's Graphic Arts division, especially Theresa Esposito, the photography section particularly Mort Rosen without whose support this lecture would not have been possible.

ABOUT THE AUTHOR

Gwyn Williams received his Ph.D. from Sheffield University, U.K., and first worked with synchrotron radiation in 1971 at Daresbury, where he remained until 1977 when the old Daresbury ring closed down. He then came to America to work at Montana State University, using the Tantalus 1 Storage Ring in Wisconsin. He moved to Brookhaven in 1979 and has played a major role in the scientific program at the VUV ring; at present he is Coordinator of the VUV Research Program. Gwyn is the North American editor of *Vacuum* and is on various advisory groups on synchrotron radiation. His main hobbies are sports, particularly squash racquets. For relaxation he keeps bees on a local farm.