1 of 1

... harmonic from U13 undulator

1982 — 1992

**Decade of Research
in the Vacuum Ultraviolet Ring at the
National Synchrotron Light Source**

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A decade of research
 at the University of
 California, Berkeley
 has produced a new
 generation of scientists
 and engineers.

A DECADE OF ULTRABRIGHT RESEARCH

scientific departments

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NATIONAL SYNCHROTRON LIGHT SOURCE

The world's foremost facility for scientific research using x-rays, ultraviolet and infrared radiation is operated by the National Synchrotron Light Source Department. In a single year, a total of about 2,500 researchers from almost 450 institutions performed experiments at the world's largest source of synchrotron light. In 1992, BNL commemorated the tenth anniversary of the vacuum ultraviolet (VUV) ring. Like the higher energy x-ray ring, the VUV ring has been the site of hundreds of significant discoveries in physics, chemistry, biology, materials science and various technologies.

BROOKHAVEN HIGHLIGHTS

for experiments in fields as varied as biology and physics, chemistry and geophysics, medicine and computer chip technology.

Now part of the most frequently used synchrotron light source in the world, the VUV ring is a beacon for approximately 500 researchers annually from industry, universities and laboratories, investigating samples as varied as metals and pro-

teins at its 30 beam lines. This work has led to hundreds of important discoveries.

SYNCHROTRON LIGHT

Synchrotron light, also known as synchrotron radiation, is produced when electrons are forced to move in a curved path at nearly the speed of light. This radiation is

measured in quanta of energy called photons. To harness this phenomenon for research, the electrons produced in the NSLS are accelerated and boosted to energies of about 750 million electron volts (MeV). Then, they are injected into two storage rings — the VUV ring and the x-ray ring.

Each produces synchrotron light in a different range of the electro-

magnetic spectrum. In a continuous fashion, the spectrum ranges from longer to shorter wavelength radiation. The VUV ring is optimized to produce light in the infrared, visible, ultraviolet and soft x-ray range, while the x-ray ring, which came on line in 1985, generates hard x-rays.

MACHINE SPECIFICS

On May 20, 1982, the VUV ring reached its design energy of 700 MeV. Ten years later, the ring now stores particles at energies of 750 MeV and operates at a typical current of 950 milliamperes.

Physics

From semiconductors to superconductors, experiments by physicists at the VUV ring help elucidate the atomic and electronic structure as well as the magnetic properties of a wide array of materials.

— **Fermi surface mapping** — Using a technique called high resolution angle-resolved photoemission to perform surface studies on beam line U4A, researchers from the University of Oregon have significantly advanced the understanding of the electronic structure of metal surfaces.

In this technique, photons in the energy range of 10 to 70 electron volts strike a sample, knocking out electrons. A spectrometer measures the energy and momentum of the electrons. This provides a measurement of the sample's Fermi surface — a surface related to the momentum of electrons in solids.

Electrons in solids seek various energy levels. The Fermi level is the dividing level. All levels below it are occupied by electrons, but those above remain unoccupied. Information about electrons near the Fermi level is basic to an understanding of the electronic

As electrons speed through bending magnets in the ring, short bursts of radiation are emitted. In producing this radiation, the electrons lose energy, but as they circulate around the storage ring, they travel through a radiofrequency (rf) cavity that restores their energy. This form of energy recovery naturally forces the electrons into compact bunches, so the synchrotron radiation has a pulsed time structure.

A relatively low rf frequency of 52.9 megahertz was selected in designing the VUV ring, which provides relatively long lapses

between pulses of radiation and enables researchers to perform timing experiments in the range of billionths of seconds.

A high current of up to 1.5 amperes creates intense photon flux and very bright beams of synchrotron light. Higher photon energy resolution can be achieved with brighter light. Thus, smaller or more dilute samples can be studied. But high currents result in a short beam lifetime because of the high density of electrons in each bunch. To increase the lifetime at high beam current, a second rf cavity was installed in

structure and magnetic properties of metals and semiconductors.

— **Magnetic structure** — At neighboring beam line U4B, AT&T Bell Laboratories researchers have modified the Dragon monochromator (see "Award-Winning Technology at the VUV Ring") to perform the first magnetic circular dichroism measurement (MCD) using soft x-rays, which have long wavelengths but low penetrating power, compared to conventional x-rays.

MCD is the difference in the absorption intensity of magnetic systems using circularly polarized

light in which an electric field rotates in either a left or right direction. The intensity of soft x-ray absorption depends on the polarization of light and the relative direction of the sample's magnetic moment — the measure of an atom's interaction with a magnetic field.

By making MCD measurements, the researchers were able to determine, with element and site specificities, the electron orbital and spin contribution to the magnetic moment of transition metals and rare earths, the most impor-

AT&T Bell Laboratories researchers Grace Ho and Hong-Ji Lin adjust two newly installed gratings in the Dragon monochromator at beam line U4B.

1990. It operates at four times the frequency of the main rf cavity in the machine, and doubles the beam's lifetime.

This innovative improvement was one of many over the decade. The VUV ring has been continuously upgraded to keep up with new technology and with the demands of its users.

For example, two special insertion devices, called undulators, were installed on beam lines U5 and U13 to intensify the synchrotron light up to fifty times. The undulator at U5, installed in 1990

by a large collaboration including BNL, Argonne National Laboratory, universities and private industry, provides enough photons to study surface magnetism using a technique called spin-polarized photoemission.

In 1987, an undulator/wiggler was installed at U13UA by an AT&T Bell Laboratories and NSLS collaboration. This beam line provides up to ten times more photon flux than a comparable bending magnet beam line for examining the atomic and electronic details of dilute systems and interfaces.

tant elements in the periodic table that are responsible for magnetism. Using conventional techniques, it is extremely difficult to measure the orbital contribution. This new technique is used to study the magnetic structure of a wide range of systems, including surfaces, thin films, alloys, ferrites and proteins.

— **Thin films and multilayers** — A large collaboration of researchers at U5, the spin-polarized photoemission beam line, also studies magnetic properties, but they are interested in thin films of magnetic materials just a few atoms thick, and multilayers, which are thin films sandwiched together. Multilayers of materials such as copper and cobalt have magnetic properties that may make them particularly useful in the magnetic recording industry.

When electrons pass through the U5 undulator, they emit an intense flux of photons. The photons then excite electrons in the magnetic film, which come spinning out, either up or down. When the electrons hit a gold atom target, scientists can determine their spin, which reveals important information about the magnetic properties of the sample.

— **Infrared beam line** — The VUV ring is also home to the

brightest infrared beam line in the world. Physicists use this highly stable beam at U4IR to study vibrational modes — the characteristic frequencies at which atoms or molecules vibrate — of adsorbates, which are materials that adhere, in an extremely thin layer, to the surfaces of a solid or liquid. Experiments performed at U4IR are important for understanding catalysis, corrosion and high-temperature superconductors.

For example, researchers from Grumman Corporate Research Center are studying how light, ranging from the infrared to visible spectrum, affects both superconductors and semiconductors. They hope to determine these materials' suitability for infrared or optical detectors and learn more about the behavior of electrons in high-temperature superconductors. These detectors are used in a variety of applications, from thermal imaging and spectroscopy to satellite surveillance and monitoring of the earth's oceans and atmosphere.

Chemistry

New possibilities in chemistry research unfolded with the arrival of synchrotron radiation. Chemists

PROMISE FULFILLED

During the VUV ring's first decade, physicists, chemists, biologists and other researchers worked side-by-side on the ever-more crowded experimental floor, making hundreds of new discoveries about the nature and functioning of samples. More than 500 articles have been published in scientific journals as a result of this work.

The section below contains a sampling of the variety and wealth of research over the years.

at the VUV ring can investigate the inner workings of molecules in the excited state, thereby gaining important information about the chemistry of their samples.

— **The dynamics of chemical reactions** — At U11, chemists use beams of molecular clusters to study energy pathways in chemical reactions. A beam of UV light intersects the cluster beam, causing a process called photoionization. One of the neutral molecules in a cluster loses an electron, transforming it into a positively charged, excited ion with properties that depend on the wavelength of the UV light. When this new ion reacts with the remaining molecules, the reaction products are studied using a mass spectrometer and a kinetic energy analyzer. By such experiments, the researchers learn more about the dynamics of chemical reactions.

For example, BNL scientists have performed photoionization studies to understand how a benzene-hydrogen chloride cluster produces a chlorobenzenium ion. Basic research of this kind may become important to industry because it shows a new way to investigate energy pathways in processes such as combustion.

— **Energy distribution** — Also at U11, chemists can examine the

At beam line U11, (from left, seated) BNL's Jack Preses and J. Robb Grover review data from a photoionization experiment with Bing-Ming Cheng from the Synchrotron Radiation Research Center in Taiwan. John E. Barry (rear), BNL, adjusts the gas mixture used in the research.

energy flow in molecules using a technique called time-resolved fluorescence. When UV light is absorbed by molecules, it is emitted at a different energy. Since different molecules emit light at particular energies and at different rates, the researchers then measure this energy to gain information on the chemistry of the sample. BNL scientists, for instance, are studying the way energy is redistributed in cyclohexane, a component of many hydrocarbon fuels.

Biology

Innovative techniques are used at the ATF ring to study the structure of biological specimens.

— **X-ray microscope** — One such notable technique is x ray microscopy. Fabricated by researchers from BNL and the State University of New York at Stony Brook, a scanning x ray microscope was first successfully operated at the ATF ring in 1982.

This instrument is unique because it lets scientists study specimens in their natural, wet state. Because x ray imaging requires high brightness, the

microscope was later moved from U15 to X1, the soft-undulator beam line on the x ray ring.

— **Protein structure and function** — In 1985, time dependent protein fluorescence experiments were performed at beam line U9B by BNL scientists and their collaborators. The team was the first to demonstrate that the amino acid tyrosine, a building block of proteins, can have more than one

configuration of its atoms with respect to the rest of the protein. These initial studies showed the feasibility of using time dependent protein fluorescence to obtain useful information about the relationship between protein structure and function.

— **Lyme disease** — More recently, BNL biologists at U9B studied the properties of the major outer surface protein A (OspA) of the Lyme disease spirochete, *Borrelia burgdorferi*. Using fluorescence and circular dichroism (CD), the scientists learned more about the structure of this protein. The techniques are complementary: CD provides information on the whole protein, while fluorescence provides more localized data.

This work shows that OspA is very low in alpha helix, a typical spatial configuration of protein chains. The small amount of alpha helix that is present, however, appears to be localized in a region of the protein that is important for recognition of the organism by the host's immune system. This structure makes the protein interesting for basic studies, but some practical bene-

At beam line U9B, (from left) Louisa Lee France, from the Plum Island Animal Disease Center, and John Trunk and Barbara McGrath, both from BNL, study the Lyme disease spirochete.

fits may also derive from the research. If additional investigations prove helpful in understanding how antibodies interact with this protein, a Lyme disease vaccine may soon become a reality.

X-ray Lithography

A significant achievement at the VUV ring is IBM's development of a technique called x-ray lithography for the production of high-resolution computer chips. Because of the very short wavelength of x-rays, chips fabricated with x-ray lithography can have higher resolution and greater density than those made using conventional optical lithography. Since increased density allows electrical signals to travel between components more quickly, IBM's innovative chips hold promise for a new generation of faster, more powerful computers.

Starting in 1982, IBM researchers worked at U6 to develop sophisticated technology to demonstrate the feasibility of x-ray lithography, culminating in 1988 with the successful fabrication of integrated circuits with features as small as 0.5 microns (about one-hundredth the width of a human hair). Currently, fundamental research is ongoing at U6 to answer some remaining questions about this new technology as the size of the printed features continues to shrink.

Also in 1988, IBM installed another lithography beam line, at U2, to focus on developing technology for manufacturing. Work at U2 has progressed on fabricating chips with sub-0.5 micron features. Based on its success at the VUV ring, IBM has recently built its own x-ray lithography facility at its development and manufacturing site in East Fishkill, New York, to continue the frontier work started at the NSLS.

VUV Ring 1980

VUV Ring 1992

Spontaneous Emission from the U13 Undulator
The Ultraviolet (VUV) Ring has two insertion devices. The device located at the U13 Undulator is a collaborative effort between the NSLS and AT&T Bell Laboratories. It is operating in both undulator and wiggler modes. This device provides a continuous UV and soft x-ray spectrum compared to the VUV bending magnet. The operation of this device involves optical metrology for projection lithography and spectroscopies. The cover figure shows the visible spectrum of the U13 Undulator with the VUV Ring electron energy at $\sim 455\text{MeV}$.

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