

search & discovery

Xenon ultraviolet laser researchers claim success

Stimulated emission from high-pressure xenon has been observed recently in the vacuum ultraviolet by three groups, all of whom believe they have demonstrated laser action. The stimulated transitions occur between the lowest bound diatomic states of xenon and the repulsive ground state. According to one of the experimenters, James Gerardo of Sandia Laboratories, this is the first example of a laser where the lower laser level is not bound. Furthermore, he said, it is the first uv laser that has the potential of being high-powered—10% efficiency is possible. One application that interests Sandia, for example, is that a

high-power xenon laser could be useful for laser-induced thermonuclear fusion (see page 46).

The experiments were done at Sandia by Gerardo and A. Wayne Johnson, who reported their results at the Denver meeting of the Optical Society of America in March and the Conference on Laser Engineering and Applications in Washington at the end of May. A second group, Charles Rhodes, Paul Hoff and James Swingle, at Lawrence Livermore Laboratory, reported its results at the Washington conference. A third group, consisting of Reed Jensen, William Hughes and Paul Robinson of Los Alamos, Alan Kolb and John

Shannon of Maxwell Laboratories, and Mani Bhaumik and Earl Ault of Northrop Corporation, reported its results at the Denver meeting.

The idea of using excited diatomic molecules that radiate to repulsive states, called "bound-free systems" or "molecular association lasers," has been discussed as a potential laser system for many years. Noble gases are particularly attractive, the Sandia experimenters say, because they offer the possibility of high quantum efficiency, high net efficiency, wavelength tunability and high power in the vacuum ultraviolet.

The first suggestion of using a
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Interest grows in synchrotron-radiation sources

The National Science Foundation has just funded a new synchrotron-radiation facility at Stanford University to be open to users throughout the US. The facility, which will use the electron-positron storage ring, SPEAR, is currently operating at 2.6 GeV at the Stanford Linear Accelerator Center. It will produce photons with a critical energy of 3.07 keV with some photon flux up to 20 keV.

Two other proposals were vying for NSF support, one from the University of Wisconsin, which has been operating its Tantalus 1 source for several years, and one from the Cambridge Electron Accelerator, which started to do synchrotron-radiation experiments in its waning days as a machine for high-energy physics. AEC support for CEA ended on 30 June.

Interest in synchrotron-radiation sources has been mounting throughout the world because these sources can be used for an enormous variety of experiments in solid state, atomic physics, chemistry, crystallography and biology.

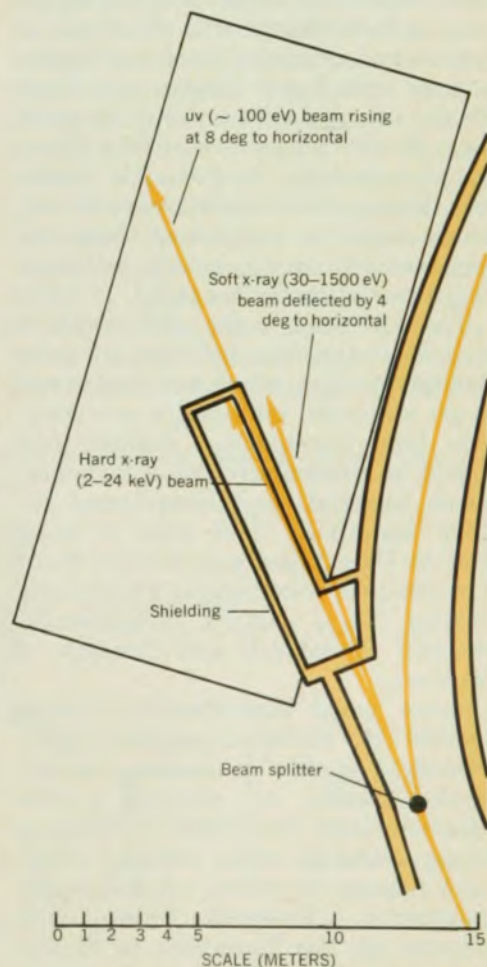
Electrons circulating in a synchrotron or storage ring emit incoherent white light with a spectrum whose peak wavelength varies inversely as the cube of the electron energy and linearly as the radius of the electron orbit. The radiation comes out as a thin wedge-shaped "pancake" with a vertical angular divergence of about 1 milliradian for high-energy machines.

To do experiments at a specific wave-

length, a monochromator is employed, and by adjusting or changing the monochromator, the source is continuously tunable. Although synchrotron radiation sources give high intensity at lower energies too, they are an excellent source in the extreme ultraviolet at photon energies of 15–500 eV, a region that is otherwise nearly inaccessible. The radiation is polarized. For storage rings, photon intensity is very stable. Typical synchrotron-radiation sources emit subnanosecond pulses. Within the vertically narrow light beam, the intensity is very high. As Richard Watson and Morris Perlman have noted,¹ for experiments that need high spatial and energy resolution this intensity is significantly greater than that obtainable from other sources.

At a Brookhaven conference on synchrotron radiation sources held last September, the following kinds of experiments were discussed: optical and electron emission experiments with solids and surfaces, photochemistry and atomic physics, optical biochemistry, photometric calibration, diagnostic x-ray radiography, x-ray scattering (both structural and nonstructural) and x-ray microscopy.

The Stanford facility will be symbiotic to the SPEAR operation and is expected to operate in 1974. It will be one large port that will then be broken into a number of beams for different experiments. One will cover the uv up to about 100 eV; a second will cover the



Stanford synchrotron radiation facility (preliminary layout). Beams come from port at SPEAR storage ring. The four or five hard x-ray beams will be both horizontally and vertically deflected.

soft x-ray region from 50–100 eV; the rest of the facility will be dedicated to x-ray experiments, for which the beam will be brought out through a beryllium window.

The NSF award is for \$750 000 the first year; the following year, an additional \$450 000 will go toward completing the construction and starting the operation. After that, NSF estimates that it will cost about \$300 000 per year to operate. Construction will include a small building alongside the SPEAR ring to house the beam run and experimental areas, beam lines, vacuum equipment and protection for the vacuum lines.

Even with the Stanford source, the US will not have as strong a capability as is available at the DESY synchrotron in Hamburg, for photon energies above 8 keV. The Stanford intensity below 8 keV is 2–3 times the DESY synchrotron intensity. DESY is constructing a storage ring, DORIS, which will increase its capability. By late 1974 the SPEAR energy is expected to be raised to 4.5 GeV.

Sebastian Doniach and William E. Spicer are co-principal investigators on the Stanford project. Herman Winnick, formerly with CEA, has joined Stanford as associate director of the synchrotron-radiation facility. Gerhard Fischer has served from the beginning as SLAC liaison with the Stanford synchrotron-radiation project. Spicer told us that Ingolf Lindau and Piero Pianetta have a pilot experiment under way. It will be used to do ESCA (Electron Spectroscopy for Chemical Analyses) studies with a resolution of 0.1 eV, which would be a factor of about five improvement over presently available ESCA resolution, Spicer said.

The next thing in the pilot project is to look at the fine structure in x-ray absorption edges, which would allow one to get structural information not available from conventional sources, and should be particularly useful for amorphous materials and complicated organic materials. This work is being done by Dale Sayers and Edward Stern (University of Washington), Farrel Lytle (Boeing Co.), Arthur Bienenstock, Mitchell Weissbluth and Doniach of Stanford.

Spicer noted that there is a large interest in biological studies—time-dependent studies of muscles, for example, should be possible. John Baldeschweiler (Cal Tech) is planning to use x-rays to study induced structural changes in retinal photoreceptor membranes. Frederick Brown (who recently left the University of Illinois to join the Xerox Research Center in Palo Alto) will be setting up the initial soft x-ray operation; he expects to extend to higher energy the optical absorption experiments he had been doing at Wisconsin. Victor Rheen of the Navy's

Michelson Lab in China Lake, California, Don Baer (Stanford) and Spicer are developing a separate uv beam line for about 100 eV.

US facilities. The first far-uv synchrotron-radiation experiments were done at the 300-MeV synchrotron at Cornell University by D. H. Tomboulion and Paul Hartman in 1956. Since then the US has had three other synchrotron-radiation sources. One, at the National Bureau of Standards, under Robert Madden, is a 180-MeV synchrotron, which was used in pioneering atomic absorption experiments that began in 1961. This source is being converted to a storage ring and is expected to operate next year with an improved intensity of more than a factor of 100.

Several years later Tantalus I, a 240-MeV storage ring, then directed by Frederick Mills and now by Ednor Rowe, started doing synchrotron-radiation experiments with support from the Air Force. It has been used by many investigators from other agencies as well. Over the past three years, the Wisconsin group has developed a "wavelength shifter" that will give usable intensity (through one port) down to about 30 Å instead of the present cutoff of about 100 Å. Meanwhile, Wisconsin proposed to NSF to build a so-called "dedicated facility," known as Tantalus 2, that would use a microtron as an injector. It would have been a 1.76-GeV storage ring with a capability down to 1 Å. Anticipated construction cost was \$1.5 million over a three-year period.

The third synchrotron-radiation source, at the Cambridge Electron Accelerator, has stored beams for synchrotron radiation up to 3.5 GeV. (Colliding beams were limited to 2.5 GeV.) Dean Eastman (IBM Research Center) and his collaborators have used CEA to extend uv photoemission studies begun at Wisconsin, studying the evolution of the photoemission spectrum as a function of photon energy. Paul Horowitz (Harvard), acting upon a suggestion of Edward Purcell, built at CEA an x-ray microscope. It is a scanning instrument with chemical discrimination, a large depth-of-field, resolution of about 1 micron and does not have to be operated in a vacuum.

CEA had proposed to NSF that it support a dedicated facility there that would have required relatively little construction. Up to 15 beam lines, each divisible into three parts, would have brought radiation into the experimental area that was used for high-energy physics. The final CEA proposal asked for about \$2.5 million over a five-year period for installation of the beam lines and full operation of the accelerator, plus an additional \$1.1 million over five years for an in-house laboratory.

Howard Etzel of NSF's Division of Materials Research told us that the

three installations were visited by a select group charged with making recommendations to the Foundation as to whether or not the US should develop a major facility, and if so, which of the three should be recommended. The decision made by the NSF was primarily determined by factors such as cost, national diversification and long-range flexibility. Eventually, the US will probably have a second-generation source, Etzel told us, but not in the next five years.

What of the rest of the world? Rowe filled us in on the status of other machines. DESY has a 7.5-GeV synchrotron whose synchrotron-radiation spectrum reaches into the hard x-ray range, about 20 keV. By putting on an appropriate monochromator, a machine of the DESY class would give a monochromatic x-ray source one to three orders of magnitude more intense than the strongest x-ray tubes in the same energy range, Rowe told us. A group from the European Molecular Biology Organization plans to use DESY to study, among other things, muscles and long-chain protein molecules. Rowe notes that synchrotron radiation may be used also to help solve the phase problem in x-ray diffraction; with phase information a lot of ambiguity in large molecular structures would be removed. The rest of the DESY program is largely solid state and atomic physics. When the new storage ring, DORIS, starts operating, circulating currents of several amperes are expected; DORIS will be used as a synchrotron-radiation source and part of the building for these experiments is completed.

In Paris, ACCO, a 530-MeV storage ring, is by late next year expected to be completely converted to a dedicated synchrotron-radiation source, and go down to 10–20 Å. A 2.2-GeV storage ring now nearing completion will be used for synchrotron-radiation experiments.

At the University of Bonn, a 2.3-GeV synchrotron is doing some synchrotron-radiation work.

NINA, the 5-GeV synchrotron at Daresbury, UK, is now taking data. The Science Research Council has recommended construction of a dedicated storage ring, which would not use the existing synchrotron as injector.

At Frascati, Italy, the 1.1-GeV synchrotron has been used for some time.

In the Soviet Union, the Lebedev Institute in Moscow is using its 680-MeV synchrotron as a radiation source. A bigger synchrotron at Lebedev, now nearing completion, may be altered to operate as a storage ring and synchrotron-radiation source. In Yerevan, a Moscow group is using the 6.5-GeV synchrotron there as a synchrotron-radiation source. It was used to calibrate the x-ray telescopes for the Salyut space station. Sergei Kapitsa of the

Institute for Physical Problems in Moscow would like to build a dedicated source using a 1.3-GeV storage ring.

At the University of Tokyo, the INS-SOR group is using the 1.2-GeV synchrotron for synchrotron-radiation studies. A 300-MeV storage ring is being added there; it is expected to be finished late this year.

—GBL

Reference

1. Research Applications of Synchrotron Radiation, R. E. Watson, M. L. Perlman, eds., proceedings of a study-symposium at Brookhaven National Laboratory, 25-28 Sept. 1972, BNL 50381 (June 1973).

Xenon laser

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bound-free transition was made by Fritz Houtermans in 1960. About six years later Nikolai Basov of the Lebedev Institute suggested using the rare gases. In 1968, Basov and his collaborators did experiments in liquid xenon and found that the radiation was dominated by stimulated emission but they did not demonstrate laser action. His group published more papers in 1970 but since then have not reported any more results, although there has been speculation that the Soviet group is keeping its experiments under wraps.

Since then experimenters have concentrated on gaseous xenon. All of the potential laser systems are excited by relativistic electron beams.

Last year, H. A. Koehler, L. J. Ferderber, D. L. Redhead and Paul J. Ebert of Livermore used a Febetron 705 and Febetron 706 as sources of relativistic electron beams. They found emission from high-pressure xenon centered near 1700 Å, observed line narrowing and reported that the output was highly directional.

In the Sandia work, Gerardo and Johnson first used a Febetron 705, which produced 250 A of 1.5-MV electrons. The optical-cavity mirrors were coated with aluminum and then overcoated with magnesium fluoride. They say they have demonstrated that the cross section for stimulated transitions from the lowest bound diatomic states of xenon to the repulsive ground state is larger than the photoionization cross section of these excited states. This they say they demonstrated by direct measurement of net optical gain at wavelengths near 1730 Å and temporal and spatial narrowing of the radiation intensity when the excited xenon was located in an optical resonator. They estimate their effective gain cross section at 1730 Å to be $7 \times 10^{-19} \text{ cm}^2$.

Subsequently, the Sandia team used the Reba electron-beam device at Sandia, operating at 1.5 MV with a peak

current of 30 kA and average current density of 800 A/cm^2 . The aluminum coating on the mirrors was completely vaporized during each shot, but Gerardo and Johnson did find the spectral width decreased from 120 Å to 20 Å. Most of the experiment was done without mirrors, and they found the spectrum narrowed from 110 to 25 Å. Although they did not determine a power output, they found that as much as 1000 J/liter was stored in the upper laser level. They estimated the effective gain cross section to be $1 \times 10^{-18} \text{ cm}^2$. In the Febetron experiments, they got an efficiency of 6-10% for conversion of electron-beam energy to energy deposited in the upper laser level.

At Livermore, Rhodes and his collaborators used a Febetron 705 that gave 1-2 MeV electrons with about 200 joules per pulse; actual energy deposited in the gas was about 40 J. A cell is placed close to the beam so that an appreciable fraction of the energy can be coupled into the xenon gas. Coupled to the gas is an optical cavity with two mirrors. Rhodes says they see a number of effects that can only be attributed to a coherent beam. One is a threshold effect—below certain gas pressures only spontaneous emission occurs, but if the threshold pressure is reached the output shows a sharp spike and the line narrows to about 15 Å. The group has measured the divergence of the beam (5 milliradians) and related this to the mirror dimensions and the size of the cavity, finding that the two match within 10%, demonstrating spatial coherence, Rhodes says. Their center wavelength ranges between 1716 and 1722 Å and is a function of gas density. Power output is 100 kW. Pulses last 5-30 nanosec, depending on pressure. Using model calculations, the Livermore group finds a

good match with experimental data; they calculate that the optical cross section is about $3 \times 10^{-18} \text{ cm}^2$.

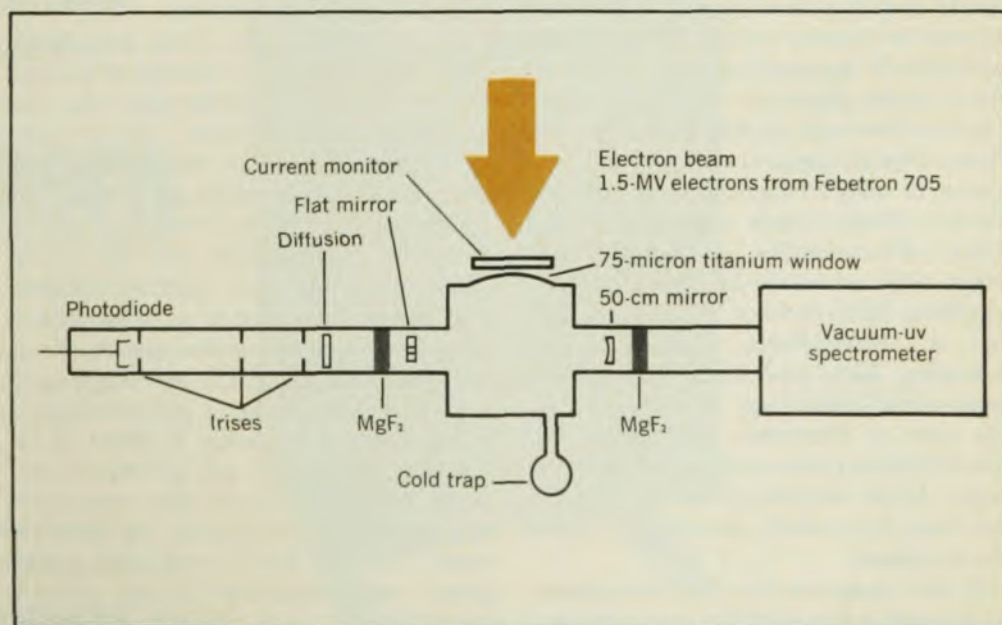
The Livermore workers have also done experiments with krypton, which behaves very similarly except that the output is a molecular continuum centered near 1457 Å; the FWHM is 8 Å.

Rhodes notes that for fusion applications, probably all the rare-gas lasers are too short a wavelength—the wavelength is short enough that one is always within shooting range of the two-photon absorption in any material.

The group's motivation is to study the prototypes of bound-free transitions and then transfer the information to other systems where the wavelengths are probably more amenable to high-power applications. Rhodes does not believe it is necessary to excite the system with electron beams—all one needs is to make a plasma that is about 1% ionized at high density and reasonably cold temperatures (electron and gas).

The Livermore group has also tried to improve the operation of the xenon device by using energy transfer from other systems. They have operated systems in which argon is added—20-30 atmospheres partial pressure compared to 3.5 atmospheres partial pressure of xenon. In such a mixture they see improved output power and efficiency, better by a factor of two.

In the Los Alamos-Maxwell-Northrop experiment the group used a Maxwell device that produced 150 kA of 0.5-MeV electrons in a 60-nanosec pulse. The $3 \times 10 \text{ cm}^2$ rectangular electron beam entered a target chamber containing xenon at a pressure of 15 atmospheres. Feedback was provided by aluminum mirrors on magnesium fluoride substrate with magnesium fluoride overcoat inside the pressure vessel. A total energy of 1200 J at



Sandia apparatus used to observe stimulated emission from high-pressure xenon.