search & discovery

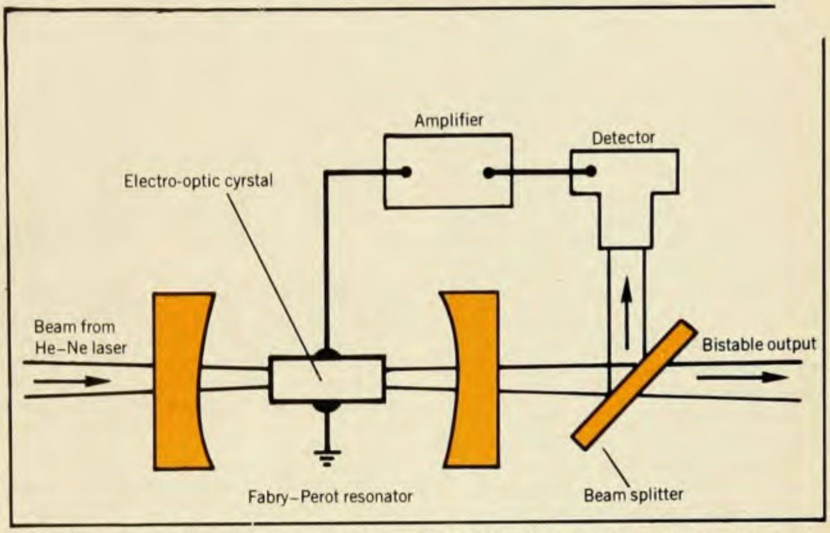
Observation of optical bistability confirms prediction

An effect predicted in 1969 has been observed experimentally: An intense beam of light can cause an optical medium to pass from one state to another, opaque to transparent. In a complete cycle (opaque–transparent–opaque), the medium exhibits hysteresis.

The discovery at Bell Labs of the effect, known as optical bistability, promises to contribute significantly to the growing technology of lightwave communications (PHYSICS TODAY, May 1976 issue).

The possibility of making bistable optical devices based on saturable absorbers was proposed in 1969 by Harold Seidel of Bell Labs (who was awarded a patent on it in 1971) and by Abraham Szöke (Lawrence Livermore), V. Daneu, Julius Goldhar and Norman Kurnit (Los Alamos).

Sodium vapor was the nonlinear medium in the first successful demonstration of optical bistability, first announced in 1975, by Hyatt Gibbs, Samuel McCall and T.N.C. Venkatesan of Bell Labs, Murray Hill. In this and later experiments, the medium was placed in the resonant cavity of a Fabry–Perot interferometer, with its length adjusted so that one of its resonances is close to one of the absorption lines of the medium. For the sodium experiment this was one of the D lines, to which a single-mode dye laser was also tuned. The gas-filled resonator transmitted very little optical power until the incident beam attained a power density of about 500 mW/cm^2; then the output power jumped dramatically. Above this value, transmitted power increased linearly with beam power. On decreasing the beam power, the experimenters found that the transmitted power decreased linearly until the input beam dropped to about 400 mW/cm^2, then dropped sharply as the sodium vapor became virtually opaque again; thus the cyclic response forms a hysteresis curve.



A bistable optical device that achieves nonlinearity by electrical feedback on an electro-optic crystal; the crystal is in a cavity near resonance with the laser beam. Earlier work showed bistability in purely optical systems with media of nonlinear refractive index. (From ref. 3)

The experiment disclosed a surprise: The apparatus functioned best when slightly detuned, demonstrating that the dominant effect was nonlinear *dispersion* (refractive index) rather than nonlinear *absorption*, as some of the theoretical predictions had assumed. In their paper,[1] Gibbs, McCall and Venkatesan developed a model of the effect encom-

continued on page 19

Accelerator technique improves radioisotope dating

Stimulated largely by recent developments in archaeology and the environmental sciences, physical scientists have been giving a good deal of attention to the practical problem of getting better carbon-14 dates. One particular area of renewed interest is the use of a mass spectrometer to separate the radioactive C^{14} from other carbon isotopes. The C^{14} content could then be measured directly, rather than by counting decays as is done now. The difficulty has been that conventional mass spectrometers are not sufficiently sensitive to detect the small percentages of C^{14} present in typical samples: The C^{14}/C^{12} ratio ranges from $1.2 \times 10^{-12}/1$ in contemporary biological samples down to about $3 \times 10^{-16}/1$ in samples older than 70 000 years or so.

Now however, three groups of experimenters, working independently of each other, have shown nearly simultaneously that C^{14} dating with an accelerator as a mass spectrometer is feasible. Two of these groups use a tandem van de Graaff; another uses a cyclotron, picking up on a suggestion first made in 1939 by Luis Alvarez and Robert Cornog.

The percentage of C^{14} in a sample is a measure of its age, that is, of how long ago it was taken out of equilibrium with the atmosphere. The radioactive isotope, with a halflife of 5730 years, is produced in the atmosphere by cosmic-ray neutrons. In the method developed by Willard Libby over 30 years ago, age is measured by counting the beta rays emitted as the C^{14} decays to N^{14}. In a typical experiment on, say, a 5000–10 000 year-old skeleton or other carbon sample, several grams of carbon are needed, and an experiment lasts ten hours or so. If the C^{14} atoms could be detected directly, much smaller amounts would be needed (of the order of milligrams) and, if the background can be kept low, much older samples could be dated, possibly up to 100 000 years, compared with a maximum of about 60 000 years now.

The experimenters working on the accelerator problem are from the US and Canada. One effort is at the Lawrence Berkeley Laboratory;[1] another group is from the University of Rochester, the

Schwarzschild, Peter Thieberger and James Cumming have been using the tandem van de Graaff as a mass spectrometer in a search for superheavy elements in monazite, found in meteorites. They described this work at the Chicago APS meeting last February.[6]

Laser enrichment. Robert Hedges of the Oxford (UK) Laboratory for Archaeology has been collaborating with C. Bradley Moore of the Berkeley chemistry department in laser separation of carbon isotopes. Others involved in the overall project are Edward Hall, director of the Oxford lab, and Roger Bennett of the Rutherford High Energy Laboratory, Harwell. The separation procedure, as described to us by Moore, is to convert the carbon sample chemically to formaldehyde (H_2CO), which has a highly structured ultraviolet absorption spectrum. The formaldehyde is then photolyzed with a tunable uv laser at the wavelength corresponding to $H_2C^{14}O$, and the collected CO product is found to be enriched roughly 100 times in C^{14}.

The Oxford group, explains Hedges, originally planned to carry out these enrichments back at their own laboratory and use the resulting samples with conventional mass spectrometry. Their aim was a C^{14} dating scheme applicable to milligram samples and possibly to earlier dates. They planned to send the beam through a thin foil to eliminate mass-14 impurities, exploiting the fact that only the negative ions formed in the foil are accelerated on to the analyzer. The success of the Rochester and McMaster groups has, however, led the Oxford group to reappraise their plans. Hedges tells us that they are about to build a small van de Graaff accelerator dedicated to C^{14} abundance measurements, and are collaborating with the Oxford nuclear-physics department in scaling the Rochester work to their own planned van de Graaff.

Prospects. Although C^{14} dating is the prospect generating the most widespread excitement, dating with other radioisotopes may turn out to be equally important. Possibilities include using the cyclotron method to measure the Be^{10} content and date otherwise undateable rocks, or using the tandem to measure the Al^{26} content of meteorites. Here the key may be that Al^{26} forms negative ions much more easily than the interfering Mg^{26}.

None of the groups now working on the new C^{14} dating techniques are claiming that their way is yet competitive with the decay-counting method, either in terms of accuracy or economics. However, the consensus appears to be that at least one of the methods (which in particular is not yet clear) will be competitive within the near future, particularly when only a few milligrams can be spared.

What about older samples? Again, all the groups are optimistic but are still testing samples being provided by their archaeologist and geologist partners. Background remains a problem. The Rochester–Toronto group, for example, believes that their most recent experiments show the need for a device dedicated solely to C^{14} detection and dating: They feel that they have confirmed their suspicion that accelerators used extensively for nuclear-physics experiments may be contaminated with C^{14}.

In terms of economics, all the groups point out that accelerators powerful enough to do C^{14} dating are not overly expensive. Particularly when the relative length of accelerator and beta-ray counting experiments are compared, the new method begins to look very good. Muller, for example, has calculated that each C^{14} date determined with a cyclotron would cost about $200, competitive with a decay-counting date. —MSR

References

1. R. A. Muller, Science **196,** 489 (1977).
2. C. L. Bennett, R. P. Beukens, M. R. Clover, H. E. Gove, R. B. Liebert, A. E. Litherland, K. H. Purser, W. E. Sondheim, Science **198,** 508 (1977).
3. D. E. Nelson, R. G. Korteling, W. R. Stott, Science **198,** 507 (1977).
4. R. A. Muller, L. W. Alvarez, W. R. Holley, E. J. Stephenson, Science **196,** 521 (1977).
5. H. E. Gove, Bull. Am. Phys. Soc. **22,** 992, 1014 (1977).
6. A. Z. Schwarzschild, P. Thieberger, J. B. Cumming, Bull. Am. Phys. Soc. **22,** 94 (1977).
7. K. H. Purser, R. B. Liebert, A. E. Litherland, R. P. Beukens, H. E. Gove, C. L. Bennett, M. R. Clover, W. E. Sondheim, *Proceedings* of the Second International Conference on Electrostatic Accelerators, Strasbourg, France, 24–27 May 1977.

Optical bistability

continued from page 17

passing both nonlinear absorption and dispersion.

The device can be operated in a binary mode, or it can be biased at a steep region of the input–output power curve to produce ac gain. The experimenters expect to develop "three-port" devices analogous to triodes, which may be driven in cascade.

Seeking to demonstrate the same effect in a solid, Venkatesan and McCall constructed a Fabry–Perot device with a ruby element as the nonlinear medium.[2] They drove the resonator with a liquid-nitrogen-cooled cw ruby laser at 6934 Å. The experimenters expected to find bistability at liquid-nitrogen but not room temperature because of the wavelength shifts of the relevant levels. They nevertheless observed bistable operation from 85 to 296 K; they explained the unexpected results as a laser-induced population redistribution between ground and excited states.

Both sodium and ruby experiments showed differential-gain, clipper and discriminator characteristics as well as bistability, "demonstrating the physical principles from which practical miniaturized optical memories . . . may be developed" [1] The authors foresee "a practical active component for integrated optical circuits." [1]

Another approach to obtaining nonlinearity is that of Peter Smith and Edward Turner, of Bell Labs's Holmdel facility. While the experiments at Murray Hill involve media with a nonlinear refractive index, this experiment is a hybrid approach using an electrical feedback loop. Smith and Turner placed an electro-optic crystal (of KDP, potassium dihydrogen phosphate) into the cavity of their Fabry–Perot resonator. A beam splitter sends a portion of the output beam to a detector, the amplified output of which is applied to electrodes on two faces of the crystal. The field, which varies with light intensity, modulates the refractive index of the crystal. Together with Ivan Kaminow they built an integrated version of this device using a lithium niobate crystal, which responds to incident light levels as low as 10^{-12} joules. Such a device will operate over a broad wavelength range; its switching times are limited by the response of the detector, not of the nonlinear media.

The advantages of thus creating an "artificial" nonlinearity are that

- the device can be made to operate at very low optical power, limited only by the sensitivity of the detector;
- it can be switched electrically as well as optically, and
- known techniques can be used to integrate the device.

In recent work with P. J. Maloney, Smith and Turner have also demonstrated "optical triode" operation as well as the possibility of multilevel optical logic and switching operations.

Many of the experimental findings were predicted in advance by theoretical models, which gave accurate values of operating parameters. In a study of electromagnetic waves in plasmas, John Marburger (University of Southern California) and Frank Felber (now at Gulf–General Atomic) realized, they told us, that a non-dissipative (dispersive) nonlinearity would be effective in producing a bistable device at about the same time the results of the Gibbs group became available.[4]

Marburger also told us of his current work with Elsa Garmire (Center for Laser Studies, USC) which resulted in their discovery of a new class of bistable devices, based on Smith's electro-optic approach, that do not require a Fabry–Perot cavity, can use multimode media and do not require precise temperature control. One concept, worked out in collaboration with Marc Levenson of USC, uses second-harmonic generation in a birefringent electro-optic material, with the phase mismatch between first and second harmonics tuned electro-optically. In a simpler, more general scheme, optical switches such as directional couplers are made into bistable devices.

A theoretical approach oriented towards incorporating bistability theory into a more quantum-mechanical picture has been pursued by Rodolfo Bonifacio and Luigi Lugiato, at the University of Milan.[6] Their steady-state analysis, made in the mean-field approximation, yields a number of striking results:

▸ The absorption of light in nonlinear media exhibits strong cooperative behavior.

▸ Even though the system is far from equilibrium, its behavior is analogous to a first-order phase transition.

▸ Critical slowing down is predicted at the phase-transition threshold.

This approach was extended to account for quantum fluctuations by Lorenzo Narducci and his co-workers Robert Gilmore and Da Hsuan Feng of Drexel University, together with Girish Agarwal (University of Hyderabad) in two papers presented at the June Conference on Coherence and Quantum Optics at Rochester. They showed that at the onset of this transition the relaxation time of one mode diverges (critical slowing down). They were also able to extend the analysis so as to relate it to catastrophe theory, demonstrating that the system behaves as a "cusp" catastrophe. The approaches of both the Milan and Drexel groups are general enough to include the more standard theory of lasers. —HRL

References

1. H. M. Gibbs, S. L. McCall, T. N. C. Venkatesan, Phys. Rev. Lett. **36**, 1135 (1976).
2. T. N. C. Venkatesan, S. L. McCall, Appl. Phys. Lett. **30**, 282 (1977).
3. P. W. Smith, E. H. Turner, Appl. Phys. Lett. **30**, 280 (1977).
4. F. S. Felber, J. H. Marburger, Appl. Phys. Lett. **28**, 731 (1976).
5. R. Bonifacio, L. A. Lugiato, Optics Commun. **19**, 172 (1976).

Two magnets set records for field intensity

A record for the most intense continuous magnetic field was set in February by a 254-kG solenoid and then surpassed in July by a 301-kG solenoid. Both magnets were hybrids built at MIT's Francis Bitter National Magnet Laboratory (NML). The designs were described at the 6th International Conference on Magnet Technology at Bratislava in August by the magnets' developers—Mathias J. Leupold, Robert J. Weggel and Yukikazu Iwasa, all of NML. A hybrid magnet consists of a large superconducting coil surrounding a compact water-cooled coil. The concept was proposed in 1965 by D. Bruce Montgomery of NML and Martin Wood of Oxford, as a method for efficiently generating a large magnetic field without unduly reducing the volume available for experiments in the central cavity. (The inner bore of both record-setting magnets is 3.2 cm.)

The 254-kG hybrid was built by NML in collaboration with the Faculty of Sciences of the University of Nijmegen, the Netherlands. When the hybrid began operating there (see box) in October, it was to be a major feature of the Nijmegen high magnetic field laboratory being established under the overall directorship of C. J. M Aarts. This field was produced with 4.5 MW of power. The Dutch facility will have 6 MW available continuously and 12 MW for periods of a few minutes at a time. The insert used by Leupold and his colleagues at NML to reach 301 kG employed a novel radially cooled rather than axially cooled coil in order to exploit the high power supply (10 MW) at MIT. (At best, magnetic field varies as the square root of the power.) They were able to test the new insert with the superconducting coil built for Nijmegen. NML is presently constructing its own superconducting magnet of similar design and hopes to have a 300-kG hybrid available for experiments in about one year.

The challenge in designing the water-cooled coils for both hybrids was to provide enough strength to withstand the intense magnetic pressure (amounting to nearly 60 000 lbs/in^2 for the 301-kG magnet) and adequate cooling to remove the large power dissipated. The insert for the 250-kG magnet was a pair of nested, axially cooled coils patterned after one in use for ten years. The innermost winding was made from an alloy of magnesium, phosphorus, silver and copper reinforced with an alloy of beryllium–copper, which has higher strength although lower conductivity. It was hoped that the outer coil could be simply copper because of the added strength provided by a new scheme for stacking the plates. During the initial tests of this twin coil, however, the motion of the plates was sufficiently great that the final insert sent to Nijmegen was fabricated entirely of the stronger, beryllium–copper material. Axial clamping of the coils was provided by tie rods through the plates themselves rather than by a surrounding barrel.

The problems of stress and heat are much more severe for the 301-kG radially cooled insert. A first step towards achieving the required ruggedness was to use the strongest, high-conductivity material commerically available—aluminum oxide dispersion-strengthened copper—and to reinforce it with stainless steel. Because tie rods are difficult to install in a radially cooled coil, the designers instead used iron coil extensions that become magnetized and thus provide the desired mechanical clamping. As the iron contributes 3 kG to the total field, it is even more truly a hybrid. In addition rotation between coil ends is prevented by keying rods that fit matching grooves in the two coils. The cooling system has many small parallel water passages that together add up to a large cross-sectional area. The flow enters from either end. This system worked so well that the temperature in the new design rose less than that in the Nijmegen design, even though nearly twice the heat was generated.

The superconducting coil common to both systems consists of a stack of 24, double pancake windings designed not to exceed a surface heat flux of 0.2 W/cm^2. The conductor is graded to a smaller thickness—and hence higher current density—at the outside to keep the magnet from becoming excessively large. The inner and outer diameters are 40 and 88 cm. Great care was taken to immobilize the innermost turn of the windings and to support evenly the irregular surface generated by the ribbon edges.

The high fields of the Nijmegen, MIT and other laboratories primarily support basic physics research in a variety of fields such as high-field superconductivity or semiconductor electronics. They may even be used to test superconducting materials for applications to large magnets for MHD or fusion plants. —BGL□

Nijmegen high-field research

The Nijmegen high magnetic-field laboratory began operating the 254-kG hybrid in October. Exceptionally high continuous magnetic fields allow a number of experiments to be done with ease that are either impossible or exceedingly difficult at lower fields.

▸ In high fields ω_c, the cyclotron resonance frequency of semiconductors, is raised into the infrared, so that accuracy and stability of laser interferometric techniques may be exploited. Peter Wyder at Nijmegen is collaborating with L. L. Chang and Leo Esaki of IBM Yorktown Heights to observe such resonances in semiconductor superlattices to obtain masses and mini-gaps in these materials.

▸ The amplitude of the de Haas–van Alphen effect in metals is exponentially dependent on field. Ton de Vroomen and Fred M. Mueller at Nijmegen are collaborating with Aloysius Arko of Argonne, Douglas H. Lowndes (University of Oregon) and Michael Springford of the University of Sussex to measure A-15 and C-15 materials (high-temperature superconductors) as well as non-dilute alloys.

▸ Mueller and Wyder are also planning cyclotron resonance experiments in metals, similar to those of S. James Allen (Bell Labs) and Pierre Goy (University of Paris at Orsay), to look for anisotropies of λ, the electron–phonon coupling constant in interesting materials. Because in high fields ω_c can approach ω_s, where ω_s is a critical frequency for electron scattering from excitations in the solid (phonon or paramagnon), line-shape analysis should yield new insights.

Other experiments are in progress in chemistry, biology and medical research.