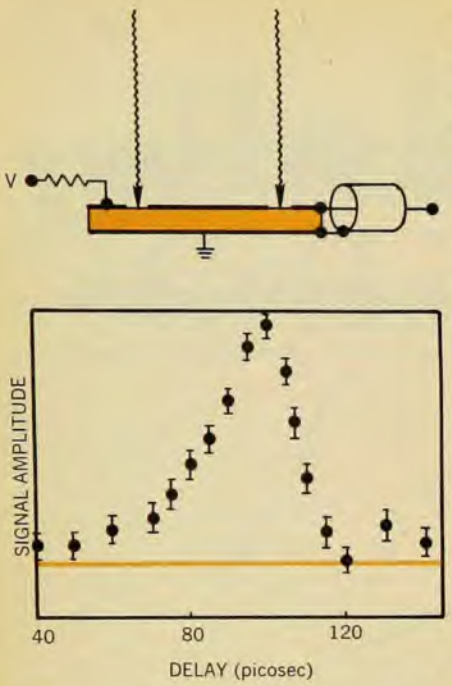

Measurement of switching speed. In left gate 0.53-micron pulse allows signal to cross gap; 1.06-micron pulse stopped it 15 picosec later. At right, a similar pair of pulses samples signal after a given delay, with result shown in the graph. The colored line is the signal that is produced without a bias.

longer wavelength pulse turns the signal off because it has a greater absorption depth and penetrates the crystal to the ground plane, shorting the line.

To measure the switching time, Auston had to build a second optical switching gate downstream from the first to sample it. His measurements indicate a switching speed from 10 to 15 picosec. Auston told us he has applied a similar technique to the generation of short bursts of microwaves, on the order of 10 picosec.

Auston looks upon the switching technique as a research tool and is himself interested in using it to study properties of high-density semiconductor plasmas. Others, however, feel it may have eventual potential for communications systems.

Ultrashort CO_2 pulses are important primarily for their applications to laser-induced fusion and to the measurement of very short lifetimes of molecular processes in the infrared. One approach to producing such fast carbon-dioxide pulses is the mode-locking method, which is used to produce most of the current ultrashort laser pulses. In mode locking, one rearranges the phase relations between axial modes of the laser. One type is active mode locking, in which a periodically driven modulator couples the modes together so that the peak power is concentrated in a train of short bursts. The other type is passive mode locking. Here, a saturable dye is placed inside the laser. It reduces the gain of the laser until there appears one peak in a noiselike signal that is large enough to saturate the dye; this pulse is then transmitted at high gain because the dye no longer affects it.

A group from the University of Essex, England, successfully used p-type germanium as a passive mode-locking element with a carbon-dioxide laser at one atmosphere of pressure.[2] Their most recent paper reports generation of a 300-picosec pulse, and describes a high-resolution detection system to measure its duration. Still shorter pulses—about 80 picosec—have been produced by John Alcock and Andrew C. Walker of the National Research Council (NRC) of Canada in Ottawa.[3] They operated the carbon-dioxide laser at pressures of 10 to 15 atmospheres, and also developed a detection system with a resolution of 40 picosec by combining the use of a streak camera with a technique of upconverting the 10-micron carbon-dioxide signal to 0.96 microns.

Alcock and Walker also tried active mode locking with an acousto-optic Brewster-angle germanium modulator and the 10- to 15-atmosphere carbon-dioxide laser but found that the pulse length was limited by the gain time of the high-pressure laser: The gain time was too short to allow the light pulse to traverse the laser cavity as many times as is required for full mode locking to occur. NRC experimenters (Alcock, Paul B. Corkum, Douglas J. James and Kurt Leopold) have also developed a technique to switch infrared pulses with pulses of visible light: The carbon-dioxide laser strikes a slab of germanium at the Brewster angle. When a 2-nanosec ruby-laser pulse shines on the crystal, it causes the light from the carbon-dioxide laser to be completely reflected, producing a pulse of 2-nanosec duration. The group feels this method can be extended to shorter pulses.

A second approach to producing ultrashort carbon-dioxide laser pulses is to exploit the very fast switching action inherent in laser-induced breakdown in gases. In this phenomenon, the laser first rapidly ionizes a neutral gas. As the ionization density increases, the index of refraction decreases toward zero, and the laser light is no longer transmitted. The plasma cutoff time is on the order of 30 picosec; exact measurements of this time are now under way. This effect was applied to the generation of ultrashort pulses by Eli Yablonovitch (Harvard).[4] He recognized that one must use the resulting step-function signal in conjunction with a spectral filter that will reject the incident laser light and transmit only the sidebands produced by sudden plasma growth. Experimenters have used various devices such as the Michelson interferometer[5] or Fabry-Perot etalon as filters, and Yablonovitch points out that each filter will produce a characteristic pulse shape. Combinations of these filters may be required to generate complicated pulse shapes such as those required for laser fusion work.

Yablonovitch and Julius Goldhar (MIT) have developed a carbon-dioxide absorption cell as a filter that they feel has a much better rejection ratio (of the transmitted to the pre-cutoff laser light) than the conventional filters.[6] The resonantly absorbing cell emits a signal that destructively interferes with the input signal prior to the plasma cutoff of the light. At the cutoff, the cell emits a signal that is no longer cancelled; this signal has a duration that is determined by the molecular collision time and by the optical thickness of the carbon-dioxide absorber. Both these factors can be adjusted by varying the gas pressure and the length of the cell, respectively. With this filter, Yablonovitch has generated picosecond pulses from laser-breakdown plasmas. —BGL

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Macroscopic yields by laser isotope separation

Laser separation has for the first time produced macroscopic amounts of isotopically enriched compounds of such elements as boron, chlorine and sulfur. Last fall experimenters at the Institute for Spectroscopy, Moscow[1] and the National Bureau of Standards[2] both described experiments on boron isotope separation from boron trichloride. An NBS group has also done work on separating chlorine isotopes. This past March the Moscow group reported their recent successes with sulfur. Shortly thereafter the Los Alamos Scientific Laboratory made public similar sulfur experiments. Results at all three places indicate that significant progress has been made since we last reported on laser isotope separation (PHYSICS TODAY, September 1974, page 17).

The people involved at the three laboratories are R. V. Ambartzumian, N.

V. Chekalin, Yu. A. Gorokhov, V. S. Letokhov, G. N. Makarov and E. A. Ryabov (Institute of Spectroscopy, Academy of Sciences, USSR); John Lyman, Reed Jensen, John Rink, Paul Robinson and Stephen Rockwood (Los Alamos Scientific Laboratory); Harry Dewey, Samuel Freund, Richard Keller and Joseph Ritter (NBS). Working with the NBS group was Michel Lamotte, who has now returned to the Faculty of Sciences of Bordeaux, Talence, France.

A feature common to the work reported by the three groups is that all are one-laser processes. Most of the earlier work has needed two lasers: one emitting in the infrared region to excite selectively one isotopic component of a mixture and a second laser, emitting in the visible or ultraviolet region, to dissociate or ionize the excited molecule. The Moscow and Los Alamos method is photophysical. They use a powerful infrared laser to dissociate one isotopic component, and they provide a chemical scavenger that may or may not be needed. The NBS process is photochemical. A visible or infrared laser excites one isotopic component, and a chemical reaction partner is provided to complete the separation. These one-laser processes are more efficient than two-laser processes. Hence—since an unspoken aim of all this work is the economical separation of uranium isotopes—the excitement.

Sulfur isotopes. In the work done at the Institute for Spectroscopy,[3] a carbon dioxide laser is focused into a molecular gas mixture and selectively dissociates one isotopic component of the mixture. This mixture is originally present in natural isotopic abundance; in the case of SF_6, this corresponds to 95% S^{32}, 0.75% S^{33}, 4.2% S^{24} and 0.017% S^{36}. The Moscow group selectively enriched either S^{34} or S^{32}, depending on which laser line they used. With the laser tuned to the $S^{32}F_6$ absorption peak at 947 cm^{-1}, they found (by measuring line amplitudes with a mass spectrometer and taking infrared spectra before and after irradiation by 2×10^3 laser pulses) enrichment ratios for the S^{34} isotope of about 2800. Here the enrichment ratio is defined as

$$K(34/32) = \frac{[S^{34}]_f/[S^{32}]_f}{[S^{34}]_o/[S^{32}]_o}$$

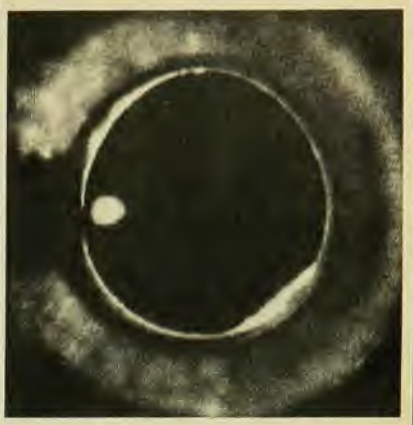
where f refers to final concentrations and o to original. After 100 pulses, they had produced 0.1 mg of SF_6 with a twentyfold increase in concentration of S^{34}.

The laser used produced power densities of $1–2 \times 10^9$ watts per cm^2 in a focal length of about 25 cm, with a 90-nanosecond pulse length. This intensity, the authors note, is one at which noncollisional dissociation usually occurs. When they tuned their laser to the $S^{34}F_6$ peak, they found $K(^{32}/_{34})$ to be 1.7 after 30 pulses and 18 after 500 pulses. When they compared irradiation of a cell containing only SF_6 with irradiation of one containing SF_6 along with H_2, NO or HBr as possible scavengers, they found no qualitative difference. This observation, they say, indicates the first reported case of a *physical* separation, not dependent on the dissociated species undergoing a chemical reaction with some third species. Unlike the same group's earlier work with boron,[1] no visible luminescence is seen. The experimenters attribute this difference to the SF_5 radical being formed in a nonexcited state, rather than to any fundamental difference in mechanism here.

The Los Alamos group[4] has also isotopically enriched SF_6 in the presence of H_2. Their laser is as powerful as that used by the Moscow group, but reached this power over a shorter distance; that is, the effective volume of SF_6 irradiated with each pulse was smaller. Pulse length was 200 nanosec, more than twice as long as for the Moscow group. The Los Alamos group achieved a K (which they call β) of about 33 for S^{34} after about 3000 pulses. Enrichment per pulse is much less than achieved by the Moscow group. Work at Los Alamos has been extended to boron (BCl_3), carbon (CF_2Cl_2) and silicon (SiF_4)—with various scavengers—with enrichment ratios after 1000 pulses of 1.5, 1.6 and 1.2. Gas pressures ranged from 1 to 10 torr, and the laser pulsed twice per second giving irradiation times of the order of 10 minutes. The aim here, Rockwood explained to us, is to show that the method is generally applicable to other polyatomic molecules.

Boron and chlorine. The studies at NBS were somewhat different, although here too a CO_2 laser has been used for some isotope separation work, in which the experimenters enriched thiophosgene ($CSCl_2$) in each of two chlorine isotopes.[5] The laser emission here excites rather than dissociates the molecules, and the excited molecules then react with a chemical reaction partner present in the cell.

For enriching chlorine isotopes, the partner is diethoxyethylene, C_2H_5O-$C_2H_2OC_2H_5$. To enrich the $CSCl_2$ in Cl^{35}, the mixture was irradiated with a 70-mW continuous-wave argon laser, whose emission at 4657.84 Å coincides with an absorption peak for $CS^{32}Cl_2^{37}$. After several hours, the enrichment was from 75% Cl^{35} to 80% Cl^{35}. For enrichment of Cl^{37}, the $CSCl_2$ was irradiated with 4705.5-Å light from a tunable dye laser. Average power was about 10 mW and peak power 50 kW. After five hours of irradiation, the Cl^{35} isotope was depleted to 64%. Noting that their results are below what would be expected for "pure" reactions of one isotope or another, the NBS group suggests that energy transfer or scrambling between species may cause the inefficiencies.



Electron-hole drop in germanium has been photographed for the first time by a group at the University of California, Berkeley, and the Lawrence Berkeley Laboratory. The drop was formed by applying a nonuniform stress to a single crystal of germanium (seen as a disc in the photo). When an Ar–Kr laser is focused onto the crystal, a single large electron–hole drop (the bright ring at the left) forms at the point of minimum drop energy. The photo was obtained by focusing the 1.75-micron recombination luminescence onto a lead-salt photoconductive surface (a vidicon tube). Drop lifetime is about 490 microsec. The existence of electron–hole drops was first proposed by L. V. Keldysh in 1968 to explain a sharp increase in the photoconductivity of germanium, and smaller droplets have been produced experimentally before the Berkeley work. The Berkeley group includes James Wolfe, William Hansen, Eugene Haller, Robert Markiewicz, Charles Kittel and Carson Jeffries. This photo first appeared in *Phys. Rev. Letters* **34**, 1252 (1975).

For boron enrichment, results appeared to be more efficient.[2,6] The BCl_3 was placed in a cell with H_2S and irradiated with a CO_2 laser at either 10.55 microns to increase the B^{10} concentration or 10.18 microns to increase the B^{11} concentration. The result is macroscopic, milligram quantities of enriched BCl_3. The laser produced about ten 300-nanosec pulses per second, with 0.1 joule per pulse. After five hours of irradiation at 10.18 microns, the B^{10} concentration is lowered from 19.5% to 14.4%, and after ten hours at 10.55 microns, the B^{10} concentration is increased from 19.5% to 29.2%. The separation methods allow enriched BCl_3 to be recovered after a single irradiation step, suggesting that it may be efficiently recycled to achieve greater enrichment.

Simple experiments. The link between these laser separations is their experimental simplicity (there are reports

that the SF_6 work has already been duplicated in a dozen or so laboratories since the work from the Soviet Union was published) and promise of energy efficiency. The work with SF_6 particularly brings to mind UF_6, the uranium compound from which U^{235} is usually separated. However, the mechanism by which the laser radiation is absorbed in the processes just described apparently requires a fairly large separation between isotopic absorption peaks, and a good deal of work remains to be done before the mechanism can be understood.

Multiple photon absorption, the term used to describe what occurs, refers to two processes: The molecule can apparently absorb as many as, say, 40 photons *successively* in a single laser pulse, going up the vibrational ladder until it dissociates, or, the molecule can *simultaneously* absorb the photons, with virtual intermediate states. Of course, there are other possibilities as well. At least for the case of the Soviet and Los Alamos work, a better term may be "collisionless dissociation." In any case, multiple photon absorption apparently requires a polyatomic molecule, with sufficient density of states, explained Rockwood (Los Alamos), that internal vibrational conversion can keep the molecule "on resonance" for the laser frequency. Irrespective of any possible application to uranium separation, then, these experiments are of fundamental scientific interest. —MSR

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Blackbody radiation

continued from page 17

ground have been particularly persistent. This persistence has been necessary for two main reasons: the difficulty of measuring the peak region with any great sensitivity, and interference from "earthshine"—emission by the atmosphere and hot objects that might be in the field of view—possibly as much as 30 000 times brighter than the sought-for signal.

A long list of experimenters have tried to measure the submillimeter background and have met with varying degrees of success. Most of the equipment packages have been sent up in rocket or balloon flights, although a few have been ground based. An advantage of rocket flights over balloon flights is that they can avoid atmospheric interference; the disadvantage, however, is the much shorter observation time (of the order of minutes rather than hours), and poorer signal-to-noise ratio. Some of the more successful past measurements have been made by groups from Cornell University, Los Alamos Scientific Laboratory and the Massachusetts Institute of Technology.

The Cornell group (James Houck, Thomas Soifer, Martin Harwit, Judith Pipher) has reported[3] results from rocket studies consistent with a 2.7-K blackbody, although earlier work from the same group had found excess radiation in the 0.4–1.4 mm (25–7 cm^{-1}) region. In 1973, the Los Alamos group (Kenneth Williamson, Allen Blair, Lloyd Catlin, Richard Hiebert, Eugene Loyd and Harold Romero) reported[4] a rocket-borne experiment that gave similar results, and that same year, Dirk Muehlner and Rainer Weiss (MIT) described[5] a set of balloon flights from which they obtained crude measurements. They used radiometers for the spectral density at regions both below and at the blackbody peak and determined an upper limit in the region above the peak which showed that a peak did indeed exist. At that time, Muehlner and Weiss commented that all these direct measurements of the submillimeter background agreed among themselves, but that it had not yet been possible to establish the shape of the spectrum above 12 cm^{-1}—even to the extent that the data above 12 cm^{-1} were also consistent with no energy at all in the background radiation.

The Berkeley experiment. That situation remained unchanged until the latest studies. Richards and his group at Berkeley used a fully calibrated spectrophotometer in the infrared region below 3 mm; the earlier studies had measured the integrated radiation over broad spectral bands. For the first time, the experimenters were able to measure the atmospheric spectrum and untangle its component gases. Separating the atmospheric and background contributions has been a problem in all the submillimeter experiments with balloons.

The radiation was collected in a conical antenna, open to the atmosphere, which was cooled with liquid helium to minimize emission. The balloon work of Muehlner and Weiss had shown that a window was not needed at high altitudes to avoid "frosting"—the efflux of helium gas keeps the region clear. The emission from a plastic window complicates the data analysis, so the Berkeley group was pleased to do without it. A polarizing Michelson interferometer, also liquid-helium cooled, served as a Fourier spectrometer, and a germanium bolometer illuminated with germanium immersion optics was the detector. The balloon launch took place on the evening of 24 July last year, and the data were taken at 39 km altitude. They measured 23 spectra with a resolution of 1.4 cm^{-1} for 69 minutes and two spectra with a resolution of 0.28 cm^{-1} for 24 minutes.

A key feature of the experiment, in addition to the spectrometer, was the careful measurement of the angular response of the antenna: Although the antenna was pointed upwards, the diffraction effects cannot be ignored, and careful design is required to minimize earthshine. The residual earthshine here was determined, by tipping the apparatus, to be less than the noise. To analyze their data, the Berkeley group used a model incorporating the cosmic background and the atmospheric emission, with a total of four adjustable parameters: the temperature of the blackbody spectrum and the column densities of water, ozone and oxygen. The calculated spectrum that gave the best fit to the observed data was for a blackbody temperature of 2.99 K, with fitted values for the three atmospheric gases that agree well with other measurements at similar elevations. The blackbody spectrum is then the difference between the measured night-sky spectrum and the atmospheric contribution; essentially, a small difference between two large numbers. But the error limits are such that the existence of a thermal spectrum between 4 cm^{-1} and 17 cm^{-1} has clearly been established.

Paul Richards tells us that the group is now planning improvements in the experiment. They plan to launch another balloon within the year, with an anticipated improvement in accuracy of a factor of three to five. In the more distant future, such measurements might become possible from satellites.

—MSR

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