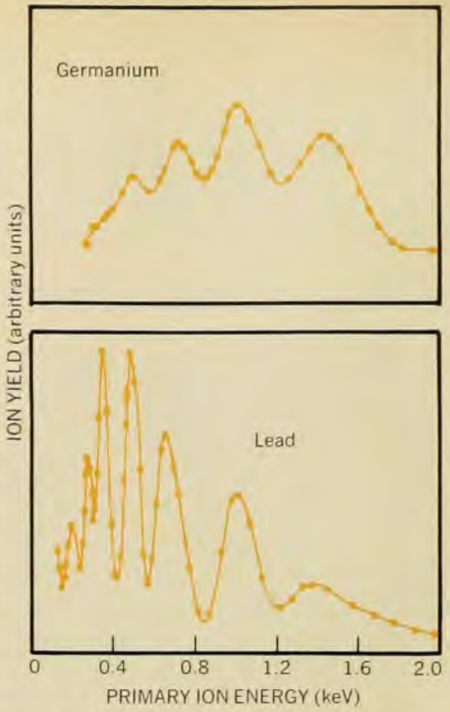
heights as a function of energy. In their own experiments, Erickson and Smith worked at a much finer energy scale. They bombarded a target surface (usually a transition metal) with noble-gas ions at a 45-degree angle and detected the ions that were scattered 90 deg. The fine structure was discovered by varying the energy of the incoming ion (usually He^+) between 0.2 keV and 2 keV, at each step tuning the detector to the energy associated with scattering from the target surface. The resulting plots of scattered-ion current versus energy show a series of peaks, with a pattern of oscillations that is characteristic of the target surface in both amplitude and location. The plots also show some evidence of chemical shift.

Why do the scattering cross sections vary with the energy of the incoming particle? According to Erickson and Smith, the velocity of the incoming ion affects the collision interaction time—the time during which the incident ion and the surface share their electrons, when the incident ion can capture one of the electrons of the surface atom before the ion scatters away. If the ion velocity is sufficiently large, the collision time will be of the right magnitude for a capture to occur, and the resulting neutralization is seen as a decrease in the detected ion yield. For a somewhat lower velocity, the electron can transfer to the ion and back again, with no decrease in the yield. At progressively lower velocities, a succession of charge-transfer events takes place, with ion-yield minima resulting at those velocities for which the end result is a neutral particle. This mechanism is fairly well established as accounting for oscillatory cross sections in gas collisions; the novelty here is its application to collisions at a surface. To test the velocity dependence, Erickson and Smith used $(He^3)^+$ and $(He^4)^+$ ions; both species gave the same result when scaled for mass difference.



Oscillations in ion yields resulted when helium ions were scattered from a variety of surfaces including lead (bottom) and germanium (top). The experimenters, Robert Erickson and David Smith (3M Company) attribute these oscillatory cross sections to the formation of quasimolecular states with electron transfer during the scattering. (From reference 1.)

Critics of the results note that the experimenters neither give an estimate of the expected cross sections nor say much about the nature of the resonant state. What Erickson and Smith do say is that their systems satisfy the initial-state–final-state degeneracy condition required in order to have quasiresonant charge transfer occur: Those elements that show the oscillatory cross sections (gallium, germanium, indium, tin, antimony, lead and bismuth) all have d-electron energy levels within 10 eV of the helium first-ionization energy (24.6 eV), whereas those elements with greater separation show no such structure. The critics comment that it is difficult to picture a quantum-mechanical phase interference (leading to crossover between energy levels of the two particles) occurring with such a low-energy projectile. Alternative explanations include multiple (as opposed to binary) scattering or ion losses through channeling. But Norman Tolk (Bell Laboratories, Murray Hill), who has done work in gas collisions,[2] tells us that he and John Tully have done some preliminary calculations for level crossing in systems similar to those studied at 3M and have found answers of the right order of magnitude.

Questions about the oscillations can most likely be cleared up with further experiments. These might include doing an angular scan—keeping the energy of the incident particle constant while varying the scattering angle; detecting the scattered neutrals, which may come off in an excited state; looking at the Auger electrons that could be given off by the surface atom when neutralization occurs; changing the incoming particle to vary the ionization energy. —MSR

References

1. R. L. Erickson, D. P. Smith, Phys. Rev. Lett. 34, 297 (1975).
2. N. H. Tolk, C. W. White, S. H. Neff, W. Lichten, Phys. Rev. Lett. 31, 671 (1973).

Excitation-transfer nitrogen lasers

A high-power, high efficiency laser with a wavelength in the visible or near-ultraviolet would be very desirable for such proposed applications as laser-induced fusion and isotope separation. Demonstration models of systems that might lead to this goal have been recently reported from the Naval Research Laboratory, Northrop Corporation, the University of Texas at Dallas and the Lebedev Physics Institute in Moscow. All these systems employ electron-beam energy deposition; they all use rare-gas and nitrogen mixtures, and they lase at wavelengths in the 3000–5000 Å range with efficiencies around 2%. At Los Alamos work is proceeding on a somewhat different approach that attempts to increase the output pulse length of lasers of this type.

The big question for all these systems is, Can the demonstration models be scaled up in size and pressure to produce the necessary output-energy per pulse (10^4–10^6 joules/pulse for laser-induced fusion, for example) without losing efficiency?

Pulsed electron-beam sources with power outputs of many gigawatts, electron energies around 1 MeV and pulse widths measured in nanoseconds are available commercially, off-the-shelf. Such an electron beam provides a particularly efficient way of storing energy in a gas (by electron ionization), and, if a reasonable fraction of this stored energy can be directed toward populating an appropriate energy level, an efficient pulsed laser should be the result.

The rare gases give very favorable energy-conversion efficiency, and there is a further advantage that their reactions have been well studied and have accurately known kinetics. The gas chosen is argon for the NRL, Northrop and Lebedev lasers and helium at UTD. In each case a high pressure, up to 7 atmospheres, provides a sufficiently dense target to the electron beam that a large part of its energy is deposited in the ionized gas; about half of the energy from the electron beam goes to produce dimerized rare-gas ions and excited states of atoms.

Molecular nitrogen has excited states suitably spaced for stimulated emission in the wavelength range desired—3000 to 5000 Å. So the next step is to add a little nitrogen and find the best mechanism for transferring the excitation energy from the ionized rare gas to molecular nitrogen, populating the upper state of the laser levels as efficiently as possible. It is at this stage that opinions diverge as to the best excitation-transfer mechanism to choose—by appropriate selection of the rare gas and manipulation of the nitrogen partial pressure—for the most efficient, scalable, laser.

Argon-nitrogen lasers. The first successful $Ar–N_2$ laser was demonstrated by Stuart K. Searles at the Naval Research Laboratory[1] in September 1973. The mechanism, first suggested by W. R. Bennett in 1962,[2] starts with argon ions and proceeds:

$$Ar^+ + 2\,Ar \rightarrow Ar_2^+ + Ar$$
$$Ar_2^+ + e \rightarrow Ar^* + Ar$$
$$Ar^* + N_2 \rightarrow N_2^*(C) + Ar$$
$$N_2^*(C) \rightarrow N_2^*(B) + h\nu$$

Searles observed strong laser emission at 3577 Å, and somewhat weaker emission at 3805 Å, corresponding to the transitions C $(^3\Pi_u)_{\upsilon=0}$ to B$(^3\Pi_g)_{\upsilon=1}$ and $C_{\upsilon=0}$ to $B_{\upsilon=2}$, respectively.

Searles's electron-beam generator produced 50 nanosecond pulses of 500-keV electrons. Peak power of his laser was 200 kW at a gas pressure of 4000 Torr. The highest efficiency was 0.4% at a lower pressure, 1000 Torr; the most effective gas mixture contained 5% of nitrogen.

Meanwhile George Hart of NRL and, independently, Don Lorents and his colleagues of Stanford Research Institute completed examinations of the kinetics of the processes involved. Lorents's model[3] contains many other reactions competing with those quoted above—31 reactions altogether. The theoretical maximum efficiency is 1–2% with this model, which does not include the effects of the laser field or electron collisions, and Lorents says "there is no way, within the restrictions of this model, that it can be made any higher." The problem is that a larger fraction of the transferred energy goes into the lower $B_{\upsilon=0}$ state than into the upper C state. This explains why the laser does not operate on $C_{\upsilon=0} \rightarrow B_{\upsilon=0}$. Besides, the upper state (which has a lifetime of only 40 nanoseconds) is collisionally quenched more rapidly than the lower state, leading to additional inefficiencies.

At the same time, Mani L. Bhaumik and Earl Ault of Northrop[4] built a similar Ar—N_2 laser, which they claim was the first high-power laser of this type; it operated at 0.5% efficiency and developed a power of half a megawatt. When they incorporated a more powerful electron beam—a Physics International Pulserad yielding 3 MeV electrons in a 60-nanosecond pulse—and increased the pressure to 7000 Torr they observed lasing, primarily at 3577 Å, with an output of 10 MW. Their efficiency is up to 2%, and "sometimes a little higher." They hope to go to 4%, an efficiency they believe will be predicted by models that take into account the effect of the laser field in the cavity.

Currently Ault is working on a "table-top" model, a laser only 20 cms long and weighing 100 lbs, with about 300 kW peak power. Pulsing at the rate of one per second, it operates at 2.8% efficiency. The primary energy source is a capacitor bank.

A group at the Lebedev Institute led by Nikolai Basov[5] has also reported an $Ar–N_2$ laser that operates on the same principle as those at NRL and Northrop. With a 600-keV, 20-nsec electron beam pulse and an $Ar–N_2$ pressure of 7000 Torr, the Lebedev group attained a specific power output of 45 kW/cm^2; efficiency at 1000 Torr is claimed to be 3%.

The quoted efficiencies of all these lasers is the ratio of the laser power to the power injected by the electron beam into the active region. Difficulties of estimating this "active volume" accurately render the claimed efficiencies rather uncertain.

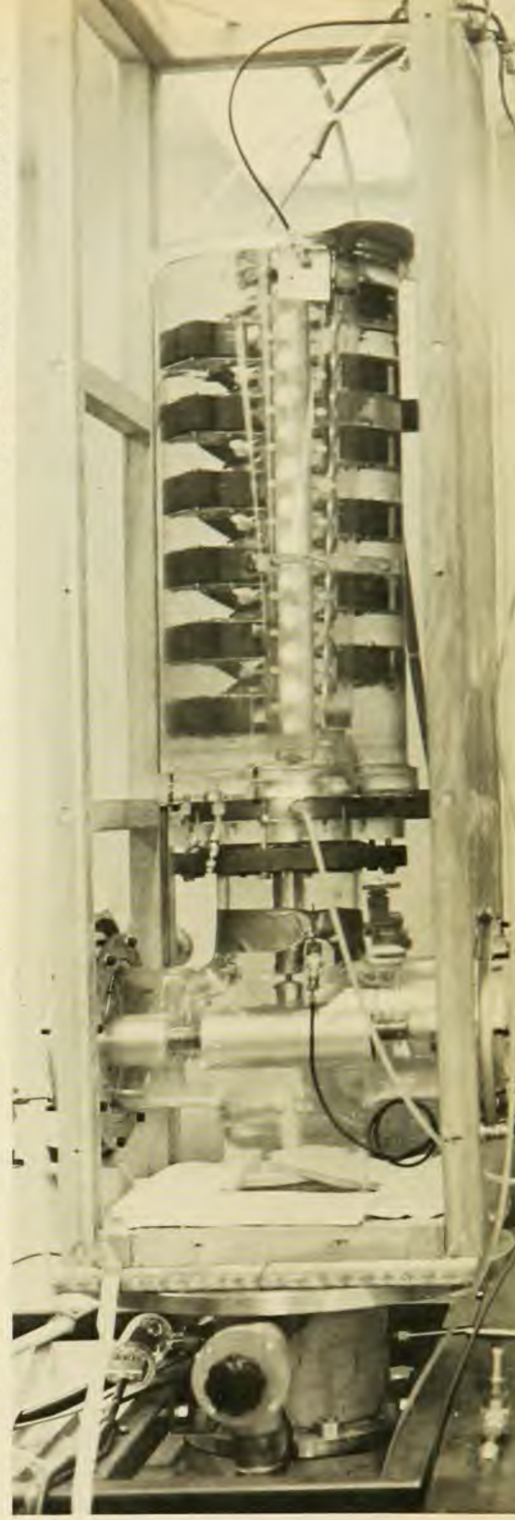
The charge-transfer laser. Carl Collins and Austin Cunningham at the University of Texas at Dallas have taken a different direction. Noting the very high cross sections for charge transfer at low collision energies, they proposed a laser in which excitation is stored in dimerized helium ions, He_2^+, and transferred to nitrogen thus:

$$He_2^+ + N_2 \rightarrow N_2^+\,(B^2\Sigma_u^+) + 2He$$
and
$$He_2^+ + N_2 \rightarrow N_2^+\,(X^2\Sigma_g^+) + 2He$$

The lasing transition is from the $^2\Sigma_u^+$ state to the $^2\Sigma_g^+$ state, provided the charge-transfer reaction populates the upper state preferentially (see figure on next page).

A pilot model proved that lasing does occur in this system, and a larger version has recently been completed.[6] It has an APEX-I electron gun (by Systems, Science and Software) that produces 950-keV electrons in 20 nanosec pulses; 3MW output at 4278 Å has been measured, at an efficiency estimated to be 2%. This is for the 0 → 1 vibrational transition. The 0 → 0 and 0 → 2 vibrational transitions also lase, at wavelengths of 3914 and 4709 Å respectively. Cunningham told PHYSICS TODAY that "the system is scaling as expected"—at higher gas pressures than the present 7000 Torr (with 2–20 Torr N_2) they expect to approach the theoretical efficiency of 6.8%.

Kinetics of the charge-transfer laser are not as well established as they are for the $Ar–N_2$ system, and it remains to be seen whether it will scale up in energy without running into some kind of unexpected difficulty, as did the xenon excimer laser. A couple of years ago, reports from the Lebedev Institute of a xenon laser (at about 1700 Å) with particularly good efficiency caused great excitement after a small demonstration model showed that lasing did occur. However, it turned out that an absorption photoionization of an upper state competes with the stimulated-emission process, and the system is not scalable to higher powers.



"Table-top" 300-kW argon–nitrogen laser built at Northrop Corp labs. The vertical structure is a Marx generator; the laser tube is the bright horizontal cylinder near the bottom of the device. The beam emerges at right.

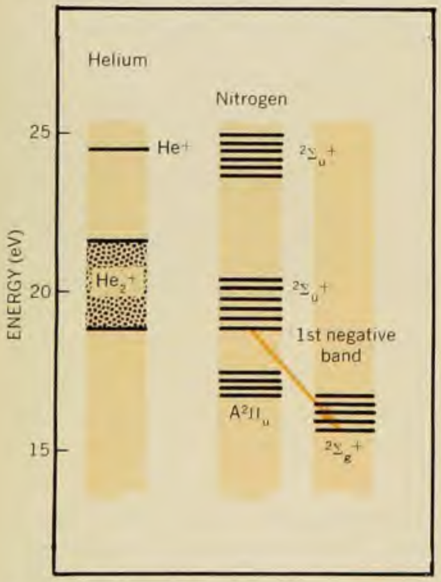
At Los Alamos, meanwhile, Ed O'Hair and Irving Bigio are examining the potentialities of nitrogen lasers as pumps for dye lasers around 3900 Å, for isotope separation. For this application they are particularly interested in increasing the pulse length to something like a microsecond, while maintaining high efficiency and high power output. Addition of SF_6 to a pure nitrogen electrical-discharge laser appears to have the desired effect, although the reason is not completely clear yet—perhaps the SF_6 quenches the lower laser state or possibly as an electronegative gas it controls the initiating discharge in such a way as to lengthen the pulse. Preliminary data obtained by Steve Suchard at Aerospace Corp., a subcontractor to Los Alamos on this project, show that in a "pin" laser (a transversely excited electron-beam laser in which a row of needle points controls the discharge) with nitrogen and SF_6, the pulse length can be extended to 400 nsec—ten times longer than the pulses without SF_6—at an efficiency said to be "high."

Bigio told PHYSICS TODAY that there is "a good chance of high power, long pulses and scalability" with this design—a sentiment echoing that of all the other physicists we talked to. It remains to be seen which, if any, of these lasers will fulfill its expectations, and during the next year or so we should know.

—JTS

References

1. S. K. Searles, G. A. Hart, Appl. Phys. Lett. 25 79 (1974); S. K. Searles, Appl. Phys. Lett. 25 735 (1974).
2. W. R. Bennett, Ann. Phys. 18 367 (1962).
3. R. M. Hill, D. J. Eckstrom, R. A. Gutchek, D. L. Huestis, D. C. Lorents, D. Mukherje, H. H. Nakano, Bull. Am. Phys. Soc. 19 No. 2, 153 (1974).
4. E. R. Ault, M. L. Bhaumik, N. T. Olson, IEEE J. Quant. Elect. 10, 624 (1974).
5. N. G. Basov, V. A. Danilychev, V. A. Dolgikh, O. M. Kerimov, A. N. Dobanov, A. F. Suchkov, Sov. Phys.—JETP Lett. 20 53 (1974).
6. C. B. Collins, A. J. Cunningham, S. M. Curry, B. W. Johnson, M. Stockton, Appl. Phys. Lett. 24 477 (1974); C. B. Collins, A. J. Cunningham, M. Stockton, Appl. Phys. Lett. 25 344 (1974).



Energy levels in ionic states of helium and molecular nitrogen. In the lasers being developed at the University of Texas at Dallas, energy is stored in dimerized helium ions, He_2^+, and transferred to nitrogen by a charge-transfer process. The lasing transition is shown here by a colored line: wavelength is 4278 Å.

Radio-wave deflection

continued from page 17

Brans–Dicke theory, which adds a scalar field with coupling constant ω to Einstein's tensor theory,

$$\gamma = (1 + \omega)/(2 + \omega)$$

Fomalont and Sramek believe that their results rule out any theory in which ω is less than about 23; they then note that for such a high value of the coupling constant, the scalar–tensor and Einstein theories are not very different, even in what they say about the early stages of the Universe or near massive objects. (Robert Dicke has most recently proposed[2] that ω has a value of 7.5.)

The Green Bank interferometer consisted of three steerable 85-foot antennas and one steerable 45-foot antenna. The larger antennas are fairly close to each other (maximum separation 2.7 km); the smaller is about 35 km distant and is connected to a control building by a phase-stable radio link. By correlating the signals of the 45-foot element to each of the 85-foot elements, three baselines of about 35 km are formed. The observations were made simultaneously at 2695 MHz and 8085 MHz on twelve days between 29 March and 25 April 1974. Each observing day was 9½ hours long and followed an identical schedule—0119, 0116, 0111, 0116, 0119 . . . .—with each observation lasting about six minutes and 1½ minutes needed to switch. Source 0116+08, then, which undergoes the largest deflection, was observed every 15 minutes, 38 times each day, and each comparison source was observed every 30 minutes. The experimenters report a relative positional accuracy of .04 arc sec among the sources. They are scheduled to repeat their experiment this month.

Dual frequency. Two features distinguish the latest NRAO experiment from most other radio-interferometric studies: the treatment of coronal bending and the use of three collinear radio sources. The solar corona bends radio waves more strongly than it bends visible light, so coronal bending has presented problems. Because Fomalont and Sramek observed at two frequencies, they were able to separate the bending caused by the solar corona, a frequency-dependent effect, from the relativistic bending, which is independent of frequency. At the same Dallas meeting, the group working at Westerbork described their own dual-frequency studies (with a much shorter baseline), which had an error of about 3.3%.

As have most others who have studied solar deflection, the Netherlands group observed two quasistellar radio sources, 3C 273 and 3C 279, one of which (3C 279) passes close to the Sun each year on 8 October. In this method of calibration, the difference in the interference-fringe phase between the two sources is assumed to be a measure of their angular separation. According to Fomalont and Sramek, their own use of three nearly collinear sources allowed them to correct for that part of the interference-fringe phase that is caused not by coronal or relativistic bending but by arbitrary, time-related (such as changes in cable path length or in receiver electronics) or time-and-direction related (water-vapor clouds, antenna movement, earth tides) shifts. The closest source to the Sun was 0116+08, and the two outer sources (0119+11 and 0111+02) were the calibrator sources. They averaged the interference-fringe phase of the outer sources and compared this phase with the phase of the occulted source so that the effective angular separation between 0116+08 and its calibrator is very small.

The Haystack–NRAO observations[1] were the first accurate application of very-long-baseline interferometry (VLBI) to test general relativity. This was a collaborative effort of scientists from three institutions: the Massachusetts Institute of Technology (Counselman, Kent, Knight and Shapiro), the Goddard Space Flight Center in Greenbelt, Md (Clark) and the Haystack Observatory (Hinteregger, Rogers and Whitney). They used two antennas at Haystack and two at Green Bank, about 845 km distant, to form two long-base-line interferometers, one directed at 3C 273 and the other simultaneously at 3C 279. They report a gravitational deflection of 0.99 ± 0.03 times the Einstein prediction.

The advantage of VLBI, Shapiro points out to us, is that because each signal is recorded independently, the baseline can be longer than in conventional or "short" baseline interferometry, which uses a direct electrical connection between the receivers. Since accuracy is roughly proportional to baseline length (up to several thousand kilometers), he continues, VLBI will eventually win out, although at present the short-baseline technique is competitive.

—MSR

References

1. C. C. Counselman III, SM. Kent, C. A. Knight, I. I. Shapiro, T. A. Clark, H. F. Hinteregger, A. E. E. Rogers, A. R. Whitney, Phys. Rev. Lett. 33, 1621 (1974).
2. R. H. Dicke, Science 184 419 (1974). □