Laser enrichment process called proliferation resistant

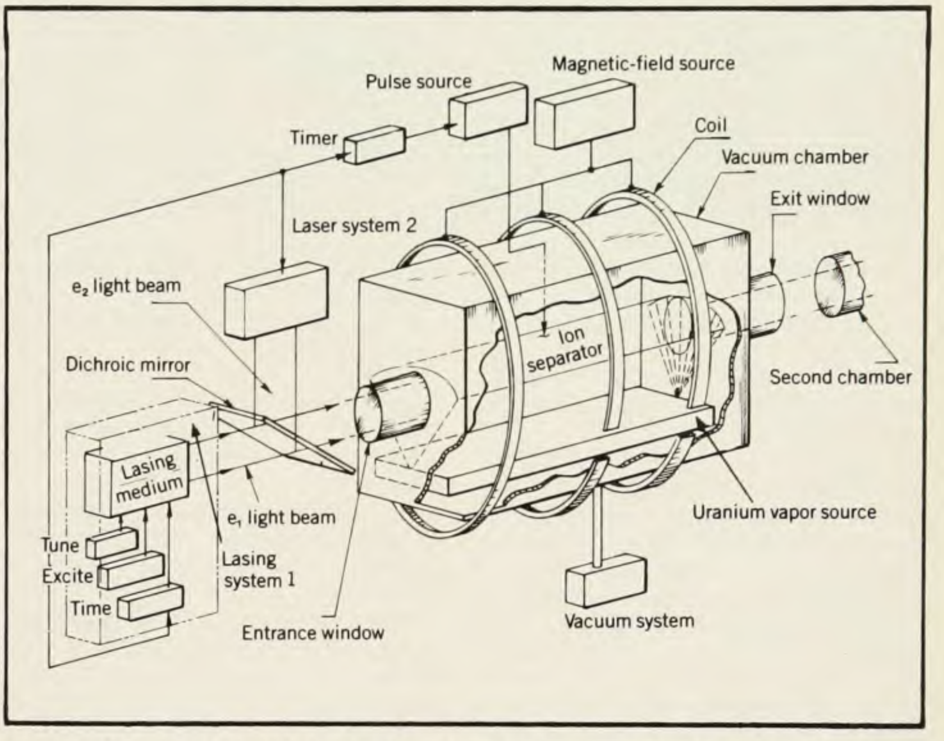
Although many technically advanced nations are attempting to develop laser isotope separation of uranium, detailed information has always been difficult to obtain. Much of the work is classified because of its potential weapons applications; still other work is considered "company confidential" by the industrial firms involved.

Last year, in a highly unusual move, Exxon Nuclear Company and Avco Corporation convened a group of 12 experts in science, foreign policy and arms control to evaluate a laser isotope separation process being developed by their wholly owned subsidiary—Jersey Nuclear-Avco Isotopes Inc (JNAI). This Laser Enrichment Review Panel, headed by T. Keith Glennan (and including Peter Auer, Hans Bethe, Harvey Brooks, Richard Garwin and Gerald Tape), recently concluded that the JNAI process, were it to be developed commercially in the US by JNAI, "would be consistent with US nonproliferation objectives."

Since 1971, JNAI has spent $50 million in developing their uranium enrichment technique, which is based on an invention of Richard H. Levy and G. Sargent Janes (US Patent 3 772 519, granted 13 November 1973). Some discussion of the atomic vapor technique has appeared in the open literature,[1] but in September 1977 the Department of Energy retroactively classified the JNAI project. The project uses selective excitation and ionization of atoms in multiple steps.

Selective excitation and ionization of rubidium atoms was reported[2] by V. S. Letokhov and his collaborators at the Institute for Spectroscopy in Moscow in 1971. Letokhov points out (PHYSICS TODAY, May 1977, page 23) that an Avco Everett Laboratory group did similar experiments with uranium atoms later in 1971 but did not report[1] their results until 1975.

Because JNAI is nearing the stage where it has to decide whether to invest $50 million more on an Experimental Test Facility for integrated testing of prototype components, the firm undoubtedly wanted indications from the US government that JNAI would not be prevented from developing its enrichment process commercially. No definitive decisions are available at this writing.



Atomic isotope separation technique used by JNAI. The laser system sends pulses into the vacuum chamber, which contains a uranium vapor source and an electromagnetic type of ion separator to remove U^{235} ions from the neutral U^{238} backgound vapor. (Figure from a JNAI patent.)

The uranium-enrichment processes now in use leave significant amounts of U^{235} in the process waste stream. U^{235} from these depleted tails stands a good chance of being recovered economically from some method of laser isotope separation.

Both Los Alamos and Livermore have large laser isotope separation programs, but results on uranium are rarely discussed. Livermore has been doing experiments with atomic vapor, and in 1974 (PHYSICS TODAY, September 1974, page 17), reported using a technique similar to that of Levy and Janes. Los Alamos has been emphasizing the molecular approach and in 1976 reported making slightly enriched uranium with UF_6; however experimental detail was withheld.

In addition to the atomic process being developed by JNAI, Exxon is said to be working on a laser isotope separation process involving molecules at its research and engineering center in Linden, N.J.

Janes, who is vice president for isotope research at Avco Everett Research Laboratory, recently told us, "Unfortunately, perhaps because of classification and proprietary requirements, the open literature tends to be unrepresentative of the real situation wherein a significant fraction of the problems involve tough engineering requirements rather than clever physics. This is particularly true of the atomic processes and has led to the publication of a number of papers suggesting schemes which concentrate on solving the wrong problems."

The JNAI approach takes advantage of the fact that the absorption lines of U^{235} and U^{238} atoms have very small shifts in some transitions in the visible range (roughly one-fourth of a wave number or 3×10^{-5} eV), which are, however, larger than the bandwidths of individual transitions for each isotope. By choosing the right transitions, a collection of lasers can be tuned to make the shifted absorption wavelengths accessible to selective excitation and ionization. JNAI uses four different wavelength dye lasers. [Has JNAI found another solution to the four-color problem?]

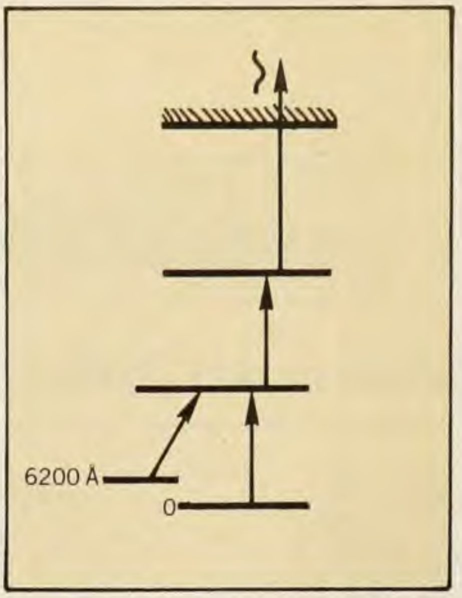
Primarily because of its high Z, uranium has one of the most complex optical spectra of any element. Janes, Harold K. Forsen and Levy note[3] that in uranium over 900 levels and 9000 transitions have been identified; perhaps as many as 300 000 visible lines are present. As the Glennan report notes, identifying the specific transitions useful for isotope separation is time consuming and exacting. So, the report goes on, the frequencies used by JNAI are classified. A further difficulty is to produce and maintain precisely tuned light to less than one part in 10^5 and still cover the entire U^{235} absorption spectrum for a selected transition.

As shown in the figure on page 17, taken from one of the 35 existing JNAI patents, the laser system sends carefully tuned and timed pulses into the vacuum chamber, which contains both a uranium-vapor source and an electromagnetic or plasma type of ion separator to remove U^{235} ions from the neutral U^{238} background vapor. Because collisions limit the vapor density, one needs a long path length for a reasonable fraction of laser light to be absorbed. So in practice the process would have several such modules.

The module is surrounded by a 100–200 gauss magnetic field parallel to the laser beams; the magnetic field is needed for both the vapor source and the electromagnetic ion extraction process. A preferred approach is to use four lasers, in which three are for excitation and one for ionization. Three-step processes allow the use of lasers in the red–orange portion of the spectrum, where dyes are more efficient. Such a three-step, four-color process is shown in the figure at the top of this page.

The vapor source is a water-cooled crucible plus a high-energy electron beam that is focused by the magnetic field along a narrow line on the surface of molten uranium. The electron beam heats the uranium to 3000 K, producing a vapor that is then allowed to expand radially to speeds comparable to that of sound. After the vapor enters the ion extraction structure, it is illuminated by the laser beams. Once the U^{235} atoms are selectively ionized, an electrical pulse is applied to the ion deflector plates. The resulting electric field produces electron currents within the vapor which, together with the magnetic field, deflect ions out of the neutral stream onto the product collection surfaces. Provided the density is low enough that neutral-ion collisions can be neglected, the neutral vapor will continue to flow through the ion-extraction structure and collect on the tails-collection surface.

For a high U^{235} ionization probability, the laser energy needed for each laser step is fairly high—tens of millijoules per cm^2. Thus, the lasers are pulsed—10 000 pulses per second. An average power for the laser system of several kilowatts is required. Assuming a 0.2% efficiency, megawatts of input power would be needed.



A preferred approach for atomic separation uses four lasers—three for excitation and one for ionization. Three-step processes allow the use of lasers in the red–orange part of the spectrum, where dyes are more efficient than in other portions of the spectrum.

In the JNAI experiments, single-stage product enrichments of 6% were produced[3]—the limit imposed by scattering considerations.

The JNAI program is aimed at producing low enriched uranium (2–3% U^{235}) for use as a light-water reactor fuel. It would operate in a single stage. To make highly enriched uranium would probably require cascading.

If JNAI decides to go ahead with its Experimental Test Facility, according to Harold K. Forsen, vice-president for laser enrichment at Exxon Nuclear Co, it would be aimed at, among other topics: the engineering demonstration of laser systems control; large-scale uranium handling; component and systems lifetime studies; long-path light propagation, and development of the necessary data to support a commercial plant license application.

Risks of nuclear proliferation exist in any enrichment process, the Glennan report notes. To use the JNAI process to make highly enriched uranium would first require substantial development and then modifications of an existing facility. If a JNAI separation facility is kept under safeguards, it would be simple to detect conversion. On the other hand, the report notes, a centrifuge plant can be converted without major modification—in less time and with far less uncertainty.

The characteristics of the JNAI process are such that one could detect clandestine plant construction or operation "through appropriate national intelligence measures which include monitoring the export of critical components and electronic intelligence for detection of plant electromagnetic emissions," according to the report.

Laser isotope separation is being developed in several countries. So even if the JNAI program is cancelled or even all US development, it is unlikely to stop foreign nations from continuing their efforts, the report says.

If the JNAI process turns out to be as economical as anticipated, the report says, it can contribute to US nonproliferation objects in these ways:

- It would allow the recovery of additional U^{235} from the growing stockpile of diffusion and centrifuge plant tails. This one-time addition to the U^{235} supply is equivalent to 60 000 tons of natural uranium, an amount sufficient to supply the operation of ten (1000 MWe) power reactors for their expected lifetimes. Laser isotope separation could reduce requirements for natural uranium by 20%, approximately the same benefit as from plutonium recycling. The process would allow nations with light-water reactors to send their tails to the US for enrichment.
- The JNAI process might be cheaper than enrichment processes not involving lasers. Any reduction in cost would affect the relative economic attractiveness of reprocessing and plutonium recycle in light-water reactors because these operations would have to compete with the lowered price of fresh enriched fuel.
- By reducing natural uranium requirements, the JNAI process would tend to stabilize yellow-cake prices.

The report notes that "the JNAI process is anything but 'garage technology.' The vaporization of metal by electron beam, the laser system, the optical system, and the extraction of ions by electric or magnetic fields are all high-technology operations which only a country with sophisticated scientific and technological capabilities could successfully achieve. Conversion of UF_6 into metal, the removal of the pyrophoric deposit from collector and tails plates, chemical processing of the metal and tails, and several other parts of the materials handling, might be accomplished by a country with medium technological capabilities but not by a subnational group . . ."

"Perhaps the best indication of the technical difficulty of the process is that after more than seven years of research and development, the JNAI process is just nearing the stage of integrated testing of prototypical components. On JNAI's own schedule, its first demonstration plant is at least a decade away from operation." —GBL

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2. R. V. Ambartzumian, V. P. Kalinin, V. S.

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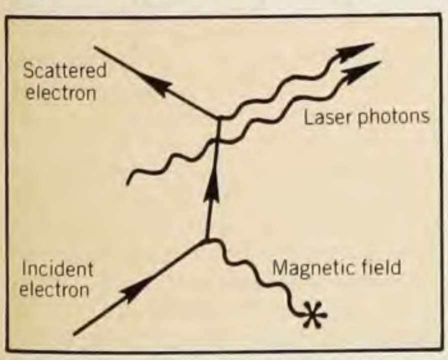
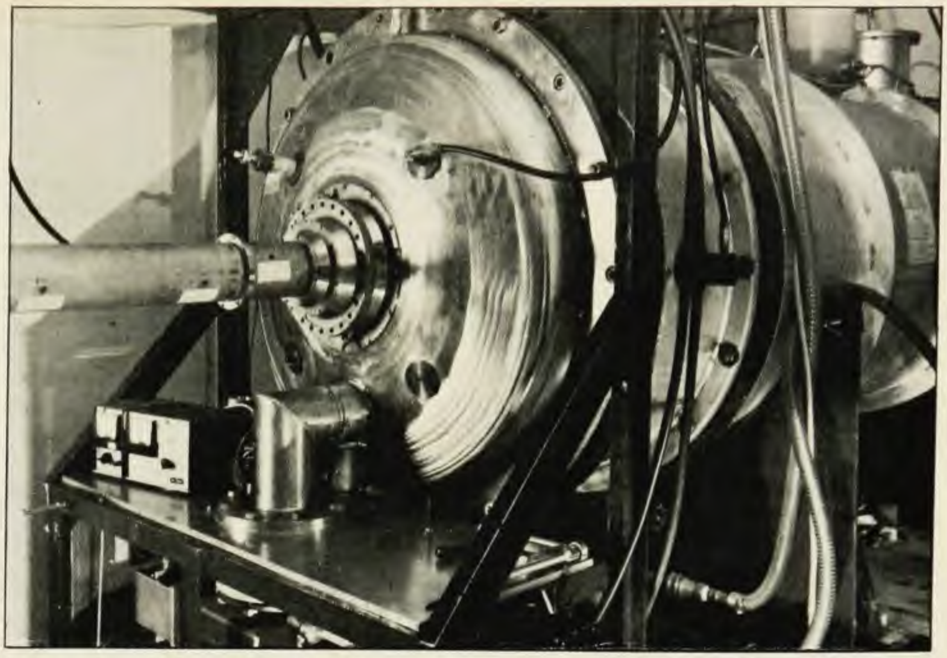
Update on free-electron lasers and applications

Lasers whose operating frequencies are not determined by energy levels in atoms or molecules have long been a goal of researchers in the field. Stimulated scattering by free electrons passing through spatially varying magnetic fields promises to meet that goal. Two years ago, a group at Stanford reported laser action from stimulated bremsstrahlung,[1] and a collaborative effort of the Columbia University Plasma Lab and the Naval Research Lab has produced a laser based on stimulated Raman scattering by free electrons.[2] These results have encouraged many other laboratories to investigate the construction and potential uses of free-electron lasers. Active research is now going on at Bell Labs, Los Alamos, The University of Trento, Frascati, Brookhaven, and the Lawrence Livermore Labs, among others. Much of the excitement is due to these lasers' promise of exceedingly high power levels at a low enough cost to make them useful suppliers of industrial process energy.

Principles of operation. The purpose of a laser is, of course, to produce a large number of coherent photons—what can, in effect, be called a collective mode of the electromagnetic field. In the free-electron lasers now in operation, the coherent radiation arises in a stimulated scattering process in which a high-energy free electron is scattered by a spatially varying magnetic field. The upper laser state consists of a fast electron together with a virtual photon from a rippled magnetic field; the lower state has a scattered photon together with a low-energy electron. One can represent the process in a Feynman-type diagram as shown:



With enough scattering events, the scattered radiation can build up to sufficiently high levels to stimulate further scattering, ultimately raising the intensity above the laser threshhold. A classical point of view can equally well be used to understand the process: The combined action of the rippled magnetic field and the signal field produces longitudinal forces that cause bunching of the electron beam, and the oscillation of these bunches in the field in turn produces radiation at the laser, or signal, frequency. The basic principles are not new, and have been in use in the microwave region since the early 1950's, in devices such as the "ubitron." In fact, the new devices could just as well be called "relativistic ubitrons" as "free-electron lasers," Norman Kroll, a theorist at the University of California at San Diego, told us.



The VEBA pulsed high-energy diode at the Naval Research Laboratory. The large tank is a transmission line that forms the pulse; the electron beam propagates along the tube to the left. In the free-electron laser the tube is surrounded by a solenoid that produces a rippled field.

The two free-electron lasers differ in whether the electrons also exhibit collective oscillations. In the Stanford work, the electron beam has a relatively low intensity (2.6-A peak current) and does not exhibit collective oscillations; each electron scatters individually. In the laboratory frame the process can be described as stimulated bremsstrahlung. In the electron's rest frame the scattering process looks very much like stimulated Compton scattering, except that the incident photon is a virtual one. The Stanford group obtained stimulated emission amplifying an external beam three years ago (PHYSICS TODAY, February 1976, page 17), and was able to obtain laser operation soon after. In their apparatus a 43-MeV beam, from the Stanford superconducting linac, passes through a helical magnet coil that produces a field whose direction varies along the beam axis with a 3.2-cm period. The output laser beam has a wavelength of roughly 3.4 microns.

In their subsequent investigations the group, which includes Luis R. Elias, John M. J. Madey, H. Alan Schwettman, Todd I. Smith, and various other faculty, postdoctoral fellows and graduate students, has been investigating the structure of the optical pulse in the time and frequency domains. Madey told us that they are particularly interested in relating properties of the optical pulse to parameters of the electron pulse and of the cavity.

The Columbia–NRL laser, which was built by David B. McDermott, Thomas C. Marshall and S. Perry Schlesinger (all at Columbia), and Robert K. Parker and Victor L. Granatstein (at NRL), involves a lower energy beam (1.2 MeV), but with a much higher intensity (25-kA peak current) and, more importantly, much higher current density. The electron beam is produced by field emission from the cathode attached to the VEBA pulsed-high-voltage diode at the Naval Research Lab. (It resembles the Aurora device at the Harry Diamond Laboratories.) After emerging from the accelerator the beam passes through a region in which a strong longitudinal field has a spatially periodic ripple imposed on it. (The ripple is produced by inserting, within the main solenoid, a set of aluminum rings that carry currents in alternate directions.) Light emitted while the electrons are in the "undulator" is reflected by annular mirrors, which serve to define an optical cavity. The cathode that emits the electron beam is inserted through the hole in one mirror, and the laser beam leaves via the other. The wavelength reported for the initial experiments is about 400 microns.

The nonlinear interaction of the rippled field and the signal wave in the electron plasma produces a disturbance that propagates as a collective wave along the beam. This plasma wave reinforces the scattering into the laser mode and produces a high-gain system. The process is, essentially, stimulated Raman scattering from the electron beam. The virtual