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Soviet Laser Chemistry Research and Applications [redacted]

A Scientific and Technical Intelligence Report

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SW 86-10008
February 1986

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Soviet Laser Chemistry Research and Applications [redacted]

Key Judgments

Information available as of 19 December 1985 was used in this report.

We believe Soviet basic research in laser chemistry is equal to or ahead of US research in most areas. Our judgment is formed primarily from analysis of open-literature publications by Soviet scientists [redacted] Laser chemistry is a technological base for the development of nuclear power and weapons, electronics, chemical engineering, process control, and genetic engineering. [redacted]

In laser chemistry, laser light is used to promote changes in the physical or chemical properties of matter. These changes can produce new chemical compounds, higher yields in processes for making conventional compounds, or compounds with properties not easily obtained through conventional chemistry. Laser chemistry can also be used to separate very similar atoms or molecules and to detect the presence of these species in extremely small quantities. The Soviets have performed extensive research in all fields of laser chemistry. [redacted]

Although the Soviets lead the United States in many areas of basic research, they have been surpassed by the United States in the industrialization of applications offering the greatest near-term economic potential. We believe that the Soviets have lagged behind the United States in industrialization primarily because of a lack of cooperation between Soviet basic research institutes and industry—not because the Soviets are technically limited in their ability to apply advances from basic research. The Soviets, however, have now established a well-defined, goal-oriented program, whose initial success could greatly increase the rate of incorporation of basic Soviet laser chemistry research into industry. If this program is successful, the Soviets could improve the development of applications by 1995. [redacted]

Laser chemistry as applied to isotope separation promises to be a more efficient and economical way of separating or enriching many nuclear isotopes—important in basic research, medical research, nuclear power, and nuclear weapons. The Soviets lead the West in the basic research of laser isotope separation (LIS). They have built the world's first two pilot plants for the separation of light isotopes, and we believe that they are now capable of operating these plants and industrial-level separation plants for light atoms and low molecular weight molecules. Their research, however, may not be as applicable to the separation of uranium and plutonium isotopes as that pursued in the United States. In our judgment, they will not be able to operate an industrial plant for the enrichment of uranium before the year 2000. [redacted]

The Soviets, according to open sources, have proposed using laser isotope separation to produce high-purity carbon-13. A potential application for large quantities of carbon-13 is for use in carbon-dioxide laser weapons. The Soviets, according to a scientific publication, are aware of the advantages of carbon-13 and may be motivated to develop a carbon-13 LIS process to meet military objectives. [redacted]

Laser chemistry as applied to ultrapurification is used to remove trace impurities from a bulk material. When applied to materials where high purity is required, such as semiconductors or pharmaceuticals, it can dramatically increase the value of the material. The Soviets lead the West in this type of basic research. Using laser purification, they have developed high-quality electronics-grade semiconductor materials in order to reduce a present shortage of these materials. We believe that by 1990 the Soviets could operate a pilot plant. [redacted]

Laser chemical synthesis offers greater control over the chemical reaction paths and products than conventional chemistry. It thus has potential to produce unique compounds, to increase the selectivity and yields of industrial reactions, and to perform controlled chemical reactions on surfaces and in living organisms. The Soviets lead in the basic research of laser chemical synthesis, and we believe they will establish a pilot plant for laser-induced chemical synthesis by 1995. [redacted]

Laser surface chemistry is important in the production of advanced microelectronic components and the coating of advanced materials. Soviet laser surface chemistry research is pursuing concepts equal to or more advanced than those in the West. This basic research, however, often has pointed toward applications that are too advanced to offer Soviet industry practical solutions to existing problems. As the Soviet electronics industry develops in the coming decade, however, we believe laser surface chemistry will play a more significant role. [redacted]

One area of laser photochemistry in which the Soviets maintain a significant lead in both basic and applied research is laser photobiology, potentially useful in genetic engineering and biological warfare research. This effort is well organized with physicists, chemists, biologists, and medical doctors working jointly in the research. The Soviets have achieved selective laser chemistry results on biological molecules and have mutated bacteria and viruses selectively. [redacted]

Table 1
Comparison of Soviet and US Achievements in Laser Chemistry

Research Area	Basic Research	Applied Research	Pilot Plants	Industrial Plants
Light isotope separation	USSR>US	USSR>US	USSR>US	USSR>US
Uranium/plutonium separation	US=USSR	US>USSR	US>USSR	None
Ultrapurification	USSR>US	US>USSR	US>USSR	US>USSR
Direct photochemistry	USSR>US	US>USSR	US>USSR	None
Laser-induced chemistry	US=USSR	US=USSR	US=USSR	None
Laser surface chemistry	USSR>US	US>USSR	US>USSR	US>USSR
Laser photobiology	USSR>US	USSR>US	USSR>US	None
Laser analytical chemistry	USSR>US	USSR>US	US=USSR	US>USSR

[redacted]

The selectivity of laser chemistry provides a highly sensitive method for detecting and measuring trace quantities of atoms or molecules. It has a wide range of applications from process and quality control in industry to the detection of pollutants or chemical weapons in the atmosphere. The Soviets, who lead in the basic research of laser analytical chemistry, are placing special emphasis on those applications that improve both the process control and automation of the semiconductor industry. [redacted]

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Soviet Laser Chemistry Research and Applications [redacted]

Introduction

This study examines the three aspects of laser chemistry: isotope separation and ultrapurification, laser photochemical synthesis, and laser analytical chemistry. Described are the basic concepts of each, research applications, industrialization, US developments, and outlook. A glossary of terms is included in the appendix to facilitate the reader's understanding. [redacted]

Background

In the early 1960s, Soviet scientists pioneered a new and promising field of chemistry based on the selective interaction of lasers with atoms and molecules. According to open literature, their initial idea was essentially to use the laser as a narrow frequency, high-power source in conventional photochemistry. In the early 1970s, with the development of tunable lasers and high-power infrared lasers, the Soviets began to examine the concept of performing bond selective or reaction path selective laser chemistry. These ideas solidified in the mid-1970s with an early theoretical framework establishing both the potential feasibility of selective laser chemistry and some of its inherent limitations. [redacted]

The Soviets have pursued a more extensive basic research program in laser chemistry than the West. Top Soviet physicists and chemists are involved and have been rewarded for their accomplishments with the highest awards for scientific achievements and leading positions at academy institutes. For example, V. S. Letokhov received the Lenin prize in 1978 for developing applications of laser chemistry and later was appointed deputy director of the Institute of Spectroscopy (IOS), the leading institute for laser chemistry. Soviet support for laser chemistry is further evidenced by the large number of facilities [redacted] involved in theoretical and experimental research in this field, and the high-quality and advanced technical equipment made available to these

Table 2

[redacted]

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Scientific Research Center for Industrial Lasers

In the early 1980s, the Soviet Academy of Sciences established the Scientific Research Center for Industrial Lasers (NITsTLAN). According to open literature, the goal of NITsTLAN is to develop industrial laser applications, to develop industrial lasers, to foster the assimilation of laser technology into the national economy, and to train the necessary industrial laser specialists. [redacted]

[redacted]

researchers. The IOS is one of the most well equipped of all Soviet research institutes, according to open-source literature and US visitors to the Soviet Union. This institute has advanced Western equipment, adequate computer support, and some of the finest Soviet technicians. [redacted]

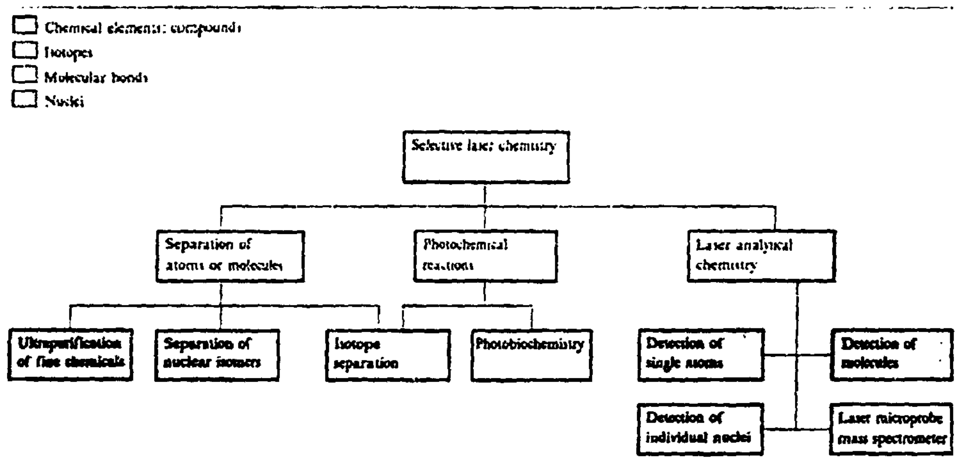
Soviet accomplishments in laser chemistry are evidenced by the large number of scientific publications on new theories and potential applications appearing in both Soviet and Western journals. A recent book, *Nonlinear Laser Chemistry*, by V. S. Letokhov, a highly respected laser chemist of the IOS, was published in the prestigious *Springer Series on Chemical Physics*. This book, containing the works of several Soviet scientists, received excellent reviews in the Western press, demonstrating the prominence of the Soviets in this field. [redacted]

Although the potential of laser chemistry was realized with the advent of the laser, only now is the technology and understanding sufficient to allow the development of practical applications (figure 1). The Soviets have extended applications from single atoms and small molecules to large biological molecules. They have demonstrated their ability to develop industrial-level processes by operating the world's first two laser isotope separation (LIS) pilot plants for the separation of sulfur and carbon isotopes. Industrial applications, however, have been slow because of a lack of cooperation between industry and basic research institutes. To stimulate the rapid development of all industrial applications of lasers, the 11th Five-Year Plan (1981-85) was approved by the State Planning Commission and the Academy of Sciences of the USSR. This plan called for the Scientific Research Center for Industrial Lasers (NITsTLAN), which was established under the direction of Ye. P. Velikhov, vice president of the Academy of Sciences (see inset, Scientific Research Center for Industrial Lasers). Continued success of these programs, coupled with the Soviet leadership in basic research, could allow the Soviets to obtain major advantages in the applications of laser chemistry by the mid-1990s. [redacted]

Isotope Separation and Ultrapurification

Initially, Soviet laser chemistry research, [redacted] was tasked with developing a more economical approach to isotope separation and, in particular, to the enrichment of nuclear fuels to meet a growing demand in the nuclear power industry. This application, generally accepted as affording the greatest potential economic advantage of laser chemistry, has been investigated by scientists in Western countries with active laser chemical research programs. Soviet research in laser chemical separations has not been confined, however, to nuclear fuel material but has led to many other potential applications for the ultrapurification of chemicals with economic, health, and military significance. [redacted]

Figure 1
Basic Processes of Laser Chemistry and Potential Areas for Applications



The Soviets are equal to or more advanced than the United States in the basic research of all these areas.

[redacted]

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Basic Concept

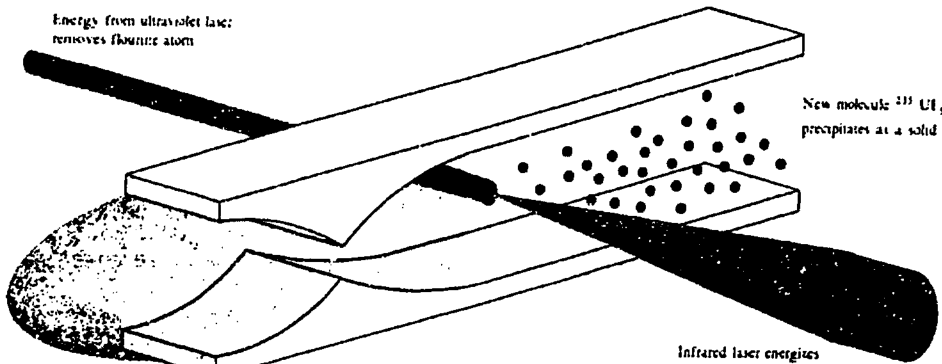
The basis for laser separation of atoms or molecules rests on the ability of a laser to selectively transform species with very similar physical properties, such as isotopes, into species with dissimilar physical properties that can be readily separated, such as neutral and charged species. The laser transformation and separation then become essentially unrelated technological problems. The following paragraphs discuss both isotope separation and ultrapurification. [redacted]

Isotope Separation

Basic Research. Soviet scientists began research into LIS of atomic and molecular species in the early 1970s. According to information in open literature, scientists at the Lebedev Physics Institute (FIAN) experimented with atomic vapor LIS of a variety of rare earth elements during the mid-1970s, gaining experience in basic laser spectroscopy and separation techniques. The major emphasis of Soviet research, however, has been on the selective laser separation of molecular species. [redacted]

Soviet scientists at the IOS pioneered the separation of molecules through the selective excitation of molecular vibrations. V. S. Letokhov and R. V. Ambartsumian discovered that a molecule could absorb many photons of the same infrared frequency leading to a highly excited state or even direct dissociation. Their discovery demonstrated the possibility of isotope selective photodissociation with a single-frequency laser (see figure 2). [redacted]

Figure 2
Molecular Laser Isotope Separation for Uranium



Depicted is the Soviet concept of a molecular laser isotope separation process for uranium based on the infrared-ultraviolet (IR-UV) photodissociation of UF_6. Only gaseous molecules containing U(235) dissociate forming a readily separated solid.

[redacted]

Molecular laser isotope separation (MLIS) involves the selective dissociation of those molecules containing an atom of one isotopic species. Selectivity in the laser excitation results from variations in the vibrational frequencies—caused by differences in the mass of the atoms—for molecules containing differing isotopes. [redacted]

Isotopic shifts in the molecular vibration frequencies are generally much larger than the corresponding shifts in atomic transitions. Molecular transitions, however, tend to be broad and overlapping because of the addition of rotational energy. These effects combine to make MLIS more suitable for some isotopes while atomic vapor laser isotope separation (AVLIS) is more suitable for others. US scientists have concluded that AVLIS is significantly more suited for uranium enrichment than MLIS, and the United States is committed to the development of AVLIS as its sole method of uranium enrichment. [redacted]

AVLIS involves the selective laser ionization of one isotopic species followed by electrostatic separation of the ionized particles. Selectivity in the laser excitation results from small variations in the electronic transition energies of the isotopes, which are caused by differences in the nuclear mass and volume because of a varying number of neutrons in the nucleus. [redacted]

In AVLIS, a laser tuned to a well-separated electronic transition promotes one isotopic species to an excited electronic state. An additional laser (or several lasers) further excites the species to higher electronic states and beyond the ionization potential. In general, high selectivity/low yield occurs at low laser powers while high yield/low selectivity occurs at high laser powers. Complex procedures involving several lasers tuned to different atomic transitions are necessary to maximize both yield and selectivity. [redacted]

Potential Applications and Industrialization. The LIS application with greatest economic potential is for the enrichment of nuclear fuels and weapons materials, such as uranium and plutonium. Soviet and Western calculations and experiments indicate that LIS could be more efficient and more economical than existing enrichment techniques. Prototype plants are presently under development in the United States. As yet, however, there are no industrial-level plants to demonstrate the feasibility of this potential. [redacted]

Another important potential LIS application is the separation of the hydrogen isotopes, deuterium and tritium. Most nuclear reactors using natural (unenriched) uranium require large quantities of deuterium—at present very expensive, accounting for as much as 15 to 20 percent of the initial cost of the reactor. A reduction in the cost of deuterium would significantly decrease the cost of operating these reactors. Another problem with deuterium at present is that, over time, neutrons captured in the deuterium form tritium, a radioactive isotope that poses a serious health hazard. LIS would facilitate separation of the tritium from the deuterium, necessary to keep the reactor working safely. Also, an additional source of tritium, used in fusion research as well as nuclear weapons, would be provided. [redacted]

The near-term application of LIS is for the separation of small quantities of light isotopes used in basic research. Numerous applications in biology and medicine depend on the use of certain isotopes as labels for structural or material analysis. In particular, the transport of a chemical containing a rare isotope through a biological system can be monitored by mass spectrometry or radiation analysis. [redacted]

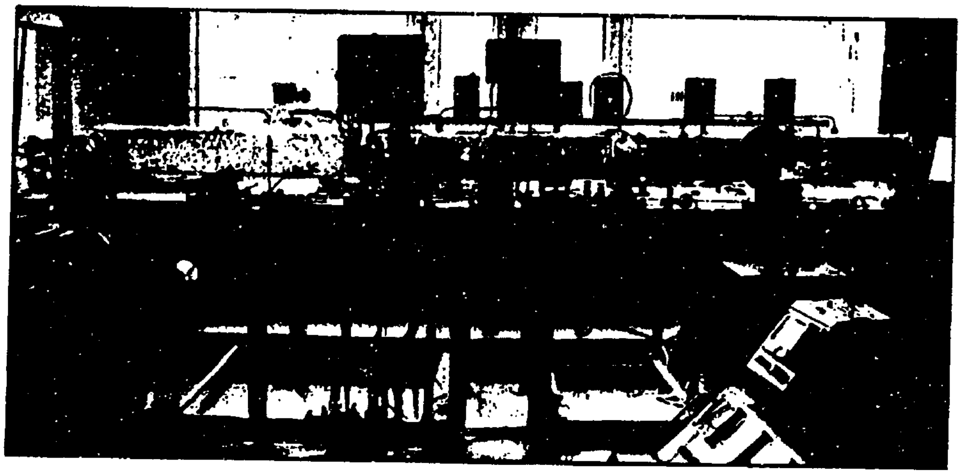
Soviet scientists have followed a consistent path toward development of practical applications. The first of these, aimed at the separation of small amounts of light isotopes, was achieved in the late 1970s with the construction of the LIS separation pilot plant. The plant, separating sulfur isotopes by the multiphoton dissociation (MPD) of sulfur hexafluoride with a single-frequency, carbon-dioxide laser (MLIS), resulted from a joint effort by scientists of the Kurchatov Institute for Atomic Energy (IAE) and of the IOS. [redacted]

In addition to proving a source of sulfur isotopes, the sulfur hexafluoride separation plant was probably used to demonstrate the efficacy of uranium enrichment by MPD of uranium hexafluoride. While both molecules have similar spectroscopic properties, sulfur hexafluoride has a larger isotope shift (providing for ease of separation) and is noncorrosive. In addition, the required laser wavelengths are more readily available. [redacted]

The Soviets followed this effort with the construction of a carbon isotope separation pilot plant in 1981 at the Institute of Stable Isotopes in Tibilisi (ISI). This plant, operated jointly by the Kurchatov Institute for Atomic Energy (IAE) and the IOS, used single-laser photodissociation of trifluoromethyl iodide (MLIS) and was expected to attain a productivity of about 1 gram per minute of highly enriched carbon-13 (figures 3 and 4). Problems with scaling this laboratory concept to industrial levels forced the Soviets back to the laboratory. In 1985, Letokhov proposed an MLIS carbon-13 separation technique based on the use of four laser frequencies, enabling optimization of yield and selectivity. [redacted]

A potential application for large quantities of carbon-13 is for use in carbon-dioxide laser weapons. The effective range of high-power carbon(12)-dioxide lasers in the atmosphere is limited by the atmospheric presence of carbon(12)-dioxide. This gas, having the same vibrational transitions as the laser active medium, absorbs the laser energy, producing a heated column of gas. Changes in the refractive index of the

Figure 3
Carbon Isotope Separation System at the Industrial Institute of Stable Isotopes in Tibilisi



This carbon-isotope separation system is operated jointly by the Kurchatov Institute for Atomic Energy and the Institute of Spectroscopy of the Academy of Sciences, at the Industrial Institute of Stable Isotopes in Tbilisi. Separation is by multiphoton dissociation of CF_3I with pulsed CO_2 laser radiation of an average power of 1 kilowatt.

[redacted]

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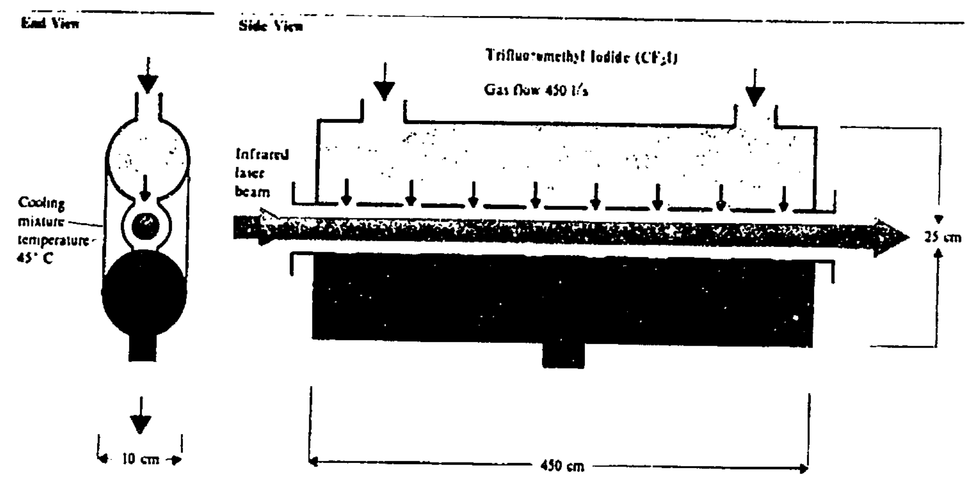
gas associated with heating leads to a diverging lens effect, known as thermal blooming, rapidly dissipating the beam energy. Substituting carbon-13 in the laser active carbon-dioxide gas shifts the laser wavelength sufficiently to avoid carbon(12)-dioxide absorption. The Soviets, according to a scientific publication, are aware of these advantages and may be motivated to develop a carbon-13 LIS process to meet military objectives [redacted]

Although the Soviets were aware of the potential economic advantages of uranium LIS, they did not rapidly proceed with the development of an industrial process. [redacted] the Soviets did not see an immediate need for additional uranium separation capacity and preferred to explore the field of LIS in depth before making a choice for an industrial process. We believe that the present rate of growth in the Soviet nuclear power industry will create a need for increased uranium enrichment capacity in the late 1990s. [redacted]

Ultrapurification of Fine Chemicals

Laser ultrapurification is achieved most readily when the substance to be purified is thermodynamically more stable than the impurities. The mixture can then be irradiated with a long-pulse infrared laser (usually a carbon dioxide laser) raising the average molecular energy density above the dissociation limits of the impurities. When the impurities are thermodynamically more stable than the substance to be purified,

Figure 4
Carbon Isotope Separation



Shown is a fast transverse flowing cell for carbon isotope separation by high-power, high-repetition rate CO_2 laser. A productivity of about 1 gram per minute of highly enriched carbon-13 was anticipated but probably not achieved by the Soviets.

[redacted]

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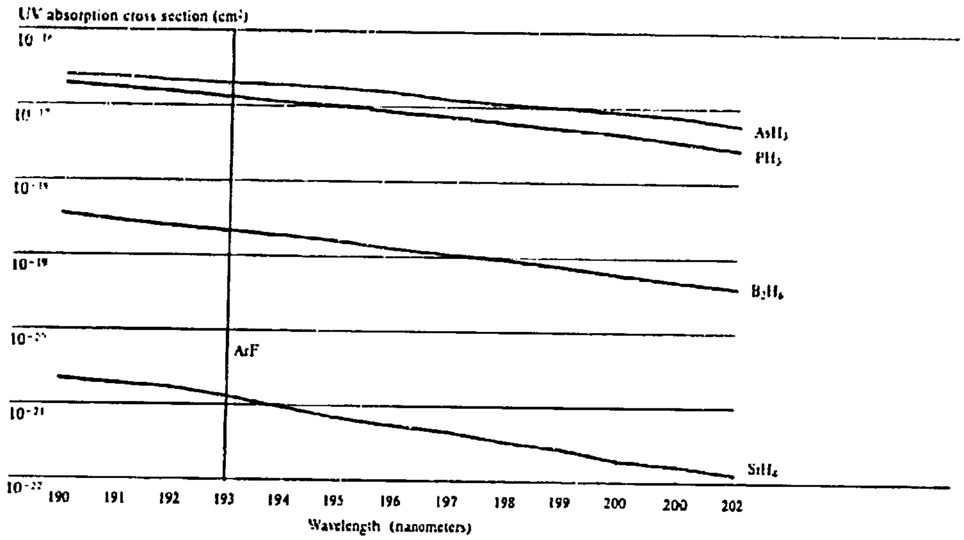
the laser wavelength, power density, and pulsewidth must be chosen with care to selectively excite only the impurities. [redacted]

Laser chemistry can be used to eliminate from a substance those impurities that are difficult to remove by standard purification techniques. In essence, the physical or chemical properties of the impurities are changed by selective laser chemistry so as to enable an efficient standard separation. [redacted]

Basic Research. According to articles in Soviet open-source literature, the first experiments at laser purification were performed in the late 1970s at the IOS. These experiments involved the ultrapurification of arsenic trichloride, a semiconductor material. Subsequent experiments, performed jointly by the Lebedev Physics Institute (FIAN) and the Institute of Fine Chemical Technology (MITKhT), concerned the purification of two other semiconductor materials, silane and boron trichloride (figure 5). The results of these experiments demonstrate the potential of performing laboratory-scale laser purification but do not address the problems of scaling to an industrial-level process. [redacted]

Figure 5
Absolute Absorption Cross Sections of Silane and Important Impurities[a]



Silane gas, a precursor of high purity silicone (Si), contains as impurities the hydrides of boron (B), phosphorous (P), and arsenic (As). The absorption cross sections of these impurities for the ultraviolet (UV) emission from an argon fluride (ArF) excimer laser, 193 nanometers (nm), is at least several orders of magnitude greater than for silane. Irradiation of the mixture selectively decomposes the impurities into solid products that are readily separated. The ultrapure silane can then be used in the manufacture of high quality semiconductor products.

[a] Data correspond to gases at 300° Kelvin.

[redacted]

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Potential Applications and Industrialization. The Soviets, to solve a present shortage, have placed particular emphasis on developing laser chemical techniques for purifying compounds for the semiconductor industry. Modern semiconductor technology requires the use of extremely pure compounds, both for the base material and for the dopants. Generally, however, these materials are not available with sufficient purity for direct application. An expensive and complicated process of conventional purification and ultrapurification is necessary. Laser ultrapurification of semiconductor materials increases the value of the materials and ultimately leads to higher quality semiconductor products (see inset on Gamma-Ray Laser for another potential application). [redacted]

The Soviets began to seriously consider the development of industrial applications of laser purification in the early 1980s. Scientists at MITKhT and FIAN previously involved in basic research began applied

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Gamma-Ray Laser

Another potential application of laser purification is the preparation of a gamma-ray laser by the separation of excited and unexcited nuclei. A gamma-ray laser operates by the stimulated emission of very-short-wavelength electromagnetic radiation (gamma rays) associated with the transition from excited to unexcited nuclear levels. Excited nuclei can be prepared by neutron irradiation, but it would be difficult to directly prepare a population inversion of excited nuclei in a particular state. The Soviets suggested that laser multiphoton ionization could be used to selectively ionize atoms with the proper nuclear state. Selective laser excitation is possible because of a weak coupling of the electronic and nuclear states. The excited ions would then be deposited on a charged filament. Soviet calculations indicate that this approach would yield a sufficient population inversion for laser action. [redacted]

Because of the extremely short wavelength, gamma-ray lasers would be extremely effective as long-range directed-energy weapons if scalable to high powers. In the 1970s, Soviet scientists at the IOS outlined a potential laser purification procedure that could lead to a gamma-ray laser, and in 1984 they reported the first separation of isomers by selective laser photo-ionization (figure 6). The ability of such an approach to the generation of a laser, however, seems doubtful because of the short lifetime of the isomers. [redacted]

research on the ultrapurification of semiconductor materials. Although Soviet scientists were the first to identify the potential of laser purification of semiconductor materials, Western scientists lead in the development of practical applications. Several applications have been developed for the purification of semiconductor dopant materials, but as yet they are not competitive with existing techniques. [redacted]

The recent Soviet emphasis on the development of practical applications of laser purification takes advantage of advanced Soviet basic research as well as Western applied research. [redacted]

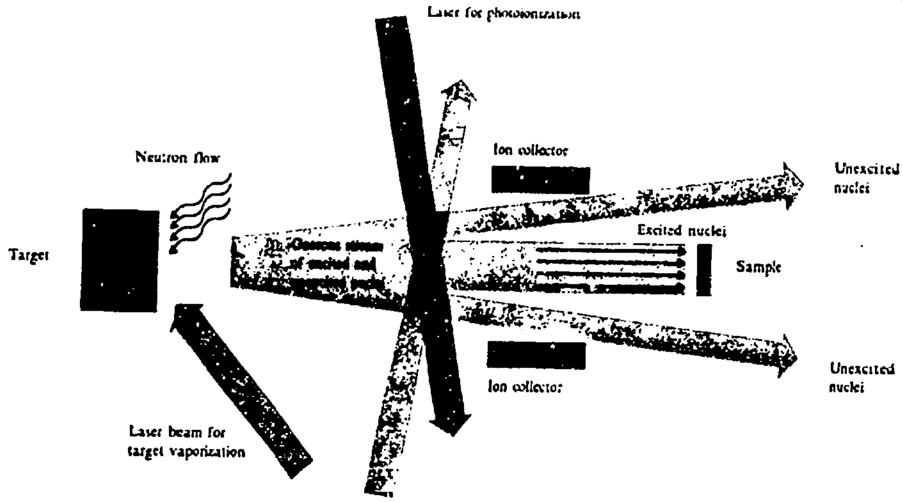
Laser Photochemical Synthesis

A photochemical process relies on the absorption of specific quanta of light energy (photons) to provide the necessary energy for a sequence of chemical reactions. In conventional chemistry, this energy would be provided through bulk heating of the reactants. Under bulk heating conditions, all reactants share a common distribution of energy and statistical processes determine the range of products. In a photochemical process, however, the reactant energy is specified by the photon energy, limiting the range of products. [redacted]

Photochemical synthesis involves the stimulation of chemical reactions with light (photons) and is significant because well-defined quantities of energy can be selectively deposited into reactant species and even specific molecular bonds. This process serves to direct a chemical reaction along a course of events leading to a specific product. The use of a laser as the photon source dramatically increases the potential selectivity of the photochemistry and makes possible some new areas of applications, such as the direct or catalytic synthesis of otherwise difficult to prepare compounds and the selective chemistry of biological molecules. [redacted]

Soviet scientists developed the basic understanding for laser photochemistry during their investigation of MLIS. The potential methods of laser separation rely on the photochemical transformation of the reactant to a product (through dissociation, ionization, or chemical reaction). The key to successful isotope separation is that only one component of the mixture of reactants takes part in the reaction path. The key to successful laser photochemistry is to limit the range of

Figure 6
A Proposed Soviet Concept for a Gamma-Ray Laser



In this gamma-ray laser the excited nuclei are prepared by neutron irradiation of a solid target. The material is then vaporized by a high-power laser and the excited nuclei are separated from the remaining unexcited nuclei in the gas phase by selective laser photoionization and deposited on the gamma-ray laser element.

[redacted]

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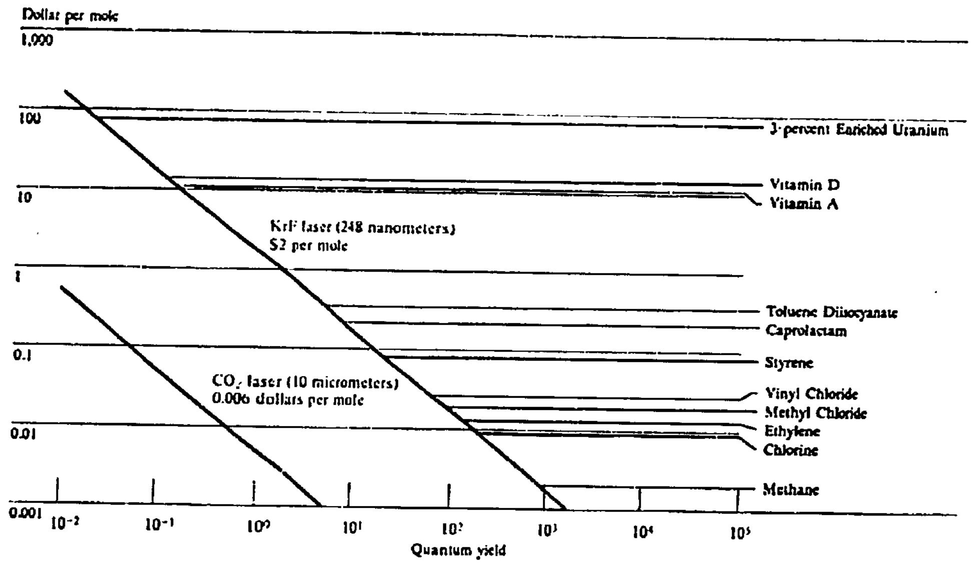
products involved in the reaction path. The breadth of Soviet research in LIS leads to a general Soviet theoretical understanding of each sequence of the laser chemical reaction. [redacted]

Laser chemistry offers the possibility to improve selectivity and yield in chemical processes. The high cost of laser photons as opposed to other sources of chemical energy such as electron beams or simple "heat," however, tends to limit its use in many practical applications (figure 7). Laser chemistry, nevertheless, offers the possibility of producing unique compounds not otherwise attainable. [redacted]

Direct Photochemical Synthesis

Basic Research. According to open-source publications, Soviet and Western scientists initially thought that laser excitation could possibly be used to selectively break or form desired chemical bonds. This potential was based on the selective excitation of molecular vibrations to direct the molecule on the desired reaction path. For the method to be successful, the excitation and reaction would have to occur

Figure 7
Laser Photochemistry: Economics



The plot shows the laser processing cost per mole of chemical product versus the quantum yield or number of product species per photon for several industrial lasers. The cost of photons represents the capital investment, energy, and maintenance costs of the laser system. Also depicted is the selling price per mole of selected chemical products considered for laser chemical processing.

[redacted]

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faster than the rate of relaxation. Soviet efforts at MLIS in the mid-1970s showed that this effect was not generally feasible, and the acceptance of this observation led to a reduction of interest in and expectations for laser chemistry in the West. Soviet scientists at the IOS continued their investigation into selective laser excitation and in the late 1970s found that, under more restrictive conditions, selective laser excitation of vibrational energy could occur. [redacted]

Potential Applications and Industrialization. Potential products of laser photochemical synthesis include catalysts, pharmaceuticals, semiconductor materials, and chemical weapons. Since the late 1970s, Soviet open research has focused on those areas that offer the greatest potential for economical synthetic techniques. With the assumption that laser photons could never compete economically with thermal energy, the Soviets identified reaction paths for which the energy costs are insignificant compared to the material costs and for which a slight increase in yield or purity would result in a dramatic increase in product value. [redacted]

Soviet attempts at the laser chemical synthesis of catalysts have not, as yet, led to the development of any unique catalysts of commercial significance. Soviet scientists have shown that new types of catalysts can be prepared but have not pursued a coordinated approach toward maximizing catalytic activity by modifying chemical structure. [redacted]

In the United States, industrial scientists are just now learning how to use selective laser chemistry to prepare novel catalysts. Using open-source information from Soviet basic research, US scientists have prepared catalysts with increased product selectivity and higher catalytic activity. At present, it is uncertain if laser chemistry will be used to prepare large quantities of these new catalysts or if conventional techniques will be developed. [redacted]

According to open literature, the Soviets recognize the potential applications of laser chemistry to the synthesis of pharmaceuticals but have not developed any practical applications. Some pharmaceuticals, such as vitamin D (figure 8), are presently manufactured by photochemical techniques using conventional lamp sources. The Soviets have considered the possibility of substituting a laser source but have not established a pilot plant. The United States has more vigorously pursued the applications of laser chemical synthesis to pharmaceuticals. Pilot plants are currently being established for the laser chemical synthesis of vitamin D. Yields and purity are expected to be considerably improved. [redacted]

The Soviets have placed particular emphasis on developing laser chemical techniques for producing extremely pure compounds for the semiconductor industry. Scientists at the MITKhT recently developed a laser chemical technique for synthesizing high-purity phosphine, a common donor dopant used in epitaxial growth techniques. The technique uses a pulsed carbon dioxide laser to vaporize a solid phosphorous target in a hydrogen atmosphere. A gas phase reaction occurs near the surface of the target and in the laser focal volume. Phosphine is the only reaction product and thus suffers from no added impurities. [redacted]

Although sufficient quantities of phosphine can be synthesized by conventional techniques, the Soviets have difficulty in meeting the necessary purity requirements for high-quality semiconductors. The Soviet method for laser chemical synthesis of phosphine from basic elements is both feasible and practical. We believe the Soviets could develop this process to a pilot-plant level for industrial evaluation by the mid-1990s. [redacted]

In 1982 Ye. A. Ryabov of the IOS told [redacted] that scientists from NITsTLAN would soon be collaborating with Soviet chemical institutes to "explore the use of lasers for the synthesis of dangerous materials." Ryabov used the term "dangerous materials" [redacted] but, when pressed for an explanation of what specific dangerous materials were to be synthesized, he refused to elaborate. [redacted]

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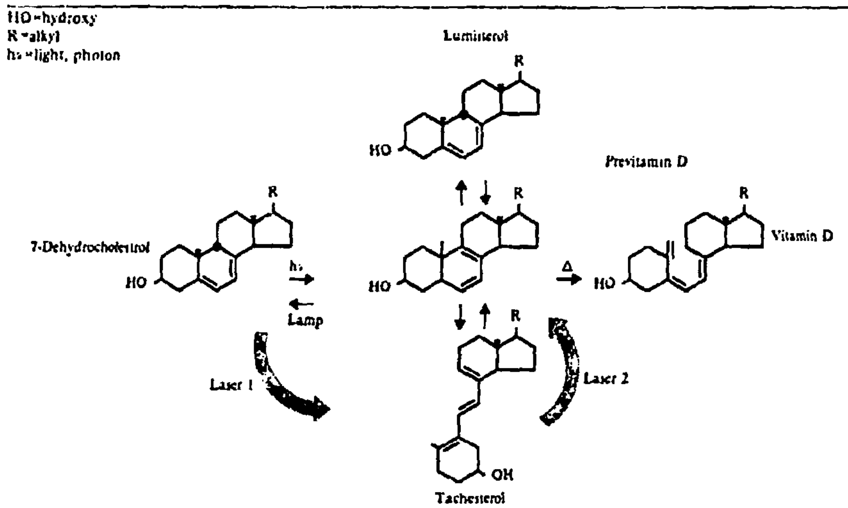
Figure 8
Proposed Laser Chemical Synthesis of Vitamin D



Conventional photochemistry is presently used to convert 7-dehydrocholesterol to previtamin D and byproducts tachysterol and lumisterol. These byproducts must be removed before conversion to vitamin D and represent a significant reduction in yield and increased cost. A laser chemical process studied by the Soviets and currently being industrialized in the West converts 7-dehydrocholesterol to previtamin D through tachisterol.

[redacted]

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[redacted]

Laser-Induced Catalytic Synthesis

Laser-induced catalytic synthesis (LICS) involves the conversion of many reactant chemical species into products for each laser photon absorbed. While the laser photon energy specifies the reaction path, the bulk of the energy required for the reaction is obtained from conventional sources, such as heating the reaction vessel. Thus, laser catalytic synthesis avoids the inherent limitation of direct laser-chemical synthesis—the high cost of laser photons—and retains much of the potential for selectivity. [redacted]

Laser-Initiated Free-Radical Chain Reactions

Chemical chain reactions are processes in which one of the products of a series of chemical reactions is identical to one of the reactants. The most important industrial chain reactions involve free radicals (a molecule or atom with an unpaired electron). Although the desired net reaction does not consume free radicals, their concentration in the reactor tends to decrease in time because of undesirable, alternate reaction paths. In order to operate a free-radical chain reaction, it is necessary to prepare an initial concentration of the free radicals and to regulate the concentration. Selective laser dissociation of molecules produces free radicals efficiently and in precise concentrations. [redacted]

Basic Research. According to open-literature publications, the Soviets have concentrated their efforts in LICS on laser-initiated free-radical chain reactions (see inset). In conventional free-radical chain reactions, thermal energy is required both to generate radicals and to sustain the reaction. The radical generation often requires much higher reactor temperatures than would otherwise be required. With selective laser chemistry to initiate the process, the operating temperature can be optimized for the subsequent chemical reactions. The radicals produced by the laser result in the conversion of many hundreds to thousands of reactant molecules to product molecules and thus make maximum usage of the laser photons. [redacted]

Potential Applications and Industrialization. Some of the most economically significant bulk industrial chemicals, such as vinyl chloride and styrene, are produced by free-radical chain reactions. The potential benefits of laser-induced free-radical synthesis are increased yield and improved selectivity. In addition, it may be possible to produce compounds by laser-induced synthesis that are not possible by conventional radical synthesis. [redacted]

[redacted]

[redacted]

[redacted]

Laser-Induced Surface Chemistry

Basic Research. Soviet scientists have pursued basic research in laser-induced surface chemistry since the early 1970s and have discovered a wide range of potential applications. Their research has focused on the creation of semiconductor junctions by laser-induced diffusion and laser annealing of semiconductor materials. Some of the most significant Soviet discoveries were by scientists engaged in LIS. V. P. Chebotayev of the Institute of Semiconductor Physics (IFP) reported in 1974 on a laser-induced surface chemical reaction between monocrystalline germanium and gaseous bromine. Although that work had originally been aimed at a bromine isotope separation, Chebotayev was aware of the practical application of surface etching in the technology of film semiconductor devices. US scientists consider his paper a classic and a basis for future research. [redacted]

Soviet scientists continue to investigate novel applications of laser-induced surface chemistry. V. S. Letokhov of the IOS has proposed the use of selective laser ionization as a source for epitaxial growth, which he terms "photoionic laser epitaxy." In his proposed concept, a molecular beam composed of a variety of elements is selectively ionized by a tunable laser. The specific ions of interest are selectively deposited onto a substrate, whereas the neutral species are collected for recycling. Switching laser frequencies allows a rapid selection of the element of interest as the ion beam is slowly deflected over the surface of the substrate. [redacted]

Potential Applications and Industrialization. The field of laser-induced surface chemistry offers the greatest number of current laser chemistry applications. The unique asset of this field is the ability to transform the physical and/or chemical properties of a surface in a highly localized fashion without affecting the bulk material properties. Most of the applications are concerned with the surface chemistry of metallic or semiconductor materials. [redacted]

Laser-induced surface chemistry can be used to harden and increase the resistance to corrosion of metallic surfaces. The local crystalline properties of the metallic surface can be transformed by rapid melting and solidification or by selective chemical reaction with powders, liquids, or gases above the surface. [redacted]

The ability to localize selective laser chemical reactions on surfaces has led to a number of techniques for semiconductor processing. These chemical reactions, occurring only within the laser focal volume, can be confined to such a small region of a solid-gas or liquid-gas interface that they are considered as part of a unique field of chemistry known as laser-induced microchemistry. Laser-induced microchemistry can be used to deposit submicron lines of conductive or insulating material on a semiconductor surface or to selectively etch submicron lines without the need for lithographic techniques. These techniques are commonly referred to as "direct writing" (figure 9). [redacted]

Although Soviet scientists originated most of the basic concepts of laser-induced surface chemistry, they have developed relatively few industrial processes. In contrast, applications of laser-induced microchemistry for semiconductor processing are rapidly being developed in the United States. These applications are essentially extensions of Soviet theoretical concepts and basic research. Many Soviet scientists have concentrated their efforts on the most esoteric surface physics questions such as the nature of phase changes and the role of surface waves in laser annealing. Until recently, there was little activity reflected in more mundane but practically useful areas. Important Soviet concepts such as the work by Chebotayev's group, which precedes all of the US activity in laser etching of semiconductors, apparently have not been pursued further in the Soviet Union. US scientists also are pursuing a wide range of future applications, which will require significant fundamental research. [redacted]

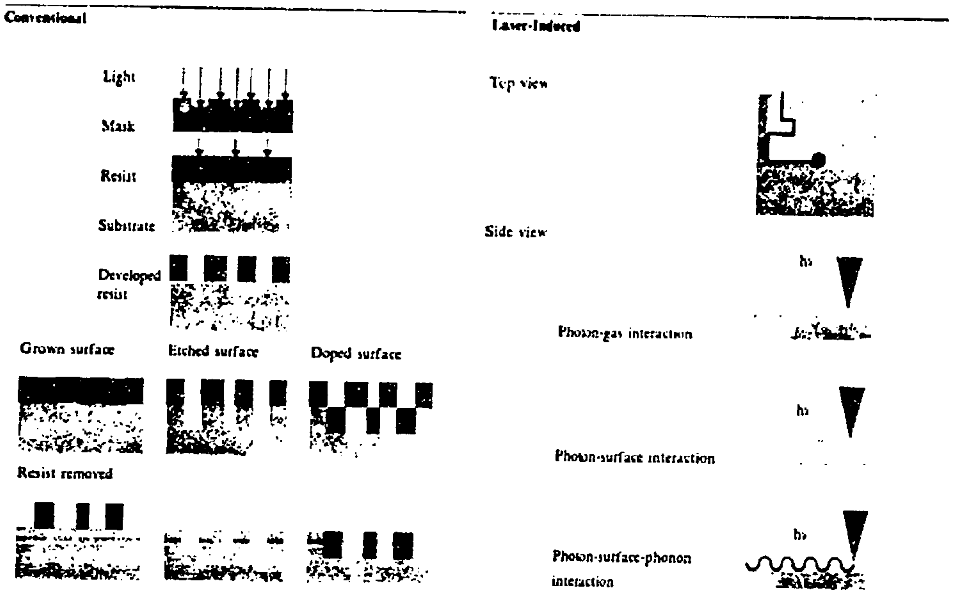
The apparent lack of Soviet motivation for applied research in laser-induced surface chemistry may be because of an absence of a diversified high-technology semiconductor industry. Soviet laser chemistry research is pursuing concepts equal to or more advanced than those in the West, while the Soviet semiconductor industry suffers from a lack of more basic technology. Although these potential applications are imaginative and might eventually lead to an industrial process, they would do little to help the Soviet electronics industry in the near future. [redacted]

Laser Photobiology

Basic Research. Soviet scientists first recognized the potential of performing selective laser chemistry on biological species in the mid-1970s. According to open literature, V. S. Letokhov of the IOS proposed that the same methods used in the selective laser chemistry of small molecules in the gas phase could be extended to biological molecules in solution. It soon became clear, however, that this method would not be a trivial extension (see inset on Selective Laser Photobiology). [redacted]

Although some Western scientists suggested in the mid-1970s that the obstacles to selective laser photobiology could not be overcome, Soviet scientists at the IOS began a coordinated series of technological developments and experimentation toward achieving this goal, according to open literature. Soviet scientists at other research institutes soon developed their own research programs oriented toward a variety of approaches. [redacted]

Figure 9
Comparison of Conventional and Laser-Induced Photolithographic Processing of Semiconductors



Depicted is a comparison of conventional photolithographic processing of semiconductors (left) to possible "direct writing" interactions of a laser beam with a gas-solid interface (right).

The laser process can occur in the gas phase above the surface, on the surface, or by imparting energy into the surface.

[redacted]

[redacted]

One of the initial Soviet concepts for laser photobiology was to use an infrared, picosecond-width laser pulse to achieve selective vibrational excitation followed by an ultraviolet, picosecond-width laser pulse for electronic excitation. Several difficulties have precluded successful application of this method. The very short lifetimes of the excited vibrational states (picoseconds) requires an extremely high-power laser pulse be used to obtain sufficient excitation. Such high laser intensity would also tend to excite the solvent molecules. The Soviets have proposed solutions to these problems but have not had access to infrared, picosecond lasers of sufficient intensity—such as are available in the United States—to test their theories. [redacted]

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Obstacles to Selective Laser Photobiology

Selective laser photochemistry of biological molecules in solution is significantly more difficult than for small, gas-phase molecules. First of all, the absorption bands of biological molecules are broad and strongly overlap so that it is not possible to achieve absorption selectivity for a single photon. Second, the lifetimes of excited electronic or vibrational states of biological molecules are short compared with the laser pulsewidths or reaction times. Even if a selective absorption were possible, the excited state would relax before additional absorption or chemical reaction were possible. Finally, the solvent molecules may be photoexcited and/or react with the biological molecule, thus inhibiting selectivity. [redacted]

The method in which the Soviets have experienced the greatest success has been using sequential electronic excitation with visible or ultraviolet lasers. In such a process, two or more photons are absorbed by the molecule, producing an electronic state not attainable through linear (single photon) absorption. Although the initial photo-absorption process will generally not be selective, the combined multiphoton excitation process may be highly selective. Selectivity results from the difference in dynamics (lifetime) of the initially prepared electronic state. [redacted]

[redacted]

Potential Applications and Industrialization. Laser photobiology has potential applications in biophysics research, laser-induced healing, and genetic engineering. According to open sources, the Soviets have achieved the selective photodecomposition of components of nucleic acids through sequential electronic excitation. Their results suggest that selective interaction with a single component of DNA and RNA can be achieved, and it may well be possible to extend this method to selective laser dissociation for sequencing of DNA and RNA, an important field of biophysics research. [redacted]

The prospects of selective laser photobiology on DNA or RNA have important implications as a selective tool for genetic engineering. The capability of selective laser-induced modifications of DNA or RNA could have significant economic impact and might also lead to the development of new biological weapons. According to open literature, the Soviets also have achieved the synthesis of amino acids by sequential electronic laser excitation of the ammonium salts of dicarboxylic acids. [redacted]

Another achievement by Soviet scientists has been selective laser chemical action on the DNA of living organisms. New types of photochemical damage were observed that had not been seen in linear photobiology. These scientists have mutated bacteria and viruses in a selective fashion. [redacted]

Efforts at Industrialization. The Soviets are proceeding quickly to develop practical applications of laser photobiology. In our judgment, they have established good connections between basic physics institutes and applied biology research institutes, and many Soviet biologists have become familiar with the use of lasers in their research. Much of this success is because of the recent establishment of NITsTLAN. [redacted]

Close communication with medical institutes has enabled new principles developed at basic research institutes to be rapidly tested and applied in medicine and biophysical research. Techniques developed at the IOS in the early 1980s are already being found indispensable by scientists at the Shemyakin Institute of Bioorganic Chemistry (IBKh) in their research on polypeptide neurotoxins, important in biological weapons research, bacteriorhodopsin, and in the development of optical memory devices and high-resolution imaging systems. [redacted]

Although some Western scientists initially rejected the potential success of laser photobiology, many are now beginning to follow the Soviet research closely. [redacted] Some US scientists have indicated that they could achieve parity with the Soviets within five years should any commercial applications become evident. [redacted]

Laser Analytical Chemistry

Basic Concept

Laser analytical chemistry combines the high selectivity associated with laser chemistry with sensitive detection methods to provide the potential for detecting a single component among a complex mixture of components with otherwise similar physical characteristics. According to open-source literature, Soviet scientists recognized this potential in the early 1970s and have been responsible for most of the major accomplishments in the field. They have pursued research aimed at the detection of single atoms, of single nuclear isomers, of specific chemical bonds, and sensitive detection of complex molecules. [redacted]

The basis for laser chemical detection of atoms or molecules relies on the selective chemical transformation of species that cannot be readily detected into species that can. The laser chemical techniques developed for isotope separation, purification, and photochemistry are all applicable to analytical chemistry, provided a suitable detection method is available. When the laser interaction ultimately leads to the production of charged species, the detection efficiency can be nearly 100 percent. [redacted]

Detection of Atoms

Basic Research. Soviet scientists at the IOS, under the direction of V. S. Letokhov, first proposed the application of nonlinear laser excitation for the detection of single atoms in 1970 and have pursued research in this field at a relatively constant level. A procedure for selective excitation followed by ionization must be developed for each atomic species of interest, and the parameters precisely tuned to obtain essentially 100 percent without loss of selectivity. Detection of the resultant charged species may be accomplished with conventional ion multipliers and does not represent a significant development of the application. [redacted]

Scientists at the IOS began experimentation with neutral atomic beams in the late 1970s. The advantage of using atomic beams is that in a collisionless environment electronic transitions have a more narrow linewidth, permitting greater selectivity. Under such conditions, the Soviets were able to detect specific nuclear isotopes with near-unit efficiency. The majority of their experiments involved detection of sodium or ytterbium isotopes. [redacted]

In the early 1980s, scientists at the IOS coupled their single atom detection system with mass spectrometry. Mass analysis of the laser ionization products gave a large improvement in selectivity, enabling a wide range of species to be studied with less stringent demands on the excitation scheme. The mass spectrometer, however, had to meet very demanding requirements in order to have good mass selectivity without loss of sensitivity. Present Soviet research is aimed at developing improved mass spectrometers, which take maximum advantage of the characteristics of selective laser ionization. [redacted]

Although Soviet scientists have generally led in the basic research of laser detection of single atoms, their work has been closely followed by Western scientists—with a research gap of no more than five years. Soviet technological achievements in the construction of the laser mass spectrometer have been duplicated in the West, where significant improvements have been achieved through computer interfacing and fast digital signal processing, giving the West a small lead in industrial applications. [redacted]

Potential Applications and Industrialization. The capability of detection of single atoms afforded by laser mass spectrometry offers a variety of analytical applications, most of which are extensions of conventional analytical applications to significantly lower limits of detection. Of particular importance are those applications where extremely small concentrations of atomic species are significant, such as for process control and quality assurance in semiconductor manufacturing, and for pollution monitoring of toxic heavy metal elements. The Soviets are also pursuing laser detection for studying ocean currents and tracing the source of metal ions in coastal waters. [redacted]

[redacted]

Soviet industry has been quick to accept laser atomic detection techniques for process control and quality assurance. The simplicity of the technique and the associated instrumentation has enabled a variety of Soviet scientists and engineers to make use of laser detection in their applied research and to quickly develop the technique for industrial applications. The Soviets take pride in their use of laser detection, a Soviet development, to solve key problems facing their semiconductor industry. [redacted]

Detection of Molecules

Basic Research. Detection of single molecules is a much more difficult task than the detection of single atoms. Indeed, detection of trace quantities (parts per billion) of a chemical in a complex mixture is rarely possible with conventional means. Soviet scientists at the IOS have vigorously pursued selective laser ionization as a means of overcoming this inherent difficulty. [redacted]

In the early 1970s, according to open literature, Soviet scientists first proposed the use of laser ionization with mass spectrometry for trace analysis of complex molecules. In the late 1970s, the Soviets developed a two-dimensional (wavelength and mass) optical mass spectrometer in which multiple laser beams induce selective ionization of a specific molecule followed by conventional mass analysis. This procedure enabled high selectivity but relatively poor sensitivity because of limitations in the mass analysis. [redacted]

Efforts to improve ion detection efficiency led to the development, in the early 1980s, of a time-of-flight mass spectrometer specifically suited for selective laser ionization. Such an integrated system finally enabled the Soviets to achieve their goal of a single molecular ion detection system (see figure 10). [redacted]

According to open literature, Soviet efforts to improve on their laser mass spectrometer have since concentrated on the laser ionization process, where the primary selectivity is determined. Each molecule of interest must be examined in connection with the environment in which it will be analyzed. Soviet scientists have combined infrared laser pulses with visible and ultraviolet laser pulses in a variety of ways to achieve high selectivity for specific molecules. They have also examined supersonic expansion of the sample gas to "cool" the species and thus reduce the vibrational energy. This "cooling" has improved both selectivity and sensitivity with mixtures of very similar complex molecules. [redacted]

Potential Applications and Industrialization. Applications of laser detection of single molecules are much more varied than for single atoms because of the relatively poor sensitivity and selectivity of conventional molecular analytical techniques. Potential applications exist for pollution monitoring, process control and quality assurance in industry, the characterization of solid surfaces, and for virtually every current application of conventional analytical techniques. [redacted]

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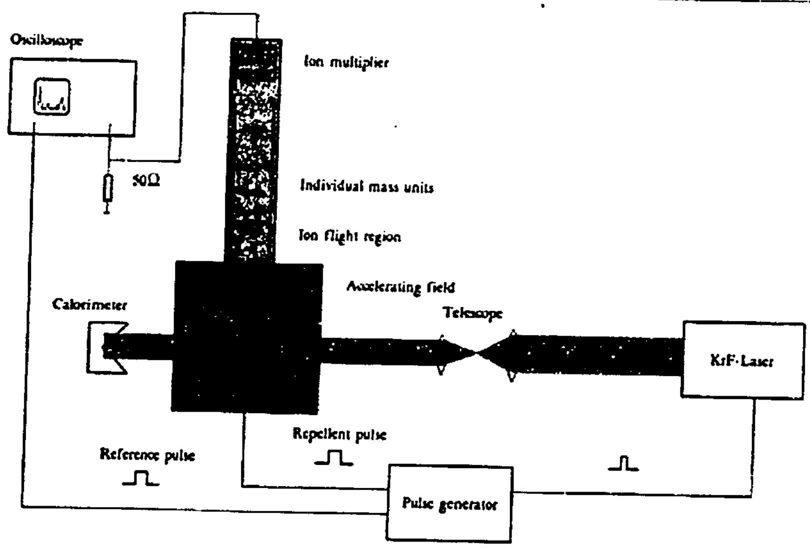
Figure 10
Experimental Setup for the Laser Photoionization Detection of Molecules in a Time-of-Flight Mass Spectrometer



After laser ionization, an electric field pulse repels the ions into a field-free drift region where they sort out into bunches according to mass. An ion multiplier records the presence of a single ion and the time-of-flight determines the mass.

[redacted]

One application of laser detection of particular importance is the characterization of solid surfaces with submicron resolution. In this technique, referred to as laser microprobe mass spectral analysis (LAMMA), a focused laser vaporizes a microscopic part of a solid surface that is subsequently ionized and mass analyzed. The technique may be designed to be highly selective or nonselective in either the vaporization or ionization phase and is applicable to the study of trace species absorbed on a surface (see insert). [redacted]

Although the Soviets have been world leaders in the basic research of laser detection of molecules and have finally reached their goal of single molecule detection, they have developed relatively few industrial applications compared to the West. In part, this lack of development is because of the isolation of basic research at the IOS and the lack of cooperation with

Laser Microprobe Mass Spectral Analysis

LAMMA employs a focused laser to vaporize and ionize a small amount of surface material for mass spectral analysis. Laser ionization can occur simultaneously with vaporization or with a subsequent laser pulse. By sharply focusing an infrared laser on a surface, a nonselective vaporization/ionization occurs. This lack of selectivity is desirable when the material is being analyzed for unknown components and when comparison to existing electron-impact mass spectral data (also nonselective) is essential. In the selective technique, a low-power laser is used to selectively remove a species from the surface and selectively ionize the species. This technique is applicable to the study of ultratrace species absorbed on a surface. [redacted]

other Soviet scientists at applied institutes. The necessary instrumentation for laser detection of molecules is significantly more complex than for laser detection of atoms. Because Soviet industry does not produce a complete detection system, it is necessary for each research group to construct their own equipment. An industrial application would require physicists and technicians to assemble and maintain the equipment. [redacted]

Soviet achievements in LAMMA have been closely followed in the United States and other Western countries, where they are quickly replicated and assessed for potential applications. Although the LAMMA technique is based on Soviet developments, it was applied first in West Germany and subsequently in the United States. West German LAMMA spectrometers are now being marketed internationally and have replaced many other surface analysis techniques as the method of choice, with the most significant application being for the characterization of semiconductor surfaces on a microscopic basis. [redacted]

The Soviets are planning, however, to attempt laser mass spectral analysis from Martian orbiters in 1988. R. Z. Sagdeyev, director of the Soviet Institute for Space Research (IKI), in Moscow revealed in an open-source publication that a megawatt laser in one of the orbiters would vaporize small amounts of material from the surface of one of the Martian moons, Phobos, for subsequent mass spectral analysis. This action would be accomplished as the orbiter approaches Phobos to within 100 meters of the surface. [redacted]

One application of laser detection of single molecules that the Soviets may have been fast to develop is the real-time detection of chemical toxins. This analysis is a particularly difficult problem because of the complexity of the molecules and the extremely low concentrations of interest. [redacted]

Industrialization of Laser Chemistry

Although Soviet scientists have pioneered many areas of laser chemistry and achieved the respect and attention of their Western colleagues, the Soviets have lagged behind the West in developing many commercial or industrial applications. Impediments to applications of this technology include a lack of effective communication between research institutes and the industrial sector, a lack of concern on the part of industry to incorporate new and unproven technology at the risk of temporarily reduced production, a lack of reliable industrial lasers and trained laser technicians, and shortages of the controls and machinery to operate the laser systems. Soviet scientists and policymakers have been concerned about methods to stimulate the development of industrial applications of laser chemistry since the early 1970s. They took significant action toward achieving this goal during the early 1980s by establishing the 11th Five-Year Plan. [redacted]

The Soviets implemented the 11th Five-Year Plan, 1981-85, which called for the "Development and Production of Laser Technology for the Economy."

Among the specific directions for this program were the development of high-power (one to 10 kilowatts) industrial lasers (now in prototype form), the establishment of a production facility for such lasers (presently under construction), and the merging of basic research institutes with industrial research institutes and with potential industrial consumers (see inset on page 2). [redacted]

Outlook

The Soviets, who clearly are the world leaders in basic research, currently are making progress in their efforts to narrow the gap between basic research and industrial applications. Because of their increasing experience and investment in pilot-plant-level developments, we believe that they have a good chance of successfully developing industrial-scale applications over the next 10 to 20 years; and, unless a comparable major effort in the West is initiated, the Soviets are likely to become the world leaders in the industrialization of laser chemistry by the mid-to-late 1990s. We believe the types of applications the Soviets will emphasize will continue to depend on their ability to develop and produce reliable industrial lasers. Before 1990, the Soviets will probably emphasize those applications of laser chemistry that can use fixed frequency gas or solid-state lasers such as ultrapurification, laser-induced synthesis, and materials processing. Current development indicates that by 1995, however, the Soviets will have a variety of frequency agile lasers in production to enable the rapid industrialization of most other potential laser chemical applications. [redacted]

Isotope Separation

Soviet emphasis on basic research into LIS with long-term interests in commercial processes has led to a rapid growth in the understanding of laser chemistry and the technology of separation. This understanding, however, has come without a large-scale effort toward an industrial-level uranium enrichment process. Establishment of the world's first two pilot plants for LIS has given the Soviets the experience needed to develop LIS plants. Because of the present rate of development, we believe that, by 1995, the Soviets will develop small industrial plants for the production of small quantities of light isotopes for basic research and medical applications. [redacted]

Open publication of US results on uranium enrichment provide the Soviets with the technical details needed to develop this type of pilot plant. Engineering of an industrial LIS process for uranium enrichment, however, would require at least 15 years for the Soviets to achieve. In addition, the Soviets need to make substantial improvements in their industrial laser technology before such a process could be operated reliably. On the basis of the current rate of Soviet progress in associated technology, we believe the Soviets could not operate an industrial plant for uranium LIS before the turn of the century. [redacted]

Ultrapurification of Fine Chemicals

Analysis of trends in scientific research indicates that the Soviets have identified the semiconductor industry as having an existing need for laser purification techniques and have shifted their research efforts toward developing practical methods for the purification of semiconductor materials. Although reliable industrial lasers are not yet available, by 1990 the Soviets could operate a pilot plant based on current laser technology to demonstrate the economic advantages of laser purification. [redacted]

Direct Photochemical Synthesis

The Soviets probably will continue as world leaders in the basic research of laser photochemical synthesis because of the size and quality of their program. Their ability to capitalize on the applications of this research, however, will depend on the establishment of pilot plants to demonstrate the feasibility of large-scale production. We believe the Soviets are now technically capable of operating a pilot plant for laser photochemical synthesis and will probably do so within this decade. [redacted]

Laser-Induced Catalytic Synthesis

We believe the Soviet leadership in laser chemistry research has placed the Soviets in a position to proceed quickly with the development of the world's first pilot plant for laser-induced free-radical synthesis. The Soviets will then have a more economical means of producing important industrial chemicals and the experience needed to promote many other potential applications. Although the Soviets have been prepared to establish a pilot plant for several years, indications that the West is considering such a step may be inducements for the Soviets to proceed more quickly. We believe that the Soviets will establish a pilot plant for LICS by 1995 on the basis of current Soviet laser technology. [redacted]

Laser-Induced Surface Chemistry

Soviet scientists and policymakers are becoming increasingly interested in the development of practical applications of laser-induced surface chemistry. Pilot plants are being considered for the modification of metallic surfaces and the processing of semiconductors. Some pilot plants are now operational and others will be completed within the next five years. Although the Soviets have demonstrated the potential benefits of laser-induced surface chemistry in a variety of industries, the lack of reliable industrial laser systems will limit industrial applications. [redacted]

One of the goals of NITsTLAN is to develop laser surface processing applications to meet the current needs of industry. The center has been highly successful in bringing to industry the simple applications that depend on the laser for local heating, such as surface hardening, but it has not yet found a market for the more advanced techniques. As the Soviet semiconductor industry develops, sophisticated laser-induced surface processing techniques probably will be developed. [redacted]

Laser Photobiology

The Soviets are devoting major resources to laser photobiology, and are establishing a network of institutes to exploit what remains essentially a Soviet field. Those scientists responsible for initiating the field of laser chemistry and exploiting its inherent selectivity for isotope separation and chemical synthesis are now devoting most of their attention to photobiology. We believe the Soviets will continue to lead in the basic research of laser photobiology and will continue to achieve success at finding novel methods for selectivity. The ultimate significance of laser photobiology for genetic engineering and the development of new biological toxins will depend on the Soviets' ability to incorporate the benefits of this technique with conventional genetic engineering methods. [redacted]

Laser Analytical Chemistry

Detection of Atoms. Although Soviet scientists have completed most of the basic research essential to the development of laser detection of atoms as an industrial tool, we believe they will continue to refine the technique to optimize the efficiency and selectivity for a variety of applications. The use of laser detection of atoms, one of the most sensitive of all analytical techniques, will place the Soviets roughly on a par with the West for these applications. [redacted]

Detection of Molecules. Soviet scientists are continuing to develop sensitive laser analytical techniques for a variety of molecular species and potential analytical applications. The uses of laser detection as a tool in other scientific research areas such as oceanography, mineralogy, and space research will grow. Although the Soviets will probably continue to lead in the basic research of these applications, they will continue to lag in the development of industrial applications until the necessary commercial equipment is available. [redacted]

The proposed LAMMA analysis of the Martian moon Phobos, if successful, will draw considerable attention to the utility and sensitivity of laser detection. We believe the Soviets will establish their position as world leaders in this research and will use the publicity associated with the mission to motivate Soviet industry to adopt these techniques. [redacted]

Future of Soviet Laser Chemistry

We believe the Soviets will continue as world leaders in the basic research area of laser chemistry. Soviet scientists in this field follow a tradition of excellence from the early 1970s, and younger scientists continue to be given the freedom to pursue imaginative directions. [redacted]

Soviet basic research efforts in the most significant areas of early research—LIS and laser ultrapurification and laser detection—will begin to decline as most of the basic research is completed and these fields become more applied. We believe the Soviets will increase their basic research efforts in the more complex and more challenging areas of laser-induced surface chemistry and laser photobiology. [redacted]

Soviet scientists will continue to pursue a wide range of potential applications of laser chemistry but with greater focus on those applications with realistic potential for industrialization. Efforts by the Soviet Academy of Sciences to stimulate academy institutes to develop practical applications and improved communication between the research and industrial communities have given scientists an understanding of the needs of industry and the incentive to develop applications to meet these needs. [redacted]

Applications of laser chemistry in the Soviet semiconductor industry are growing rapidly as the industry expands and develops. Demands for increased production and higher purity of semiconductor products will be met, in part, by a wide range of laser chemical applications. Soviet scientists were well prepared to meet this challenge having years of experience in the basic research of the laser chemistry of semiconductor materials. Scientists of the IOS, MITKhT, IFP, and FIAN are now cooperating on the development of industrial-level applications, according to open-source literature. [redacted]

Soviet scientists have dominated the field of selective laser photobiology and have consistently emphasized the importance of potential applications in biophysics research, in genetic engineering, and in laser-induced healing. The Soviet research program in laser photobiology is growing stronger, and communications links between physics institutes, medical research institutes, and medical clinics are well established. Soviet scientists recognize the unique capabilities of laser photobiology and will continue to actively pursue applications. [redacted]

Since the early 1970s, Soviet laser chemistry has been well funded with the promise of providing Soviet industry with practical industrial applications. Soviet scientists are now working in an organized program to develop practical applications and to prove the merits of their applications to industry. The Soviets are attempting to accomplish this effort by developing pilot plants at industrial facilities where they can be merged with the industrial production. Although large-scale industrialization of laser chemistry will require further developments in industrial laser technology, we believe the Soviets will be proceeding with the development of a variety of prototype and pilot plant operations. [redacted]

The Soviets have extended the Five-Year Plan to develop practical industrial applications of laser chemistry and could soon become world leaders in the application of this technology. Areas of laser chemistry such as laser photobiology, which are still essentially unexplored in the West, could lead to unexpected technological developments with industrial and military significance. The Soviet excellence in laser chemistry could enable the Soviets to meet or exceed world standards in areas where they have some key technological problems such as in the semiconductor industry and to move ahead in other areas where they are presently strong such as surface chemistry. [redacted]

Appendix

Glossary

AVLIS	Atomic vapor laser isotope separation.
Anneal	A process of heating to reduce crystal defects.
Atomic beam	A colinear beam of atoms with equal velocity.
Bacteriorhodopsin	A protein from salt-loving bacteria that serves as a solar energy converter.
Brightness, source	Light intensity per unit surface area of source and per unit solid angle.
Catalyst	A reactant that helps direct a chemical reaction without being consumed in the reaction.
Deuterium	An isotope of hydrogen having an atomic weight of 2.
Dissociation	The breaking of a molecular bond leading to molecular fragments.
Dopant	A small quantity of a substance added to a semiconductor to alter the electronic properties.
Efficiency	The ratio of energy utilized in the reaction to the energy input.
Electronic transition	A change in the energy associated with the motion of bound electrons.
Electrostatic separation	The separation of charged particles by deflection through an electric field.
Epitaxial growth	Surface growth of a crystal from the gaseous or liquid phase.
Fine chemicals	Ultrapure chemicals used as dopants to influence the properties of bulk materials.
Free radical	An atom or molecule containing an unpaired electron.
Frequency agile	A laser that can be tuned or shifted rapidly to a variety of wavelengths.
Gamma ray	A photon of energy greater than several hundred thousand electron volts.
Ion multiplier	A detector designed to produce a large current pulse when impacted by a charged particle.
Ionization	The removal of an electron from an atom or molecule.
Ionization potential	The energy required to remove an electron from an atom or molecule.

Isotope	Atoms with the same number of protons but with different numbers of neutrons leading to different masses.
LAMMA	Laser microprobe mass spectral analysis.
Laser	Light amplification through stimulated emission of radiation.
Laser chemistry	The use of laser radiation to effect a stable change in the physical properties of a substance.
Linewidth	Range of wavelength over which a transition can occur.
LIS	Laser isotope separation.
Mass spectrometer	A device that separates atoms or molecules according to mass.
MLIS	Molecular laser isotope separation.
Molecular transition	A change in internal energy of a molecule associated with a combination of electronic, vibrational, and rotational energy.
Neurotoxin	A toxic substance that acts on the nervous system.
Neutron	A particle in the nucleus of an atom with no charge.
Nuclear enrichment	An increase in the percentage of rare isotope in an isotopic mixture.
Nuclear isomers	Long-lived states of an atomic nucleus.
Nucleus	Center of an atom containing protons and neutrons.
Photobiology	The interaction of light with biological molecules.
Photochemistry	Chemical reactions driven by the absorption of light.
Photon	A single quantum of light energy.
Population inversion	A situation in which more nuclei, atoms, or molecules are in a higher energy state than in a lower energy state; a situation essential for lasing.
Product	The result of a chemical reaction.
Quantum yield	The number of product species formed per photon absorbed.
Rare-earth	Any of the metallic elements of atomic number 57 through 71.
Reactant	The starting constituents of a chemical reaction.

Reaction path — The course of a chemical reaction from reactants through intermediates to products.

Rotational transition — Molecular energy associated with the rate of rotation of the molecule.

Selectivity, absorption — The degree to which one component absorbs radiation compared to the absorption by other components.

Selectivity, reaction — The degree to which one reaction path is followed compared to other reaction paths.

Species — A general term applied to neutral or charged atoms or molecules.

Spatial coherence — The degree to which the wavefront at one point in space is in phase with another point in space.

Supersonic expansion — The expansion of a gas through a small aperture into a region of low pressure: the local sound velocity drops leading to supersonic velocities.

Surface chemistry — Chemical reactions occurring in the region of an interface between a solid surface and a liquid or gas.

Temporal coherence — The degree to which the wavefront at one point in space and time is in phase at another point in time.

Thermal blooming — A negative lens effect associated with heating of the atmosphere leading to rapid divergence of the beam.

Time-of-flight — The time it takes for gaseous atoms or molecules to pass through a known distance.

Tritium — An isotope of hydrogen having an atomic weight of 3.

Ultrapurification — The removal of trace impurities left after conventional purification procedures.

Vibrational transition — A change in the energy associated with the motion of atoms in a molecule.

Yield — The ratio of desired products to initial reactants.

[redacted]

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