

**LASER ISOTOPE SEPARATION
AND THE FUTURE OF
NUCLEAR PROLIFERATION**

Ruben M. Serrato

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Laser Isotope Separation and the Future of Nuclear Proliferation

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Abstract

Laser isotope separation (LIS) is an emerging technology that uses relatively small, widely-available lasers to achieve civilian or weapons grade concentration of fissile material to fuel nuclear reactions. To date only a few, limited proliferation risk analyses of LIS technology have been conducted. This paper provides a historically and technically informed update on the current state of LIS technology and it explains the high likelihood of increased global LIS adoption. The paper also explains how international rules governing nuclear energy are ill-equipped to handle such new technology. It traces the current limitations to broader issues in international relations theory, especially the incomplete accounts of the role of technology in the proliferation dynamic in the dominant neorealism and social construction of technology approaches. The paper introduces the concept of “international technology development structure,” a framework for understanding how technology-related opportunities and constraints at the international system-level influence state nuclear weapons choices.

It provides a thorough update of recent international laser innovations relevant to laser isotope separation and it explains how the spread of laser-related knowledge expands state nuclear options and influences their choices. The paper also provides a country-by-country update on LIS programs and it uses the example of Iran’s laser isotope separation program to show how existing International Atomic Energy Agency efforts and export control approaches will be inadequate to addressing dual-use technologies such as LIS. It concludes by proposing a new course that links good standing in nuclear non-proliferation agreements to participation in the World Trade Organization, global conferences, and fundamental university research. Ultimately, the paper attempts to provide a comprehensive account of how emerging laser isotope separation technology presents non-proliferation challenges and it attempts to explore

options for addressing this new period in technological achievement and change.

Key Words: Laser isotope separation, SILEX, AVLIS, MLIS, uranium enrichment, plutonium extraction, nuclear proliferation, neorealism, social construction of technology, constructivism, lasers, free electron laser, Iran, Kenneth Waltz, tunable laser, copper vapor laser, dye laser, solid state laser, carbon dioxide laser, UV laser, fiber laser, gaseous diffusion, gas centrifuge, nuclear fuel cycle, photoionization, photodissociation, global laser enrichment, dual use, tritium, World Trade Organization.

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I. Introduction

The first devastating demonstration of nuclear fission, the process in which atoms of a heavier element release energy as they split into lighter elements, at Hiroshima in August 1945 led to calls for global efforts to prevent the spread of nuclear weapons. The establishment of the United Nations (UN) in October 1945 provided a platform for various international efforts to control nuclear technologies, most significantly the establishment of the International Atomic Energy Agency (IAEA) in 1957. Today numerous global organizations, treaties, and agreements are in place to control the spread of the highly specialized equipment and knowledge used for the production of fissile material, the particular forms of uranium and plutonium that power fission reactions. However, a new technology, based on comparatively small, widely available lasers capable of civilian or weapons grade “enrichment” or concentration of fissile material, may undermine the technology denial and control efforts upon which the international nuclear order is built.

Laser isotope separation (LIS) is an emerging enrichment technology that has attracted little attention in recent years and for which only a few limited proliferation risk analyses have been conducted. Analyses of weapons proliferation risks have yet to go beyond the discussion of whether the lasers used in the LIS process are too specialized to ever be widely appropriated, or the opposite view that lasers are so much smaller and widespread than prior enrichment equipment that LIS emergence would mark an end to nonproliferation efforts altogether. The exclusive focus on device-related differences between laser equipment and existing gas centrifuge and gaseous diffusion equipment ignores the social and ideational factors that will be critical to the future path of LIS. Importantly, the overemphasis on device-related components of technological change is mirrored in broader international relations theory and export control policies, which fail to reflect the full range of ways new technologies may change proliferation dynamics.

Indeed, the most important differences between LIS and other uranium enrichment and plutonium extraction technologies relate to

broader, less easily definable differences involving the spread of knowledge related to the underlying systems. Focusing on the spread of knowledge at the international system level reveals that lasers are an increasingly important part of medicine, industrial manufacturing, and electronics industries. The number of countries possessing the requisite knowledge to develop LIS systems is greater than it is for existing enrichment technologies and innovation by private groups in related industries occurs at speeds previously unseen in the highly regulated nuclear energy industry.

By moving the focus on “technology” to a more complete investigation into the *ideas, systems, and institutions* involved in LIS production, it is possible to more accurately and completely define the nature of the change involved and to provide insight critical to bridging gaps in existing nonproliferation theory and export control policy. Effective LIS nonproliferation efforts will require a shift from policies solely designed to limit the spread of particular devices and equipment towards approaches that combine new international commitments with incentives such as linking participation in global laser developments and trade to honoring nonproliferation obligations. Thus, LIS systems will be difficult to track and detect not only because of their small size and high efficiency, but also because of the privatized, fast-moving, global development structure behind their development. Oversight efforts must address the motivations and means behind state technology choices by creating a new system of international incentives that makes participation in global technology trade and research dependent upon honoring nonproliferation obligations.

This paper proceeds in four parts. Sections I through III provide necessary background information on LIS that helps situate the rest of the paper. It explains the role of enrichment in nuclear weapons acquisition and compares LIS with prior enrichment technologies. It also provides a brief history of the origins of LIS development as well as technical background information, including explaining the different laser-based approaches that have been pursued.

The second part of the paper takes up sections IV through IX and addresses existing theoretical inadequacies that limit LIS proliferation analyses. It summarizes existing literature on LIS proliferation risks and argues that the failure to get beyond “what if” scenarios reflects shallow and inadequate focus on technology-

related issues in nonproliferation literature in general. The section reexamines the meaning of “technology” by pulling from definitions in economics, sociology, and other fields. It offers a new definition in order to better forecast the future of LIS. The central argument is that both of the major strands of nonproliferation theory today, neorealism and constructivism, fail to account for the importance of global technology trends, or international technology development structure (ITDS), in state decisions involving nuclear weapons. This part of the paper concludes by applying the ITDS lens to the case of Iran’s LIS program.

The third part of the paper, in sections X through XIII, explains why global technology trends virtually guarantee greater LIS availability and adoption. It provides the reader with an update on the real LIS development decisions taking place globally and it provides concrete support for the theoretical argument that information available at the international level changes state technology development choices. It details the equipment requirements of LIS systems and it shows how current trends in lasers and other technological advancements are lowering the hurdles to LIS acquisition. This part of the paper concludes with a nation by nation update on LIS efforts. The final part of the paper is its conclusion. The conclusion aims to show how the theoretical and technical discussions in this paper constitute an imperative for a new approach to nonproliferation more appropriate to the coming era of broad-based nuclear technology access.

II. The Role of Laser Isotope Separation (LIS) in Fissile Material Production and Nuclear Weapons Acquisition

Broad expansion of LIS could pose a nonproliferation challenge because, while other technologies such as the warhead, delivery and detonation systems are also required, the most difficult step in building a nuclear weapon is acquiring the requisite fissile material (Wood, Glaser and Kemp 40). In order to understand how nuclear fuel is produced, it is necessary to briefly review the basics of atomic structure.

All atoms of the same element have the same number of protons and electrons, but the numbers of neutrons may vary. Atoms of a given element with different numbers of neutrons are termed isotopes. Fissile isotopes are those that, in the presence of an additional neutron of any energy, split into lighter elements and release additional neutrons in the process to create a chain reaction. This process, termed fission, converts mass into energy as the heavier atom splits into lighter ones.¹ Fissile isotopes are extremely rare and uranium 235 (U235) and plutonium 239 (P239) are the only two that have been used to power nuclear reactions.

Natural uranium is composed of 99.3% uranium 238 (U238) isotopes and only 0.7% U235 isotopes. Uranium enrichment technologies are those that increase the U235 content. In civilian nuclear energy reactors the percentage of the final product that is U235 is increased to between 3% and 5%.² In order to power

¹ This is the meaning of Einstein's famous $E=MC^2$ equation, energy is equal to mass times a constant (acceleration).

² The 3-5% requirement applies to the light water reactors generally used in nuclear energy. Another technology, heavy water reactors are capable of being fueled by natural uranium. So far only a few nations have developed heavy water reactors and there is a debate regarding their proliferation risks and potential control measures. However, that discussion is beyond the scope of this paper.

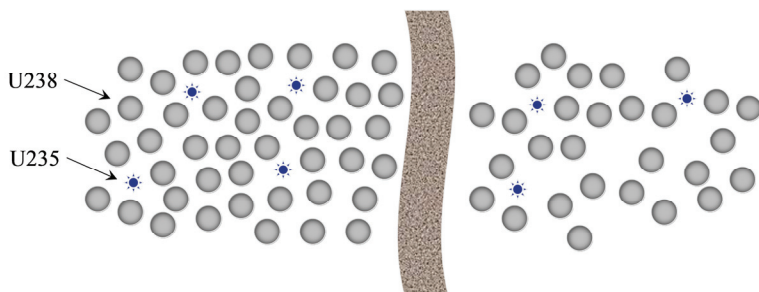
nuclear weapons the U235 content must be increased to greater than 90% of the final product (Krass, Boskma and Elzen 5-6).³

Unlike uranium, plutonium is not naturally available, but is produced when U238 is irradiated with neutrons in nuclear reactors. The product from such reactions includes a mix of plutonium isotopes, of which P239 is the desired fissile material. In order to power weapons, the P239 content must be increased to greater than 93% of the final product. LIS techniques have been developed for both U235 and P239 enrichment. LIS plutonium extraction is discussed further in Section IV. However, uranium enrichment is the main focus of this paper since global programs have primarily been focused on LIS for uranium enrichment and it will have the greatest immediate impact on the nuclear landscape. Nevertheless, growth in LIS for uranium enrichment will also likely facilitate additional efforts at plutonium extraction as well. A comparison to existing uranium enrichment technology is presented next.

Gaseous diffusion, the first dominant uranium enrichment technology, was developed during the 1940s as part of the United States (US) effort to build the first nuclear weapon in the Manhattan Project. The process exploits the fact that particles with the same kinetic and/or motional energy have different velocities depending on their mass. Thus U235 particles with slightly lower mass than U238 particles tend to have higher velocities as they are pushed through a semi-permeable membrane. The higher velocities enable the U235 particles to pass through the semi-permeable membrane more often than the heavier, lower-velocity U238 particles.

³ It is explosive at levels as low as 10%. As one goes from 90% to 10% the amounts of uranium needed to generate an explosion, so-called “critical mass,” go up and the technical difficulty of initiating the reaction is greatly increased.

FIGURE 1: GASEOUS DIFFUSION PROCESS



Gases of uranium particles are passed through a semi-permeable membrane with larger U238 particles preferentially caught leaving a higher ratio of U235 molecules.

However, because mass differences are so small between the two particles, the process is very inefficient, requiring thousands of iterations for minimum levels of enrichment. Facilities also consume enormous amounts of energy. For example, the original plant at Oak Ridge, Tennessee covered sixty acres with multiple buildings that were up to a half mile long (Bledsoe 4). *Science Magazine* noted that the inefficiency of gaseous diffusion was one of the main reasons nuclear technology was contained for so long, stating that:

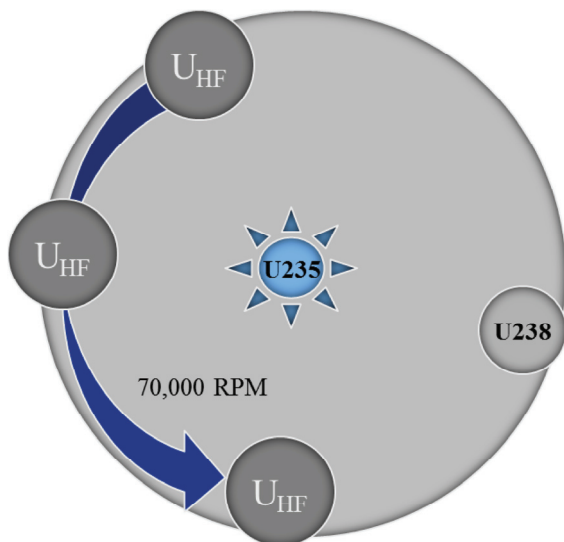
The sheer difficulty and expense of enriching uranium have worked for 30 years as effective restraints on the availability of nuclear fuel and weapons...One of the hardest things on earth to hide is a gaseous diffusion plant; its mere presence on the landscape, easily detected by satellites, is a dead giveaway of a nation's nuclear intentions. (Gillette, Uranium Enrichment: Rumors of Israeli Progress with Lasers 1172-3)

The entire US enrichment capacity remains gaseous diffusion through its three plants at Oak Ridge, Tennessee, Paducah, Kentucky, and Portsmouth, Ohio. These plants supplied nearly 100% of the market for global enrichment service outside of the Soviet Bloc through the mid-1970s (General Accounting Office 37). In recent years the US share of the world uranium enrichment

market has fallen to roughly 40%, due to the lower cost and higher efficiency of gas centrifuge technology (Laughter 4).

Gas centrifuge technology was first deployed in the 1960s by the Soviet Union as a cheaper and more efficient alternative to gaseous diffusion technology. The gas centrifuge approach also takes advantage of velocity differences based on mass but adds the effect of centrifugal force, or the tendency of spinning particles to accelerate outwards. By spinning uranium gas at very high speeds through large chambers, or centrifuges, a pressure gradient is created. Just as in diffusion, the higher velocity U235 particles diffuse through the pressure gradient at higher rates than the U238 particles. Thus the effects of centrifugal acceleration are exaggerated on the heavier U238 isotopes, which tend to end up on the outside wall while the lighter U235 isotopes tend to stay concentrated in the middle of the centrifuge.

FIGURE 2: GAS CENTRIFUGE PROCESS



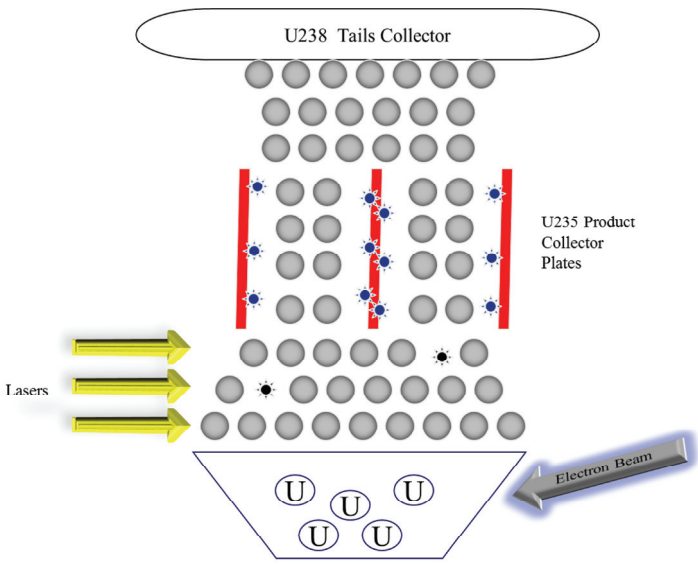
In this process uranium hexafluoride molecules are spun at high speeds, separating U_{235} and U_{238} molecules.

This approach to enrichment consumes only one twentieth of the energy of gaseous diffusion (Lester 16). By the 1970s, European groups interested in cutting into the US lead in enrichment services, especially France and the Urenco cooperative group composed of Britain, Germany and the Netherlands, launched centrifuge facilities (Committee on Foreign Affairs 140). During the last forty years, centrifuge technologies have advanced significantly as groups in the US, Japan, and China have pursued next-generation technology known as Advanced Gas Centrifuge to continue to increase efficiencies related to the centrifuge process. However, like gaseous diffusion, all centrifuge approaches require numerous iterations so that groups of centrifuges, or cascades, need to be built. The specialized equipment and technical expertise requirements of even newer centrifuge technologies still enable control and monitor strategies to be one of the key parts of today's nonproliferation efforts (Drell and Goodby 53-8).

Laser isotope separation development began in earnest in the early 1970s, as nations sought a leapfrog technology capable of

consuming less energy at lower costs than mass-based gas centrifuge and gaseous diffusion processes. While research occurred globally, the US led the way with significant investments designed to protect its lead in enrichment services. The laser isotope separation approach is based on the fact that different isotopes of the same element absorb different colors or energies of laser light. Precisely tuned monochromatic light emitted from a laser may be used to selectively excite and separate desired isotopes.

FIGURE 3: LASER ISOTOPE SEPARATION PROCESS



In this atomic vapor laser isotope separation example, uranium metal vaporizes as it is struck with an electron beam. The vapor is directed through a laser interaction zone where laser light is tuned to be selectively absorbed by U235 atoms. When enough energy is absorbed the U235 atoms become ionized. They are then attracted to negatively charged collector plates while unwanted and unionized U238 atoms pass through without being attracted to these plates.

The efficiency advantages of LIS technology are driven by the fact that light-based approaches are inherently more selective than mass-based approaches. For mass-based approaches all isotopes

must be energized to separate desired U235 particles. For example, U235 and U238 atoms have a miniscule .01 difference in mass, so physical separation requires processing 100 units to separate out 1 unit. By contrast, in LIS, only the desired isotope of interest needs to be energized since selectivity based on color signature is greater than 10,000 to 1 (RS Hargrove 4). This means that 10,000 of the desired U235 units are selected for every 1 of the unwanted U238 units the laser approach selects. Less energy is wasted processing unwanted isotopes in the laser process by a factor of 1,000,000 (Fusion 42). Selectivity also translates into a high degree of enrichment in a single step offering the potential to reduce or eliminate the numerous cascades and iterations required in mass-based approaches (Lester 15). Lasers are also smaller and less expensive to build and operate than existing centrifuge or diffusion technologies.

III. LIS Historical and Technical Background

From the time of the birth of the laser, isotope separation was seen as one of its most immediate and important applications. Work separating isotopes of various elements began almost as soon as the first workable laser was demonstrated by Arthur Schawlow and Charles Townes in 1958 (Schawlow and Townes). Indeed, Schawlow and his team at Stanford University also published the first laser isotope separation experiment in 1966 using a ruby laser to separate bromine molecules (Tiffany, Moos and Schawlow). Three years later the first LIS-related patent was granted to a French group (Robieux, Chatenay-Malabry and Auclair), and throughout the early 1970s laser isotope separation research was aggressively advanced globally.

Isotope separation was also among the very first privately funded commercial market applications pursued for the laser (Bromberg 211). The first workable LIS process was developed by private, Massachusetts-based Avco Everett Research Laboratory (AERL), which was granted the first viable process patent in 1973 (Levy and Janes). Two Israeli scientists also received a laser isotope separation patent in 1973 (Nebenzahl and Levin, Verfahren Zur Isotopentrennung) based upon a 1969 disclosure to the Israeli Atomic Energy Commission (Bromberg 212). Growing global interest in LIS culminated with the US Department of Energy (DOE) funding Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) industrialization efforts in the 1970s and 1980s. In 1981 the DOE exclusively backed the LLNL program, concluding that it was pursuing the most viable approach (Committee on Foreign Affairs 140-141). During the 1990s in an attempt to speed LIS adoption the DOE transitioned the Livermore LIS assets to private company US Enrichment Corporation (USEC) in the largest privatization effort in laboratory history (Lawrence Livermore National Laboratory 23). While USEC failed to commercialize LIS technology in the 1990s, other groups such as Australian Silex Corporation (Silex) continued to make significant strides. In 2000, General Electric (GE) licensed the rights to technology from Silex and established Global Laser Enrichment

(GLE), a joint effort between GE, Hitachi, and Cameco, to commercialize LIS technology.

Although many global LIS efforts, which will be discussed further, have been conducted since the 1970s they are all based on one of two approaches. The first approach depends upon isotopically selective *ionization* of U235 *atoms*, and the second approach depends upon isotopically selective *dissociation* of the bonds holding uranium *molecules* together.

Atomic Vapor Laser Isotope Separation (AVLIS)

Before the laser was invented, in 1905, Albert Einstein laid the theoretical foundation for laser isotope separation and launched the quantum revolution in physics with his Nobel-Prize-winning insight that the energy of a ‘quanta of light’ above a certain threshold has the ability to eject a single electron from matter. Laser isotope separation is based precisely on such light and matter interactions. Light is composed of photons, which consist of energy and travel in waves. The length of their waves depends upon their energy levels. Wavelengths between 380 nanometers and 750 nanometers are visible to the human eye and appear to us as different colors of light.⁴ Atoms, on the other hand are the constituent units of matter. As mentioned in the discussion on fission reactions, which break apart an atom to convert mass into energy, an atom possesses energy that corresponds to its mass; but it can also temporarily store additional energy at a discrete set of possible higher energy states. Magnetic interactions between the protons, electrons and neutrons that compose the atom partly determine the set of possible higher energy states it may occupy. Thus, the particular atomic structure of each isotope results in a unique set of possible higher occupied energy states. An atom will absorb a photon only if it is of the precise energy level that will move that atom to one of these possible higher states. So, a U235 atom which has three fewer neutrons than a U238 atom has a different atomic structure and will absorb photons of different energy levels.

⁴ While the human eye cannot see outside of these wavelengths, the concept of the ‘visible spectrum’ also refers to ultraviolet light with wavelengths shorter than visible between 10 and 400 nanometers, and to infrared light with wavelengths longer than visible between 750 nanometers and 100 microns.

The advent of the laser enabled the delivery of the precise color that corresponds to the exact photon energy that will selectively excite U235 or U238 atoms, but not both, to such higher energy states. As U235 atoms absorb laser energy, electrons move to higher and higher energy states until no higher state exists and the atom emits an electron. Losing this electron “positively ionizes” U235 atoms, meaning they go from having no net charge to having a net positive charge. The amount of energy an atom must absorb to kick off an electron is known as its ionization potential, and for U235 it is 6.2 electron volts (eV) (Eerkens and Miller, Laser Isotope Separation Employing Condensation Repression 2). Both ionized U235 and non-ionized U238 atoms flow from the laser reaction zone through an electromagnetic field that deflects ionized U235 atoms onto negatively charged metallic collector plates. Uranium 238 atoms pass through the laser zone and the electric field unaffected and ultimately re-condense on a separate uncharged collector plate at the top of the chamber. This process was previously shown in Figure 3.

This process of getting an atom to ionize using light, described in Einstein’s early theoretical work, is now known as photoionization. The first private market effort, funded by AERL in 1969, reflected understanding gained from Einstein and used lasers finely tuned to a color only absorbed by the U235 atoms. This process, later termed Atomic Vapor Laser Isotope Separation (AVLIS) made use of color appearing as red-orange to the human eye lying in the 590-600 nanometer wavelength region (Bokhan, Buchanov and Fateev 3). AERL performed the first successful uranium lab scale LIS separations using AVLIS between 1971 and 1973 (J. Eerkens, Laser Isotope Separation – Science and Technology 4). In 1972 AERL secured funding and needed nuclear industry know-how by partnering with a larger partner, Exxon Nuclear, creating Jersey Nuclear Avco Isotopes (JNAI) (Committee on Foreign Affairs). The following year LLNL began its AVLIS program and in 1980 the DOE informed each of the groups that, “a stronger AVLIS program would result from a consolidation of the LLNL and JNAI teams” (US Department of Energy Office of Energy Research 66). The official communication from the DOE to JNAI further stated that LLNL’s AVLIS program was superior due to the laboratory’s unique ability to develop advanced lasers (National Research Council 27). Throughout the 1980s and 1990s US commitment to the AVLIS process led dozens of other countries

to concentrate on the AVLIS approach. Consequently, it has been the most widely pursued LIS method. These countries are detailed in Section XIII.

Molecular Laser Isotope Separation (MLIS)

Despite significant government funding of the AVLIS photoionization approach, at the time of this writing it now seems that a photodissociation process will be the first laser isotope separation approach commercialized. Industrial scale photodissociation approaches began with the Molecular Laser Isotope Separation (MLIS) process pursued by scientists at the Los Alamos National Laboratory in the US. In the MLIS process, U235 hexafluoride *gas molecules* selectively absorb photons until enough energy is absorbed to “shake off” or dissociate one of the fluorine atoms (Denning 246). The resulting UF5 molecule precipitates out of the flow and can be separated and collected out. Final collection may use a filter or cyclone separation system (Boureston, Serrato and Gazze 3). The MLIS process requires two lasers, first infrared and then either infrared or UV wavelengths, which selectively impart energy on U235 or U238 molecules that break their chemical bonds (Jensen, Sullivan and Finch 513). In the 1970s Soviet and US researchers separately discovered multiphoton absorption (MPA) a phenomenon occurring in all polyatomic molecules in which they absorb more than one photon. Molecules may be excited to higher pre-ionization levels than would be possible through single photon absorption (Lathrop, *footnotes to a program).⁵ As mentioned, in 1982 the US DOE chose AVLIS over MLIS effectively ending commercialization efforts in the US. However, as detailed in section XIII, a number of other countries have continued to pursue MLIS and other photodissociation-based approaches. The major variations of other photodissociation methods are detailed next, including the method currently being pursued by GLE.

A less widely pursued photodissociation variant is Separation of Isotopes by Laser Assisted Retardation of Condensation (SILARC), which exploits differences in condensation rates between excited and

⁵ A Los Alamos National Laboratory summary diplomatically states that, “Between 1973 and 1974 both Los Alamos and the Institute of Spectroscopy in the Soviet Union demonstrated multiple-photon excitation” Lathrop, 37.

non-excited molecules. SILARC begins by selectively exciting U235 hexafluoride molecules as in MLIS. However, in the process, since U238 molecules condense at a faster rate than the excited U235 molecules, they are captured and separated using cold walls upon which they more quickly condense (Eerkens and Miller, Laser Isotope Separation Employing Condensation Repression 2). This approach reduces the laser energy that must be selectively absorbed by UF₆ molecules to break chemical bonds and does not require re-fluorination of UF₅ product material as in MLIS (Denning 243). A few private companies and smaller nations have experimented with SILARC.

A related approach is the Chemical Reaction by Isotope Selective Laser Activation (CRISLA) or Chemically Enhanced Molecular Laser Isotope Separation (CHEMLIS) which excites a molecule to such a high energy level that its chemical reactivity increases substantially.⁶ Based on the different chemical reactivities of the two molecules, it becomes easier to separate isotopes by chemical means. This approach was deeply investigated in Japan, South Africa, Australia and China (J. Eerkens, Laser Isotope Separation – Science and Technology 6).

Separation of Isotopes by Laser Excitation (SILEX)

A fourth photodissociation approach and the most likely to be first commercialized is Separation of Isotopes by Laser Excitation (SILEX). Originally developed by Australian Silex Corporation, the technology is currently in the early deployment stages at General Electric's Wilmington, North Carolina facility. As mentioned, GE has established Global Laser Enrichment, a joint venture with Hitachi and Cameco, to pursue full-scale commercialization. The exact scheme of the SILEX technology has been classified. However available published data indicates it may be a SILARC variant. Analyst Mark Prelas states that SILEX uses the different condensation rates of U235 and U238 *gas molecules* to separate isotopes (Nonproliferation Issues for Weapons of Mass Destruction 84).

⁶ Some confusion exists with the term CRISLA. Here CRISLA refers to chemical separation. The acronym has also been used to refer to Condensation Repression by Isotope Selective Laser Activation, here referred to as SILARC.