TRANSMUTATION OF NUCLEAR MATERIALS USING HIGH-POWER LASERS – POTENTIAL APPLICATIONS FOR RADIOACTIVE WASTES TREATMENT AT ELI-NP RESEARCH FACILITY

Alexandru Octavian PAVELESCU[1]

Abstract. *The paper presents the current status of the international state-of-the-art research regarding the transmutation of nuclear materials by using high intensity lasers. The potential applications for radioactive wastes and spent nuclear fuel treatment at Extreme European Light Infrastructure – Nuclear Physics (ELI-NP) from Magurele-Bucharest are briefly investigated.*

Keywords: transmutation, applications for radioactive wastes and spent nuclear fuel

1. Introduction

Power generation via nuclear fission results in the production of dangerous, long lived radioactive isotopes. Current protocol for handling this waste is typically long term storage in deep geologic repositories or shallow storage facilities, depending on the specific isotope [1].

However, accounting for the extreme half lives of some of these elements in the storage and disposal problem is not an easy task and requires strong consideration when discussing nuclear power as an option for the world's energy needs [1].

Table 1 lists some of the isotopes that are produced and/or utilized in the nuclear fuel process of ^{235}U. [1]

Table 1. Some important components of nuclear waste. [1]

Radionuclide	Half life (yr)	Type
^{126}Sn	230,200	Long lived fission product
^{99}Tc	211,250	Long lived fission product
^{129}I	15,700,000	Long lived fission product
^{238}U	4,471,000	Actinide source
^{241}Am	430	Actinide
^{237}Np	2,145,500	Actinide
^{239}Pu	24,000	Actinide

[1]alexandru.pavelescu@gmail.com

2. Nuclear Transmutation by Using Accelerator Driven Systems (ADS)

Used fuel from a conventional nuclear power reactor contains a number of radionuclides, most of which (notably fission products) decay rapidly, so that their collective radioactivity is reduced to less than 0.1% of the original level 50 years after being removed from the reactor. However, a significant proportion of the wastes contained in used nuclear fuel is long-lived actinides (particularly neptunium, americium and curium). In recent years, interest has grown in the possibility of separating (or partitioning) the long-lived radioactive waste from the used fuel and transmuting it into shorter-lived radionuclides so that the management and eventual disposal of this waste is easier and less expensive.

An example transmutation scheme from a long lived radioisotope to a stable element [2]:

$$I^{129} + n \rightarrow I^{130m} \rightarrow I^{130} \rightarrow Xe^{130} + \beta^- + \nu$$

Spallation is the process where nucleons are ejected from a heavy nucleus being hit by a high energy particle. High-current, high-energy accelerators or cyclotrons are able to produce neutrons from heavy elements by spallation. In this case, a high-energy proton beam directed at a heavy target expels a number of spallation particles, including neutrons.

A number of research facilities exist which explore this phenomenon, and there are plans for much larger ones. In this process, a beam of high-energy protons (usually >500 MeV) is directed at a high-atomic number target (e.g. tungsten, tantalum, depleted uranium, thorium, zirconium, lead, lead-bismuth, mercury) and up to one neutron can be produced per 25 MeV of the incident proton beam. These numbers compare with 200-210 MeV released by the fission of one ^{235}U or ^{239}P atom. A 1000 MeV beam will create 20-30 spallation neutrons per proton.

The spallation neutrons have only a very small probability of causing additional fission events in the target. However, the target still needs to be cooled due to heating caused by the accelerator beam.

If the spallation target is surrounded by a blanket assembly of nuclear fuel, such as fissile isotopes of uranium or plutonium (or ^{232}Th which can breed to ^{233}U-233), there is a possibility of sustaining a fission reaction. This is described as an Accelerator Driven System (ADS). In such a system, the neutrons produced by spallation would cause fission in the fuel, assisted by further neutrons arising from

that fission. Up to 10% of the neutrons could come from the spallation, though it would normally be less, with the rest of the neutrons arising from fission events in the blanket assembly. An ADS can only run when neutrons are supplied to it because it burns material which does not have a high enough fission-to-capture ratio for neutrons to maintain a fission chain reaction. One then has a nuclear reactor which could be turned off simply by stopping the proton beam, rather than needing to insert control rods to absorb neutrons and make the fuel assembly subcritical. Because they stop when the input current is switched off, accelerator-driven systems are seen as safer than normal fission reactors.

An ADS can be used to destroy heavy isotopes contained in the used fuel from a conventional nuclear reactor – particularly actinides. Here the blanket assembly is actinide fuel and/or used nuclear fuel. One approach is to start with fresh used fuel from conventional reactors in the outer blanket region and progressively move it inwards. It is then removed and reprocessed, with the uranium recycled and most fission products separated as waste. The actinides are then placed back in the system for further 'incineration'.

ADSs could also be used to destroy longer-lived fission products contained in used nuclear fuel, such as 99Tc and 129I (213,000 and 16 million years half-lives, respectively). These isotopes can acquire a neutron to become 100Tc and 130I respectively, which are very short-lived, and beta decay to 100Ru and 130Xe, which are stable. [3]

Commercial application of partitioning and transmutation (P&T), which is attractive particularly for actinides, is still a long way off, since reliable separation is needed to ensure that stable isotopes are not transmuted into radioactive ones. New reprocessing methods would be required, including electrometallurgical ones (pyro-processing). The cost and technology of the partitioning together with the need to develop the necessary high-intensity accelerators seems to rule out early use. An NEA study showed that multiple recycling of the fuel would be necessary to achieve major (e.g. 100-fold) reductions in radiotoxicity, and also that the full potential of a transmutation system can be exploited only with commitment to it for 100 years or more.

The French Atomic Energy Commission is funding research on the application of this process to nuclear wastes from conventional reactors, as is the US Department of Energy. The Japanese OMEGA (Options Making Extra Gain from

Actinides) project envisages an accelerator transmutation plant for nuclear wastes operated in conjunction with ten or so large conventional reactors. The French concept similarly links a transmutation - energy amplifying system with about eight large reactors. Other research has been proceeding in USA, Russia and Europe.

3. Laser Transmutation of Nuclear Materials

3.1. Current state of laser transmutation worldwide

Recent advances in laser technology now make it possible to induce nuclear reactions with light beams [4, 5, 6]. When focused to an area of a few tens of square microns, the laser radiation can reach intensities greater than 10^{20} W/cm^2. By focusing such a laser onto a target, the beam generates plasma with temperatures of ten billion degrees (10^{10} K) – comparable to those that occurred one second after the "big bang".

With the help of modern compact high-intensity lasers (Fig. 1), it is now possible to produce highly relativistic plasma in which nuclear reactions such as fusion, photo-nuclear reactions, and fission of nuclei have been demonstrated to occur. Two decades ago, such reactions induced by a laser beam were believed to be impossible. This new development opens the path to a variety of highly interesting applications, the realization of which requires continued investigation of fundamental processes by both theory and experiment and in parallel the study of selected applications. The possibility of accelerating electrons in focused laser fields was first discussed by Feldman and Chiao [7] in 1971.

Figure 1. Giant pulse VULCAN laser. Courtesy: CCLRC Rutherford Appleton Laboratory (left) and High-intenisty Jena tabletop laser JETI. Courtesy: Institut fur Optik und Quantenelektronik, Friedrich-Schiller-Universitat, Jena (right).

The mechanism of the interaction of charged particles in intense electromagnetic fields, for example, in the solar corona, had, however, been considered much earlier in astrophysics as the origin of cosmic rays. In this early work, it was shown that in

a single pass across the diffraction limited focus of a laser power of 10^{12} W, the electron could gain 30 MeV, and become relativistic within an optical cycle. With a very high transverse velocity, the magnetic field of the wave bends the particle trajectory through $\boldsymbol{v}\times\boldsymbol{B}$ Lorentz force into the direction of the travelling wave. In very large fields, the particle velocity approaches the speed of light and the electron will tend to travel with the wave, gaining energy as it does so.

Dramatic improvements in laser technology since 1984 (Fig. 2) have revolutionized high-power laser technology [8]. Application of chirped pulse amplification techniques [9, 10] has resulted laser intensities in excess of 10^{19} W/cm^2. In 1985, Rhodes et al. [16] discussed the possibility of laser intensities of $\approx 10^{21}$ W/cm^2, using a pulse length of 0.1 ps and 1 J of energy. At this intensity, the electric field is 10^{14} V/cm a value which is over 100 times the coulomb field binding atomic electrons. In this field, a uranium atom will lose 82 electrons in the short duration of the pulse. The resulting energy density of the pulse is comparable to a 10 keV blackbody (equivalent light pressure ≈ 300 Gbar) and comparable to thermonuclear conditions (thermonuclear ignition in DT occurs at about 4 keV).

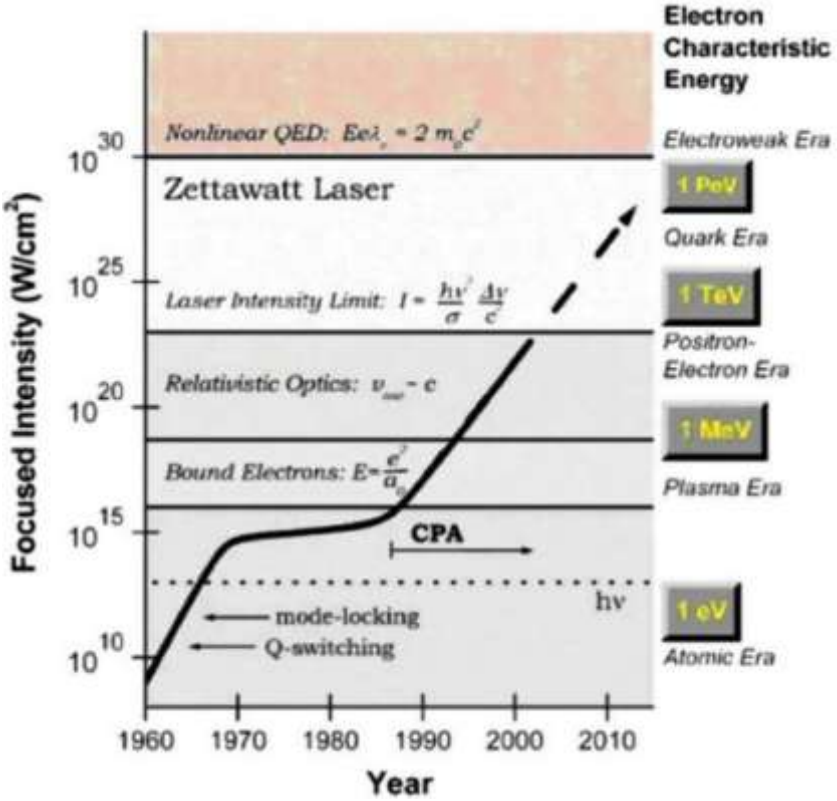

Figure 2. Dramatic increase in focused laser intensity over the past few decades for tabletop systems [8].

With the development of chirped pulse amplification (CPA) techniques in the mid-eighties, a new era of laser–matter interactions has become possible.

In 1988, Boyer et al. [11] investigated the possibility that such laser beams could be focused onto solid surfaces and cause nuclear transitions.

In particular, irradiation of a uranium target could induce electro- and photo fission in the focal region. These developments open the possibility of "switching" nuclear reactions on and off by high-intensity ultraviolet laser radiation and providing a bright point source of fission products and neutrons.

3.2. Laser-Induced Photo-Fission of Actinides – Uranium and Thorium

When a laser pulse of intensity 10^{19} W/cm^2 interacts with solid targets, electrons of energies of some tens of MeV are produced. In a tantalum target, the electrons generate an intense highly directional γ-ray beam that can be used to carry out photo-nuclear reactions. The isotopes ^{11}C, ^{38}K, ^{62,64}Cu, ^{63}Zn, ^{106}Ag, ^{140}Pr, and ^{180}Ta have been produced by (γ, n) reactions, using the VULCAN laser beam.

The first demonstrations were made with the giant pulse VULCAN laser in the United Kingdom, using uranium metal and with the high repetition rate laser at the University of Jena with thorium samples (experimental setup shown in Fig. 3). Both experiments were carried out in collaboration with the Institute for Transuranium Elements in Karlsruhe. Actinide photo-fission was achieved in both U and Th, using the high-energy bremsstrahlung radiation produced by laser acceleration of electrons. The fission products were identified by time resolved γ-spectroscopy (Fig. 4, Fig. 5).

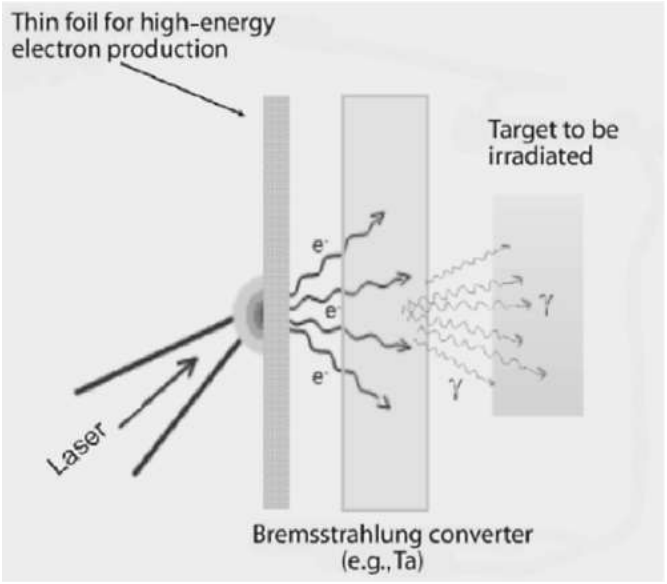

Figure 3. Schematic setup of the laser experiments.

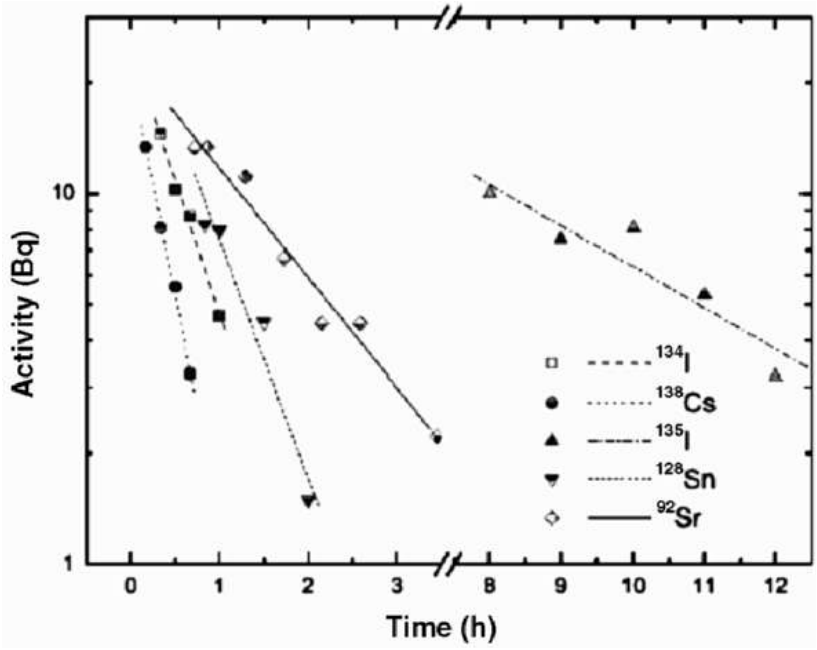

Figure 4. Decay characteristics of fission products coming from bremsstrahlung-induced fission of ^{232}Th. The deduced half-lives are in good agreement with literature values. Symbols indicate experimental data.

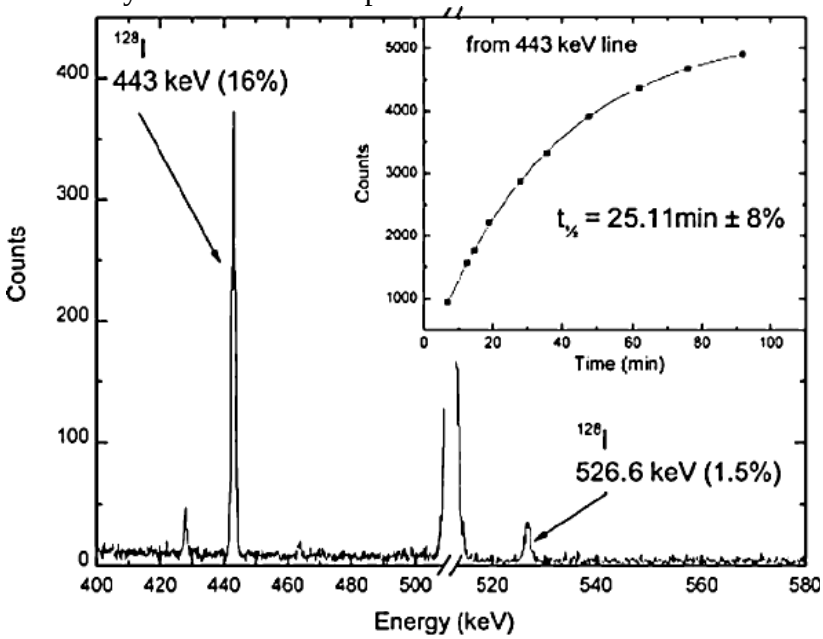

Figure 5. Gamma emission spectra from one of the iodine samples measured before and after laser irradiation of the gold target. Characteristic emission lines of ^{128}I at 443.3 and 527.1 keV are clearly observed, alongside peaks from the decay of ^{125}Sb impurity and a peak at 511 keV from positron annihilation [12, 13].

3.3. Laser-Driven Photo-Transmutation of ^{129}I

The first successful laser-induced transmutation of ^{129}I, one of the key radionuclides in the nuclear fuel cycle was reported in 2003 [12, 13, 14]. ^{129}I with a half-life of 15.7 million years is transmuted into ^{128}I, with a half-life of 25 min through a (γ,n) reaction using laser-generated Bremsstrahlung.

Iodine is present in the environment in both stable (^{127}I) and radioactive forms. The most important of the radioisotopes is ^{129}I. It is produced naturally in the upper atmosphere through cosmic-ray spallation of xenon and by spontaneous fission in the geosphere. Since the 1950^{s}, the environmental levels of ^{129}I have increased due to atmospheric nuclear tests and to the use of nuclear power. These anthropogenic activities have resulted in a global increase of the ^{129}I/^{127}I ratio by two orders of magnitude from about 1.5×10^{-12} to 10^{-10} [15], although radiological effects remain negligible. Nuclear reactors are now the main sources of anthropogenic ^{129}I. Iodine as a fission element is generated in spent fuel at a rate of about 7 kg/GWe per year, with 80% of this inventory in the form of ^{129}I and 20% in the form of stable ^{127}I [16]. World-wide, based on the currently installed nuclear generating capacity of 360 GWe, this gives rise to an annual production rate of ^{129}I of approximately 2000 kg [15–17].

^{129}I decays by emitting a beta particle (150 keV), γ -photons (40 keV) and X-ray radiation (30, 34 keV) [18].

Although the low-energy beta particles barely penetrate the outer layers of the skin, the γ - and X-rays are more penetrating and present an external health hazard. More importantly, ^{129}I can be incorporated into the body through the food chain, drinking water and breathing air. Up to 30% of the iodine uptake in the body accumulates in the thyroid and is retained with a biological half-life of 120 days. Thyroid tumors can develop from the ionizing radiation. Of the long-lived fission products (mainly ^{129}I ^{99}Tc, ^{135}Cs), ^{129}I is the most radiotoxic [18].

Due to its long half-life, high radiotoxicity and mobility, ^{129}I is one of the primary risk considerations for several risk analyses and risk assessments in the disposal of nuclear waste. One approach to limit its mobility and potential health risk is to condition the iodine by employing engineered barriers into the disposal system. Their inclusion would significantly reduce the amount of ^{129}I released into the environment. [1]

Ideally, however, the iodine released during nuclear fuel reprocessing should be transmuted to a stable product. Current proposals for the transmutation of actinides and long-lived fission products (LLFPs) are based upon neutron transmutation in fast neutron reactors [16, 19]. Through neutron-induced transmutation, for example, ^{129}I is transformed to ^{130}I, which decays with a half-life of 12 h to the stable gas ^{130}Xe. It is not clear, however, that transmutation

based on neutrons is the optimum approach for all nuclides. For some problematic nuclides, neutron cross sections are too low to be effective. In addition, isotope mixes of a particular element like e.g. cesium may cause problems, because neutron-capture reactions on the lighter cesium isotopes $^{133,\ 134}$Cs result in a production of ^{135}Cs, i.e. more ^{135}Cs may be produced rather than destroyed [20].

Alternatively to neutron-induced transmutation, ^{129}I can be photo-excited to emit a single neutron and transmute to ^{128}I, which has a half-life of 25 min. 7% of the ^{128}I nuclei capture an electron and decay to ^{128}Te. The remaining 93% undergo β- decay into the stable ^{128}Xe. This β- decay has a characteristic γ -line at 443 keV with an emission probability of Iγ = 17%, and is used to monitor successful photo-transmutation. In this case high-energy Bremsstrahlung from relativistic laser-produced plasmas was used to induce the photonuclear ^{129}I (γ,n) ^{128}I reaction.

Relativistic laser plasmas are bright incoherent sources of γ -radiation with energies up to many tens of megaelectronvolts. They can be produced by compact tabletop laser systems delivering laser pulses with joules of energy within less than 100 femtoseconds (fs). In the focus of these laser beams intensities of more than 10^{20} W/cm^2 may be generated.

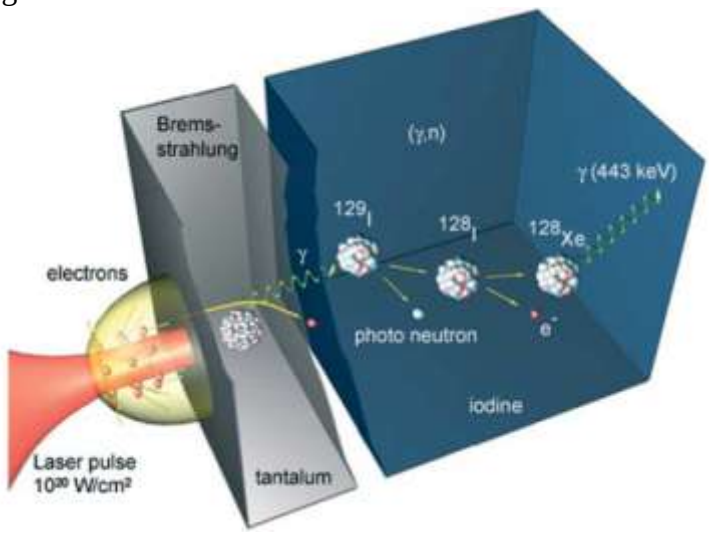

Figure. 6 Experimental scenario: the high-intensity laser pulse produces hot plasma on the surface of a tantalum foil.

The pondero-motive force of the intense light field, which is the light pressure of the pulse, accelerates the electrons to relativistic energies and pushes them in the forward direction into the target (Fig. 1) [21, 22]. At high energies a Boltzmann-like distribution with a hot-electron temperature Te is a good approximation. Te scales with the square root of the laser intensity I. At I ≈ 3×10^{18} W/cm^2 the temperature exceeds the electron rest mass of 511 keV and at 10^{20} W/cm^2 the electron temperature is Te ≈ 3 MeV [21].

Within the solid target of typically high atomic number like tantalum the hot electrons are stopped and generate Bremsstrahlung. In the extreme relativistic case an exponential energy distribution of electrons leads again to an exponential photon spectrum with the same temperature [23].

In Fig. [6] an experimental scenario is presented, that is the high-intensity laser pulse produces hot plasma on the surface of a tantalum foil. Relativistic electrons are stopped in the tantalum, efficiently generating high-energy Bremsstrahlung. The ^{129}I in the radioactive target is transformed into ^{128}I due to a (γ,n) reaction.

In the intermediate case of electron temperatures of several MeV the photon temperature is slightly lower than Te [24]. The spectra of the primarily produced electrons and the Bremsstrahlung photons have been investigated by several methods including conventional magnetic electron spectrometers [25], thermo-luminescence spectrometers [7, 24] and nuclear activation experiments [9, 26, 27]. With the last technique, several photonuclear reactions are induced and identified. If their cross sections are well known, the γ -spectrum can be deduced.

This technique is accepted to yield results with reasonable accuracy for relativistic laser-generated plasmas.

The experiments were performed with the Jena multi TW laser system, which generates pulses with a maximum energy of 1 J within less than 80 fs at a repetition rate of 10 Hz and with a centre wavelength of 800 nm. The pulses are focused onto the target, producing an average intensity of up to 10^{20} W/cm^2 within a focal area of 5 μm^2. The primary target is a 2-mm-thick tantalum sheet, which acts as electron source and Bremsstrahlung converter (Fig. 6). The iodine sample (21 g of PbI_2 with 17% of ^{129}I) is placed directly behind the tantalum converter. The target is irradiated with 10 000 laser shots.

After irradiation, γ radiation from short-lived photoreaction products in the tantalum and iodine samples is detected by two germanium detectors. Spectra are taken in successive time intervals to monitor the characteristic decay times of the radioactive nuclei.

With the efficiency calibration of the detectors absolute numbers of laser-induced reactions in units per laser shot are obtained.

Fig. 7 shows the 443-keV line of the β^- decay of ^{128}I into ^{128}Xe. The spectrum is collected during the mean lifetime of ^{128}I after the end of the laser irradiation. The identification of ^{128}I is verified by measuring the decay of the activity in the 443-keV line, as shown in the inset of Fig. 7

The half-life is determined to 28±5min, which is in good agreement with the tabulated value of 25 min [18]. From the experimental data the number of (γ,n) reactions in ^{129}I was calculated:N_I = 2 per laser shot.

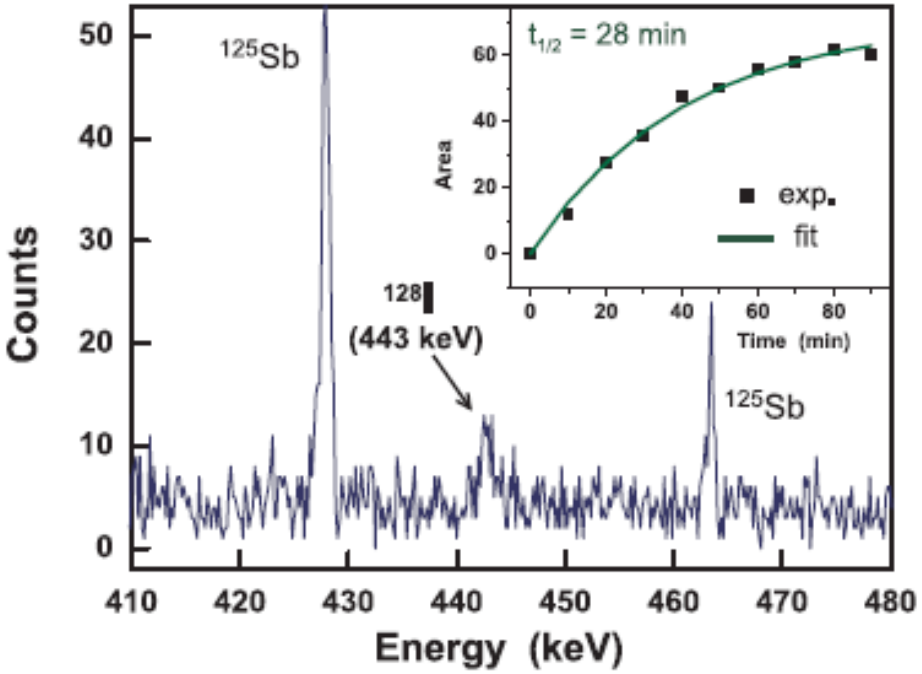

Figure 7. γ -spectrum of the iodine sample, integrated over the first 30 min after irradiation with laser-produced Bremsstrahlung.

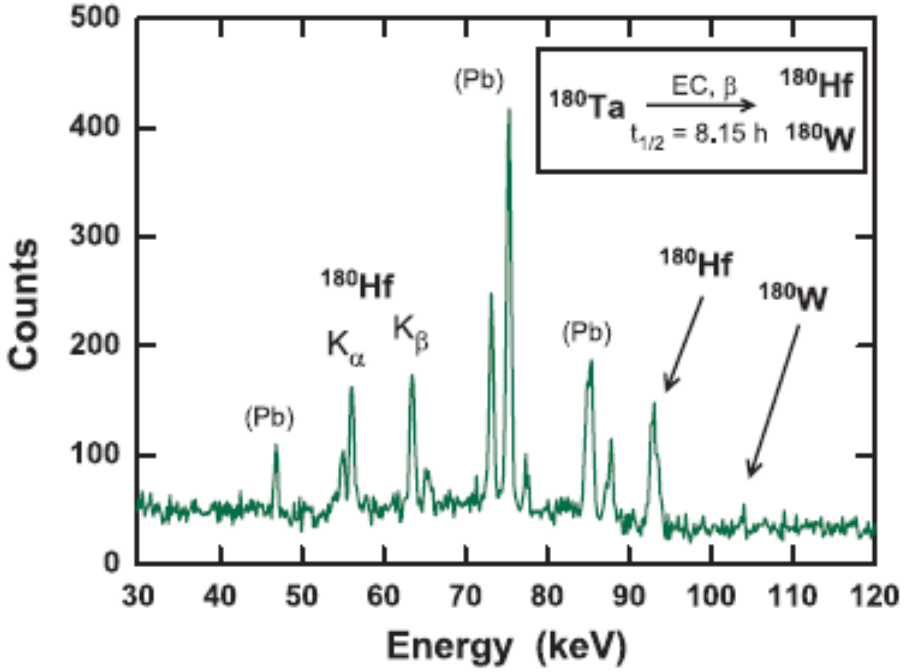

Figure 8. γ -spectrum of the tantalum converter plate.

The characteristic 443-keV emission of ^{128}I is clearly visible between two emission lines from ^{125}Sb, which is an impurity in the sample. Inset: plotted is the temporal evolution of the integrated area of the 443-keV line of ^{128}I. The data were fitted with $n_I\{1-\exp(-\ln(2t/\tau))\}$, resulting in a half-life of $\tau = 28\pm5$min. This agrees well with the tabulated ^{128}I lifetime of 25 min.

Simultaneously, γ -spectra of the irradiated tantalum target were measured (Fig. 8). A (γ, n) reaction on ^{181}Ta produces ^{180}Ta, which decays with a probability of 86% by electron capture into ^{180}Hf and with 14% by β^- decay to ^{180}W. The measured decay of the activity perfectly fits the ^{180}Ta lifetime of 8.15 h.

^{181}Ta is transformed into ^{180}Ta by a (γ,n) reaction, which decays with a half-life of 8.15 h into ^{180}Hf and ^{180}W. The X-ray line emission of ^{180}Hf at 56 and 63 keV is clearly visible, as well as two γ -lines of ^{180}Hf and ^{180}W at 93 keV and 103 keV, respectively. The Hf K_α lines were used for the evaluation of the number of induced (γ , n) reactions (the Hf K_β line is superposed by background radiation).

3.4. Laser-Induced Heavy Ion Fusion

In a recent series of experiments with the VULCAN laser, at intensities of 10^{19} W/cm^2, beams of energetic ions were produced by firing the laser onto a thin foil primary target. The resulting ion beam then interacts with a secondary target. If the ions have enough kinetic energy, it is possible to produce fusion of the ions in the beam with atoms in the secondary target.

Heavy ion beams were generated from primary targets of aluminum and carbon. Secondary target material consisted of aluminum, titanium, iron, zinc, niobium and silver. The heavy ion "blow-off" fused with the atoms in the secondary target creating compound nuclei in highly excited states.

The compound nuclei then de-excited to create fusion products in the secondary target foils. These foils were then examined in a high-efficiency germanium detector to measure the characteristic gamma radiation produced by the radioactive decay of short-lived fusion product nuclides.

Typical spectra are shown in Fig. 9 which also shows the results of experiments involving cold and heated targets. The target here was aluminum, and the secondary titanium.

The spectrum in blue is that taken for the aluminum target at room temperature, and the red spectrum is that of an aluminum target heated to 391°C.

For the heated target, many more fusion products are evident which are not observed in the cold target. This is attributed to the heating of the target to remove hydrocarbon impurities. When these layers are removed, heavier ions are accelerated more readily and to higher energies.

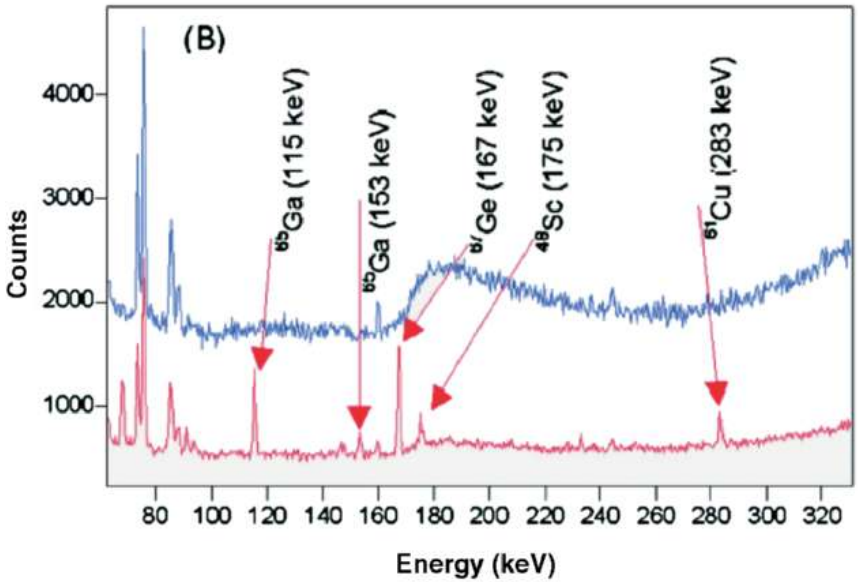

Figure 9. Main reaction products identified by their characteristic gamma emission for a Ti plate exposed to Al blow-off. Blue spectrum: cold" target, red spectrum, heated target (391°C). Fusion products are much more evident in the heated target

3.5. Laser-Generated Protons and Neutrons

Recently, (p,xn) reactions on lead with the use of very high intensity laser radiation have been demonstrated [28]. Laser radiation is focused onto a thin foil to an intensity of 10^{20} W/cm^2 to produce a beam of high-energy protons. These protons interact with a lead target to produce (p,xn) reactions (Fig. 10). The (p,xn) process is clearly visible through the production of a variety of bismuth isotopes with natural lead. Such experiments may provide useful basic nuclear data for transmutation in the energy range 20–250MeV without recourse to large accelerator facilities.

At low energies (≤50MeV), the de Broglie wavelength of the proton is larger than the size of individual nucleons. The proton then interacts with the entire nucleus and a compound nucleus is formed. At high proton energies (≥50MeV), the de Broglie wavelength is of the order of the nucleon dimensions. The proton can interact with single or a few nucleons and results in direct reactions. These latter reactions are referred to as spallation nuclear reactions and refer to non-elastic interactions induced by a high-energy particle in which mainly light charged particles and neutrons are "spalled," or knocked out of the nucleus directly, followed by the evaporation of low-energy particles as the excited nucleus heats up. Current measurements on the feasibility of proton-induced spallation of lead and similar materials focus around the need to measure nuclear reaction cross sections relevant to accelerator-driven systems desirable for use in the transmutation of long-lived

radioactive products in nuclear waste. The neutron production from the spallation reaction is important for defining the proton beam energy and target requirements. However, the measurements being undertaken require high-power accelerators to generate the proton beam. In the present work, the proton beam is generated by a high-intensity laser rather than by an accelerator.

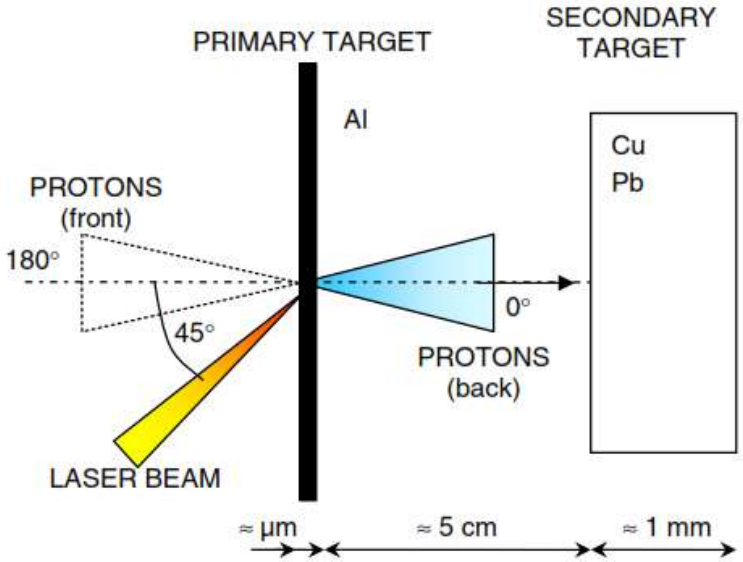

Figure 10. General Layout for proton acceleration experiments using high intensity lasers. The laser beam was focused in a thin aluminum target and protons accelerated from the back of the primary target were caught by thick secondary targets [28].

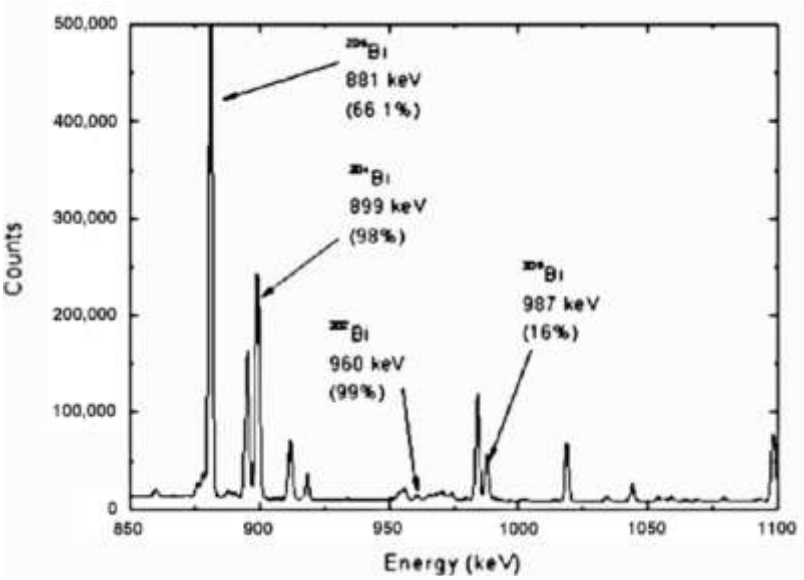

Figure. 11. Preliminary identification of bismuth isotopes produced through (p,xn) reactions in lead.

The recently developed petawatt arm of the VULCAN Nd: glass laser at the Rutherford Appleton Laboratory, U.K., was used in this experiment. Polarized laser pulses with energy up to 400 J, wavelength approximately 1 m, and average duration 0.7 ps, were focused onto foil targets at an angle of 45° and to an intensity of the order of 4×10^{20} W/cm^2. A typical spectrum resulting from the proton activation of lead to produce bismuth isotopes is shown in Fig. 11.

4. ELI Potential Applications for Technology Transfer regarding transmutation of nuclear materials

4.1. Main characteristics of European Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

The ELI-NP facility will generate particle beams with high energies and brilliances suited to studies of nuclear and fundamental processes. The core of the facility is a high-power laser system. In order to perform cutting edge photo-nuclear physics experiments, a complementary highly brilliant gamma beam, with energies in the 15 MeV range, will be generated via the laser interaction with a brilliant bunched electron beam. Thus ELI-NP will allow either combined experiments using the high power laser and the γ beam or stand-alone experiments. The design of the facility is modular, reserving the space for further extension of the laser system and allowing the extension later of the experimental area, according to the needs.

The basic objectives of the ELI-RO Nuclear Physics (NP) pillar are:

- to proceed to a precise diagnosis of the laser beam interaction with matter with techniques specific to Nuclear Physics.
- to use photonuclear reactions and laser accelerated particles for nuclear structure studies and for applications.

For the ELI-NP facility two new central instruments are planned:

- a very high intensity laser beam, where two multi-PW Apollon-type lasers are coherently.
- a very intense, brilliant, very low bandwidth, high-energy γ beam, which is obtained by incoherent Compton back scattering of a laser light on a very brilliant, intense, classical electron beam.

The core of the facility is a laser system using Ti: Sapphire technology. It will use OPCPA technology at the front-end and Ti: Sapphire high-energy amplification stages, similar to the ones developed at the APOLLON laser system.

The ELI-NP laser facility will have two front-ends. They will temporally stretch and amplify initial ultrashort pulses with 800 nm central wavelength to the 100 mJ level, preserving the needed large bandwidth of the 15 fs laser pulses and the

temporal contrast of the pulses in the range of 10−12. Due to the complexity of such OPCPA system, the alignment and maintenance time for one front-end is long. To avoid such dead-times, one front-end is planned to operate at a time, the second one being used during the maintenance of the other front-end, significantly increasing the available beam-time of the laser facility.

ELI and its national predecessor projects like ILE and Vulcan-10PW will boost the peak power of single lasers (modules) into the 10PW or multi-10PW regime at much higher repetition rates, constituting an evolution of more than one order of magnitude in both of these parameters. In addition, the high intensity pillar of ELI aims at another order of magnitude in peak power, into the 100PW regime, by coherent combination of several such modules. With these parameters ELI will certainly lead the international high power laser scenario.

The answers to these questions appear to be strongly correlated. They both lie in the observation that ELI will be the first laser research infrastructure which is the result of a co-ordinate effort of a multi-national scientific laser community. Other communities (high energy physics, synchrotrons, astronomy etc.) have long standing traditions in the operation of international user facilities. Lasers, having evolved 50 years ago from small table-top devices, are only now at the edge of such mode of operation, and ELI is the first installation world-wide to make that step.

4.2 Particle acceleration by lasers - Ions

Reaching extremely high ion energies, in the GeV range, would allow to use ELI in another extremely attractive area, namely as a source for spallation. This opens all the downstream study of neutron beams, or as a source for the transmutation of radio-nuclides. Currently there is only one very costly facility, The Oak Ridge National Laboratory Spallation Neutron Source (ORNL-SNS), recently completed in the USA) [29] that is able to perform transmutation of nuclear waste. Moreover, conventional neutron sources are currently not very flexible and are of low brilliance. Here ELI would again offer a complementary tool to conventional sources like the SNS to probe matter but in a time-resolved manner that is not possible at the SNS. Indeed, the neutron, produced through D-D monochromatic reactions, should be bunched and keep the short duration of the initial ion source.

4.3 Plasma and high energy density physics

By focusing ELI laser on high-Z material we will be able to produce intense pulse of γ-rays that can be used for nuclear transmutation of long-lived radioactive isotopes into less radioactive or short-lived products. This concept is being developed in the world for nuclear waste management. The primary risk isotope is long-lived ^{129}I with high radiotoxicity and mobility, and this may be transformed to ^{128}I that decays with a half-life of 25 minutes to stable inert ^{128}Xe. The experiments may demonstrate the feasibility of laser-induced transmutation

5. Conclusions

The future development of the field of laser transmutation will benefit from the currently fast evolution of high-intensity laser technology. Within a few years, for instance due to ELI-NP developments, compact and efficient laser systems will emerge, capable of producing intensities exceeding 1022 W/cm^2 with repetition rates of 1 shot per minute and higher. These laser pulses will generate electron and photon temperatures in the range of the giant dipole resonances and open the possibility of obtaining nuclear data in this region. These laser experiments may offer a new approach to studying material behavior under neutral and charged particle irradiation without resource to nuclear reactors or particle accelerators. Such a giant laser could cut the lifetime of a speck of radioactive waste from millions of years to just minutes. The feat raises hopes that a solution to nuclear power's biggest drawback - its waste - might be possible.

R E F E R E N C E S

[1] A. O. Pavelescu: *Analysis of the Final Disposal Systems of the Radioactive Wastes in Granite Rock*, Publishing House of the Academy of Romanian Scientist, ISBN 978-606-92161-2-5 (**2009**).

[2] Viktor Arkhipov: *Future nuclear energy systems: Generating electricity, burning wastes*, IAEA Bulletin Volume 39, Issue 2, p. 30 (**1997**).

[3] J.W. Boldeman: *Accelerator driven nuclear energy systems*, Australian Academy of Technological Sciences and Engineering Symposium, Energy for Ever – Technological Challenges of Sustainable Growth (November **1997**).

[4] E. Bertel, L. Van den Durpel: *P&T: A long-term option for radioactive waste disposal?*, NEA News No. 20.2, p20 (**2002**).

[5] K.W.D. Ledingham et al.: Science 300, 1107–1111 (**2003**).

[6] K.W.D. Ledingham et al.: Phys. Rev. Lett. 84, 899 (**2000**).

[7] H. Schwoerer et al.: Europhys. Lett. 61, 47 (**2003**).

[8] M.J. Feldman, R.Y. Chiao: Phys. Rev A 4, 352–358 (**1971**).

[9] T. Tajima, G. Mourou: Phys. Rev. Spec. Topics – Accelerators Beams 5, 031301-1 (**2002**).]

[10] O.E. Martinez et al.: J. Opt. Soc. Am. A1 1003–1006 (**1984**).

[11] C.K. Rhodes: Science 229, 1345–1351 (**1985**).

[12] K. Boyer, T.S. Luk, C.K. Rhodes: Phys. Rev. Lett. 60, 557–560 (**1988**).

[13] J. Magill et al.: Appl. Phys. B, 1–4 (**2003**).

[14] K.W.D. Ledingham et al.: J. Phys. D: Appl. Phys. 36, L79–L82 (**2003**).

[15] P. McKenna et al.: Phys. Rev. Lett. 94, 084801 (**2005**).

[16] R. Michel, D. Ernst, T. Jakob, K. Klipsch, S. Szidat, H. Synal,C. Schnabel: *'Long-lived Radionuclides in the Environment: the Case of Iodine-129'*. Presented at the Eurosafe Forum, November **2002**.

[17] L.H. Baetsl´e, J. Magill, M. Embid-Segura: *'Implications of partitioningand transmutation in radioactive waste management'*, IAEA-TECDOC, (**2003**).

[18] F. Yiou, G.M. Raisbeck, Z.Q. Zhou, L.R. Kilius: Nucl. Instrum.Methods, Phys. Res. B 92, 436 (**1994**).

[19] J. Magill: *Nuclides.net: An Integrated Environment for Computations on Radionuclides and Their Radiation* (Springer, Berlin **2003**).

[20] C. Rubbia, H. Abderrahim, M. Björnberg, B. Carluec, D. Gherardi, E. Gonzalez Romero, W. Gudowski, G. Heusener, H. Leeb, W. Von Lensa, G. Locatelli, J. Magill, J. Martinez-Val, S. Monti, A. Mueller, M. Napolitano, A. Perez-Navarro, J. Soares, J. Thomas: *'European, Roadmap for Accelerator Driven Systems for Nuclear Waste Transmutation'*, ENEA Report (**2001**).

[21] J. Magill, V. Berthou, J. Galy, R. Schenkel, H. Wiese, G. Heusner, J. Tommasi, G. Youinou: *Impact limits of partitioning and transmutation scenarios on nuclear waste isolation times*, Nuclear Energy 42 (**2003**).

[22] C. Wilks, W.L. Kruer, M. Tabak, A.B. Langdon: Phys. Rev. Lett. 69,1383 (**1992**).

[23] P. Gibbon, E. Förster: Plasma Phys. Control. Fusion 38, 769 (**1996**).

[24] G.H. McCall: J. Phys. D: Appl. Phys. 15, 823 (**1982**).

[25] R. Behrens, H. Schwoerer, S. Düsterer, P. Ambrosi, G. Pretzler, S. Karsch, R. Sauerbrey: Rev. Sci. Instrum. 74, 961 (**2003)**.

[26] C. Gahn, G.D. Tsakiris, K.J. Witte, P. Thirolf, D. Habs: Rev. Sci. Instrum. 71, 1642 (**2000**).

[27] M. Santala, M. Zepf, I.Watts, F. Beg, E. Clark,M. Tatarakis, K. Krushelnick, A. Dangor, T. McCanny, I. Spencer, R. Singhal, K. Ledingham, S. Wilks, A. Machacek, J. Wark, R. Allot, R. Clarke, P. Norreys: Phys. Rev. Lett. 84, 1459 (**2000**).

[28] I. Spencer, K. Ledingham, R. Singhal, T. McCanny, P. McKenna,E. Clark, K. Krushelnick, M. Zepf, F. Beg, M. Tatarakis, A. Dangor, R. Edwards, M. Sinclair, P. Norreys, R. Clarke, R. Allot: Rev. Sci. Instrum. 73, 3801 (**2002**).

[29] T. Žagar et al.: New J. Phys. 7, 253 (**2005**).

[30] http://neutrons.ornl.gov/facilities/SNS/.