

Nuclear Physics and Potential Transmutation with the Vulcan Laser

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Introduction

One of the biggest challenges facing the nuclear community is the safe disposal of nuclear waste. During the normal operation of nuclear reactors, various hazardous by-products are formed which are long-lived and highly radiotoxic. The main by-products are plutonium, the "minor" actinides neptunium, americium and curium and long-lived fission products of the elements technetium, iodine and caesium. The preferred solution for the disposal of this waste is to isolate it from the biosphere for periods of hundreds of thousands of years in deep underground geological repositories.

An alternative approach is to transmute this nuclear waste into shorter-lived or stable isotopes and thereby minimise the very long times during which the waste must be isolated. One way of doing this is through neutron driven transmutation in special dedicated transmutation reactors. A detailed "Roadmap" for the development of this technology has been published recently¹. In this approach, high energy protons impinge upon a spallation target to produce copious amounts of neutrons. These neutrons then enter into a sub-critical blanket containing the plutonium, minor actinides and long-lived fission products to transmute these isotopes either through fission or neutron capture reactions followed by decay.

It is, however, not clear that neutron driven reactions are the best approach to transmutation. Through a collaboration with the Institute of Transuranium Elements in Germany, the University of Glasgow, Imperial College, AWE and the Rutherford Appleton Laboratory, an investigation of alternative nuclear reactions is underway using the high intensity laser radiation from Vulcan. By focusing the laser spot very high laser intensities in excess of 10^{19} W.cm⁻² are produced. Under these conditions, matter in the focal spot is turned into a hot dense relativistic plasma with a temperature of several MeV. Under these extreme conditions, high energy electrons, photons (bremsstrahlung), and ions are produced. These particles can then be used to induce nuclear interactions in target materials. The results of the recent experiments performed with Vulcan are described here.

Laser Induced Heavy Ion Fusion

The interaction of the ultra-high laser radiation with matter results in the production of highly energetic electrons, gamma radiation and ions. 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 (Figure 1).

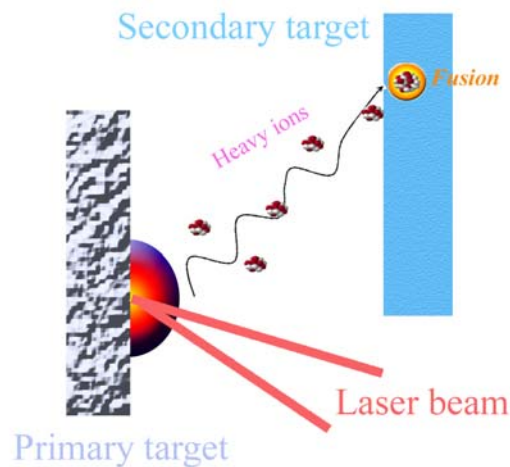


Figure 1. Setup of the heavy ion fusion experiment. The laser is focused onto a primary target (Al, C or other), where it generates a hot plasma on the surface. Heavy ions accelerated in the plasma are blown-off into the secondary target (Al, Ti, Zn, or other) inducing a fusion reaction.

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. Such fusion reactions did indeed occur and are reported for the first time in this article for a series of targets as a function of increasing Z. Heavy ion beams were generated from primary targets of iron, aluminium and carbon. Secondary target material consisted of aluminium, titanium, iron and 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 Figure 2.

Figure 2(B) shows the results of experiments involving cold and heated targets. The target here was aluminium, and the secondary titanium. The spectrum in blue is that taken for the aluminium target at room temperature, and the red spectrum is that of an aluminium 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 removing impurity layers responsible for proton production. When these layers are removed, heavier ions are accelerated more readily and to higher energies².

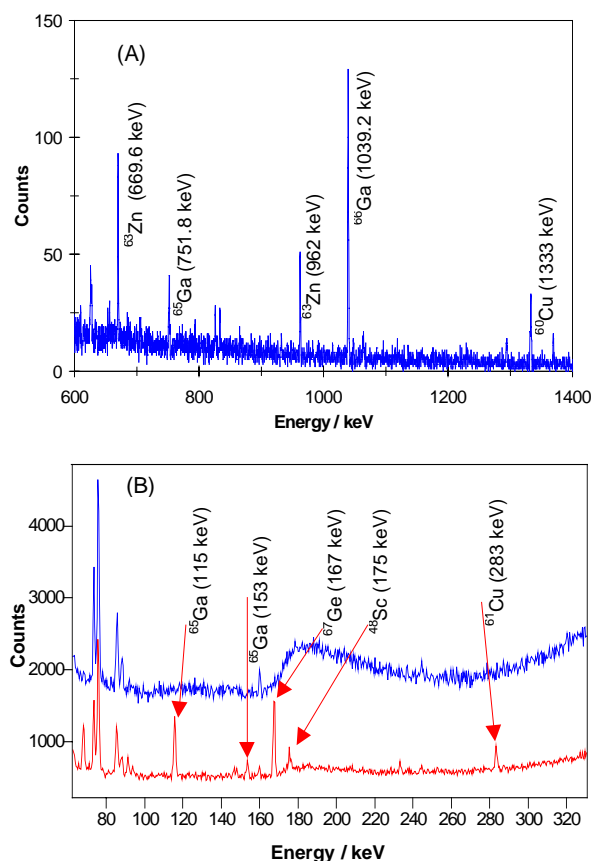


Figure 2. Characteristic emission lines observed in some heavy ion fusion experiments. (A) An Fe plate was exposed to C blow-off. (B) A Ti plate was exposed to an Al blow-off. Blue spectrum: “cold” target, red spectrum, heated target (391°C). Fusion products are much more evident in the heated target.

Some of the heavy ion beams used in these experiments together with the secondary targets materials are listed in Table 1. The main reaction products identified by their characteristic gamma emission are also shown. The measurements clearly show that fusion of the heavy ions with the target atoms, accompanied by the emission of neutrons and light particles, occurred.

Primary target material	Secondary target material	Nuclides identified in preliminary analysis
Al	Al	^{49}Cr , ^{27}Mg , ^{28}Al , ^{43}Sc , $^{34\text{m}}\text{Cl}$
Al (heated)	Ti	^{48}V , ^{44}Sc , ^{48}Sc , ^{65}Ga , ^{67}Ge , ^{61}Cu , ^{70}As
C	Fe	$^{65,66}\text{Ga}$, ^{67}Ge , ^{60}Cu , ^{63}Zn
C	Ag	^{117}Te , ^{115}Te , ^{119}I

Table 1. Heavy ions fusion measurement. The primary and secondary target material are given, with some of the measured and identified fusion products.

Previous measurements of the proton spectrum at similar intensities³⁾ showed that around 5×10^{12} protons were produced in the “blow-off” direction with a characteristic temperature of 1.4 MeV and a maximum energy of 25 MeV.

Laser Induced Photo-Fission of Actinides

Laser induced fission of metallic uranium was demonstrated⁴⁾ with the Vulcan laser in 2000. This was a world first for the Vulcan facility. In the same issue of Phys. Rev. Letts. a group at Lawrence Livermore reported laser induced fission with the NOVA laser systems⁵⁾.

In the latest experiments, laser induced fission of thorium has been demonstrated with the Vulcan laser. Similar experiments are being carried out with the high repetition rate tabletop laser at the University of Jena.

In the experiments on Vulcan, the laser beam was focused onto a 2 mm thick tantalum plate. In the focal spot, matter is turned into a hot dense relativistic plasma with a temperature of several MeV. Under these conditions the highly energetic electrons interact with the tantalum ions to produce high energy bremsstrahlung. It is this bremsstrahlung which gives rise to photo-fission in a nearby thorium sample. Following the laser shots, the sample is removed from the irradiation chamber and placed in front of a high efficiency gamma detector. The gamma spectrum showed a number of signatures of typical short-lived fission products (with half-lives from 30 min to several hours).

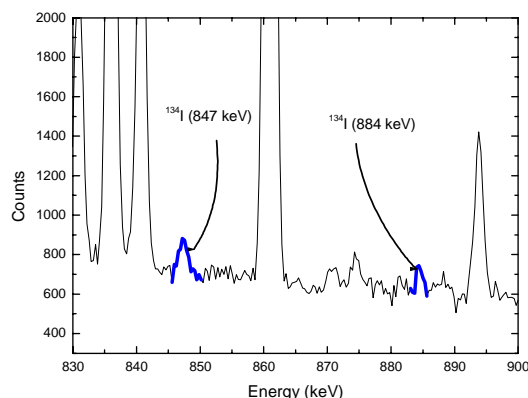


Figure 3. γ -spectrum of the irradiated ^{232}Th sample. Strong emission occurs from the ^{232}Th decay products, mainly ^{228}Ac and ^{208}Tl . Emission from fission products, in this case from ^{134}I at 847 keV and 884 keV, however, are clearly identifiable.

Laser Induced Photo-Nuclear Activation

One of the difficulties in characterising the very high energy density plasma produced in the focal spot of the laser radiation is that there are no standard techniques to determine the temperature, in particular the temperature of the resulting very high energy bremsstrahlung. A very useful method to determine this temperature is to use nuclear activation techniques. Nuclear reactions typically have a threshold energy. Below a certain energy the reaction does not proceed. Above the threshold energy, reaction products can be observed.

Several target materials with different thresholds for (γ, xn) reactions have been placed near the focus of the laser. In these reactions, a single gamma photon is absorbed by the nucleus which enters into an excited state. The excited nucleus can then de-excite by the emission of 1, 2, 3 or more neutrons, depending on the energy of the excitation. The tantalum $(\gamma, 3n)$ reaction has been measured. This reaction presents a gamma threshold of 22 MeV with a cross section at this energy of about 40 mb. Photonuclear reactions in tantalum have been used to measure the temperature of fast electrons produced in the laser-solid interaction⁶⁾.

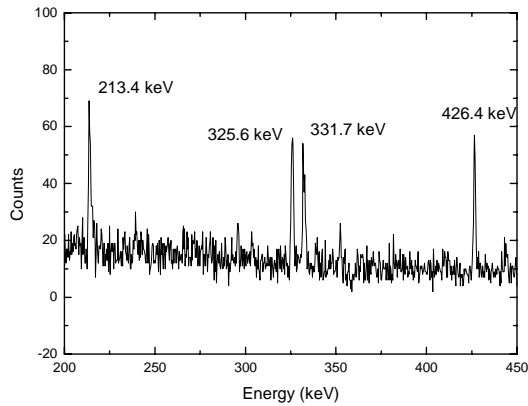


Figure 4. Characteristic γ rays emitted by ^{178m}Ta following the $^{181}\text{Ta}(\gamma,3n)^{178m}\text{Ta}$ reaction.

A praseodymium target with a 27 MeV threshold for the same $(\gamma,3n)$ reaction did not show any significant signature on the measured spectra.

Transmutation of Technetium

Technetium was the first element to be produced artificially – there are no stable isotopes. Since its discovery by Perrier and Segre in Italy in 1937, searches for the element in terrestrial material have been made without success. The element is known to exist in stars. The isotope technetium-99 with a half-life of 211,000 years is produced through the fissioning of uranium in nuclear reactors. The Tc used in the present experiment was separated out of nuclear waste and fabricated into metal elements.

In the intense bremsstrahlung field produced by the Vulcan laser, photo-neutron reactions – (γ, n) , $(\gamma, 2n)$, $(\gamma, 3n)$ etc.) are expected to occur. However both (γ, n) and $(\gamma, 2n)$ result in Tc-98 and Tc-97 respectively which have even longer half-lives than Tc-99. Only with a $(\gamma, 3n)$ reaction is Tc-96 produced with a short half-life of 4.28 d.

Since the tantalum $(\gamma, 3n)$, which has a gamma threshold of 22 MeV and a cross section of 40 mb at this energy, was clearly observed in the present experiments, there was a chance that the Tc-99 $(\gamma, 3n)$ could be detected.

The reported value of the $(\gamma, 3n)$ threshold in the literature is 25.7 MeV with a maximum cross section of 6 mb at 30 MeV. Unfortunately no evidence for the reaction was detected. It is proposed to repeat these experiments with the new petawatt laser which will become available in November.

Conclusion

Through a collaboration with the Institute for Transuranium Elements in Karlsruhe, the University of Glasgow, Imperial College, AWE and the Rutherford Appleton laboratory, a basic investigation of nuclear reactions for transmutation of key components in nuclear waste has been initiated using the Vulcan laser facility. Under the extreme conditions produced in the focal spot, very high energy electrons, photons, and ions can be produced. These projectiles can be used to bombard target materials to induce fusion, fission, and activation reactions.

Acknowledgement

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