SIMULATION OF LASER INDUCED NUCLEAR REACTIONS⋆

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An experiment performed at the VULCAN laser facility of the CCLRC Rutherford Appleton Laboratory (RAL) produced an energy intensity of $> 10^{19}$ W/cm^2 in a primary target. Heavy ions produced in the primary target induced fusion evaporation reactions in a second target. Comparing the results of measurements with state-of-the art PACE-2 calculations we show for the first time that the resulting electron plasma accelerates the heavy ions up to high energies of ~ 5 MeV/A.

INTRODUCTION

The field of laser induced nuclear reactions is an exciting and rapidly expanding new branch of physics. In the near future high power lasers are predicted to be used e.g. for isotope production in nuclear medicine and in biological and material sciences. Furthermore this kind of laser could be used as an injector for large scale ion accelerators and to provide high intensity proton beams for the transmutation of radioactive waste [1].

As in every new advanced technology there are a series of obstacles to be overcome in order to progress. The exact mechanism for the interaction of charged particles with intense electromagnetic fields has been considered for more than fifty years, but has remained unclear until today. The violent creation mechanism, the high fields that are produced by the electron plasma, the extremely short time spans and the variety of the processes involved are of such a complex nature that any qualitative and quantitative description is impossible to achieve at the moment. From the practical point of view these deficits hinder the full technological exploitation of the unique high power laser facilities. Within this frameset the onset of laser induced fusion evaporation reactions leading to specific ion species has to be regarded as a crucial milestone, as it proves in principle the feasibility of the technological concepts mentioned above.

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EXPERIMENT

We performed the experiment at the VULCAN facility of the CCLRC Rutherford Appleton Laboratory (RAL) in the UK [2]. This setup can be regarded as the World's leading instrumentation for this area of research at the present time. Exploiting the chirped pulse amplification technique the VULCAN Nd:glass laser is able to deliver 5×10^{19} W/cm^2 on a primary target. The pulse duration is around 1ps and up to 4 pulses can be delivered per day. Following their production in the laser plasma, the accelerated ions impacted on a secondary target that was placed in the vicinity. The room sized target chamber was evacuated to a pressure of 1×10^{-4} mbar and after irradiation the activated secondary target was manually dismounted. A germanium detector with $\varepsilon_{rel.} = 25\%$ which was setup in a nearby room was used to identify the reaction products by measuring their specific decay γ-energies and their half-lives. Because of the nature of the procedure only nuclides produced with half-lives greater then 10 minutes can be identified. It is worth mentioning in this respect that a direct measurement of the ions and/or the gamma-rays emitted on impact is technically impossible with current state-of-the art detectors as the creation

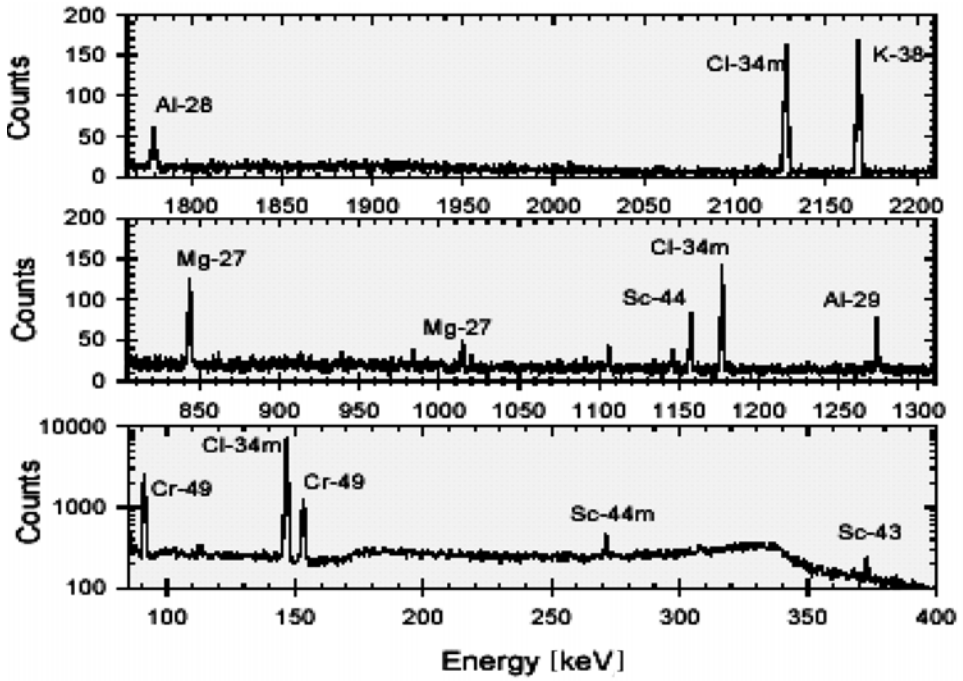

Fig. 1. – Gamma-ray spectrum in an aluminum activation sample after irradiation with ions from an aluminium target foil. ^{34m}Cl, ^{38}K, ^{28}Al, ^{29}Al, ^{24}Na, ^{27}Mg, ^{49}Cr, ^{43}Sc, ^{44}Sc and ^{44m}Sc peaks are observed.

process is of such a violent nature that any probing material placed in the reaction chamber would be destroyed on impact. Fig. 1 shows a typical γ-spectra obtained in a secondary aluminum activation target after irradiation with ions from the primary aluminum target (reaction: ^{27}Al + ^{27}Al) ref. [2].

RESULTS

The following species were identified: ^{34m}Cl, ^{38}K, ^{24}Na, ^{28}Al, ^{29}Al, ^{27}Mg, ^{49}Cr, ^{43}Sc, ^{44m}Sc (ref. [2]). It was suggested that these products are mainly created via fusion evaporation reactions. This kind of reaction will occur if the incident energy of the accelerated ion is high enough to overcome the Coulomb barrier and the formation of a compound nucleus will take place. The compound nuclei will then de-excite by the evaporation of light particles such as protons, neutrons and alphas. The procedure of compound nucleus production and its subsequent decay can be described with the PACE-2 (**P**rojected **A**ngular Momentum **C**oupled **E**vaporation) code of Gavron *et al*. [3]. PACE-2 is a Monte-Carlo code based on the statistical model which has been successfully used for the interpretation of fusion-evaporation reactions during the last two

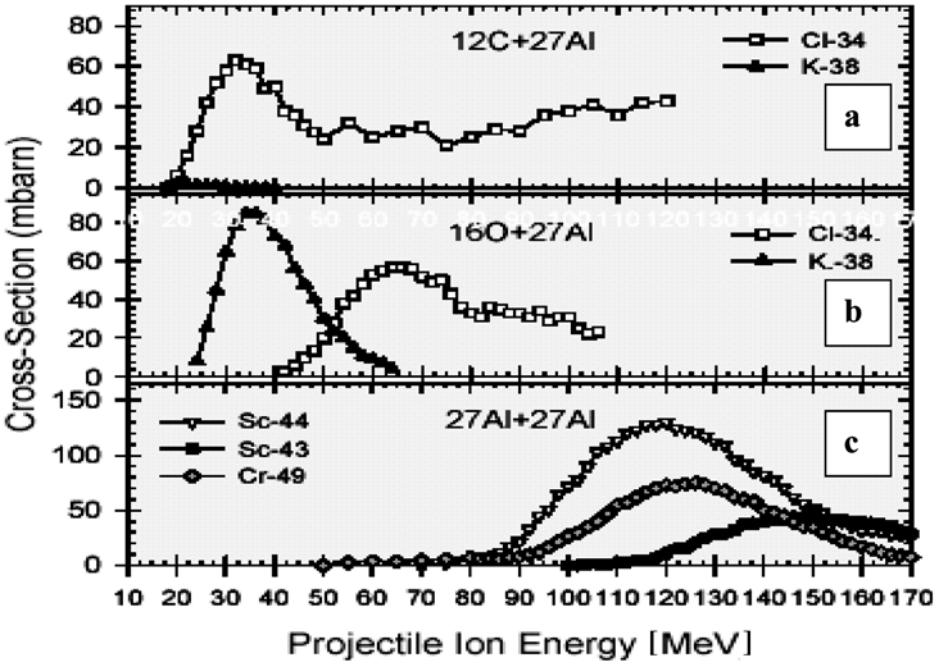

Fig. 2. – Cross-sections for the production of ^{34}Cl, ^{38}K, ^{49}Cr, ^{43}Sc and ^{44}Sc calculated using the PACE-2 evaporation code for [^{12}C + ^{27}Al], [^{16}O + ^{27}Al] and [^{27}Al + ^{27}Al] compound nucleus formation.

decades. It takes full account of angular momentum effects, including yrast levels and γ-emission at all stages of the evaporation chain. The formation of the compound nucleus is calculated via the Bass method [4] and the level density parameters are taken from Gilbert and Cameron [5]. All PACE-2 calculations were based on the newest release of the atomic mass tables by Audi, Wapstra and Thibault [6]. Within the mass regions of interest, the prediction of the final fusion evaporation cross sections is known to be of ~ 10–20% accuracy. Fig. 2c depicts the calculated results for ^{49}Cr, ^{43}Sc and ^{44}Sc produced in the ^{27}Al + ^{27}Al system. The PACE-2 calculations were performed for 60 different energies with a spacing of 2 MeV covering an interval between 50–170 MeV. For every energy a total of 10000 de-excitation processes were simulated with the code. Since PACE-2 discriminates internally against reaction channels with a low probability. The average calculation time on a SPARC Ultra 1 for a full simulation run was around 1 hr. Secondly the TRIM program (**Tr**ansport of **I**ons in **M**atter) [7] was used to include the slowing down and angular straggling of the primary Al ions within the secondary Al-activation foil.

Based on these calculations we conclude that the measured ^{43,44}Sc and ^{49}Cr are a result of the fusion evaporation reactions: ^{27}Al(^{27}Al,2αp2n)^{43}Sc; ^{27}Al(^{27}Al,2αpn)\$^{44}$Sc and ^{27}Al(^{27}Al,αn)^{49}Cr. The production of ^{43}Sc nuclei is estimated to start at an ^{27}Al kinetic energy of E ~ 115 MeV. Taking the energy loss within the secondary target into in account, the presence of ^{43}Sc clearly shows that some Al-ions must have an initial energy of around 5 MeV/A (and probably even more).

Further PACE-2 calculations for ^{27}Al + ^{27}Al were performed simulating up to 100000 decays in order to trace the weak reaction channels. This extensive set of calculations allowed us to exclude ^{34m}Cl, ^{38}K, ^{24}Na, ^{28,29}Al and ^{27}Mg as possible fusion evaporation reaction channels for this particular system. Reactions induced by the two main contaminants ^{12}C and ^{16}O on the secondary Al-foil were considered in order to understand the existence of these species. Due to the poor vacuum conditions in the target chamber these contaminants are present and can also induce nuclear reactions. It was found that ^{34}Cl and ^{38}K likely emerge from such processes. PACE-2 predicts that their cross sections peak at around 60 mbar for energies corresponding to an E/A value of around 2 MeV for the incident light ions (Fig 2 a,b). A dedicated experiment with a ^{12}C activation foil fully confirmed some of these assumptions (ref. [2]).

The interpretation of the high cross sections for some measured species such as e.g. ^{28}Al and ^{27}Mg remains more speculative. It is assumed that they emerge via (n, γ) or (n, p) reaction channels. Unfortunately cross sections for these reactions are much harder to evaluate since there is no elaborated simulation program such as PACE-2 available for that kind of reaction.

CONCLUSION

As shown, novel petawatt laser facilities are able to accelerate ion species with A ~ 30 to an energy regime where they can be used to induce fusion evaporation reactions. PACE-2 calculations in combination with TRIM evaluations are able to theoretically evaluate the results of measurements and allow important conclusions such as the fact that these heavy species can be accelerated up to very high energies of around 5 MeV/A. Further theoretical and experimental improvements are necessary in order to obtain a better description of the reaction channels. This will finally lead to the technical exploitation of laser induced ion production the near future.

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