Effect of target heating on ion-induced reactions in high-intensity laser–plasma interactions

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Measurements of ion-induced nuclear reactions have been used to diagnose ion acceleration from the interaction of high-intensity ($>10^{19}$ W cm^{-2}) laser light with solid targets. Nuclear activation of catcher materials surrounding the interaction region has been studied using a high-resolution germanium detector. It was found that, when a 100 μm thick Al target foil was preheated, the proton flux produced from the laser–foil interaction was considerably reduced. Observed heavy-ion-induced reactions are used with calculated reaction cross sections to quantify ion acceleration. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1616972]

There is considerable interest at present in the use of high-intensity ($>10^{19}$ W cm^{-2}) laser-produced plasmas as sources of energetic ions. Experimental studies have demonstrated the production of beams of protons with energies up to 58 MeV (Ref. 1) and heavier ions with about 5 MeV per nucleon.[2,3] There are many exciting applications for these potentially compact sources of energetic ions, including isotope production for nuclear medicine[4] and injectors for future large-scale ion accelerators.[5]

Nuclear (p,n) reactions on Ti (Ref. 6) and Cu (Ref. 4) have been successfully used to characterize the proton beams accelerated in high-intensity laser-produced plasmas. The protons, which result from water and hydrocarbon contamination layers on the surfaces of solid targets, carry a few percent of the converted laser pulse energy and reduce the efficiency of heavy ion acceleration. It has been demonstrated recently using Thomson parabola ion spectrometers that heating the solid target reduces the contamination layers, and hence the proton flux, thereby increasing the numbers of heavier ions accelerated.[3,7]

Fast heavier ions can interact with stationary atoms in a secondary catcher material to induce compound nucleus formation.[8] The excited compound nuclei decay by evaporating protons, neutrons and alpha particles and create residual nuclei, which emit characteristic gamma radiation. In a previous study observations of heavy-ion-induced fusion-evaporation reactions were used to make quantitative measurements of ion emission.[8] In this letter, ion-induced reactions are studied to further diagnose the effect of target heating on ion acceleration. Measurements of gamma emission together with calculated reaction cross sections are employed to quantify ion acceleration.

The Vulcan laser at the Rutherford Appleton Laboratory was used in this study. Pulses with energy up to 100 J at a wavelength of 1.053 μm and temporal duration of $\sim$1 ps were focused to maximum intensity of 5×10^{19} W cm^{-2} using an $f/3$ off-axis parabolic mirror. The p-polarized laser beam was incident on 100 μm thick, 5×5 mm^2 Al targets at an angle of 45° to the target normal, within a vacuum chamber maintained at 10^{-5} mbar. The Al target foil was radiatively heated to constant temperature for approximately 20 min before each laser shot. Secondary catcher ^{48}Ti samples were positioned at the front of the target (the blow-off direction) and analyzed after each laser shot using a well shielded (25% efficient) germanium detector. The samples were analyzed for sufficiently long counting times to identify the nuclides produced based on their emitted gamma ray energies and their half lives.

Figures 1(a) and 1(c) show regions of interest in the

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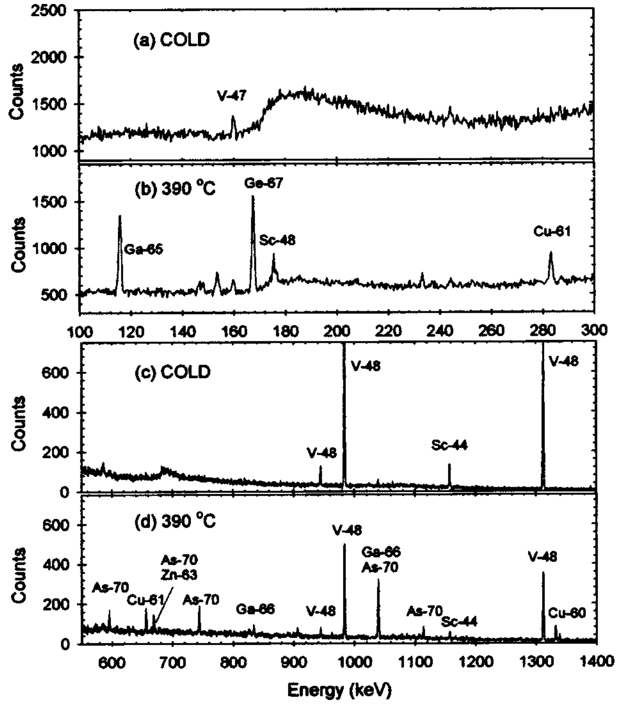

FIG. 1. Gamma-ray spectra observed in a Ti activation sample after irradiation with ions from a primary aluminum target foil which was (a), (c) unheated and (b), (d) heated to 390 °C.

TABLE I. Residual nuclei observed in the titanium activation target. The numbers of each nuclei produced are per laser shot and have been determined after correction for detection efficiency and gamma emission probability per disintegration. Proton-induced and energetically favorable heavy-ion fusion-evaporation reaction channels are identified and calculated reaction threshold energies (E_{thres}) are listed.

Nuclide	Half life	No. of nuclei ($\times 10^4$)	Reaction	E_{thres} (MeV)
Cold				
^{48}V	15.9 day	550	^{48}Ti$(p,n)^{48}$V	4.9
^{47}V	32.6 min	60	^{48}Ti$(p,2n)^{47}$V	15.7
^{44}Sc	3.9 h	0.89	^{48}Ti$(p,\alpha+n)^{44}$Sc	14.0
Heated				
^{48}V	15.9 day	180	^{48}Ti$(p,n)^{48}$V	4.9
^{44}Sc	3.9 h	0.20	^{48}Ti(p,$\alpha+n)^{44}$Sc	14.0
^{70}As	52.6 min	0.76	$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{70}\text{As}+1\alpha+1n$	18.4
^{69}As	15.2 min	1.0	$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{69}\text{As}+1\alpha+2n$	32.8
^{67}Ge	18.7 min	0.47	$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{67}\text{Ge}+1\alpha+3n+1p$	57.1
^{66}Ga	9.5 h	8.2	$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{66}\text{Ga}+2\alpha+1n$	23.0
^{65}Ga	15.2 min	0.86	$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{65}\text{Ga}+2\alpha+2n$	37.1
^{63}Zn	38.1 min	10	$^{16}\text{O}+{}^{48}\text{Ti}\rightarrow{}^{63}\text{Zn}+1n$	⋯
			$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{63}\text{Zn}+2\alpha+3n+1p$	61.5
^{61}Cu	3.4 h	5.5	$^{16}\text{O}+{}^{48}\text{Ti}\rightarrow{}^{61}\text{Cu}+2n+1p$	19.4
			$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{61}\text{Cu}+3\alpha+2n$	42.0
^{60}Cu	24.4 min	0.36	$^{16}\text{O}+{}^{48}\text{Ti}\rightarrow{}^{60}\text{Cu}+3n+1p$	34.9
			$^{27}\text{Al}+{}^{48}\text{Ti}\rightarrow{}^{60}\text{Cu}+3\alpha+3n$	60.2

measured gamma-ray spectrum observed from a ^{48}Ti catcher sample after irradiation of an unheated Al target foil with 73 J of laser energy. Characteristic gamma-ray lines of ^{48}V, ^{47}V, and ^{44}Sc are observed, signatures of proton-induced reactions (p,n), $(p,2n)$, and $(p,\alpha+n)$, respectively. Using the peaked cross sections for these reactions it has been determined that $\sim 10^{10}$ protons with energies in the range 10–30 MeV are required to produce the calculated initial numbers of each observed nuclei, listed in Table I. It should be emphasized that only proton-induced nuclear reactions were observed from the unheated Al target.

The gamma-ray spectrum obtained from a ^{48}Ti sample with an ^{27}Al foil target heated to 390 °C is shown in Figs. 1(b) and 1(d). Signature peaks of ^{48}V and ^{44}Sc are detected with a much reduced intensity and the ^{47}V peak, which was weak in the unheated target spectrum, is not seen at all. The proton flux required to induce the observed activity is reduced by a factor of between 3 and 5 for the heated compared with the unheated target. The ^{48}Ti$(p,\alpha+n)^{44}$Sc reaction, with a peaked cross section at 30 MeV, demonstrates a reduction of a factor of 4.4 compared to a reduction of a factor of 3 for the ^{48}Ti$(p,n)^{48}$V reaction with a peaked cross section at $\sim$12 MeV. This larger reduction in higher energy protons results in lower mean proton energy and lower maximum energy, largely in agreement with the previous heated target experiments utilizing a Thomson parabola diagnostic.[3,7]

Significantly, a range of additional nuclei are observed with the heated target, namely, ^{70}As, ^{69}As, ^{67}Ge, ^{66}Ga, ^{65}Ga, ^{63}Zn, ^{61}Cu, and ^{60}Cu. These heavier nuclei result from the acceleration of ^{27}Al and ^{16}O ions, which fuse with stationary ^{48}Ti atoms in the secondary target and subsequently evaporate protons, neutrons and alpha particles; see Table I. The acceleration of O ions from an Al target foil has been observed before and is attributed to the presence of H_2O and oxide layers on the target surface.[8] Figure 2 shows reaction cross sections for possible fusion-evaporation channels calculated using the projection angular-momentum coupled evaporation (PACE)-2 Monte Carlo code.[9] The production of ^{61}Cu, ^{60}Cu, and ^{63}Zn could proceed via ^{27}Al$+{}^{48}$Ti or ^{16}O $+{}^{48}$Ti evaporation reactions, although the relatively high cross sections at low energies for the latter would suggest this to be the probable channel for the production of ^{61}Cu and ^{60}Cu (Table I). The cross sections for ^{27}Al$+{}^{48}$Ti reactions have more than one peak, demonstrating more than one evaporation channel leading to the same residual nuclide. The lowest energy evaporation channels are peaked at energies between 80 and 120 MeV for the production of ^{70}As,

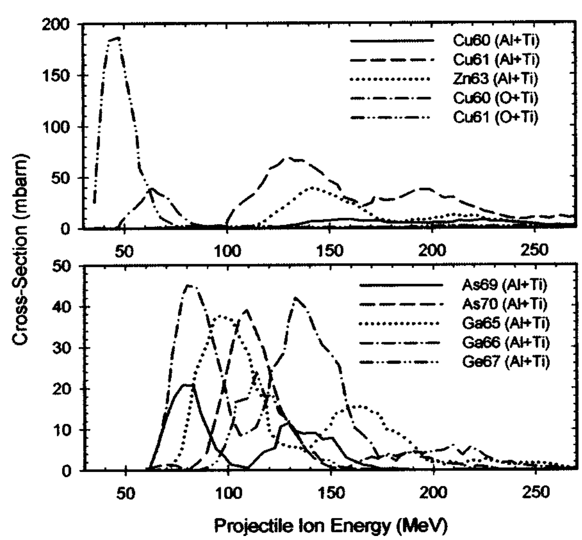

FIG. 2. Cross sections for evaporation from ^{27}Al$+{}^{48}$Ti and ^{16}O$+{}^{48}$Ti compound nuclei, calculated using the PACE-2 code.

^{69}As, ^{67}Ge, ^{66}Ga, and ^{65}Ga. It is unlikely that the evaporation scenarios leading to the cross-section peaks at higher energies will contribute significantly, since previous experimentation with this laser focused to similar intensities has shown that the energy spectrum of Al ions falls steeply between 120 and 150 MeV.[5,8] The relatively high energies required to observe even the lowest energy reaction channels would explain why these nuclei are not observed with the unheated target. With the target heated, the mean Al ion energy is increased and these reaction channels are populated with greater efficiency. This supports earlier observations of enhanced carbon ion energies from heated targets using Thomson parabola diagnostics.[3,7]

In conclusion, ion-induced reactions have been observed in high-intensity laser–plasma interaction experiments with heated and unheated Al targets. Analysis of the reaction products indicates that heating the target to a temperature of 390 °C reduced the total proton flux by a factor of between 3 and 5 and resulted in more efficient acceleration of heavier ions. From the observed numbers of the product nuclei, the peak cross sections for the most energetically favored channels and the stopping ranges of Al and O ions in Ti, it was possible to obtain a good estimate of the numbers of Al and O ions with energies above the reaction thresholds.

Assuming both ^{61}Cu and ^{60}Cu are produced via O ions only, one requires the acceleration of $\sim 5\times 10^9$ ions to $\sim$45 MeV and 1×10^9 ions to $\sim$65 MeV, respectively, into the solid angle of 2 sr subtended by the secondary target. To produce the observed ^{70}As, ^{69}As, ^{67}Ge, ^{66}Ga, and ^{65}Ga requires an Al ion spectrum of $\sim 10^{10}$ ions at 80 MeV, decreasing to $\sim 10^9$ at 120 MeV.

The use of target heating to selectively open reaction channels in the study of heavy-ion-induced reactions has been demonstrated. The ability to change the ion energy spectrum has implications for the use of laser plasma-based ion accelerators as potential injectors for future heavy ion accelerators.

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