

Detection of short lived radioisotopes as a fast diagnostic for intense laser-solid interactions

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As a diagnostic of high-intensity laser interactions ($>10^{19}$ W cm⁻²), the detection of radioactive isotopes is regularly used for the characterization of proton, neutron, ion, and photon beams. This involves sample removal from the interaction chamber and time consuming post shot analysis using NaI coincidence counting or Ge detectors. This letter describes the use of *in situ* detectors to measure laser-driven (p,n) reactions in ²⁷Al as an almost real-time diagnostic for proton acceleration. The produced ²⁷Si isotope decays with a 4.16 s half-life by the predominantly β^+ emission, producing a strong 511 keV annihilation peak. © 2006 American Institute of Physics.

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The diagnostics of fast ions from intense laser-solid interactions are historically Thomson parabolas¹⁻³ or stacks of radiochromic film and nuclear track detectors interdispersed with energy filtering foils.^{4,5} However, recently it has been shown that the production of short lived isotopes can be used as an efficient diagnostic for high-intensity laser interactions in the relativistic regime above 10^{19} W cm⁻² where laser produced nuclear reactions occur.⁶⁻⁸ This is particularly useful as a diagnostic for gamma and proton production.^{4,5,9-11} For example, most (γ,n) reactions have typical thresholds of ~ 10 MeV, and for multiple (γ,mn) reactions, the production of each successive neutron typically requires an extra 10 MeV. Clearly, a ($\gamma,7n$) reaction can diagnose photon energies >70 MeV. Giant resonance (γ,n) cross sections increase in value with increasing A number, and are typically 50–100 mb in the mid- Z region. (p,n) reactions are very useful for the production of radioisotopes and typically have lower thresholds, as low as 2–3 MeV, and cross sections which can exceed hundreds of millibarns. Isotopes commonly used for laser-plasma diagnostics are ⁶³Cu (p,n) ⁶³Zn ($t_{1/2}=38$ min) and ⁶³Cu (γ,n) ⁶²Cu ($t_{1/2}=10$ min). The samples are removed from the interaction chamber and analyzed off line using techniques such as coincidence counting, hence the choice of a half-life within the 10–60 min region. The detection of half-lives of a few minutes is precluded as the time for access into the interaction vessels after a shot and vacuum let-up typically exceeds 10 min. Fast pneumatic transfer systems, commonly used in conventional reactors and accelerators, can extract samples within seconds but have not yet been adopted in a laser facility.

This letter describes the demonstration of the production and subsequent detection of the short lived ²⁷Si isotope using a (p,n) reaction in high purity ²⁷Al as a method to diagnose energetic protons accelerated in a laser plasma. The analyzing detector is housed within the interaction chamber, negating the need to remove the sample. ²⁷Si has a 4.16 s half-life and with a maximum ²⁷Al (p,n) ²⁷Si cross section at ~ 8 MeV; this process becomes an almost real-time diagnostic for the detection of high-energy protons. The half-life needs to be short to enable measurements soon after the shot, yet long enough for the detector to recover from the initial laser-target interaction, which produces a large gamma flash.

The experiment was performed on the Vulcan petawatt laser at Rutherford Appleton Laboratory.¹² The experiment used an $f/3$ parabolic focussing optic and plasma mirrors to enhance the laser contrast. On-target laser conditions were ~ 200 J in ~ 1 ps, producing an on-target intensity of $\sim 1 \times 10^{20}$ W cm⁻². The laser was incident on 20 μ m thick gold targets at 40° to the target normal. The 1 mm thick aluminum sample (catcher) was placed at approximately 20 cm from target, covered by a 500 μ m thick aluminum plate to stop activated target debris from being deposited on the catcher—highlighted as a problem during preliminary shots. To penetrate this debris shield, the proton energy must exceed 9 MeV. Coupled with the energy required to exceed the threshold value for the ²⁷Al (p,n) ²⁷Si reaction, the system responded to a minimum proton energy of 11 MeV.

The layout is shown in Fig. 1. The catcher was held by an electromagnetic solenoid which when released allowed it to drop via guide rails to a lead shielded NaI detector lying ~ 30 cm below the target plane. The 3 in. diameter Scionix 76B76/3 NaI detector with VD141-E1 base was biased with 800 V. The signal from the detector was routed through an ORTEC 675 spectroscopy amplifier with 0.5 μ s integration and differentiation time constants. A Canberra Multiport 2

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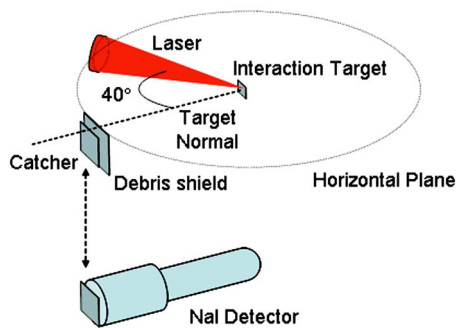


FIG. 1. (Color online) Detector and sample setup. The NaI detector is shown without the surrounding shielding for clarity.

multichannel analyzer (MCA), operating in multiscale mode, was used for data acquisition, with 10 ms dwell time per channel. The MCA has a dead time of 2 μ s, matching the signal saturation observed in the experiment. Calibration of the detector using a ^{22}Na source gave a detector efficiency of 30%. Lead shielding surrounding the detector was used to reduce the effect of the large picoseconds duration gamma flash produced by MeV electrons in the target, commonly observed during high-intensity interactions. Even with this shielding in place, spectra show a gamma flash saturating the detector (~ 1000 counts) with a recovery time of ~ 0.5 s.

Figure 2 shows the data from an unoptimized shot. The ^{27}Si component is clearly visible in the data, and the insets show the 511 keV emission line from β^+ decay (top), along with the recovery of the detector before the sample was dropped (bottom). Successful shots were also performed by remotely viewing the catcher over a small solid angle.

Typical activities observed during laser-driven medical isotope production experiments¹³ show the generation of $\sim 10^{10}$ radioactive nuclei from (p,n) reactions on ^{11}B . The generated isotope of ^{11}C , with a half-life of ~ 20 min, produces activities in the order of 10^6 Bq at $t=0$. The ^{27}Si , generated through the ^{27}Al (p,n) reaction, has a half-life of 4.16 s and the difference in half-life is much greater than the difference in cross section. This results in very large counting rates and requires heavy filtering between sample and detector to reduce the detector dead time and saturation of the photomultiplier tube (PMT). A thinner sample could also be used to limit the activity, but for these measurements a 1 cm thick lead filter was used between the catcher and detector, reducing the signal by a factor of 6. Figure 3 shows

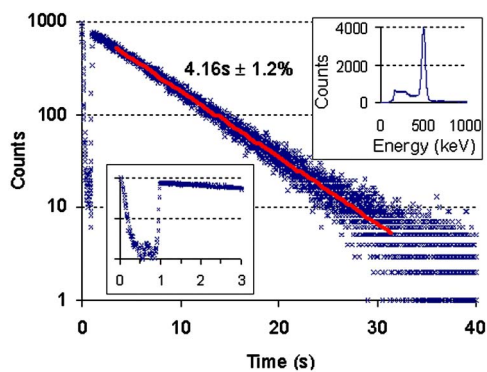


FIG. 2. (Color online) Data and fit to ^{27}Si decay. Top inset—spectrum showing 511 keV γ ray from β^+ emission. Bottom inset—response to prompt γ flash and recovery before the catcher is dropped. Detector dead time has been compensated.

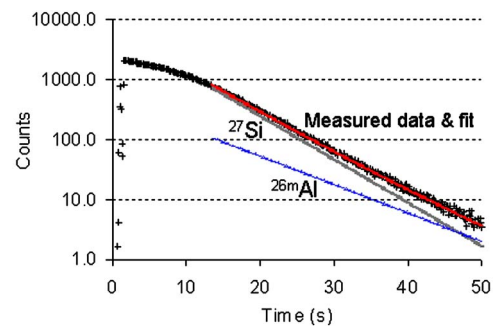


FIG. 3. (Color online) Saturated data showing ^{27}Si (4.16 s) and ^{26m}Al (6.34 s) components with combined fit. Counts at $t=0$ are calculated at ~ 6500 (^{27}Si) and ~ 450 (^{26m}Al) using a 10 ms dwell time. Detector dead time has been compensated.

data from the same experimental arrangement but under more optimal proton production conditions, resulting in the saturation of the PMT. With such high activity, it is possible to identify a second active component, matching the 6.34 s half-life of ^{26m}Al . This can be generated through $(p,p+n)$, (p,d) , (γ,n) , or $(n,2n)$ reactions in the aluminum catcher. It is likely that the $(p,p+n)$ or (p,d) reaction dominates this production as the high-energy neutron and gamma yields should be relatively low for the target type used. The cross sections for reactions are shown in Fig. 4, though no available data were found for the $(p,p+n)$ or (p,d) reactions. Calculations indicate a reaction threshold of 11.23 MeV for the (p,d) reaction and 13.54 MeV for the $(p,p+n)$ reaction, hence the (p,d) reaction is more likely if the reactions have similar cross sections. The observation of both the ^{27}Si and ^{26m}Al components may in the future allow rapid temperature measurements to be performed using the two different energies to fit an ion temperature¹⁴ assuming a Boltzmann-like energy distribution. This is an important aspect of the future work, as the use of the (p,n) generated ^{27}Si in a single catcher will only derive proton numbers at a single energy, as selected by the thickness of the debris filter. The diagnostic will therefore not derive a proton spectral measurement similar to that achieved through detector stacks.^{4,5}

The presented method opens up a new approach for the diagnosis of proton, ion, photon, and neutrons on a much faster time scale than at present. Though this is extremely useful for low repetition, high-intensity lasers, it opens up the possibility for experiments on future high repetition facilities of typically 10 Hz where shot rates will be limited by the time taken to analyze diagnostic data. For these types of facilities, half-lives in the region of 10–100 ms will be re-

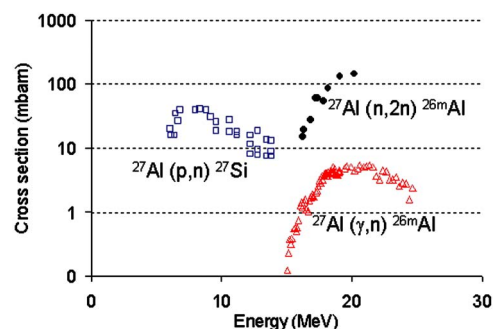


FIG. 4. (Color online) Cross section data for ^{27}Al (p,n) ^{27}Si (Ref. 16), ^{27}Al $(n,2n)$ ^{26m}Al (Ref. 17), and ^{27}Al (γ,n) ^{26m}Al (Ref. 18).

TABLE I. Examples of short half-life reactions (Ref. 19).

| Reaction | Half-life | Threshold (MeV) |
|---|-----------|-----------------|
| $^{23}\text{Na} (p, n) ^{23}\text{Mg}$ | 11.32 s | 5.05 |
| $^{27}\text{Al} (p, n) ^{27}\text{Si}$ | 4.16 s | 5.80 |
| $^{39}\text{K} (p, n) ^{39}\text{Ca}$ | 860 ms | 7.50 |
| $^{40}\text{Ca} (\gamma, n) ^{39}\text{Ca}$ | 860 ms | 15.64 |
| $^{28}\text{Si} (p, n) ^{28}\text{P}$ | 270 ms | 15.66 |
| $^{40}\text{Ca} (p, n) ^{40}\text{Sc}$ | 182 ms | 15.49 |

quired. Possible examples are listed in Table I. Reactions on this time scale will also need to make use of much faster amplifiers and detectors with recovery times below tens of milliseconds to reduce the observed dead times caused by the built-in electronics. Two techniques have been demonstrated for the detection of short lived isotopes—utilizing a moveable catcher or by remote viewing of a stationary catcher. Both principles have been achieved with the high activities observed on aluminum, and even higher activities are expected with shorter half-life isotopes.

Finally, the use of short half-life radioisotopes to generate a spatially resolvable system for particle detection is suggested to enable real-time access to the acquired data. The generated radioisotopes in the catcher can be imaged via contact radiography, providing a spatially resolved detector. This requires the use of newly developed camera technology such as pixelated CdTe or Ge detectors capable of detecting 511 keV β^+ annihilation gamma rays emitted from short half-life radioisotopes. The advantage over scintillators is that the prompt gamma flash does not need to be gated out as the half life of activated nuclei in the catcher is much larger than the evolution of the gamma flash. The catcher material can also be optimized to appropriately match the half-life to the integration period of the camera. If the signal is recorded in real time, a spatially resolved image will form after the initial gamma flash has subsided. The number of generated radioisotopes can also be derived from the decay of the recorded images. Additionally, a saturated signal will become resolvable as the catcher decays, making the dynamic range extremely large. This technique could be a route towards instantaneously accessing laser-plasma proton radiography data,¹⁵ crucial for high repetition laser facilities, though limitations generated by the observed gamma flash will also have to be addressed. This potential issue may not, however, be a serious threat, as high repetition facilities typically use low energies with ultrashort pulses, seriously reducing the gamma flash in comparison to the data acquired on the Vulcan facility with energies exceeding 200 J on target. The associated electromagnetic pulse (EMP) issues for any charge-coupled device system will also be reduced, which have caused some problems on ultrahigh-intensity laser systems such as Vulcan when used close to target. In these situations, true EMP shielding for the electronics and gating of the detector may need to be employed, possibly reducing the capable repetition rates.

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¹J. J. Thomson, *Philos. Mag.* **21**, 225 (1911).

²S. Sakabe, T. Mochizuki, T. Yamanaka, and C. Yamanaka, *Rev. Sci. Instrum.* **51**, 1314 (1980).

³E. L. Clark, K. Krushelnick, M. Zepf, F. N. Beg, M. Tatarakis, A. Machacek, M. I. K. Santala, I. Watts, P. A. Norreys, and A. E. Dangor, *Phys. Rev. Lett.* **85**, 1654 (2000).

⁴M. Zepf, E. L. Clark, K. Krushelnick, F. N. Beg, C. Escoda, A. E. Dangor, M. I. K. Santala, M. Tatarakis, I. F. Watts, P. A. Norreys, R. J. Clarke, J. R. Davies, M. A. Sinclair, R. D. Edwards, T. J. Goldsack, I. Spencer, and K. W. D. Ledingham, *Phys. Plasmas* **8**, 2323 (2001).

⁵I. Spencer, K. W. D. Ledingham, R. P. Singhal, T. McCanney, P. McKenna, E. L. Clark, K. Krushelnick, M. Zepf, F. N. Beg, M. Tatarakis, A. E. Dangor, P. A. Norreys, R. J. Clarke, R. M. Allott, and I. N. Ross, *Nucl. Instrum. Methods Phys. Res. B* **183**, 449 (2001).

⁶K. W. D. Ledingham, P. McKenna, and R. P. Singhal, *Science* **300**, 1107 (2003).

⁷P. McKenna, K. W. D. Ledingham, T. McCanny, R. P. Singhal, I. Spencer, M. I. K. Santala, F. N. Beg, K. Krushelnick, M. Tatarakis, M. S. Wei, E. L. Clark, R. J. Clarke, K. L. Lancaster, P. A. Norreys, K. Spohr, R. Chapman, and M. Zepf, *Phys. Rev. Lett.* **91**, 075006 (2003).

⁸F. Amiranoff, *Meas. Sci. Technol.* **12**, 1795 (2001).

⁹P. McKenna, K. W. D. Ledingham, S. Shimizu, J. M. Yang, L. Robson, T. McCanny, J. Galy, J. Magill, R. J. Clarke, D. Neely, P. A. Norreys, R. P. Singhal, K. Krushelnick, and M. S. Wei, *Phys. Rev. Lett.* **94**, 084801 (2005).

¹⁰S. P. Hatchett, C. G. Brown, T. E. Cowen, E. A. Henry, J. S. Jonson, M. H. Key, J. A. Koch, A. B. Langdon, B. F. Lasinsky, R. W. Lee, A. J. Mackinnon, D. M. Pennington, M. D. Perry, T. W. Philips, M. Roth, T. C. Sangster, M. S. Singh, R. A. Snavely, M. A. Stoyer, S. C. Wilks, and K. Yasuike, *Phys. Plasmas* **7**, 2076 (2000).

¹¹P. A. Norreys, M. Santala, E. Clark, M. Zepf, I. Watts, F. N. Beg, K. Krushelnick, M. Tatarakis, A. E. Dangor, X. Fang, P. Graham, T. McCanny, R. P. Singhal, K. W. D. Ledingham, A. Creswell, D. C. W. Sanderson, J. Magill, A. Machacek, J. S. Wark, R. Allott, B. Kennedy, and D. Neely, *Phys. Plasmas* **6**, 2150 (1999).

¹²C. N. Danson, P. A. Brummitt, R. J. Clarke, J. L. Collier, B. Fell, A. J. Frackiewicz, S. Hancock, S. Hawkes, C. Hernandez-Gomez, P. Holligan, M. H. R. Hutchinson, A. Kidd, W. J. Lester, I. O. Musgrave, D. Neely, D. R. Neville, P. A. Norreys, D. A. Pepler, C. J. Reason, W. Shaikh, T. B. Winstone, R. W. W. Wyatt, and B. E. Wyborn, *Nucl. Fusion* **44**, S239 (2004).

¹³K. W. D. Ledingham, P. McKenna, T. McCanny, S. Shimizu, J. M. Yang, L. Robson, J. Zweit, J. M. Gillies, J. Bailey, G. N. Chimon, R. J. Clarke, D. Neely, P. A. Norreys, J. L. Collier, R. P. Singhal, M. S. Wei, S. P. D. Mangles, P. Nilson, K. Krushelnick, and M. Zepf, *J. Phys. D* **37**, 2341 (2004).

¹⁴J. M. Yang, P. McKenna, K. W. D. Ledingham, T. McCanny, L. Robson, S. Shimizu, R. P. Singhal, M. S. Wei, K. Krushelnick, R. J. Clarke, D. Neely, and P. A. Norreys, *J. Appl. Phys.* **96**, 6912 (2004).

¹⁵A. J. Mackinnon, P. K. Patel, R. P. Town, M. J. Edwards, T. Phillips, S. C. Lerner, D. W. Price, D. Hicks, M. H. Key, S. Hatchett, S. C. Wilks, M. Borghesi, L. Romagnani, S. Kar, T. Toncian, G. Pretzler, O. Willi, M. Koenig, E. Martinolli, S. Lepape, A. Benuzzi-Mounaix, P. Audebert, J. C. Gauthier, J. King, R. Snavely, R. R. Freeman, and T. Boehlly, *Rev. Sci. Instrum.* **75**, 3531 (2004).

¹⁶J. D. Anderson, S. D. Bloom, C. Wong, W. F. Hornyak, and V. A. Madsen, *Phys. Rev.* **177**, 1416 (1969).

¹⁷G. S. Mani, G. J. McCallum, and A. T. G. Ferguson, *Nucl. Phys.* **19**, 535 (1960).

¹⁸M. N. Thompson, J. M. Taylor, B. M. Spicer, and J. E. E. Baglin, *Nucl. Phys.* **64**, 486 (1965).

¹⁹QCALC, Q-value calculator, NNDC, Brookhaven National Laboratory.