Photonuclear fission with quasimonoenergetic electron beams from laser wakefields

S. A. Reed,[a)] V. Chvykov, G. Kalintchenko, T. Matsuoka, P. Rousseau, and V. Yanovsky
FOCUS Center and Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099

C. R. Vane, J. R. Beene, D. Stracener, and D. R. Schultz
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6372

A. Maksimchuk
FOCUS Center and Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099

(Received 24 September 2006; accepted 22 October 2006; published online 5 December 2006)

Recent advancements in laser wakefield accelerators have resulted in the generation of low divergence, hundred MeV, quasimonoenergetic electron beams. The bremsstrahlung produced by these highly energetic electrons in heavy converters includes a large number of MeV γ rays that have been utilized to induce photofission in natural uranium. Analysis of the measured delayed γ emission demonstrates production of greater than 3×10^5 fission events per joule of laser energy, which is more than an order of magnitude greater than that previously achieved. Monte Carlo simulations model the generated bremsstrahlung spectrum and compare photofission yields as a function of target depth and incident electron energy. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2400400]

Significant developments in laser wakefield acceleration of high quality, quasimonoenergetic electron beams[1–4] to energies exceeding 100 MeV have enabled tabletop photonuclear physics to be explored. Such energetic electron beams have an array of applications in radiography, radioisotope production, nuclear physics, and possibly the transmutation of nuclear waste. In particular, the multi-MeV bremsstrahlung produced using the incident electrons upon a high Z converter is an effective technique to induce photofission and may have additional applications in dynamic γ-ray radiography and nuclear resonance fluorescence to detect explosives or other materials. Additionally, wakefield accelerated electrons may serve as an efficient, low cost fission product source for achieving the next generation radioactive ion beams[5] used to study nuclear structure and reactions and applications to research in nuclear astrophysics.[6]

Previous work done[7–10] realized and examined uranium photofission reactions through the generation of relativistic electrons in laser interactions with solid targets. At the LOA laboratory using an ~60 TW laser system incident upon a solid target placed in front of uranium, 10^4 fission reactions per shot were observed.[7] Liesfeld *et al.* used laser accelerated electrons with a Maxwellian-like energy distribution from He gas to induce photofission in Au and Ta to confirm the lower limit of the electron temperature.[11] Photonuclear fission using much higher laser energy was observed at the Petawatt laser in Livermore by Cowan *et al.*[9,10] The laser system delivered a 570 TW pulse onto a gold-faced uranium target, which resulted in 7×10^4 fissions/J. In this letter we report the production of more than 3×10^5 photofission reactions in uranium per joule of laser energy, roughly five times greater than in any previous experiments and roughly 30 times greater than photofission achieved with tabletop laser systems. The higher yield is attributed to the 150 MeV quasimonoenergetic nature of the wakefield accelerated electron beam, which produces a higher percentage of γ rays lying above the threshold for ^{238}U(γ, fission) compared to a Maxwellian-like electron distribution created in solid targets with an equivalent charge. The highly energetic electron beam, through bremsstrahlung, effectively creates an intense beam of tens-of-MeV γ rays, thus yielding a larger number of photofission events per joule of incident laser energy.

The experiment was performed using the Hercules laser system at the University of Michigan. The electron beam was generated using laser wakefield acceleration by focusing a 30 fs full width at half maximum, 800 nm, 10^{19} W/cm^2 intensity laser beam into a 2 mm long He gas jet with an electron density of approximately 3×10^{19} cm^{-3}.[4] A LANEX phosphor screen, placed 80 cm behind the gas jet, was imaged onto a 12 bit charge-coupled device camera to diagnose the electron beam's spatial profile, which had a divergence of about 10 mrad, or the electron momentum distribution using a 0.24 T dipole magnetic spectrometer [Fig. 1(a)]. An integrating current transformer measured the total charge to be ~0.5 nC. By varying the nozzle position and He gas density, the electron beam's spatial profile, total charge, and energy were optimized and consistently produced a quasimonoenergetic electron beam with a peak energy ranging between 100 and 150 MeV. After characterizing the electron beam and establishing its reproducibility, a 2.9 mm thick, 11 mm diameter natural uranium target was placed 15 cm behind the gas jet, where the electron beam was ~3 mm in diameter. Bremsstrahlung yield scales as the atomic number squared (Z^2); thus the uranium target was used both as a converter and as a fissionable target. The relatively thin target thickness was chosen to simplify analysis and corrections for self-absorption in deriving yields of observed γ decays of various radioactive products. However, a thicker ^{238}U sample would have absorbed a higher percentage of γ rays leading to a

[a)]Electronic mail: reedsa@umich.edu

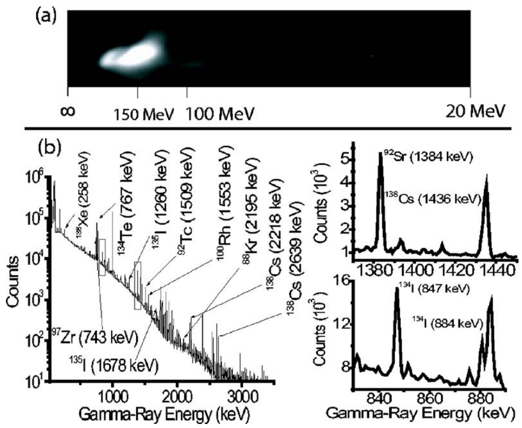

FIG. 1. (a) Typical electron beam energy spectrum showing 150 MeV quasimonoenergetic beam. (b) The γ spectra taken from the irradiated uranium target. The signature γ-emission peaks from ^{134}I (847 keV) and ^{92}Sr (1384 keV) decay are present.

higher photofission yield per laser shot. The uranium fission process produces, among other fission fragments, ^{134}I and ^{92}Sr with 53 min and 2.7 h half-lives, respectively.[12] The laser was fired 72 times over ~75 min, corresponding to roughly 1.5 ^{134}I half-lives, and an additional 18 min delay was experienced between removing the sample and the counting process. The emitted γ spectrum was recorded every 10 min for the first 1.5 h, every 20 min for the next hour, and finally every 60 min for the next 7 h.

Our work demonstrates the highest number of multi-MeV γ rays produced through the bremsstrahlung of laser wakefield accelerated electrons. The number of fission events dramatically improves as a larger percent of the bremsstrahlung γ rays lies within the giant dipole resonance range. Simulations shows that 70%–75% of the γ radiation in the relevant energy range (6–25 MeV) is contained within a half angle of ~9° with respect to the incident electron direction and the photofission yield from γ rays above ~25 MeV is small. The ^{134}I and ^{92}Sr fission products were identified, using an ORTEC GAMMX Ge(Li) γ-ray detector, through their signature γ decays of 0.847 and 1.384 MeV γ rays, as shown in Fig. 1(b). The presence and populations of ^{134}I and ^{92}Sr were confirmed by measuring the numbers of the emitted γ rays (background subtracted) as functions of time, as shown in Fig. 2. Primary fission to the ^{134}I fragment accounts for about one-third of the integrated total reactions. Feeding of the ^{134}I population through the decays of other ^{238}U fission fragment pathways causes the deviation observed during

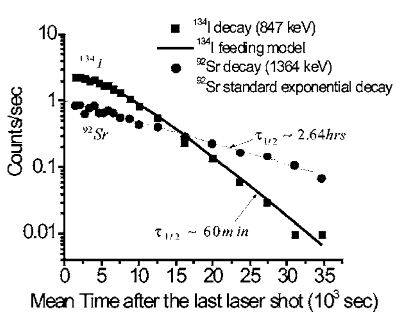

FIG. 2. Measured count rates for the 847 keV γ rays detected, as a function of time after the last laser shot for the ^{238}U(γ, fission)^{134}I process, and for the 1384 keV γ rays detected, with the background subtracted, as a function of time after the last laser shot for ^{238}U(γ, fission)^{92}Sr.

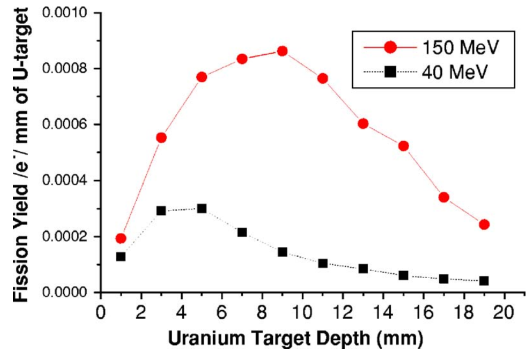

FIG. 3. Monte Carlo calculations showing the buildup of uranium fission yields as a function of target thickness for incident electron energy of 40 MeV (squares) and 150 MeV (circles).

the first 2 h of the measured ^{134}I decay. The secondary fission fragment pathways decaying to ^{92}Sr have shorter lifetimes and decayed during the 18 min delay before counting began, thus showing little deviation from the single exponential decay model. By fitting the data after several expected lifetimes, 1.0 h and 2.64 h half-lives were determined for ^{134}I and ^{92}Sr, respectively, in relatively good agreement with the literature values of 53 min and 2.7 h.

To derive the fission yield, a multiexponential radioactive series decay model was developed using tabulated lifetimes and relative fission fractions for fragments contributing to ^{134}I (and ^{92}Sr). The solid curve in Fig. 2 represents the results of the best fit to this model for ^{134}I (after correcting for backgrounds, γ counting efficiencies, target self-absorption, and radiative channel strengths). The apparent total ^{134}I and ^{92}Sr isotope production yields after the last laser pulse derived from fitting the data with this model are 1.5×10^7 and 1.0×10^7, respectively. Dividing the totals by the appropriate effective number of laser shots, and taking into account the decays between shots, gives a resultant total average fission yield of 3.3×10^5 fissions per laser shot for both the ^{134}I and ^{92}Sr data sets. From our specific γ-ray activity measurements, we thus infer the gross nuclear species activation rates per laser pulse and show enhancements of 10–100 times the photonuclear yields per joule of laser energy compared to earlier experiments.[7–10]

Based on Monte Carlo simulations uranium fission yields show a strong sensitivity to the incident electron beam energy at a specific target thickness. As shown in Fig. 3, the photofission yield displays a strong variation to the incident electron energy plotted for 150 and 40 MeV and clearly shows that the yield per millimeter can be maximized by selecting the proper target thickness. The 3 mm uranium target thickness in our experiment was chosen to allow for the yield per electron to be calculated without requiring large absorption or other correction terms, which were on the order of 15% for the 3 mm target. In order to optimize the total yield, a thicker target is needed; however calculating the yield per electron becomes more complicated due to secondary and tertiary effects. Within the target material any bremsstrahlung from primary, secondary, etc. reactions that are above threshold for photofission will contribute to the total yield produced. Therefore, by stacking multiple layers of the target material and measuring the γ radiation individually from each layer, one can determine the photofission yield depth dependence. As shown in Fig. 3, which assumes a target built from 2 mm thick layers and measuring the fission events from the 2–4 and 8–10 mm depths, the expected yields vary from 5.5×10^{-4}/electron mm of target to 8.6 $\times10^{-4}$ for 150 MeV electrons incident on ^{238}U. The total number of fission yields is obtained by integrating under the curve for a given target thickness. Future work quantifying photofission yields as a function of target thickness is in progress.

In summary, it has been shown that the use of quasimonoenergetic wakefield accelerated electrons can be employed to induce yields of at least $\sim3\times10^{5}$ fissions/J of laser energy through the photonuclear reaction ^{238}U(γ, fission). Moreover, in comparison with previous work, which used an ultraintense laser incident upon solid targets to induce photofission, we observed over an order of magnitude enhancement in the number of fission events. Analysis of the characteristic γ-ray emission was used to infer that fission products ^{134}I and ^{92}Sr were generated in good agreement with the published values. The electromagnetic shower propagating through the target was modeled using a Monte Carlo simulation, showing that ~70% of the γ-ray spectrum lies within the region of interest. These results demonstrate another step toward the development of a compact, tabletop, all-laser source as a tool for fundamental nuclear physics research and toward making the technique practical for nuclear applications.

This work was supported by the NSF through the Physics Frontier Center, FOCUS (NSF PHY 0114336). Four of the authors (J.R.B., D.R.S., D.W.S., and C.R.V.) were partially sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory (ORNL), managed by UTBattelle, LLC for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

[1] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka, Nature (London) **431**, 541 (2004).
[2] C. G. R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiller, C. Nieter, J. Cary, and W. P. Leemans, Nature (London) **431**, 538 (2004).
[3] P. D. Mangles, C. D. Murphy, Z. Najmudin, A. G. R. Thomas, J. L. Collier, A. E. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker, D. A. Jaroszynski, A. J. Langley, W. B. Mori, P. A. Norreys, F. S. Tsung, R. Viskup, B. R. Walton, and K. Krushelnick, Nature (London) **431**, 535 (2004).
[4] A. Maksimchuk, S. Reed, N. Naumova, V. Chvykov, B. Hou, G. Kalintchenko, T. Matsuoka, J. Nees, P. Rousseau, G. Mourou, and V. Yanovsky, in *Proceedings of Inertial Fusion Sciences and Applications Conference 2005*, edited by. J.-C. Gauthier, B. Hammel, H. Azechi, and C. Labaune [J. Phys. IV **133**, 1123 (2006)].
[5] J. A. Lettry, *Proceedings of the 1999 Particle Accelerator Conference*, New York, 1999, Vol. 1, pp. 92–96.
[6] A. Aprahamian, K. Langanke, and M. Wiescher, Prog. Part. Nucl. Phys. **54**, 535 (2005).
[7] G. Malka, M. M. Aleonard, J. F. Chemin, G. Claverie, M. R. Harston, V. Tikhonchuk, J. N. Scheurer, S. Fritzler, V. Malka, P. Balcou, G. Grillon, S. Moustaizis, L. Notebaert, M. Pittman, and E. Lefebvre, Proc. SPIE **4510**, 47 (2001).
[8] H. Schwoerer, F. Ewald, R. Sauerbrey, J. Galy, J. Magill, V. Rondinella, R. Schenkel, and T. Butz, Europhys. Lett. **61**, 47 (2003).
[9] T. E. Cowan, A. W. Hunt, T. W. Phillips, S. C. Wilks, M. D. Perry, C. Brown, W. Fountain, S. Hatchett, J. Johnson, M. H. Key, T. Parnell, D. M. Pennington, R. A. Snavely, and Y. Takahashi, Phys. Rev. Lett. **84**, 903 (2000).
[10] T. E. Cowan, M. Roth, J. Johnson, C. Brown, M. Christl, W. Fountain, S. Hatchett, E. A. Henry, A. W. Hunt, M. H. Key, A. MacKinnon, T. Parnell, D. M. Pennington, M. D. Perry, T. W. Phillips, T. C. Sangster, M. Singh, R. Snavely, M. Stoyer, Y. Takahashi, S. C. Wilks, and K. Yasuike, Nucl. Instrum. Methods Phys. Res. A **455**, 130 (2000).
[11] B. Liesfeld, K.-U. Amthor, F. Ewald, H. Schwoerer, J. Magill, J. Galy, G. Lander, and R. Sauerbrey, Appl. Phys. B: Lasers Opt. **79**, 1047 (2004).
[12] National Nuclear Data Center (NNDC), http://www.nndc. bnl. gov.