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Photonuclear Physics when a Multiterawatt Laser Pulse Interacts with Solid Targets

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When a laser pulse of intensity 10^{19} W cm^{-2} interacts with solid targets, electrons of energies of some tens of MeV are produced. In a tantalum target, the electrons generate an intense highly directional γ-ray beam that can be used to carry out photonuclear reactions. The isotopes ^{11}C, ^{38}K, ^{62,64}Cu, ^{63}Zn, ^{106}Ag, ^{140}Pr, and ^{180}Ta have been produced by (γ, n) reactions using the VULCAN laser beam. In addition, laser-induced nuclear fission in ^{238}U has been demonstrated, a process which was theoretically predicted at such laser intensities more than ten years ago. The ratio of the ^{11}C and the ^{62}Cu β^+ activities yields shot-by-shot temperatures of the suprathermal electrons at laser intensities of $\sim 10^{19}$ W cm^{-2}.

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The past few years have witnessed a dramatic upsurge in short pulse laser technology with its concomitant high achievable peak powers. This has been brought about by the development of chirped-pulse amplification (CPA) [1,2]. Now tabletop terrawatt lasers are to be found in many university and national laboratories, and recently the first petawatt laser has been developed at Livermore [3] with others being proposed elsewhere. With these high power lasers, focused intensities between $10^{19}-10^{20}$ W cm^{-2} have been achieved.

At these intensities, free electrons can quiver in a laser focus totally relativistically with ponderomotive energies of MeV. A number of mechanisms are proposed which can cause the electrons in plasmas to be accelerated to many times the ponderomotive potential such as wakefield acceleration [4,5], plasma wave breaking [6], $\mathbf{v} \times \mathbf{B}$ acceleration in the presence of an azimuthal magnetic field [7], and resonance absorption [8].

The reason for the current and burgeoning interest in high intensity laser-plasma interactions is their relevance to a number of diverse fields, e.g., advanced concepts of plasma high energy particle accelerators [9,10], laser-induced nuclear photophysics, astrophysics, and inertial confinement fusion [11]. Specifically, the question of carrying out nuclear physics using a laser source has been addressed by a number of authors using high repetition rate, femtosecond lasers [12–14], and by using single shot ultrahigh intensity lasers such as the petawatt laser at the NOVA facility and VULCAN [3,15–17]. A seminal theoretical paper written by Boyer, Luc, and Rhodes more than ten years ago predicted the possibility of optically induced nuclear fission [18].

The first quantitative measurement of bremsstrahlung photons with energies >2 MeV from the interaction of a laser with matter was reported by Sherman, Burnett, and Enright [19]. They showed that they were produced by relativistic electrons when a 600 ps, CO$_2$ laser pulse interacted with thick targets. Recently, more energetic electrons have been produced by terawatt and petawatt lasers of 1 μm light in $\leq$ ps pulses [16,17].

The motivation for writing the present Letter is to show how a 50 TW laser (VULCAN) can be used to carry out (γ, n) and (γ, f) reactions. These reactions are the simplest photonuclear reactions for γ-ray beams with an end point up to about 30 MeV, generated by bremsstrahlung from the energetic electrons produced by laser intensities of about 10^{19} W cm^{-2}. Typically (γ, n) reactions produce proton rich isotopes which decay to stability by positron emission, electron capture (EC), or both [20], and have thresholds for production (Q values) which are typically >8 MeV. The (γ, f) reactions are also energetically favored having thresholds of about 4 MeV.

The experiment used the ultraintense beam line of the VULCAN Nd:glass laser [21] incident on a tantalum target, 1.75 mm thick, at 45° with p-polarized light within an evacuated target chamber. The experimental arrangement has been described in greater detail elsewhere [16] as well as the principal diagnostics employed. Briefly, the VULCAN laser delivered pulses on target up to 50 J with pulse lengths about 1 ps. A 95% reflecting turning mirror located after the recompression gratings was used to steer the beam on target focused by a $f/1.7$, 22 cm focal length on-axis parabolic mirror. This turning mirror permitted 5% transmission of the laser energy for measurements of the laser spectrum, the pulse duration by a single shot autocorrelator and the focal spot quality by an equivalent plane monitor. The contrast ratio between the peak and amplified stimulated emission energies was measured by a third order autocorrelator to be 1:10^{-6}. Equivalent plane images showed that the diameter of the focal spot was 9 μm, containing 35% of the laser energy when the target holder was placed in the beam. The focused intensity on target for each shot was monitored by a penumbral imaging camera.

First, the angular distribution of the high-energy γ rays following the laser irradiation of the tantalum bremsstrahlung target was measured. The energy loss to bremsstrahlung when the laser-induced electrons slowed down in the target scales as Z^2 (atomic number) and, hence, high Z targets are favored. In the present case, tantalum (1.75 mm thick) was chosen.

Pieces of copper were placed around the target such that both horizontal and vertical distributions of the γ rays could be determined. The γ rays interact with the copper, inducing the photoneutron reaction ^{63}Cu$(\gamma, n)^{62}$Cu with a 9.74 min half-life. The β^+ activity in each piece of copper was measured separately, corrected to time zero for decay (laser shot time), and the angular distributions determined. This is the subject of a paper (published elsewhere [22]) dealing with the plasma physics implications of this observation. The laser was operated with a plasma scale length of ~7 μm corresponding to the main γ emission being along the laser beam propagation direction. This is contrary to the observations reported in Ref. [19].

A number of (γ, n) reactions from different targets were carried out (Fig. 1). Positrons slow down in materials and annihilate at rest with electrons producing two back-to-back photons of 511 keV energy. These were detected with high efficiency and signal-to-noise ratio using either two 3" × 3" or 2" × 2" NaI scintillators operated in coincidence. The absolute efficiency of these systems were determined using a calibrated ^{22}Na source. The activity of the sources were corrected to time zero and, knowing the (γ, n) cross sections [23,24], the number of high-energy photons produced by each laser shot could be determined from which could be estimated the number of initial high-energy electrons. From the maximum activity sources of ~5 kBq of ^{62}Cu, it can be calculated that in 2π steradians, 10^{8-9} bremsstrahlung photons of energies >10 MeV are produced from the suprathermal electrons. In earlier works [15,16], the activity produced in the copper sample was analyzed for two hours and, hence, any long-lived ^{64}Cu activity from the ^{65}Cu$(\gamma, n)^{64}$Cu reaction was difficult to measure unambiguously. In this Letter, the activity was analyzed for many hours and is shown in Fig. 2. The half-lives determined from the two gradients of the activity agree well with the accepted values of 9.7 min and 12.7 h.

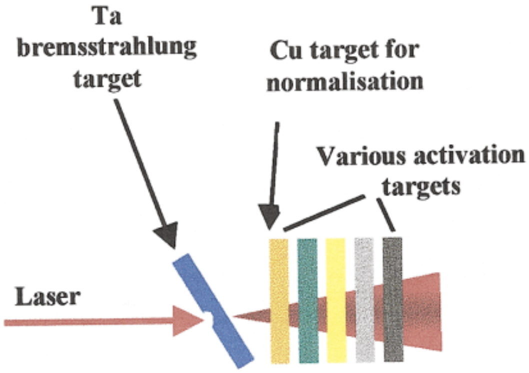

FIG. 1 (color). The arrangement for irradiating a number of different targets simultaneously. All samples had dimensions ~10 × 10 × 3 mm. The copper target was used for normalization of activities.

Figure 3 shows the activity measured as a function of time for the isotopes ^{11}C, ^{38}K, ^{63}Zn, ^{106}Ag, and ^{140}Pr. Because of the differing Q values for the isotope production, the activities can be used to establish the shape of the bremsstrahlung spectrum and, hence, the temperature of the energetic electrons. Thus, nuclear activation can be used as a powerful plasma diagnostic technique. For laser intensities of about 10^{19} W cm^{-2}, isotopes with half-lives with up to ~24 h can be readily detected for medium A isotopes. For large A isotopes, longer-lived activities can be measured since the (γ, n) cross sections increase with A.

Generally, isotopes (Z, A) which decay by EC alone or with a small β^+ fraction can be detected by the characteristic x rays of the element $Z - 1$. This was carried out in the case of the Ta target using a well shielded, 16% intrinsic Ge detector to detect the Hf X rays. The low-energy γ spectrum from Ta is shown in Fig. 4 with the Hf x rays clearly visible.

Finally, a ^{238}U (depleted uranium) sample of dimensions ~10 × 10 × 2 mm (~3 g) with a fission fragment 3005m polycarbonate foil on the front and back sides was targeted. This sandwich was shrink wrapped in plastic to contain any gaseous radioactivity and enclosed in an aluminum container. The sample was irradiated with three consecutive laser shots, 20 min apart, of nominally 10^{19} W cm^{-2} intensity and analyzed using the Ge detector. Both (n, f) and (γ, f) reactions in fissionable materials produce a double headed asymmetric fission yield distribution of fragments with maxima at mass numbers about 95 and 140 corresponding to the neutron magic numbers of 50 and 82.

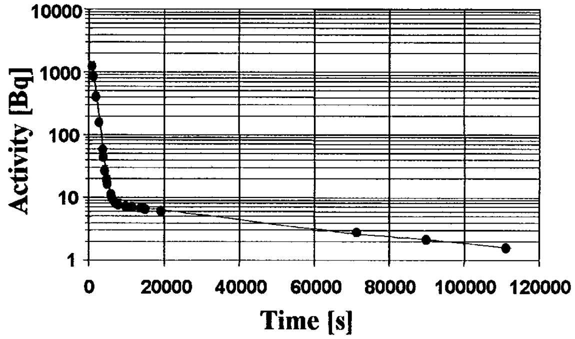

FIG. 2. The half-lives of the two isotopes of Cu: ^{62}Cu, ^{64}Cu following the irradiation of Cu at 10^{19} W cm^{-2}. The half-lives agree well with the accepted values of 9.7 min and 12.7 h.

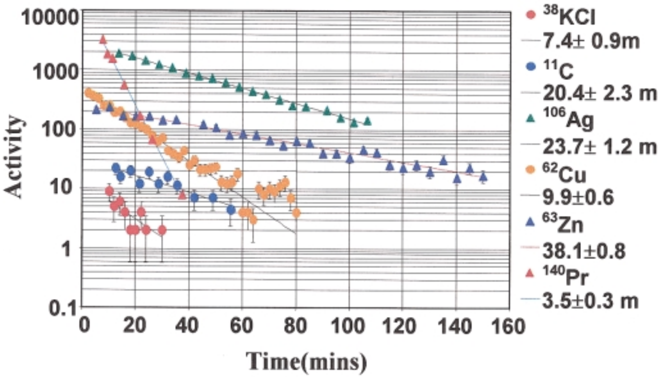

FIG. 3 (color). The activities of the isotopes listed in text as a function of time. The measured half-lives agree well with the accepted values.

The principal fission fragments amount to about 5%–6% of the total fission yield. Evidence for fission events is normally carried out by detecting the characteristic γ rays from the principal fission fragments, detection of fission fragment tracks, or fission neutrons. In the case of ^{238}U with a (γ, f) cross section which peaks at about 150 mb, the most abundant isotopes produced include ^{134}I, ^{138}Cs, and ^{92}Sr [25] with suitable γ-ray energies and half-lives. The background activity from fissionable materials is normally sufficiently large that very careful background measurements must be taken. Specifically for $^{238}\mathrm{U}(t_{1/2} = 4.5 \times 10^9$ yr), the background activity is 12.3 kBq/g. Two Ge γ-ray spectra in the region of 850 and 1400 keV are shown in Fig. 5 after background subtraction was performed. The unambiguous characteristic γ rays of the fission fragments I^{134}, ^{138}Cs, and ^{92}Sr are indicated.

From the intensity of the ^{134}I γ-ray peak in Fig. 5 using the known efficiency of the Ge detector, the fission yield to that isotope, and the (γ, f) cross section, it has been estimated that about 10^6 fission events are generated by a laser shot of $\sim 10^{19}$ W cm^{-2} in a ^{238}U target of 2 mm thickness. Any (n, f) reactions are likely to be considerably lower in intensity than the (γ, f) reactions because of the reduced numbers of neutrons [17].

In summary, it has been shown that when a beam of 1 μm light at $\sim 10^{19}$ W cm^{-2} interacts with a high Z target, a sufficiently intense high-energy γ-ray beam is generated such that photonuclear reactions can be carried out. ^{11}C, ^{38}K, ^{62,64}Cu, ^{63}Zn, ^{106}Ag, ^{140}Pr, and ^{180}Ta have been produced in measurable quantities up to activities of about 5 kBq at the highest laser intensities. In addition, photofission of ^{238}U has been demonstrated from the most abundant fission fragments. Some ten years ago, Boyer, Luc, and Rhodes [18] estimated theoretically that, for 248 nm radiation at an intensity of 10^{21} W cm^{-2}, some 10^6 fission reactions could be generated per pulse in uranium 1 cm thick. This is in reasonable agreement with fission yields from U in the present experiment at 10^{19} W cm^{-2} intensity of 1.053 μm radiation.

One of the principal applications of nuclear activation to intense laser pulse interaction with solid targets is to measure the temperature of the electrons involved. In the present work, the ratio of the activities from ^{62}Cu and ^{11}C will uniquely determine this quantity. In the following analysis, it was assumed that the spectrum was characterized by the relativistic electron energy distribution $E^2 \exp(-E/kT)$ [16]. These electrons then produce γ radiation in the Ta target with the γ spectrum determined uniquely by the electron energy. The analysis proceeded using 0.5 MeV electron energy bins and, for each, the γ

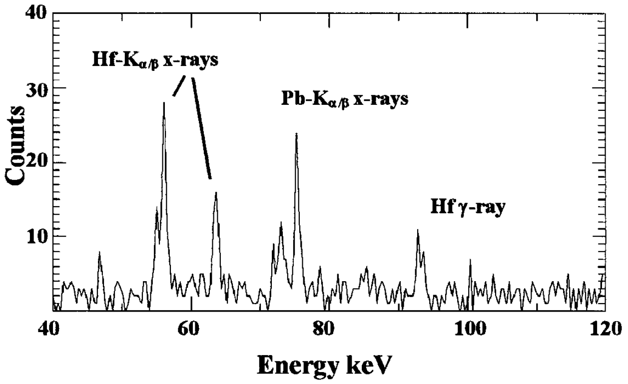

FIG. 4. The low energy γ–ray spectrum from Ta as measured by an intrinsic Ge detector. The characteristic Hf x rays from the decay of ^{180}Ta are clearly visible. The Pb x rays are background peaks.

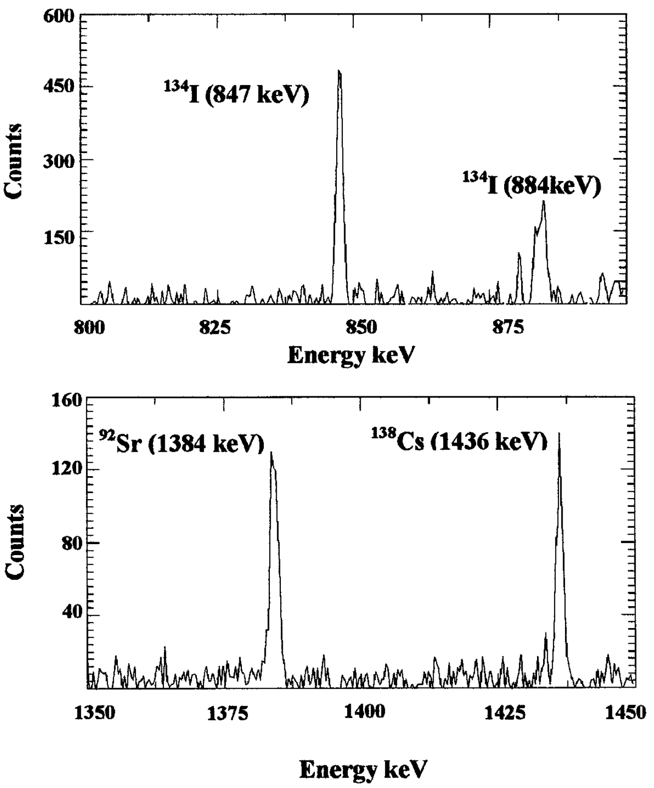

FIG. 5. Some of the characteristic γ rays emitted by three of the principle fission fragments following a $^{238}\mathrm{U}(\gamma, f)$ reaction. The details of the isotopes and half-lives are given in Ref. [25].

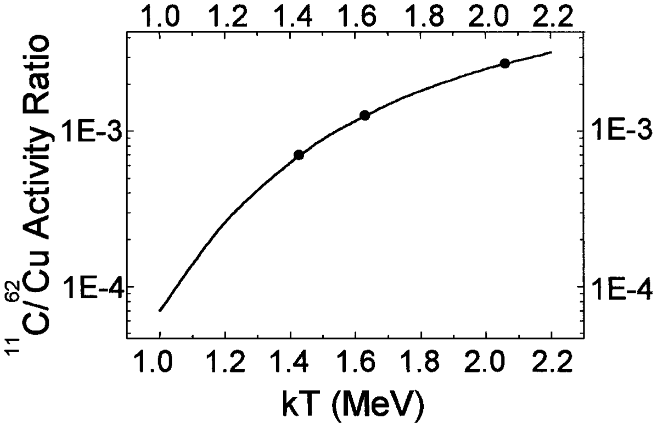

FIG. 6. The calculated $^{11}C/^{62}Cu$ ratio as a function of kT. Three typical experimental ratios are shown for three shots at laser intensities $\sim 10^{19}$ W cm^{-2}.

spectrum was estimated [26]. This procedure allows a determination of the energy spectrum for the bremsstrahlung produced in 0.5 MeV energy bins. The corresponding (γ, n) cross sections for the ^{63}Cu and ^{12}C have been measured experimentally [24]. These cross sections and the calculated γ flux for each bin were used to evaluate the expected yields of ^{62}Cu and ^{11}C. The ratio of the two activities eliminated the need for absolute electron flux measurements. The details of this procedure will be published elsewhere [27]. Figure 6 shows a graph of the calculated ratio of the activities as a function of kT. Three typical experimental measurements for this quantity for laser intensities $\sim 10^{19}$ W cm^{-2} are shown as experimental points corresponding to electron temperatures of 1.43, 1.63, and 2.06 MeV for these shots. The large shot-to-shot variation is a particularly important result. The observed fluctuation is probably due to the highly nonlinear nature of the plasma interactions at these intensities where the effects of a number of scattering instabilities play an important role.

It has been shown that a focused laser of wavelength 1 μm can be the source of energetic electrons at intensities $\sim 10^{19}$ W cm^{-2}. These generate a highly directional γ-ray beam that can produce photonuclear reactions which can be used as an exciting new diagnostic tool in plasma physics. Short-lived isotope production and fission have been demonstrated. With intensities of 10^{21} W cm^{-2} from petawatt lasers, isotopes with much higher activities and longer half-lives could be generated from a single shot. Although it is uncertain how the photon energy scales with laser intensity, pion production, energetically possible with γ rays >140 MeV, is a distinct possibility and can be demonstrated using similar activation experiments to those described in this Letter. Of considerable importance, using CPA technology, few Hz, 1 J, 100 fs tabletop terawatt lasers can deliver about 10^{19} W cm^{-2} per pulse (similar to the present experiments) but with greatly increased activities possible after integrating a number of shots from the high repetition rate capability.

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