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Published in:
Applied Physics Letters

DOI:
10.1063/1.1319526

2000

Link to publication

Citation for published version (APA):
Gahn, C., Tsakiris, G. D., Pretzler, G., Witte, K. J., Delfin, C., Wahlström, C.-G., & Habs, D. (2000). Generating positrons with femtosecond-laser pulses. *Applied Physics Letters*, *77*(17), 2662-2664. https://doi.org/10.1063/1.1319526

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APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 17 23 OCTOBER 2000

Generating positrons with femtosecond-laser pulses

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(Received 19 June 2000; accepted for publication 29 August 2000)

Utilizing a femtosecond table-top laser system, we have succeeded in converting via electron acceleration in a plasma channel, low-energy photons into antiparticles, namely positrons. The average intensity of this source of positrons is estimated to be equivalent to 2×10^8 Bq and it exhibits a very favorable scaling for higher laser intensities. The advent of positron production utilizing femtosecond laser pulses may be the forerunner to a table-top positron source appropriate for applications in material science, and fundamental physics research like positronium spectroscopy. © *2000 American Institute of Physics.* [S0003-6951(00)00143-1]

The evolvement of multiterawatt short pulse lasers has given impetus to a new regime of laser matter interaction identified as high-intensity physics.[1] Presently, compact high-repetition-rate table-top systems deliver focused intensities approaching $10^{20}\,\mathrm{W/cm^2}$ while large-scale petawatt class lasers pledge intensities beyond $10^{21}\,\mathrm{W/cm^2}$ in the near future. Interestingly, the moderate size table-top laser systems hold out the promise to cut the ''umbilical cord'' to an accelerator facility for a series of applications. Indeed, using 10 Hz, TW table-top lasers the generation of MeV γ rays in the interaction of solid targets with femtosecond laser pulses has been reported.[2,3] Generation of extreme ultraviolet radiation in the form of harmonics of the fundamental has also been demonstrated.[4–6] Furthermore, fusion neutrons using either deuterated planar targets[7] or deuterium clusters[8] heated with femtosecond laser pulses have been observed. Recently, 10^{10} electrons per laser pulse were produced in a low emittance beam with average energies of 3 MeV and maximum extending to over 12 MeV.[9] We report here an addition to this list, the generation of antiparticles.

We describe measurements of positrons produced by MeV electrons from a relativistically self-focused laser channel in underdense plasma. The scheme we have employed is analogous to the one used for the generation of positrons from high-Z moderators in linear electron accelerators. It consists of two steps: First, using laser pulses from the ATLAS laser facility at Max-Planck-Institut für Quantenoptik (790 nm, 220 mJ, 130 fs, 10 Hz), a beam of electrons was generated in a gas-jet target. In the second step, the electrons were converted in a 2-mm-thick Pb slab to positrons. We were able to produce 10^6 positrons (e^+) per laser pulse with a mean energy of ~ 2 MeV. Although for radiation safety reasons the measurements were performed using single laser pulses, there are no technical constraints hindering the operation at the laser repetition rate, i.e., 10 Hz. Under these circumstances, this experiment represents an e^+ source with an activity of 10^7 Bq. Positron emission has also been reported from the direct interaction of petawatt laser pulses with solid Au targets.[10] However, petawatt lasers operating at high-repetition rate are not yet available and such experiments are currently restricted to large-scale facilities.

The generation mechanism of fast electrons employed here has been the topic of a previous study where most of the pertinent physics and the experimental realization are described.[9] The method is simple: The laser is focused into the exit of a helium gas jet where it undergoes relativistic self-focusing when the laser power exceeds the threshold value for this process followed by plasma channel formation and direct laser acceleration of electrons to multi-MeV energies. As long as the electron beam produced in the gas jet comprises electrons with kinetic energies $E \geqslant 1.022$ MeV, there is a finite probability to generate electron–positron pairs in a high-Z converter. For few-MeV electrons interacting with a high-Z material, the most efficient processes for pair production are: (a) indirectly via bremsstrahlung photons and (b) directly in electron–nucleus collisions (the trident process).[11] An estimate of the fraction of primary electrons converted into positrons, N_{e^+}/N_{e^-} as a function of the electron primary energy can be obtained if one assumes $E_\gamma \approx E/2 + m_e c^2$ for the energy of those γ photons appropriate for pair production.[11] Using expressions for the cross sections valid in the relevant energy range of $E \leqslant 12$ MeV,[11–13] one finds that (i) the indirect process is dominant and (ii) for an $l = 2$-mm-thick lead converter and for 3 MeV electrons, a fraction of 10^{-3} will be converted into positrons. It has been assumed here that $l \ll R_e, \mu^{-1}$, where R_e is the electron range and μ the absorption coefficient for γ's in the converter material. The electron energy distribution was carefully characterized at the beginning of the experiment with the help of a multichannel electron spectrometer[14] and its reproducibility was established. The spectrum is given in Fig. 1 and it can be fitted by a Boltzmann distribution with an effective temperature of $T_{\mathrm{eff}} = 2.7 \pm 0.1$ MeV. Applying the appropriate cross sections for pair production to this electron distribution and taking into account the converter characteristics, an estimate of the expected positron spectrum can be deduced. With the approximation that the positron–

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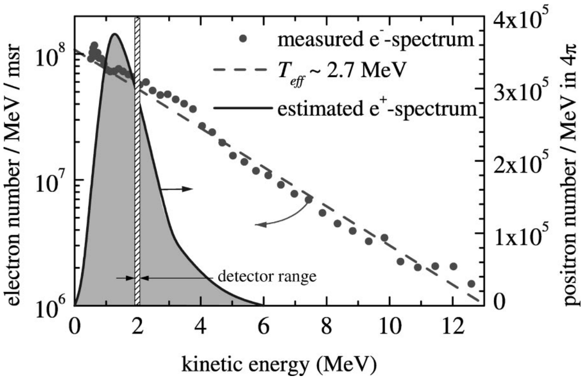

FIG. 1. Measured energy distribution of the primary electrons (closed-circles, exponential fit as dashed line) used to produce positrons (expected spectrum as solid line). The line-shaded stripe gives the energy range covered by the detector. It encompasses ∼5% of the total number of positrons.

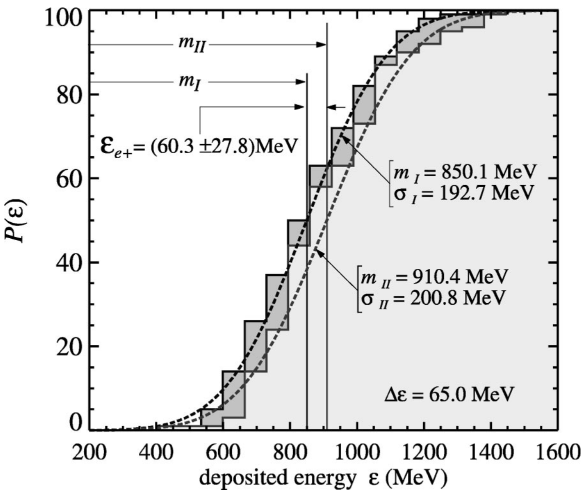

FIG. 3. The number of laser pulses $P(\varepsilon)$ that deposited an energy at the detector less than ε for case I (background only, dark shaded area) and case II (background+signal, light shaded area). The experimental data are drawn as integrated histograms. The dashed lines represent the probability integral for the mean value m and standard deviation σ calculated from the experimental data for both cases.

electron pair shares the energy of the γ photon or primary electron, the positron number per MeV is calculated and shown in Fig. 1.

The experimental setup had to be carefully chosen to suppress the background signal due to stray γ's to a minimum on account of the weak positron signal. After some iterations the arrangement depicted in Fig. 2 was deemed satisfactory. The primary electrons were collimated in a plastic block with a 1-cm-diam hole. The low-Z material stops electrons without producing undue bremsstrahlung. The converter was a 2-mm-thick lead disk positioned inside the collimator at a distance of 16 cm from the gas jet where the laser beam was focused. The collimation of the beam results in reducing the number of MeV electrons to $(8\pm1.7)\times10^8$ (from a total of 2×10^{10}) for performing a clean demonstration experiment. The positrons emanating from the converter have a quasi-isotropic distribution.[13] Those traveling in the laser direction are collimated by another 2 cm in the plastic collimator before they enter the region where a magnetic field of $B\approx150$ mT from two permanent magnets is present. Due to the magnetic field, positrons are separated from primary and secondary electrons and after they describe a 180° orbit are detected by a light tight, 1.5-cm-thick plastic scintillator coupled to a photomultiplier tube. The absolutely calibrated detector covers the positron energy range of 2 ±0.08 MeV and subtends a solid angle of $\Delta\Omega_{e^+}=7$ msr to the converter.

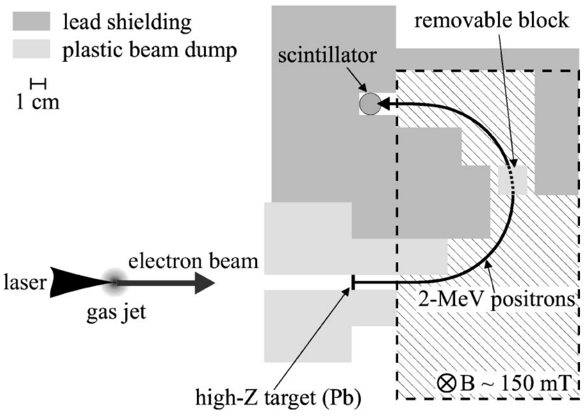

FIG. 2. Experimental setup.

First, the level of the background signal was carefully determined under different conditions. It was found that when the collimator is totally blocked with a plastic rod, the detector produces a signal corresponding to 400 MeV deposited energy despite the 5 cm lead shielding surrounding it. With the collimator open but with the channel of the 2 MeV positrons blocked with a plastic block (see Fig. 2), the signal was doubled to 800 MeV. This was also the level of the signal with the 2 MeV positron channel open, but with the B field "switched off." i.e., with the plates holding the permanent magnets replaced by surrogate unmagnetized iron plates. This means that the background signal is produced by γ's seeping through the shielding and not by scattered electrons or γ's coming via the open positron channel. As can be inferred from Fig. 1, the number of expected positrons in the 2 ± 0.08 MeV channel is ~25 per laser pulse, which means that the positron signal would amount to 50 MeV, i.e., 6% of the background signal. It is apparent that under these circumstances, statistical sampling and precise data analysis are necessary for decidedly extracting the positron signal from the background. Such analysis was actually performed after the signal from $N=100$ laser pulses and was recorded in two cases. *Case I*: with the positron path to the detector blocked (see Fig. 2). This measurement yielded the background signal level. *Case II*: with positron path to the detector open. The signal obtained in this way consists of background plus positron signal. The difference in the average value of the signal in these two cases represents the signal due to positrons that have struck the detector. This is depicted in Fig. 3, where the fraction of laser pulses $P(\varepsilon)$ (out of 100 total) that gave rise to a signal corresponding to a deposited energy less than ε is plotted as a function of ε for the two cases. The experimental data have an energy binning of $\Delta\varepsilon=65$ MeV, which matches the accuracy of the energy reading. This presentation of the experimental data best illustrates the subtle but significant difference between the two cases. In fact, the clearly discernible displacement of the curve in case II with respect to case I along the deposited energy axis is indicative of the positron existence. Using the two sets of experimental

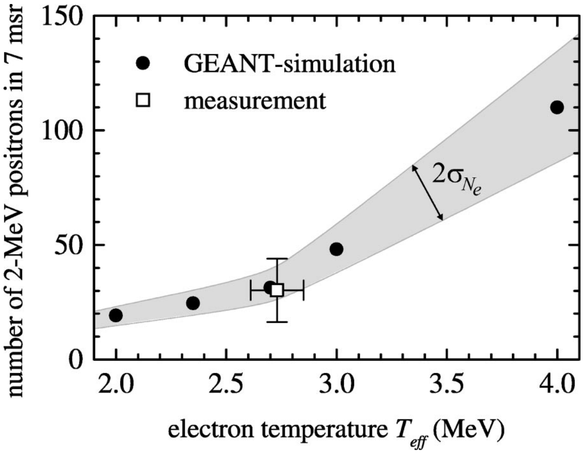

FIG. 4. Number of positrons seen by the detector as a function of the effective electron temperature: (i) simulation (circles), (ii) measurement (square). The shaded area indicates the uncertainty σ_{N_e} associated with the fluctuation in the total number of measured electrons.

data, we have calculated the mean value m and the corresponding standard deviation σ for both cases. Under the assumption that the data points follow a Gaussian distribution, the probability integral corresponding to a given set of m, σ can be evaluated. This is also shown in Fig. 3 as dashed curves. The positron signal follows from $\varepsilon_{e^+}=m_{\mathrm{II}}-m_{\mathrm{I}}=60.3\,\mathrm{MeV}$ and its uncertainty is given by $\sigma_\varepsilon=\sqrt{\sigma_{\mathrm{I}}^2+\sigma_{\mathrm{II}}^2}/\sqrt{N}=27.8\,\mathrm{MeV}$. This unequivocally shows that each laser pulse produced an average 30 ±14 positrons.

In order to further substantiate our experimental result, we have performed detailed Monte Carlo-type simulations using the code GEANT.[15] This code allows the user to exactly simulate the experimental setup, i.e., collimator, converter, shielding, magnet, vacuum chamber wall, and detector. In addition to the exact geometry, GEANT requires as input the electron energy distribution. Individual electrons are released in the direction of the laser axis in such a way as to collide with the converter. Moreover, the direction of motion is randomly assigned so that the whole converter area is uniformly covered. Their energy is likewise randomly chosen as to correspond to a Boltzmann distribution. A total number of 10^9 electrons ensure sufficient statistical accuracy of the result. The output is the total energy that is deposited at the detector irrespective of origin, hence the simulation result includes not only the actual positron signal, but also the signal due to overall γ background. Finally, the detector response is scaled to the actual number of electrons produced. Both cases were simulated, i.e., case I: with the positron channel blocked and case II: with the positron channel open.

The simulations confirmed the experimental result according to which with open collimator but blocked positron channel the background level is increased by ~400 MeV and endorsed the finding that stray γ-ray flux is responsible for the observed background signal. Additionally, two systematic variations were undertaken. First, for a fixed electron temperature of $T_{\mathrm{eff}}=3\,\mathrm{MeV}$, the converter thickness was varied leading to an optimum $l_{\mathrm{opt}}=2\,\mathrm{mm}$. Second, for fixed converter thickness l_{opt}, the primary electron temperature was varied between $T_{\mathrm{eff}}=2$ and 4 MeV. The results are detailed in Fig. 4 where the number of positrons expected within the $2\pm0.08\,\mathrm{MeV}$ channel is given. The simulations reproduce the experimentally measured number of positrons and the electrons from the gas jet having an effective temperature of $T_{\mathrm{eff}}=2.7\,\mathrm{MeV}$.

Scaling the number of positrons detected within the 0.16 MeV energy range and 7.0 msr solid angle to full energy spread (see Fig. 1) and solid angle, one obtains a total number of 10^6 positrons per laser pulse. Using the full uncollimated electron beam gives a positron number of $\sim 2\times10^7$, which corresponds to an activity of $2\times10^8\,\mathrm{Bq}$. Given the prodigious technological advances in laser technology, it is almost certain that in the near future there will be laser systems delivering pulsed power of 100 TW or more at high repetition rates. Then, at these higher attainable laser intensities an increase in the T_{eff} of the primary electrons would lead to a sharp rise on the output as manifested by Fig. 4. Under these circumstances, it is quite realistic to contemplate a compact, high-flux positron source suitable for a variety of envisaged applications like, e.g., positron-annihilation and Doppler-broadening spectroscopy in material science,[16] but also in diverse fields of fundamental research such as positronium spectroscopy[17] where a high intensity positron source is a requisite.

The technical assistance of H. Haas, A. Böswald, and P. Sachsenmeier is greatly appreciated. This research was partially supported by the Commission of the EC within the framework of the Association Euratom–Max-Planck-Institut für Plasmaphysik.

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