Plasma-laser ion discrimination by TOF technique applied to coupled SiC detectors.

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Abstract. The rate estimation of nuclear reactions induced in high intensity laser-target interaction ($\geq 10^{16}$ W/cm^2), is strongly depending on the neutron detection efficiency and ion charge discrimination, according to particles involved in exit open-channels. Ion discrimination is basically performed by means of analysis of pits observed on track detector, which is critically dependent on calibration and/or fast TOF devices based on SiC and diamond detectors. Last setup is used to determine the ion energy and to obtain a rough estimation of yields. However, for each TOF interval, the dependence of yield from the energy deposited in the detector sensitive region, introduces a distortion in the ion spectra. Moreover, if two ion species are present in the same spectrum, the discrimination of their contribution is not attainable. In this paper a new method is described which allows to discriminate the contribution of two ion species in the wide energy range of nuclear reactions induced in laser-target interactions. The method is based on charge response of two TOF-SiC detectors, of suitable thicknesses, placed in adjacent positions. In presence of two ion species, the response of the detectors, associated with different energy losses, can determine the ion specific contribution to each TOF interval.

1 Introduction

With the availability of high intensities ($\geq 10^{16}$ W/cm^2) laser-target interaction has evidenced nuclear events characterized by fast neutrons and/or recoiling ions involved in the induced specific reactions [1-8]. Estimated reaction rates and, consequently potential applications, are strongly depending on the neutron efficiency values and ion discrimination. Efficiencies of fast neutron detection are rather small, 10^{-4} to 10^{-3}, depending on neutron energies [9-11]. Ion discrimination is performed with solid state nuclear track detectors (SSNTD), as CR-39 or PM-355, by analyzing the distribution of diameter etched pit observed into sample field of optical microscope. However the discrimination effectiveness is critically dependent on calibration (especially etching time), often coupled to thin foil degraders, or restricted to short energy range. [7],[12,13]. Furthermore atomic ion flux due to target impurities, which is expected much larger than nuclear one, can contribute to produce a false signal or, at least, an high statistical error. Thompson Spectrometer (TP), which could give almost complete ion discrimination [14,15], presents the disadvantage of very small acceptance because of needed entrance-pinhole. On the other side, many attempts have been introduced in the past, to get more efficient CR-39 discrimination by coupling the diameter with other parameters (length

[16,17]), (grey levels [18]), with scarce experimental pursuance. TOF devices based on Silicon Carbide (SiC) and diamond detectors, almost insensitive to visible and near UV light, have been used to determine the possible energy of ions and to obtain a rough estimation of yields. An intrinsic problem can arise because of dependence of yields from energy deposited in the depleted region of detector subject to drifting electric field (so-called *active sample*). In fact, yield for each time interval (named also *time bin*), associated with sampling unit of TOF oscilloscope, depends on both number of ions arriving within and on energy deposited by each ion into active sample and converted in a corresponding number of electron-hole. The overall mechanisms and characteristics of charge drifting along the active electric field to the electrodes and finally converted in measured current-yield at readout circuit, are well described in many papers, as, for instance, in refs. [19,20]. Here it must be noticed that, because of energy dependence, the interpretation of measured yield as histogram height, is basically wrong. Moreover the active sample can represent full energy absorption for some ion and partial absorption (in punching through case) to others. In this paper, investigating on corrections needed to measured yields to obtain the effective distributions, a new method has been developed which, using correlated SiC

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detectors allows to discriminate the contribution of two ions in the wide energy range of nuclear reactions involved in laser-target interactions.

2. Method description

The method is based on the response of two TOF-SiC devices of appropriate depletion layers placed in adjacent positions and subjected to the simultaneous action of two species of ions produced by a plasma-induced nuclear reaction. In the absence of experimental data obtained in such conditions, the following procedure was referring to a nuclear reaction whose experimental data, obtained with a standard accelerator and ion beam hitting target, was as complete as possible. *Thus, the available data was processed in such a way as to have the required characteristics.*
To make the description of the method clear and effective, it is assumed an experimental setup similar to those commonly used today. The iodine laser system of PALS (Prague Laboratory), operating at single impulse at 1315nm, duration of 300ps, is considered. Laser is supposed to irradiate in normal incidence a solid target where the generated plasma induces nuclear reactions. Several detectors are surrounding the target to monitoring the experiment in suitable pressure conditions (10^{-5} to 10^{-6}mbar). Two contiguous SiC-TOF devices are supposed backward at $\langle\rangle = 60^{o}$ with respect to target normal. The TOF flight distance is d = 1.25m. SiC devices are constituted by 2 SiC diodes 1mm^2 in active surface and in adjacent position (1mm far), depletion layer of 5μm and 80μm, respectively.
The SiC detectors are generally built on a 4H-SiC epitaxial layer, grown with the chemical vapor deposition technique in HCl atmosphere, which allows one to obtain a very thick depletion layer (~100μm) with low dopant concentration and with very low defect concentration [19]. The Schottky diodes, reverse polarized and suitably equipped with an output-signal circuit, are coupled with a 50 Ohm input resistor to a fast digital oscilloscope (2GHz,20GS/s). Typical active areas of detectors are 1mm^2 to 5mm^2, and depletion layer of 5μm to ~100μm TOF time resolution of order of 1ns can be easy achieved [20]. In the passing through the active layer, an ion spends almost fully the energy loss in pair electron-hole production and output signal formation. (e-hole pair E$\cong$7.8 eV).When a flux of ions goes into the active area of detector simultaneously (i.e., into the time bin selected by TOF setup device), the associated charge depends on both the number of ions and the energy loss of ion into the active thickness of detector; which in turn depends on thickness and ion specie and energy.

2.1 Ion discrimination in plasma-laser nuclear reactions

Nuclear reactions produced in high intensity laser-target interaction involve, depending on atomic composition of the target, the simultaneous presence of different ion species, as proton, deuterons, ^{3}He, ^{4}He, etc. Protons, in

particular, are also present due to superficial impurities contained in targets. Typically, nuclear reactions, as d + d, d+^{3}He, p+^{7}Li, d+^{6}Li , d+^{7}Li, p+^{11}B, etc, produce output ion energies of several MeV which can be mixed its self or mixed with impurity-protons. In presence of two ion species of M_1 and M_2 masses respectively, the TOF technique, for each time bin selects two mean energies, E_1, E_2 which are proportional to the ratio of masses M_1/M_2. So, for p and α, it will be $E_\alpha = 4\times E_p$. For example, in the p+^{11}B reaction, 1 MeV of proton can compete with 4 MeV-α which is rather a central energy value for last reaction (see later). In this and similar cases, the discrimination is needed.

2.2 Simulation of TOF-SiC response and results

Let one to consider, as a physical case, the reaction p+^{11}B, which has been object of many investigations in plasma-physics [1,3,5,6,8].
At proton low energy (E$_p$ < 3MeV) The exit open channels are:
1) Be^8(GS)+ α_0 , (Q$_0$=8.59MeV) with ^{8}Be(GS) -> 2α by sequential decay, Q-value=92keV; and cross section ranging from 0.2 to 6 mbarn as proton energy varies from Ep = 0.163MeV to 1.388MeV.
2) Be^8*(excited state, E*=2.9MeV) + α_1 (Q$_1$=5.69MeV) with cross section of 10-600-150 mbarn in the energy range Ep =0.165-0.600-1.388 MeV with a resonance at 0.600 MeV.
3) ^{12}C+γ with cross section negligible with respect to previous channels.
4) ^{11}B+p elastic scattering with cross section decreasing from 500 to 200 barns with increasing energy of 0.3MeV to 1.5MeV.
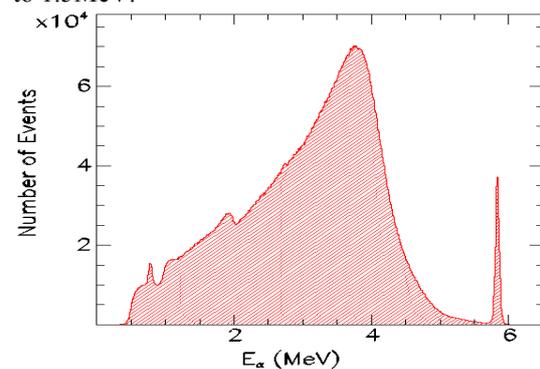

Fig. 1. Single-alpha Energy spectrum reproduced from ref. [21].

The overall contribution of channels 1 and 2 producing alpha particles, gives the energy single α-spectrum shown in Figure 1. As reported in ref.[21], this spectrum has been measured with large area, two faced silicon detectors, equipped to measure α-α coincidences. So, it can be considered as representative shaping of alpha energy spectrum. Taking into account of cross sections of channels 1 and 2, a rough estimation of alpha cross section can be of dσ/dω $\cong$ 230mbarn/sr. Elastic scattering contribution, as expected from Rutherford approximation, should be orders of magnitude higher.

However, to make the basic conditions simpler (and clear the potentiality of the method), its contribution has been fixed to the same value assumed for alpha. To convert in TOF domain the energy spectra of proton and α-particles, energy bins of 10keV and 0.10ns time bins have been used, respectively. Figure 2 reports the proton elastic scattering, the α particles and the total p+α contributions, as function of Energy (top part) and as function of TOF (bottom part), respectively. The proton and α yields are normalized to the integrated contributions. in energy ranges, by the expression:

$$\sum_{Epm}^{Epx} Yp(Ep)\,DEp = \sum_{Eam}^{Eax} Y\alpha(E\alpha)DE\alpha = 230 \text{ mbarn} \quad (1)$$

where $\mathrm{Epm} = 0.28\mathrm{MeV}$ and $\mathrm{Epx} = 1.5\mathrm{MeV}$ are lower and higher limits of proton energy, $\mathrm{E\alpha m}=0.30\mathrm{MeV}$, $\mathrm{E\alpha x}=5.99\mathrm{MeV}$ the corresponding values for α–particle and $\mathrm{DEp} = \mathrm{DE\alpha} = 10\mathrm{keV}$ the energy bins.
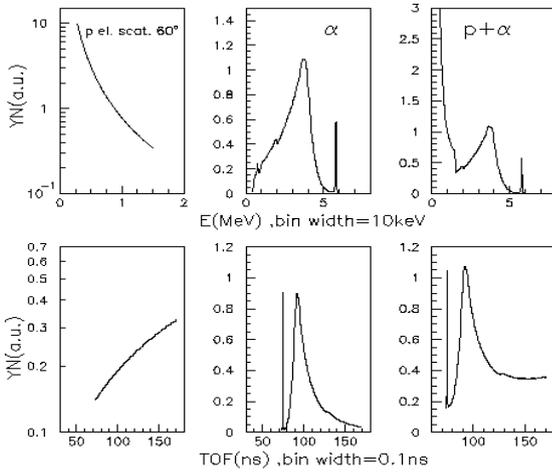
Fig.2. p+^{11}B reaction contributions for p, α and total p+α, to Energy (top) and TOF spectra (bottom), respectively. TOF spectra have been calculated in the interval 73.3-170ns with time bin of 0.10ns.

Now, by assuming these contributions as representative of data obtainable with *discriminative* detectors, we regard to the signal amplification factors related to energy losses in the depletion layer of detectors.

Taking into account these factors, the TOF spectra of Figure 2 are modified as shown in Figure 3, for devices SiC 5μm (top) and SiC 80μm (bottom). As it will be shown, last (p+α) spectra can be considered as simulated response of SiC 5μm (top) and SiC 80μm (bottom), respectively.
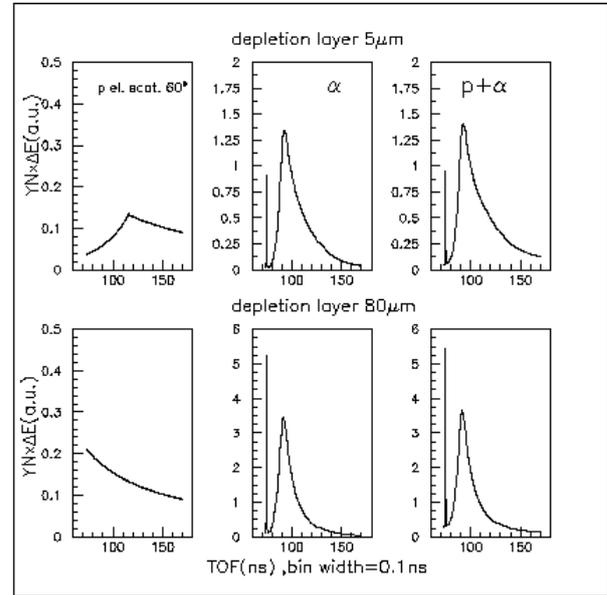
Let us consider a normalized yield ΔY_t, at time bin ΔT centered at time $\mathtt{Ti}$ were contributions of both protons and alpha particles are present:

We have: $\quad\quad \Delta Y_t = \Delta Y_p + \Delta Y_\alpha \quad\quad\quad (2)$

with $\Delta Y_p = Y_p(\mathrm{Ti})\Delta T$ and $\Delta Y_\alpha = Y_\alpha(\mathrm{Ti})\Delta T \quad (3)$

To $\mathtt{Ti}$ correspond Energy values E_p and E_α as the ratios

$\mathrm{E_p/E_\alpha = M_p/M_\alpha}$ and energy losses in the active region of detector ΔE_p, ΔE_α.

Fig. 3. Spectra of p, α, (p+α) as modified by energy loss factors, for TOF with: SiC 5μm (top), SiC 80μm (bottom), respectively.

As first approximation, it is possible to assume these energy losses to be fully converted in e-hole pairs production. So, for each p and α particle, the associated charge signal would be proportional to ΔE_p, ΔE_α. Then the charge signals (yields) in each time bin are:

$$\Delta Y_p = c\,N_p\,\Delta E_p \quad \text{and} \quad \Delta Y_\alpha = c\,N_\alpha\,\Delta E_\alpha \quad\quad (4)$$

where c is a constant depending on readout circuit and, N_p, N_α are the number of ions arriving into detector in time bin ΔT, as proton and alpha respectively.

Spectra (p+α) of figure 3 have been obtained by means of two equations (4), with c = 1, and represent the simulated responses of two SiC detectors.

We observe as the expected yields depend very strongly on ion energy losses in the active layer of detector so being possible be very different from the true values.

The method is based on the assumptions of:

(a) The active area of detectors to be equal/scaled because of collimating diaphragms and/or preventive calibration. The readout circuits of both detectors to have the same characteristics of gain and time resolution, (c=1).The contiguity, due to very small areal dimensions, and the long distance path of flight, to produce a very small change in the observation direction, assuring (within the statistical fluctuations) the same number of ions, N_{ion}, to impinge on two SiC detectors.

(b) The charge measured by SiC device be proportional to product $N_{ion} \times \Delta E_{ion}$.

Under the validity of **(a)** assumptions, it is expected, for each time Ti, within the time bin, the number of ions arriving into two detectors to be the same.

Then: $N_{p1} = N_{p2} = N_p (Ti)$, $N_{\alpha 1} = N_{\alpha 2} = N_\alpha (Ti)$ (5)

for each time bin centered at Ti:

det. 1 $(\Delta Y_{Ti})_1 = N_p \times \Delta E_{p1} + N_\alpha \times \Delta E_{\alpha 1}$ (6)

det. 2 $(\Delta Y_{Ti})_2 = N_p \times \Delta E_{p2} + N_\alpha \times \Delta E_{\alpha 2}$ (7)

$(\Delta Y_{Ti})_1$ and $(\Delta Y_{Ti})_2$ are the measured total charges for each bin centered to Ti, into detector 1 and detector 2, respectively.

As it is shown in eqs. (6) and (7), first terms $(\Delta Y_{Ti})_1$ and $(\Delta Y_{Ti})_2$ can be measured; the right sides of two equations contain the energy losses of proton and alpha into detectors, which can be calculated by SRIM2008 code [22], so that, for each time Ti, the true N_p and N_α can be determined.

Figure 4 shows the reconstructed spectra of proton, α-particles and sum contributions.
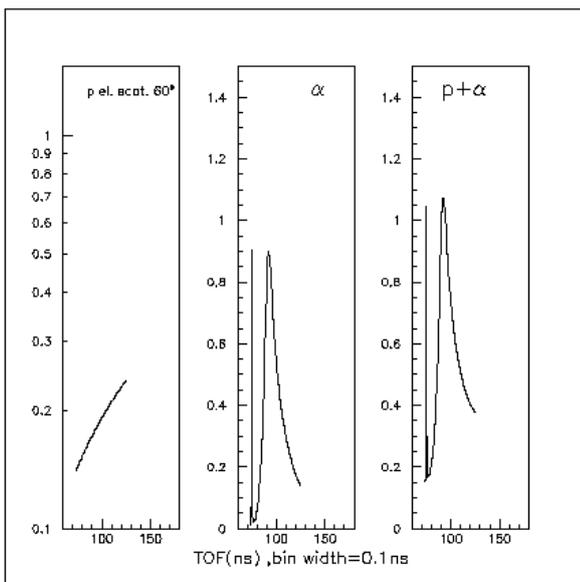
Fig.4. Reconstructed TOF spectra of proton, α-particles and sum contributions.

3. Discussion and summary

From compared inspection of Figure 2 and Figure 4 it can be noticed how the described method works. In fact, Figure 2 (bottom) reports the true expected TOF-spectra for proton and α-particles, whereas Figure 4 shows the same spectra *reconstructed* by means of eq.(6) and eq.(7) joint to simulated responses (p+α) of SiC-5μm and SiC-80μm. The obtainable proton and alpha spectra are limited to TOF range where the corresponding energy

losses for p and/or α−particles are different in one, at least, detector.

Assumption **(a)** can be verified directly by setting in contiguous positions two SiC detectors of same depletion layer and readout characteristics.

To verify assumption **(b)**, some dedicate experiment (where only one of ions to discriminate could be present) can be performed by using coupled detectors. For instance, SiC detector contiguous to an ion collector (IC) or SiC detector contiguous to pin-hole of a Thomson spectrometer equipped with CR-39 strips on focal plane. In that cases, SiC detector yield could give information on product $N_{ion} \times N_{pair}$, per each bin, whereas IC or CR-39 detectors, on true yield (N_{ion}). The discrimination has been treated only for proton and alpha particles but it can be extended to other cases as (p,d), (d,^{3}He), etc and different depletion layer SiC detectors.

To summarize, in this paper the problem of Yield-dependence on energy loss of ions in TOF-SiC technique, has been analyzed, showing the need to take into account for. On the assumption of few conditions, it has been found how the using of two contiguous SiC detectors of suitable characteristics and depleted layers, can allow to discriminate, in a large energy range, the contribution of competing light ions involved in plasma-laser induced nuclear reactions. However it has been shown the basic applicability of the method, without taking into account of limitations due to experimental sensitivities and statistical errors. Work is in progress in this perspective as well as to compare expected previsions with data of a real experiment.

References

1. V. S. Belyaev, A. P. Matafonov, and V. I. Vinogradov P. Krainov, S. Lisitsa, A. S. Roussetski, G. N. Ignatyev and V. P. Andrianov, Phys. Rev. **E 72**, 026406 (2005).

2. W. Bang, M. Barbui, A. Bonasera, H. J. Quevedo, G. Dyer, A. C. Bernstein, K. Hagel, K. Schmidt, E. Gaul, M. E. Donovan, F. Consoli, R. De Angelis, P. Andreoli, M. Barbarino, S. Kimura, M. Mazzocco, J. B. Natowitz, and T. Ditmire, Phys. Rev. **E 88**, 033108 (2013).

3. C. Labaune, C. Baccou, S. Depierreux, C. Goyon, G. Loisel, V. Yahia J. Rafelski, Nature Comms **4**:2506 doi:10.1038/ncomms3506 (2013).

4. S Cavallaro, L Torrisi, M Cutroneo, J Krása and J Ullschmied, IOP Publishing Journal of Physics: Conference Series 508 (2014) 012023 doi:10.1088/17426596/508/1/012023.

5. D Margarone, A Picciotto, A Velyhan, J Krasa, M Kucharik, A Mangione, A Szydlowsky, A Malinowska, G Bertuccio, Y Shi, M Crivellari, J Ullschmied, P Bellutti and G Korn, Plasma Phys. and Contr. Fusion, Volume **57**, Number 1 0741-3335/57/1/014030 . Published 28 November 2014 • © 2015 IOP Publishing Ltd.

6. A. Picciotto, D. Margarone, A. Velyhan, P. Bellutti, J. Krasa, A. Szydlowsky, G. Bertuccio, Y. Shi,

A. Mangione, J. Prokupek, A. Malinowska,E. Krousky, J. Ullschmied, L. Laska, M. Kucharik, and G. Korn,

Phys. Rev. **X 4**, 031030 (2014).

7.   J. Krása, D. Klír, A. Velyhan, E. Krouský, M. Pfeifer, K. Řezáč, J. Cikhardt, K. Turek, J. Ullschmied and K. Jungwirth, (2014). High Power Laser Science and Engineering, **2**, e19. doi:10.1017/hpl.2014.25.

8.   D. Giulietti, P. Andreoli, D. Batani, A. Bonasera, D.G. Boutoux, F. Burgy, M. Cipriani, F. Consoli, G. Cristofari, R. De Angelis, G. Di Giorgio, J.E. Ducret, F. Ingenito, K. Jakubowska, C. Verona, G. Verona-Rinati,
 Nucl. Instr. Methods **B** March 2017 DOI: 10.1016/j.nimb. 2017.03.076.

9.   W. Bang, H. J. Quevedo, G. Dyer, J. Rougk, I. Kim, M. McCormick, A. C. Bernstein, and T. Ditmire,

Rev. Sci. Instrum. **83**, 063504 (2012).

10.   S. Cavallaro , L. Torrisi, 41st EPS Conference on Plasma Physics Berlin 23-27 June2014P2.115. http://ocs.ciemat.es/EPS2014PAP/html/.

11.   S. Cavallaro, Rev. Sci. Instrum. **86**(3):036103·March 2015

12.   A. Szydlowski, Rad. Meas. **36** (2003) 35–42.

13.   C. Baccou,V. Yahia, S. Depierreux, C. Neuville, C. Goyon, F. Consoli, R. De Angelis, J. E. Ducret, G. Boutoux J. Rafelski, and C. Labaune, Rev. Sci. Instrum. **86**, 083307 (2015).

14.   A. Alejo, S. Kar, H. Ahmed, A. G. Krygier, D. Doria, R. Clarke, J. Fernandez, R. R. Freeman, J. Fuchs, A. Green, J. S. Green, D. Jung, A. Kleinschmidt, C. L. S. Lewis, J. T. Morrison, Z. Najmudin, H. Nakamura, G. Nersisyan, P. Norreys, M. Notley, M. Oliver, M. Roth J. A. Ruiz, L. Vassura, M. Zepf, and M. Borghesi,

Rev. Sci. Instrum. **85**, 093303 (2014).

15.   S. Cavallaro, L. Torrisi ,A. Amato ,L. Andò, M.Cutroneo, 39th EPS Conference & 16th Int. Congress on Plasma Physics. http://ocs.ciemat.es/ epsicpp2012/ pap/P4.121.pdf.

16.   V. Togo, S. Balestra, S. Cecchini D. Di Ferdinando, M. Frutti, G. Giacomelli, M. Giorgini, A. Kuma, G. Mandrio, S. Manzoor, A. Margiotta, E. Medinaceli, L. Patrizi, V. Popa, M. Spurio, Nucl. Instr. Methods **A 580** (2007) 58–61.

17.   S. Cavallaro, D. Margarone, L.Torrisi

35th EPS Conference on Plasma Phys. Hersonissos, 9-13 June 2008 ECA Vol.**32D**, P-4.154 (2008).

18.   A. Malinowska, M. Jaskóła, A. Korman, A. Szydłowski, and M. Kuk, Rev. Sci. Instrum. **85**, 123505 (2014); doi: 10.1063/1.4903755.

19.   M. Cutroneo, P. Musumeci, M. Zimbarnone, L. Torrisi, F. La Via, D. Margarone, A. Velyhan, J. Ullschmied,L. Calcagno, J. Mater. Res. 2012 DOI: 10.1557/jmr. 2012.211.

20.   Giuseppe Bertuccio, Donatella Puglisi, Lorenzo Torrisi, Claudio Lanzieri, Appl. Surf. Sci. **272** (2013) 128–131 **381** (2012) 012116 doi:10.1088/1742-6596/381/1/012116.

21.   C A Diget, H O U Fynbo, K L Laursen, K O Madsbøl, LJørgensen, O S Kirsebom,, and K Riisager
 Rutherford Centennial Conference on Nuclear Physics IOP Publishing Journal of Physics: Conference Series **381** (2012) 012116 doi:10.1088/17426596/381/1/012116 .093303 (2012).

22.   J. F. Ziegler, J. P. Biersack, SRIM-2008 code, NEA-0919/06.