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Compact neutron generator with nanotube ion source

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Abstract: In this letter, we report the observation of fast neutrons generated when a positive acceleration potential is applied to an array of orientated carbon nanotubes, which are used as an ion source. The neutrons with energy of 2.45 MeV are generated as a result of D-D fusion reaction. The dependencies of the neutron yield on the value of the applied potential and residual pressure of deuterium are measured. The proposed approach is planned to be used for the development of compact neutron generators.

Keywords: Neutron sources; Neutron detectors (cold, thermal, fast neutrons)

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Contents

1 Introduction

Radioactive isotopes and neutron guns are common neutron sources, which are also used for calibration purposes including the calibration of detectors focused on neutrino properties and Dark Matter search [1, 2].

Radioisotope neutron sources such as Pu-Be, Am-Be, ^{252}Cf obviously could be constructed compact, easily insertable into a detector. But there are at least two drawbacks of such sources — one is the increased potential risk of polluting the detector with radioactivity, and the other one is the decrease in the source intensity due to the radioactive decay which is observed for ^{252}Cf sources. Another unrecoverable problem is the impossibility to switch the source on and off, which makes the calibration process complicated and long because the insertion procedure to the low background detector and the removal of the source is usually very strict and time consuming.

Another common neutron calibration source is a neutron gun that uses D-D or D-T fusion reaction to produce quasi monochromatic neutrons with energy of 2.45 MeV or 14.1 MeV respectively [3]. The source principle is based on the effect of the D-D or D-T reaction. Originally developed as sources with very high yield, these devices produce too many neutrons than usually needed for detector calibration which overloads the data acquisition system and can cause activation. The neutron gun source could be switched on and off after insertion which makes this type of source very attractive, but the overall dimensions of such sources are usually relatively big (overall dimensions are about tens cm [3]). They include high voltage sources above 100 kV.

Thus, the ideal neutron calibration source should be compact, controllable and as low radioactive as possible when it is switched off. It is important to keep detector clean outside, to simplify the insertion procedure and to allow simple moving of the source inside the detector. It will increase the efficiency of the calibration process and decrease the possibility of impuring the detector components. It is necessary to note that the intensity of 100–1000 neutrons per second is usually enough for calibration of such detectors.

Typically, neutron guns use a Penning ion source [3]. The alternative way to ionize deuterium is to use a sharp metal needle. It allows to achieve the value of electric field up to 10^9 V/m in the local area around the tip of the needle which is enough to produce D^+ and D^{2+} ions via the field ionization effect [4, 5]. Compact neutron generators based on the principle of a D-T fusion

reaction initiated by field ionization near iridium needles have been described in [6]. The paper ensures that the intensity can reach 10^7 neutrons per second. An accelerated potential from 50 kV up to 125 kV was fed from an external high voltage source and the ion source voltage varied from 10 kV to 17 kV. Generation of neutrons with tungsten tips was researched and demonstrated in the following articles [7, 8], where a $LiTaO_3$ crystal was used instead of the external high voltage power supply. The neutron generators with pyroelectric crystal allow to avoid the use of external high voltage source which reduces the overall sizes drastically. Pyroelectric generator of neutrons experimentally demonstrates the flux with intensity of around 10 neutrons per second [9]. It must be admitted that the efficiency of ionization via needles depends on the quality of the needle tip which degrades in time proportionally to the time of operation [10].

In order to extend the lifetime of such neutron sources, we propose to use carbon nanotubes (CNT) array instead of the single metal tips. As it was presented in [11] CNT can provide the effective ionization of the residual gas when relatively low voltage is applied to the latter. An H^+ current up to 70 nA (1 mA/cm^2) was measured under conditions when a negative polarity of a bias between a target and CNT anode is 68 kV. Residual hydrogen pressure is 10 mTorr. Also, the neutrons with intensity of up to 0.1 neutrons per second were detected as a result of D-D reaction after hydrogen was replaced by deuterium. In [12] the D-D reaction was initiated under the condition when negative accelerating potential of 80 kV was applied to a deuterated target. The neutron yield of 10^3–10^4 neutrons per second was achieved for arrays of field emitters with a density of up to 10^6 tips/cm^2. In all the experiments mentioned above the highest output yield of neutrons was observed in the range of residual gas pressure between 1 to 10 mTorr.

2 Experiment

In our research, we have applied the positive accelerating potential to the array of CNT which is used to ionize the deuterium residual gas. We study how low could the value of potential be while the D-D reaction is still observable via fast neutrons of corresponding energy.

The scheme of the experiment is shown in figure 1. The ionizer (1) consists of an array of CNT deposited on a flat substrate, which is glued by conductive epoxy to the metal holder (2). The holder is connected with an external high voltage positive power supply (3) via a vacuum high voltage feedthrough. The high voltage power supply is controllable in the range from 10 to 40 kV with 100 V accuracy and 100 ppm/hour stability. The power supply allows to monitor electric breakdown which is necessary for the results analysis. The target (4) is made from stainless steel and has the form of a parallelepiped with 50×30 mm surface and 0.8 mm thickness. One surface is covered with 50 μm layer of deuterated polythene (5). The target is grounded and installed in front of the ionizer at the distance of 15 mm. The deuterated side faced the ionizer. The ionizer, the target and the metal holder are mounted in the vacuum chamber (6). The chamber is filled continuously by deuterium. The neutrons are detected simultaneously by two detection systems: one detection system is based on the ^{3}He counter of neutrons (7), while the second detection system is based on the scintillation spectrometer (scintillator — organic crystal of para-terphenyl with cylindrical shape 25 × 25 mm) (8). The axis of the spectrometer is orientated under the angle 45° in horizontal plane relative to the target surface normal. The layer of polythene (9) with 110 mm thickness and 450 × 450 mm^2 area is placed between the target and ^{3}He counter to thermalize the neutrons below 1 MeV.

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Multiwall oriented CNT have been synthesized by plasma-enhanced chemical vapor deposition (PECVD) process on the n-type high-conductive silicon substrate. The diameter of the matrix of CNT arrays is 1 mm. Each particular array represents the CNT bundle with diameter of 1.5 μm and height of 2 μm for crystals after wet etching. The average distance between individual nanotubes is about 3 μm for both types of the CNT arrays. CNT arrays are synthesized as it is shown in right side of figure 1. The CNT arrays are placed in central part of the surface of crystal substrate, which have size $4 \times 4 \times 0.5\ \mathrm{mm}^3$.

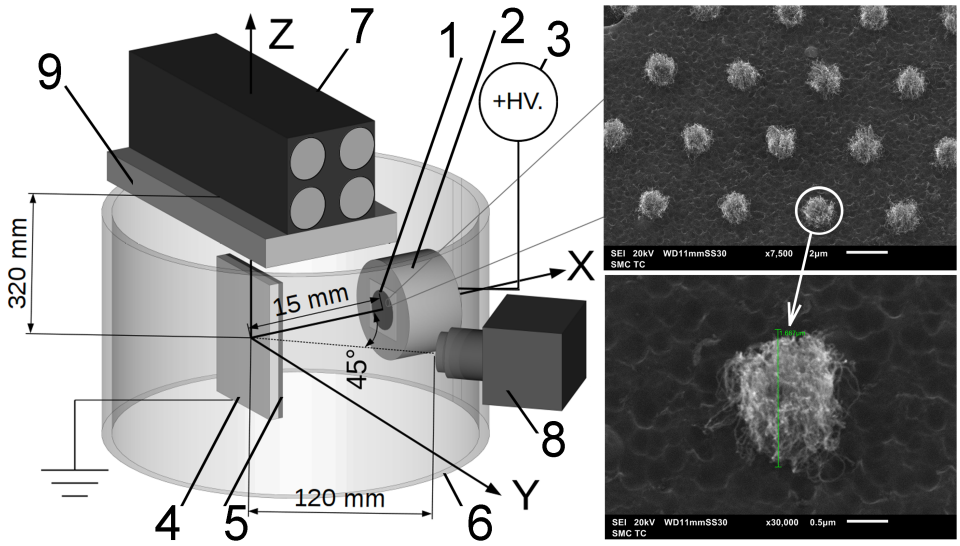

Figure 1. An illustration of experiment and SEM image of vertically oriented CNT arrays.

The experiment was performed as follows. The deuterium ions are formed in local area around the open ends of the nanotubes due to the ionization field which appears when the high voltage potential is applied to the metal holder of CNT. Then the ions are accelerated in the direction of the target by electrical field formed between the ionizer and grounded parts surrounding the experimental setup in the chamber including the target. The D-D fusion reaction is initiated by the accelerated deuterium ions interacting with deuterium nuclei on the deuterated plastic coating (5). The 45° angle spectrometer geometry is suitable, because the influence of anisotropy of neutron angular distribution is less than 3% in comparison with the total averaged value [13].

The neutron flux is measured for different values of voltage applied to ionizer within 10 kV to 40 kV range and the residual gas pressure is in the range from 1.5 mTorr to 5 mTorr. It must be admitted that increasing of the pressure up to 7 mTorr causes electric breakdown between the ionizer and the grounded target.

The received neutrons yield is estimated according to the data received from two detection systems in parallel taking into consideration the differences in neutron detection efficiency. The efficiency of the scintillation spectrometer was measured in advance in a specially organized series of experiments with an industrial neutron gun (2.5 MeV) and was estimated as 20±3%. The efficiency of the ^{3}He counter is estimated at 76% as result of modeling of interaction of neutrons with the layer of polythene and ^{3}He counter. Also, the approach of linear trajectories of the generated neutrons is used for interpretation of the measured results and following analysis.

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3 Results

The total neutron yield per 4π sr solid angle, calculated taking into account the efficiency of the detectors, backgrounds and experimental setup geometry is shown in figure 2.

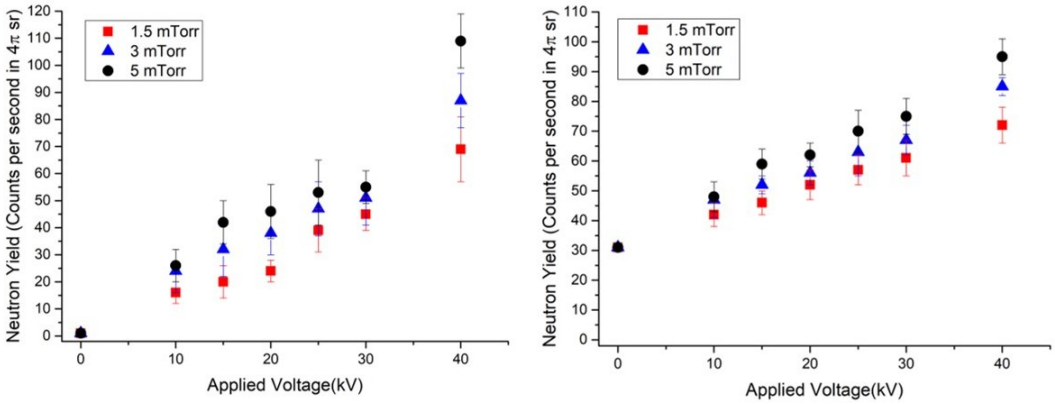

Figure 2. The dependence of the neutron yield on the ionizer potential, measured with a scintillation spectrometer (a) and a ^{3}He counter (b) at various deuterium gas pressures.

The background is measured in the same geometry of the setup and it does not exceed 1 neutron per second for scintillation spectrometer and 30 neutron per second for ^{3}He counter. The background is measured under the same conditions of experimental setup with the air as a residual gas instead of the deuterium. The figure 3 shows the dependencies of output of the ^{3}He counter detection system on the applied potential for the both air and deuterium residual gases. The background of neutrons is measured under air pressure equal to 5 mTorr. The neutron yield data are calculated as the result of averaging of the neutron yield measured when the deuterium pressure is equal to 1.5 mTorr, 3 mTorr and 5 mTorr. The curves represent mainly constant background which reaches the level of 60% of total signal when the potential equals 10 kV. The research of background contribution to the neutron yield measured by the scintillation spectrometer shows the contribution less than 4%. Thus, the performed analysis allows concluding that the neutron outputs have been registered clearly.

4 Conclusion

The experimental results show the increase of the neutron yield due to the increase of the pressure and the potential applied to the target. The yield reaches maximum value at the pressure of 5 mTorr and potential of +40 kV. It is important to notice that behaviour of the yield dependencies on the pressure and voltage is similar for both detection systems — ^{3}He counter and scintillation spectrometer. Lower absolute values of the yields registered by ^{3}He counter could be explained by diffused scattering of neutrons on the way to and inside the polythene absorber.

Thus, while we use approach of the linear trajectories in the yields calculations, the quantity of neutrons that really reaches the ^{3}He counter is less than we expect. By the way, this approach should be more precise for scintillation spectrometer, because the spectrometer detects directly neutrons with energy close to 2.45 MeV. The shape of the curve describing the increase of the neutron yield depending from the growth of ionizer potential (ion energy) is close to linear which

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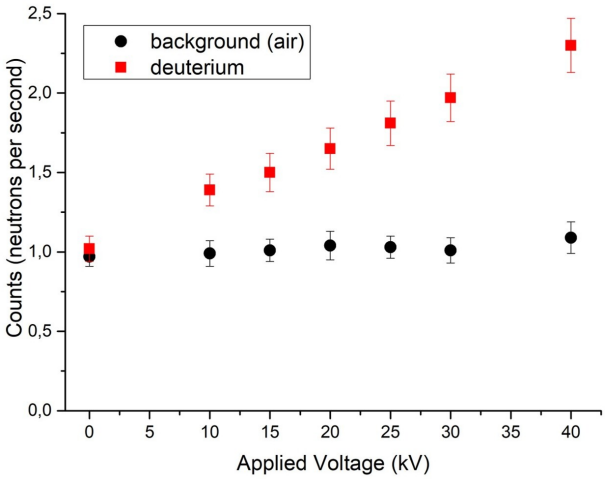

Figure 3. The dependences of number of counts of ^{3}He-counter on values of applied voltage for residual gases of air and deuterium.

do not correspond to the expected shape of the yield dependence according the experimental graph of the D-D reaction cross-section [13]. The yield should have a faster increase 10 kV to 40 kV range. We assume that this behaviour could be explained by the fact that instead of two D^+, it is mainly molecular D^{2+} initiate the D-D reactions we observe. It means that the effective energy of one accelerated nucleus of deuterium will decrease 2 times so the output of neutrons will be less according to the lower value of the corresponding cross-section [4]. The second assumption which needs to be checked additionally is non-constant ion current under different ionizer potential [6].

The neutron yield is initiated with the CNT value squared which is equal to 0.78 mm^2 only. So, the natural way to increase the yield drastically could be to increase the CNT area which could be reached very easily. The presented measurements were made with the same sample. The total lifetime of CNT array was more than 15 hours, which is greater than the lifetime of the tungsten tips [9].

The presented results demonstrate the feasibility to use CNT for constructing compact controllable neutron generators with intensity of 10–100 neutrons per second when only 10 kV power supply is used instead of power supplies above 100 kV usually used.

While 10 kV could be easily generated locally from low voltage battery the approaches described above we propose to construct compact neutron generators for neutron calibration of low-background experiments as well as for detectors for dark matter and neutrino physics. We should underline the simplicity of the neutron generator which can consist of three relatively simple parts: CNT ionizer, deuterated target and vacuum-bulb-like compact case. In addition, the result opens new possibilities for application in the neutron generators construction when the source of high voltage could be pyroelectric crystals or even pyroelectric ceramics [14, 15].

Acknowledgments

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References

[1] LZ collaboration, D.S. Akerib et al., *LUX-ZEPLIN (LZ) Conceptual Design Report*, arXiv:1509.02910v2.

[2] P. Cushman et al., *Working Group Report: WIMP Dark Matter Direct Detection*, arXiv:1310.8327v2.

[3] B.K. Das and A. Shyam, *Development of compact size penning ion source for compact neutron generator*, *Rev. Sci. Instrum.* **79** (2008) 123305.

[4] B. Reichenbach, I. Solano and P.R. Schwoebel, *A field evaporation deuterium ion source for neutron generators*, *J. Appl. Phys.* **103** (2008) 094912.

[5] B. Bargsten Johnson, P.R. Schwoebel, C.E. Holland, P.J. Resnick, K.L. Hertz and D.L. Chichester, *Field ion source development for neutron generators*, *Nucl. Instrum. Meth.* **A 663** (2012) 64.

[6] J.L. Ellsworth, S. Falabella, J. Sanchez, V. Tang and H. Wang, *Compact deuterium-tritium neutron generator using a novel field ionization source*, *J. Appl. Phys.* **116** (2014) 193301.

[7] B. Naranjo, J.K. Gimzewski and S. Putterman, *Observation of nuclear fusion driven by a pyroelectric crystal*, *Nature* **434** (2005) 1115.

[8] J. Geuther, Y. Danon and F. Saglime, *Nuclear Reactions Induced by a Pyroelectric Accelerator*, *Phys. Rev. Lett.* **96** (2006) 054803.

[9] A.S. Chepurnov et al., *Development of pyroelectric neutron source for calibration of neutrino and dark matter detectors*, *J. Phys. Conf. Ser.* **798** (2017) 012119.

[10] D. Gillich, A. Kovanen, B. Herman, T. Fullem and Y. Danon, *Pyroelectric crystal neutron production in a portable prototype vacuum system*, *Nucl. Instrum. Meth.* **A 602** (2009) 306 and online pdf version at http://homepages.rpiscrews.us/~danony/Papers/2009/Pyroelectric%20crystal%20neutron%20production%20in%20a%20portable.pdf.

[11] R.L. Fink, N. Jiang, L. Trueness, K.N. Leung and A.J. Antolak, *Setup for shot noise measurements in carbon nanotubes*, *AIP Conf. Proc.* **1099** (2009) 610.

[12] A. Persaud, O. Waldmann, R. Chapati, K. Takei, A. Javey and T. Schenkel, *A compact neutron generator using a field ionization source*, *Rev. Sci. Instrum.* **83** (2012) 02B312.

[13] A. Krauss, H.W. Becker, H.P. Trautvetter, C. Rolfs and K. Brand, *Low-energy fusion cross sections of $D + D$ and $D + {}^3He$ reactions*, *Nucl. Phys.* **A 465** (1987) 150.

[14] J.J.D. Brownridge, *Pyroelectric X-Ray generator*, *Nature* **358** (1992) 287.

[15] A.V. Shchagin, V.S. Miroshnik, V.I. Volkov and A.N. Oleinik, *Ferroelectric ceramics in a pyroelectric accelerator*, *Appl. Phys. Lett.* **107** (2015) 233505.

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