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Compact neutron generators for the calibration of low background experiments

A S Chepurnov[1], **M B Gromov**[1,2], **V Yu Ionidi**[1], **A A Kaplii**[3], **M A Kirsanov**[4], **A A Klenin**[3], **D A Kolesnikov**[3,5], **A S Kubankin**[3,6], **A Yu Maslenkina**[4], **A N Oleinik**[3,7], **D A Selivanova**[4], **A V Shchagin**[3,5]

[1] Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics,
Leninskie gory 1(2), GSP-1, Moscow, 119234, Russia
[2] Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna, Moscow region, 141980, Russia
[3] Laboratory of Radiation Physics, Belgorod National State University,
Koroleva 2a, Belgorod, 308034, Russia
[4] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute),
Kashirskoe highway 31, Moscow, 115409, Russia
[5] Kharkov Institute of Physics and Technology, Akademicheskaya 1, Kharkov, 61108, Ukraine
[6] Lebedev Physical Institute, Leninskiy Prospekt 53, Moscow, 119333, Russia
[7] John Adams Institute at Royal Holloway, University of London,
TW20 0EX, Egham, Surrey, United Kingdom

E-mail: `gromov@physics.msu.ru`, `aschepurnov@yandex.ru`, `kubankin@bsu.edu.ru`

Abstract. In the coming years, the compact monoenergetic neutron generators (CNG) producing up to 10^4 n/s may become an alternative to the standard neutron sources based on radioactive isotopes for the calibrations of neutrino and dark matter detectors. Such neutron generators have a typical size of about several centimetres, they may be manufactured using low-background materials and may require only low voltage power supply for operation. We discuss the advantages and disadvantages of two main types of the compact neutron generators, namely a pyroelectric neutron source and a high voltage neutron generator. Also the results of the technical analysis of the possibilities to apply such sources for the calibration of low-background experiments are given, the variant of the internal device design is shown and the full-size compact neutron generator prototype are presented.

1. Introduction

The modern neutrino and dark matter detectors are extremely radio-purity installations that is a basic requirement to measure or search for the rare signals. The lowest level of intrinsic radioactivity is being achieved in an innermost volume of the detector target (so-called fiducial volume) by using a passive or active shielding, applying software cuts and special procedures for selecting and purifying all the detector materials including the purification of the targets. However it is not enough to simply remove the radioactive contaminations but it is necessary to keep the detector radio-purity for years. Achieving this result is primarily hampered by the need for periodic calibrations of the detector. Literally, it means that some radioactive sources or non-radioactive devices are inserting into the fiducial volume or the veto for a while. As a consequence, it is important to minimize radioactive contamination during such procedures and to completely eliminate the possibility of loss of a radioactive source inside the detector.

The compact neutron generators (CNG) are promising devices that meet the requirements mentioned above. They are miniature vacuum chambers with a characteristic size of $3-5\,\mathrm{cm}$ in which the DD reaction takes place

$$d + d \longrightarrow {}^{3}\mathrm{He}\,(0.82\,\mathrm{MeV}) + n\,(2.45\,\mathrm{MeV}). \tag{1}$$

The reaction results in the collision of an accelerated deuterium ion with a deuterated target. The deuterium ions are produced as a result of ionization of the residual gas D_2, which fills the chamber under the pressure of a few mTorr. The applied voltage is rather high and may reach up to 100 keV. It serves to accelerate the ions.

Comparing the CNG with radioisotope neutron sources such as Pu-Be, Am-Be, ^{252}Cf the CNG is a safer neutron source for a detector environment and laboratory staff and obviously its intensity doesn't decrease over time due to any decay processes. From the organization point of view applying the CNG requires a smaller number of documents than in case of radioisotopes. Comparing the CNG with other non-radioactive sources like neutron guns there are at least two explicit advantages namely the compact size and possible low intensity of radiation at the level of $10^2 - 10^4\,\mathrm{s}^{-1}$.

The advantage of the CNG over so-called neutristor [1] is less obvious. The first problem of the neutristor is the need for an external HV power source. The second issue is an uncontrollable mode of operation. The third disadvantage of the neutristor is quite high intensity of neutron radiation that equals to 10 neutrons per pulse in a 500 ns pulse. If the device is used in a low background detector the pile-up of events spoils the calibration results dramatically.

This article includes a very short description of five types of the compact neutron generators. They are two pyroelectric neutron generators with a tungsten tip and a carbon nanotubes (CNT) array as an ionizer and the high voltage neutron generator with or without a semiconductor or scintillator detector embedded in the deuterated target. It's planned to apply the CNG during the calibrations of the Borexino [2], JUNO [3], DarkSide-20k [4] detectors. Taking into account the characteristics of their calibration systems the CNG specification is prepared (see table 1).

Table 1. The CNG specification that meets the characteristics of the Borexino, JUNO, DarkSide-20k calibration systems.

Characteristic size	– Height	$< 70\,\mathrm{mm}$ (max $100\,\mathrm{mm}$)
	– Diameter	$30 - 40\,\mathrm{mm}$ (max $50\,\mathrm{mm}$)
Housing material	acrylic, stainless steel, teflon, ceramics ($\mathrm{Al_2O_3}$), quartz	
Fixing method	hang on a tether (s) or rod (s)	
Power supply method	wired or autonomous (battery)	
Neutron yield, s^{-1}	$1 - 10^4$ (adjustable)	
Wireless switching system	preferable	

2. Pyroelectric neutron generator

The pyroelectric neutron generator (PNG) is a compact neutron generator in which the electrical field is created on the pyroelectric crystal surface by changing the crystal temperature. The most commonly used crystal is tantalate lithium ($\mathrm{LiTaO_3}$) [5], [6], [7]. The ionizer is mounted on the pyroelectric crystal surface and can be either a tungsten tip with the pin diameter of several hundred nanometers or a carbon nanotubes array. The generation of neutron radiation with the PNG and the results of some PNG tests are demonstrated in the articles [7]. Based on this article, the following positive and negative aspects of using the PNG the calibration of low background detectors can be highlighted.

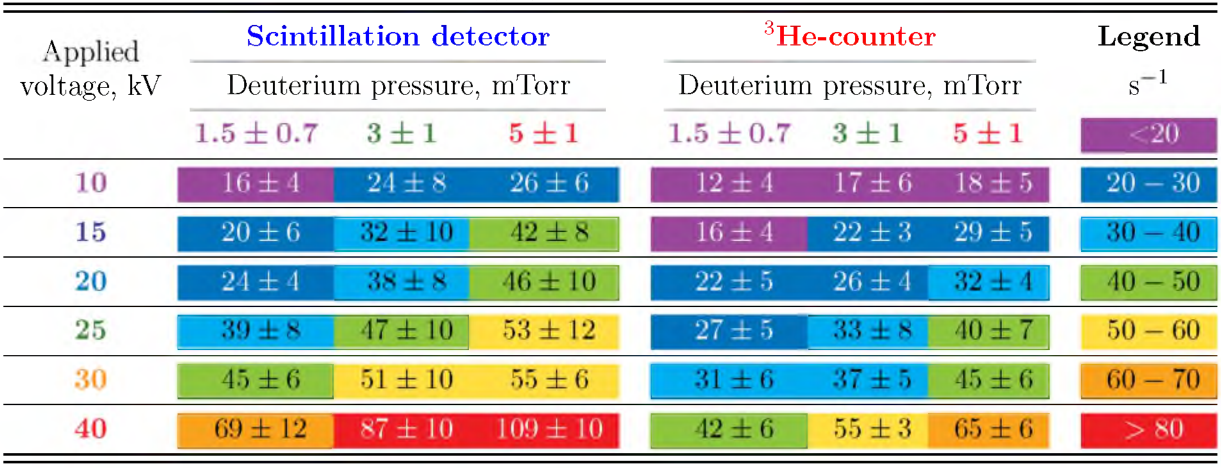
The positive aspects include the absence of necessity for high-voltage power supply and quite stable neutron yield over the residual pressure. There are a few negative features. First of all, the PNG operates in the pulse mode with duty cycle less than 50%. Than the neutron yield goes down every cycle in case of applying tungsten tips. The origin of the phenomenon is the decrease in the ionization efficiency due to the deterioration of quality of the tungsten tips. There's another problem with the tungsten tips. The electrical breakdown between the tungsten tip and the target occurs in the second half of the radiation phase and practically interrupts the neutron generation process. The degradation of the tip may be partly explained by the electrical breakdown. To overcome the problem it is better to use the CNT as an ionizer. The last negative aspect of the PNG is an intense heat production and its exchange with the surrounding environment. The heat power is not large amounting to a few watts but this may be important for the calibration of dark matter detectors.

3. High voltage neutron generator with the carbon nanotubes ionizer

The high voltage neutron generator with the carbon nanotubes ionizer (HVNG) is a compact neutron generator in which the electrical field is created with the oil filled HV power supply. The device produces continuous neutron radiation and generate the less amount of heat in comparison with the PNG. It's a reusable source that meets the periodic or routine calibration mode well. The HVNG may be controlled via adjustment of the high voltage value remotely. The investigation published in the articles [8], [9] demonstrates that increasing the residual gas pressure enhances the neutron yield. The corresponding results are given in table 2. This fact may help to satisfy the requirements of some low background detectors.

The HVNG disadvantage is an impossibility to achieve the energy of the incident deuterium ion greater than 50 keV because it is hardly feasible to create a compact 50 kV power supply.

Table 2. Measuring of neutron yield (4π) in dependence from gas pressure and applied voltage.



Applied voltage, kV	Scintillation detector			^{3}He-counter			Legend
	Deuterium pressure, mTorr			Deuterium pressure, mTorr			s^{-1}
	1.5 ± 0.7	3 ± 1	5 ± 1	1.5 ± 0.7	3 ± 1	5 ± 1	<20
10	16 ± 4	24 ± 8	26 ± 6	12 ± 4	17 ± 6	18 ± 5	$20 - 30$
15	20 ± 6	32 ± 10	42 ± 8	16 ± 4	22 ± 3	29 ± 5	$30 - 40$
20	24 ± 4	38 ± 8	46 ± 10	22 ± 5	26 ± 4	32 ± 4	$40 - 50$
25	39 ± 8	47 ± 10	53 ± 12	27 ± 5	33 ± 8	40 ± 7	$50 - 60$
30	45 ± 6	51 ± 10	55 ± 6	31 ± 6	37 ± 5	45 ± 6	$60 - 70$
40	69 ± 12	87 ± 10	109 ± 10	42 ± 6	55 ± 3	65 ± 6	> 80

4. Tagged neutron generator and the compact neutron generators prototype

The HVNG can be improved by adding a detector of the second product of the DD reaction namely the ^{3}He particles. This detector allows to control the operation of the device, tag neutrons and provide precise knowledge of the neutron yield. There are two approaches how to design this measuring cell. The first way, but not the best, is to use a semiconductor detector with deuterium deposited on its surface. In this case the device will have a short lifetime, since the sensitive area of the semiconductor detector will degrade under the influence of the ^{3}He particles. Another way is to apply a scintillator detector which consists of a SiPM and a scintillator crystal like ZnSe(Te). The respective layout of the tagged neutron generator is shown in figure 1.

Several different prototypes of the CNG have been made. One of them is demonstrated in figure 2. To select the best version of the CNG design a new experimental setup was created as well. Currently the CNG prototypes are being tested.

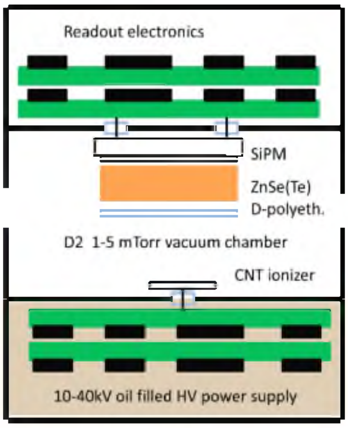


Figure 1. The structure of the compact tagged neutron source based on the high voltage neutron generator with the carbon nanotubes ionizer.

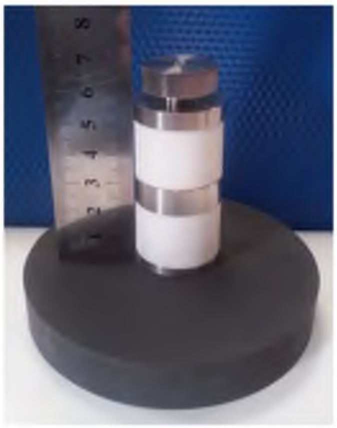


Figure 2. The prototype of the high voltage neutron generator with the carbon nanotubes ionizer which is under development.

5. Conclusion

The new generation of neutron sources is under development. Since the compact neutron generators don't contain radioisotopes their implementation will simplify the calibrations of low background detectors and will be safer for the radiochemical clean medium of the detector and laboratory staff than widespread radioactive neutron sources such as Pu-Be, Am-Be, ^{252}Cf. Any CNG can be improved by adding a measuring cell based on a tiny scintillation detector. As a result the compact tagged neutron generator has been developed for the calibration of low background experiments.

Acknowledgments

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References

[1] Jennings G, Sanzeni C and Winn D 2013 Novel compact accelerator-based neutron and gamma sources for future detector calibration Tech. rep. *Preprint* arXiv:1308.0327v1
[2] Alimonti G *et al.* (Borexino Collaboration) 2009 *NIMPA* **600** 568–593 (*Preprint* arXiv:0806.2400v1)
[3] Adam T *et al.* (JUNO Collaboration) 2015 JUNO conceptual design report Tech. rep. *Preprint* arXiv:1508.07166v2
[4] Aalseth C E *et al.* (DarkSide Collaboration) 2017 DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS Tech. rep. *Preprint* arXiv:1707.08145v1
[5] Naranjo B, Gimzewski J and Putterman S 2005 *Nature* **434** 1115–1117
[6] Geuther J, Danon Y and Saglime F 2006 *Phys. Rev. Lett.* **96**(5) 054803
[7] Chepurnov A *et al.* 2017 *J. Phys.: Conf. Series* **798**(1) 012119
[8] Chepurnov A *et al.* 2017 *J. Phys.: Conf. Series* **934**(1) 012013
[9] Chepurnov A *et al.* 2018 *JINST* **13**(2) C02035