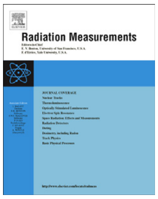
Radiation Measurements 53-54 (2013) 31–37

Contents lists available at SciVerse ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas



Total fluence influence on the detected magnitude of neutron burst using proportional detectors

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ARTICLE INFO

Article history:
Received 15 October 2012
Received in revised form
2 January 2013
Accepted 9 January 2013

Keywords:
Neutron burst
Neutron detectors
Plasma focus
Proportional counters

ABSTRACT

The measurement of very short neutron bursts, when individual neutrons cannot be counted in the usual manner, is possible with proportional detectors (such as ^{3}He) taking the integration of the total electric charge due to many overlapped interactions, as the measure of the amount of the neutron signal. This method requires a correction related to the total amount of neutrons that interacted with the detector. This correction originates in the well-known build-up of positive electric charge too slow to be dislodged from the detection volume during the neutron burst. This causes self-shielding of the applied electric field with the ensuing reduction of the charge multiplication process in the gas, described in the literature.

Short neutron bursts from a plasma focus device and a conventional isotopic neutron source were employed in the experimental phase and the known theory was applied in the analysis, which justifies assigning the observed effects to the space-charge shielding of the externally applied electric field.

This work introduces a correction to the neutron yield derived from the registered electric charge, through a model of collected charge reduction as a function of total neutrons measured.

1. Introduction

It is possible to produce steady state efficiency calibration of a detection system based upon proportional detectors, such as the ^{3}He counter, to be later applied to the measurement of a burst of neutrons closely overlapping in time (Tarifeño-Saldivia et al., 2009). The usual situation is that the burst consists of fast neutrons and the detectors are sensitive to slow neutrons, for which reason the detectors will be embedded in a neutron moderator of appropriate shape, probably polyethylene or paraffin. The moderator will spread out the original fast neutron spectrum to a partially "thermalised" spectrum and it will also spread out the time distribution of the neutrons due to the multiple scattering processes inside the moderator. The total efficiency calibration may then be carried out with an isotopic neutron source of mean energy not too far from that to be later detected.

This very common detection system is usually employed in situations where the signals from individual neutrons can be distinguished from each other, filtered through a single channel analyzer and counted. But when individual neutrons cannot be distinguished from each other due to their high time overlap (even in presence of the time spread effect of the neutron moderator), the ensuing output signal may be a charge pulse comprising the rapid pile up of many individual detected neutrons (Moreno et al., 2008). This is the case as more frequently these detection systems are applied to the neutron production measurement of pulsed devices, such as low energy plasma focus apparatus (PF). The latter generate short bursts (10–50 ns) of fusion (some may be beam target interaction) neutrons (2.45 MeV with D_2 gas) with a yield that may be less than 10^7 neutrons per shot. This low neutron field restricts the usefulness of nuclear activation methods, especially when the need exists to characterize the neutron yield shot by shot in order to advance the models which describe the dynamics of the processes which originate the nuclear fusion in such devices.

Within this scenario, the current status is to define the expected electric charge mean value of an individual neutron "η", measure the total electric charge through the oscilloscope area of the piled up signal from a neutron burst "X", and calculate the number of detected events "G"

$$G = \frac{X}{\eta} \tag{1}$$

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http://dx.doi.org/10.1016/j.radmeas.2013.01.007

Later, through a calibration factor "*j*" obtained with a steady state isotopic neutron source of known yield, operated in the usual "one pulse-one neutron" mode, the neutron yield "*Y*" of the above neutron burst is obtained as

$$Y = j\cdot G \tag{2}$$

In what follows, the shape of individual pulses from ^{3}He tubes detecting weak neutron bursts from a PF have been identified. This was accomplished recording the output charge signal for each burst in a digital oscilloscope and studying their shape frame by frame. By such process the signals corresponding to individual neutrons can be observed in the tail of the time distribution, after the high initial pile-up has died away. Finally, with such information, the pulse height spectrum (PHA) of these neutrons arisen from short bursts was reconstructed and compared with that produced with a low yield ^{252}Cf neutron source.

The aim of the work here described is to provide a correction to the number of neutrons deduced from the total electric charge collected after a neutron burst, which will be underestimating that total number due to the diminished electron multiplication inside each detector tube, caused by positive charge accumulation in the active volume. Thus, the correction must be a function of the initial neutron number deduced. It will be related to the lowering of pulse amplitude as a function of number of detected neutrons in a burst. The theory of electron gas multiplication in proportional counters from the literature will be reviewed and employed to this purpose.

2. Pulse height distribution spectrum (PHA)

The electric charge of individual pulses originated in the detection of each neutron is usually integrated in a charge sensitive preamplifier and is thus turned into a voltage signal, whose value is often called its pulse height. The circumstances that govern the variations of pulse height in a proportional counter are very well known, but for the sake of the present analysis it will be convenient to review them here.

For the particular case of the ^{3}He proportional counter employed here, the pulse height distribution exhibits a peak corresponding to the total energy of the exothermal reaction, deposited by the reaction products in the gas through ionization.

$$^3\mathrm{He} + \mathrm{n} \Rightarrow \ \mathrm{p} + {}^3\mathrm{H} + 764\ \mathrm{keV} \tag{3}$$

In this well-known ^{3}He(n,p)T reaction, the absorption of a slow neutron produces a proton and a tritium nucleus with kinetic energies 573 and 191 keV respectively, emitted in opposite directions due to momentum conservation. These charged particles ionize the gas losing a mean energy per interaction *W*. This value as given by different authors (Jesse and Sadauskis, 1953; Bortner and Hurst, 1954) ranges from 40 to 46 eV/ion pair for ultrapure Helium and is reduced to 30 eV/ion pair with small traces of impurities (Jesse and Sadauskis, 1952; Bortner and Hurst, 1954). For our detector we determined experimentally a value of 39.9 ± 1 eV, through ec. 6 and a calibrated amplifier. This value will be used throughout this paper.

Whenever any of these particles collides with the detector wall, part of the kinetic energy is not delivered to the ionization process in the gas, thus producing a charge pulse of diminished value. This is known as "the wall effect" (Shalev et al., 1969) and it induces the appearance of a plateau in the PHA spectrum to the left of the full energy peak, as depicted in Fig. 1.

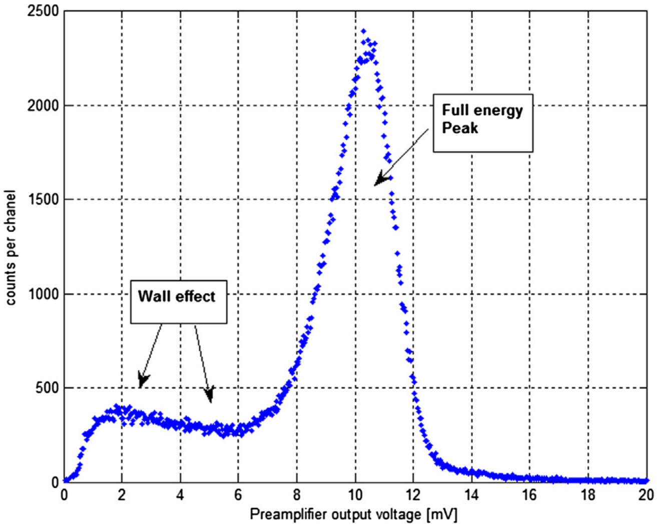

Fig. 1. ^{3}He PHA polarized at 1400 V with ^{252}Cf neutron source.

The full energy pulses in Fig. 1 exhibit a voltage which is a function of the electric charge generated by a neutron through the described mechanism. This charge may be estimated as

$$Q = n_o eM \tag{4}$$

where n_o: is the number of electron–ion pairs generated through primary (original) ionization by the ^{3}He(n,p)T reaction particles (573 keV proton, 191 KeV el triton), *e*: electron charge, *M*: gas multiplication factor of the following ionizations.

The number of electron–ion pairs can be estimated as

$$n_o = \frac{E}{W} \tag{5}$$

where *E* is the energy (in eV) of the ionizating particles liberated in the reaction (764 keV) and *W* is the mean energy necessary to ionize the gas (Fig. 2).

When the amplification system is "charge sensitive" as the one employed in this work, the ensuing pulse amplitude is directly proportional to the electric charge delivered by the detector

$$Vp = G\cdot Q = G\cdot\frac{E}{W}\cdot e\cdot M \tag{6}$$

3. Gas multiplication and its relation with detector polarization

The process of charge multiplication in the proportional detector takes place when an electron gains enough energy in the applied electric field as to ionize the neutral gas. The incremental fraction of the number of electrons ($\mathrm{d}n/n$) per unit length ($\mathrm{d}r$) can be written as the Townsend equation

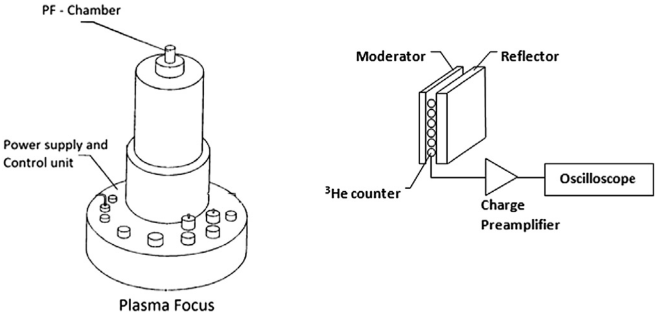

Fig. 2. Experimental setup.

$$\frac{\mathrm{d}n}{n} = \propto\left(\frac{\varepsilon}{p}\right)\mathrm{d}r \tag{7}$$

where ε is the applied electric field, p is the gas pressure and $\alpha(\varepsilon/p)$ is the Townsend coefficient for first ionization.

For cylindrical detectors the electric field is a function of the radius, so to estimate the multiplication, the last expression must be integrated.

$$M = \int_{\varepsilon(a)}^{\varepsilon(r_c)} \propto\frac{\mathrm{d}r}{\mathrm{d}\varepsilon}\mathrm{d}\varepsilon \tag{8}$$

where a is the anode radius and r_c stands for that radius where the electric field falls below the value necessary to sustain electron multiplication.

Assuming linearity between the electric field ε and the coefficient $\alpha(\varepsilon/p)$, Diethron deduces the expression (Diethron, 1956; Wolff, 1974):

$$M = \exp\left[\frac{V}{\ln\left(\frac{b}{a}\right)}\frac{\ln 2}{\Delta V}\cdot\ln\left(\frac{V}{K\cdot p\cdot a\cdot\ln\left(\frac{b}{a}\right)}\right)\right] \tag{9}$$

where V is the voltage applied to the detector and ΔV and K are two empirical fitting parameters. Parameter ΔV represents the potential difference "seen" by an electron as it moves between two ionization events while K stands for the threshold ε_c/p below which there is no multiplication.

4. Modification of multiplication due to space charge

The basis of the studied problem lies at the fact that when electron–ion pairs are generated, the electrons move in the applied electric field thousands of times faster than ions. As they migrate they leave behind a zone with net positive space charge. This charge screens the anode electric field thus diminishing gas multiplication of electrons and, consequently the amplitude of detector output pulses.

Hendricks (1969) carries out the corresponding calculation for irradiation under constant rate conditions R, considering that ions move with times characteristic of diffusion processes which depend with radius as:

$$Td(r) = \left[\frac{r^2 - a^2}{2\mu V}\right]p\cdot\ln\left(\frac{b}{a}\right) \tag{10}$$

Hendricks (1969) finds the mean charge in the detector as:

$$\rho = \frac{E}{W}\cdot M\cdot\frac{p\cdot\ln\left(\frac{b}{a}\right)}{\mu V 2\pi L}\cdot R \tag{11}$$

where a: anode wire radius, b: cathode inner radius, ρ: mean charge density [ions/m^3], E: energy of the detection reaction, W: energy necessary to create an ion–electron pair, μ: movility [m^2 s^{-1} V^{-1} Torr], L: detector length, M: gas multiplication.

This paper is devoted to the study of a situation different from that stationary case described by Hendricks (1969), as we deal with a neutron burst interacting with the detector during a time span shorter than the recollection time Tr, which is the maximum time it takes an ion to travel from the cathode to the anode. It is calculated (Ravazzania et al., 2006) as:

$$Tr = Td(b) = \left[\frac{b^2 - a^2}{2\mu V}\right]p\cdot\ln\left(\frac{b}{a}\right) \tag{12}$$

For the detector employed in the current experiment $Tr \approx 1.6$ ms.

It may be useful at this stage to point out that this time is not the pulse risetime. The shape of the pulse in a cylindrical detector when the external circuit time constant is large enough ($RC >> Tr$), is given by Kowalski (1970) as:

$$V(t) = \frac{Q}{C}\frac{1}{2\ln\left(\frac{b}{a}\right)}\left\{\ln\left[a^2 + \frac{(b^2 - a^2)t}{Tr}\right] - \ln\left(a^2\right)\right\} \tag{13}$$

Given this description of the pulse shape, the risetime $T_{1/2}$ where half of the total amplitude is reached, is calculated as:

$$T_{\frac{1}{2}} = \frac{a}{a+b}\cdot Tr \tag{14}$$

As it was mentioned, for the employed detector $T_{1/2} \approx 10^{-3}Tr \approx 1.6$ µs. This is a consequence of diffusion time being dependent on radius and of most of the ionization taking place near the anode (where gas multiplication is maximal), thus yielding very fast migration of liberated positive ions in that region, while those ions generated far from it take longer to reach the anode but provide a minor contribution to the total amplitude. To complete the scene, it may be added that the contribution of electrons, mostly liberated in the immediate vicinity of the anode, travel some thousands of times faster than ions and contribute to the signal only at the very beginning of the pulse, thus leaving the resulting shape of the signal to be dominated by the migration of slower positive charges.

We can now analyze the problem of depositing a given charge density ρ during a neutron burst:

$$\rho = \frac{E}{W}\cdot M\cdot\frac{N_i}{Vol} \tag{15}$$

where N_i is the number of neutrons interacting during the burst and Vol is the volume. By "neutrons interacting" with the detector we mean those neutrons which undergo the detection reaction, whose probability is dependent on the individual neutron kinetic energy and governed by the particular nuclear reaction cross-section.

The Poisson equation

$$\nabla^2\phi = \frac{\rho e}{\varepsilon_o} \tag{16}$$

must be solved under the boundary conditions:

$$\phi(a) = V, \quad \phi(b) = 0 \tag{17}$$

The solution for the full length L is:

$$\phi(r) = \frac{V\cdot\ln\left(\frac{b}{r}\right)}{\ln\left(\frac{b}{a}\right)} + \frac{\rho e}{4\pi\varepsilon_o}\left[\left(b^2 - r^2\right) - \frac{(b^2 - r^2)\cdot\ln\left(\frac{b}{r}\right)}{\ln\left(\frac{b}{a}\right)}\right] \tag{18}$$

The first term is the potential in the detector in the absence of charge. When multiplication is high ($M > 10$) it is assumed that all the positive ions are generated close to the positive wire electrode and, as a consequence, the field in that region ($r << b$) can be written as:

$$E(r) \;=\; -\boldsymbol{\nabla}\phi \;=\; \frac{V}{\ln\left(\frac{b}{a}\right)}\cdot\frac{1}{r} - \frac{\rho e\cdot b^2}{4\pi\varepsilon_o\cdot\ln\left(\frac{b}{a}\right)}\cdot\frac{1}{r} \tag{19}$$

Thus, the effect of accumulated positive charge is to reduce the electric field in the region close to the wire electrode,

$$E(r) \;=\; -\boldsymbol{\nabla}\phi \;=\; \frac{V-\delta V}{\ln\left(\frac{a}{b}\right)}\cdot\frac{1}{r} \tag{20}$$

The effective change in the potential is:

$$\delta V \;=\; \frac{\rho e b^2}{4\pi\varepsilon_o} \tag{21}$$

So, going back to Eq. (9) it must be re-written as

$$M' \;=\; \exp\left[\frac{V-\delta V}{\ln\left(\frac{b}{a}\right)}\frac{\ln 2}{\Delta V}\cdot\ln\left(\frac{V-\delta V}{K\cdot p\cdot a\cdot\ln\left(\frac{b}{a}\right)}\right)\right] \tag{22}$$

To write M' as a function of neutrons interacting with the detector during the burst it must be considered that the second neutron, so to speak, finds its gas multiplication diminished by the charge left by detection of the first one, adding then less charge. The detection of the third neutron finds the charge left behind by the first and the second ones and as a consequence a further reduction in multiplication will leave even less charge. This analysis is valid as the electrons abandon the zone of interest (close to the anode) in a time $T_{elec} = T_{ion}/1000 = T_r \times 10^{-6} \approx 1.6$ ns for our typical detector and also given that the sort of fast neutron burst which this study is concerned with has a duration of 10–50 ns, to which it must be added that those neutrons are later further dispersed in time by multiple collisions in the neutron moderator surrounding the detector tube, as they lose energy in the laboratory system in order to heighten their detection probability. This can be solved recursively or analytically through Eqs. (15) and (21):

$$\delta V \;=\; \frac{E}{W}\cdot\frac{N_i}{Vol}\frac{eb^2}{4\pi\varepsilon_o}\cdot M' \tag{23}$$

defining,

$$B \;=\; \frac{\ln\left(\frac{b}{a}\right)\cdot\Delta V}{\ln 2} \tag{24a}$$

$$C \;=\; K\cdot p\cdot a\cdot\ln\left(\frac{b}{a}\right) \tag{24b}$$

$$D \;=\; \frac{E}{W}\cdot\frac{eb^2}{Vol\cdot 4\pi\varepsilon_o} \tag{24c}$$

$$\delta V \;=\; D\cdot N_i\cdot M' \tag{24d}$$

we can find the relation with the number of interacting neutrons N_i as:

$$M' \;=\; \frac{1}{\exp\left[-\frac{V}{\mathbf{B}}\cdot\ln\left(\frac{V}{C}\right)\right] + \frac{D}{B}\cdot N_i\cdot\left[1+\ln\left(\frac{V}{C}\right)\right]} \tag{25}$$

As the pulse amplitude now given by the pile-up of N_i neutrons is directly proportional to M' (Eq. (6)), we can write the relative diminution of the amplitude of successive neutron interactions as:

$$\frac{V_p'}{V_p} \;=\; \frac{\exp\left[-\frac{V}{\mathbf{B}}\cdot\ln\left(\frac{V}{C}\right)\right]}{\exp\left[-\frac{V}{\mathbf{B}}\cdot\ln\left(\frac{V}{C}\right)\right] + \frac{D}{B}\cdot N_i\cdot\left[1+\ln\left(\frac{V}{C}\right)\right]} \tag{26}$$

The PHA distribution of amplitudes for successive neutrons cannot be observed when they pile-up into one sole global pulse, but it can be studied in the PHA distribution of closely arriving neutrons during weaker neutron bursts.

5. Experimental setup

The experimental study was carried out placing the detectors subtending the same solid angle in front of the PF and of the ^{252}Cf spontaneous fission neutron source. Six proportional counters embedded in a polyethylene neutron moderator were employed connected in parallel. The ^{3}He tubes, TEXLIUM model 9325, 25 mm diameter, 150 mm active length ($b = 12.5$ mm, $a = 12.5 \times 10^{-3}$mm), 10 atm filling gas pressure. The 210 × 210 mm^2 polyethylene assembly consisted in a 12 mm thick front moderator and a 30 mm thick back neutron reflector, placed 500 mm from either neutron source.

An AmpTek model A111 charge sensitive preamplifier-shaping amplifier (risetime = 25 ns, fall time = 220 ns) was coupled to the detectors under extra electrical shielding. For this detection array, a 2.6 μs risetime (see Section 4) and 12 μs falltime were measured (influenced by the electrical feed circuit *RC* constant).

6. Measurements

6.1. Measurements with the plasma focus

The PF employed in these experimental determinations has a discharge chamber with coaxial electrodes; the 30 mm diameter cathode and the 10 mm diameter anode, 25 mm length. The discharge circuit encompasses a 2.5 μF capacitor and a total measured inductance of 50 nHy. Some tests under different voltage and current regimes performed on this apparatus are described in Barbaglia et al. (2010).

The current technique to determine intensity of neutron bursts (as from PFs) with ^{3}He detectors, which could also be applied to BF$_3$, estimates the amount of neutrons detected through the area of the detector signal on a digital oscilloscope screen, knowing in advance the PHA distribution obtained with a calibration neutron source of energy spectrum as close as possible to the burst flux to be measured. The area of the detector signal due to many piled-up neutrons when compared with the evaluated most probable mean area of only one neutron under such conditions, yields the number of neutrons detected. This was introduced in Tarifeño-Saldivia et al. (2009) and a detailed statistical description is in Tarifeño-Saldivia et al. (2011).

The detection signal obtained after a neutron burst shows a high piling-up during the first moments followed by several neutron signals mounted on the tail of the original waveform; the saw blade signal depicted in Fig. 3, where the initial noise due to the PF discharge is visible at the beginning, followed by the strong pile-up and later individual signals due to neutrons that continue to flow out of the moderator with its characteristic die-away time.

6.2. Moderator die-away time determination

To register the time distribution of slow neutrons flowing from the polyethylene and interacting with the detector tubes after bursts of fast neutrons, a CANBERRA Multiport II multichannel scaler (MCS) was employed with 30 μs channel dwell-time. Due to

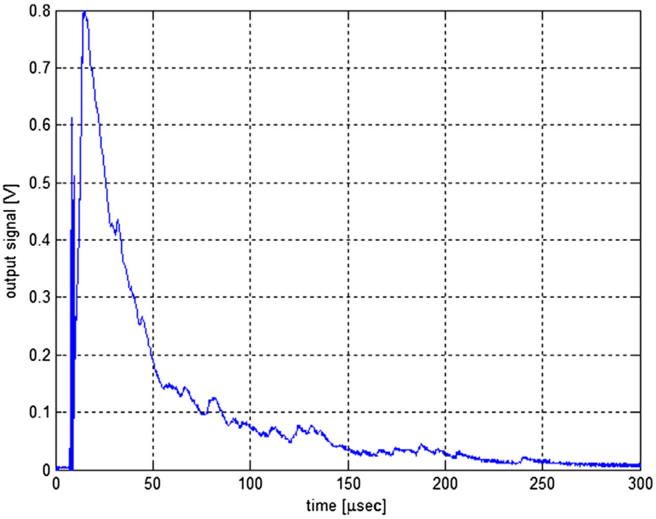

Fig. 3. Detection signal obtained after a neutron burst.

the low number of independent neutrons to be counted in conveniently low intensity bursts, the channel dwell-time was not chosen shorter.

Bearing in mind that the time-dependent solution of the neutron diffusion equation (Beckurts and Wirtz, 1964) yields an expansion with an exponential fundamental term to describe the time behaviour of the form:

$$N = N_i \exp\left(-\lambda t\right) \tag{27}$$

the described measurement yields a die-away time characterized by the constant $\lambda \approx 80$ μs. One such measurement is shown in Fig. 4. No attempt is made to measure this result through an independent method with greater accuracy, as with our electron linac pulsed neutron source, because its value will not be used in any of the determinations relevant to this paper.

6.3. PHA determination

The typical detector PHA spectrum depicted in Fig. 1 was obtained in the usual manner through a multichannel analyzer in PHA mode. This method will not be applicable to the neutron burst situation where pulse heights are derived from pulse shapes recorded on digital oscilloscope screens. Consequently, to compare PHA results for fast neutron bursts (from the PF) and results for the ^{252}Cf steady state neutron source, both measurements should be consistently derived from the direct observation of pulse height from individual or partially piled-up neutrons, recorded on the oscilloscope screens. In this manner the spectra in Fig. 5 were gathered from successive PF shots on the ensuing representative screens and equivalently for the ^{252}Cf measurements. The neutron bursts induced strong initial pile-up after which individual signals could be observed. Spectra obtained under such conditions, shown in the upper part of Fig. 5, when compared to the steady state neutron source case (lower part of Fig. 5), evince a higher proportion of piled-up signals to the right of the distribution, while an increased proportion of weaker signals appear to the left due to the herein studied diminution of gas multiplication under strong space charge accumulation during the neutron bursts.

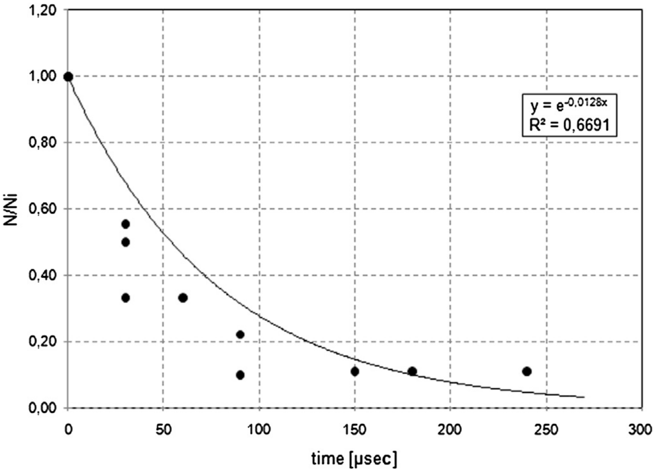

Fig. 4. MCS counting of neutrons after burst, with 30 μs e.g. dwell time window.

6.4. Gas multiplication measurement

In order to determine constants K and ΔV it was necessary to measure the gas multiplication as a function of applied high voltage polarization to one tube. This was carried out connecting one ^{3}He tube to a CANBERRA ACHP96 preamplifier/amplifier with gain $G = 40$ V/pC. Obtained values are fitted to Diethorn Eq. (9) and shown in Fig. 6. The results are $K = 1.04 \times 10^{6}$ [V/m atm^{-1}] and $\Delta V = 18$ [V]. These results are consistent with those obtained for detectors of similar characteristics (Ravazzania et al., 2006).

With the fitted constants the diminution of gas multiplication, and ensuing lowering of pulse amplitude, can be predicted as a function of the number of neutrons interacting with the detector in a time too short for the positive charge to be drifted away from the anode (Fig. 7).

For a detector with different W' value, the N_i axis in Fig. 7 will change in the proportion $39.9/W'$.

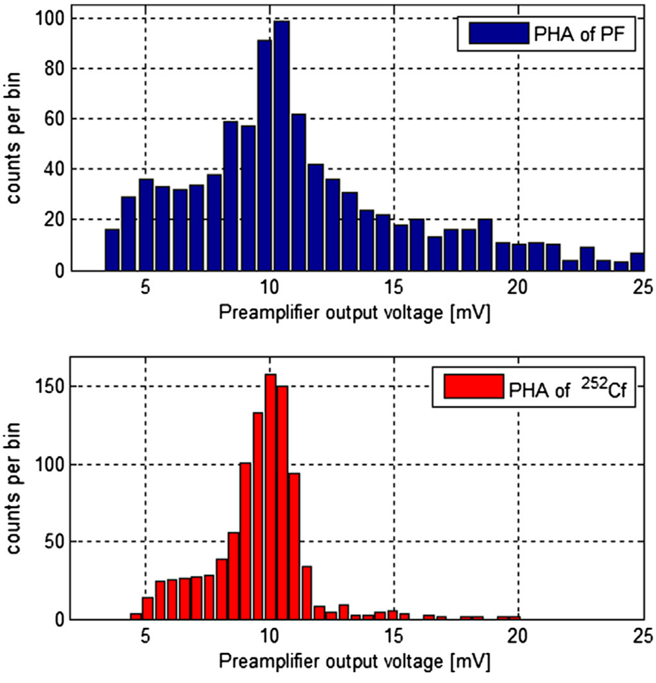

Fig. 5. PHA spectra: upper graph derived from neutron bursts; lower graph from steady state neutron source. Double and triple piling up to the right of the upper graph is consistent with the 40 ns neutron bursts from the PF incident upon the moderator. Increased signals to the left are due to diminution of gas multiplication after the initial piling-up. Both graphs have equal number of total counts.

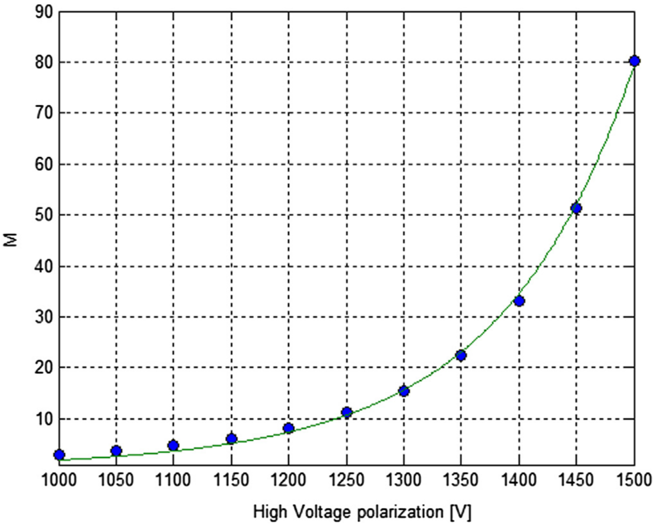

Fig. 6. Measured gas multiplication for the 25 mm diameter ^{3}He detector.

6.5. Comparison of PHAs

When the PHA spectrum of a proportional counter neutron detector, a ^{3}He in our case, obtained under steady state irradiation with a sufficiently weak neutron source, taken as the standard, is compared with the spectrum recorded under neutron irradiation in the form of intense bursts, short compared with the migration time of the positive ions, the effects described in the present paper manifest themselves in the difference observed. Under burst operation, the attenuation of pulse amplitude represented as Vp'/Vp due to electric field shielding caused by accumulated space charge (Fig. 7) is evinced as an increment in PHA area to the left of the "full energy peak" (Fig. 8). This section of the spectrum normally corresponds to the so called wall effect (Shalev et al., 1969), originated in the energy loss of reaction products which hit the wall and so do not shed all their kinetic energy to ionization (red in Fig. 8). The relation between the left side area (L in Fig. 8) to the total (L + R in Fig. 8) for both cases yields the proportion of counts affected by diminished gas multiplication during burst operation.

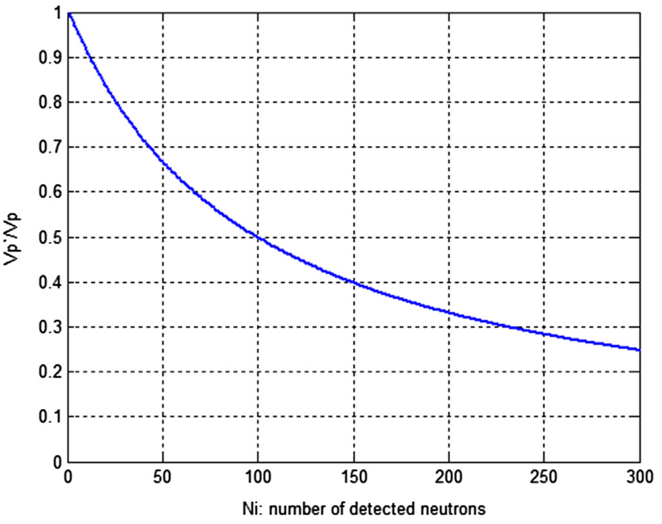

Fig. 7. Lowering of pulse amplitude as a function of number of detected neutrons in a burst.

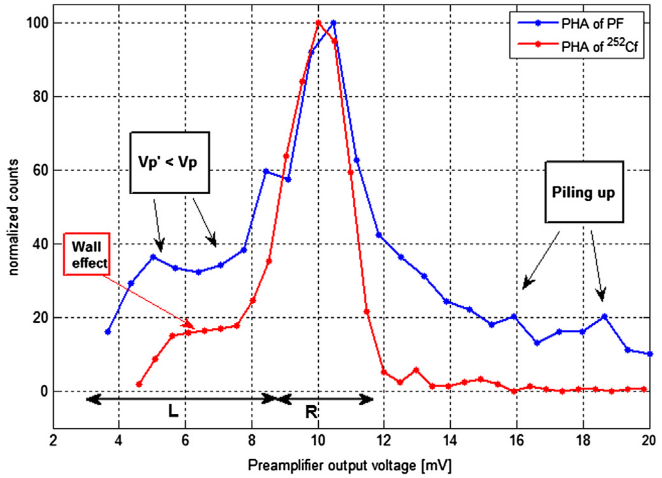

Fig. 8. Comparison of detector pulse spectrum recorded for a weak, steady state, Cf-252 neutron source and for the case of highly piled-up neutrons from bursts emitted by a plasma-focus source. The piling up, in the second case, is evident to the right of the "full energy peak", while the effect of diminished gas multiplication appears to the left of the figure. Counts have been normalized to equal height of full energy peak. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When the ^{252}Cf source is employed, the measured relation for our system is 0.357 ± 0.002.

When the PF bursts are the source of neutrons, the obtained relation is 0.508 ± 0.021.

An increment exceeding 42% results from the relation between these values, indicating the amount of diminished pulses during neutron burst counting when the degree of pile-up is small enough to measure individual pulses.

7. Conclusions

An increment in the proportion (42%) of low amplitude pulses to the left of the full energy peak in the PHA spectrum of a ^{3}He neutron detection array was found, when subjected to neutron burst irradiation with a plasma focus source.

Such effect could be satisfactorily explained as diminution of gas multiplication in the proportional detector by shielding of the electric field brought about by accumulation of slow moving positive ions left behind by the multiplication process. This effect appears when neutrons interact with the detector during a time too short for the process of positive charge recollection (dominated by the time *Tr* in the model).

A curve representing the diminution of gas multiplication with the number of detected neutrons during a burst was obtained for the described system (Fig. 7). This result is crucial in the real case of interest, which is that when the pile-up is such that individual pulses cannot be observed and the neutron count must be deduced from the area under the signal, that is the whole electric charge collected due to the almost simultaneous interaction of many neutrons.

These results are relevant to the process of gas proportional detector calibration to be employed in instantaneous yield determination of short neutron bursts as those produced by plasma focus or pulsed accelerators.

Acknowledgments

The present work was carried out with the collaboration of the Neutron Physics Group at the Bariloche Atomic Centre and with financial support from the project "Caracterización y montaje de equipo Plasma Focus de baja energía de características portables", PIP código 11220090100680, (01/08/2010 to 30/08/2012) from CONICET, and from Fundación José A. Balseiro, project "Montaje de equipo Plasma Focus de baja energía de características portables", 2011.

The authors wish to thank Dr. Alejandro Clausse for a critical reading of the initial version of the manuscript.

References

Barbaglia, M., Bruzzone, H., Rios, I., Acuña, H., Gonzalez, J., Clausse, A., 2010. Multiple pinch formations in small plasma-focus devices. Plasma Phys. Cont. Fus 52.

Beckurts, K.H., Wirtz, K., 1964. Neutron Physics. Springer-Verlag, p. 173.

Bortner, T.E., Hurst, G.S., 1954. Ionization of pure gases and mixtures of gases by 5-Mev alpha particles. Phys. Rev. 93, 1236.

Diethron, W., 1956. A Methane Proportional Counter System for Natural Radiocarbon Measurements. U. S. AEC Rep. NYO-6628.

Hendricks, R.W., 1969. Space charge effects in proportional counters. Rev. Sci. Instrum. 40, 1216.

Jesse, W.P., Sadauskis, J., 1952. Alpha-particle ionization in mixtures of the noble gases. Phys. Rev. 88, 417.

Jesse, W.P., Sadauskis, J., 1953. Alpha-particle ionization in pure gases and the average energy to make an ion pair. Phys. Rev. 90, 1120.

Kowalski, E., 1970. Nuclear Electronics. Springer-Verlag.

Moreno, J., Birstein, L., Mayer, R.E., Silva, P., Soto, L., 2008. System for measurement of low yield neutron pulses from D–D fusion reactions based upon a ^{3}He proportional counter. Meas. Sci. Technol. 19, 087002.

Ravazzania, A., Foglio Para, A., Jaime, R., Looman, M., Ferrer, M., Peerani, P., Schillebeeckx, P., 2006. Characterization of ^{3}He proportional counters. Rad. Meas. 41, 582.

Shalev, S., Fishelson, Z., Cuttler, J.M., 1969. The wall effect in ^{3}He counters. Nuc. Instrum. Meth. 71, 292.

Tarifeño-Saldivia, A., Mayer, R.E., Pavez, C., Soto, L., 2009. Use of proportional counters for yield measurement in extremely short pulses of fast neutrons: counting statistics and absolute calibration. AIP Conf. Proc. 1265, 501.

Tarifeño-Saldivia, A., Mayer, R.E., Pavez, C., Soto, L., 2011. Methodology for the Use of Proportional Counters in Pulsed Fast Neutron Yield Measurements. arxiv.org/abs/1110.2500.

Wolff, R.S., 1974. Measurement of the gas constants for various proportional-counters gas mixtures. Nucl. Instrum. Meth. 115, 461.