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Comments on the stochastic characteristics of fission chamber signals

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ABSTRACT

This paper reports on theoretical investigations of the stochastic properties of the signal series of ionisation chambers, in particular fission chambers. First, a simple and transparent derivation is given of the higher order moments of the random detector signal for incoming pulses with a non-homogeneous Poisson distribution and random pulse heights and arbitrary shape. Exact relationships are derived for the higher order moments of the detector signal, which constitute a generalisation of the so-called higher order Campbelling techniques. The probability distribution of the number of time points when the signal exceeds a certain level is also derived. Then, a few simple pulse shapes and amplitude distributions are selected as idealised models of the detector signals. Assuming that the incoming particles form a homogeneous Poisson process, explicit expressions are given for the higher order moments of the signal and the number of level crossings in a given time interval for the selected pulse shapes.

1. Introduction

The recent interest in new reactor systems and in many other fields drew an increased attention to the development of neutron detectors which are particularly suitable for deployment in such systems, especially to the technical improvement of the fission chambers. The fission chamber is an ionisation chamber in which the electron–ion pairs are generated by fission fragments in the gaseous volume of the detector. These electron–ion pairs are collected to form a detector pulse of a certain shape, and the detector signal consists of a random sum of such pulse shapes, induced by the random primary events (impinging neutrons inducing fission).

Fission chambers have certain advantages over other type of detectors which are suitable for in-core neutron measurements [1,2]. One is that they have a large dynamic range, i.e. they can be used in both low, medium and high neutron fluxes. Unlike other detectors which can operate only either in pulse or current mode, fission chambers can be operated in both. At low neutron intensities, the fissions generate individual current signals, i.e. pulses, that are generally separated and can be counted with a given efficiency. At increasing neutron intensities, the pulses tend to overlap, which finally forms a randomly fluctuating continuous current. The expectation of this fluctuating signal, that is the direct current, is proportional to the neutron flux, which is the main quantity of interest.

Under the conditions that the continuous signal is formed as the superposition of constant pulse shapes induced by independent incoming events, the higher order moments inclusive the semiinvariants of the fluctuating signal are also proportional to the intensity of the primary incoming neutrons, and hence to the neutron flux. This is expressed by the so-called Campbell theorem [3,4], which shows the relationship of the first two moments of the detector signal to the primary event intensity in the form

$$\mathbf{E}\{\eta(t))\} = s_0 \int_{-\infty}^{+\infty} f(t)\,dt \quad \text{and} \quad \mathbf{D}^2\{\eta(t)\} = s_0 \int_{-\infty}^{+\infty} f(t)^2\,dt. \tag{1}$$

Here the random process $\eta(t)$ represents the fluctuating detector signal, which consists of a random sum of deterministic current signals $f(t)$ created according a homogenous Poisson process with intensity s_0.

Eq. (1) shows the second advantage of fission chambers in that instead of the first moment, the variance can also be used to estimate the neutron flux (which is also called "Campbelling techniques" or "Campbell-technique"). Then, even if the detector is sensitive to both neutrons and gamma photons, the gamma photons will produce less charge in the detector per incoming particle than the neutrons (through the fission products), and hence will be represented by a much smaller amplitude of the corresponding current signal shape $f(t)$. Hence the contribution of the unwanted minority component, i.e. that of the gamma detections, can be significantly reduced by the use of Campbelling techniques. One can extend the relationships (1) even to higher order moments (semiinvariants), leading to higher order Campbelling techniques [5–7], lending the possibility of even further reduction of the contributions from gamma detection and other unwanted components such as alpha particles.

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The complete process of neutron detection in a fission chamber, starting with the fission in the fissile deposit of the detector, the slowing down and escape of the fission products, the charge generation, collection and amplification is a complex process. All elements of this process will influence the pulse shape, the statistics of the pulse amplitude and finally the statistics of the detector current fluctuations and hence the form and validity of the Campbelling techniques. Many elements of this process can be simulated and modelled with advanced transport codes for charged particles. Such effects have been investigated by several authors [1,2,8,9]. The emphasis in these works is that by using the basic charge transport equations, to calculate both the mean shape of an individual signal and the mean value of the saturation current.

These questions are not touched on in the present paper, which will concentrate on the understanding of the information content in the temporal randomness of a detector signal composed by a random sum of pulses of a given fixed shape but with a random amplitude distribution. No attempt will be made to derive the signal shapes or the amplitude distributions from calculation from first principles; rather, two physically reasonable shapes and amplitude distributions will be postulated and investigated.

As a first step, the higher order Campbelling techniques will be derived for a non-homogeneous Poisson distribution, with random pulse height of arbitrary distribution and arbitrary signal shape. There exist derivations in the literature of the higher order Campbelling techniques, but these contain unnecessarily complicated and often incorrect calculations. The method used in this work is the backward form of the integral master equation for the probability distribution of the detector signal. Exact relationships will be derived for the higher order moments, which constitute a generalisation of the higher order Campbelling methods. These will, among others, reproduce the results published by Lux and Baranyai [5,6] and by Bärs in 1989 [7] in a simple and transparent way.

In addition to the moments of the signal, the number of cases when the signal is higher than a given level in a given time interval also gives information on the intensity of the primary events, and hence on the neutron flux. Such a measurement on a continuous signal show similarities with measurements in the pulse mode. Because of its information content, the intensity of events when the signal exceeds a certain level is also derived.

Although, as it will be seen, the higher order Campbelling techniques state that all higher order moments are proportional to the intensity of the incoming particles, the proportionality factor is a function of the signal shape and the amplitude distribution of the pulses. Hence, insight can be gained on the performance of the Campbelling techniques if explicit analytical results are available for some concrete characteristic pulse shapes and amplitude distributions. To this end, a few simple pulse shapes and amplitude distributions are selected as idealised models of the detector signals. Assuming that the incoming particles form a homogeneous Poisson process, explicit expressions are given for the higher order moments of the signal and the intensity of level crossings for the selected pulse shapes. The results for the different pulse shapes and amplitude distributions can be compared.

Regarding the analytical work, some of the calculations require extensive derivations. Apart from the derivation of the generalised higher order Campbell relations, which will be given in detail, in the concrete calculations with selected pulse shapes and amplitude distributions, most of the details of the calculations were omitted. Details of the derivations are described in a Chalmers internal report, available electronically [10] where even other pulse shapes are considered.

It can also be mentioned that regarding the assumption of independent primary incoming events, which are essential in the derivation of the Campbell theorems, can be relaxed. The treatment used in this paper can be extended to the case when detection events are related to neutrons arising in branching processes in a multiplying medium, and which hence are not independent events. The results of this extension will be published in a later communication [11].

2. General theory

2.1. Signal probability distribution

The objective of this work is to determine the probability distribution function of the sum of random response signals of randomly appearing particles in a simple detector model. We assume that the number of incoming particles within a given time period follows an inhomogeneous Poisson distribution, and that the detector counts all arriving particles. Also, the random response signals related to different particles are considered to be independent and identically distributed. Likewise, the question of correlated detection events, induced by incoming neutrons generated in a branching process, will be treated in a forthcoming publication.

The basic quantity, the "building brick" of the stochastic model of the detector signal is the current (or voltage) pulse form generated by each incoming particle arriving to the detector. This pulse shape can be considered as the response function of the detector. As mentioned, due to the statistical properties of the generation of such a pulse from the underlying physical processes, which also contain random elements, this response pulse form cannot be given by a deterministic function $f(t)$. In the general case it is described by a function $\varphi(\boldsymbol{\xi}, t)$ which depends on the possible realisations of a random variable $\boldsymbol{\xi}$. The continuously arriving particles generate the detector current as the aggregate of such response function current signals, each related to a different realisation of $\boldsymbol{\xi}$.

In the treatment that follows we will restrict the study to cases in which the dependence of $\varphi(\boldsymbol{\xi}, t)$ on its arguments is factorised into a form $\varphi(\boldsymbol{\xi}, t) = a(\boldsymbol{\xi})f(t)$ where a is the random amplitude of the pulse and $f(t)$ is the pulse shape. Although this assumption restricts somewhat the generality of the description, it will lead to a formalism which, for several basic signal shapes $f(t)$ is amenable to an analytical treatment, while still representing a realistic model of the detector signal. For signal shapes that are constant or monotonically decreasing for $t > 0$ (square and exponential) $\boldsymbol{\xi}$ will be the (random) initial value of the response signal. For other, non-monotonically varying signal shape it can be identified with a given parameter of the signal pulse. We assume that $\boldsymbol{\xi} \in \Re$, where $\Re$ is the set of real numbers, and it has a finite expected value and variance.

The derivation of the main quantity of interest, the probability density of the stochastic signal $\eta(t)$ at time t, given that at time $t=0$ it was zero, needs the following definitions and considerations. We assume that the sequence of particle arrivals constitutes an inhomogeneous Poisson process. In this case the probability that no particle arrives at the detector during the time interval $[t_0, t], \ t \geq t_0$ is given by

$$T(t_0, t) = \exp\left\{-\int_{t_0}^{t} s_0(t')\, dt'\right\}. \tag{2.1}$$

Here $s_0(t)$ is the intensity of the particle arrivals at time t. Each particle will induce a pulse with shape $f(t)$ and a realisation x of the random amplitude $\boldsymbol{\xi}$. The cumulative probability distribution and the probability density of the amplitude distribution are