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"Influence Method" applied to measure a moderated neutron flux

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ABSTRACT

The "Influence Method" is conceived for the absolute determination of a nuclear particle flux in the absence of known detector efficiency. This method exploits the influence of the presence of one detector, in the count rate of another detector when they are placed one behind the other and define statistical estimators for the absolute number of incident particles and for the efficiency. The method and its detailed mathematical description were recently published (Rios and Mayer, 2015 [1]). In this article we apply it to the measurement of the moderated neutron flux produced by an ^{241}AmBe neutron source surrounded by a light water sphere, employing a pair of ^{3}He detectors. For this purpose, the method is extended for its application where particles arriving at the detector obey a Poisson distribution and also, for the case when efficiency is not constant over the energy spectrum of interest.

Experimental distributions and derived parameters are compared with theoretical predictions of the method and implications concerning the potential application to the absolute calibration of neutron sources are considered.

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1. Introduction

A new method for the absolute determination of particle flux in the absence of known detector efficiency, "Influence Method", was recently published [1]. This method exploits the influence of the presence of one detector, in the count rate of another detector when they are placed one in front of the other. This influence is expressed as a modification in the detection probability of a second detector after the radiation has traversed the first detector. This scheme can be interpreted as a method where the sample of the second variable is influenced by the first one, for which reason we call it the "Influence Method".

In the simplest case, let two detectors with the same efficiency ε, be placed one behind the other at a certain distance from the radiation source as schematized in Fig. 1. Particles arriving at the face of detector X (in time Δt) can be written as $n = n_o{\bullet}\varepsilon_g$ where ε_g is the geometric efficiency.

The original introductory presentation of the method was subject to the hypothetical conditions of, the particle arriving on the first detector ($\boldsymbol{n}$) being constant and both detector efficiencies ($\boldsymbol{\varepsilon}$) being also constant in the energy range of the incoming flux (the case for two different efficiencies was treated in the original work [1]). The constancy of efficiency over an energy range being realistic only in few cases, mostly in neutron time of flight spectrum determinations.

With this condition, the number of particles counted by detector X is an aleatory variable (X) whose distribution is a binomial of parameters n and ε ($X \sim Bi(n, \varepsilon)$). In the proposed scheme, particles not detected at X ($X_{out} = n - X$) impinge on detector Y. Thus, the number of those particles detected by Y are an aleatory variable (Y) whose distribution is also a binomial of parameters n and $\varepsilon{\bullet}(1-\varepsilon) = \varepsilon{\bullet}q$ ($Y \sim Bi(n, \varepsilon q)$ [1,2]), where $q = (1-\varepsilon)$ represents the probability of not being detected. Then, the expected value of the variable X is $\mu_x = n\varepsilon$ and the expected value of Y is $\mu_y = n\varepsilon q = n\varepsilon(1-\varepsilon)$.

In the simplest of these cases, the statistical estimator defined in the Influence Method for the absolute number of incident particles was defined as:

$$\hat{\boldsymbol{n}} = \frac{\boldsymbol{x}^2}{\boldsymbol{x} - \boldsymbol{y}} \tag{1}$$

where x represents the counts of the first detector and y the counts of the second.

Another estimator was defined for the detection efficiency:

$$\hat{\epsilon} = \frac{\boldsymbol{x} - \boldsymbol{y}}{\boldsymbol{x}} \tag{2}$$

Replacing the expressions of the expected values (μ) for x and y into Eqs. (1) and (2), yields precisely the parameters to be measured (n, ε). The detailed mathematical description of these

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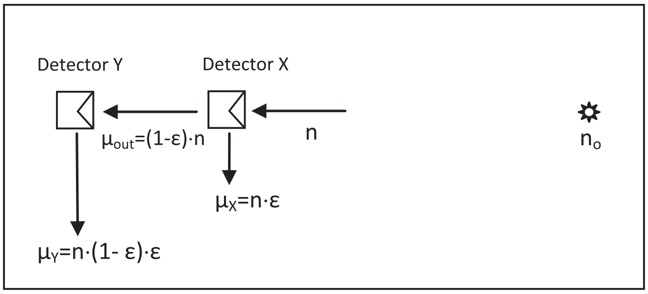

Fig. 1. Scheme of the measurement array proposed by the "Influence Method".

estimators conditions of applicability and their statistical uncertainties, are treated in [2].

In this work we present the practical application of the Influence Method for the usual case where the particle number arriving at the detector bears a Poisson distribution and, both, detector efficiency and spectral distribution of the incoming radiation are functions of energy.

In what follows, the theoretical frame is analysed for the application of the method to the general case descripted above. This is later compared with the experimental results from the application of this method to the determination of the thermalised neutron flux, emerging from a spherical light-water moderator enclosing an ^{241}AmBe neutron source, measured with two identical ^{3}He proportional counters.

It is not the purpose of this work to find an absolute value of the source strength, but to exemplify the application of the method.

2. Incoming flux whit Poisson distribution

For the introduction of the Influence Method [1,2] detectors of constant efficiency facing an also constant flux of particles, were considered. Let us now consider a radioactive source emitting particles in accordance with a Poisson distribution.

In this case, the number of particles falling on the forward detector (detector X) in time Δt, are an aleatory variable (Z) Poisson distributed with parameter $\lambda = n$ ($\boldsymbol{Z \sim Poi(n)}$). Here n is the expected value of Z, the amount of particles incident upon the detector, and they relate to the number of source particles (n_o) in the same time interval Δt through the geometrical efficiency (ε_g) through ($n = n_o \bullet \varepsilon_g$). Thus, detector X obeys a binomial distribution of parameters Z and ε ($X \sim Bi(Z, \varepsilon)$), being ε the intrinsic efficiency of that detector. In Appendix A it is demonstrated that under these conditions X is also Poisson distributed ($\boldsymbol{X \sim Poi(n \bullet \varepsilon)}$ Eq. (A.4)).

Particles not detected by the forward detector X, which have traversed it ($X_{out} = Z - X$), are Poisson distributed ($\boldsymbol{X_{out} \sim Poi(n \bullet q)}$ Eq. (A.6)) where $q = 1 - \varepsilon$ is the probability of not being counted. The backward detector Y receives those X_{out} particles. In Appendix A it is demonstrated that under these conditions Y is also Poisson distributed ($Y \sim \boldsymbol{Poi(n \bullet \varepsilon \bullet q)}$ Eq. (A.10)).

The parameters of the variables under these conditions are:

The expected value of variable X:

$$\mu_x = n \bullet \varepsilon \tag{3}$$

And its variance:

$$\sigma_x{}^2 = n \bullet \varepsilon \tag{4}$$

The expected value of variable Y:

$$\mu_y = n \bullet \varepsilon \bullet q \tag{5}$$

Its variance will be:

$$\sigma_y{}^2 = n \bullet \varepsilon \bullet q \tag{6}$$

In the present case, the expected values are the same as when n was supposed to be constant, but their variances are different.

The covariance σ_{xy} and the correlation coefficient ρ between these variables are deduced in Appendix B and both turn out to be zero in the present case:

$$\sigma_{xy} = \rho = 0 \tag{7}$$

It must be stressed that this does not imply that the variables are independent.

To find the expected values of the estimators and their variances in the present case, the same procedure described in [2] has to be applied, employing the new expressions for the expected values and variances of the variables (Eqs. (3) through (7)). This calculation yields precisely the same expressions for the expected values of the estimators as obtained in [2], when n was taken to be constant (Eqs. (11)–(15) in Ref. [2]). Consequently, the condition of applicability of the method turns out to be the same

$$n \gg 2/\varepsilon^3 + 5 \,/\, (\varepsilon \bullet (1-\varepsilon)) \tag{8}$$

For the variance of estimator $\hat{n}$, using Eqs. (3) through (7) in Eq. (17) of Ref. [2] it results:

$$\sigma_{\hat{n}}{}^2 = \mathrm{VAR}(\hat{n}) \cong \frac{n \bullet (4\epsilon^2 - 5\epsilon + 2)}{\epsilon^3} \tag{9}$$

Here we must point out an important difference with the case when n was constant. When the particle source is Poisson distributed and detectors efficiencies approach 1, the uncertainty of our estimator ($\sigma_{\hat{n}}$) approaches $\sqrt{n}$, while in the case where n was constant, if $\varepsilon \to 1$, $\sigma_{\hat{n}} \to 0$.

For the variance of estimator $\hat{\varepsilon}$, using Eq. (3) through (7) in Eq. (19) from Ref. [2] it results:

$$\sigma_{\hat{\epsilon}}^2 = \mathrm{VAR}(\hat{\epsilon}) \cong \frac{(1-\epsilon)\cdot(2-\epsilon)}{n\epsilon} \tag{10}$$

This is the same expression as for the case where n was taken to be constant.

For a given set of measured values (x, y), n and ε can be replaced in Eq. (9) by their expressions given in Eqs. (1) and (2) which finally leads to the expression of the estimator for the number of particles and its statistical uncertainty (at the 68% confidence level) for the Poisson source,

$$\boldsymbol{\hat{n}} = \frac{\boldsymbol{x}^2}{\boldsymbol{x}-\boldsymbol{y}} \pm \left(\frac{\sqrt{\boldsymbol{x}^3 \bullet \left((\boldsymbol{x}-2\boldsymbol{y})^2 + \boldsymbol{xy} \right)}}{(\boldsymbol{x}-\boldsymbol{y})^2} \right) \tag{11}$$

In the same way for the efficiency, the expression of the estimator for the efficiency and its statistical uncertainty (at the 68% confidence level) is,

$$\boldsymbol{\hat{\varepsilon}} = \frac{\boldsymbol{x}-\boldsymbol{y}}{\boldsymbol{x}} \pm \left(\sqrt{\frac{\boldsymbol{y}(\boldsymbol{x}+\boldsymbol{y})}{\boldsymbol{x}^3}} \right) \tag{12}$$

Finally, if the corresponding condition for the applicability of the method is satisfied (Eq. (8)) and n is large, the joint distribution will be normal bivariate [3–5] with parameters defined by Eq. (3) through (7), whose probability density function is:

$$f(x,y) = Q \bullet \exp\left\{ \frac{-1}{2} \left[\left(\frac{x-\mu_x}{\sigma_x} \right)^2 + \left(\frac{y-\mu_y}{\sigma_y} \right)^2 \right] \right\} \tag{13}$$

where $Q = 1/(2\pi\sigma_x\sigma_y)$.

Then, being x and y considered continuous, the estimator defined in Eq. (1) can assume any value and then $\hat{n} = N$ results a continuous variable.

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