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Absolute particle flux determination in absence of known detector efficiency. The "Influence Method"

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ABSTRACT

In this article we introduce a new method, which we call the "Influence Method", to be employed in the absolute determination of a particle flux, most especially applicable to time-of-flight spectrum determination of a neutron beam. It yields not only the absolute number of particles but also an estimator of detectors efficiencies. It may be useful when no calibration standards are available. The different estimators are introduced along with some Monte Carlo simulations to further illustrate the method.

1. Introduction

During the thrilling first years of research into the radioactivity discovered by H. Becquerel and the pioneering work of Pierre and Marie Curie, the need to quantify the phenomenon in an absolute manner became clear.

After the development of the scintillation method by Regener [1,2] and the invention of the proportional counter by Rutherford and Geiger [3], the coincidences method was developed for the absolute determination of source activity.

In 1924 Geiger and Werner Kolhorster published [4] the coincidences method applying two microscopes to the zinc sulphide scintillating screen, in order to simultaneously observe the alpha particles impinging on the screen and yielding an absolute value of the number of scintillations per unit time. The basis of this method was that alpha particles interacting with the screen give away multiple photons, allowing two observers to pick up the same event through their microscopes. Each observer made a mark on a moving strip of paper when he saw a scintillation. After a given time, if the incident alpha particles were $\mathbf{n}$ and $\boldsymbol{\varepsilon}_1$, $\boldsymbol{\varepsilon}_2$ were the efficiencies of observer 1 and observer 2 respectively, observer 1 would have registered $\mathbf{n}_1=\varepsilon_1\cdot\mathbf{n}$ and observer 2, $\mathbf{n}_2=\varepsilon_2\cdot\mathbf{n}$. As both observers acted independently, scintillations seen by both appeared as coincident marks on the paper strip and such coincidences could be ascribed a value $C=\boldsymbol{\varepsilon}_1\cdot\ \boldsymbol{\varepsilon}_2\cdot\mathbf{n}$. Thus, $\mathbf{n}$ could be determined as $\mathbf{n}=\mathbf{n}_1\,\mathbf{n}_2\,/\mathbf{C}$. This result holds in the absence of chance coincidences. This method is well known and employed, for instance, in the beta-gamma coincidence method.

At the same time Bothe and Geiger [5,6] applied the coincidence method to the study of the Compton scattering. This experiment confirmed the quantum nature of electromagnetic radiation and verified the validity of the conservation of the involved magnitudes in these elementary processes. During 1929 Bothe and Werner Kolhorster [7–9] applied the coincidence method with Geiger-Müller counters to the study of cosmic radiation.

Other techniques continue to be developed to improve the precision of estimates derived from the coincidence method, implying double-coincidence, anticoincidence, triple-to double-coincidence ratio method (TDCR) and the influence of chance coincidences [10,11]. Several techniques also appeared to determine coincidences from the spectral analysis [12]. At the same time, given the implied need for detectors to be independent, which is not always altogether possible, as is the case with 4πe-γ counting, techniques have been proposed to deal with this fact [13].

This brief historical summary has been useful for the purpose of illuminating the need to obtain absolute counting of radioactive events, through the efforts that have been centred around the exploitation of the counting of coincident events (as in beta-gamma counting), or the coincident observation of each individual event.

Let us now focus on a case where there is no manner of applying such methods. To put it in the terms already employed in this introduction, let us say that the method we develop in the

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following sections deals with cases in which there are no coincidences to be exploited and the number **n** is to be determined, while **ε** is not known. In what follows, **ε** is to be considered a constant. In the most general case, efficiency does not fulfil that condition as it is very often energy dependent. Apart from the case of time-of-flight spectrometry, which will be treated in the following section, other non constant efficiency cases can be dealt with through particular evolutions of the basic method, which will be the matter for future developments.

2. The influence method

The present method exploits the influence of the presence of one detector, in the counting of another detector. This influence is expressed as a modification in the probability of detection in a second detector after the radiation has traversed the first detector, allowing to derive a statistical estimator for the absolute number of incident events (particles), independent of the efficiency of the detectors. Another estimator is deduced for the detection efficiency, calculated from the same experiment. The statistical validity of each estimator proposed in the present work, along with the calculation of expressions for the correlated variables statistical uncertainties, will be made explicit in a forthcoming article because this rather lengthy calculation could obscure the substance of the present article only aimed at presenting the method.

One basic feature of this method is that as it does not require coincidences, there is no need for events to appear in pairs of equal or different particles. So, it is applicable to any source, momentarily subject to the limitation of constant efficiency or a monoenergetic source, although with a further development of the method, it will overcome these limitations.

In the particular case of time-of-flight spectrometry, widely employed in pulsed neutron sources spectrum determinations, the estimators could be applied to each time bin, thus rendering the particle energy spectrum in absolute terms and, almost as a by-product, the energy dependent efficiency of the detector system.

In what follows, the statistical estimators will be proposed, for the particle counts and for the efficiency. In the first place, the case of two detectors of equal efficiency will be treated, as to introduce in its simplest form the whole idea. Later, different efficiencies will be considered and the effect of scattering in the detectors will be introduced.

3. The method for detectors with the same efficiency

Let two detectors be are placed one behind the other at a certain distance from the radiation source as schematized in Fig. 1. When the two have the same efficiency, those particles arriving at the face of detector A can be written as

$$n = n_o \cdot \varepsilon_g \tag{1}$$

Where ε_g is the geometric efficiency.

The number of particles counted by detector *A* is an aleatory variable (X_A) whose distribution is a binomial of parameters *n* and ε ($X_A \sim \mathrm{Bi}(n, \varepsilon)$), and its expected value is

$$\mu_A = n \cdot \varepsilon \tag{2}$$

In the proposed scheme, particles not detected at A ($X_{\mathrm{out}} = n - X_A$) impinge on detector B. Thus, the number of those particles detected by B are an aleatory variable (X_B) whose distribution is also a binomial of parameters *n* and $\varepsilon \cdot (1\text{-}\ \varepsilon)$ (demonstration that $X_B \sim \mathrm{Bi}(n,\ \varepsilon \cdot (1\text{-}\varepsilon))$ is shown in appendix A). Then, the expected

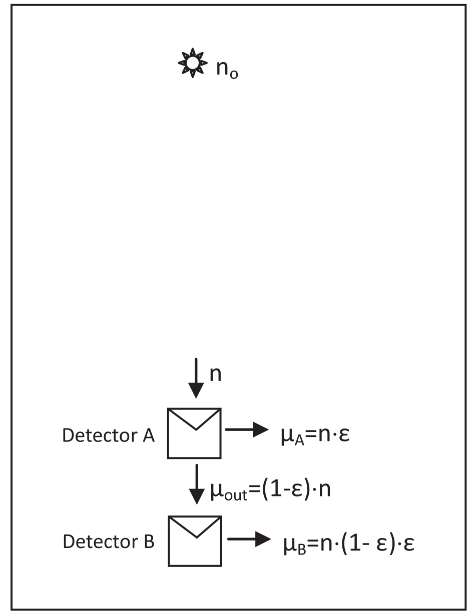

Fig. 1. Scheme of the measurement array proposed by the “Influence Method” with detectors of equal efficiency.

value for X_B is:

$$\mu_B = n \cdot \varepsilon \cdot (1 - \varepsilon) = n \cdot \varepsilon - n \cdot \varepsilon^2 \tag{3}$$

As a consequence, an estimator for *n* can be proposed as

$$\hat{\mathbf{n}} = \frac{\boldsymbol{X_A^2}}{\boldsymbol{X_A} - \boldsymbol{X_B}} \tag{4}$$

This estimator results independent of detector intrinsic efficiency.

At the same time it is possible to propose an estimator for detector intrinsic efficiency:

$$\hat{\varepsilon} = \frac{\boldsymbol{X_A} - \boldsymbol{X_B}}{\boldsymbol{X_A}} \tag{5}$$

Eqs. (2) and (3) allow us to check that the expected value of each estimator is precisely the parameter to be measured. This was the expected outcome when proposing (4) and (5).

In the practical case, it is very important for the right application of Eqs. (4) and (5), that X_A and X_B come from the same source of particles and that both detectors be protected from other spurious sources that could affect the counting (background).

It must be clear that the only condition required for the application of these estimators was that both detectors have the same intrinsic efficiency, which in practice means that both detectors be of the same nature and physically identical.

It is important to mention, at this stage, that in the scheme proposed by the “Influence Method” the two variables (X_A, X_B) are not independent, but are instead correlated. This correlation must be taken into account at the time of calculating uncertainties, a calculation which will be the subject of a forthcoming article, where the whole mathematical statistical demonstration of the properties of the distributions involved will be made explicit and expressions for the uncertainties will be calculated. As explained before, this rather lengthy calculation does not contribute to the substance of the present article aimed at presenting the main idea of the method.

3.1. Monte Carlo simulations

To illustrate the behaviour of the estimators, a virtual experiment is carried out where $n = 1000$ and the efficiency of both detectors is $\varepsilon = 0.5$. In order to show a graphic picture of estimators