Nuclear Instruments and Methods in Physics Research A 826 (2016) 80–89

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

An improved method for estimating the neutron background in measurements of neutron capture reactions

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ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form
13 February 2016
Accepted 21 April 2016
Available online 23 April 2016

Keywords:
Neutron sensitivity
Neutron background
GEANT4 simulations
Neutron time-of-flight
n_TOF
Neutron capture
Neutron scattering

ABSTRACT

The relation between the neutron background in neutron capture measurements and the neutron sensitivity related to the experimental setup is examined. It is pointed out that a proper estimate of the neutron background may only be obtained by means of dedicated simulations taking into account the full framework of the neutron-induced reactions and their complete temporal evolution. No other presently available method seems to provide reliable results, in particular under the capture resonances. An improved neutron background estimation technique is proposed, the main improvement regarding the treatment of the neutron sensitivity, taking into account the temporal evolution of the neutron-induced reactions. The technique is complemented by an advanced data analysis procedure based on relativistic kinematics of neutron scattering. The analysis procedure allows for the calculation of the neutron background in capture measurements, without requiring the time-consuming simulations to be adapted to each particular sample. A suggestion is made on how to improve the neutron background estimates if neutron background simulations are not available.

1. Introduction

The background caused by scattering of neutrons off the irradiated sample is a serious issue in neutron capture experiments. Through subsequent neutron interactions with the materials surrounding the sample, secondary reaction products are created—such as γ rays and/or charged particles—which may be detected alongside the captured γ rays emitted from the sample, contributing to the total background. This particular contribution, referred to as the *neutron background*, is most notable for the samples characterized by a large neutron scattering-to-capture cross section ratio. In general, neutron background is characteristic of environments which are strongly affected by the neutron scattering. It is intensified by the presence of any neutron-sensitive material in the immediate vicinity of the detectors, and especially by the detector proximity to the walls of the experimental hall. The neutron background is determined by two distinct components, one being the sample itself, serving as the primary neutron scatterer, and other being the sample-independent *neutron sensitivity* related to the entire experimental setup. The neutron sensitivity may be generally defined as the detector response to reaction products created by the interaction of scattered neutrons with the surrounding materials. A nontrivial effect of the neutron sensitivity on the neutron background and, consequently, the entire capture measurement has been demonstrated by Koehler et al. [1] in capture measurement on ^{88}Sr, where the reduction of the neutron sensitivity of the experimental setup has led to significant improvements in the acquired capture data.

At the neutron time-of-flight facility n_TOF at CERN, neutron sensitivity considerations have been followed since the start of its operation. This was reflected through the development of specially optimized C_6D_6 (deuterated benzene) liquid scintillation detectors, exhibiting a very low intrinsic neutron sensitivity [2]. However, the neutron background at the n_TOF facility is heavily affected by the surrounding massive walls, serving as the prime candidates for the enhanced neutron scattering. Furthermore, the much higher neutron energies available from the n_TOF spallation source introduce an additional contribution to the neutron background, when compared to the neutron sources based on electron LINACs, where the neutron energies are usually limited to ~10 MeV. Details on the n_TOF facility can be found in Refs. [3–5].

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http://dx.doi.org/10.1016/j.nima.2016.04.086
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Recently, GEANT4 [6] simulations were developed for determining the neutron background in the measurements with C_6D_6 detectors at n_TOF [7]. The results of these simulations were first applied in the analysis of the experimental capture data for ^{58}Ni [8] and the analysis of the integral cross section measurement of the $^{12}C(n,p)^{12}B$ reaction [9]. An earlier ^{58}Ni capture measurement by Guber et al. [10] has already revealed that previous experimental results and adopted evaluations of the ^{58}Ni capture cross section have been heavily affected by the neutron background, that was in the past inadequately suppressed or accounted for. At n_TOF the neutron background was accurately determined by means of dedicated simulations benchmarked against the available measurements [7], and was subtracted from the ^{58}Ni data [8].

The aim of this paper is to demonstrate that deriving the neutron background from the neutron sensitivity (Sections 2 and 3) or even the dedicated measurements (Section 4) is not a trivial issue and requires a suitable procedure. We address the issue by developing an improved method for determining the neutron background, which is based on an advanced treatment of the simulated neutron sensitivity (Section 5). The improvements regard both the event tracking in the simulations and the subsequent data analysis. In particular, we propose to study the neutron sensitivity by keeping track of the total time delays between the neutron scattering off the sample and the detection of counts caused by the neutron-induced reactions. The limitations of the method are addressed in Section 6. Section 7 summarizes the results and conclusions of this work. A detailed mathematical formalism underlying the proposed method is reported throughout the Appendices A, B, C.

2. Neutron sensitivity vs. the neutron background

When comparing the neutron background to the neutron sensitivity, a clear distinction has to be made concerning the neutron energies. The *primary neutron energy* is the true energy of the neutron (from the incident neutron beam) that has caused the reaction or the chain of reactions leading to the neutron background. The *reconstructed energy* is the energy determined from the total time delay between the neutron production and the detection of secondary particles generated by the neutron-induced reactions. In case of the *prompt counts*, caused by the reaction products immediately produced in the sample (e.g. γ rays from neutron capture), the reconstructed energy is equal to the neutron kinetic energy, due to the total time delay being equal to the neutron time-of-flight. In case of neutron scattering inside the experimental hall or some other delay mechanism, such as the decay of radioactive products created by neutron-induced reactions, the total time delay may be large and may significantly affect the reconstructed neutron energy. For these *delayed counts* contributing to the neutron background, the reconstructed energy will be lower than the primary neutron energy, often by orders of magnitude. While the reconstructed energy is experimentally accessible, the primary neutron energy is not, and can only be determined by simulations.

The neutron background estimation methods laid out in Sections 2, 3 and 4 neglect the difference between the primary neutron energy $\mathcal{E}$ (before the scattering), the scattering energy E_n (sampled in the simulations) and the reconstructed energy E_{ToF}. Hence, throughout these sections the notation E_n will be used as the universal one for the neutron energy. We follow this approach for consistency with Refs. [2,7,11], freely combining the considerations strictly valid either for $\mathcal{E}$, E_n or E_{ToF}. Starting from Section 5, these distinctions will be explicitly taken into account. In that, it should be noted that the neutron sensitivity has conventionally been expressed in terms of the scattering neutron energy [2,7,11]. On the other hand, the neutron background—as appearing in the experiments—is a function of the reconstructed energy, suggesting at once an incompatibility between the two.

In order to calculate the neutron background from the neutron sensitivity, one needs to determine the neutron detection efficiency ε_n, i.e. the efficiency for detecting a neutron through the detection of particles produced in secondary neutron reactions. This is commonly achieved by running the dedicated simulations, wherein the neutrons are isotropically and isolethargically generated from a point source at the sample position. We note that the Pulse Height Weighting Technique [12] has to be applied in calculating the efficiency, in order to compensate for the lack of correlations between γ rays in the simulated γ-ray cascades following neutron captures. This issue has already been addressed in Ref. [11]. Furthermore, the central role of applying the Pulse Height Weighting Technique to the simulated capture data was unambiguously confirmed in Ref. [7] by comparing the simulated and the experimental capture data for ^{197}Au. A detailed description of the Pulse Height Weighting Technique applied at n_TOF may be found in Ref. [13].

We adopt the definition of the neutron sensitivity from Refs. [2,7], which uses the ratio $\varepsilon_n/\varepsilon_\gamma^{\max}$, taking into account the maximum γ-ray detection efficiency $\varepsilon_\gamma^{\max}$ as an additional constant factor. In order to be able to use the weighted neutron detection efficiency $\varepsilon_n^{(w)}$, we further generalize the definition of the neutron sensitivity S, by introducing the average weighting factor $\langle w \rangle$:

$$S(E_n) \equiv \frac{\varepsilon_n^{(w)}(E_n)}{\varepsilon_\gamma^{\max} \times \langle w \rangle} \tag{1}$$

The weighted neutron detection efficiency $\varepsilon_n^{(w)}$ is:

$$\varepsilon_n^{(w)}(E_n) = \frac{\sum_{i=1}^{\delta N_{\mathrm{det}}(E_n)} w_i(E_{\mathrm{dep}})}{\delta N_{\mathrm{sim}}(E_n)} \tag{2}$$

with w_i as the appropriate weighting factors from the Pulse Height Weighting Technique, dependent on the energy E_{dep} deposited in detectors. $\delta N_{\mathrm{det}}(E_n)$ is the number of detected counts caused by neutrons of scattering neutron energy E_n, while $\delta N_{\mathrm{sim}}(E_n)$ is the total number of neutrons simulated at this energy. The average weighting factor $\langle w \rangle$ is obtained by taking into account all neutron energies sampled:

$$\langle w \rangle = \frac{\sum_{E_n} \sum_{i=1}^{\delta N_{\mathrm{det}}(E_n)} w_i(E_{\mathrm{dep}})}{\sum_{E_n} \delta N_{\mathrm{det}}(E_n)} \tag{3}$$

It may be noted that without weighting ($w_i = 1$ for all counts) the generalized neutron sensitivity reverts to the original $\varepsilon_n/\varepsilon_\gamma^{\max}$ ratio. The weighted efficiency $\varepsilon_n^{(w)}$ has been calculated for two C_6D_6 detectors used at n_TOF. One is the modified version of a commercial Bicron detector and the other one was custom built at Forschungszentrum Karlsruhe and denoted as FZK detector [2]. For the sake of simplicity and clarity, in this paper we will only show the results for the Bicron detector, with the condition $E_{\mathrm{dep}} > 200$ keV, as usually imposed on the experimental data. Furthermore, the reader's attention may be drawn to noticeable fluctuations apparent in multiple figures presented throughout this paper. With the exception of clearly recognizable resonances in the displayed spectra, the fluctuations are purely statistical in nature—a simple consequence of a finite runtime dedicated to the computationally intensive simulations. They are also naturally enchanted by the application of the Pulse Height Weighting Technique and by a fine binning that was selected for displaying the data, in order to preserve the clear appearance of some of the very narrow resonances.

In accordance with the laid out considerations, Fig. 1 shows the