A novel experimental approach for high sensitivity \((n,\gamma)\) cross section measurements

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Abstract

A new method for measuring \((n,\gamma)\) cross sections with improved peak-to-background ratio is presented. This new approach is based on the combination of the Pulse-Height Weighting Technique with high-energy resolution position sensitive radiation detectors. The latter are arranged in a two-stage compact configuration, which allows one to exploit Compton imaging techniques to disentangle true capture gamma-rays arising from the sample under study, from the background gamma-rays coming from elsewhere. A general proof-of-concept detection system for this application is presented in this article, together with a description of the imaging method and a conceptual demonstration based on Monte Carlo simulations.

1 Introduction

The two most common methods for measuring \((n,\gamma)\) cross sections as a function of the neutron energy employ either a high-efficiency total absorption calorimeter (TAC) \([1, 2, 3]\) or a low efficiency setup of \(\text{C}_6\text{D}_6\) total energy detectors (TED) \([4, 5, 6, 7]\). With either detection system, only the energy deposited (and multiplicity) of the incoming radiation is measured, which implies that background rejection has to rely on appropriate cuts on those quantities.

A new detection system is proposed in the present article, which allows one to implement a further level of background rejection based on the spatial origin (or incoming direction) of the measured gamma-rays. To this aim, the low neutron sensitivity \(\text{C}_6\text{D}_6\) TEDs commonly used in combination with the Pulse-Height Weighting Technique (PHWT) are replaced by high resolution...
position and energy sensitive radiation detectors consisting of two detection
stages. Operated in time-coincidence mode, they allow one to apply the
Compton principle in order to obtain also information on the incoming ra-
diation direction [8]. Thus, it becomes possible to disentangle whether the
registered radiation stems from the sample under study, which may indicate
a true capture event, or if it comes from the surrounding environment, which
would rather reflect a background event. The main drawback of such Com-
pton modules is the limited efficiency for coincidence events. This can be
compensated to some extent by arranging four such modules in a compact
geometry around the sample under study. Still, the largest efficiency that can
be attained is of a few percent (1-2%) and therefore the proposed detection
system has to be employed in conjunction with the Pulse-Height Weighting
Technique in order to make the capture detection probability independent of
the particular decay path. A further advantage of the present total energy
detectors with imaging capability (i-TED) is their spectroscopic resolution,
which allows one to get more detailed nuclear structure information from the
capture reaction under study. A description of such a detection system is
given in Sec. 2. Based on Monte Carlo simulations the working principle and
the improvement in signal-to-background ratio are demonstrated in Sec. 3.
Finally, Sec. 3.2 describes the sensitivity of the proposed i-TED detectors to
contaminant prompt neutron capture events in the detector itself (neutron
sensitivity).

2 Conceptual design of an i-TED detector

The detection system consists of four Compton modules arranged in a com-
 pact configuration around the capture sample. Each module consists of a
first detection layer (scatter detector), where the incoming radiation is ex-
pected to undergo just one Compton interaction. The remaining energy of
the incident gamma-ray is expected to be fully deposited in a second thick
detection layer (absorber detector). Because the aim is to apply the Compton
principle to obtain a further degree of background rejection good resolution
both in energy and position becomes mandatory. Nowadays, this can be
technically accomplished by using LaBr$_3$ monolithic crystals coupled to pix-
elated optoelectronic devices such as arrays of avalanche photodiodes, also
called multi-pixel photon-counters (MPPCs), and position-sensitive photo-
multiplier tubes (PS-PMTs).

In order to illustrate the working principle, let us consider an i-TED
prototype configured with four (scatter) LaBr$_3$ crystals with a thickness of
8 mm and a square area of 5 cm $\times$ 5 cm surrounded by four (absorber) crystals
24 mm thick, each one with an area of 10 cm × 10 cm. The gap between scatter and absorber is of 3 cm. An schematic figure showing the setup is displayed in Fig. 1.

![Schematic figure showing the setup](image)

Figure 1: The cylindrical capture sample of 2 cm diameter in the centre is surrounded by four thin scatter detectors and four thick absorber detectors configuring a compact Compton total energy detector with imaging capabilities (i-TED).

3 Performance study of the proposed method

In order to demonstrate the proposed method and quantify its performance for (n,γ) measurements detailed MC simulations have been carried out. A cylindrical sample of gold, with a thickness of 1 mm and a diameter of 2 cm is used for illustration purposes because gold is rather well known and commonly used in many time-of-flight (TOF) (n,γ) experiments as reference. In the simulation neutrons with a flat energy distribution in dE/E, i.e. isolethargic flux, from thermal up to 1 MeV impinge on the centre of the sample. Neutron transport and all possible neutron interactions are included (capture, thermal-, elastic- and inelastic- scattering and fission) using the latest GEANT4 [9] version (4.10) and the High-Precision neutron interaction libraries. Electromagnetic processes are included by means of the Low Energy package.

Both the i-TED system described in the previous section and two C₆D₆ detectors with a volume of 1 L are simulated in order to estimate the improvement with respect to existing systems.
In \((n,\gamma)\) measurements with the time-of-flight method background events arise from many different sources. Two of the main contributions are gamma-quanta cascades from contaminant prompt- and thermalised-neutron captures in the surrounding materials (concrete of the hall walls, structural materials, nearby detectors, etc) and also from gamma-rays which undergo multiple scattering, both in the sample and in the surrounding elements and are finally registered in the sensitive detection volume. In order to model such a background source in the simulation gamma-ray events are randomly generated over the surface of a 1 m radius sphere centred around the sample under study (see Fig. 2). These gamma-rays are generated with isotropic angular distribution and arbitrary multiplicity of 100 gamma-quanta per each neutron impinging on the sample. The energy distribution of the background varies from one facility to another and for each particular sample under study. In this case, just for illustration purposes, the energy distribution of the gamma-background included in the simulation corresponds to a measurement made at CERN n_TOF \cite{10} with one BaF\(_2\) detector, and is shown in Fig. 3. An additional source of background in this kind of measurements arises from the intrinsic neutron sensitivity of the detectors themselves. In this case, (beam) neutrons are scattered in the sample and subsequently captured in the sensitive detection volume. The capture gamma-rays emitted in such events have a large probability to be detected and therefore contribute as a TOF (or neutron-energy) dependent background. The (neutron) sensitivity of the proposed system to this type of background will be discussed in
more detail in Sec. 3.2.

Fig. 2 shows a schematic picture of the experimental setup and the two main gamma-ray sources included in the simulation: Gamma-rays originated at the sample due to true capture events, and background radiation emitted around the detection system.

In order to obtain statistically negligible uncertainties $10 \times 10^6$ neutron events impinging on the sample are simulated for each detection setup. The obtained capture yield as a function of the incident neutron energy is shown in Fig. 4. Because the aim is to show the performance in terms of peak-to-background (signal-to-background) ratio, all capture yield curves are normalised to the top of the 4.9 eV resonance. However, it is worth mentioning that the detection efficiency of the i-TED system is a factor of 5 lower than that of the C$_6$D$_6$ detectors. The blue curve shows the capture yield for the two C$_6$D$_6$ detectors. The background level is largest in this case, which ultimately prevents the detection of weak resonances such as the one at 46 eV.

The black curve shows the capture yield as it would be measured with the LaBr$_3$ detectors (Fig. 2) without implementing any cut in position (i.e. without imaging) or energy. The peak-to-background ratio in this case is better than with C$_6$D$_6$ detectors owing to the higher-efficiency of LaBr$_3$ for high-energy gamma-rays. However, the best peak-to-background ratio is obtained when imaging is exploited (red curve). The method is described below in Sec. 3.1. Using the ratio of the yield at 4.9 eV (peak) and at 20 eV (valley), an improvement of a factor of 7 (12) is obtained via imaging with respect to the plain LaBr$_3$ (C$_6$D$_6$) case.

Figure 3: Gamma-ray energy distribution implemented in the simulation for background events.
3.1 Exploiting the Compton principle to reject surrounding background events

At variance with another Compton camera applications the prompt gamma-cascades following neutron capture events show a rather broad energy spectrum. One possibility to exploit imaging methods would be to implement a tomographic algorithm which takes into account the different gamma-ray spectra for capture events and for background events. However, in a first demonstration stage, a more simple approach is followed here using an analytical back-projection method in combination with the fact, that the geometry of the set-up (sample position, size and distance to the i-TED detector) is known by construction. Thus, the compatibility of the measured energy and positions in scatter and absorber detectors is checked on an event-by-event basis for the sample position using the Compton formula and the aforementioned geometry constraints. The equation describing the intersection of the Compton cone with the sample is given by

\[
(n_x(x_s-a_x)+n_y(y_s-a_y)+n_z(z_s-a_z))^2 = \cos^2 \theta ((x_s-a_x)^2+(y_s-a_y)^2+(z_s-a_z)^2),
\]

(1)

where \(n_s\) are the components of a unit vector along the cone axis (the
vector between the first and second interactions), $a_s$ are the coordinates of
the first interaction in the scatter detector, $(x_s, y_s, z_s)$ is the position of the
sample (true capture gamma-ray source) and $\theta$ is the Compton scattering
angle,

$$\cos \theta = 1 + \frac{511}{E_g} - \frac{511}{E_1}$$  \hspace{1cm} (2)

where $E_g$ is the energy of the incident gamma-ray, which is assumed to
correspond to the sum of the energy in scatter $E_1$ and absorber detector $E_2$.

Thus, in order to check the compatibility of the measured radiation with
the sample position, the quantity

$$\lambda = (n_x a_x + n_y a_y + n_z a_z)^2 - (1 + 511/(E_1 + E_2) - 511/E_1)^2 (a_x^2 + a_y^2 + a_z^2)$$  \hspace{1cm} (3)

can be employed. Here the sample position has been used to define the
origin of the coordinates system, i.e. $(x_s, y_s, z_s) = (0, 0, 0)$. This value is
shown in Fig. 5 for the simulation of i-TED response to neutron capture
events shown in Fig 4.

![Figure 5: \(\lambda\)-distribution for applying a cut in space-domain.](image)

Low \(\lambda\)-values correspond to events where the Compton cone of possible
radiation directions intersect with the position where the capture sample is
placed. Thus, by applying a cut in such \(\lambda\) distribution during the analysis
stage, one can effectively reject many events which impinge on the system
from the surrounding (background events). A cut in \(\lambda \leq 90\) gives the red
yield-curve (labeled as i-TED) in Fig 4.
3.2 Intrinsic neutron sensitivity

Since many years C$_6$D$_6$ has been the material of choice for (n,$\gamma$) measurements using the PHWT owing to the very low neutron capture cross section of carbon and deuterium, which directly lead to a very low intrinsic neutron sensitivity. Thus, when replacing the sensitive detection volume by another material the first concern is obviously in terms of neutron sensitivity. The neutron capture and scattering cross sections of both lanthanum and bromine are remarkably higher than those of carbon and deuterium. However, using the proposed method, the probability that a contaminant neutron capture event in the detector mimics a good Compton event compatible with a gamma-ray coming from the sample position is very low. In order to demonstrate this, a simulation has been carried out using a carbon sample with a thickness of 1 cm. The neutron flux is as before, a white (flat) neutron energy spectrum and in this case no surrounding background events have been included in order to illustrate better the effect of the neutron sensitivity. The simulated gamma-yield as a function of the neutron energy as obtained for both C$_6$D$_6$ and i-TED detectors is shown in Fig. 6 and reflects mainly neutron scattering events in the carbon sample, which are subsequently captured in the detection volume (C$_6$D$_6$ or LaBr$_3$).

Indeed, without imaging cuts, the neutron sensitivity of the proposed set-up would be about one order of magnitude higher than that of a C$_6$D$_6$ set-up. After applying the same cut as before in $\lambda$, $\lambda \leq 90$, the neutron sensitivity is effectively reduced down to a level very similar to a detection system based on C$_6$D$_6$ detectors.

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Figure 6: Simulated detection gamma-yield for 1 cm thick C-sample with the LaBr$_3$ array (black), C$_6$D$_6$ detectors (blue) and LaBr$_3$ with imaging / i-TED (red).

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