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# A model for fitting peaks induced by fast neutrons in an HPGe detector

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## Abstract

Inelastic neutron scattering in the HPGe detector produces wide, triangular-shaped peaks in the spectrum. We develop an accurate model for the peak shape and show that the inclusion of the model in the gamma spectrum analysis makes it possible to quantify fast neutron scattering in the Ge crystal and improves the estimation of the baseline. This in turn facilitates the detection of fission products present at trace levels in environmental samples. The model, together with simulations, is used to deduce some properties of the underlying neutron energy distribution. The neutron evaporation temperature of 1.1 MeV is obtained from the analysis of environmental monitoring gamma spectra.


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## 1. Introduction

An HPGe detector is widely used in the monitoring of environmental radioactivity because of its good energy resolution. Although primarily used for the measurements of electromagnetic radiation, the HPGe detector also responds to neutron radiation. Inelastic neutron scattering in the Ge crystal produces characteristic triangular-shaped peaks, which can have widths of nearly 100 keV. Thus, the spectrum is disturbed through the increased background. The neutrons originate from cosmic ray interactions and from natural fission reactions. At ground level without extreme sheltering, neutrons are mainly produced by secondary cosmic rays, especially by negative muon capture by atomic nuclei. Muons stopped in a lead shield around a gamma-ray spectrometer are captured and they produce fast neutrons.

Muon flux and neutron flux as a function of the depth underground have been studied by many authors; see e.g. [1–5]. Studies on fast neutron

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scattering in an HPGe detector [6–9] show that simulations are able to reproduce the measured peak shape with good accuracy and that the high-energy tail of the distribution can be described by an exponential function. In addition, the neutron flux intensity depends on the measurement set-up, i.e., on the detector shielding and other materials surrounding the detector.

In this paper, we model the shape of the peak generated by the inelastic neutron scattering in Ge. Monte Carlo simulations provide enough information on the overall peak shape for developing a fit model which is accurate and easy to implement in the spectrum analysis software. Good-quality environmental monitoring data are used as a starting point for the neutron peak quantification. From these data, supported by the simulations, we extract the parameters which describe the shape of the neutron peak. After the parameters are fixed, the model can be used for operational spectrum analysis. We show that the spectrum baseline can be greatly improved, resulting in better measurement sensitivity. The data, the fit model and simulations provide means for estimating the evaporation temperature of the neutrons.

## 2. Neutron flux and interactions

### 2.1. Generation and transport of fast neutrons

Showers of secondary particles are created in the interactions between primary cosmic radiation and terrestrial and atmospheric atoms. Additional reactions are induced by these secondary particles. In the troposphere, secondary reactions are mostly induced by neutrons. At sea level, capture of the negative muon ($\mu^-$) by the nucleus becomes a competing mode of nuclear transmutation. Below sea level (corresponding to depths of over 1 m water equivalent), reactions due to muon interactions (nuclear capture) are dominant [3], especially in high-$Z$ materials. Therefore, nuclear muon capture is the main source of a neutron background in normal laboratory measurements. At very great depths (underground laboratories), neutrons from natural fission reactions start to dominate as the muon stopping rate decreases with increasing depth.

The nuclear muon capture reaction

$$(\mathrm{A,Z}) + \mu^- \rightarrow (\mathrm{A,Z}-1)^* + \nu_\mu \tag{1}$$

has a $Q$-value of the order of 100 MeV. Part of the released energy is carried off by the neutrino; the rest is converted to the excitation energy of the nucleus $(\mathrm{A,Z}-1)$. As a result, the daughter nucleus can be excited above the particle emission threshold. In intermediate mass and heavy nuclei, the emitted particles are neutrons in the majority of cases.

The fast neutrons from the excited daughter nucleus can be classified as direct neutrons and evaporation neutrons. Direct neutrons are generated in the elementary process

$$\mathrm{p} + \mu^- \rightarrow \mathrm{n} + \nu_\mu. \tag{2}$$

These neutrons can have high energies, even close to the reaction $Q$-value, but with an exponentially decreasing probability, so their amount is small compared to evaporation neutrons. Evaporation neutrons are emitted from the compound nucleus when a thermodynamical equilibrium is reached. The intermediate excited state loses energy by 'boiling off' the low-energy neutrons. The number distribution of the evaporation neutrons is approximated as [10]

$$\mathrm{d}N(E) \propto E\mathrm{e}^{-E/T}\,\mathrm{d}E \tag{3}$$

where $E$ is the energy of the emitted neutron and $T$ is the evaporation temperature. The distribution (3) has a maximum at $E = T$. The value of $T$ is expected to be around 1 MeV [11]. Muon-induced fast tertiary neutrons are produced in all materials surrounding the detector and in the detector itself.

The energy spectrum of the neutrons reaching the detector is expected to be moderated. The moderation shifts neutron energies towards lower values. We assume that this effect can be accounted for by using an effective evaporation temperature $T_{\mathrm{eff}} \leqslant T$ in Eq. (3). Moreover, we assume that the evaporation neutrons originate from the lead shield and thus the distribution is described with a single $T_{\mathrm{eff}}$ (the subscript 'eff' is dropped in the following discussion).