Localization of inclusions in multiple prompt gamma ray analysis: a feasibility study

A. Miceli[1], **G. Festa**[2], **R. Senesi**[1,3], **G. Gorini**[2], **C. Andreani**[1]

[1] Department of Physics and NAST Centre, University of Rome Tor Vergata, via della Ricerca Scientifica 1, Rome 00133, Italy

[2] Department of Physics, University of Milan Bicocca, Piazza della Scienza 3, Milan 20126, Italy

[3] CNR-IPCF, Italy

E-mail: `alice.miceli@uniroma2.it`

Abstract. We investigate the feasibility of using low energy gamma-rays from neutron capture to localize slabs inside samples. A new system based on two gamma-ray detectors with 2D collimators to be tested at the INES beamline at the pulsed neutron source ISIS (Oxford, UK) is described. The system provides a localization of slabs inside samples by using gamma-ray self-absorption. Geant4 Monte Carlo simulations of the beamline were carried out to model gamma spectra from test samples.

1. Introduction

Neutron capture prompt gamma activation analysis (PGAA) is a non-destructive analytical technique that provides information on the isotopic composition in samples. It based on the measurements of gamma-rays following neutron capture. The pattern of gamma-rays, ranging from hundred keV to 12 MeV, is unique for each isotope. The PGAA method has been applied in materials science, chemistry, geology, mining, archaeology, environment, food analysis, and medicine [1]. A current limitation of the technique is gamma-ray self-absorption. Attenuation of gamma-rays within the sample itself that may lead to significant errors [2]. In this paper, we exploit the gamma-ray self-absorption and investigate the feasibility of using low energies gamma-rays (< 650 keV) to localize metal slabs. Depending on the position of the inclusion, the gamma-rays will be attenuated differently. Using two back-to-back detectors on opposite sides of the sample we can measure the ratio of the gamma-ray intensities and calculate the approximate position of the slab. Spatial distribution of elements has recently been measured by scanning a sample with a collimated neutron beam and by using a collimated gamma detector [3]. Drawback of the technique is the high collimation of source and detector needed and the long beamtime required. The method describes in this paper, will make use of the full neutron beam area and allow for a fast localization of the slabs along the direction where the gamma-ray detectors are placed. Information on position of the inclusion could be used to correct for the self-absorption and obtain more precise quantitative analysis. This study has been performed with Monte Carlo simulations based on the GEANT4 code [4, 5].

2. Materials and Methods

2.1. Theory of measurements

The attenuation of gamma rays within the sample increases with the thickness, density, and atomic number of the attenuating medium, and increases with decreasing gamma-ray energy [2]. For gamma rays penetrating a uniform layer of material in the normal direction, the transmitted flux is:

$$I = I_0 exp(-\mu x) \tag{1}$$

where I_0 is the incident neutron flux, μ is the attenuation coefficient, and x is the layer thickness. In a neutron capture event the gamma rays are emitted isotropically. In order to ensure that the gamma ray detectors measure intensities of gamma rays that reach the detectors after traveling along a straight-line path from the gamma-ray source, i.e. the inclusion, to the detectors we employed 2D collimators. The collimators were located immediately in front of the detectors. The ratio of counts on the gamma ray detectors A and B can therefore be expressed as:

$$\frac{C_A}{C_B}(E) = \frac{I_0(E) \times \epsilon_A(E) \times \exp(-\sum_{i=1}^{N} \mu_i(E) \times x_i^A)}{I_0(E) \times \epsilon_B(E) \times \exp(-\sum_{i=1}^{N} \mu_i(E) \times x_i^B)} = \frac{\epsilon_A}{\epsilon_B}(E) \exp\left[-\sum_{i=1}^{N} \mu_i(E) \times (x_i^A - x_i^B)\right] \tag{2}$$

where $I_0(E)$ is the number of the gamma rays emitted with energy E, $\epsilon_A(E)$ is the efficiency of the detector A, $\epsilon_B(E)$ is the efficiency of the detector B, $\mu_i$is the attenuation coefficient of the material i, x_i^A is the distance traveled by the gamma ray in the material i in the direction of the detector A, and x_i^B in the direction of the detector B.

For samples in which the matrix is uniform and the slabs are small enough to ignore absorption within the slabs themselves, we can calculate the position of the slabs, knowing that $x_i^A + x_i^B = D$, as:

$$x^A = \frac{1}{2} \times \left[D - \frac{1}{\mu_M(E)} \ln\left(\frac{C_A(E) \times \epsilon_B(E)}{C_B(E) \times \epsilon_A(E)}\right)\right] \tag{3}$$

where μ_M is the attenuation coefficient of the matrix, and x^A is the distance of the center of mass of the slab from the sample edge along the x axis toward the detector A, D is the sample thickness in the direction x. The position of the slab will be:

$$x^{slab} = D/2 - x^A = \frac{1}{2 \times \mu_M(E)} \ln\left(\frac{C_A(E) \times \epsilon_B(E)}{C_B(E) \times \epsilon_A(E)}\right) \tag{4}$$

The values of $x^{slab}$are independent of the gamma ray energy. For that reason, to decrease uncertainties we averaged on all the values of x^{slab}.

This procedure was applied to several samples of Fe and Al with slabs of thickness 0.1 cm at different offsets.

2.2. Monte Carlo simulation

The proposed multi prompt gamma ray analysis system consists of two back-to-back gamma ray detectors and two 2D collimators located immediately in front of the detectors. Detectors diameter and length were 6.4 cm and 9 cm, respectively. The gamma-ray detectors were placed perpendicular to the primary beam at opposite sides of the sample at a distance of 15 cm. The 2D lead collimators were 2.2 cm thick with 0.1 cm septa and 0.4 cm periodicity. Figure 1 shows the simulated geometry. The simulation was carried out for a moderator of a spallation source. The neutron energy spectrum is shown in 2. To speed up the simulation we selected neutron energies up to epithermal range ($< 1.2keV$). The neutron beam was simulated as a parallel beam of size 2 x 2 cm^2.

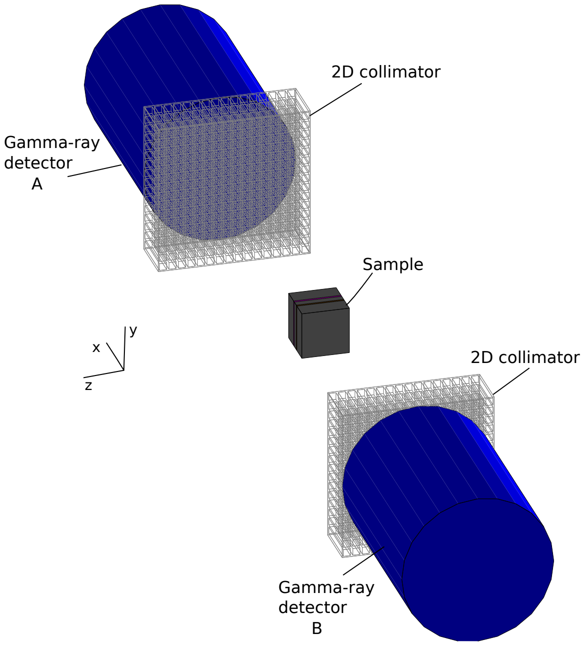

Figure 1. Simulated geometry. Gamma ray detectors, 2D lead collimators, and sample are illustrated. The neutron beam was along the z axis.

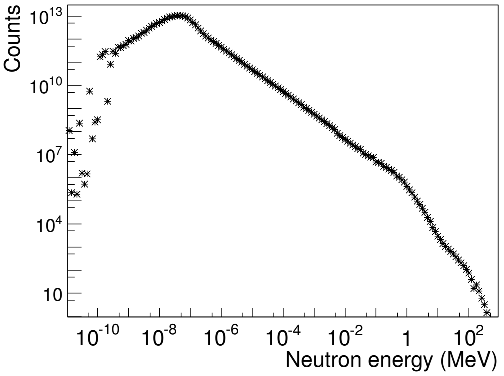

Figure 2. MCNPX simulated neutron energy spectrum (private communication with S. Ansell [6, 7]).

Samples with one and two slabs were simulated to show the capability of the system to localize slabs inside a matrix. The matrix size was 2 x 2 x 2 cm^3. The matrix material was Fe and Al. The slab size was 0.1 x 2 x 2 cm^3. The slab material was Cu and Fe. Neutrons tracks were followed through the simulated geometry until they were absorbed or exited the word volume. Inelastic and elastic scattering were simulated with the high precision neutron model of Geant4 [8]. The neutron capture was modeled by randomly sampling gamma ray energies from the nuclear decay schemes (Evaluated Nuclear Structure Data File [9]). The radioactive decay of unstable nuclei produced by neutron capture was simulated with the Geant4 radioactive model

[8]. Electromagnetic interactions were simulated with the Geant4 Livermore model [8]. Energy and measurement time were recorded for every gamma ray detected. To evaluate the feasibility of the method we considered $\epsilon_A(E) = \epsilon_B(E) = 1$ in Eq. 4. The number of simulated events was 10^9.

3. Results

Figure 3 shows a simulated energy spectrum measured by detector A from a Fe sample with a Cu slab. Gamma ray lines from neutron capture in Fe and Cu are clearly visible. Figure 4 shows the ratio of intensities of Cu lines as a function of gamma ray energies for slabs in a Fe matrix placed at offset -0.2 cm and 0.2 cm along the x axis . The ratio C_A/C_B is well separated for the two offsets for all the gamma ray lines.

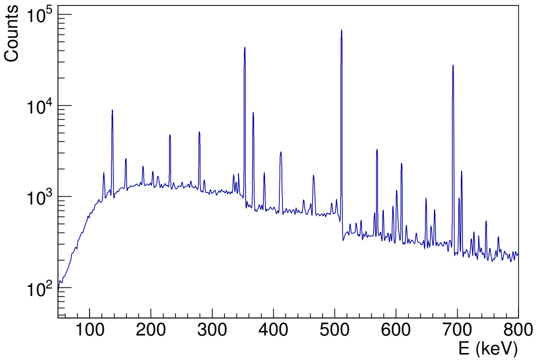

Figure 3. Simulated energy spectrum measured by detector A from a Fe sample with a Cu slab in the energy range [0, 800] keV.

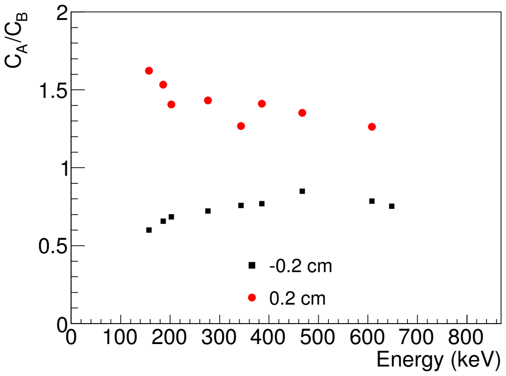

Figure 4. Ratio of counts on detector A and detector B as a function of gamma ray energies for a Cu slab in a Fe matrix placed at -0.2 cm (black) and 0.2 cm (red) offset along x.

Table 1 lists the reconstructed position of the slabs calculated from Eq. 4 for different samples. The difference between the actual and reconstructed position of the slabs is ≤ 0.1 cm for all the studied configurations. Samples containing less abundant and/or weaker gamma-emitters could be investigated using the neutron time of flight (TOF) information and the resonance

Table 1. Calculated slab positions x_R^{slab1} and x_R^{slab2}.

matrix material	slab1 material	slab2 material	x^{slab1} (cm)	x^{slab2} (cm)	x_R^{slab1} (cm)	x_R^{slab2} (cm)
Fe	Cu	-	-0.5	-	-0.5	-
Fe	Cu	-	0.5	-	0.5	-
Fe	Cu	-	0.	-	0.	-
Fe	Cu	-	0.2	-	0.2	-
Fe	Cu	-	-0.2	-	-0.2	-
Al	Cu	Fe	0.2	-0.2	0.2	-0.3
Al	Cu	Fe	0.4	-0.4	0.5	-0.3

structure of neutron capture cross section. Gamma ray lines of less abundant or weaker gamma-emitter isotopes could be discerned by selecting gamma-ray spectra at specific TOF windows. In future, simulations accounting for detector effects will be performed in order to select the most suitable detector and to study the limits of the techniques for different matrix/slab materials and thicknesses. Measurements at the pulsed neutron source ISIS (Oxford, UK) are foreseen.

4. Conclusions

The feasibility of using low energy gamma rays from neutron capture to localize metallic slabs inside a sample has been investigated with Monte Carlo simulations. A detection system consisting of two back-to-back gamma ray detectors with two 2D collimators has been proposed. The position of the slab has been correctly reconstructed using the ratio of the intensity of two gamma ray detectors placed on opposite sides of the sample. Simulations taking into account detector effects and studying the limitations of the techniques are ongoing. Information on inclusion position could be used to correct for the gamma ray self-absorption and to obtain more precise quantitative analysis. Possible applications of the technique are in metallography, geology, and archeology.

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