Imaging applications and detector testing with mono-energetic gamma rays

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Abstract

We propose to perform two (p,γ) reactions to assess the feasibility of using multi-monoenergetic gamma rays for imaging of complex objects. In addition, we propose to use the same reactions to calibrate a custom made gamma calorimeter intended to be used for radiography and tomography applications at ELI-NP.

Introduction

Non-destructive techniques based on the gamma-ray attenuation, such as tomography and radiography, are widely used in medical and industrial applications as well as in border control. Such applications involve the determination of density and effective Z of materials using single or dual energies and can be used for 2D/3D imaging and nuclear material detection. Most of the radiographic systems in use today for border control and nondestructive testing rely on bremsstrahlung beams produced by linear accelerators. Alternatively, the use of monoenergetic gamma ray for imaging have the advantage of low dose, exact determination of attenuation coefficients and no beam hardening effects [1]. Here we propose to assess the feasibility of using multi-monoenergetic gamma rays for determining the effective Z of complex objects. In cases in which the detectability limits are reached we plan to consider other methods based on scattering or pair production processes as alternatives [2, 3].

The experiments that we propose aims at determining the effective atomic number of an unknown sample based on the intensity ratio of two monoenergetic gamma-rays transmitted through the sample. In addition we plan to complement these measurements with a quantitative measurement of the 511 keV photons produced in the sample and to study the inelastic scattering to pair production ratio for different Z materials.

Another goal of this proposal is to test a gamma calorimeter developed at ELI-NP. This gamma calorimeter is designed to overcome the challenges imposed by the gamma beam time structure and will be used to measure the intensity of the gamma beam in the radiography and tomography experiments. The calorimeter is a simplified version of the one provided by EuroGammaS from the ELI-NP GBS characterization system [4]. This device will be a layer based detector made out of thin silicon detector layers followed by passive absorber layers made of polyethylene (PE). The working principle of this detector requires the determination of the beam energy by comparing the measured profile against a detailed Monte Carlo simulation of the device. Based on the comparison the beam intensity can be inferred using the monochromatic beam hypothesis. Using gamma photons produced by (p,γ) reactions we will test the working principle of this detector and we will validate our Geant4 simulation in order to obtain an absolute value of the intensity.

Experimental details

Table 1 lists the the proposed (p,γ) reactions. Both reactions use proton beam of energies below 3 MeV. The first reaction provides a large yield of gamma rays of 6.1, 6.9 and 7.1 MeV, respectively and a cascade gamma of $\approx$ 1 MeV [5]. The second reaction has a lower yield but it provides gamma rays of 10.8 MeV [6]. The first reaction is a good candidate for imaging applications and both reactions will be used for detector testing and characterization. The experimental setups that we plan to use are sketched in figures 1 and 2.

Table 1: Proposed nuclear reactions

Reaction	E_p keV	$E_{\gamma 1}$ keV	$E_{\gamma 2}$ keV	$E_{\gamma 3}$ keV	Rate events/s (4π)	Target
$^{19}F(p,\alpha\gamma)^{16}O$	> 1500	$987 \rightarrow 6129$	6917	7116	6.28×10^{8}	CaF_2
$^{27}Al(p,\gamma)^{28}Si$	992	10762.9	1778.96		36540	Al

Figure 1 shows a schematics of the first setup intended for effective Z determinations. Detector 1, 60% relative efficiency HPGe, will be used for the dual gamma attenuation method and it will be placed on the beam axis behind the sample. Detector 2, a 150% relative efficiency HPGe placed at a 70° with respect to the gamma beam direction, will detect the Compton scattered gamma rays and the annihilation photons from the pair production inside the sample. The coincident detection of 0.511 MeV photons in detector 2 and detector 3 will provide the number of pair production interactions. An additional detector will be used as a gamma-ray monitoring device. Two lead collimators will be used in this experimental setup. Collimator 1, with a length of 25 cm and a radius of 0.5 cm, will be used to shield the detectors from gamma rays coming directly from the (p,γ) reaction. Collimator 2, with a length of 12 cm and a radius of 0.25 cm, will be used to limit the angle of the Compton scattered photons reaching detector 2.

The second setup will be dedicated to the characterization of the gamma calorimeter (see Figure 2) developed at ELI-NP. The number of photons incident on the calorimeter's face will be approximated using a germanium detector, 150 % with known efficiency.

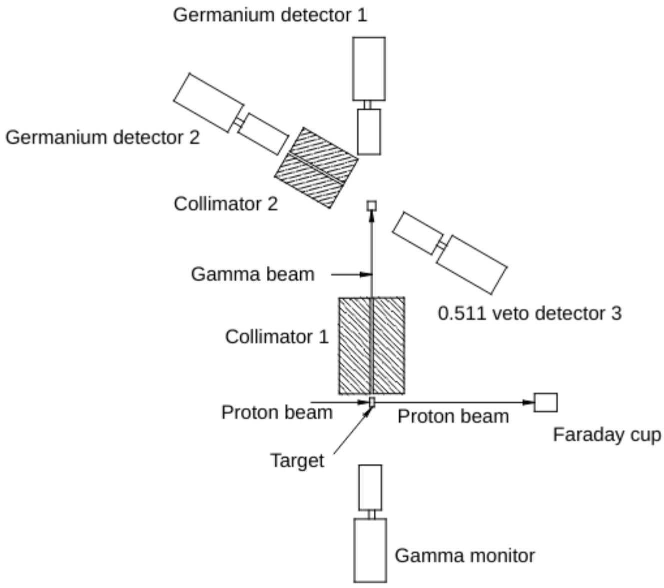

Figure 1: Effective Z determination setup

With this setup we will study the response of the calorimeter to different incident fluxes of gamma rays. The procedure to determine the beam energy and the beam intensity is similar to the procedure described in reference [4]. We propose to measure the detector response and benchmark the use of GEANT4 for beam intensity measurement. Based on these measurements and on MC simulations we will be able to characterize the transmitted photons from the pencil-beam tomography setup at ELI-NP

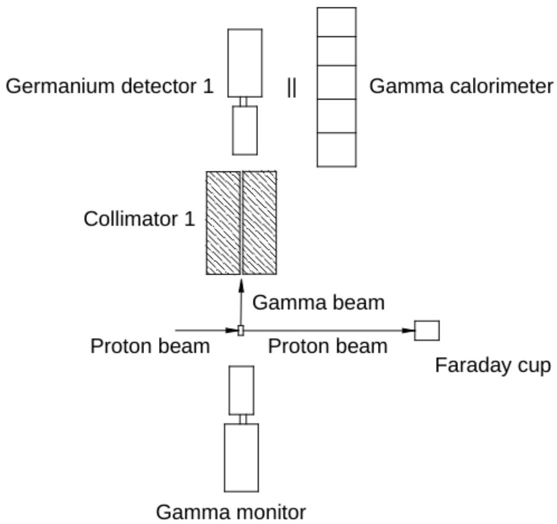

Figure 2: Experimental setup for calorimeter calibration

The readout of the silicon detectors will be made using MPR-16 lin/log charge preamplifier from Mesytec. The signal from the Mesytec module will be passed on to a MSCF-

16 shaping-/timing filter/discriminator module. The data from the germanium detector will be collected using CAEN digitizers.

Table 2 lists the expected count rates in the detectors for each process estimated for an areal density of 19.5 g/cm^2 for each material. Based on this rates and targeting a 1 % statistical uncertainty we require up to 4 days of beam time to measure the known samples. One extra day will be used to measure the unknown sample. For the calibration and testing of the calorimeter we estimated the need for measurements up to 2 days. Due to the need to change between two experimental setups we require 3 days for setup preparation. **In total we request 10 days of beamtime for the 3 MV tandem accelerator in order to carry out (p,γ) reactions. The proposed reactions will allow us to calibrate a custom made tomography detector and to asses the feasibility of effective atomic number measurements in the context of ELI-NP GBS.**

Table 2: Estimated count rates for the processes of interest in different materials of areal density of 19.5 g/cm^2.

Target	Pair production (counts/s)	Compton (counts/s)	Dual gamma attenuation (counts/s)	
	0.511 MeV	0.7 MeV	0.987 MeV	7.116 MeV
Aluminum	0.078	0.510	401.5	250.4
Iron	0.143	0.491	428.3	229.9
Copper	0.155	0.482	428.3	225.8
Tungsten	0.299	0.425	361.4	176.5
Lead	0.315	0.246	334.6	168.3

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