IFIN-HH

Proposal for the TANDEM accelerator for the period

December 2017 - March 2018

Detector efficiency calibration and polarization sensitivity for high energy γ-rays

A. Kusoglu,[1] G.V. Turturica,[1] G. Suliman,[1] D.L. Balabanski,[1]
V. Iancu,[1] S. Ilie,[1] N. Marginean,[2] C. Mihai,[2] A. Negret,[2] and C.A. Ur[1]

[1]*ELI-NP, Horia Hulubei National Institute of Physics and Nuclear Engineering, 077125 Magurele, Romania*
[2]*Horia Hulubei National Institute for R&D in Physics and Engineering, 077125 Magurele, Romania*

I. ABSTRACT

We propose an experiment to characterize and test the polarization sensitivity of high energy γ rays with existing HPGe detectors at ELI-NP for the first time. The experimental setup will detect emitted gamma rays using two HPGe segmented clover detector (part of ELIADE (ELI-NP Array of DEtectors) array) and one 150% relative efficiency HPGe detector (part of the GBS diagnostics). In order to know the detector's absolute efficiency over the 0.2-18 MeV energy range, the energy limit imposed by standard calibration γ-ray sources needed to be extended to the required energy region using the nuclear reactions. We will use several (p,γ) and one (p,$\alpha\gamma$) reactions to produce γ rays in the 0.1-18 MeV range. This photon energy range is accessible at 3 MV Tandem accelerator at the IFIN-HH laboratory. Apart from the efficiency and polarization sensitivity measurements, this experiment will provide useful data for optimization of the add-back algorithm for the segmented clover detector. In order to collect enough counts to perform our measurements, we request 9 days of beam time.

II. INTRODUCTION

The high brillance Gamma Beam System (GBS) at ELI-NP will deliver quasi-monochromatic gamma-ray beams with high spectral density and high degree of linear polarization. The GBS will be delivered in two phases with two separate beam lines: a low-energy gamma-ray line with gamma energies up to 3.5 MeV and a high-energy gamma line with energies up to 19.5 MeV. The outstanding quality of the gamma beam is suited for sensitive Nuclear Resonance Fluorescence (NRF) experiments. The NRF method allows for a direct determination of several observables such as excitation energy, intensities, polarizations, and angular intensity distributions of the fluorescent γ-radiation.

The main experimental setup for NRF measurements is ELIADE (ELI-NP Array of DEtectors) array and it consists of an array of eight HPGe detectors of the segmented CLOVER type and four large volume $LaBr_3$ scintillator detectors. Every single crystal of the CLOVER detectors has eight segments resulting from a four-fold longitudinal and one transversal segmentations. The CLOVER detectors in ELIADE will be placed on two rings, one around 90°and the other one at 135°, with four detectors on each of the rings. The geometry of the detectors was chosen such to have detectors in the polarization plane of the gamma beam and in the plane perpendicular on the polarization plane. Such a geometry will maximize the measurable asymmetry due to the anisotropy induced by the interplay between gamma beam linear polarization and excited states parities and spins and it will allow for an efficient determination of the multi-polarities and types (electric or magnetic) of the detected gamma rays [1].

Parity measurements in NRF experiments require polarization information on one of the γ quanta involved. Either a polarized γ beam must be used in the entrance channel or polarization must be measured in the exit channel. The measurement of the polarization of the scattered photon using Compton polarimeters has been very successfull at energies up to 4 MeV. However, this technique becomes difficult above 4 MeV because analyzing power Σ_{CE} is energy dependent and approches to zero at these energies [2]. The use of polarized photons in the entrance channel and the measurement of the intensity distribution with respect to the polarization plane of the beam is preferable for parity measurements of nuclear dipole excitations above about 4 MeV, the analyzing power of this process is 100% and independent of the scattered γ-ray energy.

The formalism for the description of γ-ray angular distributions and linear polarization is well-known [3, 4]. The polarization P_γ of γ rays depends on the angular distribution $W(\vartheta)$ and it is given for dipole and quadrupole transitions by:

$$W(\vartheta) = 1 + a_2 P_2(cos\vartheta) + a_4 P_4(cos\vartheta) \tag{1}$$

where the coefficients a_2 and a_4 of the Legendre polynomials $P_i(cos\vartheta)$ can be determined experimentally or some simple cases it can be calculated.

The polarization of dipole and quadrupole radiation at an angle of 90°relative to the axis of the incoming beam is given by [2, 3]:

$$P_\gamma(\vartheta = 90^\circ) = \Pi \frac{\frac{3}{2}a_2 + \frac{5}{8}a_4}{1 - \frac{1}{2}a_2 + \frac{3}{8}a_4} \tag{2}$$

where Π is the parity of the transition. P_γ refers to polarization at an angle $\vartheta = 90^\circ$.

Detection of the polarization P_γ based on the number of photons scattered in the horizontal H and vertical scattering planes V. The segmentation of the HPGe detectors can be used to define the Compton scattering plane by choosing appropriate coincidence conditions in the horizontal and vertical scattering planes. The asymmetry $A(E_\gamma)$ is proportional to the degree of polarization P_γ and depends on the photon energy E_γ:

$$A(E_\gamma) = Q(E_\gamma) \mathrm{x} P_\gamma \tag{3}$$

The factor $Q(E_\gamma)$ corresponds to the polarization sensitivity of the Compton polarimeter. The sign of $A(E_\gamma)$ directly gives the sign of the degree of polarization and hence determines the parity of the γ-transition of interest. The knowledge of the polarization sensitivity is necessary for a reliable interpretation of the measured asymmetries.

III. EXPERIMENTAL DETAILS

We are planning to seperate the experimental plan into two block, one block will be detector efficiency calibration measurement and the other block will be polarization sensitivity measurements of the detectors. We propose the use of the 3 MV tandem accelerator at the IFIN-HH laboratory to generate protons in the range of 0.4 - 2.6 MeV for (p,γ) and (p,$\alpha\gamma$) reactions.

In the first block, we wil try to obtain the detector response over the full energy range. Absolute efficiency is typically assessed by making well controlled measurements of standard γ-ray calibration sources. In this way the efficiency can be measured up to 2-4 MeV. To extend the energy range, IAEA [5] proposes a series of nuclear reactions mainly based on (n,γ) and (p,γ) reactions. We are interested in (p,γ) reactions to extend the efficiency calibration of the detectors up to 14 MeV. An additional reaction [6] was added in order to extend the efficiency calibration up to 18 MeV. In some cases similar energy gamma rays are produced to confirm the previous measurements. The proposed reactions are shown in Table I. The high energy γ-rays obtained in the proposed reactions will increase the probability of a single photon to interact with multiple crystals. The events gathered in this experiment will be used to set-up, test and optimize the add-back algorithm. In order to obtain the reactions presented in Table I, multiple targets are needed, the proposed targets are made from stable isotopes (^{11}B,^{14}N,^{23}Na,^{27}Al, ^{7}Li). Relatively thick targets will be used (up to 50 μg/cm^2).

In the second block, we will measure polarization sensitivity of the detectors using ^{19}F(p,$\alpha\gamma$)^{16}O[7] reaction for high energy γ rays as explained in the introduction part. The ^{19}F(p,$\alpha\gamma$)^{16}O reaction is chosen to produce high energy γ rays, relatively high cross section and existing several measured angular distribution of the γ rays. Required projectile beam energies and yield estimates are presented in Table I. The thickness of 60 μm CaF_2 target can be easily manufactured by evaporating on to tantalum.

TABLE I: Nuclear reactions for efficiency and polarization measurements, energies E_γ, proton energies E_p, relative intensities I_γ of the γ-rays emitted by product nucleus, required targets, yields, and run block information.

Reaction	E_p(keV)	E_γ1(keV)	E_γ2(keV)	I_γ	Target and its thickness(μm/cm^2)	Yield (cnt/p)	Run block
^{11}B(p,γ)^{12}C	675	12140	4439.03	1.000(<1%)	B_2O_3(50)	20×10^{-11}	Efficiency
	1388	12790	4439.03	1.000(<1%)		8.1×10^{-11}	
	2626	13920	4439.03	1.000(<1%)		5.42×10^{-9}	
^{14}N(p,γ)^{15}O	1058	5239.9	3042.8	1.028(12)	TaN (50)	5.5×10^{-10}	Efficiency
^{23}Na(p,γ)^{24}Mg	1318	11588	1368.633	0.960(2)	Na_2WO_4 (50)	1.92×10^{-10}	Efficiency
	1417	8925.55	2754.028	0.9850(11)		1.6×10^{-10}	
^{27}Al(p,γ)^{28}Si	767	7706	2838.67	0.981(2)	Al (50)	1.2832×10^{-10}	Efficiency
	992	10762.9	1778.96	0.806(10)		1.16×10^{-9}	
	1317	6580	4500	1.017(6)		1.6×10^{-10}	
^{7}Li(p,γ)^{8}Be	441	17255			$LiBO_2$ (50)	1.273×10^{-8}	Efficiency
^{19}F(p,$\alpha\gamma$)^{16}O	1347	6917	7117	1.168(15)	CaF_2 (60)	2.5×10^{-12}	Polarization
	1693	6917	7117	1.177(7)		5.2×10^{-12}	

ELI-NP will provide the entire digital data acquisition chain and detectors. We will use two segmented clover HPGe-detectors of the ELIADE array and one 150% relative efficiency HPGe detector to detect the emitted γ-rays. The proposed arrangement is to placed two ELIADE detectors to 90° and 150% relative efficiency HPGe detector will be placed at an angle of 55^o with respect to the beam direction in order to minimize the influence of the gamma-ray angular distribution on the measured yield. In order to mount our detectors to the specisific angles, an angular distribution table needs to be provided from IFIN-HH. The distance between the detectors and the target will be optimized in order to cover as much solid angle as possible within the acceptable rates for the acquisition system.

The data will be acquired using the new digital-electronic data-acquisition system of ELIADE. The system will be composed of nine CAEN V1725 digitizer boards, using VME communication interface. The digitizers will be controlled using MIDAS acquisition software.

The two-line method will be used to obtain the absolute efficiency for all reactions but for the ^{7}Li(p,γ)^{8}Be for which there are no γ-rays in cascade. This method is used because the emission probability ratio between two gamma-rays in cascade is known with better accuracy compared with a single emission. The two line method can be used in decays where high energy and low energy gamma transitions are present. Since the efficiency for the low energy photon can be obtained from standard calibration sources, the determination for the high energy gamma-ray is straightforward. The absolute efficiency for all the low energy photons can be obtained using ^{56}Co, ^{152}Eu, ^{88}Y and ^{60}Co calibration sources. The efficiency for the ^{7}Li(p,γ)^{8}Be reaction will be calculated based on total collected charge and the cross-section for the 441 keV resonance.

TABLE II: Beam parameters for the 3 MV tandem accelerator

Energy (keV)	Current (nA)
300	100
500	500
1000	1000
1500 $\rightarrow$ 5500	1000 $\rightarrow$ 1500

The beam time needed for the reactions was estimated based on total reaction yields [8][9][10][12][13] for the proposed reactions. The supposed beam parameters are presented in table II. An approximative value for the detector absolute efficiency was obtained by simulation for the 150% relative efficiency germanium detector, with values between 0.025 and 0.05%. We estimate that the needed beam time to obtain good statistical uncertainty for the relevant peaks is about 9 days.

IV. SUMMARY

In summary, we request 9 days of beamtime for the 3 MV tandem accelerator, in order to carry out (p,γ), and (p,$\alpha\gamma$) reactions. The reactions will be used to evaluate the absolute efficiency and to test the polarization sensitivity of our under-development detection system. We will use two of the eight new highly-segmented clover HPGe detectors that will made up the detector-array ELIADE and one 150% relative efficiency HPGe detector. This experiment will allow to test many of the features of the new detection system such as to optimize the add-back algorithm for the segmented clover detector, polarization sensitivity etc.

References

[1] C.A. Ur *et.al*, Romanian Reports in Physics, Vol. 68, Supplement, P. S483S538, (2016).
[2] B. Schlitt *et.al*, Nucl. Instr. and Meth. A 337, 416 (1994).
[3] P. Taras, Can. J. Phys. 49, 328 (1970).
[4] L.W. Fagg, S.S. Hanna, Rev. Mod. Phys. 31, 711 (1959).
[5] IAEA. Update of x-ray and gamma ray decay data standards for detector calibration and other applications, (2007).
[6] M. Ciemala *et.al*, Nucl. Instr. and Meth. in Phys. Res. A, 608:7679, (2009).
[7] R. Hellborg, L. Ask, Phys. Scr. 6, 47 (1972).
[8] Z.E. Switkowski, R. OBrien, A.K. Smith, and D.G. Sargood, Aust. J. Phys. 28(2):141154, (1975).
[9] T. Huus and R.B. Day, Phys. Rev. 91(3):599605, (1953).
[10] C. Chronidou *et.al*, Eur. Phys. J. A, 6:303308, (1999).
[11] S. Harisspulos *et.al*, Eur. Phys. J. A, 9:479489, (2000).
[12] W.A. Fowler and C.C. Lauristen, Phys. Rev 76:314, (1949).
[13] D.B. Duncan and J.E. Perry, Phys. Rev 82 (6):809, (1951).