STUDY ON NRF-CT IMAGING BY LASER COMPTON BACKSCATTERING GAMMA-RAYS IN UVSOR *

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Abstract

Study on nuclear resonance fluorescence (NRF) based - computer tomography (CT) imaging by using laser Compton scattering (LCS) gamma-ray beam has been carried out at a new LCS beamline at UVSOR-III. This LCS beamline can generate 5.4-MeV energy gamma-rays with a flux of 1×10^7 photons/s. We have measured the 5292-keV NRF gamma-rays from a lead target to take a NRF-CT image by using the NRF absorption method. A sample target consists of aluminium, stainless steel, and lead rods with a diameter of 8 mm with a 5 × 5 array. The sample was irradiated by an LCS gamma-ray beam. Although the resolution was very poor in this preliminary experiment, ^{208}Pb distribution was successfully reconstructed by taking a normalization of the NRF absorption by the atomic transmittance.

INTRODUCTION

Monochromatic gamma-ray beam in a few MeV energy region is suitable for non-destructive inspection of high density and massive objects because of its high penetrability. A specific nuclide can only be excited by the process of Nuclear Resonance Fluorescence (NRF). An atomic nucleus can be excited by the absorption of an incident photon with an energy as same as the excitation energy of a certain level and subsequently the excited level decays out through the emission of a gamma-ray [1]. The non-destructive inspection of SNMs hidden in container cargos using NRF has been proposed by Bertozzi [2]. The NRF has been proposed to be used the non-destructive evaluation of ^{239}Pu inside of spent nuclear fuel rods for the management of radioactive wastes, nuclear material accounting, and nuclear material safeguards [3]. The imaging of the density and nuclide-distributions inside of objects gives an important information for the assay of nuclear materials and nuclear safeguards.

A demonstration of a 2D NRF imaging by using a quasi-monochromatic gamma-ray beam in a few MeV energy region generated by Laser Compton Backscattering (LCS) has been performed [4] and proposed to develop an NRF-CT image in the ELI-NP [5] where an ultra-high intensity LCS beam can be available in near future [6]. To demonstrate an NRF-CT imaging by using LCS gamma-ray beams and to finalize the measurement system, we have started experimental studies at a new LCS beamline at UVSOR-III where we can use 5.4-MeV gamma-ray with a flux of 1×10^7 photons/s [7].

In this paper, we describe an experimental set up and a preliminary result of the NRF-CT image of lead rods (^{208}Pb) surrounded by aluminium rods and stainless steel rods taken at UVSOR-III. In general, there are two methods to measure NRF signals; one is a direct NRF measurement from samples and the other is an absorption method which measures NRF from a witness target after passing through samples [8]. Since the CT reconstruction uses absorption information, the latter method could be straight forward method. However, incident gamma-ray beams are absorbed, in general, by sample materials, the absorption of NRF signals have to be calculated by take into account the atomic absorption of samples. In this study we also applied the correction to the obtained NRF-CT image.

NRF-CT MEASUREMTN IN UVSOR-III

LCS Beamline in UVSOR-III

Regarding to NRF experiments, an LCS gamma-ray beam is an ideal gamma-ray source, because we can use energy tunable and quasi-mono chromatic gamma-rays which suppress a number of off-resonant energy gamma-rays that make a huge background. Therefore, we have started to construct the LCS beamline at BL-1U at UVSOR-III where we can use electron beams of the maximum energy of 750 MeV and constant current of 300 mA

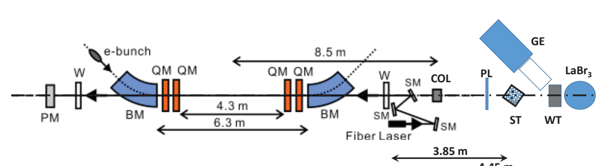

Figure 1: Schematic layout of LCS beamline in UVSOR-III. QM: Quadrupole Magnet in the Storage Ring, BM: Bending Magnet in the Storage Ring, W: Quartz Window, SM: Silver Mirror, PM: Laser Power Meter, COL: Collimator, PL: Plastic Scintillator, ST: Sample Target, WT: Witness Target, GE: Ge detector.

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by the top-up mode [9]. During this study, the storage ring was operated as the user mode, fixed energy of 750 MeV. UVSOR-III has four 4-m long straight sections and four 1.5-m short straight sections. One of the long straight sections was used for construction of the LCS gamma-ray beamline (BL-1U). To generate LCS gamma-rays, a fiber laser of 1.94-μm wavelength was used for generation of 5.4-MeV gamma-rays to excite an NRF level at 5292 keV in ^{208}Pb who has 1^- multipolarity. The laser was operated in CW mode with the maximum output power of about 5 W. The polarization axis of the laser was aligned to the vertical so as to detect the 1^- state of ^{208}Pb by using a germanium (Ge) detector set at the horizontal scattering plane. According to the energy and flux measurements of LCS gamma-rays, the maximum energy is 5.40 MeV and flux is around 1×10^7 photons/s without collimation. The schematic drawing of the LCS beamline and electron-laser collision is shown in figure 1.

A lead collimator of 5-mm diameter was placed 1.1-m downstream from the vacuum window. A sample target consists of lead, aluminium, and stainless steel rods of 8-mm diameter and 15-cm long placed 5 × 5 array in 1 cm separation. Figure 2 shows the 5 × 5 array target and the number in the left figure indicates LCS gamma-ray beam scanning paths. The sample target was placed on the X (horizontal axis), Y (vertical axis) moving stage and θ (rotation) stage.

NRF-CT Measurement

The flux of the LCS gamma-ray beam has been monitored by a 5-mm thickness plastic scintillator. The average count rate of the plastic scintillator was about 5×10^5 cps. A $LaBr_3$(Ce) scintillation detector of 3.5" × 4" was placed behind the sample target and the witness target made from lead of size of 5 cm × 10 cm and 1-cm thickness. The $LaBr_3$(Ce) detector measured the transmission gamma-ray. A 120% Ge detector was employed to measure the scattering photons from the witness target. These 3 detector signals were connected to a DSP (APU8008, Techno-AP) and a standard MCA (MCA8000D, Amptek). Figure 3 (Upper) shows a typical spectrum taken by Ge detector and Fig. 3 (Lower) is an expansion of the region of interest.

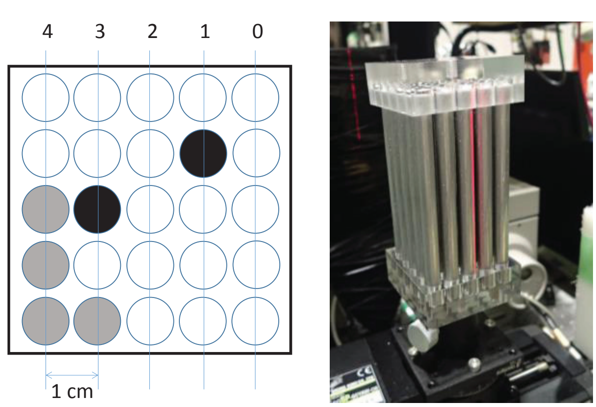

Figure 2 Left: Top-view of the 5 × 5 array sample. Black circles are natural lead rods, Grey circles are stainless steel rods, and white circles are aluminium rods. Right: Photo of the sample with moving and rotating stages.

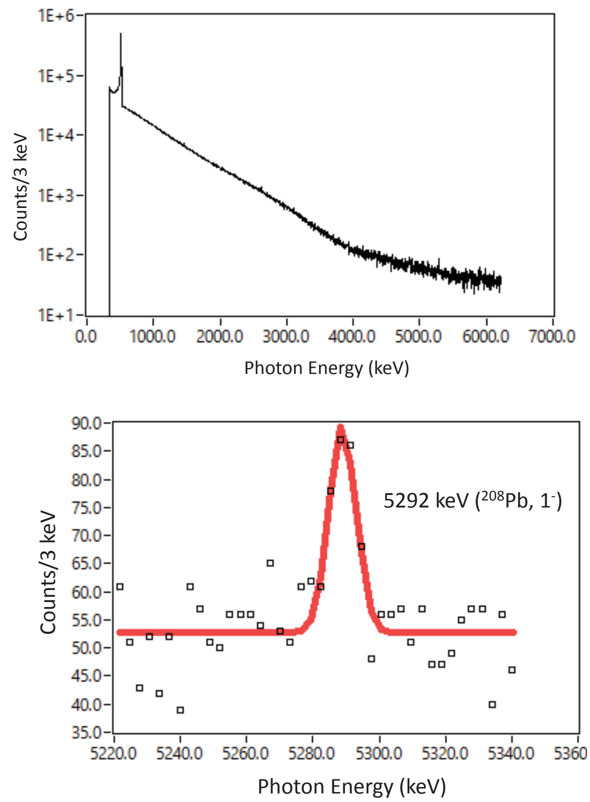

Figure 3 Upper: Typical spectrum from the witness target measured by Ge. Lower: Expanded spectrum of ROI around 5292 keV with a Gaussian peak fitting result. The peak width of about 4 keV was obtained.

In this experiment only X axis scan of 1 cm step from 0 to 4 and θ in 36 degree step from 0 to 144 degree have been measured. The data was accumulated until the peak area of 5292 keV level came up to around 100 counts and typical data acquisition time was from 1 hour to 2 hours per one projection. The total 25 projection, 5 X-axis scanning, and 5 θ-axis data, were taken during 3-day machine time in UVSOR-III.

NRF-CT IMAGE

In this study the image reconstruction was obtained by using the Algebraic Reconstruction Techniques (ART) from 25 projection images, 5 X-axis scanning from 0 to 4 cm in 1 cm interval and 5 θ-axis from 0 to 144 degree in 36 degree interval. The ART reconstruction program was developed with LabView and was confirmed with a model calculation.

The reconstructed images are shown in figure 4. In the figures, the large attenuation part is expressed by red colour. Figure 4 (a) shows a density distribution obtained by the gamma-ray transmission measured by the

$LaBr_3$(Ce) detector, a standard CT image of the density distribution. Due to rough scan in X-axis and θ-axis, the reconstructed image is poor. However, one clear absorption from lead rod is recognized. Figure 4 (b) shows the ^{208}Pb distribution image reconstructed by the transmission factors of 5292-keV NRF peaks that means all absorption factors are involved. It is noted that the reconstructed image is similar to the standard CT image of the density distribution, Fig.4 (a). This is obvious that the atomic absorption from sample materials are larger than NRF

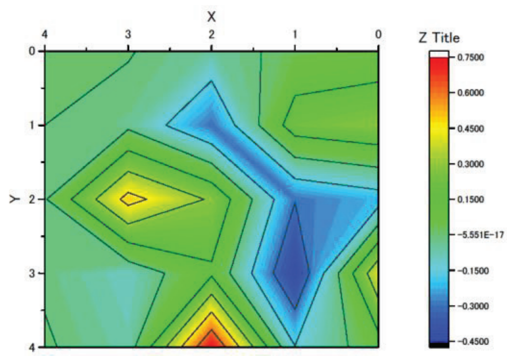

Figure 4 (a): Atomic absorption image measured by the $LaBr_3$(Ce) detector

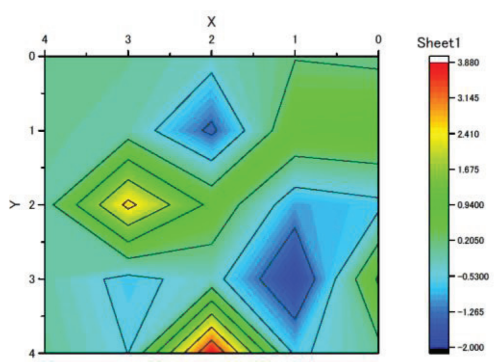

Figure 4 (b): ^{208}Pb distribution image reconstructed by the transmission of 5292-keV NRF peaks including atomic absorption.

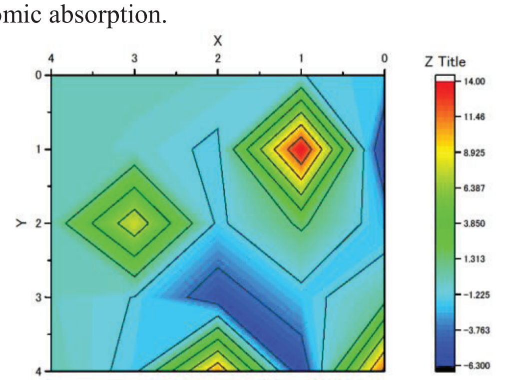

Figure 4 (c): ^{208}Pb distribution image reconstructed by the transmission of 5292-keV NRF peaks.

absorption in our measurement window. In order to deduce the NRF absorption factor, we proposed a simple correction method by using the total transmission of the measured sample [10]. Since the attenuation coefficient has small dependencies on energy and the material in this energy region, the coefficient and density along the beam axis can be described by average value $(\mu/\rho)_{ave}$ and ρ_{ave}. Thus, a transmission factor of NRF gamma-ray is written by an equation of

$$\varepsilon_{NRF} = \exp[-((\mu/\rho)_{ave}\cdot\rho_{ave}+\sigma_{NRF}\cdot\rho_{NRF}\cdot N_A/M_{NRF})L] \quad (1),$$

where L is the distance from source to the sample target, M_{NRF} is the atomic mass of the nuclide to measure, N_A is the Avogadro number, and σ_{NRF} is the cross-section of the NRF state. Since the off-resonance gamma-ray, σ_{NRF} is zero. Therefore transmission factor of the off-resonant energy is

$$\varepsilon_{OFF} = \exp(-(\mu/\rho)_{ave}\cdot\rho_{ave}\cdot L) \quad (2).$$

From eq. (1) and eq. (2), it is obvious that the ratio, $\varepsilon_{NRF}/\varepsilon_{OFF}$, depends only on the factor ρ_{NRF} which is the deduced NRF absorption of the measured sample. Figure 4 (c) shows the deduced NRF absorption (ratio of $\varepsilon_{NRF}/\varepsilon_{OFF}$) normalized by the transmittance measured by the $LaBr_3$(Ce) detector in this experiment. Consequently, we can clearly obtain the image of the ^{208}Pb rods.

CONCLUSION

A preliminary experiment of the NRF-CT imaging by using LCS gamma-ray beam has been carried out at a newly developed LCS beamline, BL-1U, at UVSOR-III. The LCS beamline generates 5.4 MeV LCS gamma-rays with a flux of 1×10^7 photons/s without a collimation. The LCS gamma-ray beam irradiated a natural lead and we obtained a 5292-keV NRF peak in this beamline. By using NRF absorption method a NRF-CT image has been taken for a sample target consists of aluminium, stainless steel, and lead rods of 8 mm in diameter which form a 5 × 5 rod array. X-axis of 1-cm interval and θ-axis of 36 degree interval have been scanned. The NRF signals from the witness target (natural lead) were measured by a Ge detector. At the same time, transmission gamma-rays have been measured by a $LaBr_3$(Ce) detector which gives a density distribution of the sample target. The CT reconstructions were performed to obtain ^{208}Pb distribution by taking a normalization of the NRF absorption by the atomic transmittance measured by the $LaBr_3$(Ce) detector. Consequently, ^{208}Pb distribution image was successfully reconstructed.

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