DESIGN STUDY OF A NUCLEAR MATERIAL DETECTION SYSTEM BASED ON A QUASI MONOCHROMATIC GAMMA RAY GENERATOR AND A NUCLEAR RESONANCE FLUORESCENCE GAMMA RAY DETECTION SYSTEM*

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Abstract

Nuclear Resonance Fluorescence (NRF) measurement is a powerful tool for isotope detection for the homeland security such as a non-destructive material testing for identification of special nuclear materials (SNM) hidden in containers at airports or harbours. In this paper, we will discuss on basic design of a hybrid SNM inspection system using a D-D neutron source, detectors of neutron and gamma ray, a quasi-monochromatic gamma ray generator based on the backward Compton scattering of laser light on high-energy electrons, and an NRF gamma ray detection system using a high-speed scintillation detector.

INTRODUCTION

A non-destructive inspection system for special nuclear materials (SNM) such as ^{235}U and ^{239}Pu is expected to play an important role in a field of nuclear security. Even the several kilograms of SNM may be hidden in gamma-ray/neutron shielded box and across the country's border. Therefore we have been developing a novel inspection system for SNMs [1, 2].

In order to develop an inspection system for shielded SNM with the weights of several kilograms, a neutron source or high-energetic photon source should be used as an incident probe. In corroboration of the SNMs from obstacles in a cargo, isotope identification is crucial.

There are several active non-destructive material testing methods for SNMs using incident neutrons and high energetic photons. A delayed neutron analysis (DNA) is one of the conventional methods for detection of fissile nuclear materials. The DNA method is based on the detection of delayed neutrons emitted after β decay of the precursor atoms generated by fission reactions induced by incident pulsed neutrons. Because, in fission processes, most (~99%) of neutrons are emitted in prompt (prompt neutrons), a combination of a delayed gamma (DG) detection is planned. The time scale of the observation of delayed neutron is seconds to minutes later after the fission. A differential die-away (DDA) technique is also one of the conventional methods. If the fissile material exists, epi-thermal (> 0.4 eV) and fast neutron population decay much slower than without SNMs [3]. A neutron multiplicity analysis (NMA) is based on the counting of prompt neutrons through fission. It is noted that these methods are sensitive to reveal the SNMs but not sensitive to isotope identification.

On the other hand, the use of high energetic photon can be also applied for a non-destructive inspection. An X-Ray fluorescence (XRF) which uses K X-rays, and a nuclear resonant fluorescence (NRF) which uses nuclear resonant levels are available. Although the XRF can be easily realized, it is not applicable for isotope identification, and easily extinguished by thick radiation shield. In the case of NRF, required incident photon energy is several MeV. For example, the resonant level of 1.733 MeV is used for the identification of ^{235}U. Therefore, penetrating power is higher than that of the X-ray used for XRF.

HYBRID SNM INSPECTION SYSTEM

Strategy of the SNM Inspection

As mentioned above, non-destructive inspection methods using pulsed neutrons and gamma ray are attractive. Thus, we have proposed a hybrid SNM inspection system which consists of a fast pre-screening system using a D-D pulsed neutron source and several neutron and gamma ray detectors and a precise identification system using a quasi-monochromatic gamma-ray generator and fast gamma ray detectors [1]. The schematic drawing of the hybrid inspection system is shown in Fig. 1. In this paper, discussions are focused on the gamma ray scanning system which consists of accelerator based gamma ray source and gamma ray detectors.

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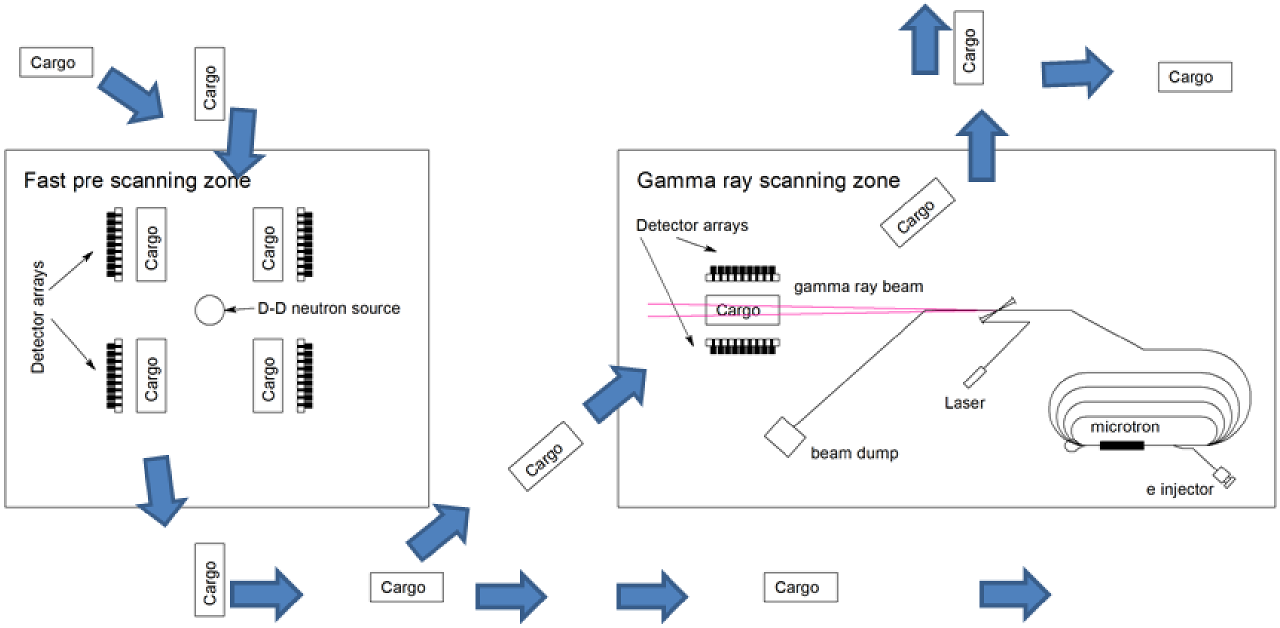

Figure 1: Conceptual drawing of the hybrid SNM inspection system. All of the cargos are quickly pre-scanned at the "fast pre screening zone" then only the suspicious cargos are particularly scanned at the "gamma ray scanning zone".

Gamma Ray Source

In order to make nuclear identification precisely in short period, there are several requirements. First of all, high gamma ray flux is preferable. Secondly, gamma ray energy should be same as the resonant level of the target nucleus. Thirdly, small energy spread of incident gamma rays is desirable.

Although bremsstrahlung is one of the most conventional gamma ray generation mechanisms, in order to generate enough gamma ray photons, unused gamma rays of which the energy is higher than the resonant energy are generated and huge lower energy background gamma rays are generated as shown in Fig. 2(a). On the other hand, laser Compton back scattering process can generated quasi monochromatic gamma rays as shown in Fig. 2(b). Maximum gamma ray intensity is obtained at the resonant energy, and small background gamma rays are generated. Thus we adopted the laser Compton back scattering as the incident gamma ray source. In our proposal, a compact 220 MeV racetrack microtron will be used [4]. Detail of the microtron and expected performance are discussed in these proceedings [2].

Gamma Ray Detectors

Selection of a gamma ray detector is another critical issue for the SNM inspection system. A High Purity-Ge (HP-Ge) detector is usually used to detect a NRF signals, because of its excellent energy resolution. On the other hand, the HP-Ge detector requires a cooling mechanism for operation, thus it is not compatible for construction of large detector array. Moreover, total price of the HP-Ge detector array system is also unacceptable.

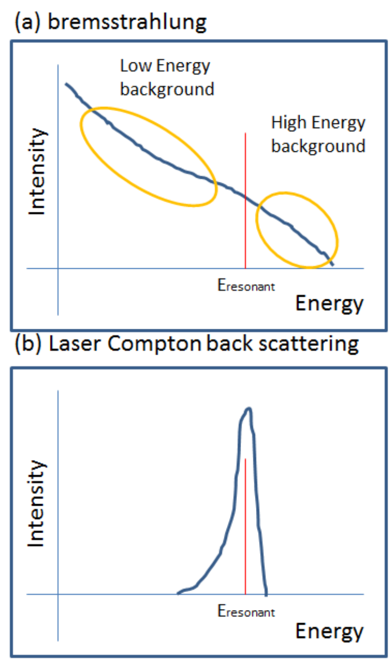

Figure 2: Schematic comparison between gamma ray spectrums generated through (a) bremsstrahlung and (b) laser Compton back scattering.

A new scintillation material, $LaBr_3(Ce)$, has been developed and an excellent energy resolution is reported [5]. We have confirmed the good performance for the laser Compton back scattering gamma rays [6]. We have also surveyed the performance of the $LaBr_3(Ce)$ scintillator through a background measurement around 1.7 MeV. However at the energy region of 1.7 to 3 MeV, there are alpha contaminations (alpha decay particle) as shown in Fig. 3. Existence of these peaks might worsen S/N ratio for 1.733 MeV NRF signals from ^{235}U.

Another new scintillation material, Pr:LuAG (Pr doped $Lu_3Al_5O_{12}$) has been also developed and good performance is reported [7]. The Pr:LuAG is expected for the detector in PET and SPECT from its high energy resolution, non-deliquescence, high time resolution. Background measurement for Pr:LuAG has been also performed as shown in Fig. 3. There are no distinguishable peaks between 1.7 to 3 MeV. The lower energy resolution of these scintillators can be improved by using gamma ray response function obtained by HP-Ge detectors constellated in the scintillator array [8]. An example of gamma detector array is schematically shown in Fig. 4. The combination of the gamma detectors should be carefully determined after further research and developments. Comparison in the three detector, HP-Ge, $LaBr_3$(Ce), Pr:LuAG are listed in table 1.

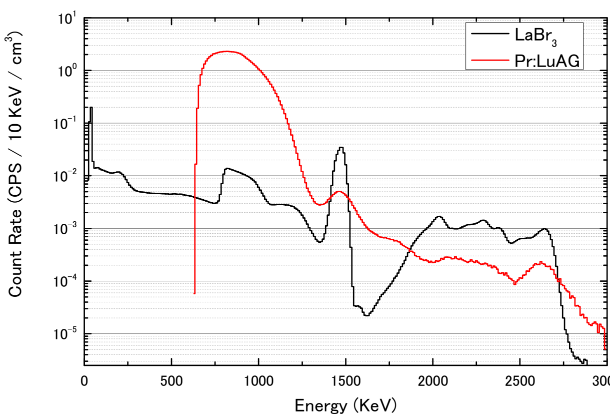

Figure 3: Background spectrums of $LaBr_3$(Ce) detector (ϕ 1.5 inch ×3 inch) and Pr:LuAG detector (1 ×1×1 inch) below 3 MeV. Self-activities of ^{138}La and alpha decay particles are observed for $LaBr_3$(Ce). No significant background are observed for Pr:LuAG.

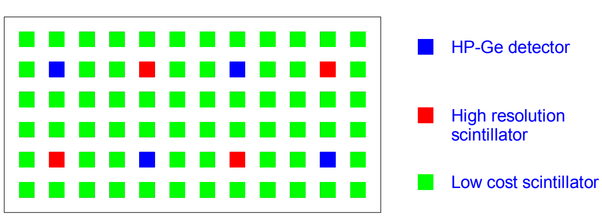

Figure 4: Example of a gamma ray detector array.

Furthermore, a time-of-flight analysis can be possible with pulsed laser Compton scattering gamma ray, because time resolutions of these scintillators are faster than 1 nsec [9] and phase stable region in the S-band racetrack microtron is about 30 psec [4]. In case of the proposed SNM inspection system, scale of the target cargo is several meters, thus the time resolution of a few hundreds of picosecond is acceptable for the position sensing of SNMs in the cargo with a few tens-cm resolution. A 3D image reconstruction is expected to improve the performance of SNM inspection considerably.

Table 1: Comparison in Gamma Ray Detectors

Detector	Energy resolution	Time resolution	Compatibility for Array
HP-Ge	2 keV at 5MeV (FWHM)	~ 10 nsec Constant Fraction Discrimination ~ 4 nsec Pulse Shape Anaysys	× Cooling system is required Very high cost
$LaBr_3$(Ce)	2.7 % at 662 keV (FWHM)	~ 150 psec [9]	△ High cost Deliquescence
Pr:LuAG	5.2 % at 662 keV (FWHM)	~ 300 psec [9]	◎ Non-deliquescence, Lower cost

SUMMARY

We have been developing a hybrid SNM inspection system using neutron based fast pre-screening system and gamma ray based precise scanning system. Laser Compton back scattering is most feasible process for generation of high flux, quasi monochromatic, and energy tunable gamma ray. Selection of gamma ray detectors is slightly complicated due to inexistence of a high-speed and high-resolution gamma ray detector. In this study, detector arrays of fast scintillation detectors and several number of HP-Ge detectors are proposed. The lower resolution of the scintillation detectors will be mitigated by the HP-Ge, and moreover, by incorporating a time-of-flight analysis, the fast scintillation arrays will be used to reconstruct 3D image of SNM. For the further development of the inspection system, an experimental evaluation for each detector at 1.7 MeV region is required.

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