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Proposal of a Non-Destructive Detection System for Hidden Nuclear Materials Based on a Neutron/Gamma-ray Hybrid System

H. Ohgaki,* T. Kii, K. Masuda and M. Omer
Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

T. Misawa and C. H. Pyeon
Research Reactor Institute, Kyoto University, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan

R. Hajima and T. Hayakawa
Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

T. Shizuma, M. Kando and I. Daito
Japan Atomic Energy Agency, Umemidai, Kizugawa-shi, Kyoto 619-0215, Japan

H. Toyokawa
National Institute of Advanced Industrial Science and Technology, Umezono, Tsukuba, Ibaraki 305-8568, Japan

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A nuclear material detection system based on a neutron / gamma-ray hybrid system has been proposed for container inspection at seaports. Neutrons from the inertial electrostatic confinement fusion source will be used for a fast pre-screening process with both neutrons and gamma-rays. The nuclear resonance fluorescence gamma-ray induced by a quasi-monochromatic gamma-ray beam from the laser Compton backscattering will be used in isotope identification for a precise post-screening process. A combination of two different probes, neutrons and gamma-rays, can detect nuclear materials hidden by any kind of shielding.

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I. INTRODUCTION

A new nondestructive inspection system for screening special nuclear materials (SNMs) at ports of entry is required to counter terrorist threats. The present nondestructive inspection system using X-rays cannot distinguish isotopes. Neutrons and high-energy X-rays, which we call as gamma-ray, are promising probes for an active inspection system because of their high selectivity and high penetration.

Active interrogation of a SNM using neutrons makes use of fission event inducement, which yields a signature discernable through an understanding of fissile materials and neutron transport in various media. This can be accomplished by the use of a D-T neutron source to generate microsecond-wide pulses of interrogating neutrons. These neutrons are thermalized upon moderation by the media present between the source and the SNM. The thermalized neutrons serve to initiate fission events in the SNM, and the presence of SNM can be made known using neutron and/or gamma analysis methodologies. One of the conventional neutron-in neutron-out detection techniques is called delayed neutron analysis (DNA) [1] and is based on the detection of delayed neutrons from β decay of precursor nuclide released by induced fission reactions. Another conventional neutron-based technique called differential die-away analysis (DDA) [2,3] makes use of the premise that, when a fissile material is present, the fast (prompt) neutron population outside the cargo decays with the decay time of the surrounding media, *i.e.*, the thermal die-away time in the cargo. This die-away time can range from hundreds of microseconds to units of milliseconds and is much slower than the intrinsic time response of the fast neutron counting outside the cargo without fissile material. The DNA is an easier

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*E-mail: ohgaki@iae.kyoto-u.ac.jp; Fax: +81-774-38-3426 approach to implement because of fewer background neutrons while the DDA allows for better counting statistics because prompt neutrons are much more plentiful in fission reactions than delayed neutrons. Both techniques, however, fail to make use of the major part of prompt neutrons emitted during the incident neutron pulses and require highly intense pulses of interrogating neutrons. A D-T neutron generator would be mandatory for cargo screening through those techniques, though the use of tritium is not favorable in the viewpoint of safety and easy operation and maintenance of the inspection system. In this context, we propose a radiation detection scheme based on detection of both gamma-rays and neutrons based on a noise analysis method [4], in conjunction with the use of a D-D neutron source based on inertial electrostatic confinement (IEC) [5,6] of fusion plasmas. A prompt gamma analysis is also to be used in order to maximize the sensitivity of the inspection system. This inspection scheme will be suitable for fast screening of SNMs. However, the spatial resolution of the system is not high enough, around several tens cm. Moreover, neutrons can be scattered by light mass obstacles that may work as effective shields of SNMs.

Several inspection methods using gamma-rays, which can penetrate a thick shielding have been proposed and examined. Bertozzi and Ledoux have proposed an application of nuclear resonance fluorescence (NRF) by using bremsstrahlung radiations [7]. An atomic nucleus is excited by absorption of incident photons with an energy the same as the excitation energy of the level, and subsequently a gamma-ray is emitted as it de-excites. By measuring the NRF gamma-rays, we can identify nuclear species in any materials because the energies of the NRF gamma-rays uniquely depend on the nuclear species. The signal-to-noise (SN) ratio of the NRF measurement with the bremsstrahlung radiation is, in general, low. Only a part of the incident photons makes NRF with a narrow resonant band (meV-eV) whereas most of incident radiation is scattered by atomic processes in which the reaction rate is higher than that of NRF by several orders of magnitudes and causes a background. Thus, the NRF with a gamma-ray quasi-monochromatic radiation beam is proposed [8]; the monochromatic gamma-rays are generated by using laser Compton scattering (LCS) of electrons and intense laser photons. The other inspection method based on NRF gamma-ray spectrometry with an energy recovery linac (ERL) to generate an intense monochromatic photon beam via Ref. 9 is also proposed. We should note that the LCS-based NRF inspection method has a good resolution of mm [10] because the LCS gamma-ray beam has a small beam profile of a few mm. Because the cross sections of NRF and the inverse Compton process are low, a long inspection time is required for this method.

Here, we propose an inspection system for SNMs employing both neutrons and gamma-rays, a hybrid system. The system consists of a fast pre-screening system using D-D IEC neutron source and precise isotope identification using NRF induced by quasi-monochromatic gamma-rays generated by LCS (Fig. 1). In the present paper, we introduce the conceptual design of the proposed hybrid inspection system.

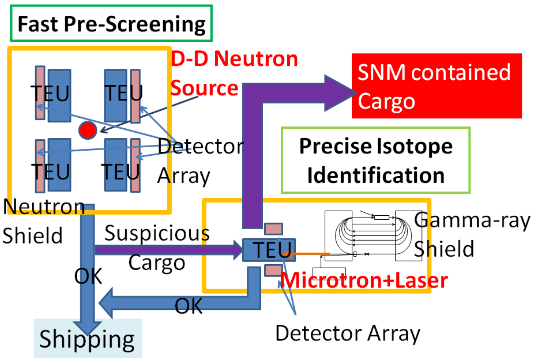

Fig. 1. (Color online) Conceptual layout of the proposed SNM inspection system.

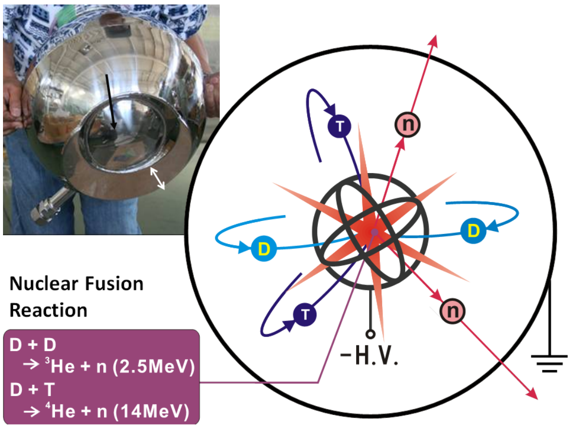

Fig. 2. (Color online) Photo and schematic cross-section of an IEC fusion neutron source developed for a landmine detection system.

II. DETECTION SYSTEM

1. Fast Pre-screening System

An IEC neutron source is a compact and simple fusion device, as shown in Fig. 2, running by electrical discharge in either D-D or D-T fuel gases. It basically consists of a transparent spherical cathode at the center of a spherical vacuum chamber serving as the anode and filled with a fuel gas. A glow discharge takes place between the electrodes, as is seen in the photo in Fig. 2, producing ions that are accelerated toward the cathode, and many of them penetrating the transparent gridded cathode undergo fusion reactions through beam-background gas collisions and/or beam-beam collisions. Actually, for the extremely compact device (25 cm in diameter) shown in

Fig 2 developed for a landmine detection system [11,12], D-D neutrons in excess of 10^7 n/sec in a steady-state operation of 80 kV and 80 mA were achieved. A higher cathode voltage of ∼200 kV is expected to result in a pulsed D-D neutron yield in excess of 10^{11} n/sec in the present pre-screening system, for tens of microseconds and up to 50 Hz.

The neutron-based system can hardly provide spatially resolved detection of SNMs because the neutron emission from the source is isotropic. Meanwhile, it is rather suited for fast pre-screening in the layout shown in Fig. 1, for example, it is capable of simultaneous inspection of multiple cargo containers with a single intense neutron source and neutron and gamma detectors placed close to the containers. With an intense D-D IEC neutron source which is being developed for the present system, the interrogating pulsed neutron flux density at the center of 20-ft shipping containers (TEU) would be $\sim 7 \times 10^4$ n/cm^2/sec.

The present neutron detection system is to detect both prompt and delayed neutrons originating from fission reactions induced in nuclear materials. The time-dependent signal originating from prompt and delayed neutrons, which is called neutron noise, contains the characteristics of fission chain reactions, and this method is newly developed for the present detection system. On the other hand, both DNA and DDA utilize a delay factor to identify if a SNM is present or not. Therefore, a combination of the two conventional neutron detection methodologies, namely DNA and DDA, and the neutron noise analysis method is effective in further reducing of the detection time. At the same time, detection of neutron-induced prompt gamma-rays from a SNM is used in the present neutron-based pre-screening system.

2. Isotope Identification Using Gamma-ray

We have proposed a combination of laser Compton scattered (LCS) gamma-rays [13] and nuclear resonance fluorescence (NRF) for a nondestructive isotope identification in a hybrid inspection system. Each nuclide has its own discrete excitation levels, which are determined by the number of protons and neutrons in the nuclei. For example, ^{235}U has an excitation level at 1733 keV. If we irradiate a material including ^{235}U with a gamma-ray tuned at this excitation level, the material absorbs the gamma-ray and re-emits another gamma-ray immediately to move back towards the ground state. Therefore, we can detect the ^{235}U by measuring the re-emitted (NRF) gamma-rays.

The LCS gamma-ray is generated by collisions of laser photons with relativistic electrons. The energy of the scattered gamma-ray photon is a function of the laser photon energy, the electron energy, and the scattering geometry. Monochromatic gamma-rays can be obtained by putting a collimator to restrict the gamma-ray divergence downstream. The LCS gamma-ray, which is energy-tunable and monochromatic, is an optimum apparatus for NRF measurements [14]. Such nondestructive detection of specific nuclides has been demonstrated in experiments. One-dimensional imaging of a block of lead (20 mm) hidden in an iron box of 15-mm thickness [10] and detection of explosives have been carried out at LCS gamma-ray facility in National Institute of Advanced Industrial Science and Technology, AIST-TERAS [15].

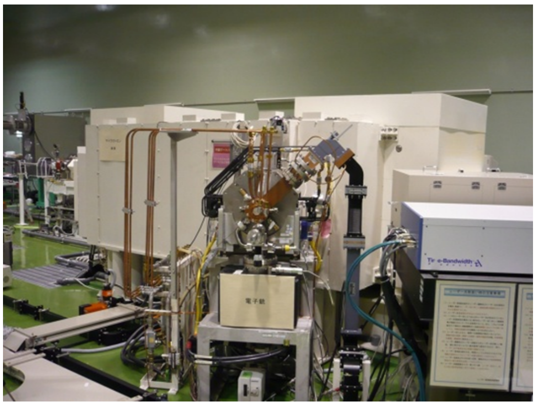

Fig. 3. (Color online) Photograph of the 150-MeV microtron installed at JAEA-Kansai.

Gamma-ray beams with energies of 1733 – 2143 keV for the detection of ^{235}U and ^{239}Pu can be obtained from laser Compton scattering of a Nd:YAG laser (1064 nm) and an electron beam of 316 – 352 MeV. The electron energy can be reduced to 223 – 249 MeV by using the second harmonic of the Nd:YAG laser. In our proposal, a microtron accelerator will be employed for the electron source. The microtron has an advantage of small footprint, which is important for real applications. We have already conducted an experiment of LCS gamma-ray generation from the 150-MeV microtron installed at JAEA-Kansai (Fig. 3). The size of the main part of this microtoron is 2 m × 4 m. In the experiment, gamma-rays of 400 keV were generated and applied to imaging an object made of lead .

In the proposed system, an electron beam from a 250-MeV microtron optimized for the hybrid inspection system will be designed in combination with the second harmonic of the Nd:YAG laser. Figure 4 shows calculated energy spectra of the incident LCS gamma-ray beam with the proposed system. We can obtain gamma-rays with abh total flux of 3.3×10^5 ph/sec. The detailed parameters of the system are summarized in Table 1.

III. DISCUSSION

The required quantity for nuclear explosive devices depends on its mechanism. For example, one of early generations of nuclear explosive devices uses a Gun-barrel-

Table 1. Paramerters of the LCS gamma-ray source.

Electron beam	
Energy	250 MeV
Bunch charge	60 pC
Bunch length	3 ps (rms)
Bunch repetition rate	10 Hz
Normalized emittance	35 mm-mrad (in x/y)
Energy spread	0.1% (rms)
Laser beam	
Wavelength	530 nm
Pulse energy	0.3 J
Pulse length	1 ns (rms)
Pulse repetition rate	10 Hz
Collision angle	180 deg. (head-on)
Collision spot	214 um (rms in x/y)
Total photon flux	3.3×10^5 ph/sec

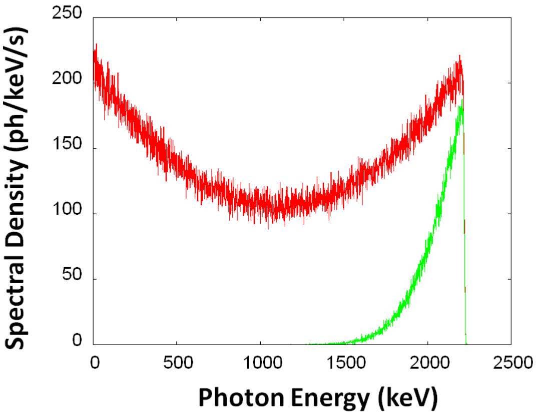

Fig. 4. (Color online) Calculated energy spectra of the incident LCS gamma-ray beam: total photons (red line) and photons collimated by an aperture of 1.4 mrad in diameter (green line).

type device, in which ^{235}U of about 60 kg was used. The quantity of SNM decreases with decreasing size of nuclear explosive device. The International Atomic Energy Agency (IAEA) defined the so-called "significant quantity" (SQ) for nuclear material control. The SQs are 25 kg and 8 kg for ^{235}U (>20% enriched) and ^{239}Pu, respectively [17]. Thus, we here consider the detection of SNM with a mass of several kg.

As for a pre-screening system by using neutron source, an earlier study [18] presented experimental and numerical results that could give a rough estimate of the measurement time for DDA of ∼4 min in the present system while for DNA, the neutron noise and prompt gamma analyses in combination with DDA are expected to reduce the time to some extent. The numerical results [18] show that 600 pulses of interrogating neutrons are required to identify 25 kg of ^{235}U by means of DDA solely for a neutron flux density of $\sim 5 \times 10^4$ n/cm/sec at the position of the SNM for a 4-ft distance between the detector array and ^{235}U. If we assume the presence of 1 kg ^{235}U at the center of a 20-ft-long, 8-ft-wide shipping container, the required measurement time will then be calculated to be as short as ∼4 min, with an interrogating pulsed neutron flux density of $\sim 7 \times 10^4$ n/cm^2/sec and 50 Hz in the present system. The experimental results for DNA [18] likewise give an estimated measurement time for the present system of ∼15 min DNA only.

With the present proposed NRF system, a block of ^{235}U with a mass of about 1.2 kg can be detected with a measurement time of 600 s. We assume that the block with a size of 4 cm × 4 cm × 4 cm is located on the axis of the incident LCS gamma-ray beam. With the NRF gamma-ray detection system with a detection efficiency of 5% and the 3×10^5 ph/s LCS gamma-rays, we can obtain a peak count of about 40 for the 1733-keV gamma-ray of ^{235}U. With the use of a laser with a power higher than the present expected value and a higher electron energy accelerator, we can obtain LCS gamma-rays larger then 3×10^5 ph/s and detect SNMs with heavy shields.

IV. CONCLUSION

We have proposed an inspection system to detect SNMs hidden in cargo. This system consists of a fast prescreening system using D-D neutrons generated by an IEC device and of a post-screening system using quasimonochromatic gamma-rays generated by laser Compton scattering (LCS). A compact microtron generates LCS gamma-rays with nuclear resonance fluorescence. These two detection methods have already been tested separately in landmine detection or in demonstration experiments. In this paper, a conceptual design and expected inspection time have been introduced. Detail design work will be continued parallel to technical improvements, such as enhancement of the neutron and gammaray fluxes and development of the detector systems.

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