APPLICATIONS OF HIGH-BRIGHTNESS GAMMA-RAYS FROM ERLS

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Abstract

Progress in accelerator physics and laser physics has enabled us to generate a new generation of laser Compton scattering (LCS) γ-ray beam. The LCS γ-ray beam has been used for the study of fundamental science and industrial applications. We present examples of some applications using the LCS γ-ray beam and possibility using the next generation of high-intense LCS γ-ray beam provided from the ERLs.

INTRODUCTION

The progress of the relativistic engineering (for example see Ref. [1]) provides a new γ-ray source with a MeV energy range. These γ-rays are generated by Compton scattering of relativistic electrons by laser photons (see Fig. 1) [2]. The LCS γ-ray beam has following advantages. The maximum energy is sharply determined in the basic QED process and that the γ-ray flux at high energy is relatively high. The energy can be changed with change of the energy of the electron beam and/or the wavelength of the laser. This method can generate almost 100% polarized γ-ray beam. The LCS γ-ray beam with the energy rage of MeV have been provided for uses at the Duke Free Electron Laser Laboratory at Duke University [3], the National Institute of Advanced Industrial Science and Technology [4], and an electron storage ring NewSUBARU in SPring-8 [5]. They have been widely used for applications with photon-induced reactions [6, 7, 8]. Recently the next generation of high-brightness LCS γ-ray sources based on the ERLs have been proposed [9, 10]. In this paper we preset examples of some applications using the LCS γ-ray beam.

INDUSTRIAL APPILCATTION

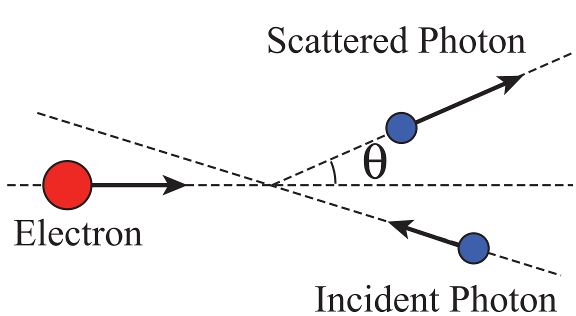

Figure 1: Schemative view of laser Compton scattering of laser photon and electron.

Detection of materials hidden by heavy shields are of importance for many industrial applications: the detection of explosive materials hidden in a package or a cargo, and the management of special nuclear materials produced by nuclear power plants. Gamma-rays have been used as a probe to detect an isotope of interest with nuclear resonance fluorescence (NRF) for industrial applications [11]. Although Bremsstrahlung γ-rays have been widely used for NRF, Pruet *et al.* have proposed a novel non-destructive detection of ^{235}U hidden in a cargo transporter by using NRF in conjunction with laser Compton scattering (LCS) γ-ray beam [12].

We have proposed an assay method of elemental and isotopic composition of materials hidden by heavy shields by measuring nuclear resonance fluorescence (NRF) scattering γ-rays with a LCS γ-ray beam provided from an ERL [9]. The NRF measurement with LCS γ-rays provides a unique finger print of each isotope. If the energy of the incident γ-ray is identical with the M1, E1, or E2 transition energy from the ground state of the nucleus of interest, the incident γ-ray is effectively absorbed in the nucleus and subsequently the nucleus de-excite by γ-ray emission. By measuring the NRF scattering γ-rays, we can detect the nuclear species of interest since the NRF γ-ray energies depend on the nuclear species as shown in Fig. 2. By measuring the energies of the NRF γ-rays, we can analyze nuclear species. The number of each isotope can be evaluated by the number of a NRF peak in the measured energy spectrum. Note that this method is applicable to detect both stable and unstable isotopes for most elements.

We demonstrated to detect isotope of interest concealed at the inside of a heavy shield with an available LCS γ-ray source at AIST [13]. A lead block was hidden by iron plates with a thinness of 15 mm. The position of the lead block was detected by measuring a 5512-keV γ-ray of ^{208}Pb with the LCS γ-rays. Our proposed nondestructive assay method is demonstrated to be a powerful tool to detect isotopes of interest shielded deeply by materials.

Detection of Nuclear Materials

Nondestructive assay (NDA) of plutonium in spent nuclear fuel is a key technology for safeguards of nuclear materials. The NDA of ^{239}Pu in the nuclear fuel assembly has not been well established yet. First we should not only detect elements but also analyze each isotope of interest. However, the nondestructive detection of such an isotope in heavy materials is generally difficult. Second high-Z element uranium in the nuclear fuel absorbs detection probes such as low-energy X-rays. Third the spent nuclear fuel is heated up due to the presence of the residual radioactivities. Thus, the spent fuel is often kept in a cooling water pool;

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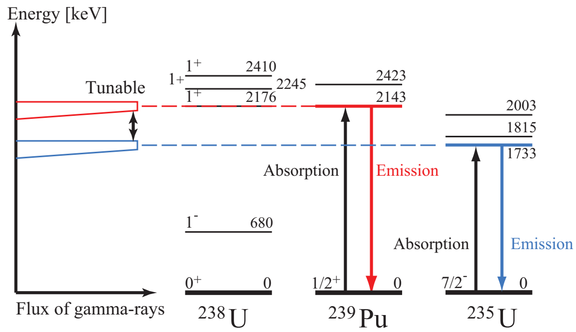

Figure 2: Schemative view of NRF measuring.

the water absorbs or scatters neutrons and low energy X-rays. We have proposed a nondestructive assay method for each isotope of uranium, plutonium, and minor actinides in spent nuclear fuel located in a water pool using NRF with γ-rays generated by a high-flux LCS source based on an ERL. This method has excellent advantages. Each isotope of elements located deeply in the nuclear fuel is detected by measuring the NRF γ-rays since high energy γ-rays of several MeV are used as the probe. In addition, the spent fuel can be analyzed with keeping in a water pool.

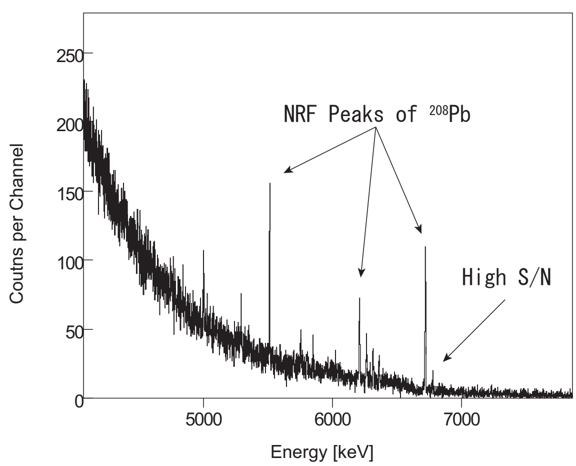

Figure 3: Example of measured NRF spectrum with LCS γ-rays.

For the nondestructive detection of materials in an industrial scale, we have designed a high-flux γ-ray facility utilizing a 350-MeV ERL equipped with a superconducting accelerator [14]. The high-flux γ-ray beams with energies of E_γ= 0.5$-$9 MeV are generated from the Compton scattering with a ytterbium-doped fiber laser with a frequency of 80 MHz and a power of 100 W, which is similar to a system shown in the previous study [15]. For the most efficient interaction of laser photons and electrons, we set the root-mean-square (rms) size of laser power density profile equal to the rms size of electron beam at the collision point: $w/2 = \sigma_e = 70$ μm. The rms size of the laser power density profile at the mirrors of the laser super cavity becomes w(at mirror) $= 2.3$ mm, which is small enough to keep the high-Q configuration with mirrors of a practical diameter $d \sim 10$ cm. The laser super cavity is assumed to have an amplification factor of 3000.

For detection of NRF γ-rays, a multi γ-ray detector array is used, which has been widely used for the study of the nuclear physics. This type of detector system typically consists of 20$-$120 high energy resolution γ-ray detectors (for example, see Refs. [16, 17]) such as high-purity germanium (HPGe) detectors. Figure 4 shows a schematic view of the detector system and a spent fuel assembly in a water pool. The γ-rays emitted from the spent fuel are measured with HPGe detectors. The spent fuel is stored in a water pool for cooling. The neutrons emitted from spontaneous fission of actinides in the nuclear fuel are absorbed by cooling water. The energy range of the incident LCS γ-ray beam is 1.7$-$2.5 MeV which is high enough to penetrate materials through shield water with a thickness of several ten centimeters.

An advantage of the use of NRF with high energy resolution HPGe detectors is to obtain the high signal-to-noise (S/N) ratio for the γ-ray peak. The energy resolution of the HPGe detectors is typically smaller than 0.2% (full width at half maximum (FWHM)) and resolve γ-ray peaks. In addition, the background is dominantly originated from the Compton scattering of the incident photons at the fuel assembly and the energies of the Compton scattered γ-rays are lower than the peak energy, and thus we can obtain high S/N ratio at NRF peak of a nucleus of interest. Figure 3 shows an example of measured NRF spectrum. One can see high S/N ratios around NRF peaks.

The nuclear fuel is vertically moved with a speed of 1 cm per 1 second to measure all the pellets. After a sequential measurement as a function of the vertical position of the fuel rods, the fuel assembly is horizontally moved for only a distance between two fuel rods. This measurements are repeated until the satisfactory data are accumulated for further computer analysis. In this manner, all the pellets in a fuel assembly can be measured for a period of 3000$-$4000 sec.

Here we estimate statistical uncertainty of the ^{239}Pu detection. The peak count at 2143 keV is 36 photons for measurement time of 5 s. This suggests that we can detect the ^{239}Pu NRF γ-rays at a rate of about 7 counts/s. For measurement duration of 4000 s, we can obtain a total count of 2.8×10^4. Note that, in the present calculation, we have assumed a spent fuel, of which PuO_2 is highly concentrated compared with the typical expected concentration (1%). If the peak count is smaller than the present result by a factor of 10, the peak can be still observed because of the high S/N ratio. In this case we can obtain the total count of 2.8×10^3 for the ^{239}Pu NRF peak. This result suggests that we can detect ^{239}Pu whose fraction of 1% in the spent fuel with statistical error of about 2%.

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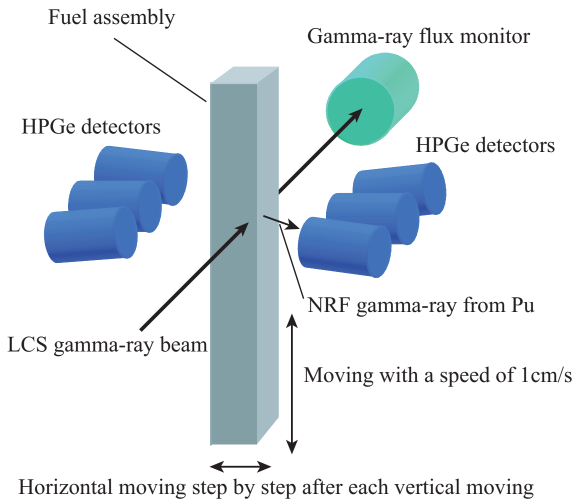

Figure 4: Schematic view of NRF measuring of ^{239}Pu in fuel assembly.

Measuring Chemical Material

We have proposed an extended non-destructive assay method for measuring molecules and chemical compounds hidden by heavy shields such as iron plates of a thickness of several centimeters [18]. The molecule or chemical compound consists of several elements and the elemental ratio depends on its chemical formula. By measuring the abundance ratio of key elements of the chemical compound of interest, we can detect the material inside heavy shields. For example, the chemical formula of melamine is $C_3H_6N_6$ and the ratio of $(C/N)_{melamine}$ is 0.5.

ASTROPHYSICS

Photon-induced Reaction Nucleosynthesis in SupernovaExplosions

Photons play an extremely important role in explosive nucleosynthesis, as might occur both in supernova explosions and in the Big-Bang. Massive stars that are at least eight times heavier than our Sun ultimately produce supernova explosions as the final stage of their evolution. High-energy photons at energies of an MeV or more are created in the extremely high-temperature environments that exist in this phase, and these photons can synthesize new isotopes, so-called "p-nuclei", by photon-induced reactions (γ-process) [19]. The p-nuclei are characterized by being at the neutron-poor extremes of the stable nuclides. Thus they cannot be produced by the two usual neutron capture processes (the rapid-neutron-capture-process, or r-process; and the slow-neutron-capture-process, or s-process), asβ-decay to them is blocked by a stable isobar. Thus they are generally of very low abundance relative to the other isotopes of each element. The p-nuclei are thought to be produced by several different processes of nucleosynthesis, one of which is the γ-process, which proceeds by successive (γ, n) and (γ, α) reactions operating on pre-existing abundant heavier isotopes, interspersed with occasional β-decays (see Fig. 5). Woosley and Howard found [19] an anti-correlation between the solar abundances of the p-nuclei and their photo-induced reaction rates, which suggests that the photo-induced reaction rates on the p-nuclei, or on their nearest neighbors, are essential for understanding the γ-process. Recently evidence that some p-nuclei are synthesized in the photon-induced reactions in supernova explosions was found in the solar abundances [20]. Indeed, these processes often occur concurrently.

Thus, experimentally measured rates for photo-induced reactions are essential for accurate theoretical simulations of the γ-process. The (γ, n) reaction rates to giant dipole resonances have been measured, but the reaction rates at energies of astrophysical interest have been studied on several nuclei. The distribution of photons in supernovae is plankian, so the photon flux decreases sharply with increasing photon energy. Thus the energy at which the photons contribute to the abundances of the p-nuclei is typically a few hundred keV above the neutron separation energy, typically 7-9 MeV. The cross sections in this energy region are typically a few orders of magnitude smaller than those at the peaks of the giant dipole resonances.

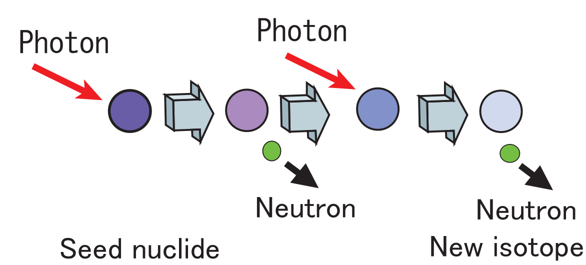

Figure 5: Schematic view of photon-induced reactions in supernova explosions.

Neutrino-process in Supernovae

The interaction between neutrinos and nuclei plays an extremely important role for supernova explosions and their synthesis of nuclides. The question of how a star collapses and makes a supernova has challenged astrophysicists for decades. A huge number of neutrinos, 10^{53} ergs, are produced from a core collapse supernova and the subsequent cooling phase of a proto-neutron star. Most of these neutrinos escape into the interstellar medium, but a small fraction of them transfer their energy to an outside exploding mantel and surrounding stellar envelope by neutrino-nucleus interactions such as neutral current reactions, charged current reactions, and inelastic neutrino-nucleus scattering. These neutrino nucleus interactions also are important for synthesis of several light isotopes, such as ^{7}Li, ^{11}B, and ^{19}F, as well as the heavy rare isotopes of ^{138}La and ^{180}Ta (see Fig. 6) [21]. However, very few neutrino reaction cross-sections are known with high accuracy since they are very difficult to measure, and their calculation depends on complex nuclear structures. The mag-

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netic dipole (M1) and Gamow-Teller responses in nuclei are particularly important for the estimation of the inelastic neutrino-nucleus scattering and neutral current reaction cross-sections. Since the LCS gamma-ray sources can generate almost 100% linear polarized gamma-ray beam, and this has a strong experimental sensitivity to M1 transitions, LCS gamma-ray sources have enabled us to detect the fine structure of weak M1 transitions with high accuracy. These measurements have been carried out using LCS gamma-ray sources at the Duke Free Electron Laser Laboratory and at AIST (for example, see Ref. [8]).

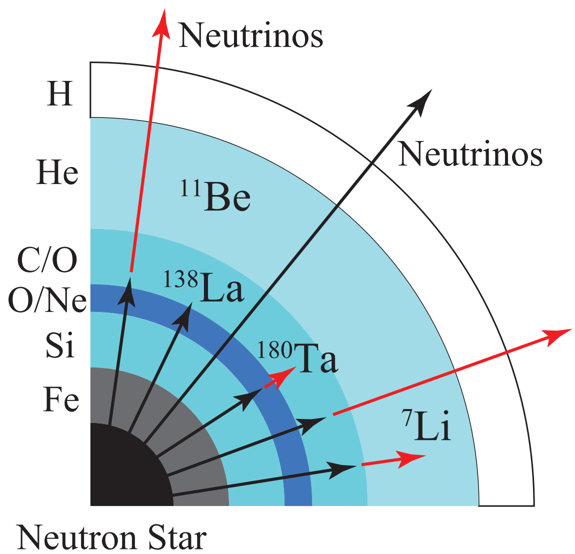

Figure 6: Schemative view of neutrino-induced reactions in supernova explosions.

FUNDAMENTAL SCIENCE

Nuclear parity violation is caused by the weak interactions on the nucleon-nucleon (NN) interactions in nuclei. In the picture of meson exchange description, one meson-nucleon vertex is coupled to the other nucleon mediated by weak interaction. Parity doublets in nuclei are mixed with each other by this PNC NN interaction. Titov *et al.* have proposed a novel method to measure the nuclear parity violation using circularly polarized LCS γ-rays [22]. Their group measured PNC asymmetry in exciting the first excited state in ^{19}F by using high intensity elliptically polarized synchrotron radiations generated by elliptical multipole wiggler at SPring-8. In case of ^{19}F, the set of the ground ($J^\pi = 1/2^+$) and 110 keV ($J^\pi = 1/2^-$) excited states is a parity doublet. In the new method, the parity mixing is studied by NRF using a circularly polarized photon beam. The experiment has been carried out using hard x-ray synchrotron radiations (SR) from the elliptical multipole wiggler (EMPW) at SPring-8. In near future, extremely high-flux γ-ray beam can provide new information for the PNC NN interaction.

CONCLUSION

The next generation of high-brightness LCS γ-ray sources based on the ERLs have been proposed. We have presented that these ERL-LCS γ-ray sources have high potential for the study of fundamental science and industrial applications.

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