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Application of Imaging Plate to Measurement of Radiation Spatial Distribution

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An imaging plate (IP) was applied to 1) detecting of low-level contamination that was difficult to detect by a conventional way, 2) measurement of spatial distributions of thermal neutrons and 3) profile measurement of fast neutrons and proton beam of low intensity. For 1), a large-size IP (BAS-IIIs) was disposed to the sample, and the position and intensity of the contamination was identified unambiguously by scanning IP. For 2), activation foils were combined with IP to avoid γ-rays from neutron sources and radioactive accelerator components. We placed small gold activation foils at many points of interest in an accelerator room and disposed them on IP after irradiation. This method enables to measure neutron spatial distribution in a single scanning. We extended this method to profiling of fast neutron by using an aluminum plate and proton beams with intensity too low to measure by beam current but too strong to measure by pulse counting by using a thin copper foil.

KEYWORDS: Imaging plate, Contamination detection, Activation foil, spatial distribution measurement

I. Introduction

An imaging plate (IP) is a high-sensitive and two-dimensional radiation sensor that is developed by Fuji Film Co., Ltd. in succession to an X-ray film used in medical diagnosis.[1)] It is an integral type of detector having good sensitivity for ionization radiation such as X-, β- and γ-rays and charged particles. Therefore it is used in many fields of applications not only medical fields but industrial radiography, autoradiography and X-ray diffraction experiments and so on. IP is a film that consists of a photostimulable BaFBr:Eu^{2+} phosphor layer which memorizes radiation information and of polyethylene telephthalate (PET) backing. The stored radiation image can be read as "Photo-Stimulated Luminescence (PSL)" which is in proportion to absorbed radiation intensity by scanning IP point-by-point with an image reader. The PSL image is obtained as digital image data that can be treated easily.[2)] IP has the following advantages: 1) high sensitivity for radiation (100 times as high as that of an X-ray film), 2) good proportionality to radiation intensity over a large dynamic range beyond 10^4, 3) good spatial resolution (less than 0.05 mm) and wide sensitive area (e.g., 20 cm $\times$ 40 cm for BAS-IIIs), 4) digital image data for radiation image, 5) no necessity of chemical treatment and 6) reusability, etc.

In this study, we applied IP to 1) detecting of low-level contamination that was difficult to detect by a conventional way, 2) measurement of spatial distributions of thermal neutrons and 3) profile measurement of fast neutrons by p-Li neutron source and proton beam intensity in $10^7 \sim 10^8$ cm^{-2} s^{-1} which is difficult to measure by charge and particle counting. The profiling is required for the characterization of radiation field like particle distribution.

For 1), we detected contaminations in lead blocks that were used to shield a Ge detector for low-level γ-ray measurement. With a GM survey meter it was not possible to localize the contamination, while a weak contamination of ^{137}Cs was observed by the Ge detector. We put a large-size IP (BAS-IIIs) in contact with lead blocks and exposed IP to the radiation to localize the contamination.

For neutron profile measurement, there has been proposed various application of IP with success such as Gd-loaded IP,[3)] a combination of a polyethylene converter with IP (IP-polyethylene method)[4)] and a combination of activation foil with IP (IP-activation method).[5)] In the methods of Gd-loaded IP and IP-polyethylene, IP is exposed directly to radiation fields mixed with neutrons and γ-rays. This results in large backgrounds by γ-rays induced by neutrons because IP has high sensitivity to γ-rays too. For the reasons, these methods are difficult to apply in neutron fields such as high-energy accelerator facilities. On the other hand, the IP-activation method is free from background γ-rays because IP is not irradiated by neutrons directly. Besides, this method enables to measure neutron spatial distribution in a single run by measuring residual activities of a set of many activation foils placed in points of interest with a large-size IP. We applied IP-activation method to measure thermal neutron spatial distribution in the 12 MeV baby cyclotron (HM-12) room at Cyclotron and Radioisotope Center (CYRIC), of Tohoku University. In the thermal neutron measurement, the Cd subtraction technique was newly applied with IP-activation method. We set pairs of small gold foils (1 cm-diam.) and Cd covered ones for activation foils in many points in the accelerator room and disposed them on IP at once after irradiation to measure their activities. It is not necessary to do time-consuming activity measurements for many foils with the usual way using a Ge detector.

We extended this method to profile measurement of fast neutrons and proton beams. Fast neutron profiling was done by using a large-size aluminum plate (20 cm $\times$ 20 cm) for an activation foil and proton beam profiling was done by us-

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ing a thin copper foil. Using the IP, we measure the activity distribution of irradiated foils that emit γ-rays. For fast neutrons, we measured a spatial distribution in collimated neutron beam which is emitted from the p-^{7}Li neutron source. For proton beam, we measured spatial distribution in collimated proton beam whose intensity was too low to measure by electric charge but too strong to measure by pulse counting.

II. Experiment and Results

1. Contamination detection

Figure 1 shows the background spectrum of a Ge detector (EURISYS MESURES EGPC50-195-R (relative efficiency 48 %)) shielded by lead blocks including contaminated one. The measuring time is approximately 40 hours. In the spectrum the γ-rays from ^{137}Cs (662 keV) that dose not exit in nature were detected in addition to radiations of ^{208}Tl (511 keV) and ^{214}Bi, etc. The peak count rate of 662 keV and 511 keV are 0.047 and 0.027 cps, respectively. The ^{137}Cs contamination was too weak to identify the contaminated block using conventional survey meters.

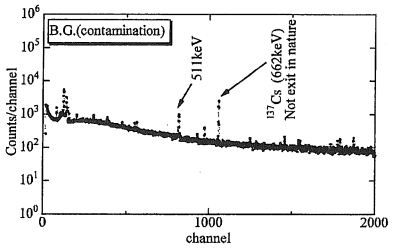

Fig. 1 γ-ray spectrum of lead blocks contaminated with a weak activity of ^{137}Cs

For contamination detection, we used IP (BAS-IIIs, 20 × 40 cm) wrapped with a light-tight polyethylene bag. The IP was put in contact with four lead blocks in question during 12 hours. We scanned IP image by a BAS-1000 scan system manufactured by Fuji Film Co., Ltd. and analyzed the data with an image analyzing software of MacBAS (ver. 2.5). The measured IP images for four lead blocks (block size 10 × 20 cm) are shown in **Fig.2.** In **Fig.2 (1)**, contaminations which are attributed to spilling of a little solution are observed on the upper left block. It should be pointed out that IP localizes clearly the contaminated points within the block. This activity was identified to be due to ^{137}Cs by the Ge detector. This fact confirms that IP is a high-sensitive radiation imaging detector. After reconstruction of the shield by using the decontaminated lead blocks, the peak of ^{137}Cs disappeared. **Figure 2 (2)** shows another example of image of lead blocks; there is no spot contamination but darkness of each blocks differ each other. In IP image, 'dark' means 'high PSL densities'. This is due to difference of ^{210}Pb content in lead blocks. ^{210}Pb (half-life: 22.3 year) originates from ^{238}U in nature. The ^{210}Pb content in lead blocks differs according to the time of refinements and the production district. The largely contaminated lead block was removed and slightly contaminated lead blocks are decontaminated by shaving the contaminated spots.

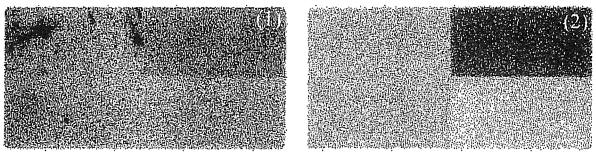

Fig. 2 Activity distribution of four lead blocks contacting IP for 12 hours: (1) Two block of left sides are contaminated with ^{137}Cs, (2) Darkness differences of each block depends on the concentration of natural ^{210}Pb

2. Neutron spatial distribution measurement

The experiment was done in a baby cyclotron (HM-12AVF, SUMITOMO Heavy Industry Co., Ltd.) room (No.1 target room; TR1) of CYRIC to study thermal neutron distribution in the room. The HM12 cyclotron is used for production of radioisotopes for positron emission tomography (PET). **Figure 3** shows a ground floor plan of TR1. The HM12 cyclotron is set 2 m left side from the room center. In **Fig.3**, C is a beam transport tube from the larger cyclotron (SUMITOMO 930) and D is down stairs to an underground passage. Numbers indicate the positions of activation foils. Thin sheets of gold (0.1 mm thick, 10 mm diameter, approximately143 mg by weight) were used as activation foils. To measure thermal neutron distribution in the room, the Cd subtraction method was applied with IP-activation method. Foils of 48 pairs (bare and covered ones with a 1mm-thick cadmium foil) were set 1.5 m apart from each other and 1.45 m high from the floor level. The HM12 cyclotron was operated on the condition that proton energy was 12 MeV, beam current about 10 μA, the target material of water ($H_2^{18}O$) and irradiation time 2 hours.

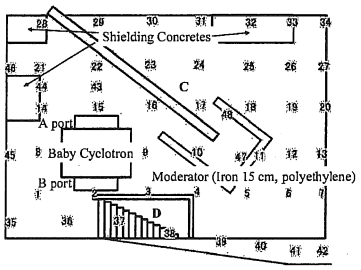

Fig. 3 Arrangement of activation foils in TR.1 48 pairs of gold foils (bare and Cd-covered)

One day after the cyclotron operation, gold foils were arranged on the IP (BAS-IIIs) as in **Fig.4** and disposed for 24 hours in a lead-shield box which reduces the natural γ-rays to 1/10. The stored image was read out by the BAS-1000 system. It has the pixel size of 100 μm and requires about 3.5 minutes for reading one image. The activities of some foils were measured with a pure Ge γ-ray detector to identify induced radioisotopes and to calculate the yields of ^{198}Au produced by

the ^{197}Au (n,γ) ^{198}Au reaction with thermal and epithermal neutrons. The absolute thermal neutron flux is deduced using the Ge detector with a cadmium subtraction method. The appropriate thickness of gold foils for the present purpose was studied by using a ^{252}Cf neutron source. As the result, the PSL density (PSL/mm^2) of irradiated gold foils reaches saturation beyond 0.05 mm due to an increase of the self-shielding effect. The result indicates the minimum appropriate thickness is 0.05 mm, but it is too thin to prepare samples and to obtain enough counts in activity measurement with a Ge detector. Therefore we chose 0.1 mm as the thickness of gold foils.

The γ-ray spectrum of No.1 sample was measured for 24 hours with a pure Ge detector. We confirmed the photo-peak of 411.8keV γ-rays from ^{198}Au but could not detect the photo-peaks from ^{196}Au by the ^{197}Au(n,2n) reaction. This is reasonable, because the maximum energy of neutrons emitted from the ^{18}O(p,n)^{18}F reaction, 9 MeV, is close to the threshold energy of the ^{197}Au(n,2n)^{196}Au (8.05 MeV). The relative activities of gold foils are measured as PSL magnitude and shown in **Fig.4**.

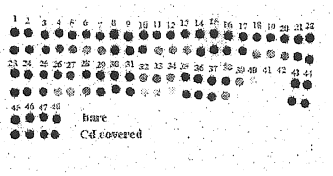

Fig. 4 The image of gold foils measured by IP in single run: pairs of bare and Cd-covered are set at upper and lower, respectively.

Figures 5 (1), (2), (3) reconstructed using the obtained PSL data with the position information show a thermal neutron spatial distribution, an epithermal neutron distribution and a Cd-ratio distribution in the plane 1.45 m from the floor level, respectively. In **Fig.5 (1)**, the maximum thermal neutron flux was 6.47×10^5 neutron cm^{-2} s^{-1} in No.15 and the minimum was 5.59×10^4 neutron cm^{-2} s^{-1} in No.34. The results of the distribution were reasonable generally because the target was around the No.15 foil. In **Fig.5 (2)** for epithermal neutrons the maximum was in the No.8 foil differing from the case of **Fig.5 (1)** for thermal neutrons. This is probably due to the following reason; this cyclotron is self-shielding type accelerator and the target surroundings are covered with 15 cm-thick boron-water and 5 cm-thick lead walls. However around the No.8 foil the shielding was not thick enough because of pipes for electrical wiring and cooling. Therefore, a lot of fast neutrons were leaking without being thermalized well. In **Fig.5 (3)** the maximum was in No.12, because there is shielding material (iron 15 cm and polyethylene 15 cm) for the other beam line in the front of No.12. By sampling in smaller meshes, we can obtain finer map, if necessary. **Figure 5 (4)** shows the thermal neutron distribution at the center of stairs. The distributions go down exponentially from the top of stair (2 m) to the underground floor (9 m). The activity in the underground floor was too weak to measure using a conventional GM counter system. Usual activation foil method employs a Ge detector, but in the case of very weak activity and a large number of foils, the present method is much more preferable.

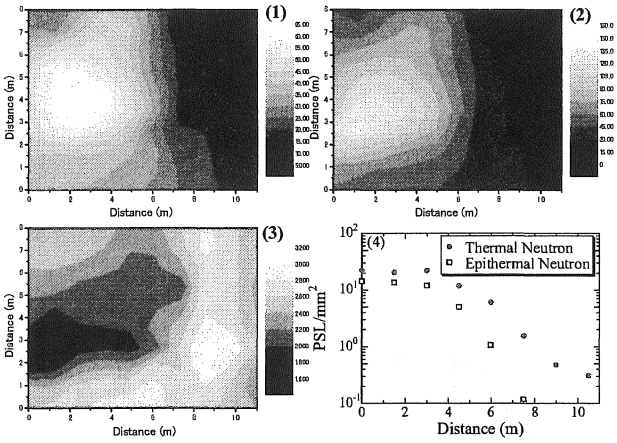

Fig. 5 (1) Thermal neutron spatial distribution, (2) Epithermal neutron spatial distribution, (3) Cd-ratio spatial distribution, (4) Thermal and epithermal neutron distributions at center of downstairs

3. Fast neutron profiling

The experiment was carried out to know the neutron profile in the measurement of activation cross-section and semiconductor soft errors at the 5th target room in CYRIC 930 cyclotron. Fast neutrons used in the experiments were monoenergetic ones obtained by bombarding a Li metal target with protons accelerated to 70 MeV. The peak neutron energy was 65 MeV. The experimental setting is shown in **Fig.6**. Protons which transmitted the target are bent to the beam dump by a bending magnet. Between the neutron source and the aluminum plate for activation, there is a concrete wall (thickness 1m, width 3 m, height 2 m) with a 20 cm $\times$ 20 cm wide collimator of iron in the center. In the up stream of aluminum plate, the samples for activation and semiconductor soft errors measurement were arranged. In these experiments the data on neutron intensity and its distribution are necessary.

The irradiation was carried out twice with and without activation samples in position to see the effect of the attenuation by samples in the up stream. The activation samples were carbon 1.5 cm thick, aluminum 1 cm thick, copper 1 cm thick, a low activation concrete 2 cm thick, etc. Each irradiation time was 10 hours at beam current 200 nA and exposure time of IP was 24 hours for both arrangements.

The fast neutron images obtained by IP with activation sample in and out of place are shown in **Fig.7** and **Fig.8**, respectively. The horizontal PSL distributions along the vertical center of the IP images are shown too, respectively. In **Fig.7**, the silhouette of activation samples is observed. It shows attenuation of the neutron flux by activation samples. The line in **Fig.8** is the silhouette of a stand for semiconductor samples. These results indicate that the neutron attenuation by many activation samples in line is as large as about a factor of two, but the attenuation by semiconductor samples whose thickness is

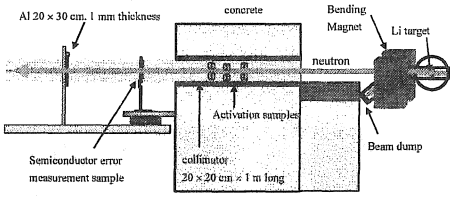

Fig. 6 The arrangement of fast neutron profiling

several mm is not so large and neutron flux is almost flat over the irradiation sample.

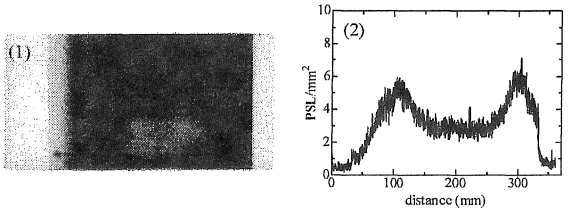

Fig. 7 (1) The fast neutron image measured by the IP-aluminum method with activation samples and semiconductor samples in, (2) The horizontal PSL distribution along the vertical center

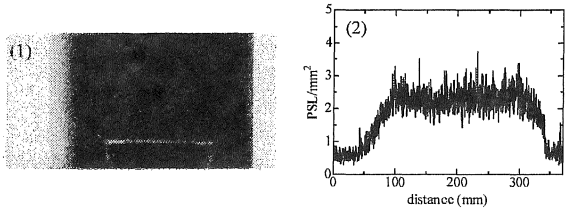

Fig. 8 (1) The fast neutron image measured by the IP-aluminum method with semiconductor samples in place, (2) The horizontal PSL distribution along the vertical center

4. Proton beam profiling

We extended the IP-activation method to proton beam profile measurement for proton-induced semiconductor single event experiment. In the experiment, a flat proton intensity distribution in the chip region is important. To obtain a flat distribution, we used a Au foil (0.4 mm thickness) as the diffuser for proton energy of 70 MeV. The beam current required in this experiment was several pA (approximately 10^{7-8} particle cm^{-2} sec^{-1}). It was too many to detect by the counter method but too few to detect as a beam current.

To measure the beam distribution and intensity on the chip, we used a copper foil (20 × 20 mm, 0.1 mm thick) for activation foils. The distribution of beam intensity was measured by IP in the similar way as that for neutrons. The distribution was measured by a copper foil and IP, and the number of protons by a copper foil and Ge detector. A proton beam was collimated within 20 mm ϕ to avoid irradiation on undesirable parts. The irradiation time was 10 minutes at beam current of 200 pA on the beam stopper up stream of the diffuser. The exposure time of IP was 1 hour.

Figure 9 (1) shows the PSL distribution of copper foil measured by IP using Au for the diffuser and **Figure 9 (2)** shows the PSL density distribution along the horizontal center of incident beam and beam diffused by a Au diffuser and TRIM calculation.[6] As seen in **Fig.9 (2)**, the shape of diffused beam intensity distribution is different from the Gaussian distribution of incident beam, close to a rectangular one by the TRIM calculation. However the flat region (approximately 15 mm) obtained by IP is narrower than TRIM calculation (20 mm). In the experiment, the beam axis might be off the center axis of beam tube. Further studies are required about this difference, but this technique was shown very effective for beam profiling.

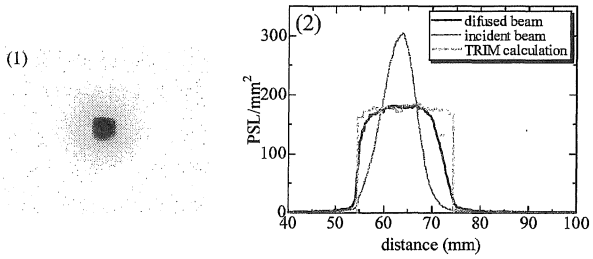

Fig. 9 (1) The proton image measured by IP and cupper foil on a semiconductor chip, (2) The vertical PSL distribution along the horizontal center

III. Conclusion

We have applied IP with very high-sensitivity and good spatial resolution (50 μm) to 1) detecting low-level contamination that was difficult to detect by a conventional way, and 2) measurement of spatial distributions of thermal and fast neutrons, 3) profile measurement of proton beam intensity. For 1), IP was very effective for the advantage of IP that is high sensitivity and good spatial resolution. For 2) and 3), the reasonable distributions were obtained by IP. The method will be useful while there are rooms for improvement. Further studies will be continued to develop the techniques.

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