Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 39, No. 12, p. 1251–1259 (December 2002)

The Luminescence from a Long Lasting Phosphor Exposed to Alpha, Beta, and Gamma Rays

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(Received August 27, 2002 and accepted in revised form October 28, 2002)

A long lasting phosphor (LLP), which emits bright green light for a long period after irradiation has been stopped, is a promising candidate as a simple and easy-to-use radiation detection element for digital radiography. Luminescence from the LLP, $SrAl_2O_4:Eu^{2+},Dy^{3+}$, exposed to various ionizing radiations has been measured to evaluate the dependence of luminescence efficiency on quality of ionizing radiation. The following items were confirmed.

(1) Total luminous intensity from the LLP was proportional to total absorbed dose on the LLP element.
(2) The average energy to produce one photon, W_p, of the LLP exposed to either beta or gamma rays at 300 K was 18±2.7 eV, while that for the exposure to alpha rays was 480±72 eV.
(3) The difference in W_p for beta and gamma rays and alpha rays arose from the difference in linear energy transfer, LET, in the LLP.
(4) The W_p values were determined by the short-term recombination rate of electron and hole pairs in the LLP as well as their generation rate.
(5) A model to evaluate the W_p based on behaviors, *e.g.*, generation, recombination and trapping, of electron and hole pairs values was proposed to explain the W_p dependence on the quality of ionizing radiation.

KEYWORDS: radiation detection, long lasting phosphor, luminescence, short-term recombination, luminescence efficiency

I. Introduction

A long lasting phosphor (LLP) shows bright green light emission when exposed to ionizing radiation.[1)] The LLP elements, which emit photons for a long period after stopping the irradiation without any external excitation, are a promising candidate as simple and easy-to-use radiation detection elements, especially for digital radiography. In order to apply the LLP as radiation detection elements, dependence of its luminescence on the quality of exposed radiation[1–3)] and ambient temperature[1,3,4)] should be determined.

A thin film of the LLP can be fabricated for an element to determine a two-dimensional distribution of relative absorbed dose. Previous studies showed that the decay curve of LLP after irradiation has been stopped consists of four components[1)] which have typical decay constants of LLP material. The controlled temperature during the whole period from irradiation until measurement makes it easy to estimate the absolute absorbed dose during irradiation by using the measured luminous intensity of the LLP at any time after stopping the irradiation and applying a set of decay constants.[1)] This means that a large number of LLP films can be applied to measurement of very large scale radiations distribution and also to data synthesis for computational tomography.[4)] Applications of LLP to radiation distribution displays and digital two-dimensional radiation profiling monitors are possible using a simple reader system, without scanning the elements, but using a charge coupled device (CCD).

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In this paper, $SrAl_2O_4:Eu^{2+},Dy^{3+}$ [1,2,4,5)] was selected for the LLP detector element. The response of luminescence emitted by a LLP to various ionizing radiations was measured. As the measure of detection sensitivity of the LLP, the average energy to produce one luminescent photon, W_p was applied. The W_p values were evaluated for various ionizing radiations and also compared with those of other conventional detector elements, *e.g.* NaI (Tl) and CsI (Tl).

II. Experimental

1. Experimental Setup

Under irradiation, luminous intensity rate is determined by energy storage rate and decay constants of luminescence, while after irradiation has been stopped, it is determined mainly by the decay constants.[1,3)] Irradiation should be quickly cut off to determine the absorbed energy by LLP elements accurately. The measurement system is shown schematically in **Fig. 1**. The LLP detector element was placed in a sample holder installed in a vacuum chamber (diameter: 15 cm, length: 45 cm). A high-speed air driven shutter for radiation cut-off, a radiation source, a photo multiplier tube (PMT) (Hamamatsu R980) for photon detection and a heat sink to keep a constant ambient temperature during measurements were also installed in the vacuum chamber.

The ambient temperature, one of the most important experimental parameters, was controlled at a constant value from 160 to 390 K with less than 0.1 K deviations. In order to get sharp radiation cut-off, a stainless steel shutter (thickness: 2.0 mm) was used. It was driven by high-pressure air; open-

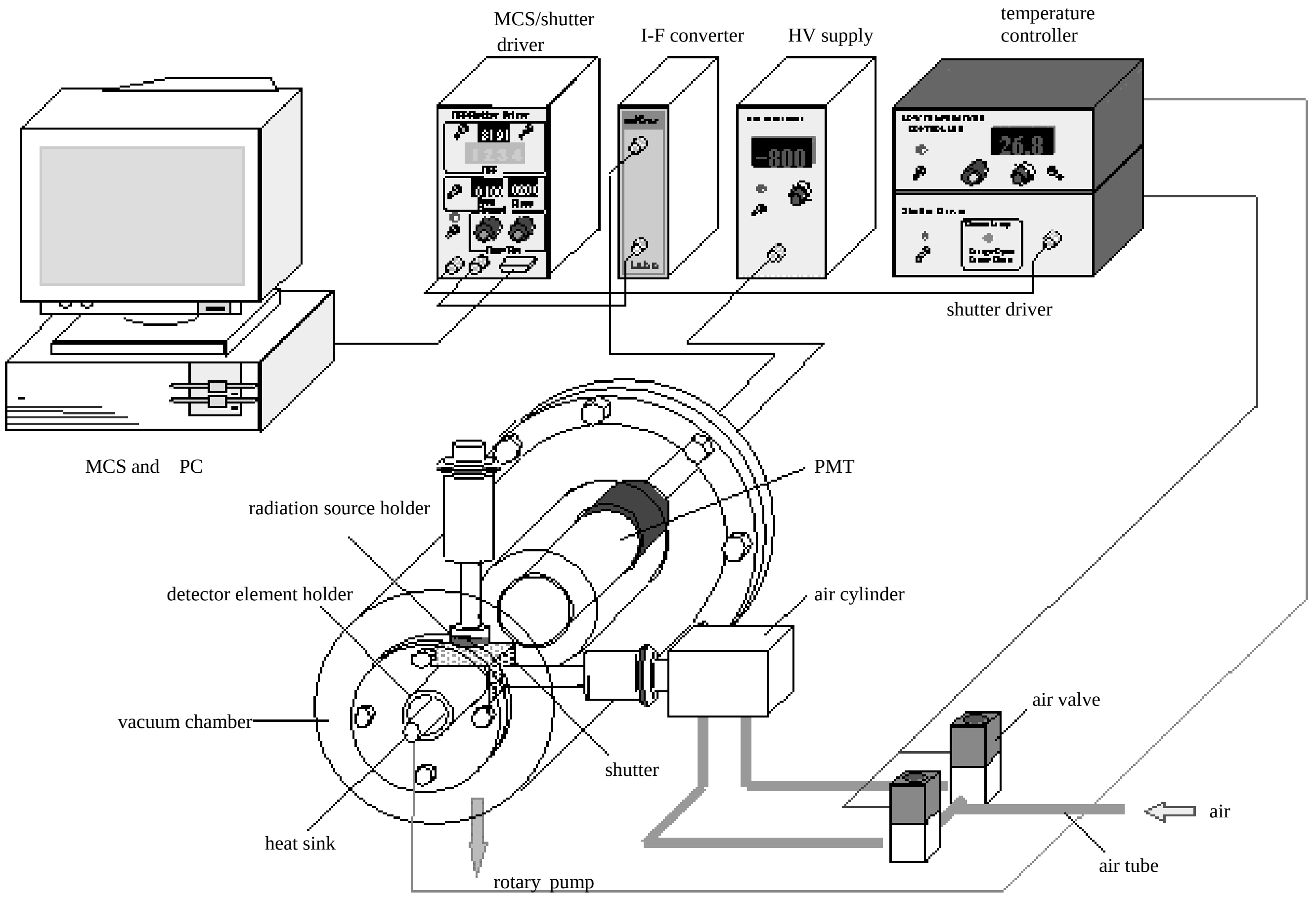

Fig. 1 Schematic diagram of light detection and measuring system

ing and closing shutter speed was 62 m/s. A current frequency converter (Labo DN9000) and a multi channel scalar (MCS) (Labo MCABX) were also used.

2. LLP Detector Element

The LLP detector element was made of $SrAl_2O_4$:Eu^{2+},Dy^{3+} powder (particle diameter: 30 μm) bound with polystyrene binder. The concentration of phosphor in the element was 58 wt%. The LLP element was 14.0 mm in diameter and 1.0 mm in thickness and had a density of 1.92 g/cm^3.

3. Sources of Ionizing Radiation

Specifications of the radiation sources are listed in **Table 1**. Alpha or beta rays from the source were arranged as a pencil beam by a lead collimator (diameter: 10 mm). Cobalt-60 was used as the gamma-ray source.

Table 1 Specifications of radiation sources

Radiation source	Species	Source intensity (MBq)	Distance from the source (mm)	Particle fluence rate (particles/s)
α	^{241}Am	2.79[a)]	30.0	4.6×10^4
β	^{90}Sr–^{90}Y	2.87[a)]	30.0	4.8×10^4
γ	^{60}Co	3.70	22.6	2.2×10^5

[a)]Measured value

4. Absorbed Dose in the LLP Element

In order to evaluate the response of the luminescence to ionizing radiation, the absorbed dose in the LLP element should be determined exactly. The energy spectra of the alpha- and beta-ray sources used in this study are shown in **Figs. 2** and **3**. The energy spectrum of the alpha-ray source was measured by using a solid state detector (SSD), which was calibrated with the standard alpha-ray source (^{241}Am: 5.486 MeV). The energy of alpha rays used in this study was determined to be 4.68 MeV. The alpha-ray source was covered with the plastic coating. Due to absorption of alpha particles in the coating of the source surface and self-absorption in the source, the energy of the alpha rays was decreased and the energy spectrum was broadened. The energy spectrum of the beta-ray source was measured using a plastic scintillation detector (NE-213) system. The ratio of the energy absorption in the LLP to that in the detector element was the mass fraction of LLP in the detector element (0.58).

(1) Alpha Rays

The range of alpha rays with energy of 4.68 MeV in the LLP element was about 34.3 μm. The alpha rays completely lost their energy in the detector elements (thickness: 1.0 mm) and were absorbed in them. **Figure 4** shows the geometrical

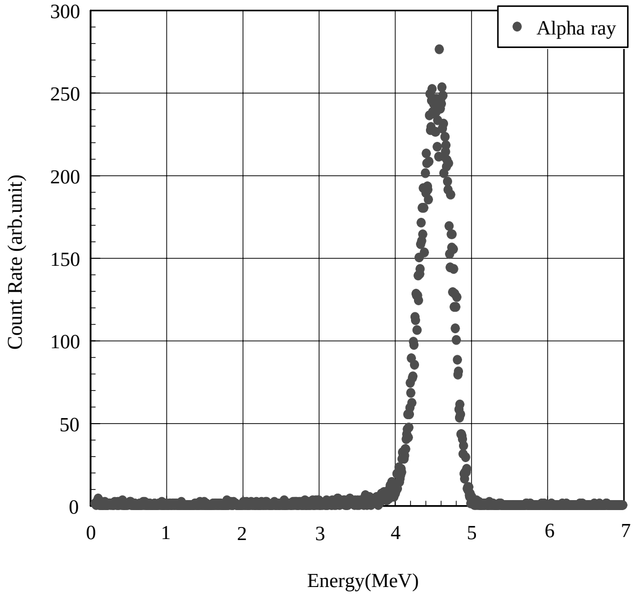

Fig. 2 Energy spectrum of ^{241}Am alpha-ray source (measured)

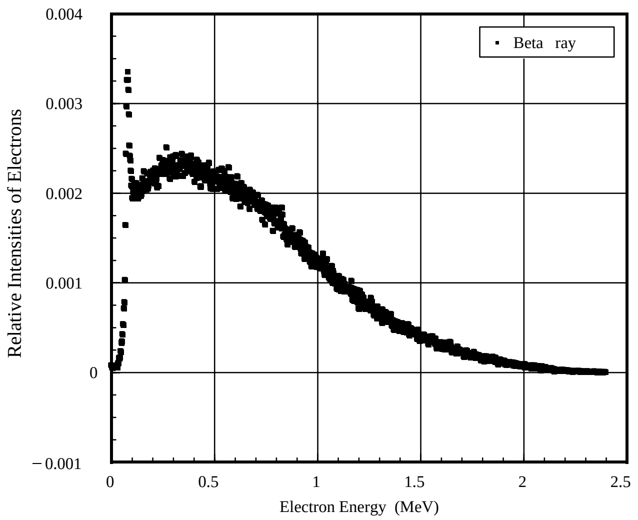

Fig. 3 Energy spectrum of ^{90}Sr–^{90}Y beta-ray source (measured)

layout of the measuring system. The total absorbed energy of irradiated alpha rays is expressed by

$$\Delta E_a = \Omega_{\text{particle}} A_{\alpha\text{-source}} E_\alpha \Delta t \varepsilon. \tag{1}$$

The ratio of the incident particles in the LLP detector elements, Ω_{particle}, is expressed as the following equation:

$$\Omega_{\text{particle}} = \frac{\pi R_{\text{LLP}}^2 / \cos\theta_{\text{source}}}{4\pi R^2}. \tag{2}$$

$\pi R_{\text{LLP}}^2 / \cos\theta_{\text{source}}$ was calculated as the area of an ellipse. The mass fraction of LLP in the detector elements, ε, was 0.58.

(2) Beta Rays

The total absorbed energy by beta ray irradiation is expressed by

$$\Delta E_\beta = \Omega_{\text{particle}} A_{\beta\text{-particle}} \int_0^{E_{\beta\text{-max}}} P_\beta(E) \times \left[\int_0^x \frac{dE}{dx} dx\right] dE \Delta t \varepsilon. \tag{3}$$

The beta rays had a continuous energy spectrum, $\beta(E)$ (Fig 3). The absorbed energy per electron of beta rays was obtained by following the procedures (a) through (c).

(a) The collision mass stopping power of electrons of beta rays was calculated by using Bethe's equation, by assuming a uniform mixing of LLP (LLP ($SrAl_2O_4$:Eu^{2+},Dy^{3+}): 58 wt%) and polystyrene $(C_8H_8)_n$: 42 wt%) binder as the target material shown in **Fig. 5**. Basic data of stopping power were obtained from the NIST data base.

(b) The LLP detector element was divided into very thin layers to estimate energy deposition of electron in each layer with collision mass stopping power.

(c) The cut off energy of electrons was 10 keV, which was the highest energy for the electrons to penetrate the LLP detector element.

(3) Gamma Rays

Secondary electron equilibrium in the detector elements was assumed to evaluate absorbed energy of gamma rays. The average energy of ^{60}Co gamma rays was assumed to be 1.25 MeV. The total absorbed energy for gamma ray irradiation is expressed by the following equation:

$$\Delta E_\gamma = 2\Omega_{\text{particle}} A_{\gamma\text{-source}} E_\gamma (\mu_{en}/\rho)_{\text{LLP}} \rho_{\text{LLP}} x_0 \Delta t \varepsilon. \tag{4}$$

Mass energy absorption coefficient of LLP detector elements was determined by the mass energy absorption coefficient and the mass ratio of each element as shown in **Table 2**.

5. Total Luminous Intensity from the LLP Detector Elements

The determination of the total luminous intensity from the LLP element exposed to ionizing radiation should also be carried out exactly. A schematic view of the measuring apparatus is shown in Fig. 4. The luminous intensity emitted at the surface of the LLP detector element was estimated from measured luminous intensity. The total luminous intensity from the LLP element was evaluated by using the following equation:

$$\Phi_{\text{total}} = \frac{1}{1-H} \cdot \frac{F}{\Omega_{\text{photon}} QE \mu_{\text{PMT}} 1.602 \times 10^{-19}} I. \tag{5}$$

The total absorption rate of the generated light in the LLP element, H, is expressed as a function of thickness as shown

Table 2 Mass energy absorption coefficient of each element and weight ratio of each element

	Sr	Al	O	Eu	Dy
$(\mu_{en}/\rho)_i$ [a] [$\times 10^{-2}$ cm^2/g]	2.342	2.451	2.669	2.557	2.570
$\omega(i)$	0.42	0.25	0.31	0.007	0.013

[a] For mass energy absorption coefficient, open data of NIST were used.

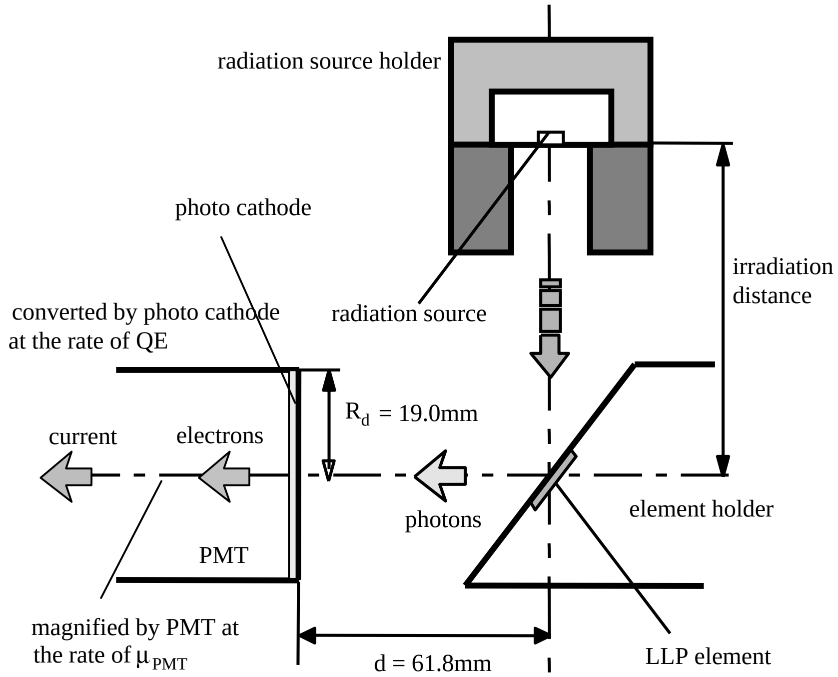

Fig. 4 Geometrical layout of measurement apparatus

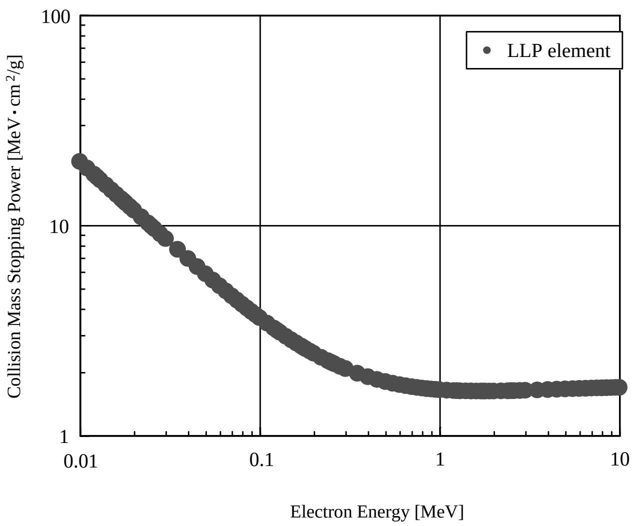

Fig. 5 Collision mass stopping power of LLP for beta rays

in Eq. (8) and **Fig. 6**. Some assumptions to obtain H are shown as follows.

(1) The intensity of the generated light in the LLP is expressed as a function of the depth, $f(x)$[6] and photons are emitted isotropically.

(2) The transparency of the generated light is calculated based on energy dependent attenuation coefficient, shown in **Fig. 7**.

(3) An isotropic disk shape uniform source with photon emission rate calculated based on the transparency shown above is assumed as the luminescence source.

The critical angle which light escapes from the element is expressed as Eq. (6) and the attenuation rate of the generated light at the depth x, $\eta(x)$, is expressed as Eq. (7):

$$\theta_c = \sin^{-1}\frac{R_{\mathrm{LLP}}}{l}. \tag{6}$$

$$\eta(x) = \frac{1}{2\pi}\int_{-\theta_c}^{\theta_c} l\mu d\theta = \frac{1}{2\pi}\int_{-\theta_c}^{\theta_c}\frac{\mu x}{\cos\theta}d\theta. \tag{7}$$

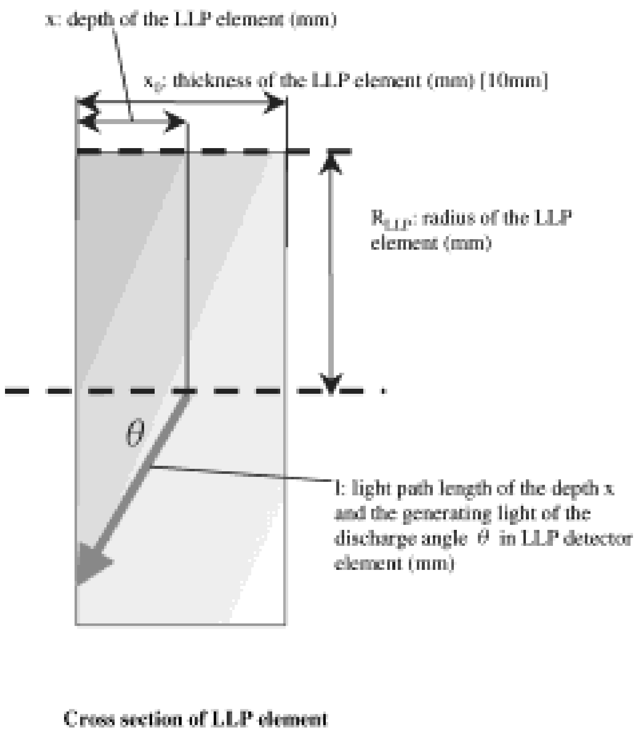

Fig. 6 Schematic view of the geometrical transparency of generating light in the LLP element

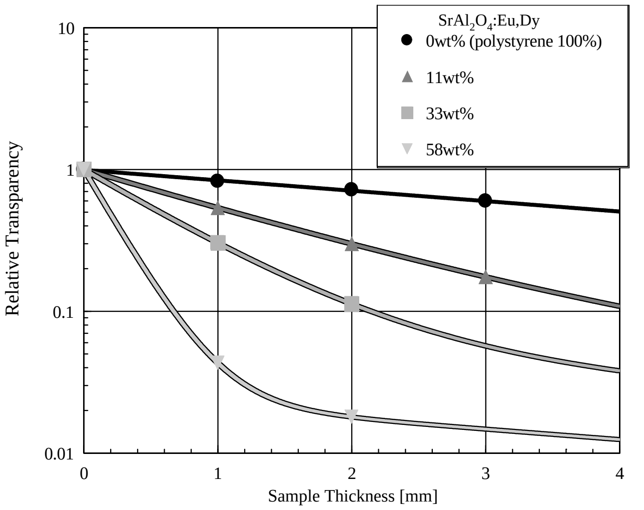

Fig. 7 Light attenuation characteristic of LLP element for 520 nm

The total absorption rate of the generated light in the LLP element, H, is expressed as follows:

$$H = \int_0^{x_0} f(E)\eta(x)dx. \tag{8}$$

The measured relative light attenuation coefficient in the LLP detector element is shown in Fig. 7. The light with wavelength of 520 nm that is the same as LLP luminescence was introduced onto sample through a hole (diameter: 1.0 mm) from a spectroscope. The light that passed through the sample was detected using the PIN photo diode. The penetrating light fluxes were measured by changing the thickness of the detector element from 1.0 through 3.0 mm and the mass concentration rate of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ from 0 (polystyrene 100%) through 58 wt%.

In this study, Ω_{photon} is obtained from the geometrical arrangement of the PMT, the radiation source, and of the LLP element, which is as follows:[7)]

$$\begin{aligned}\Omega_{\text{photon}} = \frac{\omega^2}{4}\Biggl\{ & 1 - \frac{3}{4}(\psi^2 + \omega^2) \\ & + \frac{15}{8}\left(\frac{\psi^4 + \omega^4}{3} + \psi^2\omega^2\right) \\ & - \frac{35}{16}\left[\frac{\psi^6 + \omega^6}{4} + \frac{3}{2}\psi^2\omega^2(\psi^2 + \omega^2)\right]\Biggr\}, \end{aligned} \tag{9}$$

$$\psi = \frac{R_{\text{LLP}}}{d}, \quad \omega = \frac{R_d}{d}.$$

The ellipse shaped LLP detector element was assumed to be a circle with the same surface area.

6. Measurements

The LLP detector element accumulates the absorbed energy and emits some of it as luminescence during the irradiation process, while after irradiation has been stopped, all the remaining accumulated energy is released gradually and luminous intensity decays with time. Total energy stored in the LLP detector element and decay properties are much affected by ambient temperature.[1)] In the present study, much attention was paid to temperature control of the LLP detector elements during irradiation and measurement:

A luminescence measurement run was divided into three steps.

Step 1: Before radiation exposure, background noise that is caused mainly by electrical and thermal noises was measured.

Step 2: During irradiation, the luminous intensity rate increase at a constant temperature was measured. The rate increase is determined by the balance between accumulation of absorbed energy of ionizing radiation and energy release as luminescence.

Step 3: After irradiation, afterglow intensity at the same temperature as in Step 2 was measured. Afterglow intensity decreased monotonously through release of accumulated energy as luminescence.

The ambient temperature for irradiation was controlled at 300 K. The integration of the luminous intensity rate throughout the entire measurement time for Steps 2 and 3 was defined as the total luminous intensity.

III. Experimental Results and Discussion

1. Time-dependent Luminescence

Time-dependent luminescence from the exposed element at 300 K is shown in **Fig. 8** for alpha, beta and gamma ray irradiations. During irradiation (Step 2), luminescence increased and then reached a saturated level determined by the balance of the absorption and release. After irradiation was stopped (Step 3), luminescence decayed without regard to the quality of ionizing radiation.

2. Total Luminous Intensity

The total luminous intensity designated as the sum of Steps 2 and 3 is shown in **Fig. 9** for alpha, beta and gamma rays as a function of the total absorbed dose in the LLP detector elements. For all ionizing radiations, the total luminous intensity increased linearly in the range from 3 μGy to 100 mGy. For beta and gamma rays, the responses of the total luminous

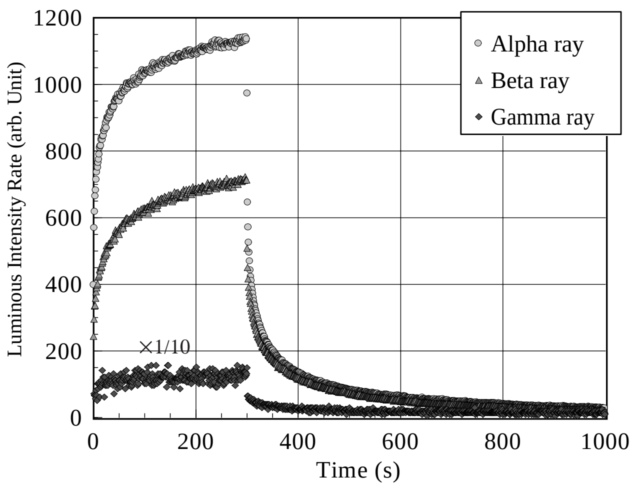

Fig. 8 Time dependent luminescence of LLP for various irradiations (Irradiation time: 300 s, Sample temperature: 300 K)

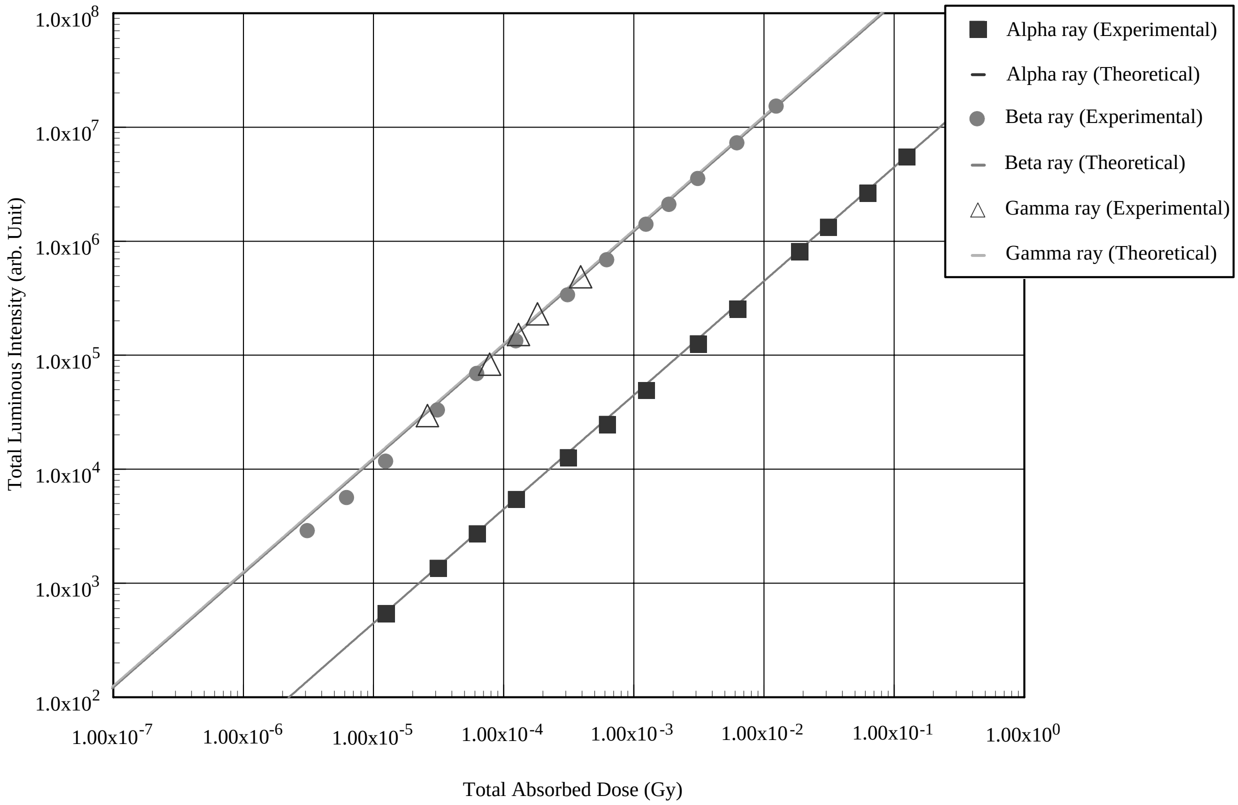

Fig. 9 Linear response of LLP luminescence for total absorbed dose (Irradiation temperature: 300 ± 0.1 K)

intensity were in complete agreement. For the alpha ray irradiation, however, the response of the total luminous intensity differed from the others.

3. W_p Values

(1) Definition of W_p Value

In order to evaluate the effects of quality of ionizing radiation on the luminous efficiency, the LLP, the average energy for production of one luminescence photon, W_p, was defined. The W_p value of the LLP detector elements for each ionizing radiation could be obtained by dividing the total photons produced by irradiation by the total absorbed energy.

(2) Evaluation of Errors in Measured Value

The errors in the measured W_p values were evaluated as follows.

(a) Error Caused by Assuming Luminous Photon Spectrum as Monochromatic

Luminescence from LLP was made into 520 nm monochromatic light in this research. Luminescence from LLP was observed as a spectrum with a certain width. In this analysis, total photon numbers from the LLP detector elements were calculated by assuming 520 nm monochromatic light. This assumption could cause error of less than 5%.

(b) Errors Caused by PMT Efficiency

The quality of the PMT was uneven. The manufacturer's value[8] for the efficiency error was less than 10%. Change in the high voltage power supply was less than ±1 V, which would cause error of less than 0.25%.

(c) Error Caused by Integration of the Total Luminescence

Finite period measurement for the total luminescence to estimate infinite integration was thought to be in error by less than 1%. And the error caused by inclination of the LLP disk source was less than 3%.

(d) Error Caused by Estimation of Absorbed Energy in the LLP Detector Elements

The absorbed energy was calculated by using energy fluence at the element and the energy absorption coefficient of the element, which give an error of less than 1%. The errors caused by discrepancy between the point source for applying Eq. (2) and the LLP disk source was estimated of less than 9% at the maximum.

Therefore, the maximum errors of W_p values could be estimated as about 15% including consideration of propagation of the individual errors. The W_p values for each ionizing radiation type were obtained as shown in **Table 3**. The W_p values for beta and gamma rays agreed with each other within the error range but the W_p value for alpha rays differed from them.

(3) Comparison of W_p Values

The W_p values of various radiation detectors for beta and gamma rays are shown in **Table 4**. The W_p value of the LLP detector elements was measured with beta and gamma ray sources, while those of the other elements was obtained with electrons ranging a kinetic energy of 1 MeV. The W_p value of the LLP detector elements was nearly the same as those of conventional scintillation phosphors.

Higher sensitivity to the ionizing radiation than for the conventional detectors indicated that the LLP was a promising candidate for a sensitive radiation detector element.

Table 3 W_p values for various radiations

Radiation source	Species	Particle energy (MeV)	W_p value (eV/photon)
α	^{241}Am	4.68[a]	480 ± 72
β	^{90}Sr–^{90}Y	0.54, 2.24[b]	18 ± 2.7
γ	^{60}Co	1.17, 1.33	18 ± 2.7

[a]Measured value

[b]Maximum beta ray energies for ^{90}Sr and ^{90}Y, respectively

Table 4 W_p values for various radiation detector elements

Radiation detection element	W_p value (eV/1 photon)
Liquid Ar[a]	25.1 ± 1.8[9]
NaI:Tl[a]	17 ± 0.6[10]
CsI:Tl[a]	15.5[11]
$SrAl_2O_4$:Eu,Dy[b]	18 ± 2.7

[a]Measured W_p value for 1 MeV electrons

[b]Measured W_p value for beta rays (this work)

4. Luminescence Efficiency

The W_p value of the LLP detector elements for alpha rays was different from those for beta and gamma rays. In order to determine the W_p value for the quality of ionizing radiations, the average absorbed energy in the LLP detector elements used to be considered. But in order to explain those differences, short-term recombination of electron and hole pairs in the LLP detector elements as well as generation of the pairs (equivalent to energy absorption) should be considered. Excess electron and hole pair generation enhances their short-term recombination. One of the measures of densities of pair generations is LET (Linear Energy Transfer) in materials. Relative luminescence efficiency is shown in **Fig. 10**, as a function of the average LET of the ionizing radiation.

The relative luminescence efficiency for alpha rays with high LET was very low. The penetration depth of alpha rays in the LLP detector elements was about 34.3 μm and the energy was absorbed in the surface vicinity. The average LET for alpha rays was defined as the ratio of the total energy absorption to the effective thickness for energy absorption. Therefore the average deposited energy density was very high.

Holes produced by the absorption of energy in the LLP are transferred through the valence band and then trapped by Dy^{3+} ions as Dy^{4+}.[2,3] At the same time, electrons are captured by Eu^{2+} ions as Eu^{+}. The holes trapped by Dy^{3+} ions are released slowly and recombine with electrons captured by Eu^{2+} ions to emit photons.[2,3] The energy accumulation rate in the LLP (equivalent to hole trapping rate by Dy^{3+} ions) is determined by hole number density in the LLP in the quasi-equilibrium state. Hole and electron densities in the conduction band and valence band respectively, $[e]$ and $[h]$, in the LLP are expressed by the following mass balance equations:

$$\frac{d[e]}{dt} = G_e - a[e][h] - \lambda[e] \tag{10}$$

$$\frac{d[h]}{dt} = G_h - a[e][h] - \lambda[h]. \tag{11}$$

The generation rates of the electrons and holes in the unit vol-

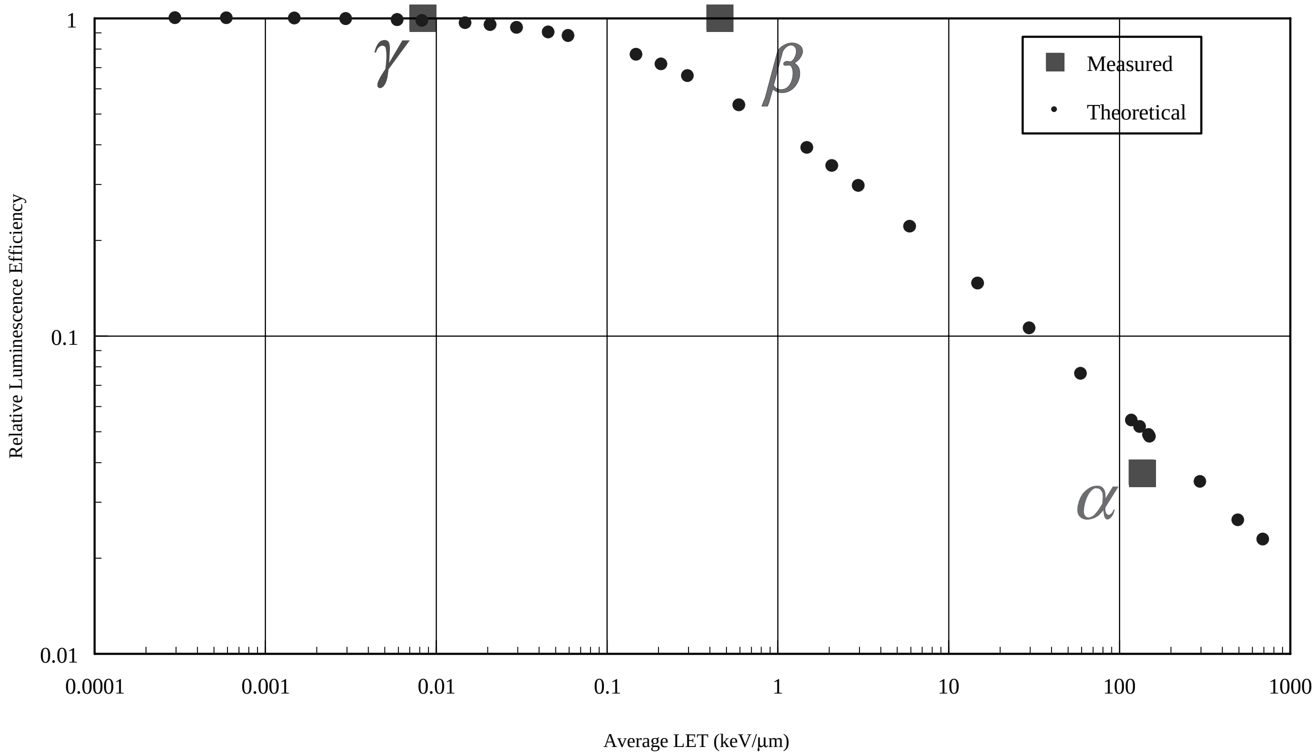

Fig. 10 Relative luminescence efficiency for the average LET

ume, G_e and G_h are obtained by the following equation:

$$G_e = G_h = \frac{\Delta E}{W}. \tag{12}$$

A couple of absorbed energy rates of the unit volume, ΔE and W value of the LLP for the ideal condition (18.0 eV) can give generation rates of electrons and holes. And capture rate of electrons and holes, λ, is assumed to be equal in this study. The recombination factor of electrons and holes was determined by the best-fit curve shown in Fig. 10. It was expected that the possibility of short-term recombination before generated electrons and holes in the LLP are captured to Eu and/or Dy ions in the case of alpha rays was very high due to its high local charge density. Conversely, for beta and gamma rays, the local charge density in the LLP was not high due to their low average deposited energy. Therefore the possibility of short-term recombination was relatively low. As a result, the luminescence efficiency was high.

IV. Conclusions

Luminescence from long lasting phosphor (LLP), $SrAl_2O_4$:Eu^{2+},Dy^{3+}, detector elements exposed to various ionizing radiations has been measured. Determination of the W_p value has been carried out. The W_p value for beta and gamma rays was estimated as 18 ± 2.7 eV, while that for alpha rays was estimated as 480 ± 72 eV. The W_p values for beta and gamma rays were almost the same as those of the conventional scintillation detectors such as NaI (Tl) and CsI (Tl). Total luminous intensity from the LLP detector elements was confirmed to be proportional to total absorbed energy in the LLP detector elements. High sensitivity to beta and gamma rays, long luminescence life-time and linearity to total absorbed energy in the LLP detector elements indicated these elements were suitable for application to two-dimensional radiation monitor for digital radiography.

Difference in the luminescence efficiency for beta and gamma rays and alpha rays was considered to be mainly due to the difference in their LET in the elements. As a result of evaluating the response of luminescence to alpha, beta, and gamma rays, it was confirmed that short-term recombination of holes and electrons generated in the LLP detector elements played an important role in energy accumulation in the elements. A model based on generation of hole and electron pairs, their short-term recombination and their trapping at Dy^{3+} and Eu^{2+} sites was proposed to explain the differences in the luminous efficiency of various ionizing radiations.

Abbreviations

CCD: Charge Coupled Device
DR: Digital Radiography
LET: Linear Energy Transfer
LLP: Long Lasting Phosphor

Nomenclature

$A_{\alpha\text{-source}}$: Source activity of alpha rays (Bq)
$A_{\beta\text{-source}}$: Source activity of beta rays (Bq)
$A_{\gamma\text{-source}}$: Source activity of gamma rays (Bq)
a: Recombination factor ($mm^2\cdot\mu m/s$)
d: Distance from the LLP element to the PMT surface (mm)
E_α: Energy of alpha rays (MeV) [4.68MeV]
$E_{\beta\text{-max}}$: Maximum energy of beta rays of ^{90}Sr–^{90}Y (MeV)
E_γ: Energy of gamma rays (MeV)
$[e]$: Density of electrons ($10^{-3}/mm^3$)
F: Conversion rate of the I-F converter (A/count)
$f(x)$: Relative deposited energy distribution in the LLP element (1/mm)
G_e: Generation rate of electrons in a unit volume ($10^{-3}/mm^3/s$)
G_h: Generation rate of holes in a unit volume ($10^{-3}/mm^3/s$)
$[h]$: Density of holes ($10^{-3}/mm^3$)
H: Total absorption rate of the generated light in the LLP element
I: Counts obtained by the MCS (counts)
l: Light path length of the depth x and the generating light of the discharge angle θ in LLP detector element (mm)
$P_\beta(E)$: Relative intensities of electrons of a given beta ray energy (1/eV)
QE: Quantum efficiency of the PMT
R: Distance from the LLP element to the radiation source (mm)
R_{LLP}: Radius of the LLP element (mm)
R_d: Radius of the PMT window (mm)
W: The W value of the LLP for the ideal condition (eV/a pair)
W_p: Average energy for which one photon was produced in the LLP (eV/a photon)
x: Depth of the LLP element (mm)
x_0: Thickness of the LLP element (mm) [10.0 mm]
ΔE: Absorbed energy rate of the unit volume (10^{-3} $eV/mm^3/s$)
ΔE_α: Total absorbed energy for alpha ray irradiation (eV)
ΔE_β: Total absorbed energy for beta ray irradiation (eV)
ΔE_γ: Total absorbed energy for gamma ray irradiation (eV)
Δt: Irradiation time (s)
ε: Mass fraction of LLP in the LLP element [0.58]
$\eta(x)$: Attenuation rate of the generated light in the section $[x,\ x+dx]$
θ: Generating light of the discharge angle in LLP element
θ_c: Critical angle to which this generated light is emitted at the surface of the LLP element
θ_{source}: LLP element angle to the radiation source [45°]
λ: Capture rate of electrons and holes (s^{-1})
μ: Light attenuation coefficient of the LLP element (cm^{-1})
μ_{PMT}: Current magnitude of the PMT
$(\mu_{en}/\rho)_{LLP}$: Mass energy absorption coefficient of LLP for 1.25 MeV (cm^2/g)
ρ_{LLP}: Measured density of the LLP element (g/cm^3) [1.922 g/cm^3]
Φ_{total}: Number of photons emitted from the surface of the LLP element (photons)
$\Omega_{particle}$: Geometrical efficiency of incident particles from the radiation source
Ω_{photon}: Geometrical efficiency of the light collection of the PMT.

Acknowledgments

We wish to express our thanks to Dr. Carol Kikuchi for their suitable advise on English expressions.

References

1) M. Kowatari, D. Koyama, Y. Satoh, *et al*., "The temperature dependence of luminescence from a long lasting phosphor exposed to ionizing radiation," *Nucl. Instrum. Methods A*, **480**, 431 (2002).
2) T. Matsuzawa, Y. Aoki, N. Takeuchi, *et al*., "A new long phosphorescent phosphor with high brightness, $SrAl_2O_4:Eu^{2+},Dy^{3+}$," *J. Electrochem. Soc.*, **143**, 2670 (1996).
3) H. Yamamoto, T. Matsuzawa, "Mechanism of long phosphorescence of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ and $CaAl_2O_4:Eu^{2+},Nd^{3+}$," *J. Luminescence*, **72–74**, 287 (1997).
4) S. Uchida, M. Kowatari, Y. Satoh, "A two-dimensional radiation monitor," Japanese Patent, Application No. 2001-223409, July 24, 2001, [in Japanese].
5) T. Matsuzawa, Y. Aoki, N. Takeuchi, *et al*., "Effect of composition new on the long phosphorescent $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphor crystal," *J. Electrochem. Soc.*, **144**, L243 (1997).
6) G. F. Knoll, *Radiation Detection and Measurement* (2nd Ed.), Wiley, New York, 222 (1989).
7) N. Tsoulfanidis, *Measurement and Detection of Radiation*, Translated into Japanese by E. Sakai, Gendai-kogakusha, 269 (1986), [in Japanese].
8) "General Catalogue for Photomultiplier Tubes," Hamamatsu Photonics, (1990).
9) H. J. Crawford, T. Doke, A. Hitachi, *et al*., "Ionization and scintillation signals produced by relativistic La ions in liquid argon," *Nucl. Instrum. Method A*, **256**, 47 (1987).
10) M. Miyajima, S. Sasaki, H. Tawara, "Numbers of scintillation photons produced in NaI(Tl) and plastic scintillator by gamma-rays," *IEEE Trans. Nucl. Sci.*, **NS-40**[4], 417 (1993).
11) T. Doke, E. Shibamura, S. Kubota, "Maximum scintillation yield in NaI(Tl)," *J. Phys. Soc. Jpn.*, **68**[7], 2433 (1999).