Simultaneous Measurements of Absolute Numbers of Electrons and Scintillation Photons Produced by 5.49 MeV Alpha Particles in Rare Gases

K. Saito, S. Sasaki, H. Tawara, T. Sanami, and E. Shibamura

***Abstract*—The absolute numbers of scintillation photons and electrons produced by 5.49 MeV alpha particles were measured simultaneously in argon, krypton and xenon in the gas pressure range from 1.01 $\times 10^5$ Pa to 1.01 $\times 10^6$ Pa. The ratio of the number of excited atoms to the number of electron-ion pairs is an important quantity for understanding the energy pathway of the absorbed radiation energy and was found to be 0.52, 0.55, and 0.60 in argon, krypton and xenon, respectively. The ratios were determined by measuring the number of scintillation photons originating from the excited atoms and the number of electrons. The value of W_s, which is defined as the average energy to produce one photon, in the case that all of the electron-ion pairs recombine was estimated to be 17.5, 15.4, and 13.0 eV in argon, krypton and xenon, respectively. From the relation between the numbers of electrons escaping from the recombination with ions and the numbers of scintillation photons, it is confirmed experimentally that one scintillation photon is emitted from one recombination process. This means that an excited molecule caused by three-body collisions is not de-excited without emitting a scintillation photon in the vacuum ultraviolet region.**

***Index Terms*—Absolute number of scintillation photon, ionization, radiation detector, rare gas, scintillation yields.**

I. INTRODUCTION

RARE gases are used as a fundamental medium in radiation detectors because of their resistance to radiation damage and their flexible shape and density properties [1]. In addition, rare gases are one of few materials in which both scintillation and ionization can be measured simultaneously and many researches have been performed on the processes of ionization and scintillation in rare gases.

The efficiency of ionization by charged particles in a gas is generally evaluated as W, which is defined as the average energy expended per ion pair. The expression "ion pair" is used to describe electron-ion pair. The value of W is given by

$$W = \frac{E}{N_\mathrm{i}} \tag{1}$$

where E is the kinetic energy of the charged particle absorbed in a gas and N_i is the average number of ion pairs. Platzman represented the energy balance of E by the following [2]:

$$E = N_\mathrm{i}E_\mathrm{i} + N_\mathrm{ex}E_\mathrm{ex} + N_\mathrm{i}\varepsilon \tag{2}$$

Manuscript received May 17, 2003; revised July 1, 2003.

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Digital Object Identifier 10.1109/TNS.2003.820615

where N_i is the average number of ion pairs produced for an average energy expenditure of E_i, N_ex is the average number of excited atoms for an average energy expenditure of E_ex and ε is the average kinetic energy of subexcitation electrons, which are too slow to excite an atom or a molecule in a gas. Equation (2) shows that the energy of the particles is expended in ionization and excitation, and is dissipated as heat. Equation (2) is transformed as follows:

$$W = \frac{E}{N_\mathrm{i}} = E_\mathrm{i} + \left(\frac{N_\mathrm{ex}}{N_\mathrm{i}}\right) E_\mathrm{ex} + \varepsilon. \tag{3}$$

As Platzman pointed out, the ratio of W to the first ionization potential I is noteworthy because the value of W/I for fast charged particles is 1.7 in helium, neon, and argon and is 2.1 – 2.6 for common molecule gases [2]. W/I is written as

$$\frac{W}{I} = \frac{E_\mathrm{i}}{I} + \left(\frac{N_\mathrm{ex}}{N_\mathrm{i}}\right)\left(\frac{E_\mathrm{ex}}{I}\right) + \left(\frac{\varepsilon}{I}\right). \tag{4}$$

$N_\mathrm{ex}/N_\mathrm{i}$ is equal to the ratio of the corresponding average cross-sections, which is averaged over the degradation spectrum of the particle energies in ionization and excitation. Although $N_\mathrm{ex}/N_\mathrm{i}$ is an important parameter for understanding the energy pathway of radiation energy, there have been few experimental determinations of $N_\mathrm{ex}/N_\mathrm{i}$ [2], [3].

The scintillation from the rare gases above atmospheric pressure originates from the excited atoms and the recombination of the ion pairs produced by the ionizing radiation. In order to understand the energy balance of the absorbed energy, it is essential to obtain the number of scintillation photons caused by each origin. However, few measurements of the absolute number of scintillation photons have been made because determining the detection efficiency of photons is difficult as the scintillation photons from the rare gases lie in the vacuum ultraviolet (VUV) region. We measured the absolute number of scintillation photons originating from both the excited atoms and the recombination of ion pairs in argon, krypton, and xenon by determining precisely the collection efficiency of scintillation photons and the conversion efficiency from photons to electrons at the photocathode of the vacuum photodiode used to measure the photons, and determined the values of W_s for the rare gases [4], which is defined as the average energy expended per a scintillation photon [5]. The value of W_s is given by

$$W_\mathrm{s} = \frac{E}{N_\mathrm{p}} \tag{5}$$

where N_p is the average number of scintillation photons. W_s is used to evaluate an efficiency of scintillation.

One of the purposes of this work is to obtain knowledge corresponding to $N_{\rm ex}/N_{\rm i}$ through simultaneous measurements of the number of scintillation photons originating from excited atoms and the number of ion pairs. In this study, the scintillation processes caused by the excited atoms and the recombination of ion pairs were observed separately, and the number of scintillation photons originating from each process and that of the electrons produced in ionization were measured. The measurements were performed in argon, krypton and xenon at pressures from 1.01×10^5 Pa to 1.01×10^6 Pa.

II. Scintillation Processes in Rare Gases

The scintillation spectra from rare gases above atmospheric pressure have been observed [6], [7]. In the previous paper [4], we re-measured the spectra in argon, krypton and xenon above atmospheric pressure using a VUV monochromater with known overall transmission efficiency in the VUV region. At these pressures, the spectrum presents a Gaussian-like continuum distribution, in which the maximum amplitude occurs at 127, 148, and 175 nm and the width is 11, 13, and 15 nm in FWHM for argon, krypton, and xenon, respectively [4]. As described above, scintillation photons in rare gases above atmospheric pressure have two origins, and are considered to be emitted through the following mechanisms [8]. One is the scintillation originating from excited atoms

$$\mathrm{R}^* + \mathrm{R} + \mathrm{R} \rightarrow \mathrm{R_2}^* + \mathrm{R}, \quad (6)$$

$$\mathrm{R_2}^* \rightarrow \mathrm{R} + \mathrm{R} + h\nu(\mathrm{VUV}). \quad (7)$$

The other is the scintillation originating from ionized atoms

$$\mathrm{R}^+ + \mathrm{R} + \mathrm{R} \rightarrow \mathrm{R_2}^+ + \mathrm{R} \quad (8)$$

$$\mathrm{R_2}^+ + \mathrm{e_{th}} \rightarrow \mathrm{R}^{**} + \mathrm{R} \quad (9)$$

$$\mathrm{R}^{**} + \mathrm{R} + \mathrm{R} \rightarrow \mathrm{R_2}^{**} + \mathrm{R} \quad (10)$$

$$\mathrm{R_2}^{**} + (\mathrm{R}) \rightarrow \mathrm{R}^* + \mathrm{R} + (\mathrm{R}) \quad (11)$$

$$\mathrm{R}^* + \mathrm{R} + \mathrm{R} \rightarrow \mathrm{R_2}^* + \mathrm{R} \quad (12)$$

$$\mathrm{R_2}^* \rightarrow \mathrm{R} + \mathrm{R} + h\nu(\mathrm{VUV}). \quad (13)$$

Here, R is a rare gas atom, R^* an excited atom, R^{**} a highly excited atom, $\mathrm{R_2}^*$ an excited molecule, $\mathrm{R_2}^{**}$ a highly excited molecule, R^+ an atomic ion, $\mathrm{R_2}^+$ a molecular ion and $\mathrm{e_{th}}$ a thermalized electron. The scintillation originating from the former processes is called "excitation luminescence" and that from the latter is called "recombination luminescence." It should be noted that both processes lead to the production of a single VUV photon from one excited atom and the recombination of an ion pair. If the excitation luminescence occurs through only reactions (6) and (7), $N_{\rm ex}$ can be obtained by measuring the number of scintillation photons originating from the excited atoms. However, it is not easy to distinguish the origin of the respective scintillations by only measuring the scintillation because a scintillation photon is emitted from $\mathrm{R_2}^*$ in both the excitation luminescence and the recombination luminescence processes [8]. In this study, the excitation luminescence was measured separately by applying an electric field to a rare gas medium so as to prevent the recombination of ion pairs.

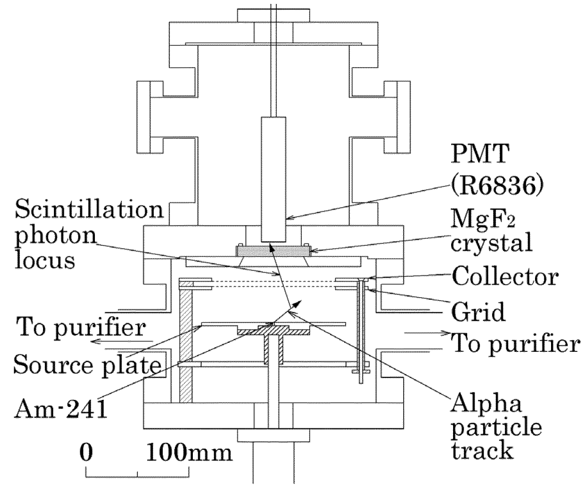

Fig. 1. Cross-sectional view of chamber.

III. Experimental

Fig. 1 shows a cross-sectional view of an experimental apparatus. The original apparatus is described in a previous paper [4]. A modification was made in order to measure scintillation photons and ionized electrons produced by alpha particles simultaneously. The geometry of the gridded ionization chamber, which consists of a source plate as a cathode, a grid and a collector, was introduced to measure the number of electrons. An alpha particle source ($^{241}\mathrm{Am}$) was electrochemically deposited on the top surface of a 2 mm diameter stainless-steel screw, which was fixed to the center of a 140 mm diameter source plate made of stainless steel. The grid and the collector consist of an array of tungsten wires coated with gold. The wire is 0.1 mm in diameter and is strung with 1.0 mm spacing on a ring-shaped flange (ID: 120 mm, OD: 184 mm). The grid geometry was introduced to the collector in order to observe the scintillation that occurred in the grid-to-cathode region through the grid and the collector. The distance between the collector and the grid is 5 mm. The shielding inefficiency of the grid [9] is calculated to be 4%. The minimum ratio $Z_{\rm min}$ of the electric field between the grid and the collector $E_{\rm gc}$ to the electric field between the source plate and the grid $E_{\rm kg}$ necessary to prevent electrons from attaching to the grid wires [9] is calculated to be 1.96. Measurements of the number of electrons produced by 5.49 MeV alpha particles were performed with $Z = E_{\rm gc}/E_{\rm kg} = 3.0$. The distance between the source plate and the grid can be varied between 3 and 35 mm. The distortion of the electric field between the source plate and the grid was examined by relaxation method and found to be less than 0.1% at 35 mm from the center axis of the electrodes.

In order to observe the scintillation photons, a 28-mm diameter PMT (Hamamatsu Photonics, R6836) with a $\mathrm{MgF_2}$ window and a Cs-Te photocathode was used. The R6836 is sensitive to photons in the wavelength region from 115 nm to 300 nm.

The apparatus is connected to a vacuum and gas-filling system with a purifier for the continuous purification of rare gases. The details of the vacuum and gas-filling system are described in the previous paper [4]. The purifier contains approximately 5000 pellets of getters, which are made of zirconium, vanadium, and iron. Before filling with rare gases,

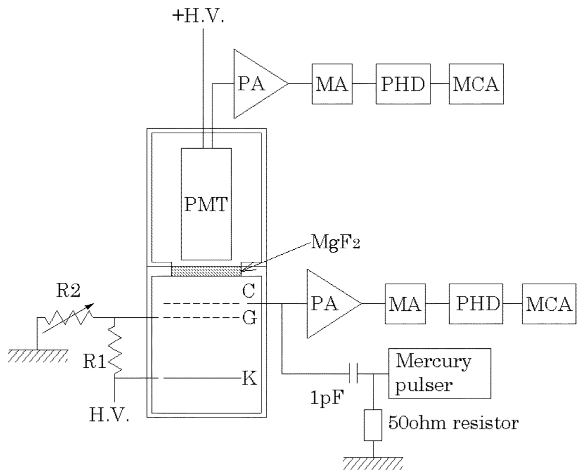

Fig. 2. Circuit used for measuring the numbers of electrons and the scintillation intensity. C is the collector, G the grid, and K the cathode in the chamber. R1 is a resistor and R2 a variable resistor in the divider circuit. PA is the charge sensitive preamplifier, MA the active-filter amplifier, PHD the peak hold detector and MCA the multichannel analyzer system.

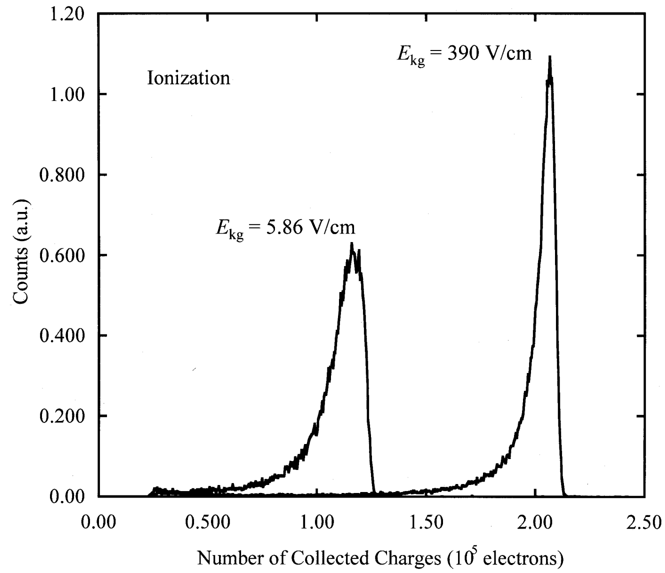

Fig. 3. Pulse height distribution obtained with a gridded ionization chamber in argon at 9.12 $\times 10^5$ Pa with Z = 3.

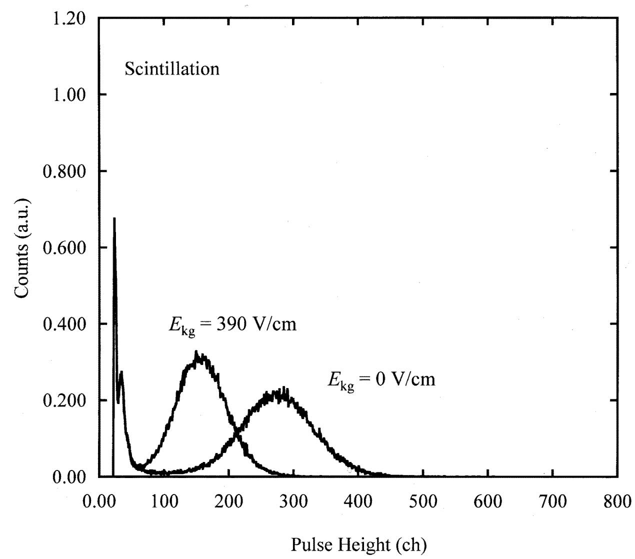

Fig. 4. Pulse height distribution obtained from the PMT in argon at 9.12 $\times 10^5$ Pa with $Z = 3$. The signals less than approximately 50 ch are due to noise.

the systems were evacuated to less than 1.0 $\times 10^{-5}$ Pa and the getters were activated. After evacuation, the systems were filled with research-grade rare gases having a purity of 99.9995%.

The measurements were carried out in the pressure range from 1.01 $\times 10^5$ Pa to 1.01 $\times 10^6$ Pa at room temperature (23°C) to investigate the pressure dependence of the scintillation and ionization yields. The accuracy in the pressure measurements is 0.5%. In order to introduce high-pressure rare gases, the PMT region was separated with a thick window of a MgF_2 crystal, as shown in Fig. 1. The PMT region above the window was filled with the same rare gas for measurements at a pressure of 1.01 $\times 10^5$ Pa.

Fig. 2 shows the electronic system, which consists of circuits for measuring scintillation and ionization. The signal pulses from the anode of the PMT were fed to a charge-sensitive preamplifier (Clear Pulse, CP1715), amplified by an active-filter amplifier (Clear Pulse, CP403) with a shaping time constant of 50 μs and stored in a multichannel analyzer system via a peak hold detector (Clear Pulse, CP4060). In the measurement of the number of electrons produced by alpha particles with the gridded ionization chamber, a negative potential was applied to the source plate and the grid through a divider circuit. The output signals from the collector of the gridded ionization chamber were fed to a low-noise charge-sensitive preamplifier (Clear Pulse, CP580H), amplified by an active-filter amplifier with a shaping time constant of 50 μs (Clear Pulse, CP403) and analyzed using a multichannel analyzer system through a peak hold detector (Clear Pulse, CP4060). The low-noise charge-sensitive preamplifier is equipped with a charge calibration system consisting of a charge terminator and a high-precision pulser. The system was calibrated with an alpha particle of known energy using a Si detector and another gridded ionization chamber. The pulse height of an alpha particle signal can be converted into the number of electrons with this system, achieving an accuracy of better than 0.5% [10].

The distance between the source plate and the grid was fixed during a series of the measurements at each pressure in order to keep the collection efficiency of photons at the photocathode of the PMT constant. Typical pulse height distributions obtained using the gridded ionization chamber and the PMT in argon at 9.12 $\times 10^5$ Pa are shown in Figs. 3 and 4, respectively. The horizontal axis in Fig. 3 shows the number of electrons gathered at the collector N_e, and that in Fig. 4 corresponds to the relative scintillation intensity. The relative scintillation intensity $I_s(-)$ was obtained by applying negative potentials to the ionization chamber during simultaneous measurement of N_e. N_e and $I_s(-)$ in argon at 1.52 $\times 10^5$ Pa are plotted as a function of E_{kg} in Fig. 5. Contrary to an expectation that $I_s(-)$ would be constant in the presence of an electric field, $I_s(-)$ increases with increasing E_{kg}, as shown in Fig. 5. This is because the scintillation photons originating from the atoms excited by electrons

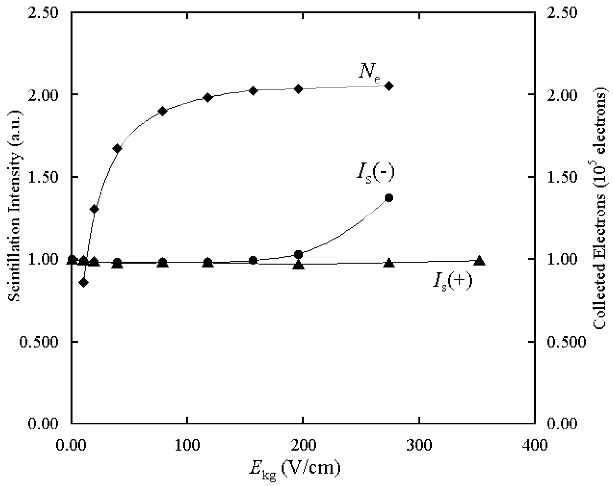

Fig. 5. N_e, $I_s(-)$ and $I_s(+)$ measured as a function of E_{kg} in argon at 1.52×10^5 Pa with $Z = 3$. $I_s(-)$ is the scintillation intensity obtained by applying a negative potential was applied to the ionization chamber and $I_s(+)$ is that for a positive potential was applied.

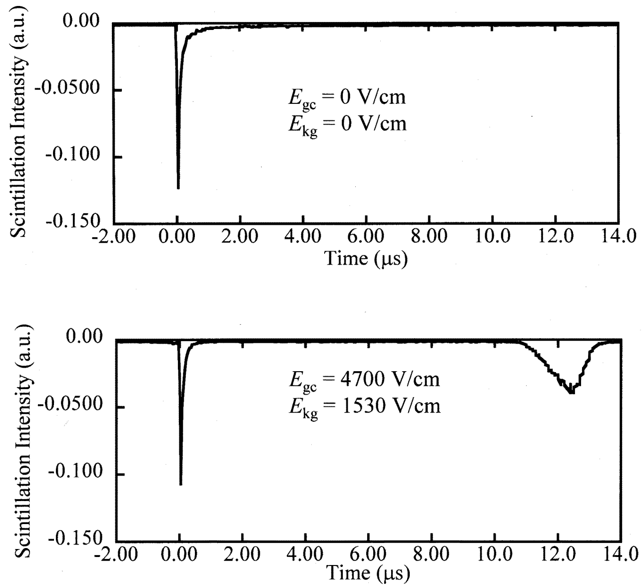

Fig. 6. Time profile of the scintillation intensity $I_s(-)$ in xenon at 1.01×10^6 Pa for $E_{gc} = 0$ and $E_{gc} = 4700$ V/cm with $Z = 3$.

accelerated by the electric field are emitted. This photon production is called "proportional scintillation." On the other hand, N_e becomes constant with increasing E_{kg}, as shown in Fig. 5, which shows that extra ionization by accelerated electrons dose not occur and that only the electrons produced by alpha particles are collected fully at the collector (namely, N_e in this case equals N_i). Proportional scintillation was also observed in krypton and xenon. The time profile of the scintillation signal at $E_{gc} = 4700$ V/cm in xenon at 1.01×10^6 Pa is shown in Fig. 6, where the profile at $E_{gc} = 0$ V/cm is also shown. The signals at 0 μs in both cases of $E_{gc} = 0$ V/cm and $E_{gc} = 4700$ V/cm correspond to the scintillation produced directly by alpha particles (primary scintillation) and the signal at around 12 μs at $E_{gc} = 4700$ V/cm is due to proportional scintillation. In these measurements, the distance between the source plate and the grid was set to 11 mm. The drift velocities of the electrons in xenon at 1.01×10^6 Pa with $E_{gc} = 4700$ V/cm (E_{kg} is equal to 1530 V/cm) are approximately 1.0×10^5 cm/s between the source plate and the grid and 1.5×10^5 cm/s [11] between the grid and the collector. The drift times of the electrons from the source plate to the grid and to the collector are calculated to be approximately 11 μs and 14 μs, respectively. Judging from the drift times, the proportional scintillation is supposed to occur in the region between the grid and the collector. As shown in Fig. 6, the slow decay component in the scintillation signal is observed at $E = 0$ V/cm but disappears under the existence of electric fields. This indicates that the slow decay component in the scintillation in high-pressure rare gases originates from the recombination of ion pairs. In order to prevent both recombination luminescence and proportional scintillation, the scintillation intensity $I_s(+)$ was measured by applying positive potentials, of which the absolute values were the same as those of the negative potentials used to measure N_e, to the source plate and the grid. In this case, though ions move toward the grid and the collector, they do not obtain sufficient energy to excite rare gas atoms. $I_s(+)$ is also plotted as a function of E_{kg} in Fig. 5. $I_s(+)$ does not increase with increasing E_{kg}.

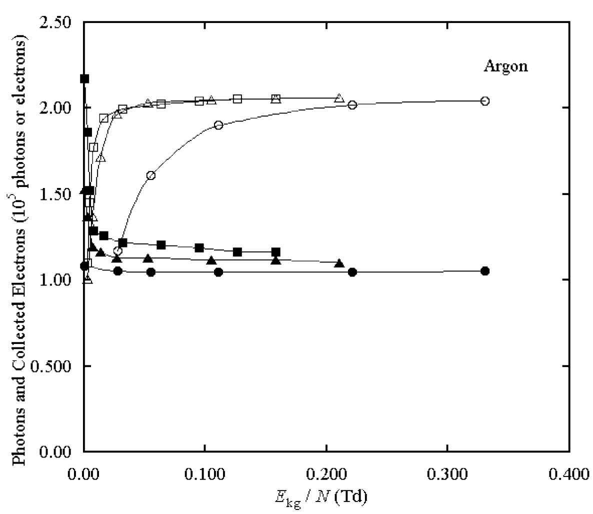

Fig. 7. Numbers of scintillation photons (black) and collected electrons (white) in argon at 2.03×10^5 Pa (circle), 6.08×10^5 Pa (triangle), and 1.01×10^6 Pa (square) with $Z = 3$. The unit of E_{kg}/N is denoted by "Td," where $1\ \text{Td} = 10^{-17}\ \text{Vcm}^2$.

In the present study, the number of scintillation photons at E_{kg} $N_p(E_{kg})$ is determined from the following:

$$N_p(E_{kg}) = \frac{I(+, E_{kg})}{I(+, 0)} \frac{5.49 \times 10^6}{W\text{s}} \tag{14}$$

where $I_s(+, E_{kg})$ is $I_s(+)$ obtained at E_{kg}. Here, W_s is the absolute scintillation yield measured without electric fields and is taken from the results in the previous measurements at each pressure [4]. N_p and N_e in argon, krypton and xenon are plotted as a function of E_{kg}/N in Figs. 7–9, respectively, where N is the number density of rare gas.

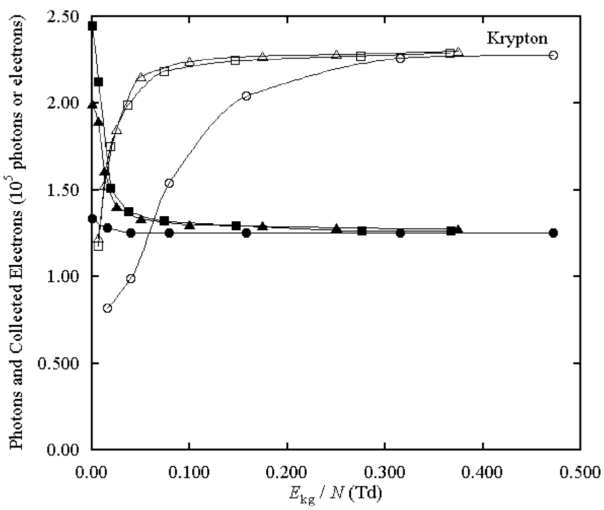

Fig. 8. Numbers of scintillation photons (black) and collected electrons (white) in krypton at 2.03×10^5 Pa (circle), 6.08×10^5 Pa (triangle), and 1.01×10^6 Pa (square) with $Z = 3$.

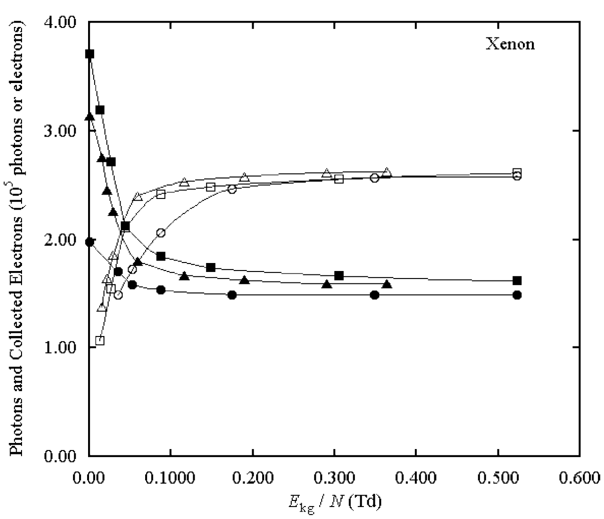

Fig. 9. Numbers of scintillation photons (black) and collected electrons (white) in xenon at 2.03×10^5 Pa (circle), 6.08×10^5 Pa (triangle), and 1.01×10^6 Pa (square) with $Z = 3$.

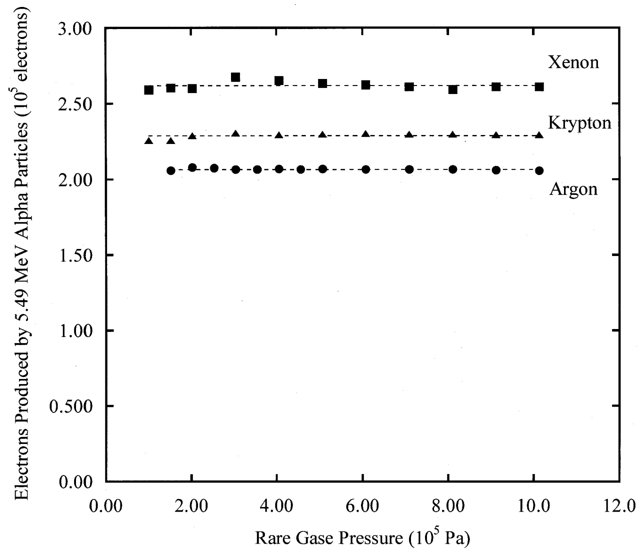

Fig. 10. Numbers of electrons produced by 5.49 MeV alpha particle in argon (circle), krypton (triangle), and xenon (square) as a function of the gas pressure.

TABLE I
W FOR 5.49 MEV ALPHA PARTICLES IN RARE GASES

Rare gas	W (eV) Present value 1.52×10^5 Pa	1.01×10^6 Pa	Summarized in ICRU Report 31
Argon	26.4 ± 0.5	26.7 ± 0.5	26.4
Krypton	24.0 ± 0.5	23.8 ± 0.5	24.1
Xenon	20.9 ± 0.4	21.0 ± 0.4	21.9

IV. Results and Discussion

The numbers of electrons collected fully at the collector of the ionization chamber in argon, krypton and xenon are plotted in Fig. 10 as a function of gas pressure. In the pressure range from 1.01×10^5 Pa to 1.01×10^6 Pa the numbers are independent of pressure. The values of W determined in the present study are given in Table I, where the values summarized by ICRU [12] are also shown. The present values of W are in good agreement with those summarized by ICRU. The uncertainty in the determinations of the peak position from the pulse height distributions is estimated to be within 1% in the measurements of N_e. The accuracy for the shielding inefficiency is 10% and the errors caused by the shielding inefficiency are evaluated to be within 0.1%. The uncertainty in the charge measurements using the charge calibration system is 0.5%. The uncertainties for N_e are obtained summing the errors described above and are less than 2%.

Figs. 11–13 represent the average number of scintillation photons produced by 5.49 MeV alpha particles at $E_{kg} = 0$ V/cm ($N_p(E_{kg} = 0)$) and that at $E_{kg} = E_{kg-sat}(N_p(E_{kg} = E_{kg-sat}))$, where the recombination of ion pairs is prevented completely, measured as a function of the gas pressure in argon, krypton and xenon, respectively. In the determinations of the number of scintillation photons, the uncertainties for W_s in argon, krypton and xenon are 4%–5%, 3%–7% and 3%–5%, respectively, as described in the previous report [4]. The uncertainty in the determinations of the gas pressure is evaluated to be less than 1%, and the errors related to this uncertainty for W_s is within 0.2%. The uncertainties in the determination of the peak position from the pulse height distribution are estimated be within 1% in the measurements of $I(+, E_{kg})$. Total errors in the present determinations of the numbers of scintillation photons are evaluated summing the errors described above. As shown in Figs. 11–13, $N_p(E_{kg} = E_{kg-sat})$ almost equals to $N_p(E_{kg} = 0)$ in the pressure range from 1×10^5 Pa to 2×10^5 Pa, where there is little contribution to scintillation yield from the recombination luminescence. Scintillation photons obtained at $E_{kg} = E_{kg-sat}$ are emitted only from excited molecules $R_2{}^*$ originating from the excited atoms. The excited molecule $R_2{}^*$ is formed by a

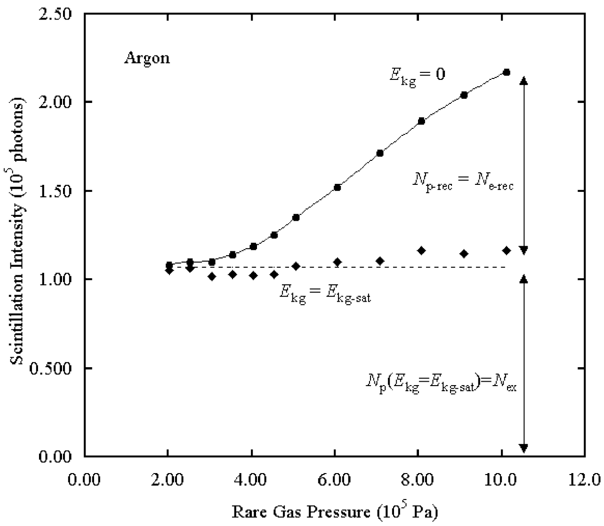

Fig. 11. Number of scintillation photons at $E_{\rm kg} = 0$ and $E_{\rm kg} = E_{\rm kg-sat}$ in argon.

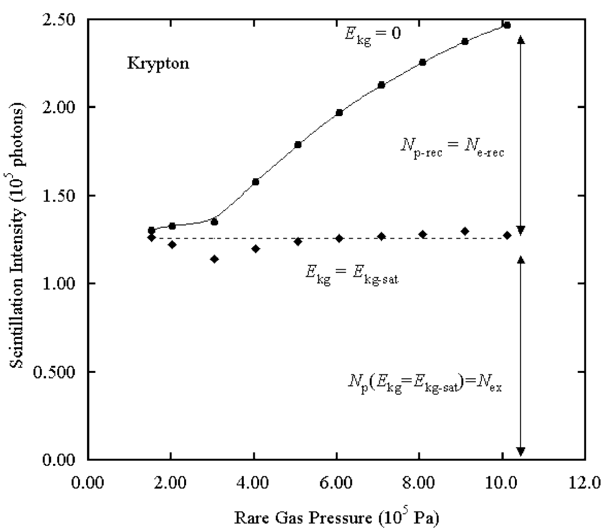

Fig. 12. Number of scintillation photons with $E_{\rm kg} = 0$ and $E_{\rm kg} = E_{\rm kg-sat}$ in krypton.

three-body collision as shown by reaction (6), and hence the rate depends on the gas pressure. However, above atmospheric pressure, $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ is independent of the gas pressure, and is constant, as shown in Figs. 11–13. This suggests that every excited atom contributes to the generation of an excited molecule ${\rm R_2}^*$ in reaction (6). Then, from reactions (6) and (7), the average number of excited atoms $N_{\rm ex}$ produced by alpha particles is given by $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ above atmospheric pressure. A further discussion will be made later. The average values of $N_{\rm i}$ and $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ obtained at each pressure are shown in Table II. The values of $N_{\rm ex}/N_{\rm i}$ are calculated from $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})/N_{\rm i}$ and to be 0.52, 0.55, and 0.60 in argon, krypton and xenon, respectively. Platzman calculated the values of $N_{\rm ex}/N_{\rm i}$ in helium, neon and argon to be 0.4 [2]. Kubota obtained experimentally the value of $N_{\rm ex}/N_{\rm i}$ to be 0.48 [3] in helium by using the Penning effect.

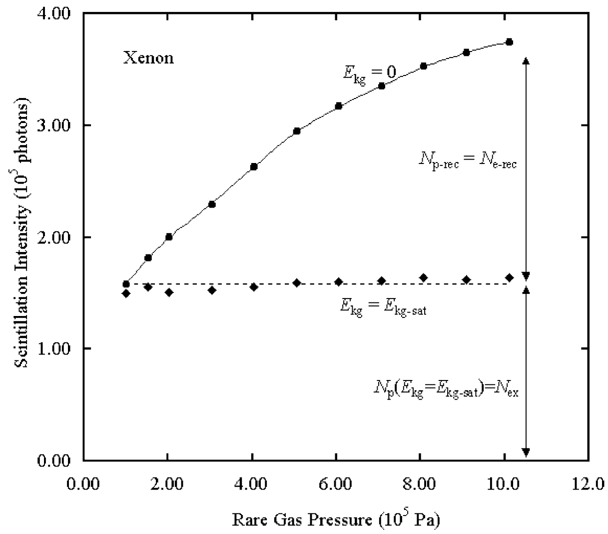

Fig. 13. Number of scintillation photons with $E_{\rm kg} = 0$ and $E_{\rm kg} = E_{\rm kg-sat}$ in xenon.

TABLE II
$N_{\rm i}$, $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ AND $N_{\rm ex}/N_{\rm i}$ IN RARE GASES FOR 5.49 MEV ALPHA PARTICLES

Rare gas	$N_{\rm i}$	$N_{\rm p}(E_{\rm kg}=E_{\rm kg\text{-}sat}) = N_{\rm ex}$	$N_{\rm ex}/N_{\rm i}$
Argon	2.07×10^5	1.07×10^5	0.52
Krypton	2.31×10^5	1.26×10^5	0.55
Xenon	2.63×10^5	1.59×10^5	0.60

The value of $W_{\rm s}$ becomes a minimum ($W_{\rm s,min}$) when all of the ion pairs recombine and result in scintillation. The value of $W_{\rm s,min}$ can be obtained from $N_{\rm ex}$ and $N_{\rm i}$ as follows:

$$W_{\rm s,min} = \frac{E}{(N_{\rm ex} + N_{\rm i})}. \tag{15}$$

The value of $W_{\rm s,min}$ is calculated to be 17.5 eV, 15.4 eV and 13.0 eV in argon, krypton and xenon, respectively. The value of $W_{\rm s,min}$ in xenon is smaller than the value of $W_{\rm s}$ measured in liquid xenon (16.3 ± 0.3 eV) [5], where the effect of quenching may cause the larger value. The value of $W_{\rm s,min}$ in xenon is close to $W_{\rm s}$ in liquid xenon (13.8 eV), which was evaluated assuming no effect of quenching [13].

$N_{\rm p}(E_{\rm kg} = 0)$ increases with increasing gas pressure, which is due to an increase in the number of recombining ion pairs. If the number of electrons recombining with ions $N_{\rm e-rec}$ is equal to the number of scintillation photons originating from the recombination process $N_{\rm p-rec}$, the number of escaping electrons $N_{\rm e-esc}$, which do not recombine with ions, is given by

$$N_{\rm e-esc} = N_{\rm i} - N_{\rm e-rec} = N_{\rm i} - N_{\rm p-rec} \tag{16}$$

$$N_{\rm p-rec} = N_{\rm p}(E_{\rm kg} = 0) - N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat}). \tag{17}$$

A proof that $N_{\rm e-rec}$ is equal to $N_{\rm p-rec}$ will be given later. The ratio of $N_{\rm e-esc}$ to $N_{\rm i}$ is plotted as a function of the gas pressure

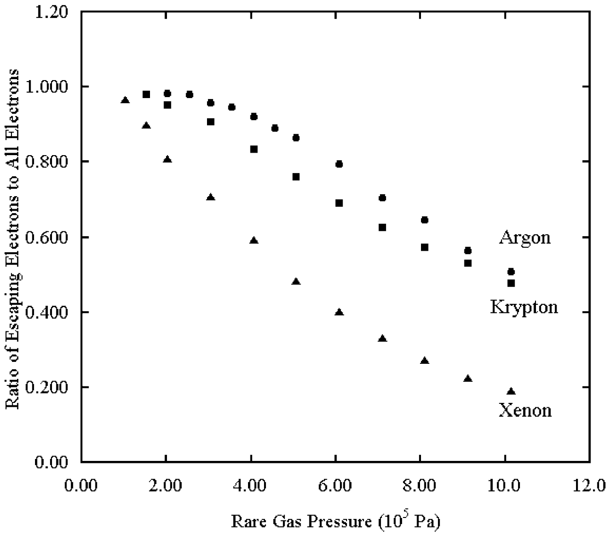

Fig. 14. Ratio of the number of escaping electrons to the total number of electrons produced by an alpha particle in argon (circle), krypton (square), and xenon (triangle).

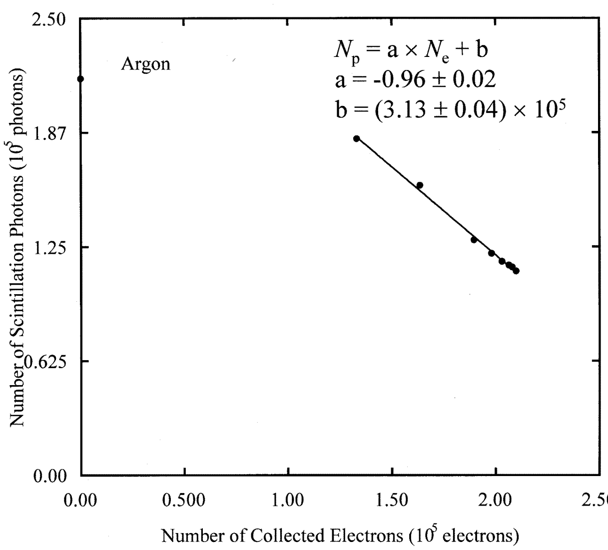

Fig. 15. Numbers of scintillation photons $N_{\rm p}$ as a function of the number of collected electrons $N_{\rm e}$ in argon at 1.01 $\times 10^6$ Pa.

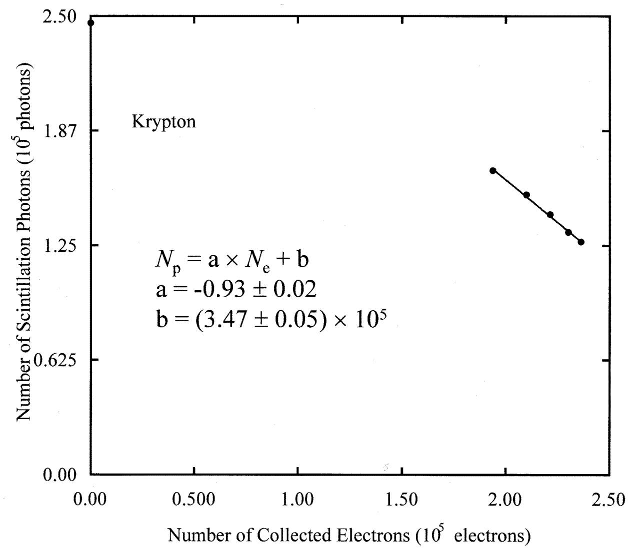

Fig. 16. Numbers of scintillation photons $N_{\rm p}$ as a function of the number of collected electrons $N_{\rm e}$ in krypton at 1.01 $\times 10^6$ Pa.

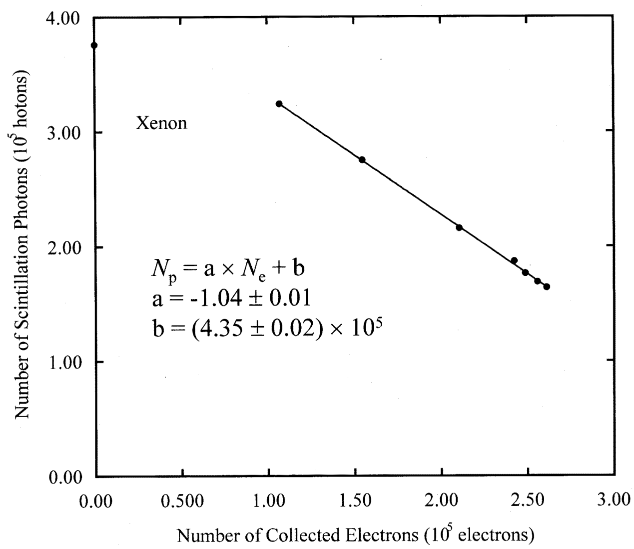

Fig. 17. Numbers of scintillation photons $N_{\rm p}$ as a function of the number of collected electrons $N_{\rm e}$ in xenon at 1.01 $\times 10^6$ Pa.

in Fig. 14, where it can be seen that $N_{\rm e-esc}/N_{\rm i}$ decreases with increasing gas pressure. After an energetic electron slows down to thermal energy by collisions with rare gas atoms, the thermalized electron recombines with an ion. The average distance between an ion and an electron is smaller at higher pressures. When the coulomb potential between the electron and the ion is less than the kinetic energy of a thermalized electron, the escaping probability of an electron from the influence of an ion increases.

The numbers of scintillation photons $N_{\rm p}$ are plotted as a function of the number of collected electrons $N_{\rm e}$ in argon, krypton and xenon at 1.01 $\times 10^6$ Pa in Figs. 15–17, respectively. These measurements were performed at sufficiently higher values of Z (5.0, 5.0 and 3.0 in argon, krypton, and xenon, respectively) than $Z_{\min}$ in order to prevent electrons from being captured by the grid due to the diffusion of electrons, even in a small $E_{\rm kg}$.

TABLE III
FITTING PARAMETERS OF A STRAIGHT LINE AND THE SUMS OF $N_{\rm ex} = N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ AND $N_{\rm i}$

Rare gas	a	b	$N_{\rm ex} + N_{\rm i}$
Argon	-0.96 ± 0.02	(3.13 ± 0.04) × 10^5	3.15 × 10^5
Krypton	-0.93 ± 0.02	(3.47 ± 0.05) × 10^5	3.57 × 10^5
Xenon	-1.04 ± 0.01	(4.35 ± 0.02) × 10^5	4.23 × 10^5

The straight line was obtained by least-squares fitting to data other than $N_{\rm e} = 0$. The parameters of the line are summarized in Table III, where a is the slope and b is the intercept of the line. The values of a in argon, krypton and xenon take a value close to -1. The values of b indicate the number of scintillation photons in the case that all ion pairs recombine. The sum of $N_{\rm ex} = N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ and $N_{\rm i}$ from Table II is also given in Table III, and it is in good agreement with b in argon, krypton and xenon.

The number of scintillation photons is complementary to the number of electrons gathered at the collector. These results provide a proof that one photon is necessarily emitted from one recombination process (namely, $N_{\rm e,rec}$ is equal to $N_{\rm p,rec}$). It is also confirmed that one excited molecule ${\rm R_2}^*$ results from one ion pair, and ${\rm R_2}^*$ caused by the recombination cannot be de-excited without emitting VUV photons. The luminescence spectrum in atmospheric pressures, where the luminescence is almost due to the excitation luminescence, does not differ from that in high pressure [4], [14] where the recombination luminescence also exists. This means that the molecular state of ${\rm R_2}^*$ for photon emission is the same in each process. It can be also confirmed that ${\rm R_2}^*$ originating from an excited atom is also not de-excited without emitting one VUV photon. From the results mentioned above, and that $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ is constant and independent of the gas pressure, one may conclude that the number of excited atoms $N_{\rm ex}$ is equal to the number of scintillation photons originating from excited atoms $N_{\rm p}(E_{\rm kg} = E_{\rm kg-sat})$ above atmospheric pressure.

V. Conclusion

We performed simultaneous measurements of the numbers of electrons and the numbers of absolute scintillation photons produced by 5.49 MeV alpha particles in argon, krypton and xenon. The numbers of scintillation photons originating from excited atoms and from recombination of ion pairs were measured separately. It became clear in this study that one recombination process generates one VUV scintillation photon and that one excited atoms leads to one VUV photon. It may be concluded that the excited molecular states ${\rm R_2}^*$ caused by recombination and excitation of atom are not de-excited without emitting a single VUV photon. Namely, $N_{\rm ex}$ can be determined by measuring the number of scintillation photons originating from excited atoms. Both $N_{\rm ex}$ and $N_{\rm i}$ are independent of the pressure in the range from 1.01×10^5 Pa to 1.01×10^6 Pa. The value of $N_{\rm ex}/N_{\rm i}$ is obtained to be 0.52, 0.55, and 0.60 in argon, krypton, and xenon, respectively.

Acknowledgment

The authors would like to thank Prof. K. Kondo and Prof. T. Shibata for their useful discussion, comments, and encouragement throughout this work. Thanks are also due to the staff of Radiation Science Center at KEK for their support in this study.

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