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Absolute Scintillation Yields in Liquid Argon and Xenon for Various Particles

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For the determination of the absolute scintillation yields —the number of scintillation photons per unit absorbed energy— for a variety of particles in liquid argon, a series of simultaneous ionization and scintillation measurements were performed. The results verified that scintillation yields for relativistic heavy particles from Ne to La are constant despite their extensive range of linear energy transfer. Such a constant level, called "flat top response" level, manifests the maximum absolute scintillation yield in liquid argon. The maximum absolute scintillation yield is defined by the average energy to produce a single photon, $W_{ph}(\max) = 19.5 \pm 1.0$ eV. In liquid xenon, the existence of the same flat top response level was also found by conducting scintillation measurements on relativistic heavy particles. The $W_{ph}(\max)$ in liquid xenon was evaluated to be 13.8 ± 0.9 eV using the W_{ph} for 1 MeV electrons, obtained experimentally. The ratio between the two maximum scintillation yields at the flat top response level obtained in liquid argon and xenon is in good agreement with the estimation by way of the energy resolutions of scintillation due to alpha particles in both liquids. [DOI: 10.1143/JJAP.41.1538]

KEYWORDS: liquid rare gas, scintillation yield, LET dependence

1. Introduction

In the late 1980s, a series of experiments[1–8)] were conducted utilizing the ionizing particles from radioactive sources as well as non-relativistic or relativistic heavy ions from accelerators in order to investigate the linear energy transfer (LET) dependence of scintillation yields. In those experiments, absolute scintillation yields, the number of scintillation photons per unit absorbed energy, for test particles were determined through simultaneous measurements of ionization and scintillation.[9,10)] In 1988, Doke *et al.*[9)] summarized the scintillation yields in liquid argon for a variety of particles as a function of LET of individual particles. The constant yield was identified for a respective relativistic heavy particle from Ne to La, with the LET range of 10^2 to 10^3 MeV/g/cm^2. Such a flat region was named the "flat top response" region and it was considered that the scintillation light is fully emitted without any reduction process in the flat top response region for LET.[9)] Thus, the scintillation yield in the region was absolutely evaluated to be $W_{ph} = 19.5$ eV, which is the average energy to produce a single photon. Consequently, the authors expected the existence of an identical flat top level in liquid xenon as well, considering a scintillation mechanism similar or identical to that for liquid argon.[10)] In an effort to confirm such an expectation, a series of scintillation measurements were conducted by the authors on relativistic heavy particles in liquid xenon,[11)] applying instruments essentially identical to the one used for liquid argon. As expected, the flat top response in liquid xenon for relativistic heavy ions was found.[11)] Until now, liquid argon and liquid xenon experiments have been performed from the standpoint of the detector medium. In this paper, however, the results of two series of experiments are summarized from a physical viewpoint and conclusive results are presented.

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2. Scintillation Mechanism of Liquefied Rare Gases

The wavelength spectrum of most scintillations from a liquefied rare gas shows a single peak, corresponding to 129 nm for liquid argon or 178 nm for liquid xenon, with a width of approximately 10 nm, which is almost equal to that of scintillation from its gas state. In addition, the scintillation from liquid argon or liquid xenon has two decay time constants, corresponding to the decay from the singlet state of an excited dimer and the decay from its triplet state.[12)] On the basis of such experimental results, the scintillation from a liquefied rare gas is considered to be produced by the following two processes of excitons R^* and ions R^+ produced by ionizing radiation:[13)]

(i) R^*:

$$\begin{aligned} R^* + R + R &\to R_2^* + R, \\ R_2^* &\to 2R + h\nu \end{aligned}$$

(ii) R^+:

$$\begin{aligned} R^+ + R &\to R_2^+, \\ R_2^+ + e^- &\to R^{**} + R, \\ R^{**} &\to R^* + \text{heat}, \\ R^* + R + R &\to R_2^* + R, \\ R_2^* &\to 2R + h\nu, \end{aligned}$$

where $h\nu$ denotes the ultraviolet photon and the process $R^{**} \to R^* + \text{heat}$ corresponds to a non-radiative transition. In processes (i) and (ii), the excited dimer R_2^*, at the lowest excited level, should be de-excited to the dissociative ground state by emitting a single UV photon, because the energy gap between the lowest excitation level and the ground level is so large that there exists no decay channel such as non-radiative transitions. Although this is not yet fully confirmed by experiments, here, we assume that each excited dimer emits a single photon.[14)] Assuming the absence of a photon reduction process as will be described later, the average energy required for the production of a single photon,

W_{ph}(max), can be written as,[1,9,10,15)]

$$W_{ph}(\mathrm{max}) = W/(1 + N_{ex}/N_i), \quad (1)$$

where W is the average energy required for an electron-ion pair production, the so-called W-value. N_{ex} and N_i are respectively the numbers of excitons and ion pairs produced by an ionizing radiation. These values in liquid argon and xenon are shown in Table I.[18–20] The W-values in liquid argon and in liquid xenon are experimental.[18,19] Also, see ref. 19 for the N_{ex}/N_i calculation for both liquids. The ratio in liquid argon is in good agreement with the one experimentally obtained[20] and is supported by other experiments[21] as well, whereas the calculated ratio (0.06) in liquid xenon is not in agreement with the experimental value (~0.20) as will be discussed later. If the value of 0.20 is correct, one may conclude that W_{ph}(max) in liquid xenon should be smaller than the calculated one (14.7 eV[10]) in the same medium. It is reasonable to surmise, therefore, that this ratio of N_{ex}/N_i gives the lower limit and the calculated one, the upper limit of W_{ph}(max). In other words, the total uncertainty of W_{ph}(max) in liquid xenon estimated based on eq. (1) should be at most 11 or 13%, while the estimation error of the W_{ph}(max) for liquid argon should be a mere 4–5%.

Until now, the absolute ionization yield and the relative scintillation yield in liquid argon were simultaneously measured for relativistic heavy particles[1–3] as well as ionizing particles emitted from radioactive sources such as 1 MeV conversion electrons, α-particles and fission fragments.[4–8,13,22–24] Drawing on such data, the measurement of absolute scintillation yields for the particles may be performed, assuming that a single excited dimer emits a single photon.[9,25] Furthermore, the scope of relative scintillation yield measurement[11] in liquid xenon has recently been extended to relativistic heavy particles in addition to non-relativistic particles from various radioactive sources, as was made for liquid argon experiments. The result shows that the simple theory for scintillation from liquefied rare gases, which is expressed by eq. (1), may be successfully applied to explain the ratio of both scintillation yields at the flat top response levels for liquid argon and liquid xenon.

Table I. Measured values of W, calculated values of N_{ex}/N_i and previously estimated values of W_{ph}(max) in liquid argon and liquid xenon. The experimentally determined values of N_{ex}/N_i are also shown in parentheses.

	Liq.Ar	Liq.Xe
W (eV)	23.6 ± 0.3[18]	15.6 ± 0.3[19]
N_{ex}/N_i	0.21[19]	0.06[19]
	(0.19,[20] 0.29[a])	(0.20[a])
W_{ph}(max) (eV)	19.5[10]	14.7[10]
	(19.8, 18.4)	(13.0)

[a]Present paper.

3. Scintillation Yield and Its LET Dependence in Liquid Argon for Various Particles

The ionizing particles used in liquid argon experiments are summarized in Table II together with the energies ΔE deposited in the sensitive region of the chamber. From simultaneous measurements of ionization yields, $Q(\mathcal{E})$, and relative scintillation yields against alpha particles, $S_r(\mathcal{E})$, variations $Q(\mathcal{E})/Q_0$ and $S_r(\mathcal{E})/S_{r0}$ in liquid argon for relativistic Ne, Fe, La and Au particles expressed as a function of electric field, $\mathcal{E}$, are shown in Fig. 1(a),[1–3] where Q_0 is the charge to be collected under an infinite electric field and is given by $e\Delta E/W$, and S_{r0} is the relative scintillation yield at zero electric field. As expected, variations of the scintillation and ionization are complementary to each other in the electric field. Pre-flat top level response variations $Q(\mathcal{E})/Q_0$ and $S(\mathcal{E})/S_{r0}$ for relativistic H and He particles are shown as a function of electric field in Fig. 1(b).[3] Such variations are almost identical to those shown in Fig. 1(a). The data shown in Table II for the ionizing particles from the accelerators and from the radioactive sources serve as the basis for the data in Fig. 2 delineating the LET dependence of relative scintillation

Table II. Various ionizing particles used in the liquid argon experiment and their energies deposited in the sensitive region.

Particle	Source	Deposited energy	Range (cm)
Internal conversion electrons	^{207}Bi	0.976 MeV[5,8]	0.39
Alpha particles	^{210}Po	5.305 MeV[6,8]	5.6×10^{-3}
Fission fragments	^{252}Cf		$\sim 3 \times 10^{-3}$
heavy fragments		80.3 MeV[6,8]	
light fragments		106.2 MeV[6,8]	
Protons	the cyclotron of INS	17.8, 38.2 MeV[7]	0.38, 1.5
	the cyclotron of INS	11.9–24.1 MeV[24]	0.18–0.62
	the cyclotron of INS	7.3–18.0 MeV[24]	0.078–0.37
1.04 GeV/n protons	LBL Bevalac	4.04 MeV[a)3]	2.0
He ions	the cyclotron of INS	13.8–20.8 MeV[24]	0.022–0.043
1.04 GeV/n He ions	LBL Bevalac	17.0 MeV[a)3]	2.0
613 MeV/n Ne ions	LBL Bevalac	511 MeV[1]	2.0
705 MeV/n Fe ions	LBL Bevalac	3.31 GeV[1]	2.0
626 MeV/n Kr ions	LBL Bevalac	6.98 GeV[2]	2.0
1.08 GeV/n La ions	LBL Bevalac	15.5 GeV[2]	2.0
870 MeV/n Au ions	LBL Bevalac	32.4 GeV[3]	2.0

[a]These values are given as the most probable values in the energy loss distributions.

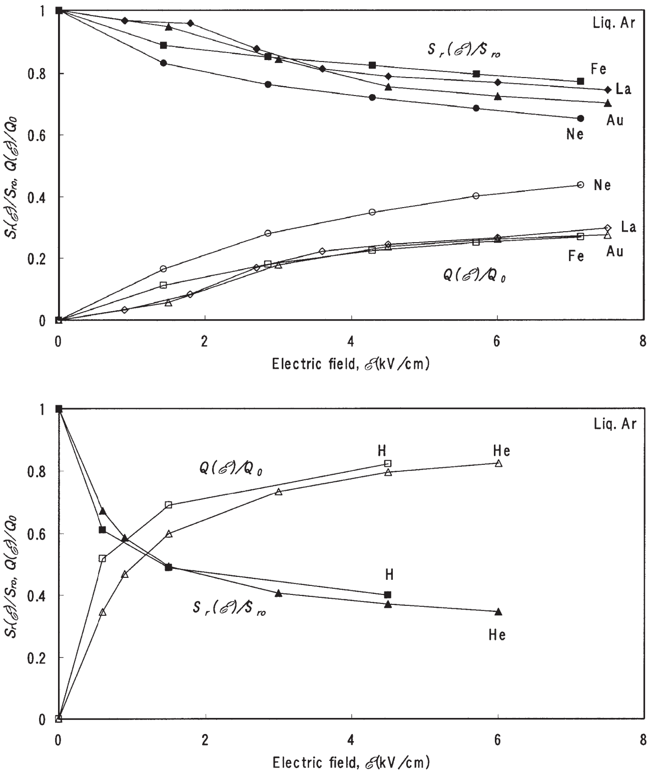

Fig. 1. (a) A set of the saturation curves of ionization (open symbols) and scintillation (solid symbols) for relativistic Ne (○,●),[1] Fe (□,■),[1] La (◊,♦),[2] and Au (△,▲)[3] in liquid argon as a function of the electric field strength. (b) A set of the saturation curves of ionization (open symbols) and scintillation (solid symbols) for relativistic H (□,■)[3] and He (△,▲)[3] particles in liquid argon as a function of the electric field strength.

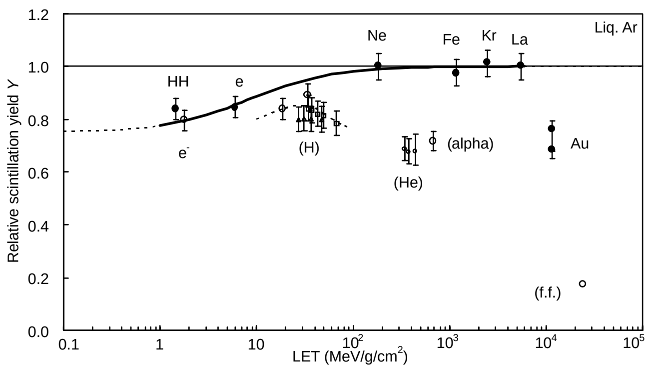

Fig. 2. LET dependence of scintillation yield, Y, in liquid argon. Solid circles show the yields for relativistic particles.[1–3] Non-relativistic particles are represented by open circles.[5–8] Open squares and triangles show the yields for non-relativistic protons[24] whereas small open circles show those for non-relativistic helium ions.[22]

yield in liquid argon. In Fig. 2, a flat top response for relativistic heavy particles from Ne to La is shown. The flat level corresponds to the maximum scintillation yield as will be shown later. Hereafter, therefore, we will take this level to be unity of the relative scintillation yield.

Next, let us examine the sum of ionization and scintillation, namely, the sum total of the number of electrons $Q(\mathcal{E})/e$ and the value of the relative scintillation yield $S_r(\mathcal{E})$, $Q(\mathcal{E})/e + aS_r$, where "a" is the conversion factor from the relative scintillation yield to the absolute number of photons

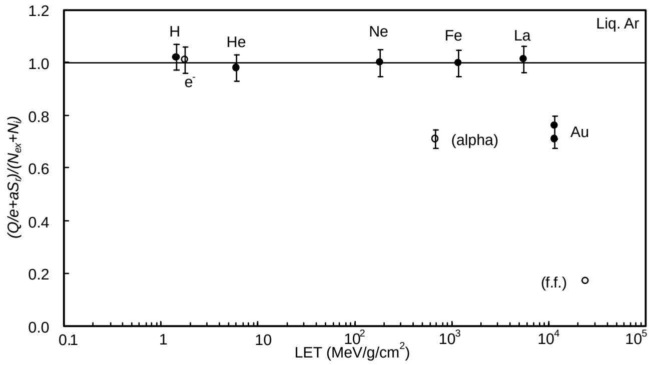

Fig. 3. LET dependence of the ratio, $(Q/e + aS_r)/(N_{ex} + N_i)$, in liquid argon. Non-relativistic particles are given in parentheses.

produced and is derived from the following relation at the flat top level,

$$aS_{r0} = \Delta E/W_{ph}(\max). \tag{2}$$

If such a conversion factor "a" is used, the value $\{Q(\mathcal{E})/e + aS_r(\mathcal{E})\}/(N_i + N_{ex})$ should be unity in the absence of photon-reduction processes as described later. Figure 3 shows the sum total of the scintillation and ionization values divided by $(N_i + N_{ex} \equiv E/W_{ph}(\max))$ as a function of particle LET. The error bars of $\pm 5\%$ in Figs. 2 and 3 comprise the counting errors as well as uncertainty factors related to $W_{ph}(\max)$ and beam location. As expected, the ratio expressed as $\{Q(\mathcal{E})/e + aS_r(\mathcal{E})\}/(N_i + N_{ex})$ for relativistic particles other than Au was unity whereas the ratios for Au, alpha particles and fission fragments as well as the ratio for the 1 MeV electron were smaller than unity. When the relativistic particle response is flat, $Q(\mathcal{E})/e + aS_r(\mathcal{E}) = N_i + N_{ex} = \Delta E/W_{ph}(\max)$ gives the total number of species, namely, the total number of scintillation photons and ion pairs produced by a single ionizing particle.

The LET dependence of the relative scintillation yield in regions other than the flat top shown in Fig. 2 may be caused by the escape of electron from recombination and/or the high density quenching of the scintillation photon.

3.1 Effect of escape electrons

The reduction in scintillation yields in the low LET region shown in Fig. 2 is explained as follows. According to the Onsager theory,[26] when an electron produced by an ionizing particle is slowed down to thermal energy within the Onsager radius from the parent ion, the electron cannot escape from the influence of the parent ion and the electron-ion pair recombines. Strictly speaking, the escape probability of the electron at the Onsager radius, where the Coulomb energy is equal to the thermal energy, is e^{-1}. Conversely, an electron thermalized outside the Onsager radius should be free from the influence of the parent ion even if the external electric field may be nil. The electron thermalization range in liquid argon is estimated to be 1500–1800 nm for liquid argon[27] and 4000–5000 nm for liquid xenon[28] and they are beyond the Onsager radius (127 nm for liquid argon and 49 nm for liquid xenon). Therefore, it is reasonable to surmise that there exist a large number of electrons that will not recombine with the parent ion for an extended period of time (>ms) in the absence of an electric field. Such electrons will cause scintillation reduction in the low LET region, especially during a brief observation taking place within dozens of microseconds. These electrons are classified as escaping electrons. The Onsager theory falls short of thoroughly explaining the recombination process between electrons and ions in liquid argon, due to the fact that the mean interval of electron-ion pairs produced by a minimum ionizing particle is approximately 100 nm, a value comparable to the Onsager radius itself in liquid argon. In order to explore the subject matter further, a "volume recombination", i.e., electron recombination with ions other than the parent ion, should be taken into consideration. Assuming such a volume recombination, the scintillation intensity per unit absorbed energy, dL/dE, is given by the following equation,[9]

$$dL/dE = [A(dE/dx)/1 + B(dE/dx)] + \eta_0, \qquad (3)$$

where dL/dE is normalized to the scintillation yield at the flat top level, that is, in the limiting case of $dE/dx \to \infty$, eq. (3) becomes $A/B + \eta_0 = 1$. A, B and η_0 are adjustable parameters, and η_0 means the scintillation yield at zero electric field in the limit of zero LET. The data for the 1 MeV electron are the most reliable of all as the relative measurement has been repeated several times. Accordingly, we consider that the response curve always passes through the 1 MeV electron data point. Then, the parameters A and B are given by solving eq. (3) and the equation, $A/B + \eta_0 = 1$, for various values of η_0. The best fit curve to the data other than the 1 MeV electron data point, which is given in Fig. 2, is obtained for $\eta_0 \sim 0.75$ for liquid argon.[9]

The reduction factor, η, caused by escaping electrons for the 1 MeV electron may be directly obtained from Fig. 2. The average energy required for a single photon production, $W_{\rm ph}(\beta)$, is given by $W_{\rm ph}(\max)/\eta$.

3.2 *Quenching effect*

In the case of particles that give high LET, the ratio $\{Q(\mathcal{E})/e + aS_{\rm r}(\mathcal{E})\}/(N_{\rm i} + N_{\rm ex})$ values are less than unity. This means that scintillation quenching occurs for particles such as non-relativistic proton, alpha particle, fission fragment and relativistic Au ion, as shown in Fig. 3. In an effort to clarify the quenching effect in liquid argon, Hitachi *et al.*[25] devised a biexcitonic model in 1992 based on the spatial distribution of the energy deposited along a particle track. The application of the model has delineated a mechanism where the excitons produced via the processes described in §2 are quickly self-trapped within $\sim 10^{-12}$ s and each of them subsequently emits a vacuum ultraviolet scintillation photon. Prior to such self-trappings, free excitons may diffuse themselves to undergo biexcitonic quenching as

$$\mathrm{R}^* + \mathrm{R}^* \to \mathrm{R} + \mathrm{R}^+ + e^- \quad \text{(kinetic energy)}.$$

Here, the electrons emitted carry away the excess energy, close to one excitation energy, and consume it before recombination and self-trapping. In the case of the extremely high excitation density, the reaction specified above may be considered as the basic mechanism of scintillation quenching,[25] and capable of verifying the experimental result.

Figure 2 includes data obtained recently for the non-relativistic proton and helium particle by Kato *et al.*[24] Their scintillation yield data apparently fall short of the flat top level; furthermore, the data for protons seem to give a small peak. However, these facts are reasonably acceptable against the background of the two processes specified above; namely, these can be explained by considering that the two processes of §3.1 and §3.2 occur in the same track because the ionization densities in the track cores of these particles are higher than those of relativistic heavy particles with the same energy loss rates, while those in the delta ray area are lower than those of the relativistic ones.

Table III. Most probable values of $W_{\rm ph}(\max)$, η-factor, q-factor, η_0, α/β ratio, $W_{\rm ph}(\alpha)$ and $W_{\rm ph}(\beta)$ in liquid argon and in liquid xenon.

	Liq.Ar	Liq.Xe
$N_{\rm ex}/N_{\rm i}$	0.21	0.13
$W_{\rm ph}(\max)$ (eV)	19.5 ± 1.0	13.8 ± 0.9
η	0.80 ± 0.04	0.64 ± 0.03
q	0.72 ± 0.04[a]	0.77 ± 0.04[a]
β/α	1.11 ± 0.05	$0.81^{+0.07-0.13}$
η_0	–0.75	0.1–0.5
$W_{\rm ph}(\alpha)$	27.1	17.9 (16.3 ± 0.3[33])
$W_{\rm ph}(\beta)$	24.4	21.6

[a] These values are obtained from scintillation yield curves as shown in Figs. 2 and 4. As a result, the value of 0.72 ± 0.04 for liquid argon is slightly different from the original one ($q = 0.71$[6]), which was obtained from Fig. 3.

The scintillation quenching factor q is defined by the reduction factor of scintillation intensity against the flat top level, that is, for no quenching, $q = 1$ and for complete quenching, $q = 0$. The q value for the 5.3 or 6.1 MeV alpha particle is directly evident from Fig. 2. Furthermore, the average energy required for a single photon production, $W_{\rm ph}(\alpha)$, is given by $W_{\rm ph}(\max)/q$.

To reiterate, Fig. 2 may be utilized to determine the values of the absolute scintillation yield, $W_{\rm ph}$, the reduction factor attributed to escaping electrons, η, and the quenching factors, q, within the scope of the experiment. Table III summarizes the three values mentioned above for the 1 MeV electron and the 5.3 MeV alpha particle as well as the ratio of the scintillation yield of the 1 MeV electron to that of the 5.3 MeV alpha particle, (β/α), in comparison with relative data obtained in the liquid xenon experiment described in the next section.

4. Scintillation Yield in Liquid Xenon for Heavy Particles

Throughout the series of experiments conducted in liquid xenon, only scintillation intensity was observed for various particles without simultaneous measurement of ionization signals except for the case of 1 MeV electrons. In liquid xenon, therefore, we cannot show the flat response of the sum total of scintillation and ionization divided by $N_{\rm ex} + N_{\rm i}$ over a substantially extensive LET region, as seen in Fig. 3. Furthermore, the calculated value of $W_{\rm ph}(\max)$ in liquid xenon[10] is less reliable than that in liquid argon. From the simultaneous measurement of the ionization and scintillation for the 1 MeV electron, however, one can fine tune $W_{\rm ph}(\max)$ in liquid xenon in order to arrive at an acceptably

Table IV. Various ionizing particles in liquid xenon experiment and their energies deposited in the sensitive region.

Particle	Source	Deposited energy	Range (cm)
Internal conversion electrons	^{207}Bi	1.0 MeV[4)]	0.23
Gamma rays	various radioisotopes	0.060–1.853 MeV[29)]	0.0038–0.48[a)]
Alpha particles	^{241}Am	5.49 MeV[11)]	0.0043
Alpha particles	^{252}Cf	6.12 MeV[4,8)]	0.0051
Fission fragments	^{252}Cf		$\sim 2 \times 10^{-3}$
heavy fragments		80.3 MeV[4,8)]	
light fragments		106.2 MeV[4,8)]	
Protons	the cyclotron of INS	38.2 MeV[7)]	0.97
397 MeV/n Fe ions	NIRS HIMAC	8.52 GeV[11)]	2.0
589 MeV/n Ar ions	NIRS HIMAC	3.21 GeV[11)]	2.0
546 MeV/n Si ions	NIRS HIMAC	1.98 GeV[11)]	2.0
370 MeV/n C ions	NIRS HIMAC	422 MeV[11)]	2.0

[a)]The range of photoelectrons.

reliable yield. Using the thus obtained value of $W_{\rm ph}$(max) and, in addition, assuming that the flat top level corresponds to 100% of the scintillation yield, the absolute scintillation yield in liquid xenon can be estimated from measurements of the relative scintillation yields in liquid xenon. In this section, we show the latest relative scintillation yield response experimentally obtained.[11)] In the subsequent section, we demonstrate the fine-tuning process applicable to $W_{\rm ph}$(max) in liquid xenon, making use of 1 MeV electron data.

In liquid xenon experiments, for particles from radioisotope sources, gridded ionization chambers of almost identical design were used and for particles from accelerators, apparatus of an identical design were used with their ionization chamber removed. As in liquid argon, the scintillation light excited by alpha particles was used as the standard signal. Table IV lists the types of excitation as well as particles emitted from radioactive source in conjunction with their respective levels of energy deposition in the sensitive region of 2 cm for the relativistic heavy particle. The results thus obtained for liquid xenon are shown in Fig. 4. Error bars (±7%) in this figure include both statistical and instrumental errors.[11)] Figure 4 manifests the

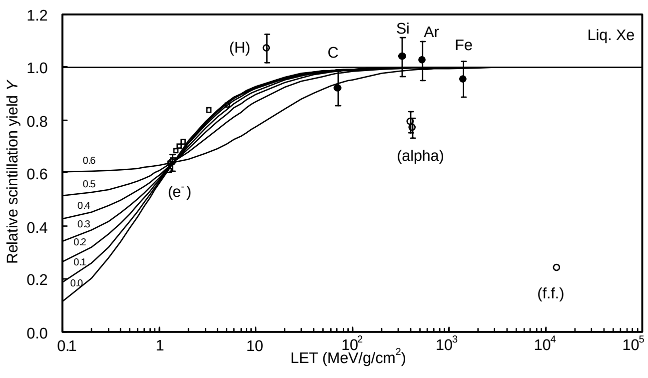

Fig. 4. Dependence of scintillation yield on LET in liquid xenon. Solid circles represent yields for relativistic heavy particles[11)] whereas open circles represent those for electrons,[10)] alpha particles [4,8,11)] and fission fragments.[4,8)] Open squares represent gamma-ray data obtained by Barabanov *et al.*[29)] Solid curves are obtained from eq. (3) by using seven values within the η_0 range of 0.0–0.6.

flat top level as observed in the liquid argon experiment.

Data for gamma rays obtained by Barabanov *et al.*[29)] were plotted by assuming that the scintillation yield for the 1 MeV electron is equal to that for gamma rays of 1.275 MeV from ^{22}Na measured by Barabanov *et al.* The solid lines in the figure represent the seven values identified within the $\eta_0 = 0$–0.6 range, as a result of computation utilizing eq. (3). The curved line manifesting the best fit of the seven including the data by Barabanov *et al.* appears to be the one for $\eta_0 = 0$. However, upon removal of Barabanov's data, the $\eta_0 = 0.1$–0.5 line may be considered to manifest the best fit. At any rate, these η_0 values are reasonable compared with that (∼0.75) in liquid argon, because the value of η_0 in liquid xenon should be theoretically smaller than that in liquid argon.[30)]

Assuming that the flat top level corresponds to the 100% scintillation level, the reduction factor η and the quenching factor q were obtained from Fig. 4 for the 1 MeV electron as well as for the alpha particle and are shown in Table III. The scintillation yield ratio between the 1 MeV electron and the 5.5 MeV alpha particle (β/α) and η_0 are also shown in Table III.

5. Relationship between Scintillation and Ionization Yields for 1 MeV Electrons

Approximately 20 years ago, the author's group[22)] conducted simultaneous measurement of the ionization and scintillation signals, $Q(\mathcal{E})$ and $S_{\rm r}(\mathcal{E})$, as a function of the electric field $\mathcal{E}$ for internal conversion electrons (∼1 MeV) from ^{207}Bi in liquid xenon as well as in liquid argon, the results of which are as shown in Fig. 5. The figure suggests the existence of a relationship between the two sets of signals. Subsequently, in 1990[10)] and again in 1994,[30)] such signal data were analyzed in order to estimate the average energy required to produce a single photon for 1 MeV electron, $W_{\rm ph}(\beta)$. This section is a reevaluation of such an attempted estimation in the past.

Figure 6 shows the relationship between $S_{\rm r}(\mathcal{E})/S_{\rm r0}$ and $Q(\mathcal{E})/Q_0$ obtained in liquid argon for the 1 MeV electron, whereas Fig. 7 shows the same relationship manifested in liquid xenon,[30)] where $S_{\rm r}(\mathcal{E})$ is the relative scintillation yield for alpha particles at $\mathcal{E}$ and $Q(\mathcal{E})$ is the charge collected at $\mathcal{E}$. The relationship between these quantities is expressed as

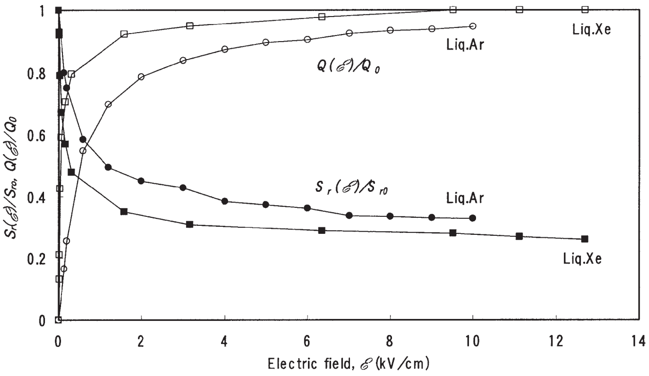

Fig. 5. Saturation curves of ionization (open symbols) and scintillation (close symbols) for 1 MeV conversion electrons from ^{207}Bi in liquid argon (○,●), and liquid xenon (□,■) as a function of the electric field strength.[22]

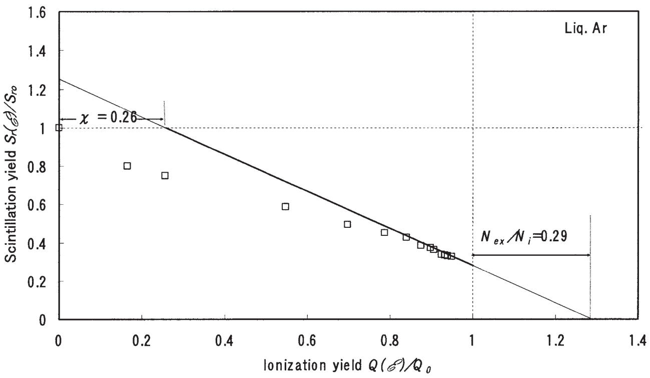

Fig. 6. Relationship between S_r/S_{r0} and Q/Q_0 in liquid argon.

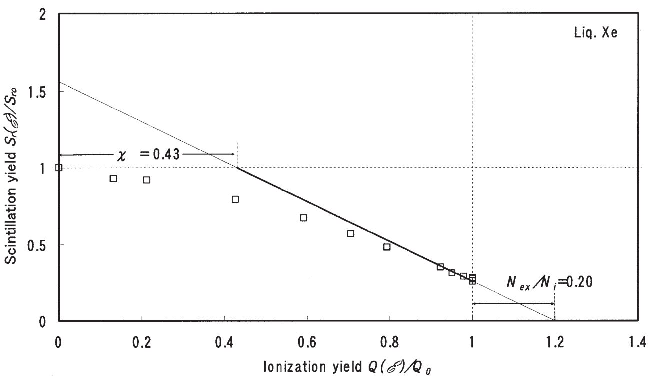

Fig. 7. Relationship between S_r/S_{r0} and Q/Q_0 in liquid xenon.

follows:[30)]

$$S_r(\mathcal{E})/S_{r0} = \{1 - Q(\mathcal{E})/Q_0 + N_{ex}/N_i\}/(1 + N_{ex}/N_i - \chi). \tag{4}$$

The reduction factor attributable to escaping electrons at the flat top is defined as follows:

$$\eta = (1 + N_{ex}/N_i - \chi)/(1 + N_{ex}/N_i), \tag{5}$$

where $\chi = N_{i0}/N_i$, that is, the ratio between the number of escaping electrons at zero electric field, N_{i0} , and N_i. As a result, η is easily obtainable from a plot of the dependence of scintillation yields on LET.

According to the definition given above, $S_r(0)/S_{r0} = 1$ and $Q(0)/Q_0 = 0$. At a very low electric field, $\mathcal{E}$, where only escaping electrons can be collected, eq. (4) satisfies $S_r(\mathcal{E})/S_{r0} = 1$ and $Q(\mathcal{E})/Q_0 = \chi$. At higher electric fields, the relationship between S_r/S_{r0} and Q/Q_0 is expressed by a thick straight line in Figs. 6 and 7, which is given by eq. (4). However, the real data do not lie on the thick straight lines as seen from the figures except the data at the high electric field. Such a deviation can be attributed to the lack of linearity in the amplifier for slow rise ionization signals at the low electric field, on the one hand, and to the attachment of drifting electrons to electro negative impurities taking place in the low electric field, on the other.

Values for N_{ex}/N_i and χ may be obtained by solving the above-quoted equations. The solution is obtained by using the $S_r(\mathcal{E})/S_{r0}(\mathcal{E})$ and $Q(\mathcal{E})/Q_0(\mathcal{E})$ values measured at the high electric field together with the η value determined based on either Fig. 2 or Fig. 4. Data thus utilized were obtained at 10 kV/cm for liquid argon and at 12.7 kV/cm for liquid xenon.

In Figs. 2, 5 and 6, the parameters for liquid argon were specified to be $S_r/S_{r0} = 0.33$ and $Q/Q_0 = 0.95$ for the electric field of 10 kV/cm. On the other hand, $\eta = 0.80 \pm 0.04$ was specified based on the data obtained for relativistic heavy particles and for 1 MeV electrons.[9)] As a result, both N_{ex}/N_i and χ were specified to be 0.29 and 0.26, respectively. For liquid xenon, the values for S_r/S_{r0}, Q/Q_0 and η were specified to be 0.26, $\sim$1 , and 0.64 ± 0.03, respectively based on data obtained from the relativistic heavy particle measurement conducted recently and the data of the 1 MeV electron as summarized in Figs. 4, 5 and 7.[11)] This resulted in the values of $N_{ex}/N_i = 0.20$ and $\chi = 0.43$. The N_{ex}/N_i value thus obtained for liquid argon is approximately 1.4 times larger than the calculated figure. The difference between 0.20 and 0.06 (which is the calculated value) for liquid xenon requires a proper explanation. Although our group is not yet in a position to offer a proper explanation, we surmise that the true figure resides somewhere between 0.20 and 0.06.[31)]

In this study, we use a value of $N_{ex}/N_i = 0.21$ for the estimation of W_{ph} in liquid argon because that value is supported theoretically[18)] as well as experimentally.[20,21)] For the estimation of W_{ph}(max) in liquid xenon, however, we assumed an envelope consisting of the upper and lower limits of 0.20 and 0.06, respectively. Based on the middle value of 0.13, the W_{ph}(max) value was estimated to be 13.8 ± 0.9 eV. W_{ph}(max) values and N_{ex}/N_i ratios thus computed using the 1 MeV electron data are shown in Table III for both liquid argon and liquid xenon. W-values, $W_{ph}(\beta)$, $W_{ph}(\alpha)$ and the theoretical and experimental ratios of N_{ex}/N_i are also shown in Table III for both liquid argon and liquid xenon.

The flat top is considered to correspond to the 100% scintillation yield, i.e., the number of emitted photons is specifiable to be $N_{ex} + N_i$. Subsequently, Fig. 2 is superimposed over Fig. 4 by applying the ratio of [W_{ph}(max) in liquid argon]/[W_{ph}(max) in liquid xenon] to that between both flat top levels in liquid xenon and in liquid argon. The superimposed figure thus realized is shown in Fig. 8. The ordinate on the left shows the relative scintillation yield where the flat top level for liquid argon is assumed to be

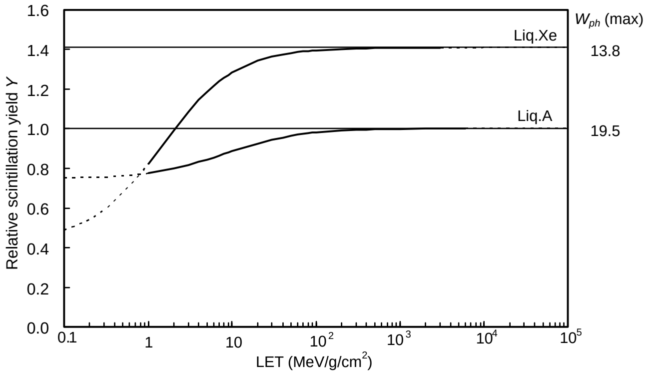

Fig. 8. Two LET dependences of scintillation yield curves, one for liquid argon and other for liquid xenon, superimposed over each other.

unity whereas the ordinate on the right shows $1/W_{\rm ph}(\max)$, or, the absolute scintillation yield.

6. Comparison of Flat Top Level between Liquid Argon and Liquid Xenon

In order to accurately superimpose Fig. 2 over Fig. 4, it is required to use signals obtained for the same particles with the same apparatus in liquid argon and in liquid xenon simultaneously but this is impossible. However, a well-accepted linear relationship is already available between the energy resolution and the square root of the number of photoelectrons for alpha particles within the range of 5 to 9 MeV, provided that the alpha particle sources are set at a fixed location[4,10,32] and the number of photoelectrons is sufficiently small to allow the determination of energy resolution by their statistical fluctuation. Therefore, the ratio between the number of photons for 6.1 MeV alpha particles in liquid xenon and the number of those in liquid argon is estimated to be 1.4 ± 0.2[4,10] on the basis of energy resolution levels realized in a chamber of identical design for both liquids.

In the present consideration, the ratio between the flat top levels is defined by

$$[(dL/dE)_{\max}]_{\rm liq.Xe}/[(dL/dE)_{\max}]_{\rm liq.Ar} = [W_{\rm ph}(\max)]_{\rm liq.Ar}/[W_{\rm ph}(\max)]_{\rm liq.Xe} = 1.41 \pm 0.11. \quad (6)$$

using the $W_{\rm ph}(\max)$ values shown in Table III. The ratio (1.4 ± 0.2) obtained from energy resolutions of the alpha particle is in agreement with the ratio defined by eq. (6). This agreement strongly supports the simple theory described in §2 and the experimental results for liquid argon and liquid xenon obtained so far.

The apparent $W_{\rm ph}(\alpha)$ value in liquid xenon for the 5.3 MeV alpha particle is 17.9 ± 1.5 eV $(= 13.8/0.77$ eV$)$. Ten years ago, Miyajima *et al.*[33] obtained a $W_{\rm ph}(\alpha)$ value of 16.3 eV in liquid xenon using a different method. Although the fitting error reported in their paper was only ± 0.3 eV, the overall error including uncertainty in quantum efficiency would be as high as 10%. On the basis of errors of this magnitude, the two sets of $W_{\rm ph}(\max)$ values in liquid xenon may be interpreted as being in good agreement with each other.

7. Conclusion

Through a simultaneous measurement of the relative scintillation yield and the absolute ionization yield for the 1 MeV electron in liquid xenon, the ratio $N_{\rm ex}/N_{\rm i}$ in liquid xenon is estimated to be 0.20 at a maximum. If the calculated value of 0.06 is specified as the lower limit, it is possible to recognize 0.13 as the most probable $N_{\rm ex}/N_{\rm i}$ value, and 13.8 ± 0.9 eV as the most probable $W_{\rm ph}(\max)$ value. Based on these values, it is possible to determine the absolute scintillation yield for alpha particles, fission fragments and relativistic heavy particles employing the methodology identical to the one employed for liquid argon. The flat top response presents itself, whether the liquid used is xenon or argon, the intrinsic scintillation yield. The ratio between maximum scintillation yields realized in the two liquids is in good agreement with the ratio estimated on the basis of energy resolutions obtained for alpha particles for the two liquids. In addition, the $W_{\rm ph}(\alpha)$ value in liquid xenon is in agreement with the corresponding value derived from an independent measurement. These agreements strongly support the simple model that each of the ion pairs or excited atoms produced by an ionizing particle emits a single photon with 100% efficiency.

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