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Fano factor in xenon

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The Fano factor and W value in xenon have been measured with a gridded ionization chamber for 5.3-MeV α particles. We obtained a value for the Fano factor of 0.29 ± 0.02 and the W value of 21.9 ± 0.3 eV. This W value is nearly equal to those for α and β particles measured by Jesse and Sadauskis [Phys. Rev. **90**, 1120 (1953); **97**, 1668 (1955)]. The Fano factor is considerably larger than the value reported for x rays using a proportional scintillation counter. The reason for this difference is discussed.

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I. INTRODUCTION

Radiation-produced ionization is not only basic to dosimetry but it is also the most elementary among radiation effects on matter. The W value is the mean energy required for radiation to generate an electron-ion pair in matter. The Fano factor is an index that represents fluctuations in the number of electron-ion pairs. The two quantities numerically characterize the radiation-induced ionization.

In the measurement of W values, largely reproducible results were obtained in the 1950's for noble gases other than helium. For helium, there were still large discrepancies among different measurements. However, recent measurements using α particles [1–3] converge on a value of approximately 43 eV. This value is very close to that obtained by Jesse and Sadauskis [4,5]. Also, the value of 42.0–43.5 eV is predicted theoretically by considering the possibility that excited helium atoms with $n > 3$ may be converted into ionization through thermal collisions [6,7]. Jesse and Sadauskis compared the W values in noble gases for α and β particles, and found that the ratio W_α / W_e is constant for noble gases and that this constant is unity [5,8]. Therefore, it is reasonable to assume that, as mentioned later, W_e obtained for electrons produced by soft x rays is equal to W_α.

The Fano factors for electrons in noble gases, on the other hand, were calculated by Alkhazov, who used the optical approximation and obtained the values of 0.21, 0.13, and 0.16 in helium, neon, and argon, respectively [9]. In addition, he made a detailed calculation of the Fano factor in helium for electrons using a realistic set of cross sections, and again obtained the value of 0.21 [Ref 10]. The Fano factors in these rare gases are also obtained by Monte Carlo simulation. The values in argon calculated by Unnikrishnan and Prasad [11] and in helium, neon, and argon by Grosswendt [12] agree well with those of Alkhazov. Dayashankar, Prasad, and Unnikrishnan obtained the value of 0.19 in krypton [13]. Recently, Kowari, Kimura, and Inokuti have calculated the Fano factor in argon for electrons and obtained the value of 0.16 [Ref. 14].

The Fano factors in noble gases have been measured by several investigators since the 1970s, using the following two methods: (i) the gridded ionization chamber method, and (ii) the proportional scintillation-counter method. The former method, which is used for α particles, can be applied to all noble gases. Until now, however, only the Fano factors in helium and argon have been measured (F_α in He$=0.24\pm0.02$ [Ref. 3], F_α in Ar$=0.20^{+0.01}_{-0.02}$ [Ref. 15]) and they are slightly but clearly larger than the above calculated values. The latter method, on the other hand, can be applied to heavy rare gases like krypton and xenon using soft x rays with the energies of 1.49 and 5.9 keV (F_e in Kr$=0.17$ [Ref. 16], F_e in Xe$=0.13\sim0.17$ [Refs. 16–18]). For the Fano factors for electrons in noble gases obtained so far, as seen from the above comments, there are no experimental data to be compared with theory, except for in krypton or with measurements for α particles. The experimental value in krypton obtained by the scintillation-counter method agrees fairly well with the theoretical calculation.

In a previous paper, we found a small discrepancy in helium between the experimental Fano factors for α particles and the theoretical Fano factors for electrons, and pointed out that this may be due to nuclear elastic collision. To confirm experimentally such a difference, we have recently measured the Fano factor for α particles in xenon using the new gridded ionization chamber method. In this paper, the results are presented and the reason for the difference between the Fano factors for α particles and for electrons is discussed.

II. EXPERIMENTAL METHOD AND RESULTS

The method and apparatus are described in detail in a previous paper [3], in which the Fano factors in helium and argon-doped helium have been reported. We mention here only the experimental conditions used in the present measurements.

In this measurement, the pressure dependence of ionization fluctuation was investigated carefully because of the possibility that the apparent Fano factor at high pressure may be considerably larger than that at low pressure [19]. Therefore the Fano factor was measured at three different pressures of 760, 610, and 390 Torr. The distance between the cathode and the grid was set at 30 mm for pressures of 760 and 600 Torr, and 60 mm for the pressure of 390 Torr. The ranges of α particles at 760, 610, and 390 Torr are 2.1, 2.7, and 4.1 cm, respectively. The integration time of the gated integrator was set between 17 and 30 μsec according to the collection time of electrons.

The Fano factor was calculated as

$$F(\Delta E_i/2.35)^2/(WE_0) \, , \tag{1}$$

where

$$\Delta E_i=[(\Delta E_t)^2-(\Delta E_n)^2]^{1/2} \, . \tag{2}$$

Here ΔE_i, ΔE_t, and ΔE_n represent the energy spread due to the ionization fluctuation, the total-energy resolution [full width at half maximum (FWHM)] of the gridded ionization chamber, and the noise width (FWHM) in the electronic system, respectively. E_0 represents the α-particle energy and W represents the W value that was determined by comparing the ionization yields in xenon relative to that in argon, assuming that the W value of argon is 26.31 eV [Ref. 20]. We obtained the value of 21.9±0.3 eV. This value is the same as the results of Jesse and Sadauskis [4,5].

As shown in Fig. 1, good saturation characteristics are obtained for 5.3-MeV α particles in xenon when pulse height is plotted against E_1/p for five different field ratios. When the vertical scale is magnified, however, sufficient saturation could not be obtained. The pulse height increases by 0.3% as E_1/p increases from 0.2 to 0.6 V cm^{-1} Torr^{-1}. We do not understand whether this slope is due to recombination or electron multiplication around the grid wire. Nevertheless, there is no difference between the results of the Fano factor in xenon. Therefore we conclude that the contribution of these effects to the Fano factor is not significant.

From these results, we obtained an average value of 0.29±0.02 for the Fano factor in xenon. The results are listed in Table I together with the experimental conditions. In the table, "gap" represents the distance between the cathode and the grid, "field ratio" represents the electric-field ratio in the grid-collector region to the grid-cathode region, and "E_1/p" represents the electric-field strength per unit pressure in the grid-cathode region. The measurement at each pressure was repeated more than ten times and the quoted errors give the maximum and the minimum values. As shown in the table, no important differences exceeding the experimental error can be observed in the results for this pressure range.

III. DISCUSSION

In Table II, the Fano factors for α particles and electrons in rare gases are compared. The Fano factors for α particles have been obtained with a gridded ionization chamber so far. The Fano factors for electrons in helium, helium plus argon, and argon were calculated by Alkhazov [10]. The Fano factor for electrons in xenon was measured by Policarpo *et al.* to be 0.17 [Ref. 16], using the proportional scintillation technique, then by Anderson *et al.* to be 0.13 [17], and again by Lima *et al.* to be 0.15 [18].

As shown in the table, it is clear that the Fano factors for α particles are larger than those for electrons. To make such a difference clear, it is assumed that the following quadratic difference has other causes,

$$(\Delta E)^2=(2.35)^2(F_\alpha W_\alpha E_0-F_e W_e E_0) \, , \tag{3}$$

where F_α and F_e are the Fano factors for α particles and for electrons, respectively, W_α and W_e are the W values for α particles and for electrons, and E_0 is the energy of 5.3-MeV α particles from ^{210}Po. Here we assume that $W_\alpha=W_e$ and the two terms in the above equation are independent of each other. The results are shown in the sixth column of Table II. As an explanation for such

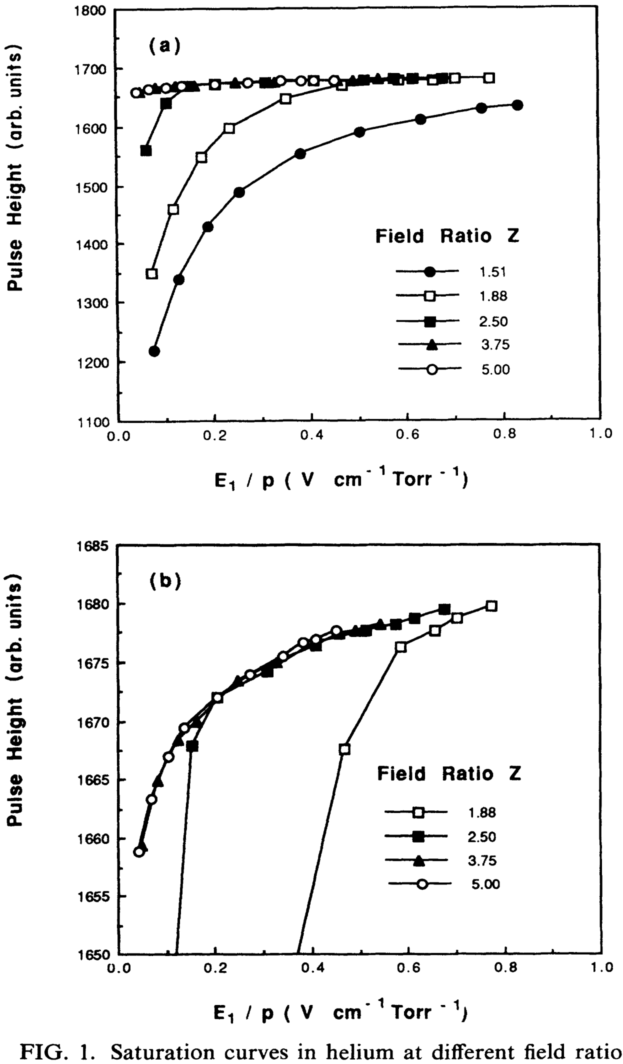

FIG. 1. Saturation curves in helium at different field ratios. (a) Normal vertical scale. (b) Magnified vertical scale.

TABLE I. The Fano factor in xenon at different pressures and for different experimental conditions.

Pressure (Torr)	Gap (cm)	Field ratio	E_1/p ($\mathrm{V\,cm^{-1}\,Torr^{-1}}$)	Fano factor
760	3.0	2.50	0.56	0.29±0.02
		1.88	0.66	0.29±0.03
610	3.0	3.75	0.48	0.29±0.02
		2.50	0.58	0.28±0.03
		1.88	0.67	0.29±0.03
390	6.0	6.25	0.30	0.30±0.02
		5.00	0.34	0.29±0.03
		3.75	0.43	0.30±0.03

differences, we can consider the two following causes.

(i) α particles passing through matter produce many slow electrons as secondary particles. These might increase Fano factors, because Fano factors for electrons increase with a decrease in the energy of incident electrons.

(ii) Most of the energy of α particles is consumed by ionization collisions in matter, and near the end of the track a small part of the energy is consumed by nuclear collisions. The fluctuation in the energy loss due to nuclear collisions increases the fluctuation in the number of ion pairs produced by α particles.

Recently, Inokuti *et al.* have made a detailed calculation of the Fano factor in argon for protons [21] and showed that the contribution of (i) is too small to explain the differences between the Fano factors for α particles and electrons. To investigate case (ii), we can compare the results shown in Table II to those calculated by the formula given by Lindhard and Nielsen [22] for the fluctuation in the energy loss due to nuclear elastic collisions. In the derivation of the formula, it is assumed that the ionization collisions and the nuclear elastic collisions are independent of each other. According to their formula, such a fluctation $\Delta\nu_n$ has the following dependence on the kinds of incident particles and target atoms:

$$(\Delta\nu_n)^2 \propto \frac{Z_1^{5/6} Z_2 Z A_1^2}{A_2^{1/2}(A_1+A_2)} , \tag{4}$$

where Z_1 and Z_2 represent atomic numbers of incident particle and target material, A_1 and A_2 represent mass numbers of incident particle and target material, and $Z^{2/3}=Z_1^{2/3}+Z_2^{2/3}$. In their paper, the width (full width at half maximum) $\Delta\nu_n$ in silicon is given to be 6 keV for 6-MeV α particles. From this value we can estimate the values of $\Delta\nu_n$ in helium, argon, and xenon using the above relation. The last column of Table II shows the results using this method. Unfortunately, the formula cannot be successfully applied to a material whose atomic number is smaller than 10 because it is derived on the basis of the Thomas-Fermi model. This is the meaning of the parentheses in the last column. The value for argon is almost equal to that estimated from Lindhard and Nielsen within the experimental errors. The $\Delta\nu_n$ in xenon is slightly larger than, but still remains within the border line of, the experimental errors, except for the case of $F_e=0.13\pm0.01$, which is 1.5 times $\Delta\nu_n$. Thus, the

TABLE II. Fano factors in He, He+Ar (1%), Ar, and Xe. Reference numbers in footnotes refer to the work from which the data has been obtained.

			Experimental Fano factor			
Gas	W value (eV)	Theoretical Fano factor for electrons	Proportional scintillation for electrons	Ionization chamber for α particle	Experimental ΔE (keV)	Theoretical $\Delta\nu_n$ (keV)
He	43.3±0.03[a]	0.21[b]		0.24±0.02[a]	$6.2\pm^{1.8}_{2.7}$	(3.9)
He+Ar (1%)	28.9±0.02[a]	0.06[b]		0.11±0.02[a]	$6.6\pm^{1.2}_{1.4}$	
Ar	26.3[c]	0.16[d−h]		$0.20\pm^{0.01}_{0.02}$[f]	$5.6\pm^{1.2}_{1.6}$	5.9
Xe	21.9±0.03		0.17±0.007[i]	0.29±0.02	$8.8\pm^{1.0}_{1.2}$	6.8
			0.13±0.01[j]		$10.1\pm^{1.0}_{0.9}$	
			0.15±0.03[k]		$9.5\pm^{1.6}_{2.0}$	

[a] Reference [3].

[b] Reference [10].

[c] Reference [20].

[d] Reference [9].

[e] Reference [11].

[f] Reference [12].

[g] Reference [13].

[h] Reference [14].

[i] Reference [16].

[j] Reference [17].

[k] Reference [18].

difference from the experimental results roughly agrees with the prediction by Lindhard and Nielsen.

IV. CONCLUSION

The Fano factor in xenon for α particles is nearly twice as large as that for electrons. This difference seems to be explained by considering the contribution from energy straggling due to nuclear elastic collisions. Namely, Fano factors for α particles are larger than those for electrons, and the differences increase moderately with the mass number of target material, as predicted from the Lindhard and Nielsen formula.

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