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Theoretical study of energy deposition in ionization chambers for tritium measurements

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Energy deposition in ionization chambers has been theoretically studied for tritium measurements in gaseous form. A one-dimension model is introduced to establish the quantitative relationship between energy deposition rate and many factors, including carrier gas, gas pressure, wall material, chamber size, and gas temperature. Energy deposition rate has been calculated at pressure varying from 5 kPa to 500 kPa based on some approximations. It is found that energy deposition rate varies greatly for different parameters, especially at low gas pressure. For the same chamber, energy deposition rate in argon is much higher than in deuterium, as much as 70.7% higher at 5 kPa. Gold plated chamber gives highest energy deposition rate in the calculations while aluminum chamber results in the lowest. As chamber size gets smaller, β ray emitted by tritium will deposit less energy in the sensitive region of the chamber. For chambers flowing through with the same gas, energy deposition rate in a 10 L chamber is 23.9% higher than in a 0.05 L chamber at 5 kPa. Gas temperature also places slight influence on energy deposition rate, and 373 K will lead to 6.7% lower deposition rate than 233 K at 5 kPa. In addition, experiments have been performed to obtain energy deposition rate in a gold plated chamber, which show good accordance with theoretical calculations. [http://dx.doi.org/10.1063/1.4825032]

I. INTRODUCTION

With the development of fusion technology, tritium related research, especially tritium measurement technologies, becomes more and more important to fulfil the fusion target.[1–5] Tritium decays with a half-life of 12.33 years by emitting β particles with a maximum energy of 18.6 keV, which can travel only 6 mm at most in the air at pressure 1.0 atm. For its weak penetrating ability, tritium in gas must be introduced into detector to be measured in most situations. Flow-through ionization chamber is widely used for measuring tritium in gaseous form for its fast response, wide range, and simple structure.[6–8] The steady-state ionization current (I) measured for a given quantity of tritium in gas can be expressed by

$$I = \frac{E \times C \times V \times e}{\overline{W}} \times \epsilon \times \kappa. \quad (1)$$

In Eq. (1), E is the energy of β ray emitted by tritium. C is tritium concentration in gas of the chamber. V is effective volume of an ionization chamber. $\overline{W}$ is ionization power per ion pair. ϵ is energy deposition rate of β ray in the sensitive volume of the ionization chamber. κ is charge collection efficiency in the chamber, while e is the charge of one electron. It is obvious that for a given chamber and operating conditions, E, C, V, e, $\overline{W}$ are constant. Therefore, the values of both ϵ and κ are the key points to determine the value of measured current I. For collection efficiency κ, it mainly depends on combination and diffusion loss of ions, which can be diminished to negligible level by maintaining the potential on the cathode of the chamber high enough to make sure the chamber works in saturation mode[6] (in saturation mode, $\kappa \approx 1$). Then, in saturation mode, the energy deposition rate ϵ becomes the only parameter to determine the measured ionization current in an ionization chamber and thus it is very important to study the energy deposition in ionization chambers to improve their performance in tritium measurements.

Several people have observed in experiments that the variation of either carrier gas or gas pressure places significant influence on measured ionization current.[9–13] Uda *et al.*[10] have obtained that different carrier gas results in great difference in output current, and also pointed out the difference might be related to atomic number of carrier gas composition besides average energy required for production of one electron-ion pair. To calculate the amount of energy consumption in an chamber, Matsuyama and Watanabe[11] have developed a formula to approximate it, in which only chamber size and gas pressure have been taken into consideration. However, the physical meaning of the parameter in the formula is obscure, which limits its use in calculations for different chambers at different operating conditions. Chen *et al.*[12] have also developed a qualitative relationship of counting losses on the chamber wall and studied counting losses with two chambers at pressure from 71 to 721 mmHg experimentally. Wagner *et al.*[13] have noticed in experiments that using SS, Cu, Au as the wall material would lead to variation in output current, but provided no theoretical calculations to illustrate the difference. Up to now in literatures, there is no study focussing on theoretical analysis of energy deposition in ionization chambers for tritium measurement. Therefore, the effect of chamber dimensions and operating conditions on energy

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deposition still remains unspecified. In this article, a quantitative relationship between energy deposition rate and parameters, including carrier gas, gas pressure, wall material, chamber size, and gas temperature has been established based on an one-dimension model, and the influence of all these factors has also been specified.

II. THEORY

Generally β ray losses its energy into two regions, the sensitive region of the chamber and the chamber wall. The former one contributes to the saturation current, while the latter one results in the decrease of energy deposition rate. Therefore, to calculate the energy deposition rate in an ionization chamber, we first analyze the interaction between β rays and wall materials to determine the main factors which lead to energy loss on chamber wall. There are five different kinds of interactions: (1) bremsstrahlung, (2) secondary electron emission, (3) characteristic x-ray, (4) auger electron emission, (5) backscattered electrons.

The energy loss of β ray can be denoted as follows:

$$-\frac{dE}{dx} = \left(-\frac{dE}{dx}\right)_{ion} + \left(-\frac{dE}{dx}\right)_{rad}. \tag{2}$$

For fast electron, the quantitative relationship between radiation loss and ionization loss can be approximated as Eq. (3).[14]

$$\frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} \approx \frac{E \cdot Z}{750}. \tag{3}$$

In Eq. (3), E is the energy of an electron, MeV. Z is the atom number of materials. For tritium, the average energy of β ray is 5.7 keV. Taking gold ($^{197}_{79}$ Au) as an example, referring to Eq. (3), the energy loss due to radiation is just 0.06% of energy loss caused by ionization. It is obvious that the energy loss caused by radiation (bremsstrahlung) is negligible comparing with ionizing loss.

The work of Haque shows that for low-energy β ray, the probability of β ray interaction with inner layer electrons of Au is negligible, which also indicates that the induced characteristic x-ray and auger electron are also negligible.[15,16] For elements with lower Z number, the lower the Z value, the weaker the probability is. Therefore, the influence of the first four kinds of interaction will not be taken into consideration in the following calculations, while backscattered electron emission should be taken as the main factor to determine the energy deposition rate ϵ.

To better describe the energy deposition process in a chamber, a one-dimension model was established according to the isotropic character of a column ionization chamber, as shown in Fig. 1.

In this model, only β rays emitted by tritium located in the region (ΔV), within the range (λ) of β rays, can have the opportunity to interact with chamber wall and deposit their energy in it. For an electron locates at position z, suppose that the chance for this electron to reach the chamber wall is k_z and the energy of this electron when it reaches chamber wall is E_z. Then energy deposition rate (ϵ) in the ionization chamber can

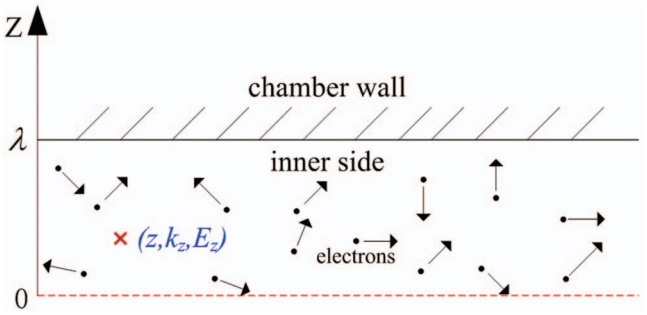

FIG. 1. One-dimension model for energy deposition calculations in a column ionization chamber.

be denoted as follows:

$$\epsilon = 1 - \frac{\Delta V}{V_{tot}} \times \frac{1-\eta}{\lambda E_0} \int_0^{\lambda} k_z E_z dz - \frac{\Delta V}{V_{tot}} \times \frac{\eta}{\lambda E_0} \int_0^{\lambda} k_z (E_z - E_z') dz, \tag{4}$$

where η is the backscattering coefficient of an electron on the wall. E_0 is the energy of β rays. E_z' is the energy of backscattered electron. V_{tot} is the volume of the chamber. In Eq. (4), the second item is energy loss due to electron absorption on the chamber wall, while the third item is the results of energy loss of scattered electrons during backscattered process. In fact, the transport of an electron in materials is very complicated and its pathway is always unpredictable, which indicates that it is very difficult to obtain accurate expression of both k_z and E_z. Therefore, to simplify the calculation, we assume that the average chance of β rays to reach the chamber wall is 50% and the energy of β rays at the chamber wall $E_z \simeq E_0$. Then energy deposition rate (ϵ) can be approximated as follows:

$$\epsilon = 1 - \left[\frac{1}{2}(1-\eta) \times \frac{\Delta V}{V_{tot}} + \frac{1}{2}\eta \times \frac{E_0 - E'}{E_0} \times \frac{\Delta V}{V_{tot}}\right], \tag{5}$$

where E' is the energy of backscattered electron. Take elastic backscattering as the main progress in backscattering on the wall, then the energy of backscattered electron is almost the same as the injected one ($E_0 \approx E'$). Substituting the items (ΔV) in Eq. (5) with the dimensions of a column chamber (r, radius of the chamber; h, height of the chamber), then the relationship between energy deposition rate and chamber dimensions can be expressed as

$$\epsilon = 1 - \frac{1}{2}(1-\eta)\left[2\left(1+\frac{r}{h}\right)\frac{\lambda}{r} - \left(1+\frac{4r}{h}\right)\left(\frac{\lambda}{r}\right)^2 + \frac{2r}{h}\left(\frac{\lambda}{r}\right)^3\right], \tag{6}$$

where λ can be approximated by extrapolated range R, $\lambda = R/\rho$. ρ is the density of carrier gas in the chamber.

According to Tabata, Ito, and Okabe's semi-empirical formula, TIO formula,[17] extrapolated range R can be expressed as follows:

$$R = a_1\left(\frac{ln[1+a_2(\gamma-1)]}{a_2} - \frac{a_3(\gamma-1)}{a+a_4(\gamma-1)^{a_5}}\right), \tag{7}$$

where $a_1 = 2.335A/Z^{1.209}$, $a_2 = 1.78 \times 10^{-4}Z$, $a_3 = 0.9891 - 3.01 \times 10^{-4}Z$, $a_4 = 1.468 - 1.18 \times 10^{-2}Z$, $a_5 = 1.232/Z^{0.109}$, $\gamma = (E + Mc^2)/Mc^2$. A is the atomic weight of an atom, and Z is the atomic number of an atom. Using Clapeyron equation, $PV = nRT$, finally, energy deposition rate can be obtained as follows:

$$\epsilon = 1 - \frac{1}{2}\left[1 - \eta(E)\right]\left[2\left(1 + \frac{r}{h}\right)\frac{1}{r} \times \frac{P_0 T R}{T_0 \rho_0} \times \frac{1}{P} - \left(1 + \frac{4r}{h}\right)\frac{1}{r^2} \times \left(\frac{P_0 T R}{T_0 \rho_0} \times \frac{1}{P}\right)^2 + \frac{2r}{h}\frac{1}{r^3} \times \left(\frac{P_0 T R}{T_0 \rho_0} \times \frac{1}{P}\right)^3\right]. \quad (8)$$

In Eq. (8), it is obvious that energy deposition rate is a function of many factors, including backscattering coefficient ($\eta(E)$), chamber dimensions (r, h), extrapolated range (R), gas pressure (P), and temperature (T). According to Eq. (7), extrapolated range R is determined by both the compositions of carrier gas and energy of β particles. Backscattering coefficient ($\eta(E)$) depends on both the materials of chamber wall and energy of β particles.

III. THEORETICAL CALCULATIONS AND EXPERIMENTS

A. Energy deposition in different carrier gas

As shown in Eqs. (7) and (8), energy deposition rate depends on the range of β ray, which is determined by the types of gas in an ionization chamber. In fact, several kinds of carrier gas are commonly adopted in experiments, such as air, argon, hydrogen, and deuterium. To estimate the influence of these gas on energy deposition rate, an ionization chamber with volume 1.0 L is employed and calculations are performed at different gas pressure, from 5 kPa to 500 kPa. Results are shown in Fig. 2. In the calculations, the average energy of β ray emitted by tritium, 5.7 keV, is used.

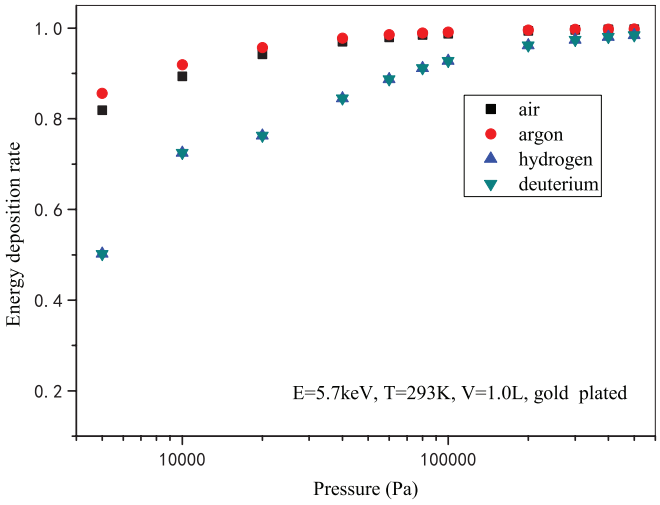

FIG. 2. Results of energy deposition in different carrier gas at different pressure.

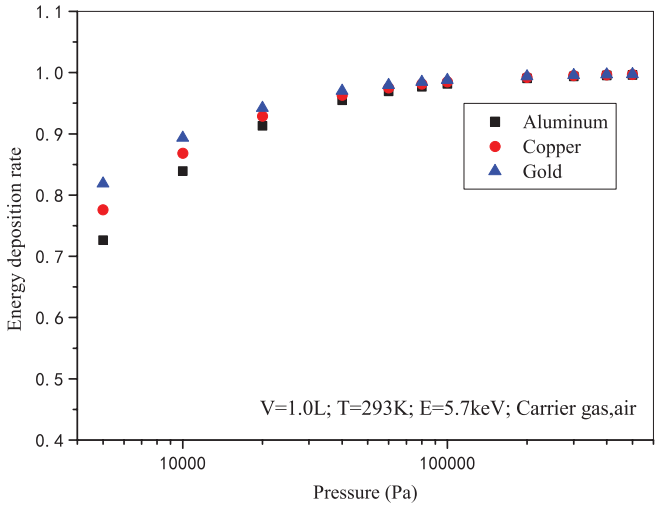

FIG. 3. Results of energy deposition in chambers with different wall materials.

Temperature used in the calculations is 293 K, and the inner wall of the chamber is gold plated.

In Fig. 2, for all the kinds of carrier gas, energy deposition rate rises as gas pressure increases, and gradually approaches 1.0 at pressure higher than 100 kPa. It is obvious that energy deposition rate in air or argon is much higher than in hydrogen and deuterium at low pressure, nearly 70.7% higher at pressure 5 kPa. Energy deposition rate in air gives similar results as in argon due to their similarity in range of β ray, as well as in hydrogen and deuterium. The difference between argon (or air) and hydrogen (or deuterium) should be attributed to the range difference of β rays in them, as shown in Eq. (7).

B. Energy deposition in chambers with different wall materials

For different applications, several kinds of metal might be adopted as the inner wall material of ionization chambers for tritium measurements, such as Cu, Al, Au, and SS. According to Eq. (8), backscattering coefficient is an important parameter to determine the energy deposition rate. To estimate the influence of commonly used wall materials, the average energy of β ray of tritium, $E = 5.7$ keV, is chosen in calculations. Referring to Assad's work,[18] for $E = 5.7$ keV, the backscattering coefficients are $\eta_{Al} = 0.17$, $\eta_{Cu} = 0.32$, $\eta_{Au} = 0.45$, respectively. The chamber size in calculations is 1.0 L and gas temperature in the chamber is set to be 293 K. Air is the carrier gas in the chamber. Calculation results are shown in Fig. 3.

In Fig. 3, it is apparent that energy deposition rate in chambers with different wall materials varies a lot due to the difference in backscattering coefficient, especially at pressure lower than 10 kPa. Gold as chamber wall gives higher energy deposition rate than copper, which agrees well with experimental results obtained in Wagner's work.[13] According to the value of backscattering coefficient, aluminum wall leads to most serious energy loss on chamber wall. At pressure 5 kPa, energy deposition rate in chamber of gold wall is about 11.3%

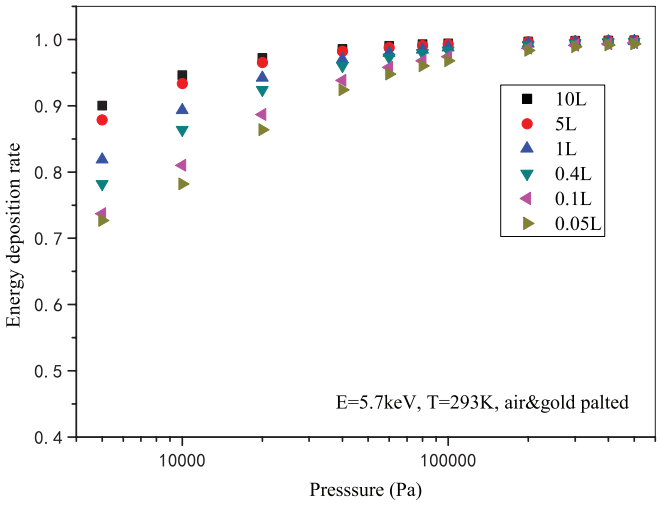

FIG. 4. Results of energy deposition in chambers of different sizes.

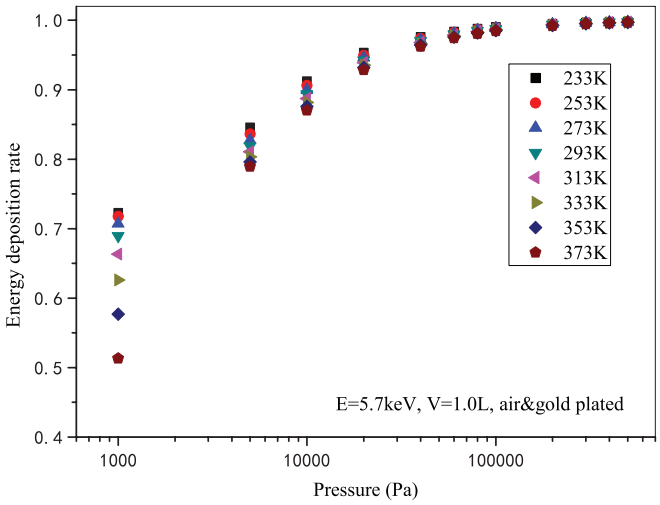

FIG. 5. Results of energy deposition in chambers at different temperature.

higher than in chamber of aluminum wall. As pressure gets higher than 100 kPa, the value of volume (ΔV) in Eq. (5) is negligible comparing with 1.0 L and only a small portion of electrons will loss their energy on the wall, which results that the influence of different wall materials on energy deposition rate becomes negligible.

C. Energy deposition in chambers of different size

In Eq. (8), for the same wall material, carrier gas and gas temperature, energy deposition rate in an ionization chamber is mainly determined by its size. To examine the influence of chamber size, energy deposition rate is calculated with chambers of different sizes from 50 mL to 10 L. In the calculations, the energy of β ray is set to be 5.7 keV, and temperature is 293 K. Gold is chosen to be the wall material and air is the carrier gas in the chamber. Results are shown in Fig. 4. In Fig. 4, it indicates that energy deposition rate in small chamber is much lower than in large ones, especially at low pressure. At pressure 5 kPa, energy deposition rate is as low as 0.73 for 0.05 L chamber while 0.90 for 10 L one. At pressure higher than 100 kPa, the influence of chamber size on energy deposition rate becomes less than 3%.

In fact, the influence of chamber size on energy deposition in chamber can be qualitatively illustrated with the help of Eq. (5). Generally, as chamber size becomes smaller, the ratio of volume (ΔV) in which β ray can reach chamber wall and the total volume (V_{tot}) will get larger, which directly results in more β particles get opportunities to interact with chamber wall and loss their energy. As a result, energy deposition rate in the chamber becomes smaller. In contrary, for large chamber or high gas pressure, the volume (ΔV) is negligible comparing with V_{tot} and then energy deposition rate will be closer to 1.0.

D. Energy deposition in chambers at different temperature

Another factor might affect the performance of an ionization chamber is gas temperature. To evaluate the influence of temperature, all the other factors are fixed in the calculations. The energy of β ray, gas composition, wall material, and chamber size are set to be 5.7 keV, air, gold, and 1.0 L, respectively. Calculation results indicate that the variation of gas temperature might place some influence on energy deposition, as shown in Fig. 5. At 5.0 kPa, energy deposition rate is about 0.79 at 373 K, nearly 6.7% less than deposition rate at 233 K. As pressure increases, difference between deposition rate for different temperature becomes smaller, especially for pressure higher than 100 kPa.

The difference in energy deposition rate at different temperature should be attributed to the variation of the range of β ray. According to Clapeyron equation, $PV = nRT$, if gas pressure and chamber volume are constant, as temperature goes up, the number of gas molecular will decrease and the range of β ray will increase. Therefore, more particles will get the opportunities to loss their energy on chamber wall at higher temperature, which will result in the decrease of energy deposition rate.

E. Experiments

In order to verify the reliability of the theoretical calculations, experiments have been done with a gold plated ionization chamber of 1 L to obtain energy deposition rate between 10 kPa and 100 kPa. During these experiments air was chosen to be carrier gas. To make the comparison clearly, the parameters used in both experiments and theoretical calculations were the same. The energy of β ray emitted by tritium is set to be 5.7 keV. Comparison results indicate that theoretical calculations give good accordance with experiments within 7% relative deviation at the given conditions, as shown in Fig. 6.

IV. DISCUSSION

A. Influence of approximations on calculations

The effect of carrier gas, wall materials, chamber size, and gas temperature has been quantitatively estimated at different pressure based on the established formula. However,

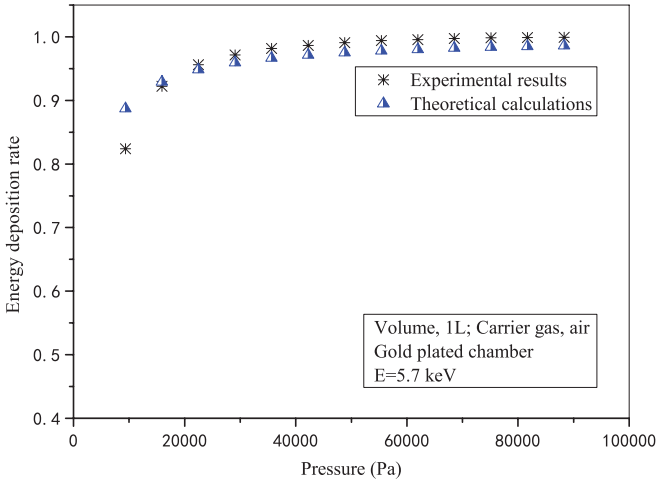

FIG. 6. Comparison of theoretical calculations and experimental results.

some approximations in the calculations might lead to higher or lower estimation of the energy deposition rate in an ionization chamber for tritium measurements. First, we have assumed that half of β rays in the region of ΔV could reach the chamber wall without energy loss and the other half would go directly towards inner region without scattering, especially backscattering. In fact, β rays emitted towards chamber wall will loss part of their energy on their way, while some β rays towards the inner region will also be scattered back by particles in the chamber. Therefore, the factor in Eq. (5) might slightly deviate from 1/2 and the value of E_z might be a little smaller than E_0, which might devote to underestimate the energy deposition rate. Second, we also assumed in Eq. (6) that all the backscattered electrons followed elastic backscattering law. In fact, some electrons might loss their energy during this progress and E' will be smaller than E_0, which might lower the energy deposition rate slightly. The third one is about the values of exact backscattering coefficient and extrapolated range, and both of them are affected by the energy of β particles. According to Assad's work,[18] backscattering coefficient of electrons on gold increases sharply from 0.18 to 0.45 as electron energy increases from 0.5 keV to 4.0 keV, and then becomes constantly. By contrary, backscattering coefficient of electrons on aluminum decreases from 0.22 to 0.17 as electron energy increases from 0.5 keV to 4.0 keV. In the calculations with gold plated chamber we use 0.45 as backscattering coefficient, which might lead to overestimating the deposition rate. In addition, as extrapolated range increases as energy of β particle gets larger, the use of average energy (5.7 keV) in all the calculations might also cause higher estimation of deposition rate, according to that the energy of around 40% β particles emitted by tritium is larger than 6 keV.[19]

B. Energy deposition calculations for small volume chambers or at lower gas pressure

In all the calculations above, in fact there is another assumption, $\lambda < r$, that is $\Delta V < V_{tot}$. However, when ionization chamber is small (such as 1 mL) or the gas pressure in the chamber is low (for example, lower than 1 kPa), the range of β rays (λ) might become larger than the radius of the chamber (r). Once this happens, all the β particles in the chamber will get the chance to reach chamber wall, which means that another approximation should be used instead of Eq. (8). Under this situation, Eq. (4) should be rewritten in the following form:

$$\epsilon = 1 - \frac{1-\eta}{\lambda E_0}\int_0^{\lambda} k_z E_z dz - \frac{\eta}{\lambda E_0}\int_0^{\lambda} k_z (E_z - E_z')dz. \quad (9)$$

To perform further calculations, experiments should be done to obtain the proper approximation of both k_z and E_z in Eq. (9).

V. CONCLUSIONS

Energy deposition of β ray in ionization chambers for tritium measurements has been studied theoretically by considering effects of the following factors: carrier gas, wall material, chamber size, gas temperature, and gas pressure. Conclusions are listed as follows.

1. It is very important to evaluate the energy deposition in an ionization chamber before its construction to improve its performance with theory established in this article. Proper correction should be applied according to its operating conditions noted above.
2. Difference in carrier gas, gas temperature might lead to great variation in energy deposition rate. Therefore, it is necessary to reestablish a calibration curve when operating conditions change. For example, calibration curve must be re-established when carrier gas changes from deuterium to argon. However, calibration curve for hydrogen is also suitable for deuterium.
3. Gold plated wall is helpful to obtain higher energy deposition rate due to its larger backscattering coefficient, compared with copper and aluminum. By the way, it is also useful to decrease tritium absorption in chamber wall by plating gold.
4. Chamber size and gas pressure will significantly affect energy deposition rate. It is necessary to choose proper chamber size and gas pressure for tritium measurements if it is optional. Otherwise, proper calibration should be performed at the same pressure with the very chamber to obtain a correction factor.

[1]L. Mercadier, J. Hermann, C. Grisolia, and A. Semerok, J. Nucl. Mater. **415**, S1187–S1190 (2011).
[2]Y. Kawamura, W. Shu, M. Matsuyama, and T. Yamanishi, Fusion Sci. Technol. **60**, 986–989 (2011).
[3]T. Kawano, T. Yamano, K. Yamada, M. Tanaka, Y. Asakura, T. Uda, Fusion Sci. Technol. **54**, 189–192 (2008).
[4]M. Matsuyama, K. Takatsuka, and M. Hara, Fusion Eng. Des. **85**, 2045–2048 (2010).
[5]D. Diprete, R. Raymond Sigg, L. Leah Arrigo, and D. Donald Pak, Fusion Sci. Technol. **54**, 167–169 (2008).
[6]Z. L. Chen, R. M. Chang, L. Mu, G. Y. Song, H. Y. Wang, G. Y. Wu, and X. Y. Wei, Rev. Sci. Instrum. **81**, 073302-1–073302-4 (2010).
[7]R. A. Jalbert, Fusion Technol. **8**, 2077–2081 (1985).
[8]L. Rodrigo, J. M. Miller, S. R. Bokwa, R. E. Johnson, B. M. MacDonald, and J. Senohrabek, Fusion Technol. **21**, 629–635 (1992).

[9]Yu. V. Gott and M. M. Stepanenko, Instrum. Exp. Tech. **52**(2), 260–264 (2009).
[10]U. Tatsuhiko, O. Kenji, M. Yuji, and N. Yuji, J. Nucl. Sci. Technol. **28**, 451–458 (1991).
[11]Masao Matsuyama and Kuniaki Watanabe, Fusion Eng. Des. **18**, 91–96 (1991).
[12]Z. L. Chen, X. Y. Wei, L. Mu, H. Y. Wang, R. M. Chang, and G. Y. Wu, Nucl. Instrum. Methods Phys. Res. A **622**, 136–138 (2010).
[13]R. Wagner, U. Besserer, D. Demange, H. Dittrich, T. L. Le, K. H. Simon, and K. Guenther, Fusion Sci. Technol. **60**, 968–971 (2011).
[14]N. Tsoulfanidis, *Measurement and Detection of Radiation* (Taylor & Francis, Washington, DC, 1995).
[15]A. K. F. Haque, M. A. Uddin, A. K. Basak, K. R. Karim, and B. C. Saha, Phys. Rev. A **73**, 012708-1–012708-7 (2006).
[16]A. K. F. Haque, M. A. Uddin, A. K. Basak, K. R. Karim, B. C. Saha, and F. B. Malik, Phys. Rev. A **73**, 052703-1–052703-8 (2006).
[17]T. Tabata, T. Ito, and S. Okabe, Nucl. Instrum. Methods **103**, 85 (1972).
[18]A. M. D. Assad and M. M. ElGomati, Scanning Microsc. **12**, 185–192 (1998).
[19]*DOE Handbook. Design Consideration* (DOE-HDBK-1132-99, 1999).