Electron Transport Properties in Xenon Gas Detectors

H. Date, Y. Ishimaru[†], and M. Shimozuma

College of Medical Technology, Hokkaido University, Sapporo 060-0812, Japan
[†] present address: Hakodate Municipal Hospital, Hakodate 041-8680, Japan
e-mail: date@cme.hokudai.ac.jp

ABSTRACT

In this study, we investigate electron transport properties in xenon gas by using a Monte Carlo technique for electrons with energies below 10 keV. First of all, we determine a set of electron collision cross sections with xenon by scrutinizing the cross section data taken from many publications. Then, the W value and the Fano factor for electrons in gaseous xenon are computed by the Monte Carlo simulation on the assumption that electrons undergo single collision events including elastic, excitation and ionization processes. We also evaluate the production number of excited atoms.

Keywords: xenon gas detectors, electron transport properties, W value, Fano factor, Monte Carlo simulation.

1. INTRODUCTION

Xenon gas has been used as an effective medium for gamma ray detectors, and attempts to gain not only ionization signals but also scintillation photon pulses in xenon have been made. A combination of the ionization signal and the photon detection may provide a promising method for capturing a spatial distribution and a high-resolution rate of the radiation. In order to maximize the utility of xenon gas in such applications, it is essential to know the electron transport properties associated with microscopic collision processes. In this study, we investigate electron dynamics in xenon gas by using a Monte Carlo technique for electrons below 10 keV. To perform a precise simulation, firstly, we determine a set of electron collision cross sections by looking up a lot of data in the literature. Then, a Monte Carlo simulation considering single collision processes based upon the set of cross sections is made to deduce the electron W value and the Fano factor in xenon. In addition to these calculations, we try to examine the production rate of excited atoms, which may lead to an estimation of the scintillation efficiency.

2. ELECTRON COLLISION CROSS SECTIONS

Three types of collisions are considered for xenon: the elastic, the ionization and the excitation. So many investigators have reported the electron collision data for total cross section or differential cross section (DCS) in xenon. However, those are usually fragmentary with respect to electron energy or scattering angle, and there exist quite a few discrepancies among the reported values. In this situation, we combine pieces of the data for the total cross section to obtain a unique curve in a wide range of energy below 10 keV for each reaction process.

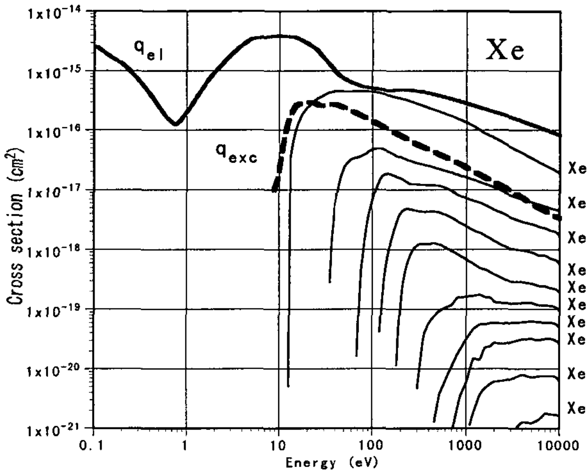

Fig.1 Set of cross sections

According to circumstances, we perform the integration of differential cross sections over the scattering angle to deduce the total cross section. The scattering probability with solid angle in each collision event is assumed to be "isotropic" because of a lack of the DCS data for these ranges of energy. This assumption does not affect the calculation of the W value nor the Fano factor. A policy for selecting the data is as follows:

(1) as new one as possible;
(2) to estimate by interpolation or extrapolation if the data points are missing;
(3) to adopt the average if the values are scattering in the experimental data;
(4) to reconfirm (if possible) by means of another technique.

A set of cross section determined in our study is shown in Fig.1. The elastic cross section (q_{el}) was constructed by combination of the data from Jost et al.[1] for 0.01-0.65eV, Gibson et al.[2] for 0.76-0.86eV, Mayol & Salvat[3] for 150-10000eV and the integration of DCSs from a lot of reports for 1-100eV. The total ionization cross section arises from partial ionization cross sections, as in the form of

$$q_i^{\mathrm{total(gross)}} = \sum n q_i^{n+} = q_i^{+} + 2q_i^{2+} + 3q_i^{3+} + \ldots \quad . \qquad (1)$$

The partial ionization cross sections (denoted by Xe^{n+} in Fig.1) were respectively taken from several papers. The total excitation cross section was constructed with a modification of the data from Filipovic et al.[4] and de Heer et al. [5]. The references for the elastic DCSs and the partial ionization cross sections are not listed in this paper for want of space.

3. METHOD OF CALCULATION

The transport calculations are performed by a free-flight-time (FFT) Monte Carlo technique, in which the motion of every electron is followed as time elapses by Δt. The energy distribution of secondary electrons in the ionization collision can be evaluated by using an algorithm by Grosswendt & Waibel[6]. In their algorithm, the energy of the secondary electrons is determined by

$$k = T_0 + \Gamma \tan\left\{\zeta\left[\arctan\left(\frac{T_m - T_0}{\Gamma}\right) + \arctan\left(\frac{T_0}{\Gamma}\right)\right] - \arctan\left(\frac{T_0}{\Gamma}\right)\right\} \qquad (2)$$

$$T_0 = T_s - T_a/(T + T_b), T_m = (T - I)/2, \Gamma = \Gamma_s T/(T + \Gamma_b).$$

Here, T is kinetic energy of an incident electron, I the ionization threshold, ξ a random number, and T_s, T_a, T_b, T_s and Γ_b are fitting parameters taken from the publication of Green & Sawada[7]. The thresholds of the ionization and the excitation are 12.12eV and 8.32eV, respectively. The energy loss in the excitation collision is chosen to be a value between 8.32eV and 12.12eV, uniformly (by a random number), taking account of the excitation to a variety of energy levels. The W value for electrons with a given energy is defined by

$$\frac{E_0}{n} = \frac{\text{Initial energy of electron}}{\text{Total number of electron - ion pair}}, \qquad (3)$$

and the Fano factor may be written as

$$\frac{\text{Observed variance}}{\text{Variance by Poisson statistics}} = \frac{\frac{1}{N-1}\sum_{i=1}^{N}(n_i - \bar{n})^2}{\frac{1}{N}\sum_{i=1}^{N} n_i \ (= \bar{n})}, \qquad (4)$$

where N is a trial number of incident electrons. A large number of electrons (N>2000) with the same initial energy are followed until the energy goes down to a value below cutoff energy (= the ionization threshold). We also calculate the frequency of the excitation and evaluate the ratio of energy loss by the excitation to that by the ionization. The parameters in the simulation are listed in Table 1.

Table 1 Parameters in the Monte Carlo simulation

Time step, Δt, in FFT (free-flight-time) method	10^{-12}/p (Torr) sec
Gas pressure	e.g., 100Torr
Initial electron energy	T ~10keV
Electron collision cross sections	elastic, ionization (gross), total excitation
Scattering angle of electron	isotropic scattering is assumed → this assumption does NOT affect the calculation of the W-value and excitation rate
Energy distribution of secondary electron	by the algorithm of Grosswendt & Waibel[6]
Loss-energy per excitation collision:	randomly chosen between thresholds of the lowest excitation level and the ionization

4. RESULTS AND DISCUSSION

Figure 2 shows mean W values (averaged over trials) as a function of incident electron energy. The values are gradually approaching the fixed value of 21.7eV with the electron energy increasing. Combecher[8] presented the high energy W value for xenon as 22.0 eV, and our result is in good agreement with it. The distribution of W values for the trial on 10-keV initial electron is given in Fig.3. From the distribution in Fig.3, it can be derived that the Fano factor is 0.151. Figure 4 shows the distribution of excitation number of times for 10-keV initial electrons. Mean value of the number per 10-keV electron is 228. Accordingly, the mean ratio of energy dissipated by the excitation and the ionization, E_{exc}/E_{ion}, is found to be 0.38. In order to see the effect of the excitation collision process on the parameters above, we also attempted the calculations with a slight modification of the excitation cross section value by ±10%. The result showed that the mean W value varies from 21.4 eV to 22.0 eV and the Fano factor from 0.145 to 0.161 for the change of multiplication factor on the cross section from 0.9 to 1.1. By considering the amount of scatter in the data for the collision cross sections, we estimated the total error of the calculation arising from the cross sections roughly to be ±2%.

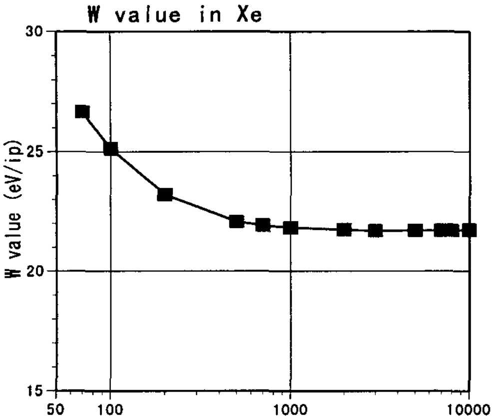

Fig.2 Mean W value

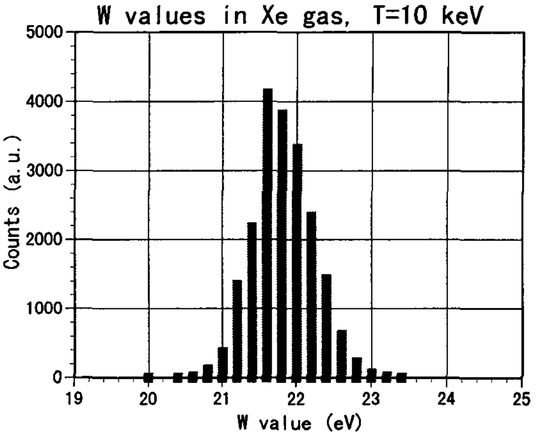

Fig.3 Distribution of W value

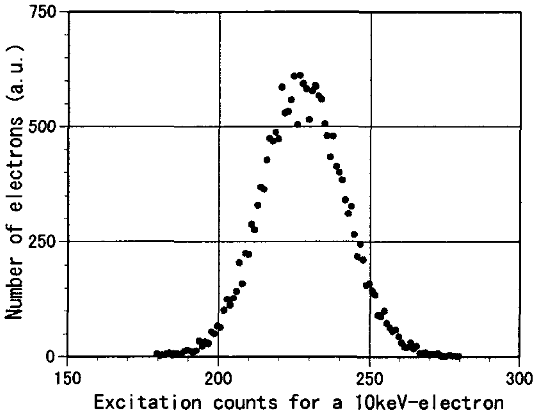

Fig.4 Counts for excitation collision events

5. CONCLUSION

We have determined a set of electron collision cross sections for xenon by examining a lot of data from the many publications, and investigated electron transport properties by a Monte Carlo simulation. We found that the mean W value and Fano factor in gaseous xenon are 21.7 eV and 0.15, respectively, for 10-keV electron. In addition, the ratio of energy loss by the excitation collisions to that by the ionization was shown to be 0.38.

REFERENCES

1. K Jost, P G F Bisling, F Eschen, M Felsmann and L Walther, XII Int. Conf. on. the Physics of Electronic and Atomic Collisions (Berlin: ICPEAC) p91 (1983)
2. J C Gibson, D R Lun, L J Allen, R P McEachran, L A Parcell and S J Buckman, J. Phys. B: At. Mol. Opt. Phys. **31** 3949-3964 (1998)
3. R Mayol and F Salvat, Atomic Data and Nucl. Data Tables **65**, 55-154 (1997)
4. D Filipović, B Marinković, V Pejčev and L Vušković, Phys. Rev. A **37**, 356-364 (1988)
5. F J de Heer, R H J Jansen and W van der Kaay, J. Phys. B: Atom. Molec. Phys. **12**, 979-1002 (1979)
6. B Grosswendt and E Waibel, Nucl. Instr. and Meth. **155**, 145-156 (1978)
7. A E S Green and T Sawada, J. Atmospheric Terrest. Phys. **34**, 1719-1728 (1972)
8. D Combecher, Radiat. Res. **84**, 189-218 (1980)