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Longitudinal and transverse diffusion of electrons in high-pressure xenon

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ABSTRACT: High-pressure xenon is an attractive medium for radiation detection in that the time projection chambers can be constructed by combined measurements of charge and light signals. The electron transport properties are essential information for developing and operating high-pressure xenon detectors. In this paper, our recent experimental results of electron diffusion coefficients in high-pressure xenon are presented. We measured the longitudinal diffusion coefficient of electrons under external applied electric fields in high-pressure xenon, ranging from 0.17 to 5.0 MPa in pressure at room temperature. A significant pressure dependence was found in the density-normalized longitudinal diffusion coefficient for low electric field region. We compared the longitudinal diffusion coefficient with the transverse one at a pressure of 1.0 MPa, and obtained the difference between both the diffusion coefficients. The longitudinal diffusion was found to become smaller than the transverse one when increasing the external electric field.

KEYWORDS: Gaseous detectors; Charge transport and multiplication in gas; Time projection Chambers (TPC); Gamma detectors (scintillators, CZT, HPG, HgI etc)

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2013 JINST 8 C01028

Contents

1 Introduction

High-pressure xenon has many features suitable for X/γ-ray and particle detectors such as its large stopping power, high ionization and scintillation yields, and flexibility for designing detectors. Additionally, among the most remarkable characteristics of xenon is that ionization charge and scintillation light are simultaneously observable. The three-dimensional trajectory of charged particles in such detectors can be determined from charge and light signals on the basis of the principle of time projection chambers (TPCs). TPCs filled with high-pressure xenon have the potential to be used for the MeV-region γ-ray imaging [1–3] or neutrinoless double-β decay searching [4]. Electron transport properties in high-pressure xenon under external applied electric fields are essential to developing and operating such TPCs. In particular, the electron diffusion coefficients are important from the viewpoint of the position resolution in TPCs.

Electron diffusion in gaseous xenon has been experimentally studied near or below atmospheric pressure (1 atm = 1.01 bar = 0.101 MPa). It has been found out that magnitudes of electron diffusion under an external electric field are different between parallel to and perpendicular to the electric field, which are characterized by the longitudinal (D_{L}) and transverse (D_{T}) diffusion coefficients, respectively. The density-normalized longitudinal diffusion coefficient ND_{L}, where N denotes the number density of gas atoms, was measured by Hashimoto and Nakamura [5] at pressures below 0.12 MPa, and the ratio of the longitudinal diffusion coefficient to the mobility D_{L}/μ was measured by Pack et al. [6] at pressures below 0.096 MPa. Also, the characteristic energy ε_{T}, which is related to the transverse diffusion coefficient as $\varepsilon_{\mathrm{T}} = eD_{\mathrm{T}}/\mu$, where e is the elementary charge, was measured by Koizumi et al. [7] at pressures below 0.193 MPa. These parameters were revealed to be functions only of the reduced electric field E/N at near or below atmospheric pressure. Note that the reduced electric field E/N is defined as the electric field normalized by number density of gas atoms, of which unit is Td, and 1 Td = 10^{-17} V$\cdot$cm^2.

In the case of high-pressure xenon, on the other hand, there are only a few studies on the electron diffusion. Only the characteristic energy was measured at pressures below 1.0 MPa and in the reduced electric field range from 0.05 to 1.2 Td [8, 9], and no significant pressure dependence was observed. In high-pressure xenon, therefore, many of electron transport properties remain to be unveiled.

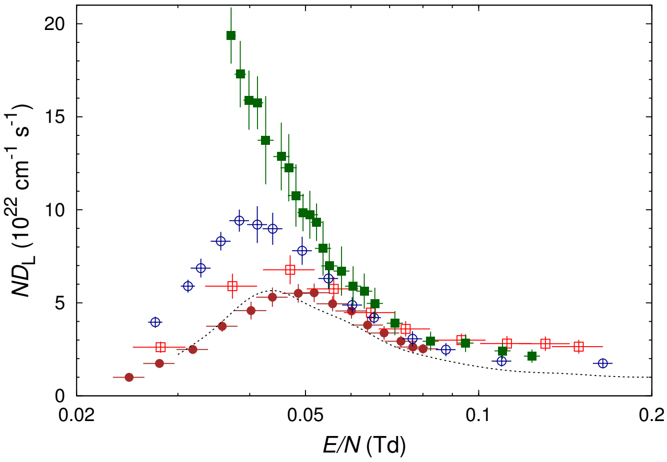

Figure 1. Density-normalized longitudinal diffusion coefficient ND_L as a function of reduced electric field E/N. The xenon pressures for our results [10, 11] are 0.17 (●), 1.0 (□), 3.0 (○), and 5.0 (■) MPa. The corresponding gaseous densities are 4.19×10^{19}, 2.55×10^{20}, 8.69×10^{20}, and 1.73×10^{21} cm^{-3}, respectively. The dashed line represents the previous experimental results [5] obtained at pressures below 0.12 MPa.

Recently, we measured the longitudinal diffusion coefficient in a wide range of gaseous pressures [10, 11] for the purpose of better understanding of the electron transport properties in high-pressure xenon. In this paper, our recent experimental results of the longitudinal diffusion coefficient are summarized in section 2, and a comparison between longitudinal and transverse diffusion in high-pressure xenon is made in section 3. Since the density-normalized diffusion coefficient and reduced electric field are related to the number density of gas atoms, we also indicate the gaseous density with the gaseous pressure for high-pressure data.

2 Pressure dependence of the longitudinal diffusion

The longitudinal diffusion coefficient of electrons at room temperature was measured in a wide range of gaseous pressures using two parallel-plate drift chambers with different pressure ranges [10, 11]. At relatively low pressures ranging from 0.17 to 1.8 MPa (from 4.19×10^{19} to 4.82×10^{20} cm^{-3} in density), a xenon flash lamp was used as a UV source, and electron swarms were generated by UV flashlights at a photocathode positioned in the chamber [10]. On the other hand, at high pressures ranging from 1.0 to 5.0 MPa (from 2.55×10^{20} to 1.73×10^{21} cm^{-3} in density), electron swarms were generated by 5.49-MeV α-particles [11]. For the measurements with both chambers, the electron mobility and longitudinal diffusion coefficient were derived from the time evolution of current signals formed by drifting electrons under an uniform electric field between parallel plates. The signals induced on the anode of the chamber were fed to a charge-sensitive preamplifier, and the output signals from the preamplifier were stored using a digital oscilloscope. The electron mobility and longitudinal diffusion coefficient were determined by analyzing the waveforms of preamplifier signals.

Figure 1 shows the results of the density-normalized longitudinal diffusion coefficient ND_L [10, 11] as a function of reduced electric field E/N for several representative pressures. Previous experimental results at near or below atmospheric pressure [5] are also shown. As a

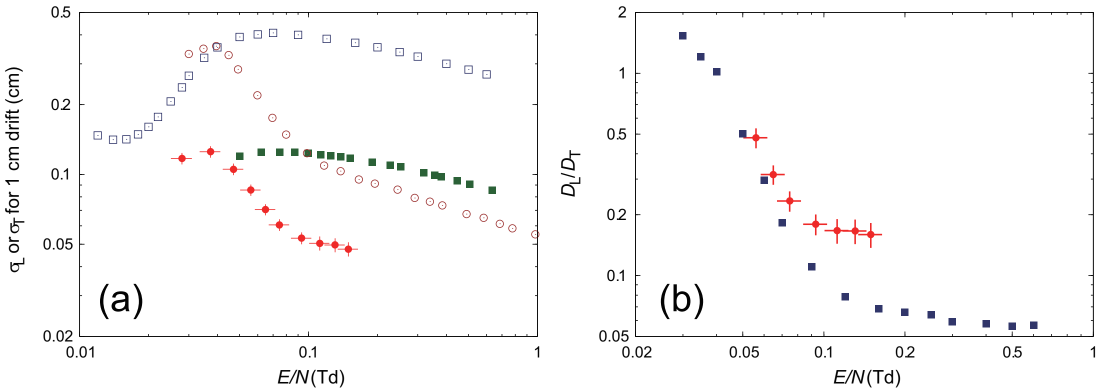

Figure 2. (a) Magnitudes of longitudinal diffusion σ_L and transverse diffusion σ_T for the drift length of 1 cm as a function of reduced electric field E/N. The data shown are σ_L at 1.0 MPa (●) and at atmospheric pressure (○), and σ_T at 1.0 MPa (■) and at atmospheric pressure (□), respectively. (b) The ratio of longitudinal to transverse diffusion coefficient D_L/D_T at 1.0 MPa (●) and at atmospheric pressure (■) as a function of reduced electric field E/N.

result, a significant pressure dependence of ND_L was observed for $E/N \approx 0.04$ Td. In contrast, no pressure dependence was observed for $E/N \gtrsim 0.06$ Td. This finding indicates that the effective momentum-transfer cross section for electron-atom scattering varies with increasing pressure. Since the maximum of ND_L at $E/N \approx 0.05$ Td is related to the minimum of the momentum-transfer cross section known as the Ramsauer-Townsend minimum, the effective momentum-transfer cross section decreases with increasing pressure around the region of the Ramsauer-Townsend minimum. Although the density-normalized mobility $N\mu$ also depends on the gaseous pressure, the pressure-dependent variation of ND_L was found to be much larger than that of $N\mu$ [11].

3 Longitudinal and transverse diffusion at high pressure

Figure 2(a) shows the magnitudes of the longitudinal electron diffusion σ_L and transverse electron diffusion σ_T for the drift length of 1 cm at a pressure of 1.0 MPa (a density of 2.6×10^{20} cm^{-3}) and at atmospheric pressure as a function of reduced electric field E/N. The magnitude of diffusion σ is related to the diffusion coefficient D as $\sigma = (2D\tau)^{1/2}$ for longitudinal and transverse diffusion, respectively, where τ is the drift time of electrons. The ratios of longitudinal to transverse diffusion coefficient D_L/D_T at a pressure of 1.0 MPa and at atmospheric pressure are also shown in figure 2(b) as a function of reduced electric field E/N. These data are derived from the experimental results of electron mobility in ref. [12] and electron diffusion coefficients in refs. [5, 7, 9, 11]. It is to be noted that the data at atmospheric pressure are just as valid for near or below atmospheric pressure.

As shown in figure 2(a), the electron diffusion is suppressed at high pressure for the same drift distance. Magnitude of electron diffusion is proportional to $N^{-1/2}$ when the density-normalized diffusion coefficient is independent on pressure. Therefore, σ_L is not proportional to $N^{-1/2}$ for $E/N \approx 0.04$ Td because ND_L depends on pressure for this electric field as described in section 2. Although it was not measured in previous studies [8, 9], there may be a pressure dependence of ND_T for low electric field region around $E/N \approx 0.04$ Td.

2013 JINST 8 C01028

At a pressure of 1.0 MPa, σ_L and σ_T are almost comparable at low electric field around $E/N \approx$ 0.05 Td. In contrast, the difference between σ_L and σ_T becomes larger with increasing electric field. The longitudinal diffusion decreases with increasing electric field from $\sigma_L \approx 0.1$ to 0.05 cm, whereas the transverse diffusion remains nearly constant at $\sigma_T \approx 0.1$ cm. This trend is also obtained in the ratio D_L/D_T as shown in figure 2(b); the ratio D_L/D_T decreases with increasing electric field. The difference between the longitudinal and transverse diffusion coefficients arises from the fact that the longitudinal diffusion coefficient is related to the gradient of the momentum-transfer cross section [13]. The longitudinal diffusion coefficient is larger than the transverse one when the momentum-transfer cross section decreases with increasing electron energy, and is smaller than the transverse one when the momentum-transfer cross section increases with increasing electron energy. Since the pressure dependence was not observed in ND_L and ND_T for $E/N \gtrsim 0.06$ Td, there seems to be no pressure dependence of D_L/D_T between $E/N \approx 0.05$ and 0.1 Td in figure 2(b). However, D_L/D_T at 1.0 MPa is slightly larger than that at atmospheric pressure for $E/N \gtrsim 0.1$ Td. The cause of this difference is presently unknown, and further detailed studies will be needed to understand the electron diffusion in high-pressure xenon.

4 Conclusions

The longitudinal diffusion coefficient of electrons was measured in high-pressure xenon at room temperature, extending the previous published results in the high pressure end up to 5.0 MPa. It was found that the density-normalized longitudinal diffusion coefficient significantly increases with pressure for reduced electric fields around 0.04 Td, which can be attributed to the decrease in the effective momentum-transfer cross section. The longitudinal diffusion becomes smaller than the transverse one, when increasing the reduced electric field from approximately 0.05 to 0.2 Td at a pressure of 1.0 MPa. There seems to be no significant pressure dependence in the ratio of the longitudinal to transverse diffusion coefficient for reduced electric fields above approximately 0.05 Td, however, further investigations are necessary on the electron diffusion in wider ranges of gaseous pressures and electric fields.

References

[1] N. Hasebe et al., *Nuclear γ-ray imaging spectroscopy for planetary exploration*, in the proceedings of the 2nd *International Workshop on Applications of Rare Gas Xenon to Science and Technology (XeSAT2005)*, March 8–10, Tokyo, Japan (2005).

[2] S. Kobayashi et al., *A new generation γ-ray camera for planetary science applications: high pressure Xenon time projection chamber*, *Adv. Space Res.* **37** (2006) 28.

[3] M. Mimura, H. Kusano, S. Kobayashi, M. Miyajima and N. Hasebe, *Xenon time projection chamber for next-generation planetary missions*, *J. Phys. Soc. Jpn. Suppl. A* **78** (2009) 157.

[4] V. Álvarez et al.,*NEXT-100 Technical Design Report (TDR). Executive summary*, 2012 *JINST* **7** T06001.

[5] T. Hashimoto and Y. Nakamura, *Electron transport coefficient in Xe gas and electron collision cross section of a Xe atom* (in Japanese), papers of *IEEJ Gas Discharge Technical Committee ED-90-61* (1990).

[6] J.L. Pack, R.E. Voshall, A.V. Phelps and L.E. Kline, *Longitudinal electron diffusion coefficients in gases: noble gases*, *J. Appl. Phys.* **71** (1992) 5363.

[7] T. Koizumi, E. Shirakawa and I. Ogawa, *Momentum transfer cross sections for low-energy electrons in Krypton and Xenon from characteristic energies*, *J. Phys.* **B 19** (1986) 2331.

[8] S. Kobayashi et al., *Ratio of transverse diffusion coefficient to mobility of electrons in high-pressure Xenon*, *Jpn. J. Appl. Phys.* **43** (2004) 5568.

[9] S. Kobayashi et al., *Ratio of transverse diffusion coefficient to mobility of electrons in high-pressure xenon and xenon doped with hydrogen*, *Jpn. J. Appl. Phys.* **45** (2006) 7894.

[10] H. Kusano, J.A.M. Lopes, M. Miyajima, E. Shibamura and N. Hasebe, *Density dependence of the longitudinal diffusion coefficient of electrons in xenon*, *Jpn. J. Appl. Phys.* **51** (2012) 048001.

[11] H. Kusano, J.A.M. Lopes, M. Miyajima, E. Shibamura and N. Hasebe, *Electron mobility and longitudinal diffusion coefficient in high-density gaseous xenon*, *Jpn. J. Appl. Phys.* **51** (2012) 116301.

[12] S.R. Hunter, J.G. Carter and L.G. Christophorou, *Low-energy electron drift and scattering in krypton and Xenon*, *Phys. Rev.* **A 38** (1988) 5539.

[13] H.R. Skullerud, *Longitudinal diffusion of electrons in electrostatic fields in gases*, *J. Phys.* **B 2** (1969) 696.

2013 JINST 8 C01028