

Experimental Measurement of the Ne^+ and Ne_2^+ Mobilities in Ne and the Reaction Rate Coefficient for $\text{Ne}^+ + 2\text{Ne} \rightarrow \text{Ne}_2^+ + \text{Ne}$

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Abstract—We measured the reduced mobilities of the atomic, Ne^+ , and dimer, Ne_2^+ , ions in Ne, under different pressures and reduced electric fields, at 300 K. Extrapolation to zero field yields values of $4.4 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ for Ne^+ and $6.2 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ for Ne_2^+ , which are in relative good agreement with other published data. The Ne^+ ions are converted to Ne_2^+ by a three-body reaction with a rate constant that was also measured. Its average value for reduced electric fields in the 8 to 12 Td range was $(5.6 \pm 0.1) \times 10^{-32} \text{ cm}^6 \text{s}^{-1}$ at 300 K, also agreeing with the results from other authors using other techniques.

Index Terms—Ion mobility, neon, reaction rate constant.

I. INTRODUCTION

MEASURING the mobilities of ions in gases is a matter of great importance for many fields of physics and chemistry. For example, in gaseous radiation detectors based on avalanche processes, the drift of positive ions near the anode plays an important role in the pulse formation [1]. In order to fully understand these detectors it is important to study the transport properties of the ions produced in the detector gases.

When a group of ions moves in a weakly ionized gas under a uniform electric field, they collide with the neutral atoms of the gas, losing kinetic energy in the collisions and gaining/losing kinetic energy from the field. After a number of ion-neutral collisions, a steady state is attained. Under these conditions, the average speed of this group of ions, also known as drift velocity, v_d , is directly proportional to the electric field intensity. Thus, $v_d = KE$, where K is the ion mobility. To facilitate the comparison and use of data, the mobility is usually converted into a reduced mobility, K_0 , defined by $K_0 = KN/N_L$ where N is the bulk gas number density and N_L , the so-called “Loschmidt number”, is its value at 273 K and 1 atm ($N_L = 2.687 \times 10^{19} \text{ atoms/cm}^3$).

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The measurement of the drift velocities in gases is simple in concept, but complications may arise when several kinds of ions, including impurities, are present in the experimental system. In this work, we extend our previous studies [2], [3] to Ne, a commonly used gas in gaseous radiation detectors either pure or as part of a gas mixture. Preliminary results have already been described [4]; we add here new measurements of the mobilities of Ne_2^+ ions.

II. EXPERIMENTAL SETUP

The measurements were carried out using a setup described in detail in a previous article [2]. The only difference is that in this case, given that the Ne ions are faster, we increased the drift distance up to 42.73 mm to make sure that, for the pressures and E/N (in Td, $1\text{Td} = 10^{-17} \text{ Vcm}^2$) values considered, sufficient collisions occur and the steady state is attained.

The experimental setup consists on a vessel filled with Ne (purity $\geq 99.999\%$), containing a Xenon UV flash lamp (Hamamatsu L2439), a standard Gaseous Electron Multiplier (GEM [5]) covered with a 250-nm-thick CsI photocathode, and two closely spaced grids (0.5 mm apart). Photons from the pulsed UV flash lamp (with a repetition rate of 10 Hz and a pulse duration inferior to 500 ns) cause the release of photoelectrons from the CsI photocathode which then enter the GEM holes where they ionize the surrounding gas atoms. Since the calculated mean free path for Ne at 8 Torr by 30 eV electrons (typical values for the pressure of the gas and for the maximum energy of the photoelectrons in this experiment) is 4 mm (using the ionization cross section from [6]), the probability of cascading avalanches across the GEM hole is very small. The ions that are produced are extracted from the GEM holes and made to drift along a region under the influence of a uniform electric field. The grid that is closest to the GEM acts as a Frisch grid [1] shielding the other grid where the ions are collected.

The electronic pulse is fed to a voltage preamplifier, before being recorded in a digital oscilloscope that enables the continuous calculation of the average of up to 128 pulses. The impulse is further digitally processed, first by subtracting the signal induced by the UV lamp and after by removing the high frequency noise. In order to do this, we calculate the signal’s fast Fourier transform, using the *fft* function from Python’s [7] *scipy* package, then we remove the high frequency terms and finally we calculate the inverse fast Fourier transform using the *ifft* function from the same Python’s package.

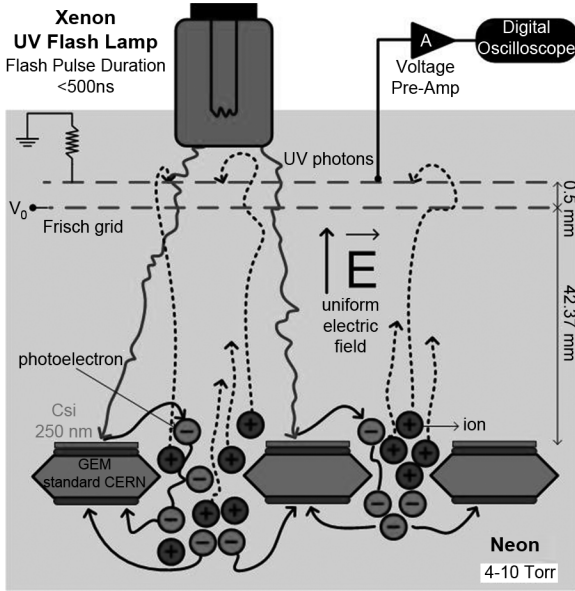


Fig. 1. Schematic representation of the physical processes that lead to the production and detection of the ions (for details, see [2]).

Measuring the time that the ions take to travel the distance between the GEM and the Frisch grid allows for the calculation of their average drift velocity and consequently their mobility.

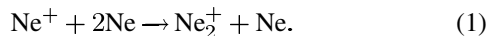
This technique does not require the use of radioactive sources to produce the ions and that may be of interest for some applications. Given the fact that the ions are produced in the GEM avalanche region, which is a very thin region when compared to the drift distance, the ion's initial position, with this technique, is known with great accuracy. In this particular case of the Ne gas, we followed a new approach (based on the area below the ion's peaks) to calculate the conversion rate constant of the Ne^+ ions into Ne_2^+ .

III. RESULTS

We measured the mobilities of the Ne^+ and Ne_2^+ ions in Ne, for different reduced electric fields (from 6 to 26 Td) and for different pressures (in the 4–10 Torr range). A typical pulse is depicted in Fig. 2(a).

Two types of ions, Ne^+ and Ne_2^+ , were identified. After removing the high frequency noise [solid gray line in Fig. 2(b)], we fitted a Gaussian function to the atomic ion peak [dashed line in Fig. 2(b)], the centroid of which [t_a in Fig. 2(b)] corresponds to the average drift time of the Ne^+ ions. We performed the Ne^+ mobility measurements at lower pressures and high reduced electric fields, because under these conditions, the atomic ion is the dominant species.

The atomic ions are converted to the dimer ions by a three-body reaction:



Assuming that only atomic ions are created in the GEM holes (discarding the production of dimer ions by associative ionization), the number of atomic ions, N_a , varies with time according to

$$\frac{dN_a}{dt} = -\beta N_a N^2 \quad (2)$$

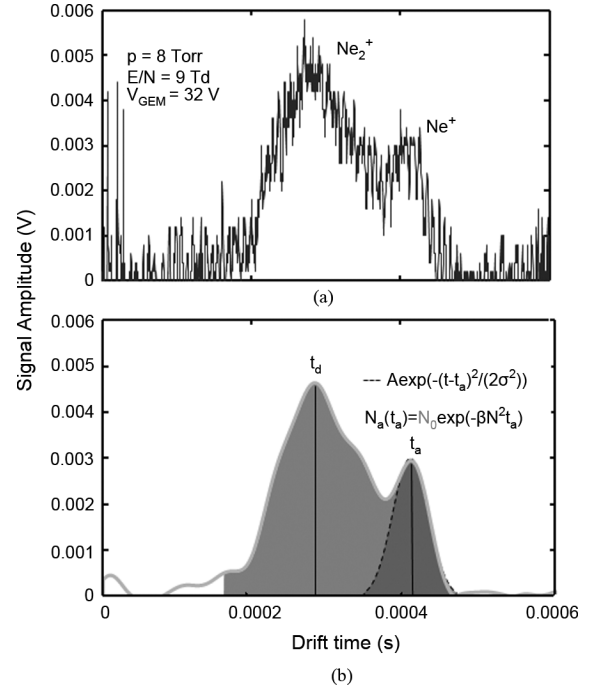


Fig. 2. a) Average of 128 digitalized pulses recorded in Ne at a pressure of 8 Torr, for a reduced electric field of 9 Td and for a voltage across the GEM, V_{GEM} , of 32 V (the signal induced by the UV flash lamp has already been subtracted). The solid gray line in b) consists of the signal a) after removing its high frequency noise. The total gray area is proportional to the total number of ions, N_0 . The dashed line is the Gaussian curve fitted to the atomic ion peak. The darker gray area is proportional to the number of atomic ions, N_a , at instant t_a .

where β is the rate constant of reaction (1) and N the gas number density. If N_0 is the total number of ions (atomic and dimer), the number of atomic ions at a given time t is then given by

$$N_a(t) = N_0 \exp(-\beta N^2 t). \quad (3)$$

The mobility of the dimer ion was measured at higher pressures (7.5–10 Torr) and lower reduced electric fields (6–10.5 Td). Under these conditions, the Ne_2^+ is the most abundant ion and its average drift time corresponds to the ions' pulse maximum [t_d in Fig. 2(b)].

The reduced mobilities of the two ions were calculated (Table I) and are depicted in Fig. 3.

Taking into account the drift distance and the E/N values considered in this work, for pressures lower than 4 Torr mobility measurements begin to deviate from their expected value. Under these conditions, the insufficient number of ion-neutral collisions prevents the steady-state from being attained.

The occurrence of discharges makes it difficult to make measurements at higher E/N values. On the other hand, very low values of E/N (below 6 Td) result in long ion drift times which increase the probability of collisions with impurity molecules.

Impurities, mostly outgassing molecules like H_2O , contribute decisively to the degradation of the ion's pulse. So, every measurement was performed within 2-3 minutes after the gas filling. Prior to each gas filling, the vessel was vacuum pumped down to pressures of $10^{-7} - 10^{-6}$ Torr.

The rate of reaction (1) was measured at pressures ranging from 6 to 9 Torr and for reduced electric fields from 8 to 12 Td.

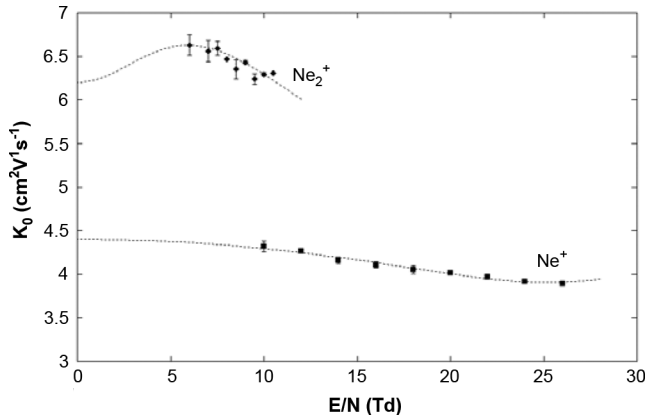


Fig. 3. Reduced mobilities of the atomic (Ne^+) and dimer (Ne_2^+) ions in Ne. Measurements were carried out for pressures between 4 and 10 Torr and for E/N values in the 6–26 Td range. For the fitting curves see text (Section IV).

TABLE I
 Ne^+ AND Ne_2^+ REDUCED MOBILITIES IN Ne at 300 K

E/N (Td)	K_0 ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	
	Ne_2^+	Ne^+
6	6.63±0.12	---
7	6.56±0.12	---
7.5	6.59±0.08	---
8	6.47	---
8.5	6.35±0.11	---
9	6.43±0.02	---
9.5	6.24±0.06	---
10	6.30±0.02	4.32±0.06
10.5	6.31	---
12	---	4.26±0.01
14	---	4.15±0.04
16	---	4.11±0.04
18	---	4.05±0.05
20	---	4.01
22	---	3.97±0.02
24	---	3.91
26	---	3.89

In this work, we have used a different technique based on the area below the ion pulse. The total area, A_0 [total gray area in Fig. 2(b)], is proportional to the total number of ions that are collected, N_0 . On the other hand, the area below the Gaussian curve, A_a (dark gray area), is proportional to the number of atomic ions at instant t_a , $N_a(t_a)$, where t_a is the Gaussian's centroid. Following from (3),

$$A_a(t_a) = A_0 \exp(-\beta N^2 t_a) \quad (4)$$

which means that

$$\beta = -\ln \left(\frac{A_a(t_a)}{A_0} \right) / (N^2 t_a). \quad (5)$$

The reaction rate coefficient values, $\hat{\alpha}$, were calculated and are displayed in Tables II and 4. Our results indicate that, for this range of values, the reaction rate coefficient does not depend on E/N .

IV. DISCUSSION

In the absence of charge exchange effects, the mobility of the ions would be described by the Langevin limit. According to the Langevin's theory [8], a limiting value of the mobility is reached

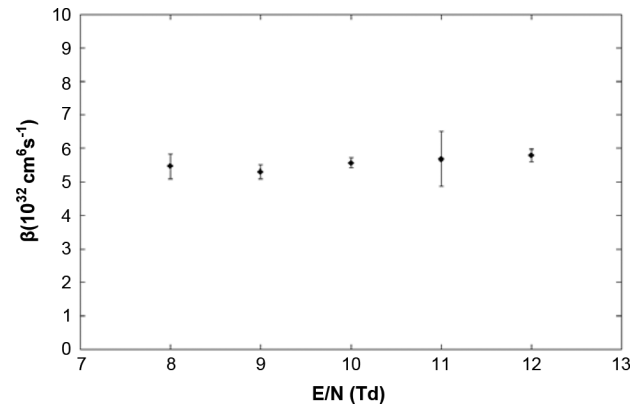


Fig. 4. Rate constant, β , for reaction $\text{Ne}^+ + 2\text{Ne} \rightarrow \text{Ne}_2^+ + \text{Ne}$. Measurements were carried out for pressures between 6 and 9 Torr and for E/N values in the [8]–[12] Td range.

TABLE II
RATE OF REACTION $\text{Ne}^+ + 2\text{Ne} \rightarrow \text{Ne}_2^+ + \text{Ne}$ at 300 K

E/N (Td)	β ($\times 10^{32} \text{cm}^6 \text{s}^{-1}$)
8	5.5 ± 0.4
9	5.3 ± 0.2
10	5.6 ± 0.2
11	5.7 ± 0.8
12	5.8 ± 0.2

when the repulsion cross section becomes negligible when compared to the polarization effect. In this case the reduced mobility when $E/N \rightarrow 0$ is given by $K_0 = 13.88/\sqrt{\alpha\mu}$, where α is the neutral polarizability in cubic angstroms ($\alpha = 0.394 \text{ \AA}^3$ for Ne [9]) and μ is the ion-neutral reduced mass in atomic mass units [10]. The Langevin limits are 6.9 for Ne^+ and 6.0 for Ne_2^+ . Since the Langevin limit has proved, in many circumstances, to describe correctly the mobility of the ions in the low-field region, many authors often chose to calculate by extrapolation the limiting value of the ion mobility when $E/N \rightarrow 0$.

To assist the extrapolation of the Ne^+ and Ne_2^+ mobilities towards $E/N = 0$, numerical fits were made to the same functions used by Beatty and Patterson in [11]. The authors of this article discuss the use of these two functions. They were chosen taking into account that K_0 has to be an even function of E/N [10] and K_0 goes as $E/N^{-1/2}$ for high E/N values (as shown by Wannier [12]). Regarding the atomic ions, the function used was

$$K_{0a} = \frac{a_0}{\left[1 + a_1 \left(\frac{E}{N}\right)^2 + a_2 \left(\frac{E}{N}\right)^4\right]^{-1/8}} \quad (6)$$

where $a_0 = 4.4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, $a_1 = -0.00193 \text{ Td}^{-2}$ and $a_2 = 1.51 \times 10^{-6} \text{ Td}^{-4}$. As for the dimer ions, we used the function [11]

$$K_{0d} = b_0 \left\{ \frac{[1 + b_1 \left(\frac{E}{N}\right)^2]}{[1 + b_2 \left(\frac{E}{N}\right)^2 + b_3 \left(\frac{E}{N}\right)^4]} \right\}^{1/4} \quad (7)$$

where $b_0 = 6.2 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, $b_1 = 0.0355 \text{ Td}^{-2}$, $b_2 = 0.0139 \text{ Td}^{-2}$ and $b_3 = 0.00019 \text{ Td}^{-4}$. The dashed lines in Fig. 3 represent these two functions.

TABLE III
VALUES OF THE ZERO FIELD MOBILITIES AND REACTION RATES FOR
CONVERSION OF Ne^+ INTO Ne_2^+ IONS IN Ne

Ref	K_0 ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)		β	T (K)
	Ne^+	Ne_2^+		
[13]	4.4	5.85	---	300
[14]	4.0	6.5	---	300
[15]	4.2	6.5	---	300
[16]	3.9	7.5	---	300
[17]	4.1	6.5	---	300
[18]	4.0	---	5.8±0.8	300
[19]	4.0±0.05	6.45±0.1	1.56	294
[20]	4.0	---	4.2	335
[11]	4.07	6.14	5-7	300
[21]	4.6	---	7.9±0.4	295
[22]	4.0	---	7.7	300
[23]	4.0±0.1	---	4.4±0.4	300
[24]	4.13±0.04	6.20±0.07	4.6±0.35	300
[25]	---	---	6.4±1.2	304-326
This work	4.4	6.2	5.6±0.1	300

Regarding the Ne^+ ion, the zero field reduced mobility (a_0 in (6)), $4.4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, is consistent with the value presented by [13] and is not very different from the other values in Table III.

As the Ne^+ ions move along the drift region, they collide with the gas atoms and they are slowed down by the symmetric charge transfer process [26]



The Langevin formula is valid only if the ions are not involved in reactions with the atoms of the gaseous medium. So, due to reaction (8), the Ne^+ zero field reduced mobility deviates from the value predicted by the Langevin formula. This reaction also explains why the atomic ions are slower than the dimer ones. The dimer ions are less likely to be involved in symmetric charge transfer processes with the atoms of the gaseous medium.

Our zero field reduced mobility value for of the Ne_2^+ ion [b_0 in (7)], $6.2 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, agrees with the results presented by [11] and [24] and is not very different from most of those values presented in Table III.

As for the reaction rate coefficient, our results (Fig. 4) are practically constant over the E/N range considered. So, we calculated the weighted average and its uncertainty [27], $(5.6 \pm 0.1) \times 10^{-32} \text{ cm}^6\text{s}^{-1}$, and this value agrees with the ones presented in [18], [11], and [25].

V. CONCLUSION

We measured the mobilities of Ne ions in Ne under different pressures and reduced electric fields. Two ions were identified (Ne^+ and Ne_2^+) and their reduced mobilities were obtained ($4.4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and $6.2 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, respectively). These results are in relative good agreement with those from other authors. We also measured the rate constant for the reaction $\text{Ne}^+ + 2\text{Ne} \rightarrow \text{Ne}_2^+ + \text{Ne}$ and our result, $(5.6 \pm 0.1) \times 10^{-32} \text{ cm}^6\text{s}^{-1}$, agrees with those published by other authors in the scientific literature, using other techniques.

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