Electron drift velocities in mixtures of helium and xenon and experimental verification of corrections to Blanc's law

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Measurements of electron drift velocities were performed in pure Xe and He and in a number of mixtures ranging up to 70% of Xe. The data were obtained by using a pulsed Townsend technique over the density-normalized electric field strength E/N between 1 and 100 Td. Even for pure gases there are no data in the entire range covered here, and these data represent an extension of accurate drift velocities to higher E/N. A selection of well-established cross sections for low energies, which was extended to higher energies, led to a reasonably good agreement of the calculated transport coefficients with the available data. At the same time we have applied the standard (common E/N) Blanc's law and two forms of common mean energy (CME, due to Chiflykian) procedures. Blanc's law fails for most mixtures at low and moderate E/N, while the CME procedure is capable of following the experimental data for the mixtures much more closely, and even predicting the negative differential conductivity region when such effect does not exist for pure gases. Thus the present paper also represents an experimental test of procedures to correct the standard Blanc's law. Finally, we have used the data for two mixtures to obtain results for the third mixture and in all cases this procedure gave excellent results even though only the standard Blanc's law was used in the process.

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I. INTRODUCTION

During the past several decades, the binary gas mixtures have been used in a number of technologies involving low temperature plasmas (nonequilibrium collisional plasmas), such as plasma display panels [1], gaseous lasers, and plasma etching devices [2]. In addition, it is necessary to use mixtures in a range of devices associated with gaseous electronics that do not qualify as plasmas, such as detectors of elementary particles and ionizing radiation, including drift and wire chambers [3], electron multipliers, and ionization and scintillation chambers [4]. Synergistic effects may be of great importance for the development of gaseous dielectrics [5] that would not involve [6] SF_6, which is known to have a major capacity for global warming. Modeling plasmas and gaseous dielectrics involves the application of *complete* sets of cross sections and/or transport coefficients (drift velocities, characteristic energies, diffusion coefficients, and ionization coefficients) [7].

In particular, studies in rare gas mixtures have been recently performed for the purpose of optimizing plasma displays which usually involve He-Xe or Ne-Xe mixtures with the addition of He and/or Ar to optimize power deposition and transfer into UV radiation [8], and also for the purpose of increasing the speed of multiwire and drift chambers required to detect elementary particles [9]. Mixtures of rare gases have been studied as an example of negative differential conductivity (NDC) [10,11] that appeared not to be consistent with the older models [12,13] if one did not include the energy loss in elastic collisions [14]. However, the effect of a lighter rare gas in the gas mixture was shown to be similar to the effect of a molecular gas in mixtures with heavier rare gases (those having a Ramsauer-Townsend minimum) [15,16], and this behavior could be used to determine the cross sections [11,16] for one of the constituents.

In this paper we present experimental results for the electron drift velocities in pure and mixed He and Xe. While the technique cannot match the highest accuracy swarm experiments in the low energy range, it is possible to extend the measurements over a broad E/N range and overlap with higher mean energies where ionization becomes important. This range of mean energies is of interest in the plasma modeling of practical devices based on ionized gases and nonequilibrium collisional plasmas, so that this work may be regarded as an attempt to test the existing sets of cross sec-

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tions proposed for plasma modeling. We have also tried to test the techniques to determine the drift velocities for mixtures, bearing in mind that in practice the data for each and every mixture may not be available.

Application of Blanc's law to determine the drift velocities for gas mixtures

One possible approach in an attempt to obtain drift velocity values for mixtures from the the corresponding data for pure gases (and other mixtures) is the well-known Blanc's law [17]

$$\frac{1}{W_{mix}} = \sum_{\alpha} x_{\alpha} \frac{1}{W_{\alpha}}, \tag{1}$$

where W_{mix} and W_{α} are the drift velocities of the mixture and αth component, respectively, and x_{α} is the fractional gas concentration. A standard Blanc's law may be labelled as a common E/N (CEON) procedure, since all the data are taken at the same value of E/N.

The application of Blanc's law for electrons has been considered as impossible even for the lowest fields. On the other hand, Blanc's law has been used quite extensively for the ions since the mean energies of the ions are closer to the thermal energy, and are therefore more similar both in the pure gases and in the mixtures. However, even under these circumstances it was necessary to make a correction which originally involved elastic collisions only [18]. It was suggested that Blanc's law would be applicable for electrons at high E/N, where the distribution functions and the mean energies at a fixed value of E/N are more similar than those of, for example, a mixture of molecular and atomic gases at moderate energies [19]. A procedure to correct Blanc's law by applying it at different E/N values corresponding to the same mean energy in pure gases and in the mixture was proposed by several authors, but the most complete proposal and discussion came from Chiflikyan [20]. We could name this procedure as that of common mean energy (CME). In this case drift velocity for the mixture can be found from

$$1 = \sum_{\alpha=1}^{n} x_{\alpha} \frac{(\mathrm{E/N})_{\alpha}}{(\mathrm{E/N})_{mix}} \left(\frac{W_{mix}}{W_{\alpha}} \right)^{\pm 1}, \tag{2}$$

where x_{α} is the fractional concentration, n is the number of components in the mixture, and $(\mathrm{E/N})_{\alpha}$, W_{α}, $(\mathrm{E/N})_{mix}$, W_{mix} are the values of the reduced electric field and the drift velocity in the αth component and mixture, respectively. The formula was developed for very restrictive approximations, although it was shown to work well in a wider set of circumstances on the basis of model calculations. In addition, both forms (with exponent +1 and with −1) were shown to work well though not equally well. We will label the procedure with +1 as the CME 1 procedure and the one with the −1 exponent as the CME 2 procedure.

Jovanović *et al.* [21] have developed corrections for the CEON procedure that include inelastic collisions and have developed a theoretical foundation of the CME procedure for a more general set of circumstances. The two forms of Chiflikyan's equations were shown to originate either from momentum (+1) or energy balance equations (−1). Their tests were confined to model calculations. In this paper, however, we perform the experimental tests of the application of Blanc's law in a corrected form for electrons in the energy range where the application of this law turns out to be most difficult. One particular set of circumstances was found to be the most effective test of the transport theory and of the applicability of Blanc's law, namely that of the mixtures of heavy and light rare gases where negative differential conductivity (NDC) occurs [12–14,20,21]. In this paper we concentrate on the drift velocity of electrons in Xe-He mixtures.

II. EXPERIMENTAL DETAILS

A. The apparatus

A thorough description of the pulsed Townsend apparatus used in these measurements has been given elsewhere [22–25]. Briefly, this method relies on the time-resolved observation of the total displacement current—electrons and positive ions in the present case—flowing through a parallel-plate capacitor (12 cm diameter) filled with the research gas mixture, under the action of a constant, highly uniform electric field over a central portion of 1.5 cm diameter. The initial photoelectrons are released by a UV flash from a 1.4 mJ Nitrogen laser ($\lambda = 337$ nm). The gap distance was kept fixed at 3 cm, to within an accuracy of 0.025 mm.

The vacuum vessel was evacuated down to 300 μPa, prior to filling it with the gas mixture. The range of working pressures was 0.067–26.7 kPa. The gas pressure and mixture composition were measured with an absolute capacitance manometer to an accuracy of 0.01%, while the gas temperature was measured to an accuracy of 0.2% over the range 293–302 K. The Xe and He samples, with a quoted purity of 99.999%, were introduced into the discharge vessel without further purification. The displacement current was measured with a 40 MHz trans-impedance amplifier, and recorded on a 100 MHz digital oscilloscope.

B. Analysis of the electron transients

In the presence of electron drift, longitudinal diffusion, and ionization, the temporal development of the electron current within the gap is described by the expression [26]

$$i_e(t) = \frac{n_0 q_0}{2T_e} \exp(\alpha W t) \left\{ \left[1 - \Phi\left(\frac{(W + \alpha D_L)t - d}{\sqrt{4 D_L t}} \right) \right] + \exp\left(\frac{W + \alpha D_L}{D_L} d \right) \left[\Phi\left(\frac{(W + \alpha D_L)t + d}{\sqrt{4 D_L t}} \right) - 1 \right] \right\}, \tag{3}$$

where n_0 is the initial photoelectron number, q_0 is the electron charge, d is the gap spacing, $T_e = d/W$ is the electron transit time, α is the ionization coefficient, and

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_{u=0}^{x} \exp(-u^2) du \tag{4}$$

is the error function of argument u. Equation (3) was derived on the assumption of a simultaneous photoelectron release

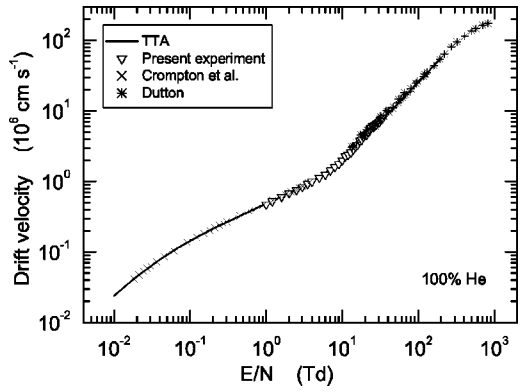

FIG. 1. The electron drift velocities in pure He. The present experimental data are compared with the previous ones of Crompton *et al.* [39] and other data from glow discharges as tabulated by Dutton [40]. The calculations by a two-term code are shown as a solid line.

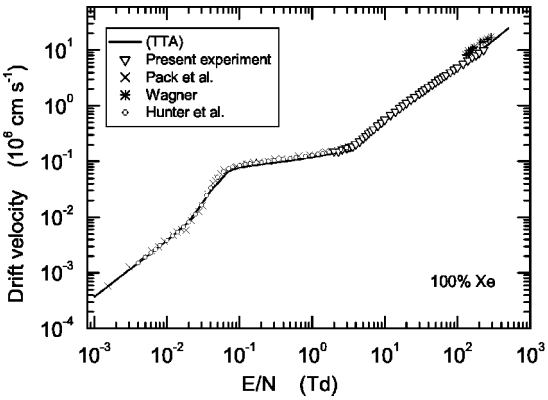

FIG. 2. The electron drift velocities in pure Xe. The present experimental data are compared with the previous ones of Pack *et al.* [41] and Wagner [44] as tabulated by Dutton [40] and also those of Hunter *et al.* [38]. Calculations by a two term code are shown as a solid line.

from the cathode at time $t=0$. Because of the finite laser pulse duration and of the instrumental bandwidth, the rise of the measured electron avalanche is not sharp, yet it displays a Gaussian-like shape resembling that of the laser pulse [24]. On the other hand, the fall is affected by longitudinal diffusion effects which, for fixed E/N, become more apparent as the gas pressure is reduced. When diffusion is either negligible or absent, Eq. (3) reduces to [23,25,27]

$$i_e(t) = \begin{cases} (n_0 q_0/T_e)\exp(\alpha W t), & 0 \leqslant t \leqslant T_e, \\ 0, & t > T_e. \end{cases} \tag{5}$$

Initial values of W and of α/N were derived from Eq. (5) to fit the electron transients were derived in a manner that has been described in detail before [23,25]. The electron transit time T_e is the time elapsed between the midpoints of the rising and falling edges of the pulse, from which W is calculated, and the density-normalized ionization coefficient α/N is obtained from a least-squares fitting procedure applied to the rising exponential part of the avalanche. Both W and α/N are obtained simultaneously from the same electron transient. Under some conditions of E/N and N, when α is large, the ionic currents during the electron transit may contribute to the total, measurable current; even though its contribution is relatively small, this can be readily subtracted from the total current by approximating their exponential rise to a straight line, thereby obtaining an even closer measurement of the electron current.

When the above procedure was completed, then full use of Eq. (3) was made to obtain the longitudinal diffusion coefficient. Examples of waveforms and resulting transport coefficients were shown in our previous papers [22–25]. Usually, corrections to the drift velocity rendered values slightly larger, between 2% and 4%, although the ionization coefficient remained essentially unchanged. In this paper, these final drift velocities are the ones to be reported below. Most of the measured drift velocities reported in this paper represent the average of at least three values taken at different pressures. Thus, the overall, typical uncertainties lie between 1% and 2%.

Since the purpose of this paper is to discuss the application of Blanc's law to the measured drift velocities, we defer the presentation of α/N and $\mathrm{N}D_L$ for a second paper.

III. INPUT DATA AND CALCULATION TECHNIQUE

The calculated values of the drift velocities are obtained by using several methods. First, we used a two-term code ELENDIF [28]. The two-term approximation is sufficiently accurate for gases with elastic processes or small inelastic cross sections [29–31]. Nevertheless, we have also performed calculations by a well-tested Monte Carlo code [32] which confirmed the accuracy of the two term results.

The basic set of cross sections, adopted from the Sigmalib database of the code [33], was supplemented by Hayashi's data [34,35] and extrapolated to higher energies. For He, the momentum transfer cross section coincides with that of Crompton *et al.* [36]. The data for Xe were mainly based on the results of Frost and Phelps [37] and Hunter *et al.* [38] but were extended by the results of Hayashi. In both cases, higher energy momentum transfer cross sections were taken from the unpublished work of Hayashi [34,35] and by selected sources on cross sections for ionization and excitation. Monte Carlo simulations were performed by using momentum transfer cross sections and assuming isotropic scattering.

IV. EXPERIMENTAL RESULTS, CALCULATIONS, AND DISCUSSION FOR PURE GASES

The experimental data for drift velocities are presented in Fig. 1 for He and in Fig. 2 for Xe. The data for the pure gases are also given in Table I. All the other data included in Figs. 1 and 2, together with the mixture data shown later in this paper, will be available at the web page www.phy.bg.ac.yu. In the case of He there is a large overlap with the high precision data of Crompton *et al.* [39], and the agreement in that range is very good. On the other hand, there is some discrepancy with other sources of data tabulated in the compilation of Dutton [40], but such results were mainly based on glow discharge experiments, and their uncertainty ex-

TABLE I. Present experimental drift velocities in pure He and Xe.

He		Xe	
E/N (Td)	W (10^6 cm s^{-1})	E/N (Td)	W (10^6 cm s^{-1})
1	0.473	2	0.152
1.2	0.523	2.3	0.152
1.6	0.604	2.6	0.167
2	0.683	3	0.173
2.5	0.757	3.3	0.183
3	0.839	3.6	0.186
3.5	0.922	4	0.204
4	0.992	4.5	0.231
5	1.13	5	0.262
6	1.25	5.5	0.289
7	1.44	6	0.323
8	1.6	6.5	0.353
9	1.77	7	0.379
10	2	8	0.441
11	2.27	9	0.502
12	2.39	10	0.562
13	2.57	12	0.68
14	2.84	14	0.782
15	3.11	16	0.9
16	3.34	18	1.01
17	3.81	20	1.12
18	3.91	23	1.29
19	4.38	26	1.44
20	4.59	30	1.65
21	4.61	33	1.81
22	4.93	36	1.96
23	5.3	40	2.17
24	5.71	45	2.41
25	6.08	50	2.66
26	5.99	55	2.9
27	6.33	60	3.13
28	6.43	65	3.37
29	6.7	70	3.6
30	6.95	80	4.04
31	7	90	4.5
32	7.43	100	4.9
33	7.67	120	5.69
34	7.9	140	6.57
		160	7.5
		180	8.15
		200	9.04
		230	10.1

ceeds that of those from the present experiment; thus having in mind the estimated uncertainty of the latter results, the agreement is still good. We believe that the present results should be regarded as the most accurate in the moderately high E/N region. For Xe there is little overlap with the most accurate available data of Pack *et al.* [41], Patrick *et al.* [42], and Hunter *et al.* [38]. In the range of overlap with the low energy data of Pack *et al.* and Hunter *et al.* there are only three points and for those values our data appear to be somewhat lower, but since for both sets these points are at the border of the covered range, and since both sets are connected smoothly by the calculated drift velocities, we may claim that the agreement between the two sets of data is good. In addition, the Monte Carlo calculations proved that two-term results were sufficiently accurate for the present analysis.

The sets of cross sections were tested by making comparisons of calculated and measured drift velocities in pure gases in present experiment (He in Fig. 1 and Xe in Fig. 2). A fairly good agreement was achieved over the entire range of the reduced electric field E/N for He. The agreement for Xe is not perfect in the low energy region where there is a Ramsauer-Townsend minimum, and thus it may require some further adjustment of the cross sections. One such proposal was made by Hunter *et al.* [38] but the question of the best cross section for Xe appears to be still open as none of the available sets could predict the data for drift velocities and characteristic energies in He-Xe mixtures very well, as discussed by Elford *et al.* [43].

The cross section set that was adopted was, however, very good for the range of E/N (mean energies) of our experimental data. As our experimental data could provide little new information for the low energy region we did not attempt to improve the fit at low E/N values. Thus we may conclude that in the relevant energy range the agreement between calculated and experimental drift velocities was very good. Also it should be noted that the negative differential conductivity region (NDC) [12,13] does not exist in any of these two pure gases. The agreement extends to the measured ionization rates, which also provides a more strict test of the cross sections at higher energies.

V. RESULTS AND DISCUSSION FOR THE MIXTURES

A. Calculation procedure for mixtures

We applied the standard Blanc's law (CEON), which implied combination of drift velocities for the mixture components at the same value of reduced electric field (points *A* and *B* in Fig. 3) in order to get the drift velocity for the 50% mixture (point *E*). As it can be seen from the figure the mixture has a slight NDC, but Blanc's law did not predict it. In addition, Fig. 4 shows the calculated mean energies versus E/N for pure gases and for the 50% mixture. The values of mean energies that correspond to the same value of $E/N = 0.59$ Td ($1\ \text{Td} = 10^{-21}\ \text{V m}^2$) are about 1.3, 0.36, and 0.58 eV for He, Xe, and the 50% mixture, respectively. The electron energy distribution functions (EEDF) are quite different as it is shown in Fig. 5. On the other hand, the points *C*, *E*, and *D* (Fig. 4) all represent the same mean energy that is 0.57 eV. The corresponding values of E/N are 1.02, 0.07, and 0.59 Td for He, Xe, and the 50% mixture, respectively. For these E/N EEDFs show a much more similar behavior (Fig. 6). That illustrates the basic idea behind the common mean energy technique [Eq. (2)] [20,21].

B. Experimental results and comparison with calculations

The experimental data were obtained for a range of mixtures consisting of 1%, 5%, 10%, 20%, 50%, and 70% Xe and for the pure gases He and Xe. The results are shown in

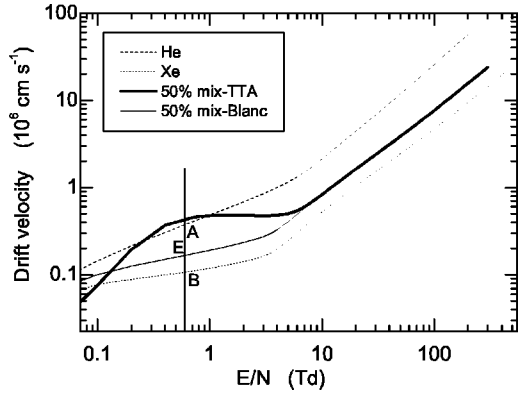

FIG. 3. The calculated electron drift velocities in He (dashed curve) and Xe (dotted curve) and in the 50% mixture of He and Xe (thick solid line) from the TTA (two term) approximation and by the application of Blanc's law (solid line).

Figs. 7–12. The data are compared with the calculations by using the Boltzmann equation and various forms of mixture (Blanc's like) laws. The data for 1% of Xe mixture are not shown since, not surprisingly, these turned out to be essentially the same as those for pure He; Blanc's law in all forms performed very well.

The data for 5% Xe are shown in Fig. 7. In this case there is a visible discrepancy with the prediction from Blanc's law, while the corrected procedure CME 1 gave an excellent agreement. The application of CME 2 departs from the correct values in a narrow E/N range although still indicating a possible negative differential conductivity (NDC) region.

We have also applied the standard Blanc's law on two different mixtures of Xe and He (instead of the data for the pure gases) in order to obtain the drift velocity for the third mixture. This procedure was not often used, while in principle the data for mixtures may be used in any combination to provide new data for other mixtures, and even for the pure gases [19]. The predicted values according to this procedure agree very well with the experimental data and results of calculations.

Further data for the mixtures containing 10% Xe, 20% Xe, and 50% Xe are given in Figs. 8–10 respectively. In all

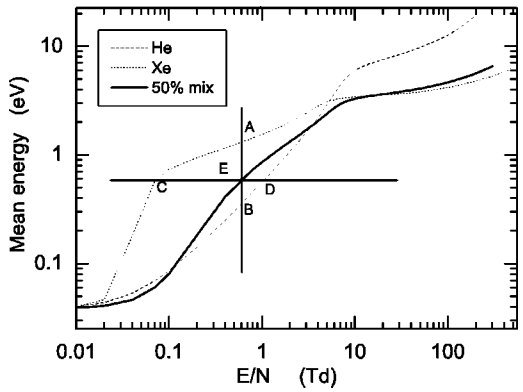

FIG. 4. The calculated mean energies (TTA approximation) versus reduced electric field in He (dashed curve), Xe (dotted curve), and 50% mixture of He and Xe (solid curve).

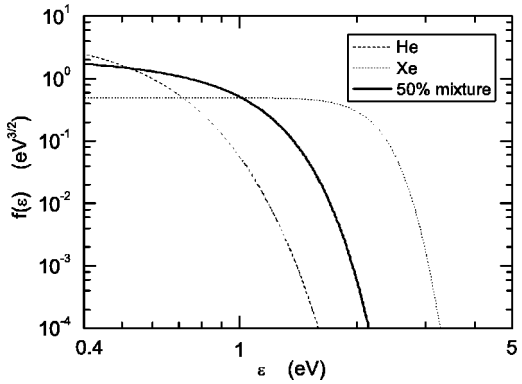

FIG. 5. The electron energy distribution function at E/N = 0.59 Td in He (dashed curve), Xe (dotted curve), and the 50% mixture of He and Xe (solid curve).

cases, the general picture is the same. Blanc's law fails more and more seriously as the abundance of He decreases. The explanation for this effect stems on the fact that for mixtures where He is present in small percentages it acts as an energy controlling constituent through more effective energy transfer in elastic collisions [10,11,14].

Thus, there is a larger difference between mean energies for the pure gas (Xe) and the mixture, while there is also a large difference between the mixture and pure He due to the reduced content of He. In all cases the common mean energy procedure CME 1 performs really well while the CME 2 has a range of E/N where it shows large departures from the correct values, and even the discrepancy grows with the abundance of Xe. Most surprisingly, combinations of two mixtures always yield very good results even though the CEON procedure was applied.

Most importantly, the data for the 50% mixture shown in Fig. 10 bears a clear NDC region. As it has been discussed elsewhere [20,21] the NDC effect is a difficult test of the transport theory and, since the pure gases do not show it on their own, then it becomes a particularly difficult test for the procedures to combine the data for pure gases. The effect is shown most clearly in Fig. 11, where we show the results for the mixture with 70% Xe. As this mixture has the most pronounced NDC, we shall use this mixture as the critical test case to draw conclusions.

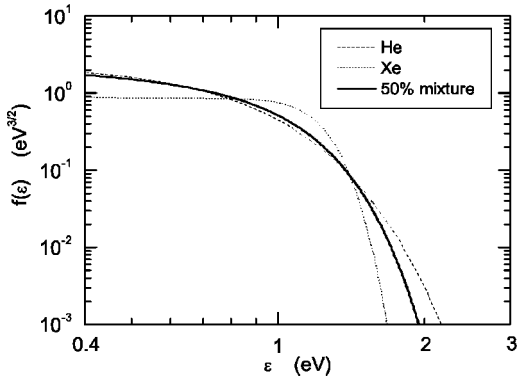

FIG. 6. The electron energy distribution function in He at 1.02 Td (dashed curve), Xe at E/N = 0.07 Td (dotted curve), and 50% mixture of He and Xe at 0.59 Td (solid line).

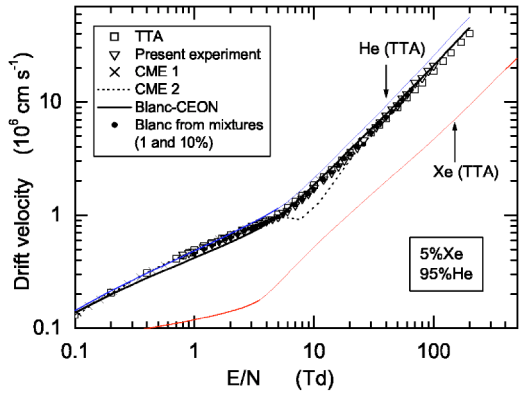

FIG. 7. (Color online) Comparison of measured and calculated drift velocities in the 5%Xe+95%He mixture. CME1 and CME2 in the legend denote the calculations of the electron drift velocity with the positive and negative exponent, respectively, in Eq. (2). TTA denotes the Boltzmann equation calculations and Blanc-CEON denotes the calculation from the classical Blanc's law. The drift velocities for the pure gases are shown with separately marked solid lines, but the lines for pure He and the mixture are almost indistinguishable, since they merge into each other very closely.

We should discuss the accuracy of the two-term approximation by comparing it to the Monte Carlo calculations. We have stated that the two-term approximation (TTA) is sufficiently accurate for our needs. In principle, the situation is more complicated than that. It has been generally assumed that for the rare gases the TTA would be exact or, if not exact, then very accurate [29]. In the case of the drift velocity for mean energies where electronic excitation is not the dominant energy controlling mechanism for rare gases, the TTA works very well. However, if we go to higher mean energies, and the present study overlaps with these, then the applicability of the two-term approximation may become questionable, even for the rare gases. In our case (70% Xe-He mixture), the drift velocities were calculated very well for all the E/N range covered here. The maximum dis-

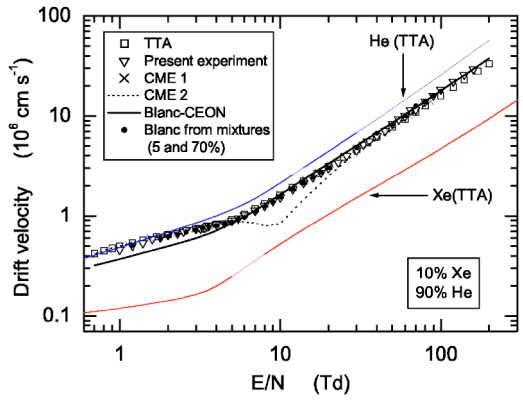

FIG. 8. (Color online) Comparison between measured and calculated drift velocities in the 10%Xe+90%He mixture. The notation is the same as that for Fig. 7. The solid circles represent the result of applying the standard Blanc's law on the data for two mixtures (1%Xe+99%He and 10%Xe+90%He) in order to obtain the drift velocities for the third mixture.

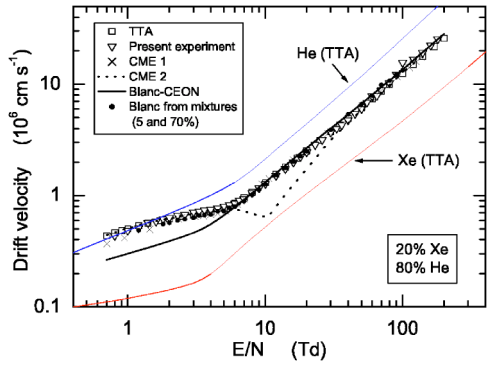

FIG. 9. (Color online) Comparison of measured and calculated drift velocities in the 20%Xe+80%He mixture. The notation is the same as that for Figs. 7 and 8. The solid circles represent the result of applying the standard Blanc's law to the data for two mixtures (5%Xe+95%He and 70%Xe+30%He).

agreement for the mean energy is of the order of 2%. However, above 10 Td the discrepancy between the TTA and the MC values for the characteristic energy D_T/μ (μ is the electron mobility) begins to grow up to 13% at the maximum value of E/N covered here. Thus we may conclude that the use of the TTA in the present paper should not imply that it is accurate for calculating all transport coefficients at any E/N. As pointed out by White it *et al.* [30] the drift velocity converges much faster than D_T/μ. It is of interest to point out, however, that in the region of NDC (less than E/N =9 Td), the TTA appears to be correct (to less than 1% discrepancy) for all transport coefficients.

There is another issue where the TTA as used in the present paper may fail. That is the effect of nonconservative collisions [45], which we shall discuss in terms of the 70% Xe-He mixture. Above 70 Td, the effects of ionization becomes observable, leading to a difference between the so-called bulk and flux transport properties. The difference grows very rapidly and it is as large as 10% at 200 Td. Thus we have allowed experimental results to be somewhat higher than the TTA calculations at the highest E/N to compensate for the effect of nonconservative collisions. The results are shown in Fig. 12.

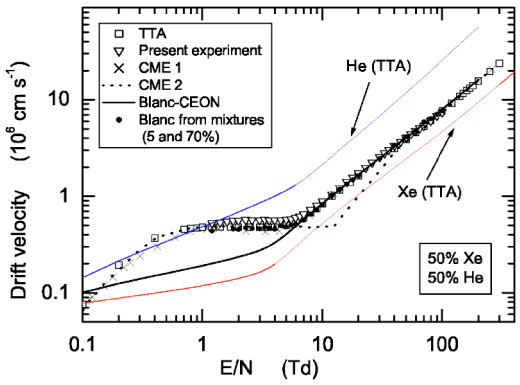

FIG. 10. (Color online) Comparison between measured and calculated drift velocities in the 50%Xe+50%He mixture. The notation is the same as that for Figs. 7 and 8. The solid circles represent the result of applying the standard Blanc's law to the data for two mixtures (5%Xe+95%He and 70%Xe+30%He).

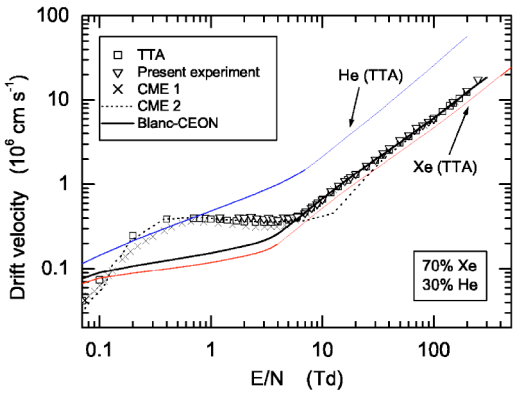

FIG. 11. (Color online) Comparison between measured and calculated drift velocities in the 70%Xe+30%He mixture. The notation is the same as that for Figs. 7 and 8. The calculation has been extended down to $E/N<0.1$ Td to show clearly the region of NDC, and the very good agreement between the TTA and CME2 calculations up to $E/N<6$ Td. Further on, the agreement between TTA, CME1, and the experiment is excellent.

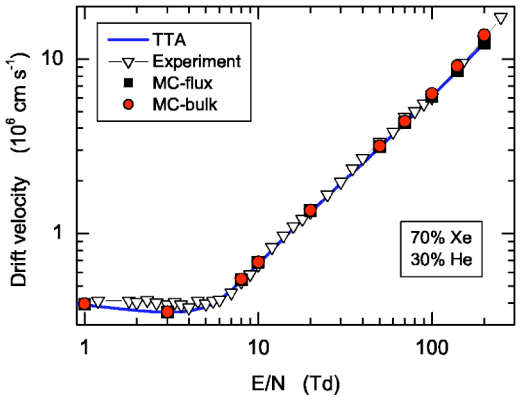

FIG. 12. (Color online) The electron drift velocities in the 70%Xe−30%He mixture calculated from TTA, MC-bulk, and MC-flux methods, including the effects of ionization, and their comparison with the present experimental results. For other calculations in this mixture, see Fig. 11.

Nevertheless, the present paper was based on the cross sections existing in the literature. There is definitely a need to improve the cross sections relevant for the higher mean energies, but in that case present data should be extended by fits of other transport coefficients, excitation and ionization coefficients in particular, and also additional data describing angular dependence of the cross sections, inelastic as well, should be taken into consideration.

VI. CONCLUSION

A fairly good agreement was found between the two-term calculations (these were also tested by a Monte Carlo simulation) of the electron drift velocity in the Xe—He mixture and the experimental data when standard, generally available cross sections are used. Provided that the low-mass component in the mixture has a smaller abundance, and since it controls the energy balance, then the NDC is induced, even though it does not exist in any of the two pure gases.

The first conclusion that may be drawn is that, for lower E/N values, Blanc's law is clearly inapplicable, while for high E/N it provides a very good approximation [21]. Of the two possible equations proposed by Chyflikyan [20] (and given a better theoretical foundation in Ref. [21]), the CME 1 (obtained from momentum balance) provides an excellent approximation over the entire range of E/N. Moreover, this includes the prediction of the NDC [21] even when both gases have no indication of the effect, which should clearly rule out the standard Blanc's law. The other equation (CME 2, the Chiflikyan's equation with the negative exponent, which can be obtained from the energy balance equation) also predicts the NDC, but it fails over a portion of the E/N range, where even the standard Blanc's law works very well. The correction to Blanc's law (corrected CEON) developed on the basis of elastic collisions [18] and inelastic collisions [21] is in excellent agreement with the data and the first form of CME approximation but the corrected CEON is much more complicated for application and thus we show only the data for CME 1. It should be noted that only elastic collisions are effective in the range of E/N where departure from Blanc's law is most pronounced. We have also tested the application of Blanc's law by using data for two mixtures in order to determine the results for the third mixture, and in all cases this worked very well. It appears that the energy distribution functions for mixtures are much closer, and therefore the standard Blanc's law procedure is more applicable. The application of two sets of mixture data may be of great importance for applications where the experimental data may be available and the simple standard Blanc's law procedure would not require additional information for the application of CME or CEON procedures.

Numerical tests show that the common mean energy procedure works very well for all mixtures covered so far including rare gas mixtures (such as He-Kr mixture) or rare gas-molecular gas mixtures such as the Ar-N_2 mixture [21]. In addition, the procedure for correction due to inelastic collisions for the standard common E/N procedure appears to be equally valid. The same conclusions may also be drawn for the high E/N limit where even the standard uncorrected Blanc's law works well.

The present results may open a question as to whether the same procedure or some other form analogous to Blanc's law or corrected Blanc's law may be applicable for transport coefficients such as ionization and excitation coefficients. In a separate study it was shown that the CME procedure is applicable for ionization coefficients, except for very low E/N, where there are differences for the coefficients of several orders of magnitude [46]. It was also shown that even the basic uncorrected combination of ionization coefficients weighted by the relative abundance works well for very high E/N in a similar range where Blanc's law works for drift velocities.

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