Corrigendum

Corrigendum to "Experimental investigations on the first Townsend coefficient in pure isobutane" [Nucl. Instr. and Meth. A 670 (2012) 55–60]

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In the conversion process of the original files to the Tiff format some errors occurred in Figs. 3–6, as follows:

(a) Fig. 3: the points related to "Data 1" and those from "S.C. Haydon and O.M. Williams" did not appear;
(b) Fig. 4: the points related to "Our previous results" did not appear;
(c) Fig. 5: the data from "C. Lu et al." did not appear and its corresponding legend was incorrect;
(d) Fig. 6: the points from "C. Lu et al." did not appear.

Please find below the figures amended.
The authors apologize to Nucl. Instr. and Meth. A and to the readers for any inconvenience these errors may have caused.
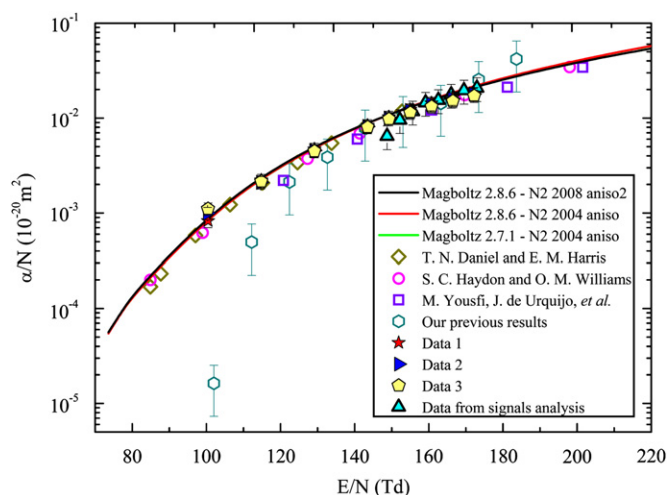

Fig. 3. Magboltz results for N_2 and measured values at atmospheric pressure (star, side triangle and diamond) for α/N as a function of E/N in the range 100–170 Td. The data sets (1–3) refer to independent measurements. The displayed error bars correspond to 15% of the values. Data from Daniel and Harris (lozenge) [19], Haydon and Williams (circles) [20], M. Yousfi et al. (squares) [21], from our previous results (hexagon) [5] and from signal analysis (triangle) are also shown.
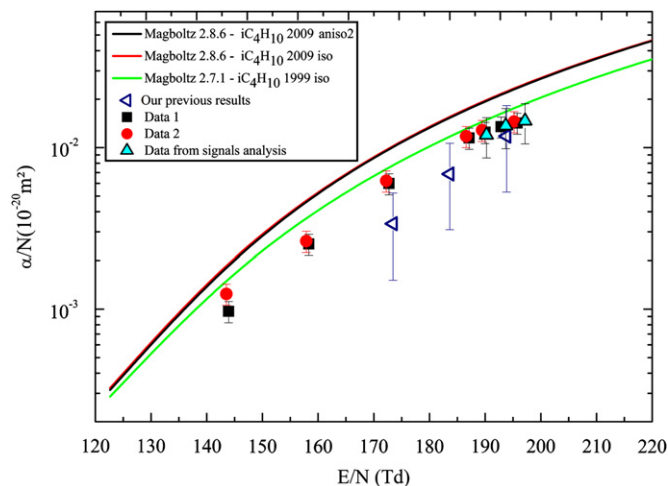
Fig. 4. Magboltz results for iC$_4$H$_{10}$ and measured values at atmospheric pressure (square and circle) for α/N as a function of E/N in the range 145–200 Td. The data sets (1 and 2) refer to independent measurements. The displayed error bars correspond to 15% of the values. Data from our previous results (side triangle) [5] and from signal analysis (triangle) are also shown.
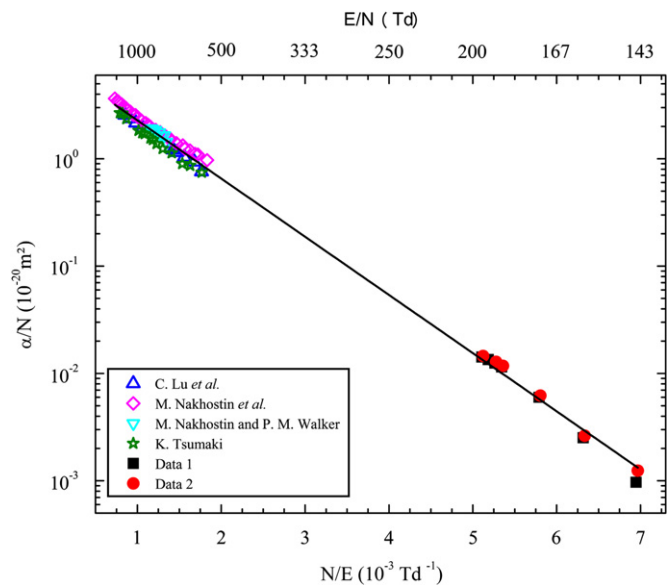

Fig. 5. Korff parameterisation fitted to our measurements for iC$_4$H$_{10}$ together with data from literature [6–9], covering the range 145–1300 Td. The values for A and B are, respectively: 7.9×10^{-20} m^2 and 1.25×10^2 Td.
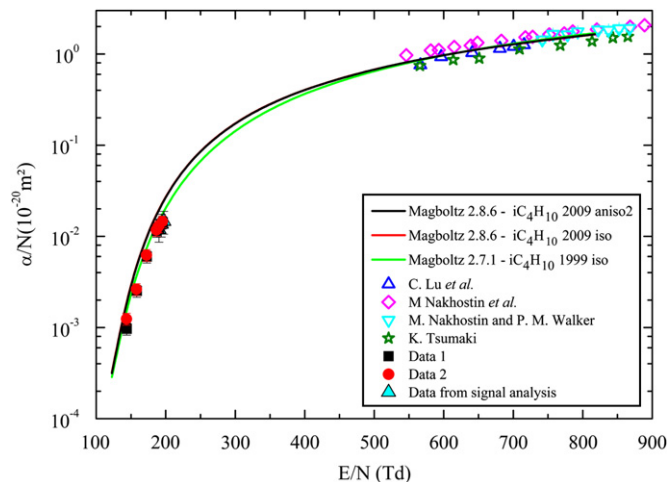

Fig. 6. Magboltz results for isobutane, data sets obtained by the current method, values determined by signal analysis and data from literature at higher E/N [6–9].

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Nuclear Instruments and Methods in Physics Research A

Experimental investigations on the first Townsend coefficient in pure isobutane

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ARTICLE INFO

ABSTRACT

In this work we present results of the first Townsend coefficient (α) in pure isobutane by measuring the current growth as a function of the electric field strength in a pulsed irradiation regime. A Resistive Plate Chamber (RPC)-like configuration was used. To validate this method, as well as to crosscheck the experimental apparatus, measurements of the α parameter were firstly carried out with pure nitrogen and the results compared to the accurate data available in the literature. The data obtained with isobutane in a field range from 145 Td up to 200 Td were well-matched to those calculated with Magboltz versions 2.7.1 and 2.8.6. The experimental consistency of these results with other published data in the range of 550–1300 Td was very good, as demonstrated by the use of the Korff parameterization.

1. Introduction

Despite the extensive use of isobutane as a quenching component in detectors operating in the electron avalanche regime, there are scanty data on swarm parameters (mainly drift velocity and first Townsend coefficient) in this gas, especially for density-normalized electric field intensity (E/N) below 500 Td. New demand of such data, that are important to predict the overall performance of gaseous detectors, has been created by the rapid growth of experimental micro-dosimetry, where isobutane is a promising filling gas of soft human tissue-equivalent proportional counters (TEPC) [1–4]. Data on the drift velocity (v_d) and the first Townsend coefficient (α) gathered in pure isobutane with a dedicated setup based on the pulsed Townsend technique were published by our group [5]. In this apparatus, the detection chamber adopted a typical Resistive Plate Chamber (RPC) structure that allowed extending the electric field strengths over which the drift velocity was known. Indeed, it was the first time that v_d was measured in the saturation region with good agreement with expectations from Magboltz code. However, concerning the first Townsend coefficient in pure isobutane, our results

seemed to be underestimated in comparison with the predictions from Magboltz. The most likely origin of this discrepancy was a laser misfocusing effect responsible for the extraction of electrons from regions with reduced electric fields strengths. To minimize this problem, the experimental apparatus was improved by increasing the dimensions of the electrodes as well as replacing the N_2 laser by another with lower divergence and better time resolution. Data on the first Townsend coefficient in pure isobutane obtained with the modified setup are presented in this paper. Due to the lack of other experimental values of α in the electric field range investigated here (145–200 Td), the consistency of our results with all data available in literature [6–9], covering the range of 550–1300 Td, was verified through the Korff parameterization [10] following the same procedure adopted by Nakhostin et al. [8,9]. Furthermore, the agreement between our results and those calculated with Magboltz versions 2.7.1 and 2.8.6 is analyzed in a dedicated section.

2. Experimental method

The Pulsed Townsend (PT) technique is a powerful method to measure drift velocity (v_d) and ionization rate (R_i) from the analyses of transient signals induced by a swarm developing between parallel plate electrodes [11–14]. Basically, the setup

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used in this work consisted of an RPC-like chamber, with one metallic cathode and one resistive (glass) anode, coupled to a high voltage power supply and a fast amplifier. The output amplified signal, started with electrons released from the cathode by the incidence of a pulsed nitrogen laser beam, was readout with a large bandwidth oscilloscope to record the fast signal induced by the electron movement. Based on this method, we have measured both drift velocity and the first Townsend coefficient (α) in pure isobutane for E/N up to 200 Td, where the differences between R_i and αv_d are not significant. The validity of this assumption was verified by Magboltz simulations [5,15]. As the ionization rate, rather than α, is the physical parameter defined in the PT method and it is almost uncorrelated with v_d (at least at the data analysis level), the α values are calculated as R_i/v_d. The values of R_i and v_d are obtained from the analysis of the digitized waveforms by fitting a function that is a convolution of an exponential growth, with rate R_i during a time window from 0 to $w = d/v_d$, where d is the gas gap thickness, with a Gaussian of standard deviation σ [5]. However, the time resolution of the measurement system ($\sigma \cong 1$ ns) imposes a limitation on the maximum electric field intensity that can be reached to avoid pulse shape distortions, observed when the electron drift time across the gap is comparable with σ. Considering this constraint and the flexibility of the experimental setup, an alternative method is used in this work to obtain the first Townsend coefficient by measuring the current growth as a function of the electric field strength in the gas gap. As long as both the avalanche (I) and primary ionization (I_0) currents can be precisely measured, the α parameter is given by $\alpha = d^{-1}\ln(I/I_0)$. Although this equation is derived from the Steady State Townsend (SST) technique, where indeed the α parameter is defined [16], we have assumed that it holds to good approximation for pulsed irradiation of the cathode provided that E/N $\leq$ 200 Td and the time constant RC of the external chamber network is large enough to serve as an integrator for the whole range of the laser beam repetition rate. To validate this method as well as to crosscheck the experimental apparatus, measurements of the α parameter were firstly carried out with pure nitrogen and the results compared to the accurate data available in the literature.

3. Experimental setup

The present setup has been improved in comparison to that described elsewhere [5]. In order to guarantee the uniformity of the electric field over the drift distance, the electrodes were replaced by others of larger dimensions. The cathode, made of aluminum (40 mm diameter), was manufactured observing the same criteria as before, as far as flatness and smoothed borders are concerned. The anode (3.5 mm thick and 32.5×32.5 mm^2 area), consisted of a high resistivity glass (2.10^{12} Ω.cm), was polarized in its back through a brass plate (14 mm diameter) by using a Bertan 225-30 R high voltage supply. This electrode was electrically insulated from the chamber by a piece of steatite 20 mm diameter and 30 mm longer. The mechanism used to perform the parallel anode-cathode displacements remained unchanged (Huntington 2241-2 and Mitutoyo 189 μm). If not stated otherwise, all measurements were carried out at a gap distance of 1.5 mm within an uncertainty of 0.1%. Details of this assembly are depicted in Fig. 1, where the circular shaped aluminum cathode was electrically insulated from the micrometer actuator structure by a Teflon ring to allow current measurements.

The primary electrons were liberated from the cathode by the incidence of a low divergence nitrogen laser beam (MNL200-LD Lasertechnik Berlin) with 700 ps pulse duration, 337.1 nm wavelength and nominal peak power about 90 kW at 15 Hz. The repetition rate of the laser could be varied from 1 up to 20 Hz,
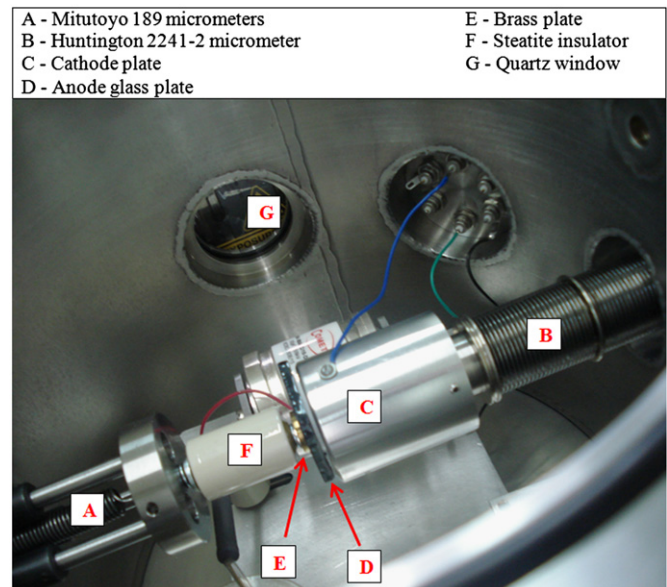

Fig. 1. View of the chamber, showing the micrometric motion systems (A and B) to achieve the electrodes (C, D and E) parallelism and the steatite insulator (F) coupled to the anode assembly.
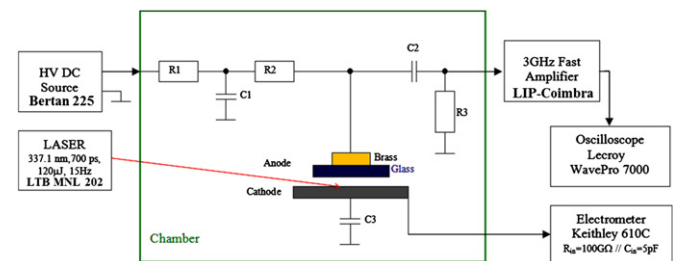

Fig. 2. Schematic drawing of the electronic circuit for extraction of the electrodes signals.

but in this work all measurements were performed at 15 Hz. An internal laser beam splitter delivered a trigger signal to be used as the start of the electron drifting time. The beam entered the chamber through a Melles Griot quartz window transparent to the UV photons.

Focusing the laser beam onto the center of the cathode through a small entrance gas gap is a difficult task. It was accomplished by using an optical system consisting of plano-concave and plano-convex Melles Griot quartz lenses designed to meet the requirement of optimum beam focus in a situation involving aperture constraints. A He-Ne laser, together with mirrors and a periscope, was used to align the whole system. A similar technique is described by Colucci et al. [17]. The apparatus was sitting on an optical table to prevent any kind of disturbance due to mechanical vibration.

The average current was measured with an analogic electrometer Keithley 610 C with accuracies of 2% and 4% of full scale on 0.3 to 10^{-11} A and 3.10^{-12} to 10^{-14} A ranges, respectively. In Fig. 2, the capacitance C3 is chosen to meet the requirements of pulse currents integration by the external chamber network. The anode signals were fed to a 3 GHz bandwidth fast amplifier through a low-noise high-voltage vacuum decoupling capacitor of 350 pF/ 9 kV from Comet. The fast amplifier was based on a Philips-BGM 1013 integrated circuit (nominal gain of 35.5 dB) [18]. The amplifier outputs were digitized by a Lecroy WavePro 7000–10 GS/s and 1 GHz bandwidth oscilloscope. These signals were analyzed to
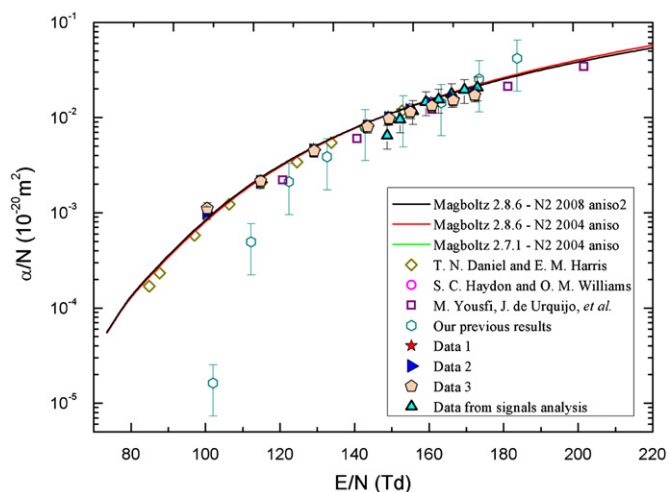
Fig. 3. Magboltz results for N_2 (Colors online) and measured values at atmospheric pressure (star, side triangle and diamond) for α/N as a function of E/N in the range 100–170 Td. The data sets (1, 2 and 3) refer to independent measurements. The displayed error bars correspond to 15% of the values. Data from Daniel and Harris (lozenge) [19], Haydon and Williams (circles) [20], M. Yousfi, et al. (squares) [21], from our previous results (hexagon) [5] and from signal analysis (triangle) are also shown.

calculate the first Townsend coefficient through the values of the ionization rate and the drift velocity. In this work, each fitted signal is actually the average of 100 independent time-aligned waveforms. The results of R_i and v_d agreed within the experimental uncertainties with those previously published by our group [5].

All measurements were carried out at room temperature ($\sim 20\,^\circ$C) and at atmospheric pressure (~ 1013 hPa). Isobutane and nitrogen from Praxair of 99.9% and 99.999% purity, respectively, were introduced in the chamber without further purification.

4. Results and discussion

To test the reliability of the experimental apparatus and to validate the current method proposed to obtain the α parameter, measurements of α as a function of the electric field strengths were performed with the well-known N_2. Both results obtained from the pulse shape analysis and the current measurements are plotted in Fig. 3, within the E/N range of 100–170 Td. The agreement between the (α/N) values obtained by the current method in three independent data sets, named Data 1, 2 and 3 in Fig. 3, evidenced the repeatability of the results. The instrumental uncertainties were less than 1%. The total systematic uncertainties were estimated in 15% by comparing the results taken in several runs, at the same E/N. Concerning the α/N values obtained from signal analysis, the error bars represent systematic errors (30%) and were estimated in the same way as those from current measurements. In the latter case, the voltage signals are more affected by electronic noise due to the amplifier properties than the current measured by the electrometer. The data on α/N available in the literature [19–21], including our previous results [5], are also shown in this figure for comparison. It can be seen that the agreement is very good, irrespective to the technique used. It is worth noting that the variation of the sets lays within their stated uncertainties in the range 120–180 Td, except for the point at the lowest value of the E/N range. This discrepancy is somehow related to the fact that, for lower values of the electric field, the signal to noise ratio is not very good, rendering the extraction of α from the waveform analysis more difficult. Also, in

the former setup, the effects of non-uniformities of the electric field due to the small size of the electrodes were more important at lower field strengths.

The experimental data were also compared to the predictions of the Magboltz code by S.Biagi [22–23]. It is a freely available FORTRAN program based on the Monte-Carlo approach to follow individually each electron-atom collision and derive the corresponding transport parameters. For the present study, attention was paid to compare the versions of Magboltz 2.7.1 and Magboltz 2.8.6 in the range of E/N under study. Three typical simulation results are shown in Fig. 3, where "N2 2008" and "N2 2004" stand for different cross-section sets. The "N2 2004" set includes cross-sections for electron collisions in nitrogen from A. V. Phelps and L. C. Pitchford [24], while the "N2 2008" set comprehends values from several authors [23]. Concerning the first Townsend coefficient, the "N2 2008" was tuned to reproduce α values from the J. Dutton compilation [25]. Nevertheless, it can be seen clearly that there is no appreciable difference between the various Magboltz versions over the range 80–170 Td. Also, a fairly good agreement is found between the experimental data and the trend given by the simulations. Further details concerning the differences between the Magboltz versions are given in section 4.

Having accomplished the commissioning of the setup, measurements with pure iC_4H_{10} were carried out to obtain the α coefficient in the E/N range of 145 to 200 Td. For comparison, the independent data sets (Data 1 and 2) are plotted with values of α/N determined by the waveform analysis and with values published in our previous work [5] (Fig. 4). All measurements agree within their quoted uncertainties, except for the point at 172 Td from our previous publication. This discrepancy, as already pointed out in the previous discussion about nitrogen, is due to the poor signal to noise ratio, making it difficult to extract the temporal information from the voltage signal.

The results of the simulations are also superimposed on the present data in Fig. 4. Two cross-section sets "ISO 1999" and "ISO 2009" are available in the two different versions of Magboltz 7.1 and 8.6, respectively. They are both largely undocumented. It should also be noted that no commonly accepted cross-section set exists for Isobutane. There is a tendency of the old cross-section set to be in better agreement.

Since no data on the first Townsend coefficient in pure isobutane are available in the literature for E/N smaller than
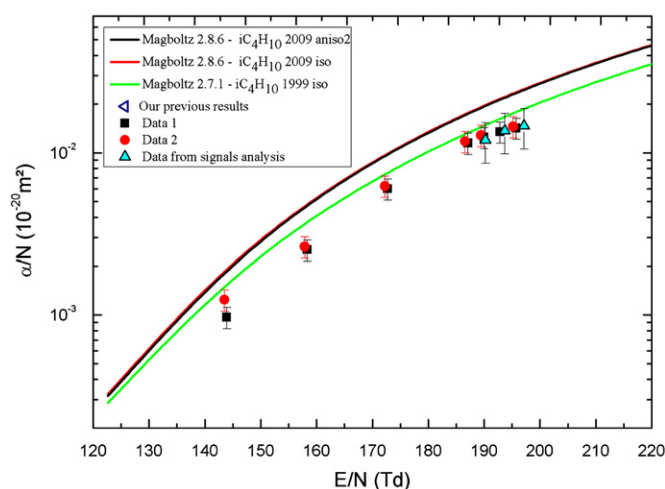

Fig. 4. Magboltz results for iC_4H_{10} (Colors online) and measured values at atmospheric pressure (square and circle) for α/N as a function of E/N in the range 145–200 Td. The data sets (1 and 2) refer to independent measurements. The displayed error bars correspond to 15% of the values. Data from our previous results (side triangle) [5] and from signal analysis (triangle) are also shown.

525 Td [6–9], the consistency of our results was verified through the Korff parameterization [10] $\alpha/N = A \exp^{(-BN/E)}$, where A and B are parameters related to the gas under investigation. The present α/N values are plotted as a function of N/E in Fig. 5 together with those available in the literature [6–9]. The fit with the Korff parameterization is also superimposed in the same figure. The values obtained for A and B are, respectively: $7.9 \cdot 10^{-20}$ m^2 and $1.25 \cdot 10^2$ Td. According to the classical theory of ionization of gases, the constants A and B can be expressed in terms of effective molecular parameters, as the effective mean free path length (λ_{mo}) and the effective ionization potential (V_i) [26]. V_i can be determined by the ratio B/A, and its value should lie between the first ionization potential and the mean energy required for an electron to produce ionization in the gas. Considering the values for A and B obtained in the present work, the effective ionization potential V_i is 16 eV. Since the ionization potential in isobutane is 10.68 eV [27] and the mean energy to produce an electron is 26.17 eV [28], our results seem to be coherent. Furthermore, it is very reassuring that the present α/N values match very well with those gathered in uniform electric field strengths higher than 525 Td.
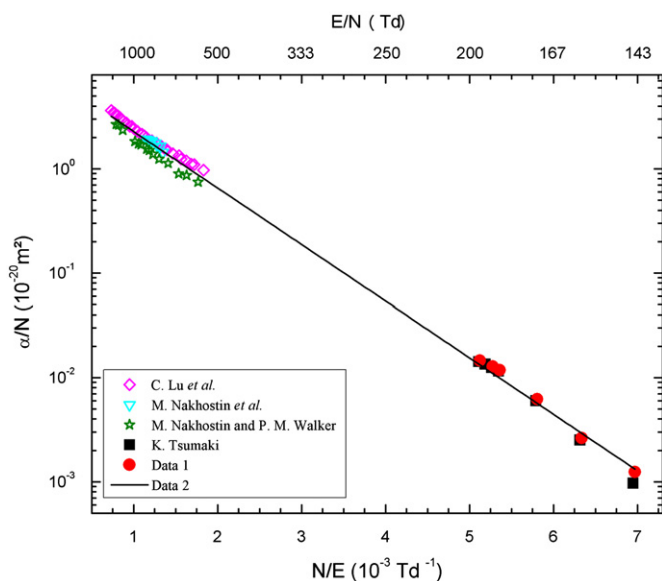

Fig. 5. Korff parameterization fitted to our measurements for iC$_4$H$_{10}$ together with data from literature [6–9], covering the range 145–1300 Td. The values for A and B are, respectively: $7.9 \cdot 10^{-20}$ m^2 and $1.25 \cdot 10^2$ Td.

5. Magboltz simulations

To gage the quality and accuracy of the data needed to discriminate between different sets of elementary electron impact cross-sections, the computer code Magboltz 2, developed by S. F. Biagi, has been employed. Attention has been restricted to two versions in particular, 7.1 and 8.6, because both they were available from our previous work and contain different cross-section sets for the gases Nitrogen and Isobutane. It should be also noted that no further developments of Magboltz, concerning the cross-sections sets for these two gases, have been released to this date after version 8.6. The program employs the Monte Carlo method to calculate the electron transport parameters in both the SST and PT regimes. The energy sharing in ionizing collisions is parameterized with the C. B. Opal, W. K. Peterson and E. C. Beaty formula [29]. A treatment of anisotropies in the elastic scattering of electrons is included for Nitrogen in version 7.1 and is fully extended to all processes and included for Isobutane in version 8.6. Moreover, version 8.6 allows also selecting between two parameterizations of the anisotropies: the one from S. Longo and M. Capitelli (option 1) [30] and the one from A. Okhrimovskyy et al. (option 2) [31], the latter being the default. The correspondence is not straightforward because, in version 7.1, different gases were defined for the same cross-section set with and without anisotropic elastic scattering, while, in version 8.6, the inclusion of the anisotropies is controlled, for two of the gases considered, by a flag defined at compilation time. In the following, reference will be made to the Magboltz gas number. The available choices for Nitrogen and Isobutane are summarized in Table 1.

By comparison of the same cross-section set for Nitrogen (GAS 58), it has been established that negligible discrepancies (below 1–2%) are to be found for all transport parameters between the two codes, so that all the differences present in the other cases can be tentatively ascribed to the cross-sections used.

The results of the calculations with Nitrogen are superimposed on the data obtained in the present work in Fig. 3.

The Monte Carlo simulations employed a sample of 10^{10} electron-atom collisions to reduce statistical uncertainties below the percent level even on the diffusion coefficients, the most difficult to determine. No appreciable difference can be noted for alpha on the figure between the showed cases. The most relevant discrepancies are to be found between GAS 16 and GAS 58 cross-sections sets in version 8.6, but only for the drift velocity (up to ~8% at ~200 Td), the transverse diffusion coefficient (up to ~8% at ~200 Td) and the longitudinal diffusion coefficient (up to ~15% at ~150 Td). The parameterization of the anisotropy in version 8.6 does not play an important role, the differences being at most few percent in the diffusion coefficients. The presence or absence

Table 1
Summary of the available cross-section set in versions 7.1 and 8.6 of the Magboltz code for Nitrogen and Isobutane.

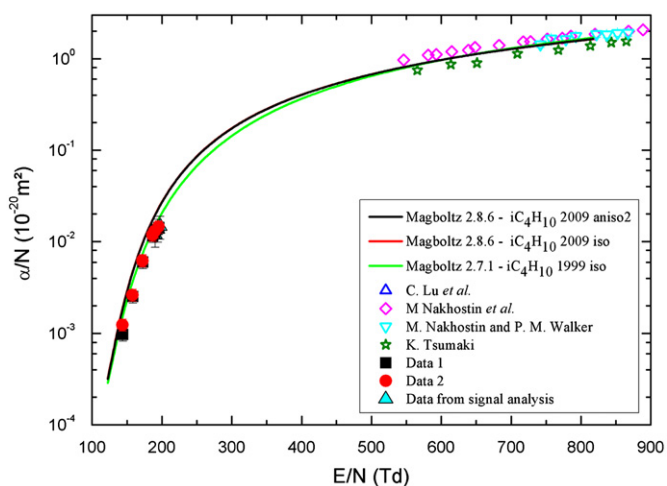|	Magboltz 7.1	Magboltz 8.6
Nitrogen - GAS 16	"N2 2004" Phelps-Pitchford [24] Isotropic	"N2 2008" Isotropic Anisotropic (option 1) Anisotropic (option 2)
Nitrogen - GAS 58	"N2 2004" Phelps-Pitchford, Aniso. El. Scat.	"N2 2004" Phelps-Pitchford, Aniso. El. Scat.
Isobutane - GAS 11	"ISO 1999" Isotropic	"ISO 2009" Isotropic Anisotropic (option 1) Anisotropic (option 2)

Fig. 6. Magboltz results for isobutane, data sets obtained by the current method, values determined by signal analysis and data from literature at higher E/N [6–9].

of the anisotropy affects mostly alpha at the level of 5% between 150 and 200 Td. Comparing GAS 16 and GAS 58 in version 7.1, where they are the same cross-section set without and with anisotropic elastic scattering, respectively, again the highest differences are found in alpha at a level of 5% between 150 and 200 Td and in the longitudinal diffusion coefficient up to 5% at 350–400 Td.

The results for the simulations with isobutane are compared to the data of the present work in Fig. 5 and with the available measurements at higher E/N values in Fig. 6. The difference with Nitrogen is clearly apparent: being isobutane a less well known gas, there is room for the cross-section sets to lead to discrepant expectations. It should be remarked that both cross-section sets agree in the value of alpha at high field strengths where data were available before the present work. In the region of fields strengths covered by the present work, a preference has been found for the older cross-section set (see Fig. 4). It is worth noting that for the other transport parameters, the discrepancies between the two cross-section sets are less important being at most around 5% in the drift velocity and 10% in the diffusion coefficients, as compared to 20–30% on alpha. Detailed investigations have shown minor influence of anisotropies in the cross-sections on the calculated transport parameters than in Nitrogen, reaching a few percent in the diffusion coefficients.

6. Conclusions

Data on the first Townsend coefficient in pure isobutane were gathered in this work by measuring the current growth as a function of the electric field strength in a pulsed irradiation regime. The improvements done in our previous setup, especially concerning the dimensions of the electrodes and the laser focusing onto the cathode, reduced significantly the systematic errors on the determination of the first Townsend coefficient.

It is very reassuring that the present method leads to α values in agreement with the results from the analysis of the induced fast signals. Furthermore, no correlation is introduced between the first Townsend coefficient and the drift velocity, as happens when the shape of the induced pulses is used. The present data obtained in a field range from 145 Td up to 200 Td are well-matched to those calculated with Magboltz versions 2.7.1 and 2.8.6. However, these results are in a better agreement with the

predictions from the Magboltz 2.7.1 probably due to the cross-section set included in this older version.

The experimental consistency of our results with other published data covering the field range of 550–1300 Td is very good, as demonstrated by the use of the Korff parameterization. It is important to note that there is a lack of α values in pure isobutane for electric field strengths between 200 Td and 550 Td. Nevertheless, to extend our method into this range a detailed investigation on the correspondence of the transport parameters gathered with the PT and SST techniques is under way.

We still plan to modify the laser beam injection scheme to further improve the experimental setup and to fully explore both pulse shape analysis and current measurement methods.

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