Study of a self quenching streamer mode in pure gases of DME and isobutane

Yu.I. Davydov\textsuperscript{a,b,⋆}, R. Openshaw\textsuperscript{b}

\textsuperscript{a}RRC "Kurchatov Institute", Kurchatov sq. 1, Moscow, 123182, Russia
\textsuperscript{b}TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3

Abstract

A self quenching streamer (SQS), or limited streamer mode has been studied in single wire chambers with cross-sections 12·12 mm\(^2\) and wire diameters 15, 25 and 50 \(\mu\)m. Chambers were filled with either pure dimethyl ether (DME) or isobutane gases and irradiated with \(^{148}\text{Gd}\) alpha and \(^{55}\text{Fe}\) x-ray sources. Clear transitions from a proportional to 100% SQS mode were observed on all three diameter wires with both gases irradiated with alpha particles. Double SQS discharges due to inclined tracks observed in DME gas allowed an estimation of a streamer size along the wire of less than 1 mm. The second SQS discharge appears less than 1 mm from the first within about 500 ns. Charge spectra obtained with DME irradiated with \(^{55}\text{Fe}\) x-rays might also be interpreted as a transition to a SQS mode, although no direct evidence of that was seen in the observed pulse shapes.

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\textit{Key words:} Self quenching streamer, limited streamer, DME, isobutane.

1 Introduction

Since the first observation of self quenching streamer (SQS), or limited streamer signals [1,2], most models attempting to explain this discharge have employed the mechanism of photon ionization of the gas [3,4,5]. In fact, most studies of a SQS mode have been done with noble gas based mixtures. The high probability of gas ionization by photons emitted by the excited atoms makes it possible to produce SQS signals due to an initial ionization by x-rays or

\* Corresponding author.
E-mail address: davydov@triumf.ca (Yuri Davydov)
beta-particles. However, the observation of SQS discharges in pure quenching gases of hydrocarbons irradiated with alpha particles [6,7] demonstrated the more complicated nature of this type of discharge.

This work presents a study of the transition from proportional to SQS mode in single wire chambers filled with either pure dimethyl ether (DME) or iso-C$_4$H$_{10}$ gases irradiated with $^{148}$Gd alpha particles or $^{55}$Fe x-rays. Both DME and iso-C$_4$H$_{10}$ are excellent quenchers and should provide a transition from a proportional to SQS mode without influence of photons. This could provide data for a better understanding of the nature of this discharge.

2 Experimental setup

Single wire chambers with 15, 25 and 50 µm diameter wires were used to carry out the tests. The chambers have square 12·12 mm$^2$ cross sections and were made of aluminum alloy with 6.35 µm thick aluminized mylar windows on two sides. Wire lengths are approximately 20 cm.

Chambers were irradiated with 3.183 MeV $^{148}$Gd alpha particles and 5.9 keV $^{55}$Fe x-rays. During most test measurements sources were placed directly over the wires on a 1.6 mm thick aluminum plate with 1.2 mm diameter collimating hole. The distance from the source to the cathode foil is about 2.3 mm. Under these conditions alpha particles entering normal to the chamber lose about 1.65 MeV energy in the chamber gas volume. Their track lengths are about 2.35 mm in chambers filled with iso-C$_4$H$_{10}$, and 3.1 mm with DME. Alpha particles produce about 7·10$^4$ ion-electron pairs, while the x-ray particles produce about 250 pairs. The alpha particle track ranges and energy losses were estimated with the ion range-energy code SRIM [8]. Signals from the chambers were self triggered and fed into a LeCroy 2249W ADC. The ADC gate signals had a duration of 2.5 µs for alpha particle irradiation and 1.5 µs for x-rays.

3 Results and discussion

Charge spectra obtained on all three wire diameters with pure iso-C$_4$H$_{10}$ irradiated with alpha particles, became wider in proportional mode upon increase of high voltage. This could be explained by the wide angle distribution of alpha particles entering the chamber volume. Further high voltage increase resulted in the appearance of SQS signals and then a 100% transition from proportional to SQS mode on all three tested wires. On all 3 wire diameters, the peaks of the SQS signals on the charge spectra are well separated from the proportional signals. However, all SQS spectra have tails in the lower portion
Fig. 1. Measured charge as a function of high voltage in pure iso-C$_4$H$_{10}$ filled chambers with 15, 25 and 50 µm diameter anode wires irradiated with $^{148}$Gd alpha particles and 50 µm wire irradiated with $^{55}$Fe x-rays.

of charge spectra, down to the level of the proportional signals. Fig. 1 shows measured charge as a function of applied high voltage on 15, 25 and 50 µm diameter wires irradiated with the alpha source. Mean values of proportional and SQS spectra are plotted. The few points in the transition region and above the mentioned tails in the SQS charge spectra could indicate that SQS signals had not been fully developed at this voltage range.

Charge spectra from the chamber with a 50 µm wire filled with pure iso-C$_4$H$_{10}$ and irradiated with $^{55}$Fe x-ray source do not show any transition to SQS mode (see fig.1). Our measurements for the chamber with 50 µm wire filled with pure iso-C$_4$H$_{10}$ are consistent both for alpha particles and x-rays with [7], where a single wire chamber with a similar geometry had been employed (50 µm wire, cell with 10.5·10.5 mm$^2$ cross-section).

Similar to the pure iso-C$_4$H$_{10}$, in pure DME with alpha particle irradiation of all three tested wires, the increase of high voltage on the chambers in the proportional mode at first resulted in a widening of the charge spectra. Further increase of high voltage produced a clear transition from the limited proportional to SQS mode on a 50 µm wire, resulting in the appearance of a well separated second peak on the charge spectrum. For a 25 µm wire, a second peak overlapping the upper portion of the main peak appeared in the charge spectrum as the chamber high voltage was increased. Upon further increase in high voltage, all signals moved up into the second peak. Observation of the pulses with an oscilloscope clearly demonstrated that these were SQS
Fig. 2. Amplified signals on the DME filled chamber with 15 µm diameter wire at 2050 V, irradiated with alpha particles. Wide proportional and narrow SQS signals with high amplitude are clearly seen on the graph.

Signals had shorter width and much higher amplitude than proportional signals. Charge spectra on a 15 µm diameter wire do not show any additional peaks upon increase of high voltage. However, clear SQS signals were observed on an oscilloscope at a high voltage starting at about 2000 V. Fig. 2 presents amplified signals from a 15 µm diameter wire at U=2050 V. The oscilloscope scale was configured to provide details of the proportional signals. Long proportional and short SQS signals with high amplitude are clearly seen on the graph.

In order to derive the relative fractions of SQS and proportional signals, charge spectra have been taken with different thresholds in the transition regions for 15 µm and 25 µm wires (low threshold for the total distribution, high threshold for SQS, and differential threshold for proportional signals). Fig. 3 presents the total charge spectrum on the 15 µm wire at 2050 V, and shows the separate contributions of the SQS and proportional signals to the total spectrum. The charge spectrum of SQS signals overlaps the wider charge spectrum of proportional signals.

Further increase in high voltage resulted in the appearance of a second SQS peak on the charge spectra of all wires. This second SQS peak comprises a small fraction of all events and is well separated from the first SQS peak for all three wires.

Fig. 4 presents measured charge versus applied high voltage for all three wire diameters. Mean values of measured charge spectra for both proportional and SQS signals are plotted. 25 µm and 50 µm diameter wires have big jumps
in the measured charge when moving from the proportional to SQS mode, while the 15 \( \mu \text{m} \) wire has almost no jump. The jumps are almost the same magnitude for all three wires when moving from the first SQS peak to the second one.

Further tests revealed that the second SQS peak is due to the development of a second SQS discharge along the wire, from alpha particles entering the chamber volume at big angles, with tracks which are nearly co-planar with the wire. Fig. 5 presents charge spectra taken from the chamber with 15 \( \mu \text{m} \) diameter wire at 2900 V with a 0.5-5 mm\(^2\) slot collimator. In first case the collimator slot was placed perpendicular to the wire (dashed line). The second case presents data for the collimator slot placed parallel to the wire (solid line). The \(^{148}\text{Gd}\) alpha particle source was set at the same height over the chamber foil as during tests with an aluminum plate hole collimator. The second SQS peak appears only in the case of a slot collimator parallel to the wire. These second SQS signals are delayed relative to the first ones by a few hundred nanoseconds and have a smaller amplitude, as shown on fig. 6 for 50 \( \mu \text{m} \) diameter wire at 3100 V with 50 \( \Omega \) load. Note that the shortest drift time from the cathode to wire at this applied voltage, estimated using Garfield [9], is longer than 800 ns. Also, delayed proportional signals appear initially on the wires.
at lower voltages before they transfer into the second SQS discharge as the voltage is increased.

The source placed over the collimator plate with a 1.2 mm hole emits alpha particles with angles up to 37° relative to the normal. The alpha particles entering the chamber at this maximum angle have a track length inside the chamber about 2.15 mm. The maximum projection of that track on the wire occurs when they are co-planar, and is equal to about 1.3 mm. Two streamers developing from these inclined tracks indicate that streamer size along the wire is less than 1 mm. Moreover, this demonstrates that the wire becomes sensitive to another discharge, at less than 1 mm distance from the initial streamer, within about 500 ns, as can be seen on fig.6. The dead zone values, defined as the product of dead length and dead time, obtained by other authors for noble gas based mixtures [10,11,12], are orders of magnitude bigger than that observed for DME. This suggest that photons from the excited noble gas atoms play a major role in increasing the streamer size along the wire, increasing both dead length and especially dead time.

Fig.7 presents the fraction of events in the second SQS peak (sqs2) for three wire diameters as a function of applied high voltage. For all three wire diameters, the fraction of events in the second peak reaches a maximum value at some high voltage and then decreases with further increase of high voltage. Two processes cause the drop in the fraction of events in the second peak. Firstly, the dead zone increases as the first streamer size increases. Secondly,
Fig. 5. Charge spectra from the DME filled chamber with 15 µm diameter wire at 2900 V. The chamber was irradiated with alpha particles with a 0.5·5 mm slot collimator. The long side of the collimator was set perpendicular (dashed line) or parallel (solid line) to the wire. There is one SQS peak in the first case while the latter has two peaks.

in unsaturated DME gas, the drift time spread of electrons from the track decreases with increasing high voltage, and becomes comparable to the dead time. The thinner wire has the highest fraction of events in the second peak due to having the longest drift time spread at these applied voltages.

Many other authors have observed multi streamer discharges. To our knowledge, these multistreamer discharges were observed only in noble gas based mixtures. In those mixtures the new streamers occur due to photons emitted by the excited noble gas atoms. In the case of gas photoionization, the following streamers are indistinguishable in time from the initial ones [10]. When afterpulses appear due to a photoelectric effect on the cathode surface, the following streamers are separated by electron’s drift time from the cathode to anode wire [13,14,15].

In our case with DME, the second SQS discharge along the wire occurs due solely to the initial ionization from the alpha particle tracks. The absence of second SQS discharges with a 0.5·5 mm² slot collimator placed perpendicular to the wire (see fig. 5) confirms that photoionization does not play any role in the formation of SQS discharge in pure DME at these voltages.

A similar behaviour was observed for chambers with 15 µm, 25 µm and
Fig. 6. Signals on the 50 μm diameter wire at 3100 V with 50 Ω load. Chamber is filled with DME. Second SQS signals are delayed by a few hundred nanoseconds and have smaller amplitudes.

Fig. 7. Fraction of events in the second SQS peak (sqs2) as function of a high voltage for 15, 25 and 50 μm diameter wires irradiated with alpha particles. Chambers are filled with DME.
Fig. 8. Charge spectra of the DME filled chamber with 15 $\mu$m diameter wire at 2400 V, 2500 V and 2600 V irradiated with $^{55}$Fe x-rays.

Increasing the chamber high voltage resulted at first in the appearance of a tail on the upper portion of the charge spectra, and then of a second peak overlapping that tail. Signals from the first peak moved up into the second peak upon further increase in high voltage. Fig. 8 shows these features of the charge spectra on the 15 $\mu$m diameter wire at 2400 V, 2500 V and 2600 V.

Fig. 9 shows collected charge from $^{55}$Fe irradiation as a function of high voltage for all three wire diameters. The data points represent the most probable values of the charge spectra. One can see that the charge characteristics look similar to the ones obtained by irradiation with an alpha particle source. However, the curves will have smooth shapes if one plots the mean values of the total charge spectra. Observation with an oscilloscope did not show clear differences between the signals in the two peaks.

The observed charge spectra on all wires irradiated with $^{55}$Fe x-rays could be due to the properties of DME. The widening of charge spectra of proportional signals upon increase of high voltage on all three wires irradiated with alpha particles, as shown on fig. 3 for 15 $\mu$m wire, supports this view. On the other hand it could be a real transition to SQS mode. The signals in the two peaks are not distinguished by oscilloscope observation because the drift time spread of electrons produced in DME by 5.9 keV x-ray ionization is
Fig. 9. Collected charge as a function of applied high voltage on 15, 25 and 50 µm diameter wires irradiated with $^{55}$Fe x-rays. Chambers are filled with DME.

about 50 ns, which is comparable to the duration of the typical SQS signals.

4 Conclusion

We have studied a transition from a proportional to SQS mode in single wire chambers with wire diameters 15, 25 and 50 µm, filled with either pure DME or iso-C$_4$H$_{10}$ gases. Chambers were irradiated with $^{148}$Gd alpha or $^{55}$Fe x-ray particles.

All three wires demonstrate a 100% transition from proportional to SQS mode in both gases for the ionization produced by alpha particles. All wires show a second SQS peak with DME gas with further increase of high voltage. It was shown that the second peak is due to the inclined tracks allowing a second SQS discharge to develop along the wire. No second SQS peaks were observed with iso-C$_4$H$_{10}$ gas irradiated with the same alpha source.

Double streamer discharges indicate that the wire in pure DME irradiated by alpha particles has much smaller dead length and dead time compared to those of noble gas based mixtures. The streamer size along the wire is less than 1 mm. The second SQS discharge occurs at less than 1 mm distance within approximately 500 ns.

The tests with a slot collimator suggest that in the applied voltage ranges used, photons do not play any role in SQS formation in pure DME.
Charge distributions observed on all three diameter wires with DME filling irradiated by $^{55}$Fe x-rays are not fully understood. Increasing high voltage resulted first in the appearance of a tail on the upper portion of the charge spectrum, followed by a second peak overlapping that tail. All signals moved up into the second peak upon further increase of high voltage. This could be interpreted as a transition from a proportional to SQS mode, however the observation of signals on the oscilloscope did not provide clear evidence for this premise.

The observed difference in charge characteristics of chambers, filled with iso-C$_4$H$_{10}$ and DME and irradiated with alpha particles, are most likely due to the different electron drift velocities in the two gases and as a result, different space charge development dynamics.

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